Programme Area: Energy Storage and Distribution

Project: Consumers, Vehicles and Energy Integration (CVEI)

Title: D1.3. Market Design and System Integration (summary report)

Abstract:

This report represents Deliverable D1.3, Market Design and System Integration. The purpose of this report is to illustrate structures that can facilitate efficient, mass-market, deployment and use of Ultra-Low Emission Vehicles (ULEV) and their integration into the energy system and to help inform the high level design parameters of the trial to be conducted in Stage 2 of the project.

This document should be read in conjunction with the D4.2 Final Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure Report, from WP4 as the information in D4.2 has been used to inform the scope of analysis conducted in WP1a. From the review of evidence to date it was clear that there had been limited work undertaken to explore how mass-market roll-out and use of ULEVs could be facilitated when considering a more holistic assessment across the four key dimensions of the:

- Customer Proposition.
- Physical Supply Chain.
- Commercial Value Chain.
- Market and Policy Framework.

Context:

The objective of the Consumers, Vehicles and Energy Integration project is to inform UK Government and European policy and to help shape energy and automotive industry products, propositions and investment strategies. Additionally, it aims to develop an integrated set of analytical tools that models future market scenarios in order to test the impact of future policy, industry and societal choices. The project is made up of two stages:

- Stage 1 aims to characterize market and policy frameworks, business propositions, and the integrated vehicle and energy infrastructure system and technologies best suited to enabling a cost-effective UK energy system for low-carbon vehicles, using the amalgamated analytical toolset.
- Stage 2 aims to fill knowledge gaps and validate assumptions from Stage 1 through scientifically robust research, including real world trials with private vehicle consumers and case studies with business fleets. A mainstream consumer uptake trial will be carried out to measure attitudes to PiVs after direct experience of them, and consumer charging trials will measure mainstream consumer PiV charging behaviours and responses to managed harging options.

Consumers, Vehicles and Energy Integration Project: TR1006_D1.3. Market Design and System Integration

Summary

CLIENT: Energy Technologies Institute

DATE: 03/04/2017

This report is delivered under the Consumers, Vehicles and Energy Integration project, commissioned and funded by the Energy Technologies Institute

Version History

Version	Date	Description	Prepared by	Approved by
V1_0	11/11/2016	Draft	JG, EP, NB, OR (Baringa) CC, TD, AS (Element Energy)	DS (Baringa) SS (TRL)
V2_0	03/04/2017	Final	JG, NB, OR (Baringa)	SS (TRL)

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0 Acronyms

A list of key acronyms used in this summary document is provided in Table 1.

Table 1 List of acronyms

Item	Description
BaU	Business as Usual (Narrative)
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CPAT	Commercial, Policy and Accounting Tool
CVEI	Consumers, Vehicles and Energy Integration (Project)
DNO	Distribution Network Operator
DSO	Distribution System Operator
DM	Demand Management
ESME	Energy System Modelling Environment
ECCo	Electric Car Consumer Model
ETI	Energy Technologies Institute
FCV	Fuel Cell Vehicle
ICEV	Internal Combustion Engine Vehicle
MCPT	Macro Charging Point Tool
MEDT	Macro Electricity Distribution Tool
MHDT	Macro Hydrogen Distribution Tool
MLDT	Macro Liquid Distribution Tool
PiV	Plug-in Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
SMC	Supplier-Managed Charging
SO	System Operator
ToU	Time of Use
TCO	Total Cost of Ownership
TNO	Transmission Network Operator
TSO	Transmission System Operator
ULEV	Ultra-Low Emission Vehicle (zero tailpipe emission)
UMC	User-Managed Charging
VAT	Value Added Tax
VED	Vehicle Excise Duty

1 Context

Light vehicles contribute around 15-20% of UK CO_2 emissions and are a major contributor to congestion and urban air quality. Light vehicles are likely to remain central to UK mobility over the coming decades, and therefore the importance of decarbonising this sector is widely recognised. Indeed, even under the most optimistic of scenarios for greenhouse gas emission reduction in other sectors, it will be necessary to materially reduce the CO_2 impact of light vehicles to meet the UK's 2050 emissions targets. Quicker progress in decarbonising the power and industrial sectors means that the transport sector now has the highest annual greenhouse gas emissions of all sectors in the UK[1].

The Energy Technologies Institute (ETI) has already completed and published major work, set out in its report 'Transport: an affordable transition to sustainable and secure energy for light vehicles in the UK'. This explored the associated challenges of a transition to low carbon vehicles in the context of overall energy system decarbonisation and defined a clear, strategic, least cost and least risk pathway for this transition. To build on previous work, the ETI has commissioned and funded the Consumers, Vehicles and Energy Integration (CVEI) Project, with the aim of examining how to deliver mass deployment and use of Ultra-Low Emission Vehicles (ULEVs) in the UK. It is focused on cars and light vans – including Plug-in Hybrids (PHEVs), Battery Electric Vehicles (BEVs), hydrogen Fuel Cell Vehicles (FCVs) and Internal Combustion Engine Vehicles (ICEVs) – and addresses the challenges and opportunities of ULEV integration with the full energy system over the period from 2015 to 2050.

This report is a summary of the full deliverable *D1.3 Market Design and System Integration Report*.

All projections of monetary value in this report are in real 2014 price terms.

[1] Emissions are discussed in more detail in section 5.1.2 of the *D1.3 Market Design and System Integration Report*.

2 Aims

The purpose of this deliverable is two-fold. One objective is to help understand the most promising market and policy framework and energy system requirements to facilitate the integration of ULEVs in the energy system. Another objective is to help inform the high-level design parameters of a subsequent (Stage 2) trial involving Plug-in Vehicles (PiVs) (i.e. PHEVs and BEVs) and *mainstream* consumers (represented by a large, diverse, 'majority' group of consumers that comprise the mass-market).

In this project, a 'good' solution is defined as one that attempts to strike an appropriate balance of decarbonisation in transport versus the wider system at a low overall cost, and in a manner that successfully engages private consumers and fleets to achieve critical mass-market uptake and use of ULEVs at the appropriate points in time (e.g. balancing the need for anticipatory investment as an enabler versus the risk of stranding from making key decisions too early).

The analysis aims to provide a holistic assessment of what 'good' looks like for successful mass deployment and use of ULEVs, considering four key areas:

- The ***Customer Proposition*** that is seen by private consumers and fleet managers (for cars and vans)
  - What propositions may private consumers and fleet managers be presented with for vehicles and associated energy use (including direct costs and non-monetary factors such as access to infrastructure), and how will they respond?
- The technologies and infrastructure associated with the ***Physical Supply Chain***
  - What new infrastructure is needed to deliver the Customer Propositions, considering reinforcements in the existing energy system and specific new developments such as electricity charging points for PiVs and hydrogen distribution channels?
- The entities on the ***Commercial Value Chain*** delivering the Customer Propositions and Physical Supply Chain, including an analysis of business models
  - What do the cash flows and returns look like for these entities, e.g. new charging point operators or Demand Management (DM) aggregators, and what does this mean for the consumer costs of owning / leasing and operating a vehicle?
- The ***Market and Policy Framework*** implemented by Government and others (such as local authorities)
  - What is the right set of regulatory incentives to deliver the required infrastructure in a timely manner in order to meet policy aspirations and customer requirements?
  - What are the implications for Government net tax and spend?

There has been very limited work to date trying to frame a holistic, quantitative, and forward-looking assessment of how mass-market ULEV uptake and use can be facilitated, considering all of the four key areas of interest to try to understand the potential interactions and trade-offs that may be required. This is largely driven by the fact that deployment to date has been limited and future studies have tended to focus on a small number of elements to make the analysis more tractable. Similarly, previous trials have only covered PiV 'Innovators' who are unlikely to be representative of the broader population.

3 Analytical framework

In order to understand the most promising structures to facilitate efficient, mass-market, deployment and use of ULEVs and their integration into the energy system, an analytical framework was created. This framework allowed testing of different scenarios (or 'Narratives') in order to provide a holistic, multi-criterion assessment of what 'good' looks like for successful mass deployment and use of ULEVs. The analytical framework has been used to further understanding of how effectively the choices fit together across the four overarching areas that are being considered[2].

The analytical framework is an integrated, holistic suite of modelling tools, which broadly divide into three groups:

- Tools used to assess the use of technologies and scale of underlying investment on the ***Physical Supply Chain***. This is bounded by the use of the ETI's whole energy system model Energy System Modelling Environment (ESME), which gives a consistent picture of how the UK can meet its greenhouse gas targets in a feasible manner, for both transport and the wider energy system. As part of this it provides internally consistent estimates of, for example, wholesale electricity and hydrogen costs which are used elsewhere by the other tools.
  - By considering the whole system, ESME is naturally less detailed on a sector by sector basis and it is supplemented by tools to understand the costs of infrastructure investment for electricity (via the Macro Electricity Distribution Tool - MEDT), hydrogen distribution (via the Macro Hydrogen Distribution Tool - MHDT), liquid fuels (via the Macro Liquid Distribution Tool - MLDT) and charging infrastructure (via the Macro Charging Point Tool - MCPT).
  - In a similar manner, PLEXOS is used as a means to explore the operational feasibility of the electricity system in more detail. PLEXOS is not part of the core suite of tools and is used in selected Narratives only.
- A tool to understand the response of consumers and fleets to different ***Customer Propositions*** (price and other behavioural aspects such as perception of access to charging) on the uptake and utilisation of ULEVs.
  - This is based on the Electric Car Consumer Model (ECCo), which models a range of power trains beyond electric vehicles, including hydrogen.
- A Commercial, Policy and Accounting Tool (CPAT) - to represent the flows across the ***Commercial Value Chain*** as this acts as two-way interface between the demands placed on the Physical Supply Chain by the uptake and use of ULEVs and the prices seen by the end ULEV-consumers as part of the Customer Proposition.
  - The CPAT tool calculates the cash flows for (and between) each of the business entities considered (e.g. to recover the investment in developing and operating infrastructure and energy supply, and to provide various ULEV-related goods and services). From this it constructs an estimate of the retail prices that need to be charged to attempt to make these entities commercially viable.

