An ETI Insights Report

SMARTER CHARGING A UK TRANSITION TO LOW CARBON VEHICLES: FULL REPORT

energy technologies institute

Contents

SUMMARY

Enabling and managing vehicle charging is an urgent challenge to overcome in preparing the UK to deliver the economic and climate change benefits of a transition to electric cars.

Significant progress has been made with decarbonising electricity supply; now a start needs to be made with decarbonising transport, heating and industry. Most analysts identify cars and vans as the next most economic and practical sector to decarbonise, by switching to plug-in electric vehicles (PiVs), which are then recharged with low carbon electricity. Continued improvement in conventional vehicle efficiency also has a part to play.

As well as implications for CO_2 emissions, electric vehicles are a new kind of load for the electricity system. Currently the only domestic loads which are so large, and that demand several hours of continuous supply, are night storage radiators, used in a small minority of households, typically in areas with high capacity local networks. The potential for disruption and significant increased investment in supply and networks has been validated by multiple vehicle trials. Avoiding significant electricity cost increases and maximising emissions savings will require charging to be managed, a new concept for domestic electricity supply, going beyond the concept of off-peak tariffs.

Households that drive a lot of miles on electricity, and charge mostly on electricity from low carbon supplies, will be critical to meeting Fifth Carbon budget targets. If current dual-fuel[1] households were to drive all their miles on electricity, charging their cars on average would require nearly as much electricity as all their other domestic electricity uses put together. In some households, electricity for mobility will be significantly higher than for other uses.

This report focusses on the operation of the UK energy system out to 2030, on the assumption that a high level of electric vehicle uptake by then is both possible and indeed likely. It draws together key insights from across a range of recent activities by different UK and other centres of expertise. The report has been prompted by the completion of the ETI Consumers, Vehicles and Energy Integration (CVEI) project, which included trials with mass-market consumers to test charging management and uncover range requirements. It considers which drivers and journeys will need to be converted to electric miles for UK climate targets to be met.

The main conclusion of this report is that it is by no means certain that the development of vehicle charging infrastructure over the next ten years will be sufficient on its own to support mass market adoption.

We need a strategy to provide enough capacity, with enough intelligence to meet drivers' needs, while avoiding risks to the electricity infrastructure or additional investment in high-carbon peak generating capacity. This will involve the electricity and vehicle industries working with different tiers of government.

Providing mechanisms for managing charging at or near home is the most critical issue. If charging at home can be managed, wherever hotspots of vehicle uptake occur, the overall effect of vehicle electrification on the electricity industry could be significantly positive. The additional revenues should only require moderate additional investments to support them. It seems that drivers can be engaged in managed charging, provided it is designed around their needs, and aligns the capabilities of the supply-side on those needs in an effective way.

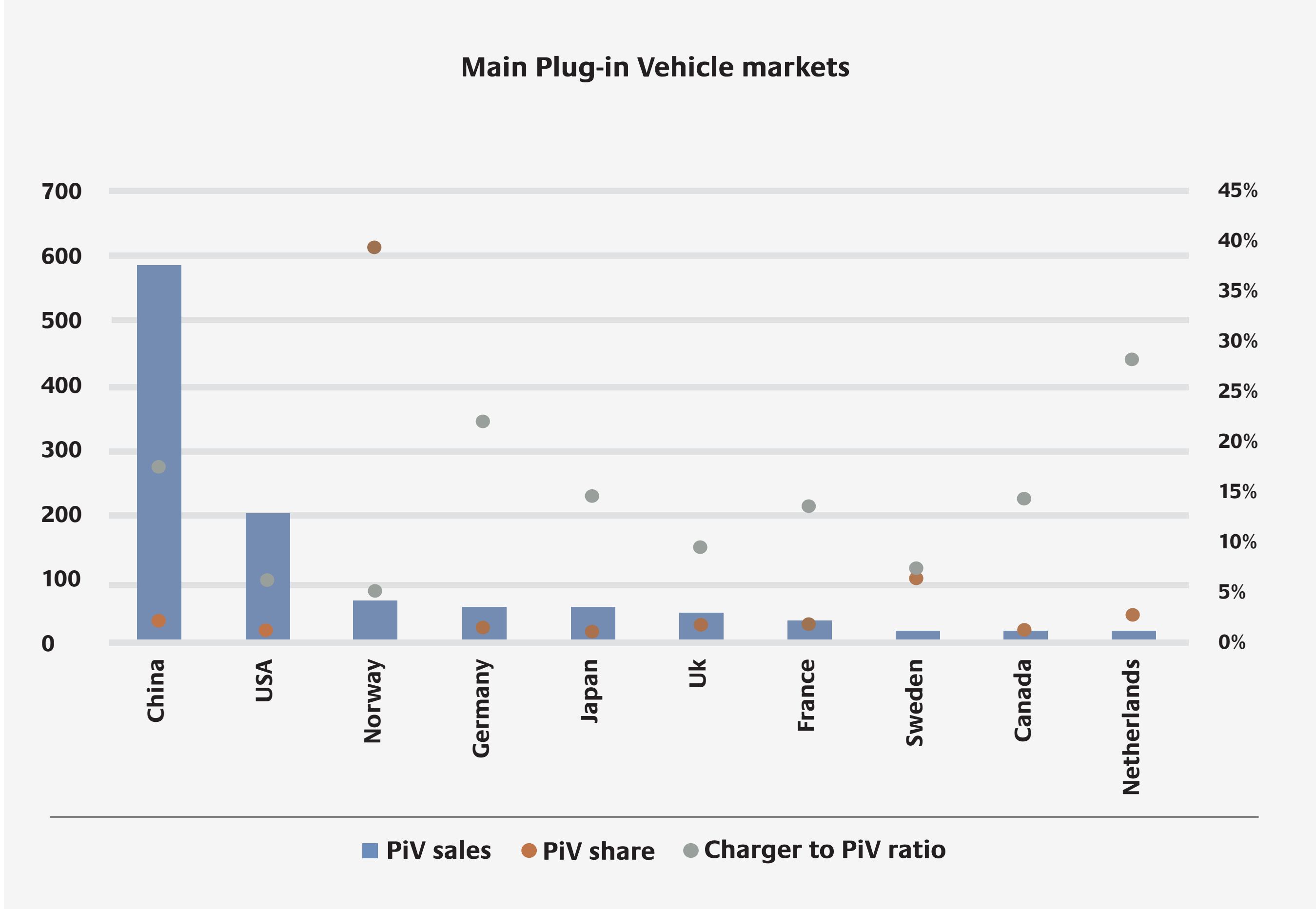
The CVEI project has generated a wealth of detail, models, data and analysis. This report uses data from CVEI, in combination with other analysis, to consider the implications for decarbonisation of the UK energy system out to 2030. The key reports from CVEI are available in the ETI Knowledge Zone and the tools and data can be accessed through the Energy Systems Catapult. The project Summary Report is the best starting point[2]. The CVEI project had a broad mission, covering a wide range of factors involved in vehicle uptake to 2050. Although the project gathered a large amount of granular data around its two on-road trials, most of this was intended for the kind of analysis reported here, not to support the primary outputs of CVEI.

The economic benefits of the UK becoming one of the leaders in vehicle electrification has also been recognised by Government. For example, the UK is making significant new investments in battery innovation, and in 2017, the UK announced that the sales of pure fossil fuel cars will end from 2040 onwards. Typically, such intentions are a ratchet mechanism; progress is stimulated and leads to targets being tightened, well before the deadline is reached.

The latest report on vehicle electrification from the International Energy Agency[3] shows a wide variation across different countries in PiV sales and provision of public charge points. Norway and Sweden stand out as on the journey to vehicle electrification, although The Netherlands has a large stock of Plug-In Hybrid Electric Vehicles (PHEVs) from a period when there were business tax incentives for their purchase. Annual PiV sales in The Netherlands reached nearly 10% market share at the peak but have since fallen back, due to changes in the business tax regime.

The split between pure Battery Electric Vehicles (BEVs) and PHEVs varies widely between countries, but globally PHEVs represent one-third of sales. PHEVs are a slight majority of sales outside China. Provided that PHEVs are driven in order to use their battery, the exact split between BEVs and PHEVs is not important to decarbonisation, but both are required in the UK to achieve 2030 decarbonisation goals.
Public charge point availability on a global basis is slightly more than the EU target of 10% (1 charge point per 10 PiVs). There is no obvious pattern to public charging point provision, apart from countries with higher penetration of PiVs managing successfully with lower provision than the EU target. Fast charging is at an early stage, except in China and Japan. The UK is third in terms of fast charger penetration. The Netherlands has the highest public charge point provision, but less than 3% are faster than 22kW. Looking at trends in each country over the last few years, the impression is of a rapidly developing picture, with country specific factors, but underpinned by economies of scale in both battery cell manufacture and battery pack size. Different factors interact to deliver battery pack cost and performance[4].

Figure 1
2017 PiV sales, market share and public charge point to PiV ratio (from IEA data)



The Committee on Climate Change (CCC) and National Grid both anticipate high levels of UK electric vehicle uptake by 2030 in scenarios in which carbon budgets are met – towards 70% of sales[5] and 9M in the fleet[6]. This is partly in recognition of the current momentum and partly to compensate for slower progress in other areas, principally electricity generation. ETI scenarios show a similar pattern[7]. The CVEI project examined what combination of policies might be needed to achieve these levels of uptake. This report is about charging, so the drivers of uptake are not discussed here in any detail.

