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Consumers, Vehicles and Energy Integration Project: Market Design and System Integration

James Greenleaf[1], Natalie Bird

[1]*Author (Corresponding Author), Baringa Partners, Dominican Court, 17 Hatfields, London, UK SE1 8DJ, james.greenleaf@baringa.com*

Summary

The Consumers, Vehicles and Energy Integration Project has been commissioned by the Energy Technologies Institute to examine how to deliver mass deployment and use of Ultra-Low Emissions Vehicles in the UK. An innovative, quantitative modelling framework supported by detailed qualitative analysis was used to characterise the market and policy frameworks, business propositions and the integrated vehicle and infrastructure system under different scenarios. The analysis will be supported by trials with mainstream consumers, starting in summer 2017, which aim to gain a better understanding of what will drive ULEV choice and use, in particular consumer charging behaviour under different tariff propositions.

Keywords: ULEV, state government, business model, car-sharing, mass-market

1 Context

Light vehicles contribute around 15-20% of UK CO_2 emissions and are a major contributor to congestion and urban air pollution. 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.

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 today to 2050[1]. In this paper, BEVs and PHEVs are designated as Plug-in Vehicles (PiVs).

The CVEI project has been split into two stages:

- Stage 1, which is now complete, aims to characterise the market and policy frameworks, business propositions, and the integrated vehicle and infrastructure system and technologies that appear best suited to enabling efficient, mass-market deployment of ULEVs and their integration into the wider

[1] All projections of monetary value in this paper are in real 2014 price terms.

energy system. This is in contrast to the majority of studies in the UK thus far, which have focussed on more specific aspects rather than taking a holistic approach.

- Stage 2 is comprised of a set of trials which will be carried out starting in 2017 with 440 participants, with the aim of gaining a better understanding of what will drive the choice of ULEVs and their use, in terms of charging behaviour under different tariff propositions, from the perspective of 'mainstream' consumers, which represent more than 80% of consumers, rather than only 'innovators' or 'early adopters'.

This paper is a summary of the full Stage 1 D1.3 Market Design and System Integration Report.

2 Aims of Stage 1

The Stage 1 analysis aims to provide a holistic assessment of what 'good' looks like for successful mass deployment and use of ULEVs, considering the four key areas below. 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.

- **Customer Proposition:** 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?
- **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?
- **Commercial Value Chain:** What do the cash flows and returns look like for the 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?
- **Market and Policy Framework:** 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?

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).

3 Approach to Stage 1

The approach to Stage 1 was largely theoretical, examining ULEV uptake via the creation and application of an innovative, quantitative modelling framework, supported by detailed qualitative analysis of barriers and risks. 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.

3.1 The Analytical Framework

The analytical framework is an integrated, holistic suite of modelling tools, comprising of the:

- **Energy System Modelling Environment tool –** used to assess the use of technologies and scale of underlying investment on the Physical Supply Chain. This tool 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. It is supplemented by more detailed tools used to understand the costs of infrastructure for electricity, hydrogen distribution, liquid fuels and charging points.

- **Electric Car Consumer Model tool –** used 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.
- **Commercial, Policy and Accounting Tool –** used to calculate the cash flows for (and between) each of the business entities considered[2] (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.

The analytical tools have been used in an integrated manner to assess each Narrative. The tools were 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.