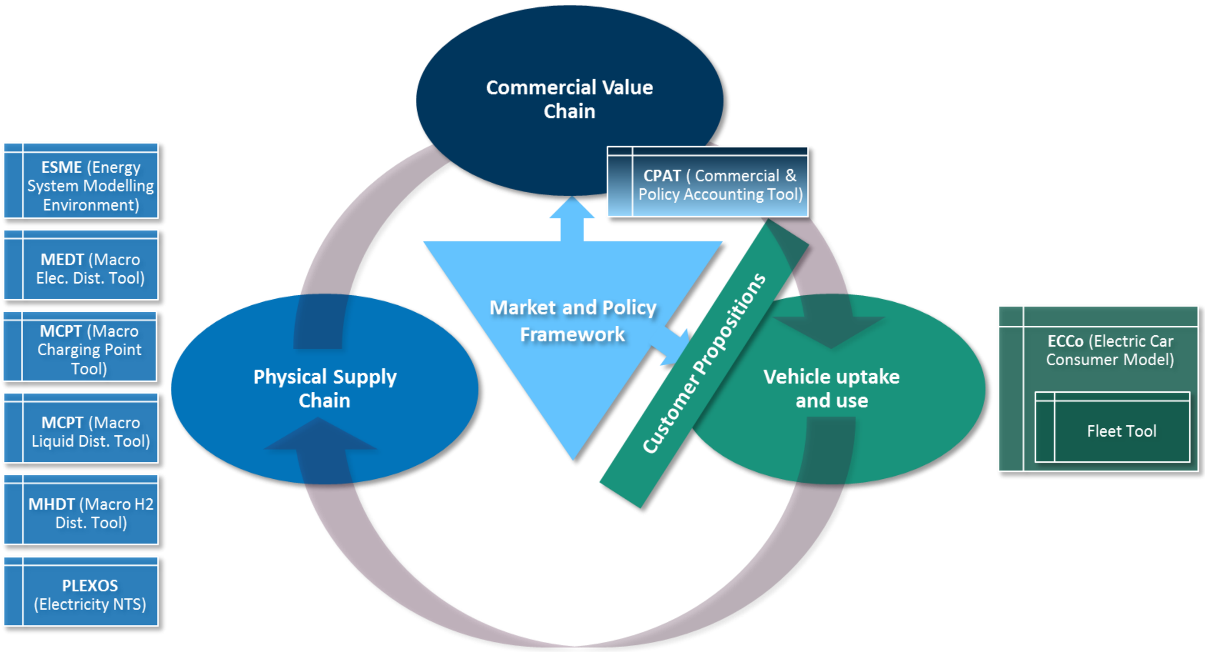
[2] The analytical tools used are described in detail in Appendices A to D of the *D1.3 Market Design and System Integration Report*.

- The ***Market and Policy Framework*** is also included within CPAT, both to track various transport-related Government revenue streams (taxes, subsidies, wider investments), but also because the impact of Government policy acts either directly on commercial entities or at the intersection point between the Commercial Value Chain and the final price the consumer sees (e.g. in the form of VAT).

The analytical tools are used in an integrated manner to assess each Narrative. The tools are run in a sequential loop for each Narrative until a convergence criterion is met (the number of remaining conventional vehicles in the parc in 2050) which reflects an overarching supply / demand equilibrium position for the scale of the market for ULEVs (i.e. the uptake) and the price of the Customer Propositions.

The alignment of the tools to the key areas is illustrated in Figure 1[3].

Figure 1 Overview of analytical tools



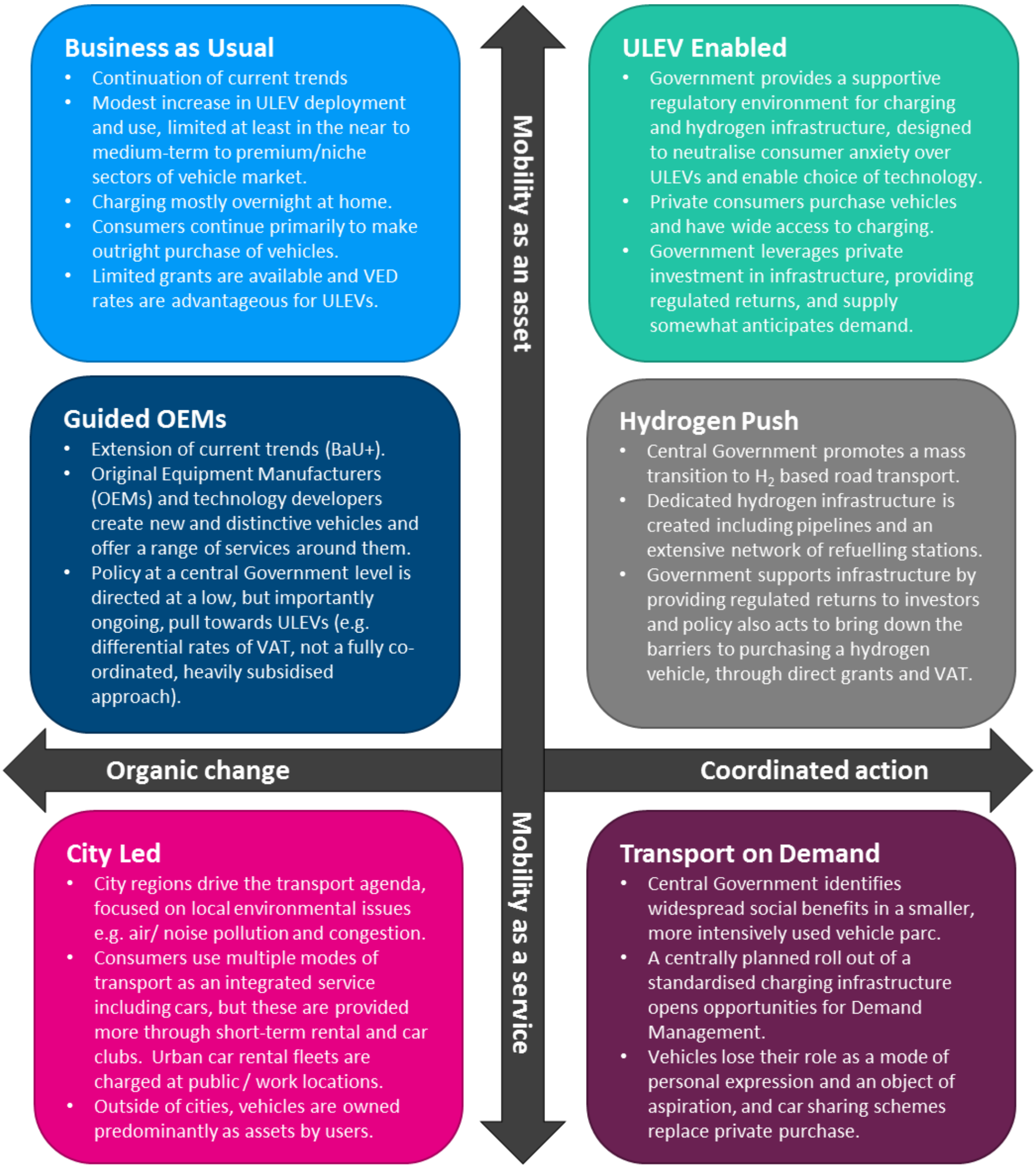
[3] More information, together with a schematic showing the interactions between the analytical tools is shown in section 4 of the *D1.3 Market Design and System Integration Report*.

3 Using the framework

The ultimate aim of the analytical framework is to analyse, compare and contrast different Narratives against each other in order to understand the aspects that may facilitate better successful mass-market deployment and use of ULEVs, and where any particular trade-offs or key decision points may occur.

Six detailed Narratives, including a Business as Usual (BaU) case, have been developed and quantified to explore possible future worlds for ULEV deployment and use (including uptake), and these are summarised in Figure 2.

Figure 2 Summary of the six Narratives



The Narratives have been developed in a systematic way, using both ‘top-down’ and ‘bottom-up’ approaches.

The ‘top-down’ approach was used to identify two overarching axes framing important and opposing themes that could shape the evolution of the domestic and fleet transport sector. The axes are:

- ***Organic Change vs. Coordinated Action***, i.e. the extent to which the pathway is driven by consumer choice and the actions of market agents versus Government / regulatory intervention and active incentivisation of ULEVs (potentially targeting particular ULEV technologies), and
- ***Mobility as an Asset vs. Mobility as a Service,*** i.e. addressing upfront barriers to ULEV adoption when vehicles are owned by users versus the ongoing barriers to ULEV adoption when vehicles are treated as shared assets and accessed as required.

The ‘bottom-up’ approach identified ***between 20 and 40 distinct ‘components’ in each of the four key areas***, grouped into categories, e.g. the ‘fuel pricing options’ category in the Customer Proposition area contains flat tariffs, static Time of Use (ToU) tariffs, dynamic ToU tariffs, Demand Management payments and use of vehicle-to-grid. Components have been assigned to the Narratives in a way that appropriately reflects the position of the Narrative on the two axes. An illustration of some of the quantitative components of the Customer Proposition and their assignment to the Narratives is provided in Table 2[4].

Table 2 Example quantitative components considered for the Customer Proposition

<table>
<tr><th>Narrative</th><th>BaU</th><th>Guided OEMs</th><th>City LED</th><th>ULEV Enabled</th><th>Hydrogen Push</th><th>Transport on Demand</th></tr>
<tr><td>Position of Narrative on axes</td><td colspan="2">Organic, Mobility as an Asset</td><td>Organic, Mobility as a Service</td><td colspan="2">Coordinated, Mobility as an Asset</td><td>Coordinated, Mobility as a Service</td></tr>
<tr><td>Outright purchase vs. contract purchase/ hire</td><td>Fleet leasing, consumer purchase</td><td colspan="2">2-4 year lease depending on user group to overcome upfront cost barrier</td><td colspan="2">As per BaU - upfront purchase with Government subsidies overcoming cost barrier</td><td>2-4 year lease depending on user group to overcome upfront cost barrier</td></tr>
<tr><td>Short-term hire/car club</td><td colspan="2">N/A</td><td>Car sharing (urban areas)</td><td colspan="2">N/A</td><td>Extended car sharing[5]</td></tr>
<tr><td>Charging</td><td>Flat tariff as per standard domestic supply contract</td><td colspan="2">Static time of use tariff and User-Managed Charging (UMC)</td><td>Supplier-Managed Charging (SMC) at home / work</td><td>Flat tariff as per standard domestic supply contract</td><td>Supplier-Managed Charging at home / work</td></tr>
<tr><td>Vehicle choice</td><td colspan="2">As current</td><td>Distribution of vehicles favours smaller cars (for car sharing schemes)</td><td colspan="2">As current</td><td>Distribution of vehicles favours smallest cars (for extended car sharing)</td></tr>
</table>

[4] The components are described in more detail in section 3.1.2 of the *D1.3 Market Design and System Integration Report* and their application to Narratives in section 3.4 of the same report.