Implicit in meeting these targets and expectations is an assumption that large numbers of people buy and use PiVs. This will only happen if the PiVs meet their needs. The needs of average and higher than average mileage drivers are particularly important, as they drive the majority of miles in the UK. This report therefore considers what a 2030 world would look like for PiV purchase and use to be at the levels foreseen in typical scenarios, where it would be possible to end the sale of pure fossil fuel vehicles by 2040 or earlier. It discusses the challenge – how to design and operate the energy system to make that possible.

Three key questions are discussed:

- The nature of the driver experience and the levels of service that could be provided by innovative use of modern internet technologies and infrastructure
- The kinds of public and private charging infrastructure that will be required and what this might mean for charging points in different locations, including the network upgrades required to support them
- The integration and operation of the whole system including charging management, the effective carbon intensity of the added electricity load, and the impact on networks and the economics of generation

[1] Dual-fuel means heating is by gas, oil or LPG, rather than electricity
[2] https://www.eti.co.uk/programmes/transport-ldv/consumers-vehicles-and-energy-integration-cvei
[3] Global EV Outlook: towards cross-modal electrification, IEA, May 2018

[4] BatPaC: A Lithium-Ion Battery Performance and Cost Model for Electric-Drive Vehicles, Argonne National Laboratory, http://www.cse.anl.gov/batpac/index.html
[5] An independent assessment of the UK's Clean Growth Strategy, the Committee on Climate Change, January 2018
[6] Two Degrees, Future Energy Scenarios 2017, National Grid
[7] Options, Actions, Choices: Updated, Milne, ETI, October 2018

From detailed analysis of CVEI and other data, we highlight the following key points:

1. PiVs are attractive to the majority of UK drivers, provided they cost the same (over a 4 year period) as current cars, have sufficient range, and recharging is straightforward and cost-effective.

> PHEVs will gain significant traction in the private market when their typical effective electric range is 50 miles[8].

> EVs will gain significant traction in the private market for the second vehicle in a household when their typical effective range is 150 miles and for the primary vehicle when it is 200 miles.

2. Drivers interpret effective range in terms of journeys that they take, rather than a nominal drive cycle.

> Effective range therefore depends on the nature of the journeys and driving styles and will be uncovered through the socialisation of many individual experiences.

> It is typically less than headline range figures given by original equipment manufacturers (OEMs).

3. There are clues in the trial results that support an alternative model, with more limited BEV range but widespread access to very rapid charging, and battery technologies that can withstand this.

> The cost-benefit ratio of this approach is untested, especially in terms of infrastructure.

> There are early signs that market actors will set out to test it.

4. Unmanaged charging by mass-market drivers peaks at the same time as current electricity demand, with potentially serious consequences for UK infrastructure.

> This is consistent with the charging behaviours observed in large samples of early adopters, such as the Electric Nation project.

> Drivers are very open to managing their own charging against fixed time-of-day tariffs or letting their supplier manage charging, where the proposition is made attractive, easy and credible.

> Fixed time-of-day tariffs risk creating super-peaks, shortly after the low tariff period starts[9]; this becomes a problem once many drivers own PiVs.

5. High levels of conversion of fossil fuel miles to electricity by 2030 will require uptake amongst the two-thirds of drivers who currently drive between 5,000 and 25,000 miles per year.

> They drive nearly 80% of UK car mileage.

> Although the just under 3% of drivers with more than 25,000 annual miles drive more than a tenth of all miles, they are challenging to convert to electricity.

> The 30% of drivers who drive 5,000 or less miles annually account for less mileage than this 3%.

> Many low mileage drivers would be better served by shared access to electric vehicles, and other modes of travel.

6. The CVEI project collected very detailed[10] journey and charging data from 127 BEV and 121 PHEV drivers whose journeys, age and gender distribution, and geographic locations are a very good match to the core two-thirds of drivers; each driver had the car for 8 weeks.

> The data covers over 52,500 trips with a total distance in excess of 440,000 miles.

> 80MWh of electricity were used in 10,500 charging events, of which 8,700 were at home.

> This data has potential to support detailed modelling, after further analysis.

7. CVEI participants with a PHEV on average drove a modest number of miles on electricity, even less than company car fleet PHEV drivers achieve on average, although many achieved a high fraction of electric miles.

> Low electric mileage seems to have been caused by using the engine to recharge the battery.

> Evidence from the trial suggests that changes to vehicle design and user interface, combined with changes to the social environment, could dramatically increase average electric miles.

> High levels of conversion are possible, where drivers choose not to recharge from the engine, as the data shows.

8. More than half of all new cars are currently bought by fleets.

> This proportion is likely to rise, as the total number of sales falls.

> Given the low electric miles fraction driven by many fleet PHEV drivers[11], incentives should focus on electrification of miles, rather than vehicle purchase.

> Fleets are therefore a critical target for policy, to ensure that second-hand vehicles entering the UK parc are suited to higher mileage drivers and that the socio-technical environment is increasingly supportive of maximising miles on electricity.

> Workplace charging will be part of this, given that it is the second largest charging opportunity, after the home.

9. ETI deliberately chose to study mass market drivers, since they are critical to 2025 and 2030 targets.

> It is right that the needs and behaviours of early adopters are also being studied (by others), since they are an important step on the pathway.

> Although the focus of the study was vehicle uptake and charging management, detailed analysis of the data poses some important questions for attracting different people, with different needs, in different locations to use electric vehicles.

> The pattern of vehicle ownership and use may change significantly by 2030, with more current low mileage drivers deciding not to own a car.

> Access to travel on demand through a combination of different modes will increase in many cities. This will combine public transport, cycle rental, Uber style taxi services and occasional car hire, as a packaged offer.

> Supporting the charging of high mileage taxi and ride hailing BEVs around the centres of these cities will be a new type of load.

> The aim should be to attract visitors to these cities to park & ride style integrated travel services, thus reducing visitor fossil fuel mileage.

Points relating to charging management are discussed and evidenced in this report; points relating to other aspects of electric vehicle uptake are discussed in reports delivered by the CVEI project team.

Based on the detailed analysis, there may be a gap between the kind of charging services that drivers will need to have available and the current collective expectations and plans of the wide range of stakeholders involved in vehicle electrification. As this gap is addressed through a joined-up series of actions, there will be less risk that driver concerns and experiences about access to and cost of charging will seriously impact on progress with vehicle electrification. The Recommendations section suggests a set of actions to progress preparations for large scale use and charging, focusing on research and experimentation to provide public shared evidence for energy companies, vehicle manufacturers and policy makers.

Personal mobility has a strong local and individual flavour. A business car driver in rural Leicestershire is very different from a driver living in a London suburb and commuting by train or bicycle. Understanding driving patterns and needs and providing appropriate infrastructure will need national policies and standards to support local plans and investments. Providing a fast charging infrastructure along major routes is very important but has been well discussed already[12].

There are many uncertainties in the trajectory of PiV uptake and use. Discussions often focus around a set of implicit beliefs within the range of these uncertainties. Key uncertainties are high-lighted in Appendix V, so that readers can form their own views about their impact on vehicle charging. They provide an important context for the issues discussed in this report. The economic, social and environmental performance of personal mobility in 2030 will depend critically on who drives which vehicles, on what journeys, and how they are recharged. Within the body of the report there is an illustrative scenario, which shows how 5M PiVs could meet UK targets.

However, it should be noted that it is entirely possible to construct scenarios with 7-8M PiVs on the road in 2030, in which targets are missed, at greater public and private cost. Now is the time to lay the foundations for extensive public and private vehicle charging, and charging management, to prevent charging becoming a barrier to mass-market uptake. We don't want to reach a situation where there are many hundreds of thousands of cars and vans on the roads that are incompatible with smart charging management standards. It would be difficult to recover from this position. In many households, the amount of electricity used to recharge vehicles will be similar to or even greater than current domestic electricity use. This presents both a major opportunity and a significant challenge. Further dramatic reductions in fuel sales, driven by greater vehicle efficiency, electrification and other factors, will also have implications for fossil fuel availability and prices[13].

[8] Similar to the nominal 69 miles threshold for government support
[9] See Figure 9 for evidence from the charging trial
[10] Typically key GPS and vehicle parameters on 1s frequency
[11] See for example data from The Miles Consultancy on real-world fleet PHEV performance

[12] Plugging the gap: An assessment of future demand for Britain's electric vehicle public charging network, Conolly et al, CCC, January 2018
[13] An affordable transition to sustainable and secure energy for light vehicles in the UK, Batterbee, ETI, November 2013

RECOMMENDATIONS

The Energy Technologies Institute is closing down in an orderly fashion. The following would have formed our "to do list", if we were continuing. It is for the broader stakeholder group for vehicle electrification to decide whether any of them should be taken forward and, if so, how.

OVERVIEW

The UK stands at the end of the first phase of vehicle electrification. Measures to encourage the early uptake of electric vehicles and the provision of public charging points have been effective. Evidence from this early uptake, and related trials, points towards the issues for the next phase. Attention is now turning to the framework for continued progress in an effective and robust way, especially a transition from push by focused point support mechanisms to a more commercially led series of activities, where policy support stimulates private investments and innovations within a broadly technology neutral and competitive environment.