3.2 Use of 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 1.

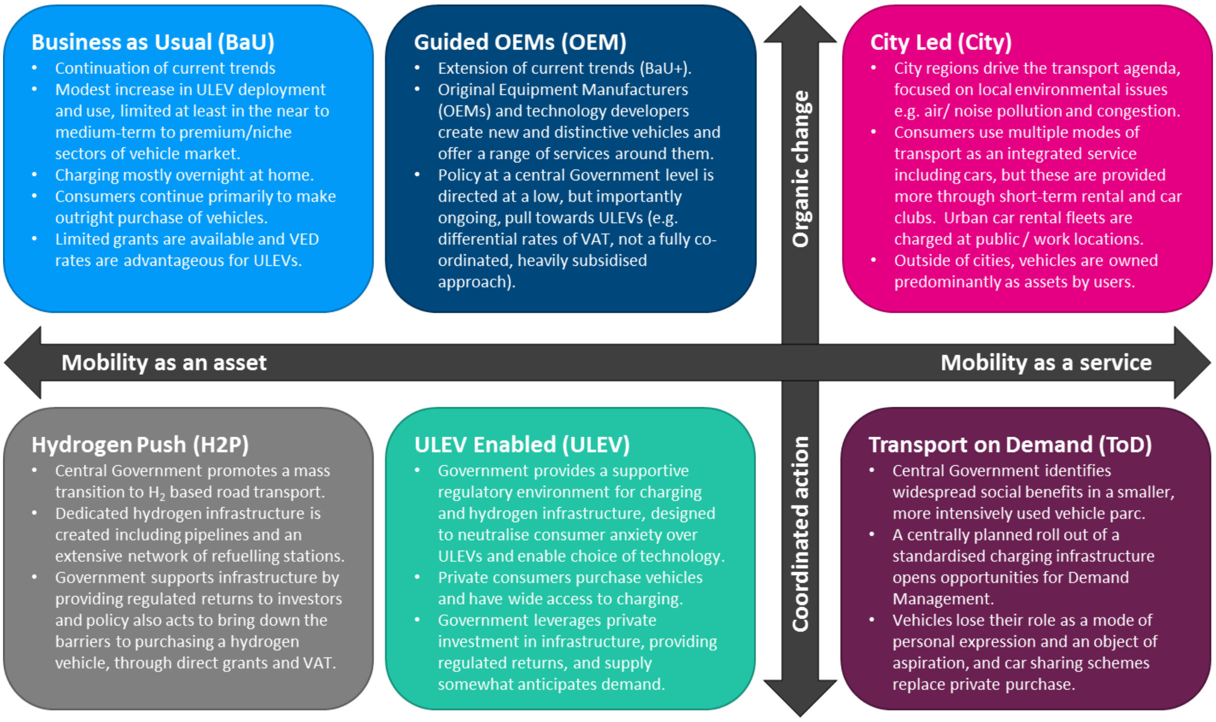

Figure 1: Summary of Narratives

The Narratives have been positioned on 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

[2] 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).

- **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.

A literature review was used in identifying 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.

The analytical framework was used to quantify the costs and benefits of each Narrative. 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 taxes (£bn).

Sensitivity analysis has been used to 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 fails to materialise); higher and lower liquid fuel prices (indirectly making ULEVs more or less competitive); and a slower reduction in ULEV vehicle prices.

4 Key Results from Stage 1

4.1 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 2.

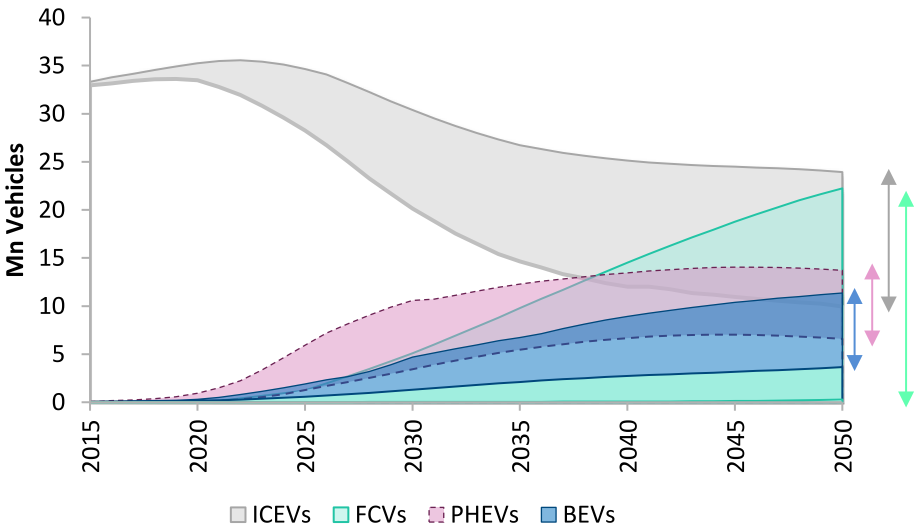

Figure 2: Uptake of different vehicle types across the Narratives

With these levels of ULEV uptake, a significant proportion (38 to 68%) of all light vehicle km driven in 2050 are 'low-carbon'. 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 (without accounting for the effect of 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 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.