[5] Part of the Narrative story is to have plenty of public charging and car sharing, thus public charging in subsidised in line with this.

The analytical framework was used to quantify the costs and benefits of each Narrative[6]. In order to draw out key insights and conclusions*, **a number of metrics were assessed across the four key areas**:*

- the proportion of vehicle km (vkm) that are 'low-carbon' in 2050 (%),
- light vehicle transport cost in 2050 (pence/vkm),
- the cost of remaining light vehicle CO_2 emissions (£billion (bn)),
- total subsidy needed to support infrastructure development (£bn), and
- impact on Government revenues from the transport sector accounting for subsidies and relevant taxes (£bn).

Many of these are considered over the pathway to 2050 and at the end of the pathway, to establish how effective the Narrative is in the facilitation of ULEV deployment during this time horizon and what end state the system reaches[7].

This project takes into account the business models of the commercial entities that are involved in the manufacture or sale of ULEVs, the building and operation of infrastructure and the supply of energy, specifically the:

- charging point operators,
- hydrogen refuelling station operators,
- localised hydrogen producers,
- hydrogen distributors (who may use tankers and/ or pipelines),
- Demand Management aggregators,
- electricity suppliers, and
- Distribution Network Operators (DNOs).

The analysis has focused on the viability of UK-wide 'generic' entities in its holistic assessment of the system; the actual cash flows may differ between individual entities.

Sensitivity analysis has been used test how resilient a given Narrative might be to changing external conditions. The conditions that have been explored are: a greater need for decarbonisation from transport (for example if Carbon Capture and Storage (CCS) fails to materialise); higher and lower liquid fuel prices (indirectly making ULEVs more or less competitive); and a slower reduction in ULEV vehicle prices[8].

Private consumers are assumed to base their decision on whether to purchase a ULEV upon several attributes such as cost, the extent of available charging infrastructure, driving range, and the

[6] The analytical tools used are described in detail in Appendices A to D of the *D1.3 Market Design and System Integration Report*.
[7] The quantitative key metrics are set out for each Narrative in section 5.2 of the *D1.3 Market Design and System Integration Report*, together with an indication as to whether the Narrative scores poorly or favourably on each metric relative to other Narratives. A more detailed description of these metrics, and the qualitative metrics, is provided in section 2.3 of the same report.
[8] The sensitivities are described in more detail in section 3.5 of the *D1.3 Market Design and System Integration Report* and the sensitivity results are set out in section 5.3 of the same report.

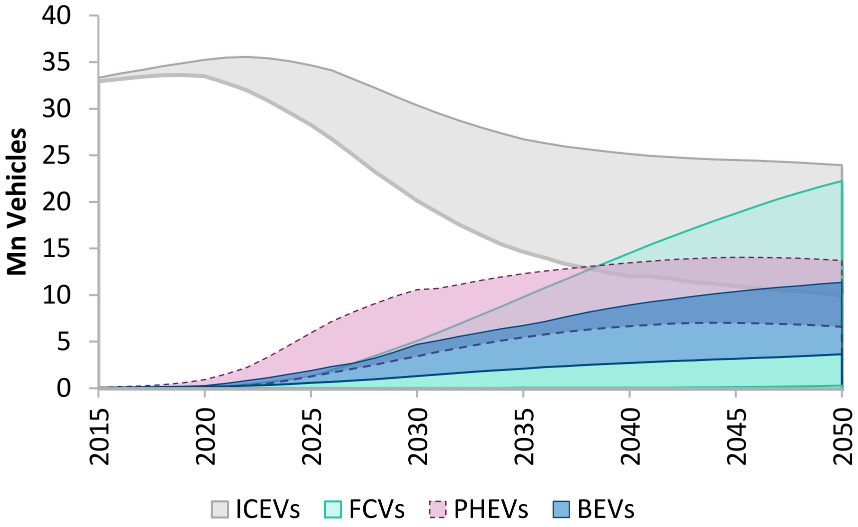
availability of their preferred model or make. For cars, private consumers are further divided into six consumer segments that have differing attitudes to PiVs. Fleets are separated into company owned cars, for which the driver is given free choice in the purchase decision (i.e. resembling a private consumer) and company owned cars and vans, for which the purchase decision lies with the company or fleet manager and purchase decisions are assumed to be taken on a largely commercial basis (by comparing the total cost of ownership (TCO) of different vehicle types, and evaluating the suitability of vehicle types for the required duty cycle.

3 Key results from Stage 1 analysis

Summary of vehicle uptake and use

The uptake of ULEVs is a key output of the analysis for each Narrative and can be used to assess the effectiveness of different development pathways. An overall $MtCO_2$ target is set for the wider energy system and the Narratives meet this in different ways, in terms of the number and type of ULEVs deployed, for a defined transport service demand (in vkm). By 2050, across the Narratives, there is a range of 4 to 11 million (mn) BEVs in the parc, 7 to 14 mn PHEVs, <1 to 8 mn FCVs (with one Narrative that has a strong push towards hydrogen reaching 22 mn FCVs) and a decline in ICEVs from 33 mn to between 10 to 24 mn as illustrated in Figure 3.

Figure 3 Uptake of different vehicle types across the Narratives



With these levels of ULEV uptake, a significant proportion (38 to 68%) of all light vehicle km driven in 2050 are 'low-carbon'[9]. The reduction in the associated light duty transport emissions is substantial, with emissions falling from 88 $MtCO_2$/year in 2015 (taken from the analysis and associated with light vehicles specifically) to between 16 and 32 $MtCO_2$/year in 2050. This occurs despite a significant increase in vehicle km travelled, from around 490 bn vkm in 2015 to 660 billion vkm in 2050 in all Narratives except those with car sharing.

The associated undiscounted cost of the remaining CO_2 emissions in the light vehicle sector ranges from £5 to £9 bn/year in 2050. This represents the 2050 volume of tCO_2 emissions at the 2050 carbon price. The price is dictated by the wider energy system, including transport, whereas the volume of emissions is driven by ULEV uptake. The cost of remaining emissions in 2050 is much

[9] The results are described in more detail in section 5 of the *D1.3 Market Design and System Integration Report*. This includes results on the vehicle parc, service demand and sales, the carbon emissions, and the retail fuel and electricity prices. More in-depth results and analysis on particular key 'themes' is set out in section 6, these themes being the role of demand management, infrastructure and energy prices, the effectiveness of Government intervention and the shift towards mobility as a service.

lower than the counterfactual of no further ULEV uptake, i.e. the 2015 volume of emissions at the 2050 carbon price, resulting in a cost of around £23 to £25 bn/year.

Findings related to vehicle uptake and use

- In the near and medium-term the uptake of BEVs and PHEVs is much greater than FCVs. PHEV car deployment tends be similar to BEV car deployment, providing some fuel flexibility and system resilience.
- Van fleets are restricted by their 'duty cycles' (i.e. they must be able to drive the required distance to complete their jobs each day without needing to stop and charge throughout the day) and this tends to reduce the potential role of PHEVs in the van sector because BEVs can be used for short duty cycles, and ICEVs or FCVs can be used for longer duty cycles. As there is no opportunity to charge a PHEV during the duty cycle the proportion of miles driven on electricity is therefore small, which raises their running costs. The proportion of PHEVs in the van parc by 2050 is only 8 to 17% across the Narratives, compared with 16 to 34% in the car parc.
- In the last few years of the pathway there is a gradual decline in the absolute size of the PHEV parc whereas BEVs and FCVs continue to increase. Towards the end of the pathway all Narratives show non-trivial penetration of FCVs. The economics of PHEVs seem less favourable by this time – the battery capacity and range of BEVs is sufficient for the vast majority of journeys and, when insufficient, FCVs can be used (especially as, by this time, the effective retail price of hydrogen is similar to that of electricity, accounting for the different energy densities and vehicle efficiencies). Aside from the (City Led) Narrative that is specifically designed to test the use of localised hydrogen production with electrolysis, the hydrogen is produced using large, centralised facilities and primarily by gasification-based routes with CCS.
- There is a decrease in conventional (ICE) vehicles (even under Business As Usual conditions) driven by the reduction in ULEV costs and the improvement in battery range. However, ICEVs still account for a substantial proportion of the parc in 2050, specifically around a quarter to half of the car parc and between one-third and half of the van parc (the proportion being higher for vans due to the higher cost differential between ULEV and ICEVs).
- There is a decrease in the absolute size of the vehicle parc in later years in the Narratives that incorporate car sharing, although this does not take into account potential modal shifts (e.g. from walking, cycling and buses to cars or vice versa), which have not been considered as part of this project.
- Moderate uptake of ULEVs by consumers and fleets is seen in the Business as Usual Narrative with limited Government intervention and uptake can be increased with a greater extent of intervention.

Scale and cost of the supporting infrastructure

- The charging infrastructure needed to support the ULEV uptake levels consists of various types of charging point networks: public (ranging from around 75,000 to 2,450,000 installed charging points in 2050), workplace (from around 210,000 to 1,000,000), rapid (from around 5,000 to 45,000), and home (a charging post is built for each PiV that charges at home). The wide range in the number of charging points needed is dependent on the level of PiV uptake and the Narrative, for example, more public charging is installed in a Narrative that supports extended car sharing. PiV owners who store their vehicles at home overnight, such as private consumers and some fleet vehicle drivers, carry out the majority of their charging there and are all assumed to have a home charging point installed. The capital cost to install the charging infrastructure ranges from £0.3 to £3.8 bn across the pathway to 2050 in present value terms (including upgrades needed for the distribution network).