This policy environment is still developing, so we need to describe its potential outline as a back-drop for specific recommendations on knowledge and capability development. Over time the body of evidence from real-world commercial activities will become the main contributor to policy development and policy mechanisms will therefore build in collection of evidence as an integral part of their design.

The ETI does not have the experience to make policy recommendations and the following policy backdrop is intended only to illustrate the issues. Within the next phase, we expect the main issues to be vehicle uptake, electrification of miles and overall fuel use decline, and providing cost effective private and public charging access. Fuel use decline will reduce greenhouse gas emissions but has implications for tax revenues and the availability of petrol stations. Ensuring that the electricity used for recharging is mostly low carbon is, we believe, a challenge for a later phase that should be considered today in the technical standards for charging management. Our recommendations are focused on the more technical challenges, which will support the interpretation of real-world data and especially its use for planning by businesses and policy makers.

POLICY BACKDROP

1. Fleets

This is a very important group, both for the introduction of new vehicles into the UK parc, and also the electrification of miles. Over half of all new cars are bought by fleets and they sell them on after first use. The market for used PiVs will therefore be led by vehicles that fleets purchased earlier. Company car drivers, and other drivers with similar journey patterns, represent a large fraction of UK miles. Private hire taxi vehicles represent an important special case, especially given the strategies of companies like Uber.

Fleets are therefore a critical target for policy. Fleet managers and their supply chains, including vehicle OEMs, represent a large body of skill, experience and ingenuity. Within the right environment they can and will deliver considerable reductions in fuel usage and electrification of miles. The technical and social environment for cost-effective electrification and fuel use reduction will develop around lead fleet users and spread out to others.

Managing recharging and paying for recharging electricity across multiple sites and providing workplace charging will also be on the agenda of fleet managers.

It is imperative to incentivise electric miles, not just PiV purchase. One might anticipate two elements to policy: taxation support for fleets which deliver targets for fuel use per mile and use of electricity, supported by minimum vehicle standards. The main driver of progress will be the tax benefits, supported by lower fuel bills and (in the case of BEVs) less maintenance. Minimum standards are intended to avoid low performing vehicles entering the used car market and to set market expectations. Significant price support to vehicle OEMs for PiV sales to fleets will probably diminish; support would be mainly through the fleet level tax benefits. Minimum standards might include a minimum electric range for PHEVs.

Once vehicles in a fleet met the minimum standards, the whole fleet becomes eligible for tax benefits. Vehicle mix selection, operational factors and driver training and motivation will be the responsibility of fleet managers. In order to receive the tax benefit, they will provide an auditable return to HMRC stating that they have met the minimum standards and providing evidence of levels of fuel and electricity use per mile. HMRC has considerable experience of developing appropriate requirements for auditable returns and supporting records.

There will probably be multiple bands of benefits, for example tiers 1 to 3. The lowest tier (1) would represent a realistic aspiration at the beginning of a company's journey and the highest tier (3) would represent an aspiration for the highest performing fleets, whose performance would provide role models and a source of industry wide learning. Over time the requirements for fuel efficiency and electric miles for tier 2 would become those for tier 1 etc., so that the performance of the whole industry would move forward. Even fleets not yet at tier 1 would still benefit from the availability of vehicles and approaches to minimise their fuel use and therefore their costs.

Analysis by HMG of tax return data and case studies provided by the industry will provide a rich source of evidence for policy development and business planning. Undoubtedly, these analyses will prompt the development of research designs for combinations of social and technical research to explain important features of this real-world data. The process for collecting this data should deliver high quality, without additional interventions and cost. Data collection is an inherent part of the process.

2. Private first purchasers

Current policy is focused on price support to vehicle OEMs for first sale of BEVs. This seems entirely appropriate. BEVs are likely to be most attractive to lower mileage drivers who represent a large cohort within the population of UK drivers. Maintaining momentum in this segment is also socially and economically important, even if it turns out that electrification return on public investment is less than for fleets.

Support for PHEVs is currently limited to those with a nominal electric range that corresponds to the CVEI target effective range (of 50 miles). Although this might seem restrictive, it does mitigate against the risk that PHEVs are driven low electric miles fractions. As evidence emerges on progress with PHEV fuel consumption reductions, the most appropriate support for PHEV purchase can be reviewed. How efficiently range extension is achieved is also important. There will also be a segment of somewhat higher mileage drivers who can afford a long-range BEV. Although price support will probably be important to them, their decisions are not primarily driven by economics and there is a risk that relating price support to range would exceed what is required to stimulate purchases by this segment.

3. Electricity and fuel use

Government statisticians have developed methods to collect data on fuel use. The challenge for electricity used for recharging is to untangle it from electricity for other uses.

Underlying this whole report is an assumption that recharging is a new load class that will require to be managed separately from other uses, probably with a different cost structure. The reasons for this are touched on at various places but might be summarised as providing incentives to make best use of existing generating and network capacity by reflecting costs appropriately. This is especially so for incentives to make best use of low carbon generating capacity.

These incentives are important because recharging vehicles has a much higher degree of flexibility than other load classes (as we have evidenced in the CVEI project) and it is a very large energy requirement, not dissimilar to existing domestic consumption (on a per household basis).

Provided that the right technical standards and data collection requirements are developed, extensive data on vehicle recharging will be collected from fleets and individuals. The primary driver for collecting this data will be operational and investment planning by the electricity industry and charging businesses. Analysis of it will however be invaluable for policy development and business planning.

There will be a significant need to explain characteristics of charging behaviour through a combination of social and technical research.

4. Charging access

In one sense, this has already moved from a support push phase to a more commercial phase. Businesses are showing a great deal of interest in investing in charging technologies and charge point locations. Government is providing innovation support for understanding current charging patterns, Vehicle-to-Grid technology development, and using Smart Meters to ration local network capacity through connecting their Auxiliary Load Control to the charge point. However, this market is only emergent. Vehicles will develop, more PiVs will be bought and driven differently, existing network capacity will be used up, etc. etc.

In particular the competition between battery technologies that can withstand rapid charging and those that are less resistant has only just started. The network implications of supporting this competition are considerable.

The main challenge is to collect and analyse complex evidence to support policy and planning, rather than new policy development.

Against the backdrop of these perspectives on possible policy approaches, the ETI recommends:

AREA MODELS

Tools are required that combine simulation of drivers and transport patterns with the location of charging and its impact at the scale of a regional distribution system. Key challenges for these tools include modelling of driver behaviour on a Monte Carlo basis, together with the impact of charging loads on the local network. It is important that these tools should provide sufficient granularity in time and space, since system failure is due to random combinations of localised events, as shown by Infield[14]. The models need to include the data, communications and control activities in the system (for example the Smart Meter infrastructure) and the operation of different actors. Actors include drivers, building occupants and suppliers, with some representation of the wider energy system, including the Electricity System Operator (ESO).

The ETI has funded the Energy Systems Catapult (ESC) to carry out research and prototyping on modelling building occupant behaviour and network loading for low carbon heating, which showed that these kinds of models may be tractable and provided a platform for further development. Something like these capabilities should be expanded to including journeys and drivers, and charging away from home.

NATIONAL MODELS

There are a number of significant system control challenges involved in managing charging, when drivers are responsive to supplier managed charging as seems likely from our CVEI project. Area models can give some sense of how many drivers are likely to be plugged in and available for a variety of responses, ranging from Enhanced Fast Frequency Response through to load shifting. Dispatch modelling at an ESO scale is required to understand how the addition of a large and complex "Demand Response" system might impact system design and operation.

[14] Markov Chain Monte Carlo simulation of electric vehicle use for network integration studies, Wang & Infield, International Journal of Electrical Power and Energy Systems, 99, 85-94.

The ETI recently commissioned an extension by Baringa Partners to our ESME tool to include system flexibility and dispatch analysis on a multi-vector basis[15]. Learning from Area models could be used to calibrate the demand response profiles of both vehicle charging and heat-pumps. Vehicle charging is the clear priority.

CONSUMER TRIALS

The EA Technology Electric Nation project has gathered charging data from drivers who have purchased a PiV (i.e. very early adopters), including charging management. The starting point has been methods of managing rationing of network capacity, investigating both the technical and consumer aspects. This work is important to network companies and should continue. These drivers could also be used to test responses to different charging management propositions, while recognising that very early adopters do not predict mass market behaviours and attitudes.

There should also be further trials of charging management with mass market consumers, looking at supplier managed charging. Although CVEI has met its objectives and shown that mass market consumers are open to managed charging, there are many detailed aspects that require further research.

One approach might be to leave this proposition development and segmentation work to commercial companies. However, the potential economic value to the UK, the barrier to innovation presented by the cost and complexity of consumer trials, the need for the trial design and analysis to be strongly coupled with the operation of the wider energy system and the pace of policy development required to implement in time, all argue for a set of trials whose outputs are more generally available.

TECHNICAL STANDARDS AND GOVERNANCE

If charging is to be managed effectively, a whole range of standards and codes will need to be developed or modified, and adopted within the system governance, including any primary or secondary legislation.