4.1.1 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, 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. 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).
- 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.
- 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 in 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.

4.1.2 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.

4.2 Key Metrics and the Roadmap

The findings on vehicle uptake and use are primarily based on the Physical Supply Chain (i.e. the vehicles and infrastructure), however, key messages have been derived for all four key areas through comparing and contrasting the key metrics in Table 1 and through 'deep dives' on a number of themes[3].

Findings across all key areas have been used to identify potential elements of a 'good' solution and to set these out on a roadmap, shown in Figure 3. 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 Sensitivities. 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.

The essential, desirable and provisional elements of a 'good' solution are set out in Table 2, with more detailed information and further explanation on how each message was established provided in the D1.3 Market Design and System Integration Summary and the corresponding full report. The risks and barriers associated with the key elements of a 'good' solution were assessed qualitatively and taken into account in constructing the roadmap[4].

[3] More in-depth results and analysis on particular key 'themes' is set out in the D1.3 Market Design and System Integration Report, 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.

[4] 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 the D1.3 Market Design and System Integration Report.

Table 1: Results for key quantitative metrics in the Narratives[5]

Narrative scores poorly relative to other Narratives — Narrative scores favourably relative to other Narratives

Key quantitative metrics[6]			BaU	OEM	City	ULEV	H2P	ToD	Context
Consumer	Low carbon vkm 2050[7]	%	38%	62%	42%	54%	68%	62%	The corresponding transport emissions across the Narratives are 16-32 $MtCO_2$/year in 2050, compared to 88 $MtCO_2$/year in 2015. The share of total emissions from transport is around 16-31% across the Narratives, compared to 18% in 2015 - only decreasing in H2P.
	Car transport costs 2050	p/km	24.9	26.6	30.7	25.8	23.1	21.4	In 2015, the average cost of transport is 29 p/km in BaU.
Physical	Present value of residual carbon cost over pathway at Social Discount Rate (SDR)	£bn	33.2	28.2	36.0	31.3	23.2	27.6	The present value of the residual carbon cost if emissions continue at 2015 levels ranges from £78-84bn across the Narratives.
	Undiscounted residual carbon cost in 2050	£bn/year	8.8	5.4	8.1	6.1	4.6	5.8	The residual carbon cost in 2050 if emissions continue at 2015 levels ranges from £23-25bn across the Narratives.
Commercial	Present value of subsidy required over pathway for selected entities at weighted average cost of capital/margin	£bn	0.1	0.4	0.1	3.8	8.0	0.4	The subsidy represents up to 6% of the total discounted capex spend over the pathway for the charging point operators and up to 16% or 37% of the H_2 infrastructure, with and without pipelines respectively.
	Present value of vehicle manufacturer penalty	£bn	*5.2*	*2.0*	*1.7*	*1.2*	*3.5*	*0.8*	The manufacturer penalty represents <1% of the retailer revenues on an net present value basis over the pathway and a maximum of 3% in any one year across the Narratives.
Government	Present value of net tax and spend gap over pathway at SDR	£bn	261	287	135	311	378	332	The 'gap' is between 15-45% of the taxes received from transport due to spending on grants and subsidies. Net revenues from transport represent around 2.5% of GDP in 2015, reducing to 0.5-1.5% across the Narratives by 2050.
	of which direct subsidy	*£bn*	*0.7*	*18*	*12*	*26*	*52*	*38*	
	Undiscounted net tax and spend gap in 2050	£bn/year	38	46	15	35	57	44	

[5] Note that the results for these metrics are for specific Narratives which are comprised of a number of varying factors, i.e. the results should not be generalised to draw conclusions about the relative benefits of transitions of these particular natures.
[6] A detailed definition of what is captured within each metric is set out in the D1.3 Market Design and System Integration Report.
[7] A key principle underpinning all of the Narratives is that they must meet UK targets for CO2 reduction for the energy system as a whole.