- Hydrogen tankers are used in all Narratives, with the number in operation reaching up to 4,500 by 2050. The tankers transport hydrogen to refuelling stations of which there are up to around 9,400 by 2050 in the Narrative that has a strong coordinated push to hydrogen (Hydrogen Push) – these refuelling stations range in size from 200 to 1000 kg/day. Both new-build transmission and distribution hydrogen pipeline networks are built in selected Narratives, covering 4,300 and 12,700 km respectively. Without hydrogen pipelines, the cost of the remaining hydrogen infrastructure (including a significant proportion of localised production in a selected Narrative (City Led)) ranges from £1 bn to £2.7 bn in present value terms across the pathway to 2050. With hydrogen pipelines, the capital expenditure ranges between £10 and £33 bn depending on the scale of the network. Although the capital cost of the pipelines is greater than that of the tankers, the pipeline lifetime is much longer at around 40 years (and can potentially be extended further with some refurbishment cost) versus the 15 year lifetime of the tankers. The operating cost is around 2 to 3% of the capital cost for both the pipelines and tankers, however, there are additional 'driving' costs (for the fuel and personnel) that will be incurred when using tankers.

Note that the findings related to vehicle uptake and use, and the scale and cost of the supporting infrastructure, generally describe the pathways or end points of the Narratives. They are primarily based on the Physical Supply Chain (i.e. the vehicles and infrastructure) rather than the Customer Propositions, the Market and Policy Framework that is implemented, or the viability of the entities on the Commercial Value Chain that enable uptake and use of ULEVs. However, key messages have been derived for all of these areas and have been used to develop the roadmap, which is discussed in section 4[10].

[10] The key messages are set out in section 5.2 of the *D1.3 Market Design and System Integration Report* for each of the four key areas. The uncertainty associated with these key messages is discussed in section 5.6, together with an explanation of the modelling and data limitations.

4 Roadmap / recommendations

The analysis has been used to identify potential elements of a 'good' solution and to set these out on a roadmap, shown in Figure 4[11]. The roadmap gives broad timing guidelines both for when Government intervention is required and when key industry participants should act.

The individual elements of a 'good' solution have been categorised as follows:

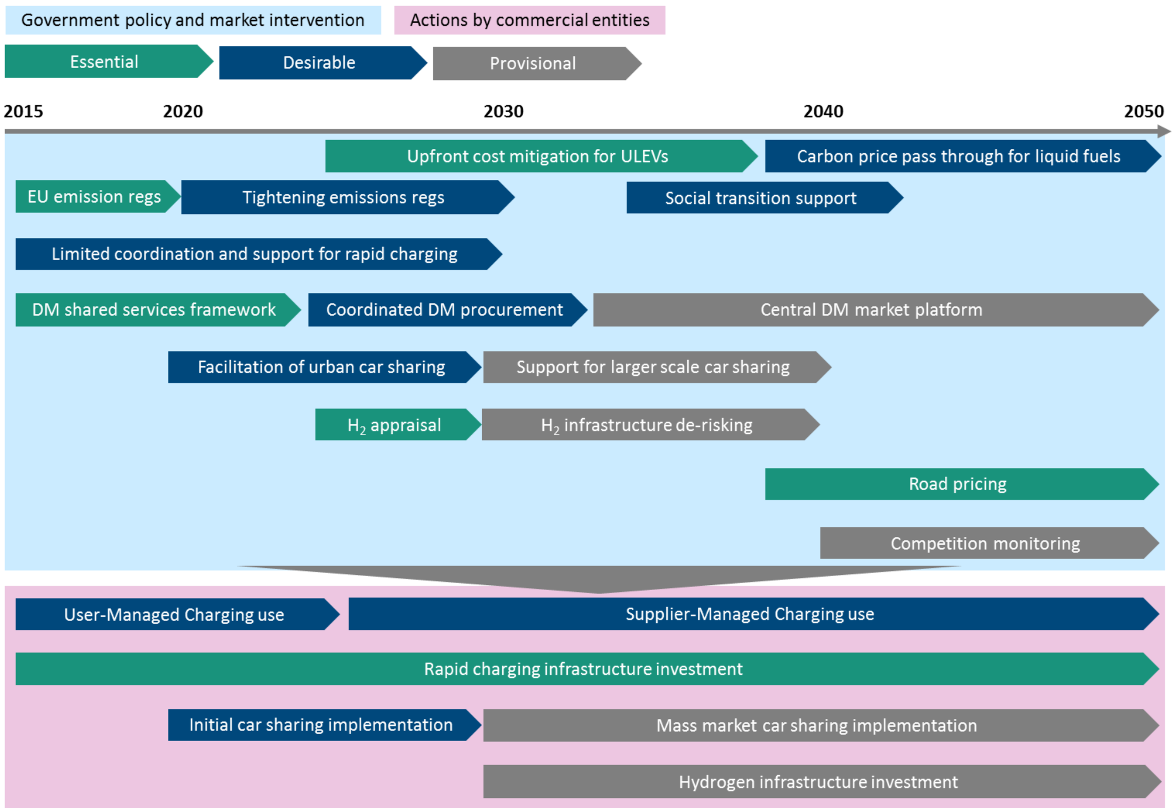
- **Essential** – these actions have been clearly identified as good, and found to be robust to different circumstances explored through the Sensitivity analysis. They are considered to be no or low regret actions.
- **Desirable** – actions for which a strong case exists and which are likely to have a positive impact under most circumstances. However, a failure to employ these actions is unlikely, by itself, to lead to a failure to achieve mass uptake and use of ULEVs. Additional evidence or reduced uncertainty may also be desired by individual actors before a decision to implement them.
- **Provisional** – an additional categorisation implying actions for which a positive case may exist, but for which the extent or timing of deployment is likely to depend on reduction of uncertainty in the basis of analysis. This may occur through the passing of time and, for example, realisation of outturn costs. It may alternatively occur through obtainment of additional or expanded evidence from trials or initial pilot scale deployment.

This section discusses the essential, desirable and provisional elements, along with a number of elements that are deemed to be ineffective or unnecessary in reaching a 'good' solution. The risks and barriers associated with the key elements of a 'good' solution were assessed qualitatively and taken into account in constructing the roadmap[12].

Whilst the roadmap is forward looking, it does take today's market and policy landscape as a starting point. Existing policies have primarily centred on reducing the upfront cost of ULEVs through the provision of grants (Plug-in Car, Van, Motorcycle Grants), incentivising the installation of charging points, for example with match funding through the Plugged in Places scheme, and funding a range of innovative projects to support uptake in cities via the Go Ultra Low Cities scheme[13].

[11] The roadmap is also discussed in section 5.5 of the *D1.3 Market Design and System Integration Report*.
[12] The risks and barriers relating to Demand Management, infrastructure investment, car sharing, mitigating the upfront cost of ULEVs, and mitigating a decline in tax revenues are discussed in detail in section 7 of the *D1.3 Market Design and System Integration Report*.
[13] More information on different market and policy measures can be found in the *D4.2 Final Analysis of Technology, Commercial and Market Building Blocks for Energy Infrastructure Report* and the supporting *D4.2 Building Blocks Catalogue* spreadsheet, including the results of a literature review focused largely on aspects of the Consumer Proposition.

Figure 4 Roadmap for efficient ULEV deployment and use



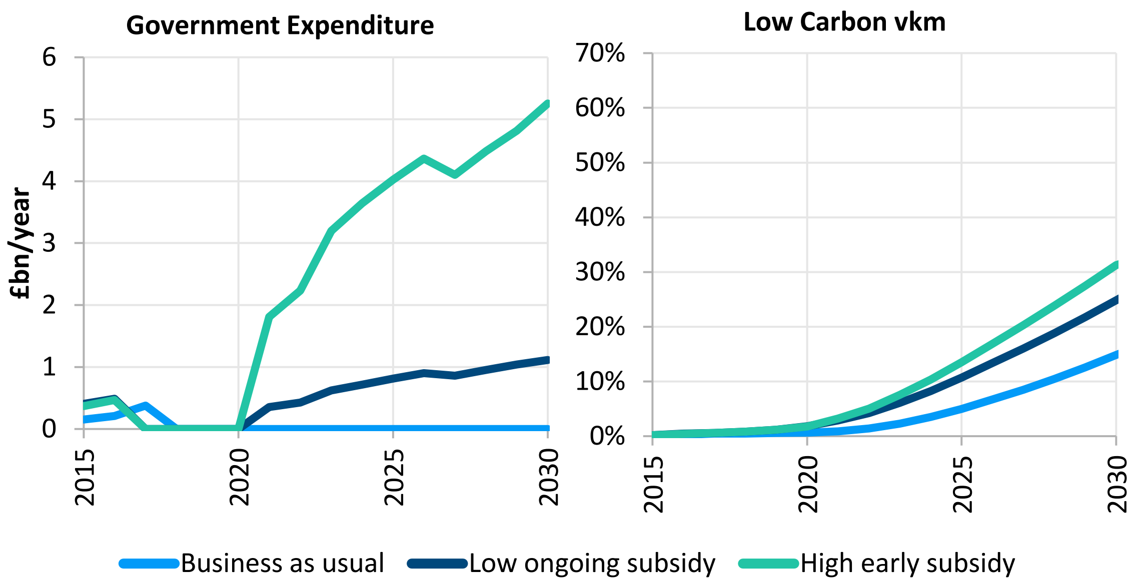
Essential elements (and associated provisional support)

Upfront cost mitigation for ULEVs

Reducing upfront ULEV costs (via subsidy, VAT differentiation and / or leasing) is crucial to driving enhanced uptake particularly in the near to medium-term.

- The implementation of Government subsidies has a significant impact on the uptake as shown in Figure 5, in which the proportion of low-carbon vehicle km is higher in a world with 'low ongoing subsidy' (£500 per ULEV car upon purchase) as opposed to no subsidy beyond the current PiV schemes (Business as Usual). However, relatively high subsidies appear to be less effective when compared to the additional cost that Government is likely to face in order to implement them. This is implied by the comparison of the Government expenditure and low carbon vkm in the (ULEV Enabled) Narrative with a 'high early subsidy' (£2000 per ULEV car) with that in the (Guided OEMs) Narrative with a 'low ongoing subsidy'. Subsidies are a key driver of ULEV uptake but the uptake is also a function of other factors that have been implemented in the Narratives.