Examples include:

- Communication between charge points and vehicles
- Communication between charge points and Smart Meters
- The basis on which Smart Meters can be used by multiple suppliers
- Standards for monitoring network loading
- Standards for preventing network overload by communicating with charge points
- Market structures to implement incentives and rewards for suppliers to manage charging to allocate network capacity, minimise additional systems costs and minimise additional systems carbon emissions

There will also need to be agreement amongst the energy and automotive industry as to the form that managed charging should take and how it should evolve over time. To inform these decisions, the impacts should be assessed using the aforementioned Area Models, National Models and Consumer Trials.

While the ETI would not have expected to be directly involved in such activities, we would build evidence from new analysis to inform stakeholders about whole systems implications and the perspective and likely reaction of consumers. Implementing such a complex change that spreads out across the whole energy system, including the liquid fuel system, should be undertaken in a structured way. One approach to this is described in the ESC technical report headlined in an ETI Perspective[16].

[15] As with ESME, this is now hosted by the Energy Systems Catapult (ESC)
[16] Tools for Future Energy Systems: An ETI Perspective, Haslett, November 2017

INTRODUCTION

A world in which we achieve significant electric vehicle uptake by 2030 presents some challenges, but is both plausible and desirable

CONTEXT

We stand at the beginning of a transition to low carbon vehicles in the UK. At the end of March 2019 there were over 200,000 rechargeable cars on the road (0.6% of the total parc). Rechargeable cars accounted for 2.7% of new vehicle sales in 2018. As at September 2018, PHEVs represented two-thirds of PiVs sold in the UK. By the end of June 2019, PiV sales share had fallen to just over 2%, with BEV sales continuing to grow and PHEV sales falling; BEV sales in 2019 are slightly ahead of PHEV sales. Uber have announced the intention for all 40,000 of their drivers in London to be driving BEVs by 2025, with significant progress by 2021. BMW and Daimler-Benz have announced a joint-venture in electric mobility services branded Your Now; this brings together their existing fleet access management capabilities, which have strong IT platforms, like Uber.

Unless there are significantly more than 4 million (M) PiVs on the road in the UK by 2030, important government policy targets will not be met. Currently, it appears that PiVs will be the dominant low carbon technology for cars and vans, but it is less clear what the solution might be for other vehicles. It might still be that hydrogen wins out for light vehicles in the long run, and we should keep the option open, at least until battery-electric light vehicles represent a significant fraction of the UK parc.

There are signs that walking, cycling and mass-transit are all likely to play a greater role in personal mobility across the UK in future, especially in, around and between cities. Although they will have a significant impact in these locations, there will still be extensive car and van usage across the UK. There are many benefits to an increase in these modes of travel and it is encouraging to see examples of serious and well-organised efforts to support them.

On average cars currently spend less than 5% of their time on the road. Around 30% of cars are driven less than 5,000 miles per year. The social and individual return on the higher upfront in-vestment in a replacement electric vehicle for low mileage cars is quite low. Arguably these journeys would be better served by some combination of shared access to cars, car rental, better public transport, cycling and walking, especially in integrated public and private transport systems. Different ownership models and autonomous vehicles may transform vehicle use in future. Much higher utilisation of cars would change their design parameters, making the up-front cost of the vehicle a lower element of cost per mile and changing the basis of competition, for example between electric and hydrogen vehicles. Refuelling requirements would change, because of the reduced availability of "charging windows".

Although autonomous vehicles hold great promise, they have challenges to overcome, not least in terms of safety. It is well-established that the public require autonomous systems (of any kind) to deliver much higher levels of safety than systems that they operate themselves. Travelling by autonomous vehicles will eventually be safer and make better use of congested roads than human drivers. It will however take time to get to mass adoption; how long is very hard to predict.

This report assumes that manufacturers will design and sell ranges of BEVs and PHEVs. Over time the cost of these vehicles will have a decreasing premium over pure fossil fuel cars, especially as efficiency and emissions standards for these Internal Combustion Engine Vehicle (ICEVs) are raised. Levels of direct public support will reduce, so that the total cost to taxpayers will remain the same, while the number of vehicles supported rises[16]. This report also assumes that fossil fuels will continue to be taxed at a similar premium over electricity as today, acting as a proxy for an effective carbon price. There are different approaches to this, which are also not discussed.

Out to 2030, it seems likely that a considerable fraction of UK drivers will be prepared to make up a difference between the level of taxpayer support and the prices of BEVs and PHEVs, compared to equivalent Internal Combustion Engine (ICE) cars. Different segments and vehicles will accept a modest premium for different reasons and manufacturers can be relied on to target vehicles effectively, just as they do for other premium features of car design. Previous work established that BEVs and PHEVs appeal to different purchaser segments, for a range of reasons[17].

These various assumptions remain to be tested, as electric vehicles, both BEVs and PHEVs, become a true mass-market purchase choice in the UK, and drivers use and charge them. They are however based on judgements based on significant research and analysis. Readers can form their own opinion about them from the references.

The split between BEVs and PHEVs is less important to decarbonisation and charging than the miles travelled using electricity, and the greenhouse gas emissions produced by generating the additional electricity. As batteries continue to improve cost, range and charging rate, BEVs will become attractive to a larger proportion of car owners. PHEVs can travel a high proportion of miles on electricity, with a much smaller battery than the driver would require in a BEV. The availability of PHEVs opens up miles to electrification that would otherwise be driven by a pure fossil fuel vehicle. In terms of decarbonisation, BEVs and PHEVs are complementary, not competitive. Drivers will choose vehicles that meet their needs. PHEVs are likely to become an important gateway to later BEV purchase, as battery costs and performance improve. An overview of battery technologies is provided in Appendix I.

New cars sold in the UK in 2017 had nominal fleet average emissions of about 200 gCO_2e per mile[18]. Electric vehicles

[16] These issues are extensively discussed in reports from the CVEI project
[17] "Who will adopt electric vehicles?: A segmentation approach of UK consumers", Anable et al, Proceedings of the European Council for an Energy Efficient Economy, June 2011.
[18] https://www.smmt.co.uk/industry-topics/emissions/facts-and-figures/

would have similar emissions if charged with electricity with a carbon intensity of 600 gCO_2e per kWh. UK fleet average carbon savings from switching to vehicles running on truly low carbon electricity would be around 1.5 Te CO_2e per vehicle per year. These figures are intend-ed to illustrate the issues – real-world results will be different, due to journey patterns and driving styles. Using electricity from coal would probably increase emissions, as coal power stations have emissions significantly over 800 gCO_2e per kWh.

In the UK, it is likely that gas turbines will be operated to meet additional demand from vehicle charging at times of peak electricity demand. That might reduce the savings to as little as 0.2-0.4 Te CO_2e per vehicle per year, unless demand can be managed away from peak. The embedded carbon in vehicles with different drivetrains and supply chains is also important to global lifecycle emissions, but beyond the scope of this report.

UPTAKE

The report has been informed by a range of scenarios for vehicle uptake. Scenarios where Carbon Budgets[19] are met were given greater weight than those where they were missed. Although it is possible that carbon targets will not be met, this document discusses the role of charging in delivering a successful outcome. We focused on scenarios that were developed through systematic and careful primary analysis, for example from groups such as National Grid, the CCC and the UK Energy Research Centre, as well as ETI projects on whole systems analysis, including CVEI. There is broad consistency across the scenarios from different groups (where carbon targets are met). The example Higher and Lower scenarios in Figure 2 were informed by these scenarios but simplified to draw out key points.

Whole system scenarios consider the uptake and charging of electric vehicles and fuel consumption for non-electric miles as part of a total system design. Systems without significant electric vehicle uptake by 2030 can only meet carbon targets at much greater cost, if at all. Unless the UK is well along a trajectory of travel decarbonisation by 2030, 2050 targets cannot be met. This is simply due to the large emissions associated with cars (and vans) and the time it takes to turn over the UK car parc through new vehicle purchases.

The Lower scenario represents a pathway that is likely to fall short of carbon targets, while providing significant challenge to the electricity system. Higher exceeds carbon targets by three years, while presenting a major challenge in providing and managing charging in 2030. Low PiV sales will also present risks to the UK economy.

The current average lifetime of cars already on UK roads is just under 14 years. Accelerating the scrappage of existing fossil fuel cars would have negative impacts on the UK economy and global greenhouse gas emissions. Given the limited number of opportunities there will be before 2050 for new car buyers to choose a rechargeable vehicle, sales of rechargeable vehicles need to accelerate, if they are to be a large enough proportion of the 2050 parc. Reaching 100% of sales by 2040 means a high and rising level in 2030. The important role of fleet purchases of both cars and vans in new vehicle sales is discussed in Appendix III.

From the perspective of drivers, the factors that act as drivers and blockers to uptake can be broadly categorised as:

1. Cost and performance of vehicles
2. Availability of a suitable range of vehicles in sufficient numbers
3. Access to convenient and cost-effective charging
4. Other factors – e.g. social norms, insurance requirements, availability of parts and maintenance, preferential access to parking, road lanes, congestion charging etc.

The main uncertainty in cost and performance of vehicles is the extent to which government will continue to support vehicle purchase (and maintain tax differentials between liquid fuels and electricity). The cost premium of PiVs over ICEs should fall significantly, as a result of reduced supply chain costs, making this an issue mostly for the early 2020s. National and local government policies can have direct impacts on 1, 3 & 4 as explored in the CVEI project reports, and on 2 indirectly.