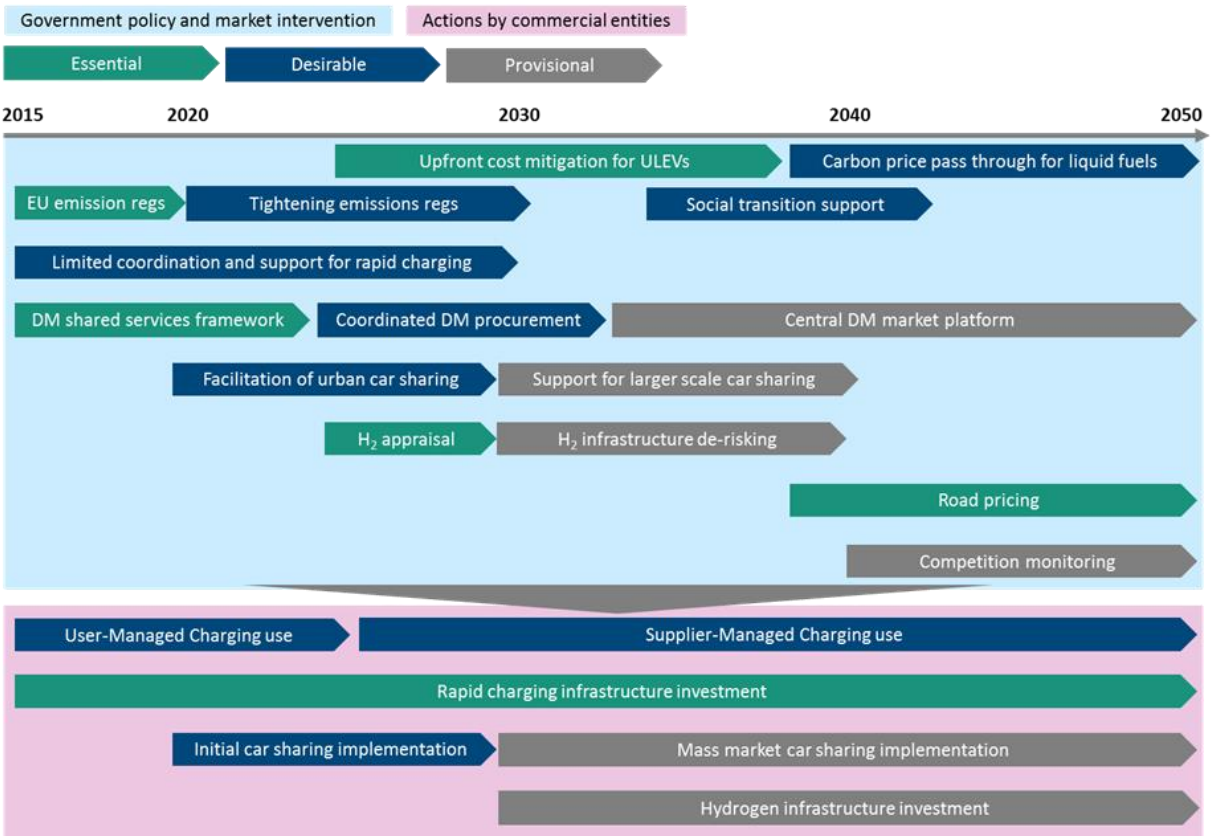

Figure 3: Roadmap for efficient ULEV deployment and use

Table 2: Explanation of the key elements of the roadmap

Element of the Roadmap

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: 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. 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 a 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’, shown in the D1.3 Summary report.

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. 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.

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, for which deployment should occur on a commercial basis where it is considered viable.