Figure 5 Early Government expenditure on vehicle grants and electricity or fuel subsidies versus the proportion of low-carbon vkm achieved in selected Narratives



EU emission regulations

It appears unnecessary to subsidise too much and too soon *(given more cost effective sources of carbon abatement elsewhere in the energy system, such as buildings and the power sector)* ***provided that there is a reasonable underlying regulatory driver (e.g. in the form of tightening new vehicle CO_2 targets) to encourage innovation and learning in the near-term that consequently reduces the cost of ULEVs****.*

- Delaying the introduction of subsidies until the late 2020s would ensure that the momentum in early uptake is not lost without overly subsidising carbon abatement through transport. By this time, the wholesale cost differential between ULEVs and ICEVs should have narrowed, effectively reducing the upfront cost 'barrier' associated with ULEVs. Other sectors will have undergone some decarbonisation by this point and further abatement from such sectors is likely to be more costly and much closer to the cost of decarbonisation of the transport sector.
- Barriers to the implementation of a support (subsidy) scheme revolve primarily around political questions of spending priorities. A well-designed support scheme would have the objective of establishing a competitive position for ULEVs in the vehicle market around the 2030s, after which the emphasis of policy intervention would switch towards disincentivising ICEVs. Regardless of the specific structure, the scheme should allow entities to innovate and to adapt to evolving market conditions and should not over-subsidise the value chain as this may not drive entities to decrease costs and may breed an industry dependent on Government support. A 'degression' mechanism could provide a model for adjusting the value of support offered under a subsidy scheme and, if the step down is done in a mechanistic and forecastable way, could provide a signal to industry on the need to innovate and reduce costs. It may be preferable, for social policy reasons and uptake, to focus the support provided on lower priced models and / or the second-hand

market to make ULEVs more accessible to a greater cross section of society rather than favouring certain sectors, such as higher income groups.

- The effectiveness of reducing the upfront cost will depend on the transport landscape (for example, if extensive car sharing materialises then it may be more important to target the reduction of the short-term hire costs instead).

Rapid charging infrastructure investment

For private consumers (and home-based fleets), the primary place of charging is at home and having access to overnight charging is key. To supplement home charging points and give certainty of access to charging outside of the home, a widespread, dense network of non-home charging points is desirable in the near to medium-term. This should focus on the development of (public) rapid charging (i.e. 50kW and greater) *as there is a more limited long-term role for (standard) public charging (i.e. up to 22kW) and workplace charging.*

- The long-term case for lower power public or workplace charging is uncertain, and deployment should occur on a commercial basis where it is considered viable. A rapid charging network however appears to have long-term value in enabling PiV uptake and use. Some initial government intervention may be desirable to ensure standardisation (in the absence of this being delivered by industry).
- The analysis shows that the electricity demand is similar at workplace and at rapid charging posts even though there are several times more workplace charging posts installed than rapid posts (e.g. 480,000 vs. 20,000 in Business as Usual by 2050), meaning that the rapid charging posts are better utilised. As a result the business models look consistently positive for the rapid charging point operator across all of the Narratives.

H_2 appraisal | H_2 infrastructure de-risking /investment

In the longer-term, after 2040, the modelled vehicle sales suggest that FCVs may be favoured over PiVs for incremental ULEV uptake. Major decisions on Government support for FCVs and the associated infrastructure can be postponed until the later 2020s or early 2030s *to allow time for uncertainty over long-run costs to reduce. If a strong, coordinated 'push for hydrogen' is preferred (i.e. that includes the use of FCVs instead of, rather than in addition to, BEVs) then decisions may need to be taken earlier, given the time needed to plan and execute large-scale infrastructure projects such as pipeline networks. The potential for a transmission-only pipeline network for hydrogen (supported by local tanker distribution from the transmission network points into urban areas) should be assessed, as this may prove commercially viable in the long-term if the cost can be shared effectively with the other sectors using hydrogen (such as the power sector).*

- The greater cost of FCVs means a decision on enabling actions is not required until the later 2020s or early 2030s. FCVs are assumed to be available for *mainstream* consumers in 2020, by which time the FCV purchase price is expected to have reduced from around £53,000 to £32,000 for a segment C (medium-sized) car through a combination of UK and global innovation. This is still around £9,000 higher than its closest rival, the BEV, and around twice the price of a petrol car. By 2050, the purchase price has declined further to around £24,000 which is considerably closer to petrol cars and BEVs, which at that time are expected to cost around £18,000 and £22,000 respectively.

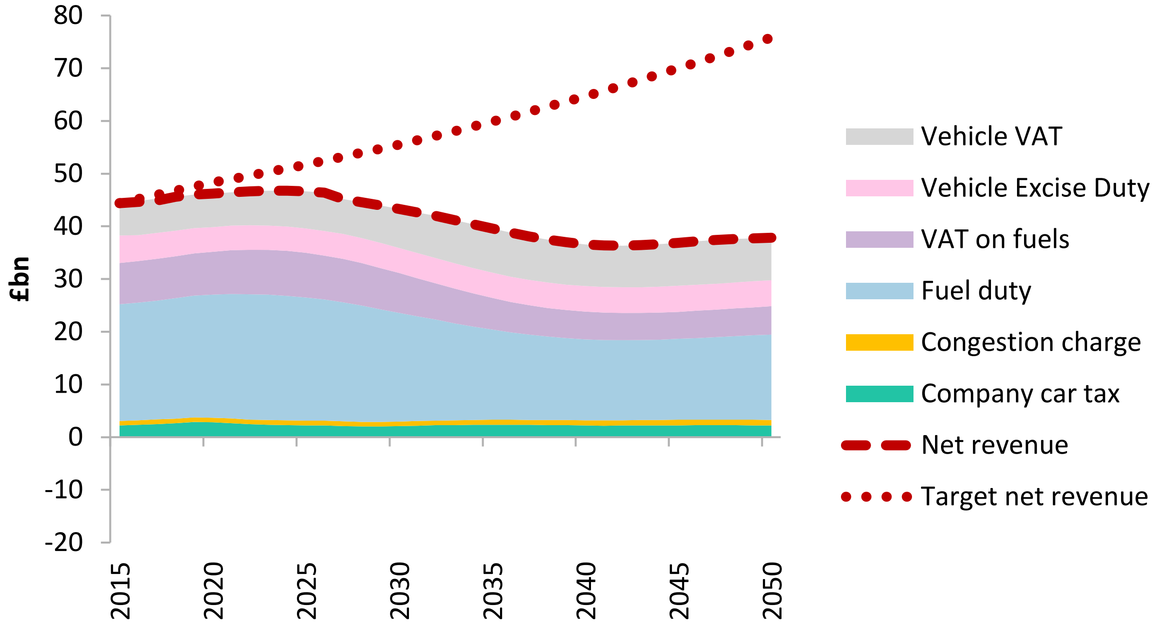
- The convergence in the cost of ownership of FCVs and PiVs is accelerated by the changes in the wholesale fuel costs, which are driven by changes in the wider energy system – under Business as Usual, the wholesale hydrogen price falls from around 128 p/kg in 2020 to around 108 p/kg in 2040, whereas the wholesale electricity price rises from around £87 /MWh in 2020 to around £127 /MWh in 2040 (this price includes the variable, fixed and capital cost of generation). As a result, in 2040 a private consumer would pay 2.9 p/km for the electricity to run a BEV, compared with 2.2 p/km for the hydrogen to run a FCV (on a Total Cost of Ownership (TCO) basis).
- An assessment of the need for FCVs in meeting decarbonisation targets may be required in the early 2020s. If this shows that FCVs are necessary then a full 'H_2 Appraisal' should take place in the mid-2020s. The detail of the appraisal will depend on the market and policy landscape at the time and it should at least incorporate an evaluation by the Government and regulatory authorities of the need to support a widespread hydrogen network, whether that is comprised of pipelines and /or trucks.
- A challenge for providers of hydrogen refuelling infrastructure is that they can expect to operate on low volumes of hydrogen fuel sales initially and consequently prices will need to be high (to recover fixed and capital costs) which may act as a barrier to further growth in sales. In practice, the developers of new infrastructure may need to endure a period of loss making operation (in the absence of a subsidy regime) in order to achieve volume growth and profitability at a later date. This issue will be particularly acute where investment is more 'lumpy' and occurs further ahead of need. As these 'ahead of need' investments will be based on an assumed level of future demand, it is important that there is no uncertainty around policies that affect ULEV uptake as this will only serve to further exacerbate the investment risk.

Road pricing

The market and policy measures implemented, together with the declining ICEV parc, result in a sizeable gap between the net revenues received by Government from the transport sector and a 'target' revenue (based on growth of the current revenues with GDP per capita).

- The present value of the 'gap' in Government revenues over the period from 2015 to 2050 relative to this target ranges from £135 to £378 bn across the Narratives. The Government cash flows in the Business as Usual Narrative are illustrated in Figure **6** (note that there are other measures beyond current schemes that are not included in this Narrative but that are tested in other Narratives, for example a subsidy on fuel and a tax on CO_2). The Government could use other routes to bring down spending or obtain tax receipts from elsewhere in the economy; however, this project has explored options to meet the target revenue for road transport from within the road transport sector.

Figure 6 **Government tax and spend in a 'Business as Usual' Narrative**



The gap between the projected net revenue and the assumed Government target revenue would need to be filled through the use of a technology-neutral mechanism such as road pricing, in order to produce a sustainable and substantial source of tax revenue from the road sector and avoid the long-term revenue cannibalisation that could be expected if only measures that differentiate ULEVs from ICEVs are used *(i.e. the Government may raise taxes on conventional vehicles only in order to increase its revenues, however, there will be a tipping point after which higher taxes could lead to lower uptake of ICEVs thus having the effect of reducing tax revenues overall).*

- A proposed technology-neutral mechanism is road pricing, which would apply to drivers based on their distance travelled. The analysis indicates that the cost of this could range between 0.6 and 1.8 p/km on average across the pathway, representing between 5% and 16% of the actual cost of transport across the Narratives. Extensive taxation of road usage would require new technology, such as increased data telemetry capability in vehicles, but this is expected to become more prevalent in future in any case. Charges could be differentiated by type of road and time of travel to help address congestion, unless simple congestion charges (which could also support long-term revenues) are already in place. It is likely that, since road capacity will not grow to match demand, some mechanism for managing peak road usage will be necessary in order to make use of this very limited resource in an economically efficient manner (regardless of the extent to which the vkm travelled are low-carbon).
- A supplementary per-vehicle annual tax is an alternative structure for a technology-neutral mechanism and the analysis indicates that the tax should range from around £100 to 300 /vehicle/year. This would be a significant increase on the current annual rate of vehicle excise duty, which is to be applied uniformly across all non-zero emission vehicles at £140 /year from 2017 (previously this was differentiated by vehicle, depending on the emissions level). A per-vehicle tax could also change consumer attitudes towards mobility, for example encouraging a shift to car sharing and increased use of public

transport. However, the inability of this type of mechanism to simultaneously tackle congestion and apportion costs to use may make it a less appealing policy option.