VEHICLE CHOICE AND USE – DRIVER NEEDS

The market is developing a range of attractive BEV and PHEV[20] models, which are converging on the requirements of different mass market segments. Provided that PiV uptake in the UK continues to progress, the only supply-side issue might be insufficient manufacturing capacity for the most attractive models, leading to rationing by price. This would most likely be a short-term blip, that would only reinforce the general attractiveness of PiVs in the minds of consumers and manufacturers[21].

Different drivers will choose different vehicles and drive them quite differently. Partly this will be down to individual driving habits, partly down to local geography and partly down to the patterns of daily life. From the National Travel Survey, we can estimate the distribution of annual mileage across English drivers and the distribution of journey lengths.

[19] Reducing UK emissions: 2018 Progress Report to Parliament, CCC, June 2018
[20] We are assuming that OEMs will respond to the market and policy signals they are receiving (for example UK changes in PHEV support) and design PHEVs so that more drivers drive on electricity, for more of their journeys
[21] The potential for limits to the availability of cobalt, for battery manufacture, might present a more significant shock to the PiV market

Figure 2
Growth of rechargeable car sales and proportion of UK total parc (based on Fisher-Pry substitution modelling)

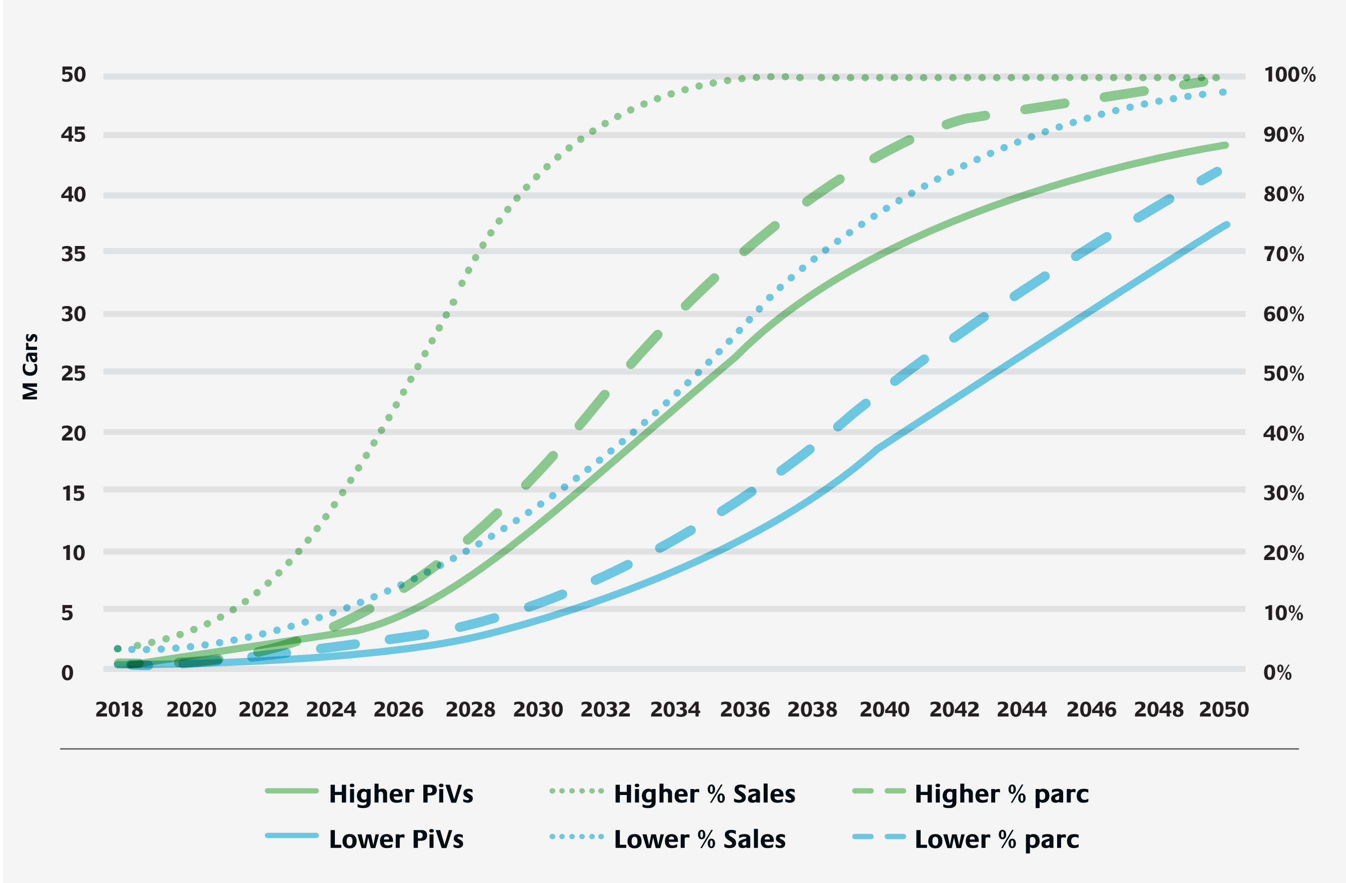
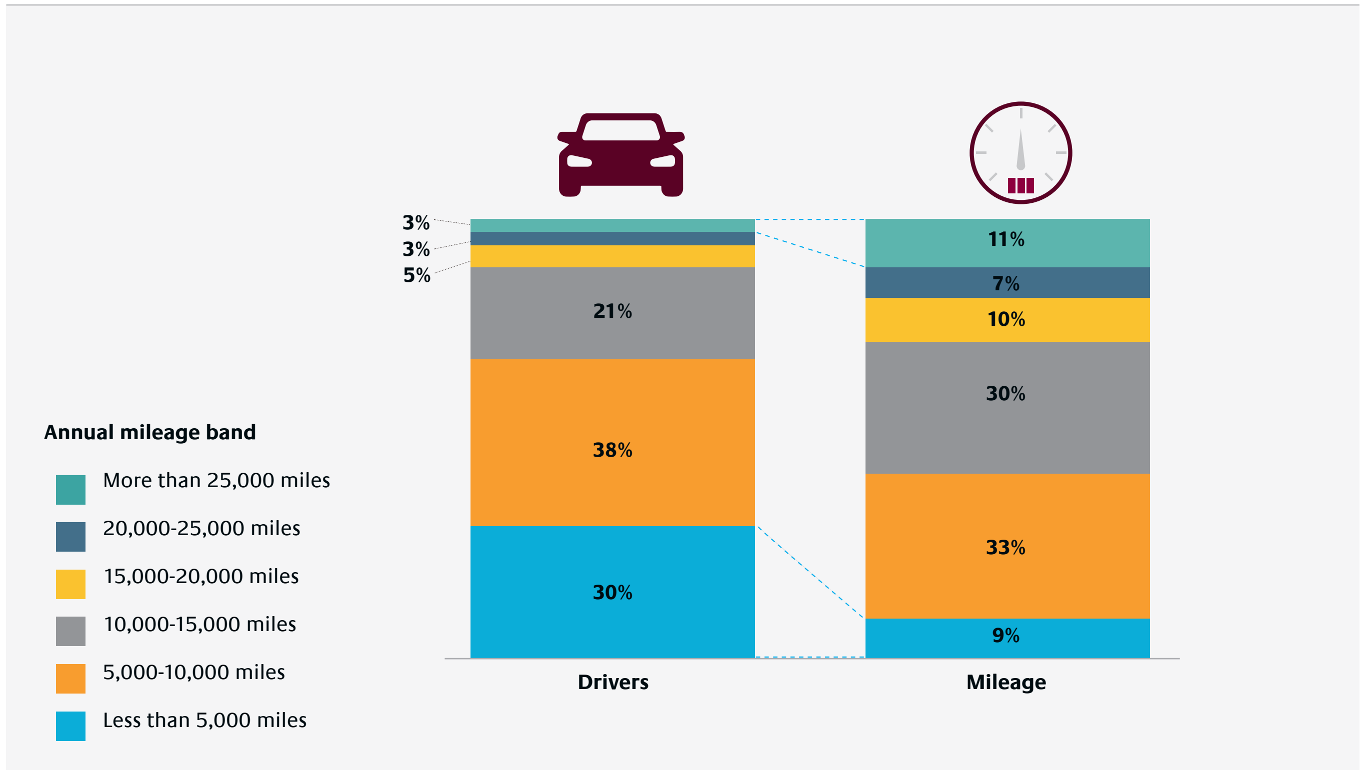


Figure 3
Proportion of drivers by annual mileage and their contribution to total mileage



30% of drivers drive less than 5,000 miles per year. They account for just 9% of miles. A small number of drivers cover more than 25,000 miles per year. They account for 11% of miles. In total, drivers with mileage over 15,000 miles per year cover more than a quarter of mileage in England, despite being only about one in ten drivers.

The distribution of trips is also important. An annual mileage can consist of a large number of short trips or a smaller number of long ones, or any other combination. The distribution of trips and opportunity to recharge between them will determine the maximum number of annual miles that could be driven on electricity in a PHEV. How suitable a BEV is for an individual depends very much on the detail of their trip patterns, the effective range of the battery, the resistance of the battery to fast-charging, and the opportunity to recharge within longer sequences of trips; such opportunities would include breaks at motorway service stations or when the car is parked for longer periods at the station or workplace.