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. The convergence in the cost of ownership of FCVs and PiVs is accelerated by changes in the wholesale fuel costs, which are driven by changes in the wider energy system. In 2040 a private consumer would pay 2.9 p/km for the electricity to run a BEV versus 2.2 p/km for the hydrogen to run a FCV (on a Total Cost of Ownership (TCO) basis).

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). This 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.

- 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. A proposed technology-neutral mechanism to fill this gap 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. 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.

- 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 but this should not be technically difficult.

- The potential stages of development in the regulatory framework for Demand Management are (1) set up and implement a 'DM shared services framework', which would aim to establish coordination between the entities that have an active interest in DM, (2) further increase coordination of procurement and operation of DM, e.g. with the system operator responsible for contracting services and then selling them on to other entities when they need them or place a higher value on them, and (3) creation of a 'central DM market platform' that allows demand to be optimised across all buyer and sellers of DM services.

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 infrastructure cost reduction, particularly for the Transmission System Operator (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). 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). Avoided network reinforcement by the DNOs accounts for savings of between £1 and £4.5 bn. The avoided reinforcement costs for the Transmission Network Operator (TNO) are negligible by comparison.

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.

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).

Carbon price pass through for liquid fuels A long-term CO_2 tax appears to be effective at encouraging a switch, supporting Government revenues (to an extent) and driving an economically-efficient level of investment in ULEVs and the supporting infrastructure. There will be decarbonisation of other aspects of the energy sector and thus it makes sense to carefully balance the level of Government support over the pathway to 2050, incentivising ULEVs at times when the value associated with the resulting carbon abatement is greatest.

- The Narratives have been used to show 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). 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 suggests a long-term CO_2 tax could be worth implementing.

Initial/urban car sharing → **Support/ implementation of mass-market car sharing**

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 could lead to more efficient vehicle use.

- ‘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). 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.
- 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. 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. 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 TCO whereas for an ICEV it is around 70%.

Limited coordination 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). Note that 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.

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.

In addition to the elements described above, there are a number of elements deemed ineffective or unnecessary, such as: a full push to FCVs in the near to medium-term, a regulated regime for charging point infrastructure, roll-out of localised hydrogen production and a widespread subsidy to keep the network of liquid fuel forecourts open (although there is likely to be a need for targeted subsidies, e.g. in rural areas).

5 Stage 2 Trials

This analysis has been used to support and inform the high-level design parameters of the subsequent Stage 2 trials involving PHEVs and BEVs and *mainstream* consumers, through:

- **Identifying ‘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.

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 for successful Demand Management. The trials 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 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 deepen the understanding of fleets' own perspectives on the factors that influence their vehicle uptake decisions, at strategic, operational, and personal levels.

Subsequently, the system analysis carried out in Stage 1 will be updated based on the learnings from the consumer trials.

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Authors

James is a Director in the Baringa Energy Markets and Analytics practice and has 14 years' experience in the energy sector working for a range of clients across the private (e.g. energy utilities, SOs, O&G majors) and public sectors (e.g. UK Government and European Commission). James has extensive experience of policy development, appraisal and evaluation, including electricity markets (with a particular focus on balancing markets) and climate change mitigation options such as energy efficiency policy, renewables and emissions trading. James also has a wide range of expertise in future energy systems analysis, looking at the implications of decarbonising the energy system across power, heat, transport and industry. To support this James has been involved in the development of a number of national-level and local-area specific 'energy system modelling frameworks' using optimization and stochastic modelling techniques to understand future pathways for decarbonisation. James has BSc in Natural Sciences (Physics), an MSc in Environmental Technology with Energy Policy, and an MSc in Applied Environmental Economics.

Natalie is a Senior Consultant in the Baringa Energy Markets and Analytics practice and has over 6 years' experience in the energy sector, including several at EDF Energy. Since joining Baringa, Natalie has worked on various projects involving economic analyses and financial modelling, including Cost Benefit Analyses for electricity interconnectors and valuations of gas storage and CCGT assets. Natalie has also focused on policy and regulation work, for example supporting a large market participant with analysis to inform their response to the Competition and Markets Authority. Natalie has a MEng (Hons) in Chemical Engineering.