- The value of congestion charging is not insignificant, equivalent to around 10% of the revenues from various taxes by the end of the pathway in the Narrative in which it is tested and, although this is second order compared other taxes, it could still be an efficient way of recovering revenues whilst also providing secondary benefits such as reduced congestion.

DM shared services framework

- Once the roll-out of smart metering has occurred, technical barriers to the delivery of ToU tariffs should be low. This should affect the extent of User-Managed Charging (i.e. the assumed consumer response to static ToU tariffs, whereby the consumer shifts their load to cheaper periods, changing their charging profile).
- Supplier-Managed Charging (i.e. more complete load shifting, controlled directly by a third-party acting as a 'Demand Management provider') will require some additional communications infrastructure, for example to understand the state of charge of each PiV and to enable a dynamic response to price signals. This is unlikely to be technically difficult and will require the establishment of standard communication protocols between the on-board vehicle charger, the charging points and the electricity system.
- The wider market arrangements will also need to evolve to ensure that there are clear routes-to-market that enable the use of flexibility provided by Supplier-Managed Charging. The potential stages of development in the regulatory framework for Demand Management are illustrated in the roadmap. The timing is indicative only as development should occur as soon as efficient operation of the market requires it.
  - The first step is to set up and implement a 'DM shared services framework', which would aim to establish coordination between the entities across the Commercial Value Chain that have an active interest in DM. A shared services framework would set out how DM resource could be shared between DNOs and the System Operator (SO), which could be the Transmission System Operator (TSO) and potentially the Distribution System Operators (DSOs, i.e. DNOs that have moved away from only the provision of infrastructure and towards actively managing networks in order to efficiently accommodate multiple sources of generation and demand).
  - The second step, 'co-ordinated DM procurement', would further increase coordination of procurement and operation of DM, with an entity such as the SO responsible for contracting services, and then selling them on to other entities, such as the DNOs, when they need them or place a higher value on them. Such a model would represent a more substantial change to the market framework requiring, for example, reconsideration of price control frameworks.
  - The ultimate step would be the creation of a 'central DM market platform' that allows demand to be optimised across all sellers of DM services and buyers for all purposes, including those with specific locational needs. Developing, operating and regulating such a platform would be complex and costly, and would be provisional on the size and sophistication of the DM market justifying it.

- Current Demand Management trials are largely seeking to address near-term network constraints, using 'command and control' mechanisms to switch off or delay load with the aim of preventing PiVs overloading distribution networks, which will become increasingly important as clusters begin to appear in the early stages of deployment. The technical, regulatory and policy infrastructure related to this requires further consideration. This project has focused on how to address the longer-term challenge, using a Demand Management aggregator to shift PiV charging to lower priced periods, thus simultaneously reducing the peak on the system and the charging cost to the customer.

Desirable elements (and associated provisional support)

User-Managed Charging use | Supplier-Managed Charging use

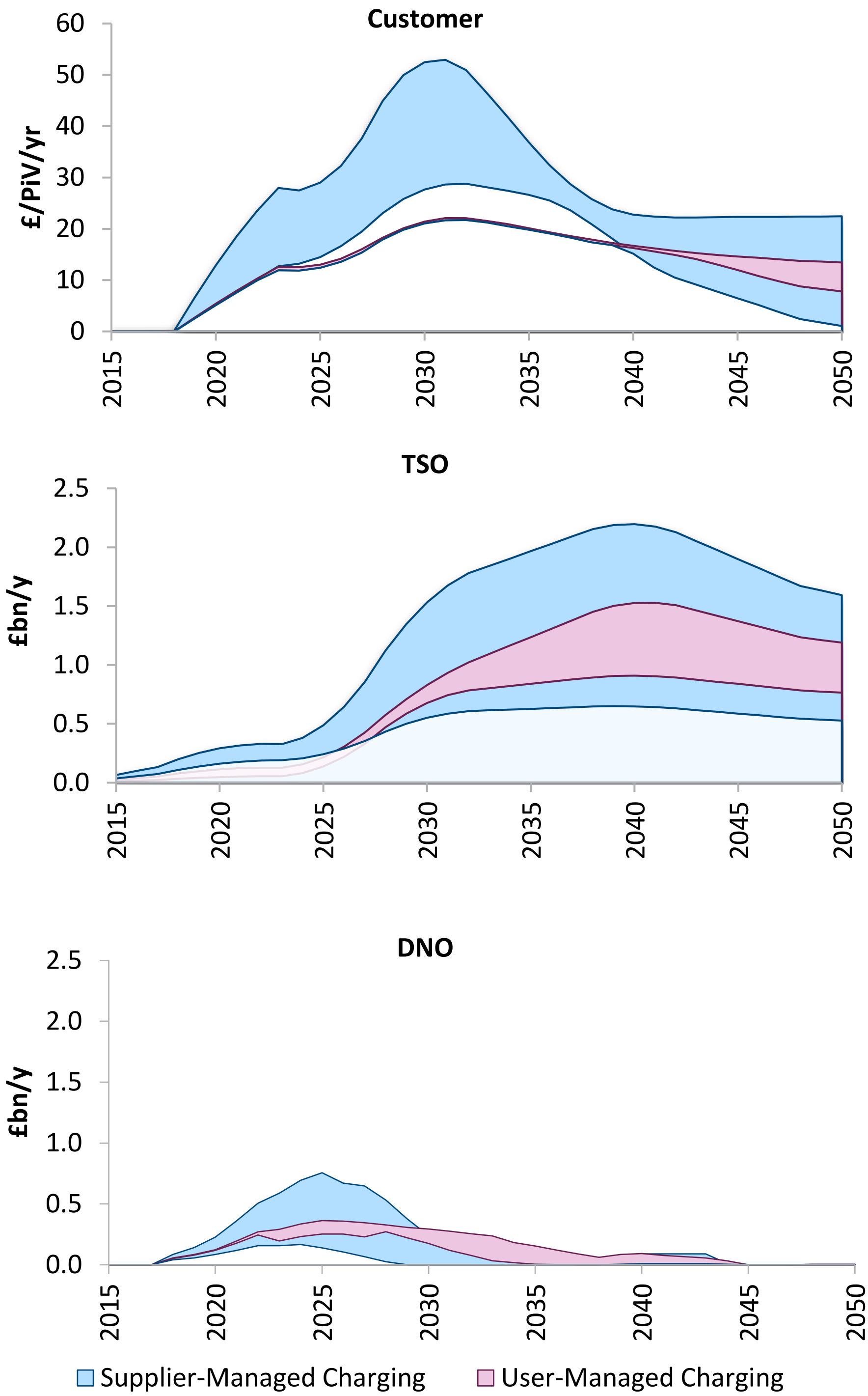
If private consumers and fleets take advantage of Managed Charging propositions, they stand to receive a direct cost benefit, as well as enabling a substantial cost reduction in infrastructure, particularly for the TSO and the DNOs.

- Assuming a 'modest' level of consumer response through User-Managed Charging leads to a sizeable reduction in costs compared to Unmanaged Charging. More significant savings appear possible under Supplier-Managed Charging. The Demand Management aggregator business model appears viable at a high level (subject to the complexities of implementing this in practice) but is dependent on savings from TSO balancing operations rather than avoided network reinforcement in the longer term.
- Across the Narratives in which a form of Managed Charging is implemented, users save on average around £13 to £21 /PiV/year on their charging costs due to load shifting (this represents up to 16% of their annual charging cost) and in addition users benefit from an assumed 'reward' paid by the DM Aggregator in return for their engagement in Supplier-Managed Charging (£50 /vehicle/year for BEVs and £25 /vehicle/ year for PHEVs, excluding car sharing fleets). It does not account for any redistribution of TSO savings, for example, back to private consumers and fleets. At this point in time, there is little evidence that can be used to understand whether the stated levels of savings and rewards would be large enough to encourage consumers to choose a Managed Charging tariff, hence the consumer response to a range of savings will be tested in the Stage 2 trials.
- Potential savings in the costs of balancing the system in the longer-term associated with the TSO are substantial, with the present value of the savings across the pathway accounting for between £7 and £20 bn across the Narratives (at most, with Supplier-Managed Charging, this rises from £330 mn/year in 2020 to £2.3 bn/year by 2040). These are the long-run avoided costs of (more expensive) energy balancing and peaking plant, covering part of the balancing market, short term operating reserve and additional peaking plant. Avoided network reinforcement by the DNOs accounts for savings of between £1 and £4.5 bn. The avoided reinforcement costs for the TNO have also been considered but are negligible by comparison. The network and consumer savings are shown in Figure 7. Note that the Managed Charging profile differs from the Unmanaged Charging profile from 2020 onwards, however, the savings are shown on a 5-year rolling average basis.
- The need for network reinforcement is driven by a mix of the ULEV and wider energy system demand, with electrified heating demand having a relatively significant impact

(contributing around 21 GW to peak demand in the Business as Usual Narrative in 2050 compared to the peak PiV load of approximately 8 GW).

- A key area that will be tested in the Stage 2 trials (for both UMC and SMC) is whether the level of consumer engagement (i.e. the shift in charging) that has been assumed in the modelling is likely to materialise in practice.

Figure 7 Avoided costs for the Customer, TSO and DNO due to Managed Charging



Coordinated DM procurement | Central DM platform

To supplement a DM shared services framework, more complex intervention and market redesign would allow for coordinated procurement and use of electricity for PiV charging through the establishment of a central market platform.

- This would facilitate the trading of the demand for – and supply of – flexible resources (including DM aggregation of PiV charging), allowing the resource to be directed to where it is of most value across the electricity system. The market would need a locational and dynamic element to be added to its design to recognise the localised requirements of the DNOs. Developing, operating and regulating such a platform would be complex and costly, though the cost would not have to be borne only by the transport sector if the platform could also be used to manage heating demand. This step is only likely to be justified once DM becomes a significant activity and the additional benefits from a more efficient market structure outweigh the costs of such a platform.