About 75% of the distance driven by car in England is made up of trips less than 50 miles. This is a promising background to converting those miles to electricity by a combination of BEVs and PHEVs (or to another mode of transport). All three drivers in Figure 4 drive around 23,000 miles per year. The data from Driver 1 is taken from the 8 weeks during the trial, when they were driving a PHEV. Driver 0 was not involved in the trial, has a similar annual mileage in an ICE vehicle, but quite a different pattern of trips. Driver A data is from the 8 weeks in the trial when they were driving a BEV.

Driver A appears to have a regular journey of around 32 miles, and Driver 1 a regular journey of around 18 miles.

Driver 0 does not appear to have regular journeys. Although annual mileage is used as a shorthand for the suitability of different types of vehicles, the distribution of trips is also very important. The driver in the Charging Trial with the highest mileage was a BEV driver, with the equivalent of over 30,000 miles per year. Someone who does high annual mileage with many short to medium range journeys would be ideal for a BEV, provided that:

- They have access to charging that matches their trips and destinations; and
- They are prepared to use another vehicle or mode of transport for trips that are outside the effective range of their BEV.

The PHEVs used in the trial have an effective electric range of around 20 miles. Driver 0 could electrify up to half of their miles with 20 miles range and Driver 1 could electrify up to 60%. This assumes that they drive to maximise miles on electricity and that the vehicle can be fully re-charged between trips, so this is a theoretical ceiling rather than a practical estimate. In the trial, Driver 1 managed to drive 38% of their miles on electricity, which is still a reasonable proportion of the 60% theoretical ceiling.

If the PHEV effective range was extended to 50 miles (the range that would satisfy half the Uptake Trial participants), then both drivers would have a theoretical limit of over 80% electrification. We can see also that Driver 1 might need a longer-range BEV than Driver 0, before they would consider a BEV in preference to a PHEV.

This overview glosses over important details in the performance of ICEs and PiVs on different types of journey, with different driving styles. The energy consumption per mile of ICE, BEV and PHEV vehicles differs, even on the same journeys. For example, regenerative braking makes a big difference on sections with lots of stop-start driving; driving style is important to fuel consumption by an engine. Very granular data was collected on trial journeys in CVEI, so it would be possible to investigate these effects in more detail. Efficiency of individual trips in PiVs is not critical to decarbonisation, since we are trying to electrify.

However, it does matter in terms of the expectations that drivers have of their effective range in PiVs. With so many trips of different types included in the CVEI data, we can get good estimates of effective range; the values for population average miles per kWh and effective range used in this report were derived from the CVEI data. Some adjustments were applied by reference to limited other data, mostly from the grey literature.

CHARGING

Access to convenient and cost-effective charging might become the main determinant of the growth in PiV sales in the UK. The benefits to UK wealth creation and decarbonisation of vehicle electrification might therefore depend on finding vehicle charging solutions. An attractive approach to vehicle charging is to use the spare network and generating capacity (required to meet the winter early evening peak) to charge vehicles overnight, while drivers are asleep.

In principle the system should have significant spare capacity to supply and distribute electricity at times other than the winter maximum peak.

However, this may not be so simple in practice:

- Unless they are users of an overnight tariff, people tend to plug in and start charging when they arrive home. This coincides with the winter evening peak.
- With increasing proportions of variable renewables, the supply will vary, so that sometimes the maximum supply of low carbon electricity will be during the day, especially if there is a significant capacity of PV.

In the longer term, probably well beyond 2030, there may well be significant competition for electricity from electrification of space and water heating, probably requiring widespread network upgrades, as well as more low carbon generating capacity, especially in the winter.

Figure 4
Distribution of mileage by trip length

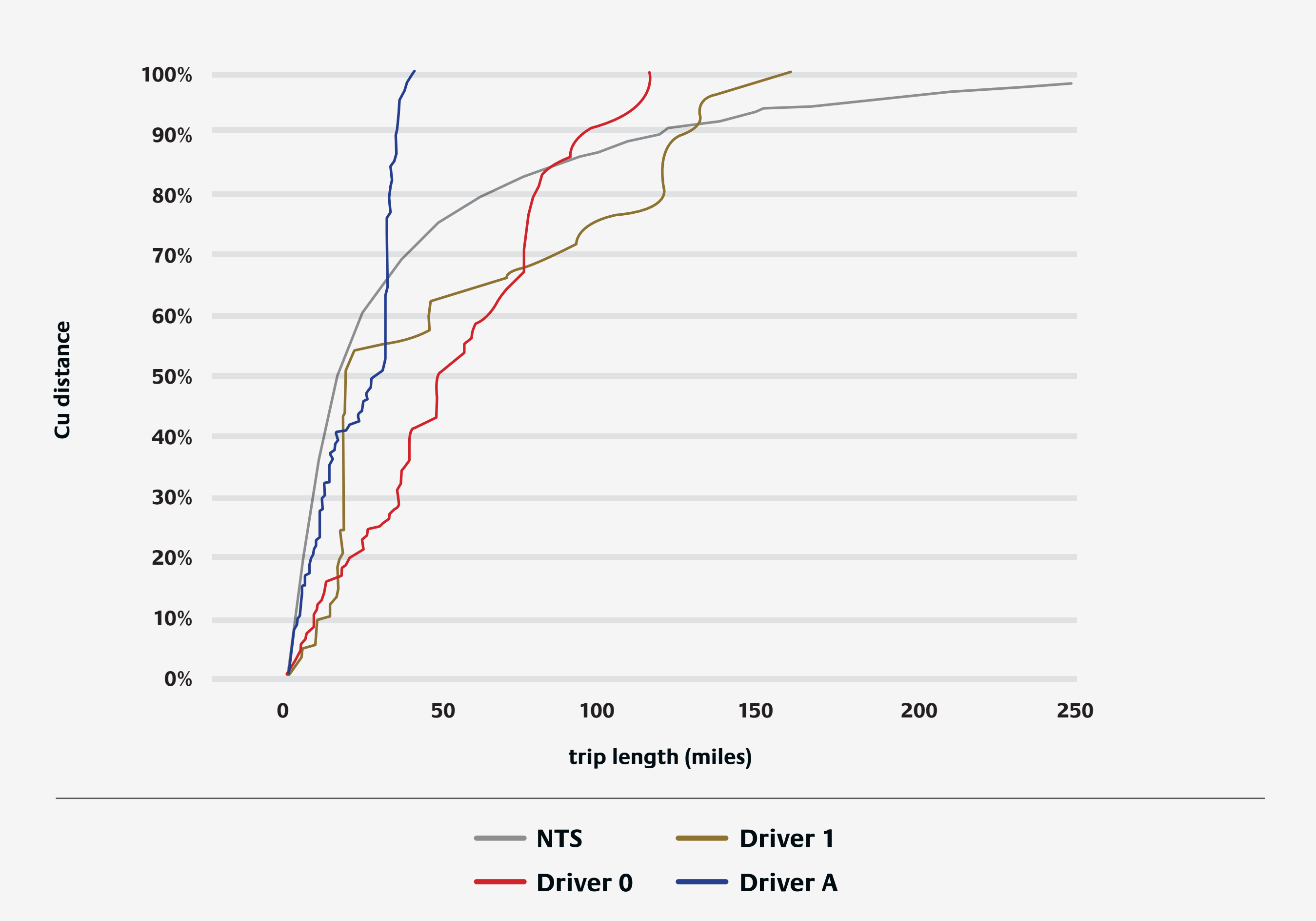
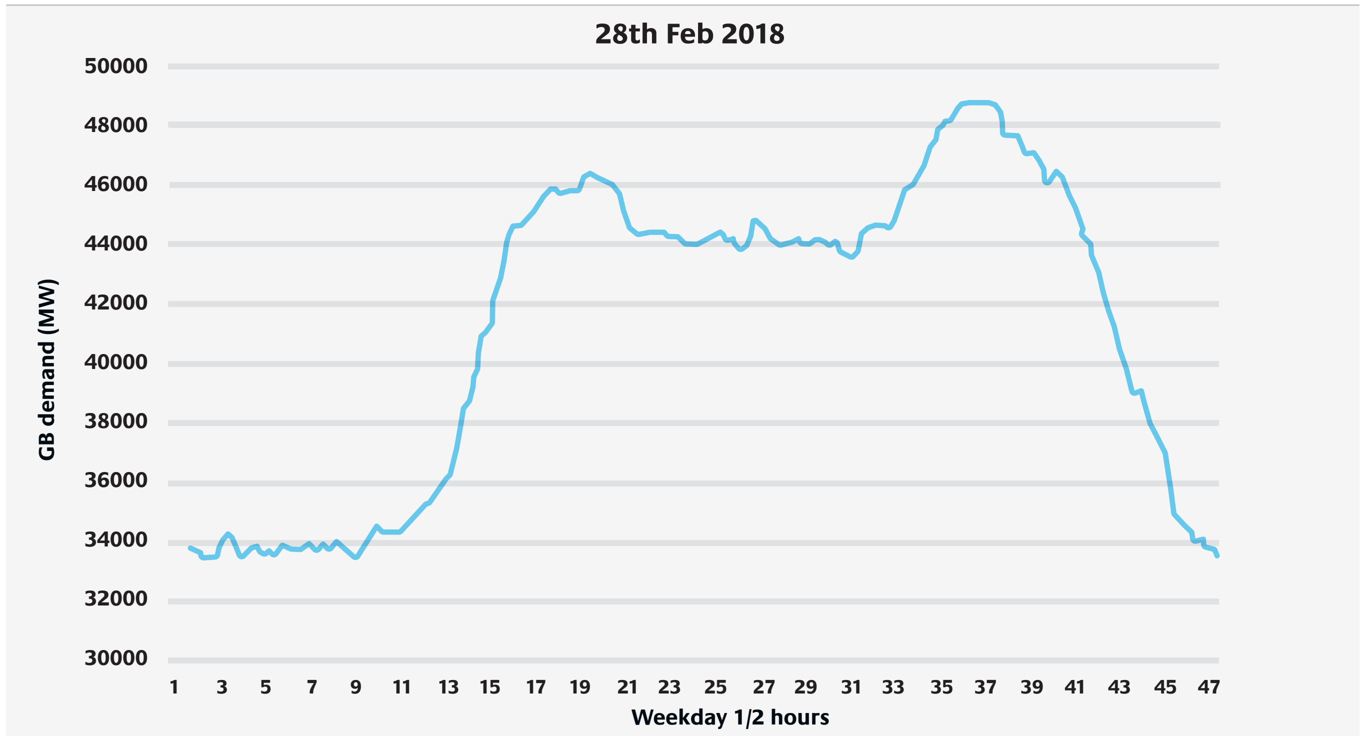


Figure 5
Proportion of drivers in the National Travel Survey by annual mileage



Based on early consumer trials of BEV charging, it seems that the likelihood of unmanaged charging coinciding with the evening peak is significant[22,23].

The final link in domestic electricity distribution is an 11kV/400V (LV) substation. In a typical urban and semi-urban setting, these supply around 150 dwellings on each 3-phase circuit. Each dwelling has a supplier fuse, typically rated up to 100A, and each phase has a fuse at the substation board. A minority of circuits are currently fitted with circuit breakers rather than fuses.

Although each dwelling has a supplier fuse, typically rated between 14kW and 24kW, the shared capacity assumes significant diversity in exactly when people use high powered appliances such as microwaves, kettles and especially showers. Typically, the shared capacity is 1-2kW per dwelling; in areas with high penetration of electric heating, the typical shared capacity is 8kW per dwelling, but this is used overnight in winter, possibly requiring charging to be managed differently in these areas.

PiV penetration will not be the same at every LV substation. The suitability of PiVs for journey patterns, word-of-mouth from early purchasers, strong promotions by local vehicle dealers etc. will cause clusters, where uptake is much higher than the regional average. As the modelling by Infield shows, the random arrival times of drivers will occasionally cause significant peaks in substation load. These peaks may cause loads beyond the ratings of various parts of the local circuit, for example voltage drops down the line, transformer ratings etc. Unless these cause operating problems, they may just lead to faster than typical loss of component life and occasional damage to consumer appliances. If the circuit fuse blows, then a field engineer will need to replace it. At this point options to prevent further problems without an urgent upgrade will depend on the local network configuration. There are also potentially issues with the 11kV backbone, if LV clusters are close together.

We are at far too early a stage of market development, before mass-market uptake, to get a sense of the scale of this problem of overloaded local networks. It will happen much earlier than any significant increase to the peak of the overall GB demand curve. There are some clues from ETI projects about which postcodes are most likely to be early adopters[24]. Fortunately, postcodes that appear more likely to be early EV purchasers are also more likely to have higher shared capacity, closer to 2kW per dwelling.

If outages requiring substation fuse replacements start to occur when the national average penetration reaches 3% of the vehicle parc, then that would occur in 2023 in the Higher scenario and 2024 in the Lower. If it only starts at 5% that would delay Higher until 2024 and Lower to 2027. Part of the uncertainty is that we don't know how clustered high-mileage PiV drivers will be. Many current PiV drivers are low-mileage or low electric mileage (in the case of PHEVs).

A further concern would be two EV households, where the dwelling supplier fuse is very likely to blow if both vehicles are charging and someone uses an electric shower (in some dwellings the background load would be enough). As the ability to recharge at or close to home is seen as a significant consumer advantage, the impact of adverse reports of such events in the press and on social media is likely to be significant. Many households own two or more cars or have a company van as well as a car.

There are three broad strategies to address the risk of locally overloaded distribution networks:

1. Respond & React

The recent history of regulated networks has created an environment where investment in advance of need is difficult. There is an obvious concern that this emerging and poorly understood load might prompt significant over-investment, especially if the uptake of PiVs lags behind the rate necessary to meet decarbonisation targets. There are a series of measures which network companies could use to manage the loss of service events and reduce their frequency. In the event that PiV sales take off and clustering is a serious problem, these may buy them somewhere between months and a few years of lead time.

2. Predict & Prepare

A more aggressive strategy would be to gather and use data from trials and modelling of typical networks to understand the potential issues and develop a range of technical measures and the human capacity to respond more rapidly and flexibly than the reactive strategy.

3. Invest & Stimulate

This approach anticipates success in delivering government policy objectives for PiV uptake. It seeks to invest in the range of charging options that are most likely to match driver needs to electricity supply at the lowest cost. As driver behaviour is emergent, the investments will adapt to feedback from real-world experience. Systems to enable charging management are a core element of this approach. It balances the risk of early over investment in infrastructure against the risk of a severe barrier to uptake. It also avoids money being wasted on investments that are potentially short-lived stop-gaps.

Although the first benefits of smart charging will be seen in avoiding local network overloading, as PiV penetration increases it will be important in avoiding additional investment in generating capacity and in maximising the use of low carbon electricity. This will be discussed in more detail later. Benefits beyond avoiding overloading local networks cannot be delivered by local network companies throttling access to their networks; they will require supplier led charging management. Restricting charging when the network is overloaded is different from maximising charging when low carbon electricity is available, at a time when there is available network capacity.

OTHER FACTORS

It is difficult to foresee the overall impact of "other factors". There will undoubtedly be glitches that have a negative impact, but the overall impact is likely to be positive. In the broader context of a virtuous circle of continued government and manufacturer support for electric vehicles, the "other factors" are likely to become increasingly positive. City clean air zones, preferred access to parking, etc can all influence driver vehicle choice and driving behaviour. These factors are more extensively discussed in the CVEI project reports.

[22] CIRED 2015, Quirós-Tortós et al, University of Manchester
[23] Markov Chain Monte Carlo simulation of electric vehicle use for network integration studies, Wang & Infield, International Journal of Electrical Power and Energy Systems, 99, 85-94.
[24] Identification of Relevant Consumer Segments, RPN1768, Anable et al, TRL, April 2011

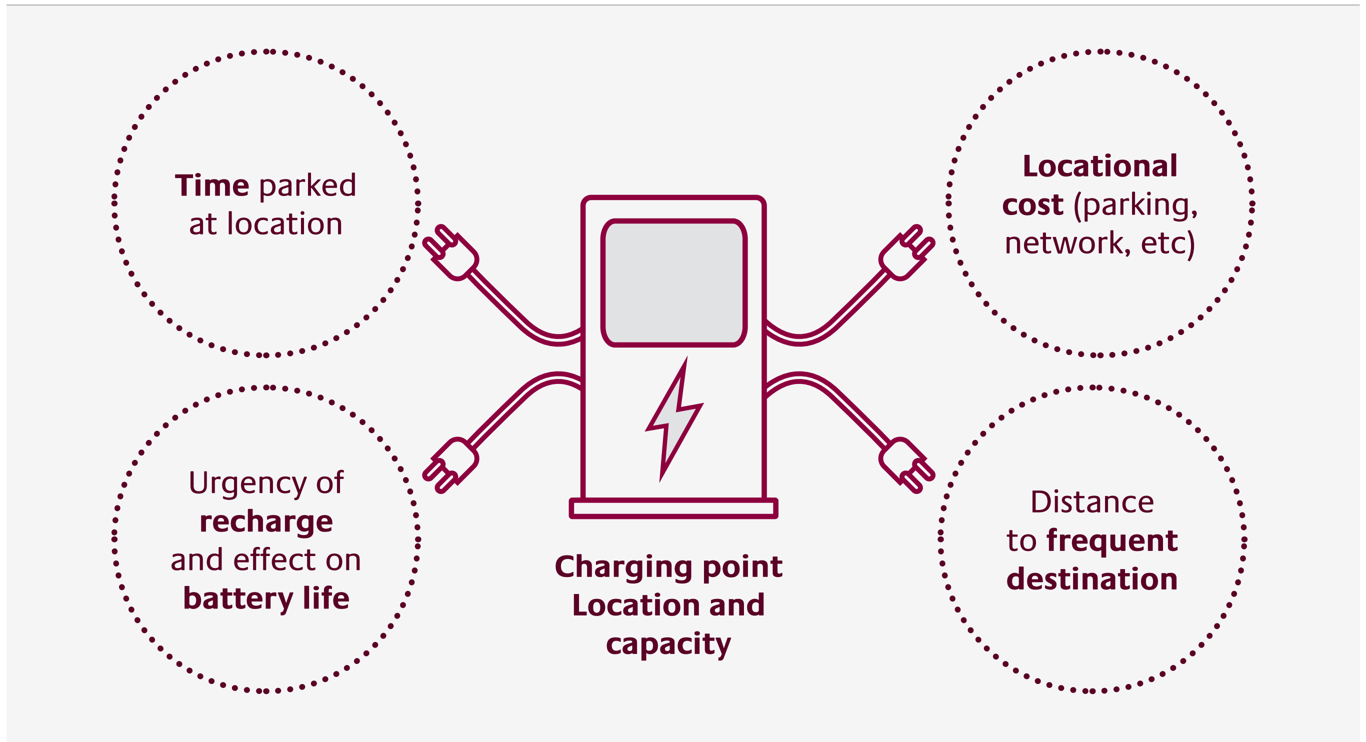
THE EXPERIENCE OF TRAVEL

Electric vehicle drivers and passengers are more likely to represent the digital Uber and AirBnB generation than the world of petrol stations – managing travel and charging through “an App” will be the obvious solution for them.