Tightening emissions regulations

It appears desirable to further tighten national CO_2 limits on new cars and vans beyond the values already set by the EU for 2020/21*, as both a backstop measure to enforce decarbonisation and as stimulus for manufacturer innovation. However,* ***it is important to set a gCO_2/km target that is neither too lax*** *(resulting in very little decarbonisation)* ***or too stringent*** *(where decarbonisation may prove too costly and manufacturers elect to pay a penalty instead).*

- The penalties imposed on the manufacturers relate to the European Commission's 'excess emissions premium', applied as a price of *£70 x gCO_2/km above target x vehicles sold*, however, there may also be other penalties involved in not meeting EU regulations on carbon, or following guidelines on factors such as air quality. The current target is for new cars sold in the EU to emit on average 95 gCO_2/km by 2021 and for new vans 147 gCO_2/km by 2020. In all Narratives, the target is assumed to decrease to 65 gCO_2/km for cars and 100 gCO_2/km for vans (as measured on the New European Driving Cycle test procedure) by 2030 and held constant thereafter
- The total penalty relating to UK vehicle sales ranges from £1.2 to £5.2 bn across the Narratives in present value terms, though this could be higher if the potential cost of reputational damage were also included. As with infrastructure, the manufacturer penalties suggested by the analysis are small compared to the scale of the entities (i.e. having a total present value over the pathway of less than 1% of the revenues associated with the retail of the vehicles across the Narratives with a maximum of 3% in a single year).
- Holding the gCO_2/vkm target flat from 2020 as opposed to tightening it to 2030 leads to around 10% fewer ULEVs in the parc in the Business as Usual Narrative by 2030 (note this is based on a single pass of the model and not fully optimised as with the Narratives). In the model, manufacturers respond to lower CO_2 targets by cross-subsidising their ULEVs with higher-priced ICEVs. Beyond 2025, there are no penalty payments made in Business as Usual, which implies that the rate of emissions reduction is steeper than the target

trajectory thus a much more stringent target would be needed for a more material impact.

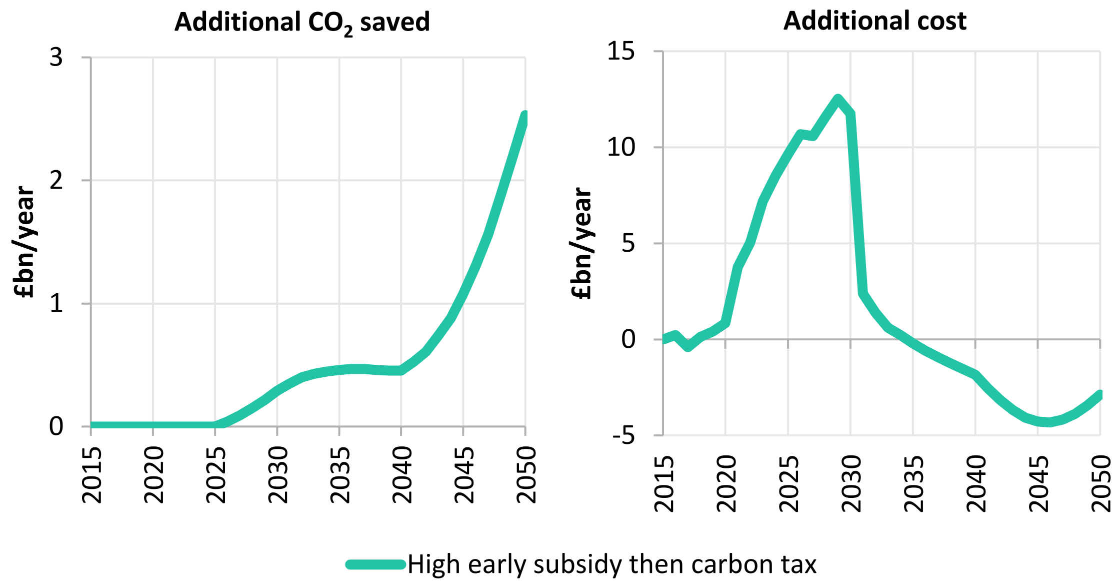
- For vans, a more gradual tightening to 2030/35 may be preferred, due to the greater challenges involved in decarbonising this vehicle segment compared to cars. The near-term cost differentials between ICEV and ULEV vans and the additional restrictions imposed by duty cycles prevent BEV vans from being deployed more widely until there are improvements in driving ranges.

Carbon price pass through for liquid fuels

A long-term CO_2 tax appears to be worth implementing in addition to emissions standards, *to support Government revenues and drive an economically-efficient level of investment in ULEVs and the supporting infrastructure.*

- The push for decarbonisation from ULEVs needs to be considered together with decarbonisation of other sectors such as industry, building heat and power generation. In general, lower decarbonisation of transport (i.e. a lower proportion of low carbon vkm) leads to a higher cost of abatement for the residual emissions.
- The price of carbon (i.e. an economy-wide estimate of what is needed to drive a cost-effective level of decarbonisation across the UK energy system to meet its overarching CO_2 targets) increases gradually in the near to medium-term before increasing more rapidly after 2030, up to £270 /tCO_2 in 2050 in the Business as Usual Narrative. This is due to the increasing cost of further carbon abatement after cheaper options have been exhausted. The higher costs of ULEVs versus conventional vehicles results in a relatively high cost of decarbonisation of road transport in the nearer-term. Therefore it makes sense to carefully balance the level of Government support over the pathway to 2050, to incentivise ULEVs at times when the value associated with the resulting carbon abatement is greatest. Figure 8 compares Business as Usual (in which the value of the CO_2 saved reaches £9 bn/year by 2050) with an alternative Narrative (ULEV Enabled) that has a high early subsidy which is removed in 2030 and replaced with the pass through of the CO_2 price as a tax (applied as a component in the liquid fuel retail price for both petrol and diesel). This shows the impact of shifting away from subsidising ULEVs directly (creating a market pull to ULEVs) to taxing conventional vehicles (creating a market push away from ICEVs) in terms of the value of CO_2 savings (i.e. the combination of the amount of CO_2 saved and the price of CO_2) and the cost of making these savings (i.e. the cost to Government of implementing these policies).
  - Prior to 2030, when there is a market pull, the additional gap in Government revenues (on top of the gap that already exists in the Business as Usual Narrative) is significant due to the high subsidies in place (£2000 per ULEV car and £4000 per ULEV van). However, although the subsidies help drive uptake, they do not drive high CO_2 savings at this time.
  - Post-2030, when there is a market push, the new CO_2 tax on liquid fuel means that the value of the CO_2 savings is greater, whilst the cost to Government is less (in part as subsidies towards the upfront cost of the vehicles are no longer awarded). This indicates that a long-term CO_2 tax could be worth implementing.

Figure 8 Additional CO_2 abated (relative to BaU) and the additional cost to Government of this abatement



Note: The value of CO_2 saved is the additional abated emissions above those in Business as Usual at the carbon price of the Narrative. The cost of saving that CO_2 is represented by the additional gap in Government revenues above that in Business as Usual, which depends on both the subsidies applied and taxes received. As these are Narrative results they also include the effect of other factors that vary between Narratives.

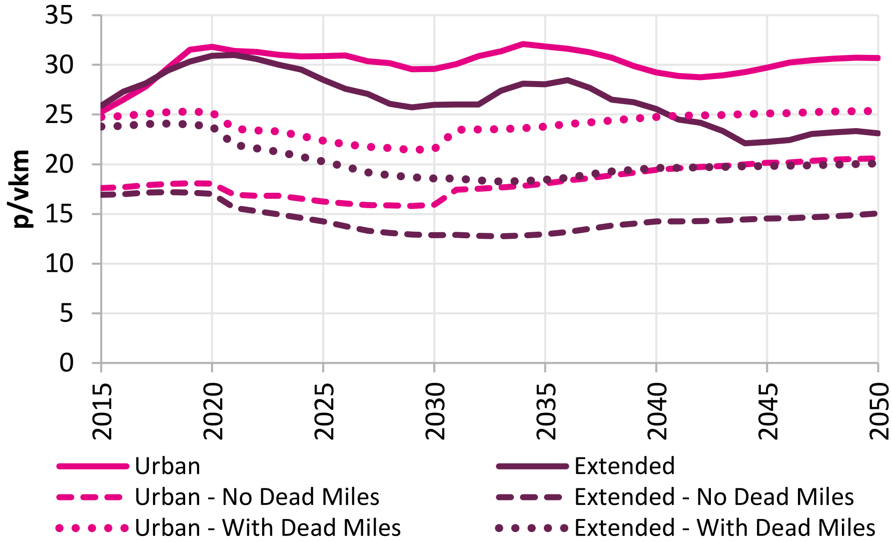
Facilitation of urban car sharing / Initial car sharing implementation	Support for larger scale car sharing/ Mass-market car sharing implementation

***The economics of car sharing appear positive for private consumers,** especially when widespread car sharing is used, though **priority should be given to car sharing in urban areas** as this is likely to lead to more efficient use of the vehicles.*

- ‘Car sharing’ in this context refers to fleets of vehicles that are notionally accessed by consumers hour-by-hour as required, such that vehicles are driven by multiple users throughout the day (i.e. the vehicle assets are shared rather than used solely by one individual). The underlying journey patterns and requirements of the users are maintained (i.e. no modal shifting is assumed). However, there is some accounting for ‘dead miles’ – the miles travelled by the vehicle that are not directly related to the consumer’s underlying service demand, e.g. driving from or returning to a base not fully aligned with the consumer’s desired start or end destinations. Reducing the ‘dead miles’ that these vehicles drive is important as this will reduce the cost of transport further, as shown in Figure 9. This figure shows that, over the majority of the pathway, the average cost per vkm travelled is lower in shared cars than in privately-owned consumer cars. This cost is reduced further with more ‘extended’ car sharing, where shared cars account for almost 70% of the total mileage of all vehicles in 2050, compared to ‘urban’ car sharing, in which shared cars are used to cover nearly 30% of the total distance travelled.
- Technological advancement, specifically the advent of autonomous vehicles, could significantly enhance the prospects of car sharing and enable more efficient and intensive

use of vehicles. From a consumer's perspective, vehicles could then be delivered and deposited at locations of maximum convenience, rather than being tied to docking stations. The implications for vehicle manufacturers are unclear. Greater acceptance of sharing may lead to consumers regarding vehicles as interchangeable, commoditised providers of a service, rather than objects of aspiration or personal expression, which may require the vehicle manufacturers to adapt their business models.

Figure 9   Evolution of costs per vkm for shared cars (dashed without dead miles and dotted with dead miles) versus other cars (solid) – for urban schemes and with more extended use



- Government revenues may be largely unaffected, or even positively impacted, by car sharing despite a smaller overall vehicle parc (although this depends on the taxation policy). For example, under extended car sharing the total parc in 2050 is around one-third less than the parc without car sharing. However, because of higher utilisation the vehicles are generally retired more quickly, leading to a more rapid stock turnover and higher associated levels of VAT on new sales (and leading to higher revenues from road pricing if implemented).

Similarly, leasing models appear desirable from the consumer perspective *due to the shift in costs that the consumer pays from an upfront to an ongoing basis.*

- This has a more positive impact on ULEVs than on conventional vehicles. In 2015 the 'upfront' cost of a BEV is around 90% of the Total Cost of Ownership whereas for an ICEV it is around 70%. The TCO is comprised of the underlying vehicle cost, including VAT and the margins of the manufacturer and retailer, together with the insurance, maintenance, fuel costs and other taxes. Lease payments somewhat mitigate the upfront cost barrier by indirectly forcing the buyer to account for the residual value of the vehicle and thus to recoup around 30% of the upfront cost. To ensure the Narratives are sufficiently distinct, contract (lease) hire is modelled as the alternative to outright purchase. However, consumers could in reality also choose a contract purchase scheme, whereby they still purchase the vehicle after a number of years leasing it. In this model, there would likely still be a perceived benefit of shifting upfront costs to the less considered ongoing costs.

Limited coordination and support for rapid charging

Some de-risking and direct support for new ULEV-related infrastructure is required to encourage investment. However, this appears modest and the optimal timing depends on the type of infrastructure. For charging points, investment is more important in the nearer term and should primarily be targeted at rapid charging and depots, and less so at public charging (except where this is needed to facilitate car sharing).

- The subsidy needed to build the required infrastructure is small in comparison with the capital cost of building the infrastructure, representing up to 6% of the total discounted capital expenditure over the pathway for the charging point operators, and up to 37% for hydrogen entities (pipeline and tanker distributors, localised producers and refuelling stations) depending on the scale of the pipeline network. Excluding a hydrogen pipeline network, the present value of the required subsidy from 2015 to 2050 is less than £0.5 bn in total for all other entities considered in the Commercial Value Chain (and around £36 mn for just the charging point operators in Business as Usual). This increases to around £3.8 bn with a transmission hydrogen pipeline network and around £8 bn if this is extended to include a distribution hydrogen pipeline network.
- The requirement for infrastructure subsidies is generally small in comparison to the subsidies attributed to vehicles and electricity / fuel to encourage uptake (around £24 to £146 bn in present value terms across the Narratives).

Social transition support

Around the point of transition from upfront incentives for ULEVs to ongoing disincentives for ICEVs, a programme may be needed to prevent vulnerable sectors of society from being left stranded with increasingly expensive to run fossil fuel vehicles.

Other provisional support

Competition monitoring

Some of the new businesses established as part of the switch to ULEVs (e.g. charging networks or car sharing businesses) should benefit from natural economies of scale. As these mature and consolidate later in the modelled pathway, market supervision and price regulation may become necessary to ensure fair treatment of consumers and avoid formation of oligopolies.

Elements that appear to be ineffective or unnecessary

A full push to FCVs in the near to medium-term does not look cost-effective *given the scale of intervention required on the consumer side (i.e. to reduce the upfront cost of the vehicle) in order to stimulate the necessary market demand.*

- However, there may be an industrial benefit associated with being an early mover (i.e. the vehicle manufacturers might base themselves and invest in those countries leading the way in policy and funding support for hydrogen). This has not been considered in this project but should form part of the 'H_2 Appraisal' identified in the roadmap.

***There is likely to be a need for intervention to ensure that the geographic coverage of liquid fuel forecourts remains sufficient** (i.e. through some specific targeting of subsidies in rural areas). However, a **widespread, general subsidy appears unnecessary to justify keeping a skeleton network of liquid fuel forecourts open** as there are a sufficient number of conventional liquid fuel vehicles on the road in 2050 in all Narratives to allow an 'average' forecourt (in present day terms) to recover its costs*

- This assessment is based on a forecourt that has an 'average' usage and does not account for the variation in system dynamics across individual forecourts or 'types' of forecourt (i.e. by size, location and ownership). Understanding the need for targeted subsidies requires a more detailed investigation that considers a range of forecourt types and usage patterns (including any short-term shifts between electricity and liquid fuels, driven by PHEVs).
- Note that the modelling does not include geographic representation of commercial entities and instead considers them across the Commercial Value Chain at a UK-level.
- For the 'average' forecourt, the utilisation is sufficient to allow recovery of the fixed costs of operation and distribution of the fuel, without the need to pass through higher operating costs into the liquid fuel retail price.

***A regulated regime for investment in charging point infrastructure appears unnecessary.** The potential subsidy required for the charging point operators is relatively small compared to the capital outlay, implying they are likely to be commercially viable. They also have the advantage that the lead-time for investment is relatively short, allowing investment to be undertaken on an incremental basis and to be tailored to meet demand. Given the greater scope for competing providers, the charging point operators are not considered a natural monopoly to the same extent as hydrogen pipeline or electricity network.*

- To date, the Government has supported the deployment of charging infrastructure, e.g. through the Plugged-in-Places grant scheme to 2013 and subsequently through further investment. However, in the longer-term it expects investment on a purely commercial basis and does not foresee support through a regulated asset base system of underwritten returns. It should be noted that some forms of regulation may still be necessary in the future, e.g. to ensure interoperability across networks or sufficient transparency in electricity pricing information.

***Localised hydrogen production seems expensive compared to centralised hydrogen production**, even allowing for some ancillary services revenues and the avoided costs of transporting the hydrogen from centralised production to the forecourt. Consequently, the uptake of FCVs is suppressed in the Narratives that deploy localised hydrogen production.*

- Higher localised production costs are driven primarily by the long-term increases in electricity retail prices and higher per unit electrolyser costs compared with large, centralised production. Economies of scale and a wider range of production routes, such as Steam Methane Reforming or gasification with CCS, mean that centralised production appears more cost-effective than small-scale localised production, even with the additional network capital expenditure required.

5 Next steps

Implications for the Stage 2 trials

The overarching focus of the Stage 2 trials, determined prior to the start of this project, is on the ***Customer Proposition***. The trials aim to gain a better understanding of what will help drive ULEV uptake and use from the perspective of *mainstream* consumers. This contrasts with previous trials which have only covered ULEV 'Innovators' who may not be representative of the broader population.

This analysis has been used to support and inform the high-level design of the trials in two main areas:

- *'Key gaps' or limitations in understanding the quantitative drivers of ULEV uptake and use (including integration into the energy system and suitable charging and refuelling practices, etc.) that could be explored in the trial.* These elements have been identified through scoping and literature reviews feeding into this analysis.
- *Analysis to inform the broad structure and parameterisation of some elements of the trial design.* For example, the value of applying DM at the system level to guide the extent to which this should be explored within the experimental conditions in the trial (i.e. as part of a representation of Supplier-Managed Charging) and help anchor the values that might be presented to consumers within the trial itself as part of the simulated tariff proposition.

The intention, as far as is possible, is to use elements of the Stage 2 trial results to improve the way these factors are currently modelled within the analysis summarised in this report and add them to the analytical framework. For example, one of the trials is aimed at quantification of BEV and PHEV uptake by *mainstream* consumers in a future market where they are familiar with both BEVs and PHEVs. The results from this will be used to improve on the modelling in Stage 1, which has been based on data from consumers who have had little or no direct experience of these types of vehicles.

To address the 'key gaps', the elements that it would be useful to understand further through the trial are grouped into:

- ***To what extent users engage and how they respond to new electricity charging tariffs*** and what this means for charging behaviour, e.g. via some load shifting in response to ToU tariffs as part of User-Managed Charging, or more optimal load shifting through Supplier-Managed Charging.
- ***Indirect factors affecting the decision to purchase a ULEV*** over a conventional vehicle, such as uncertainty over the variability of costs of electricity charging at non-home locations, and other 'components' that were identified in the *four key areas* but not quantified in Stage 1.
- An overarching lack of understanding about the ***conditions required to enable a shift towards mobility as a service*** (e.g. what level of financial compensation might be required for any perceived loss of convenience, status and how this varies across different consumer groups.)

A further aim of Stage 2 is to deepen the understanding of fleets' own perspectives on the factors that influence their vehicle uptake decisions, at strategic, operational, and personal levels. This may help identify the ***factors that may be driving fleets away from the starting assumption of economic and technically rational decision making*** on a TCO basis (i.e. lack of adoption due to a misunderstanding of the true costs or for other reasons such as range anxiety, administration, access to public and workplace charging, and re-optimising routes to maximise benefit from adopting PiVs).

Stage 2 trials

A set of trials with *mainstream* consumers will be carried out over several months to (1) address the specific knowledge gaps identified, (2) understand mainstream consumer acceptance of vehicles, charging behaviour and responses to measures to enable tighter integration of vehicles and supporting energy infrastructure, and (3) test selected elements of the systems required to implement successful Demand Management. The trials will consist of:

- ***Consumer Uptake trials,*** which will give a sample of *mainstream* consumers sufficient experience of both a BEV and PHEV and measure their attitudes towards adoption of such vehicles, and
- ***Consumer Charging trials,*** which will give a sample of *mainstream* consumers sufficient experience of using a BEV or PHEV, along with either a User-Managed Charging or Supplier-Managed Charging scheme, and measure their charging behaviour and attitudes towards such schemes.

Furthermore, some ***in-depth fleet case studies*** with organisations that operate fleets will be conducted, to address knowledge gaps relating to uptake, focusing on the fleet types which are likely to have the greatest impact on the energy system.

Subsequently, the system analysis carried out in Stage 1 (discussed in this report) will be updated based on the learning from the consumer trials.