A thought experiment of what coffee shops would be like if they sold the cheapest coffee, rather than the best consumer experience, illustrates the difference between supplier and customer focus. It is possible that customers will be willing to pay for services that suppliers find it difficult to provide, within current market and governance arrangements.

There is a natural pattern to charging, which intersects with driving patterns on the one hand and electricity supply and distribution on the other. If batteries were like fossil fuel tanks (i.e. 400-800 mile range was a modest cost and space claim), then charging would be located wherever it was cheapest to provide, close enough to where people live and along major routes. The lower cost of a BEV (compared to an ICEV) would compensate for the higher cost (in the absence of taxes) of low carbon electricity supply and distribution (compared to liquid fuels). It will be many decades, if ever, before batteries are the combination of that cheap, that small and able to be charged at over 400kW without capacity deterioration.

Figure 6
Driver factors in charging point selection



The weighting of these will depend on individual driver preferences, whether their vehicle is a PHEV or BEV, and the size of the battery. Reliability will be a critical factor; if charge points are already occupied, or out-of-service, when required, the drivers will not seek them out. Convenience and use of their time are important driver considerations. From a driver perspective, the ideal charging locations are ones where:

- They are conveniently located for their daily life - typically at home, at work, at long-stay car parks and at destinations where they spend several hours such as cinemas, restaurants, shopping complexes, hotels, etc.
- The charge point is important to the range required for a sequence of journeys between opportunities to slow charge cheaply
- Additional costs (such as new network investments) are only a modest premium over the basic charge-point installation cost and the cost of parking is seen as good value (especially if it is free)

These might be grouped as:

- Up to 7 kW at or close to home (and hotels)
- Up to 50 kW at work and other business destinations (including hotels with conference centres)
- Up to 450 kW en-route on major routes for long distance journeys
- Up to 20 kW at long-stay car parks at transport nodes (stations, airports etc.)
- Up to 100 kW at car parking at destinations such as shopping centres, in cities, etc.
- Up to 450kW at refuelling stations, where the purpose of the trip is a bulk, cost-effective charge
- Up to 100kW for taxi and delivery drivers (as a special case of refuelling)

The underlying cost of the charge in p/kWh will be dominated by:

- Cost of the parking place, including any infrastructure (such as a multi-storey structure, security systems, etc)
- Additional network costs
- Effective capacity utilisation of the network and charge point assets

The price that is charged will depend on other factors, including how various elements of electricity system costs are charged out to the charge point supplier. IT costs are often neglected, as marginal use of existing systems, for example a domestic internet connection. However, they may be large enough in some circumstances to be significant, for example the transaction cost of charging a small amount of electricity to a debit card.

The cost of parking (land and car park infrastructure cost) is likely to be the most significant factor in many circumstances. The wholesale cost of electricity will have a minor effect on charging cost, until EV penetration is high enough and charging is sufficiently peaky to require more generating capacity. If charging can be managed, the overall effect might be to make better use of existing generating and network assets thus reducing the average delivered cost of electricity. Beyond 2030, increasing electrification of heating will create a new environment, but this is beyond the scope of this report.

Electricity distribution is expensive, so it makes sense to use spare capacity on existing circuits before adding new ones. The main exception to this is for en-route charging on long distance journeys. Given the significant proportion of energy consumed on major roads, especially busy motorways, the best solution is likely to be new charging capacity, sited to make best use of the existing high voltage transmission and regional distribution networks[25]. Tesla and Ecotricity appear to have followed a strategy of using historic spare capacity at motorway service stations. Pivot Power have announced a plan to locate rapid chargers at sites identified by National Grid, combining this with batteries to provide system services as an additional revenue stream.

A further complication is the effect of aggressive charging on the life of current vehicle battery technologies. As a rough rule, fully charging a battery in less than 1 hour will rapidly degrade its capacity. The range that can be added through rapid top-up (in 20 minutes or less) is therefore a fraction of the battery capacity. Slow charging is best for battery life but requires the vehicle to be parked for several hours for a large charge. Battery management will manage fast charging to protect battery life. The balance between the use of the driver’s time and the loss of battery life is important in any system where frequent fast-charging is required to support journey patterns.

Where the battery is rented from the OEM, they will replace it when the capacity falls to 75% (typically) of the original specification and the charging profile of the battery management system is therefore part of their business model.

As more electric miles are driven, more total charging will be required. However, the requirements will change over time:

- Initially charging will need to be available over a wide area and the capacity will not be fully used; as more vehicles are on the road, utilisation will increase and additional capacity will be required, but area coverage extension will be incremental.
- As batteries become cheaper and larger in capacity, the focus will shift away from enabling journeys (except on long journeys), towards filling-up where it is cheapest and easiest. There will always be some need for enablement for people who do not charge ahead of need, but this need will look like high powered charging at a small number of defined points.

There is an alternative scenario, where batteries remain small but become very resistant to fast charging and therefore charging away from home is more significant (but expensive). From the perspective of drivers, a supplier of services could combine journey planning, parking reservation, and charging. Alternatively, different suppliers could provide elements of these and drivers would then need to plan and integrate these elements themselves. For example, driving to an airport to travel could be seamlessly integrated, so that the travel manager could book the planes, book the parking, ensure that the vehicle was recharged on return and cope with flight delays automatically and invisibly. Knowing the underlying itinerary allows an integrated service manager to manage the capacity and marketing of car parking spaces and to optimise within the recharging window. If the parking has a shared Vehicle-to-Grid capacity, then the service provider can sell system services as an additional source of revenue. All of this can be presented to the driver as a premium service, as well as operational cost and revenue optimisation activities[26].

Conceptually, there might be three levels of service, with increasing levels of integration and delivery complexity:

Home-charging

Each charging point provides a separate service, where the charge point recognises the user as having a rechargeable identity (for example a credit card) and the vehicle as having

[25] Plugging the gap: An assessment of future demand for Britain’s electric vehicle public charging network, Connolly et al, Systra for the Committee on Climate Change, January 2018
[26] Mobility as a Service: Exploring the Opportunity for Mobility as a Service In the UK, Transport Systems Catapult, July 2016

a compatible charging management interface. At home, the charging forms part of the overall bill for the meter point as part of an overall energy service supply; at work, charging cost data is fed back to the site owner; at other locations, it is part of an overall service transaction, including probably parking charges. There is no scheduling between charge points only against the required State of Charge at each individual charge point. The driver gets separate bills for each location, possibly each transaction.

Location Managed charging

This service gives access to charging at home and other defined locations (for example at work) and also networks of public charging points (including probably parking reservation and billing). Vehicle charging costs are separated from the domestic (or work) energy bill, so that the costs follow the vehicle (or driver). Young drivers using the family cars can have their own accounts, with parental controls on use, budgets etc. Employed drivers can charge to their own or the company account. Domestic and mobility energy services suppliers will be different entities, even if they are part of the same enterprise and share infrastructure. Both will need access to the domestic energy supply, which implies multiple supplier access to the Smart Meter.

The driver specifies their needs and the system meets them cost-effectively. Scheduling across multiple journeys is only between known charge points. For example, the system might not charge at home if the vehicle has a user defined opportunity to charge later at work and the cost-to-charge is expected to be less later, due to good midday sunlight.

Although the user can plan their vehicle use, there is no integration with other transport modes or optimisation by the system. Location managed charging requires the user to manually reconfigure the charging plan, if there is a change of travel plan. Although the system will register delays, it doesn't know where the vehicle is now, apart from registering early arrivals at a parking place with charging.

Full-service

This provides:

- Planning – identifying routes and charging points, enabling the acquisition of parking and charging services and minimisation of tolls, potentially integrating other transport modes.
- Access – enabling use of charging at home, at other homes and third-party sites and public access charging points in a seamless fashion (think Oyster card).
- Charging management and notification – meeting charging requirements and accepting updates to available charging window(s); providing real-time information on charge state and miles available etc.
- Cost management – providing historic data on journeys, charging, road tolls and charging, parking charges etc., including both prepay and credit services
- Condition monitoring – providing analysis and warning on the health of the vehicle and battery and also of charge points and infrastructure.
- Emergency support – solutions to inadequate charging availability, blocked or failed charging points, impossible journey schedules, battery or other vehicle problems, etc.

In this model the secure identities of both the vehicle and the driver enable drivers to navigate personal journeys in a seamless way, in which the full potential of various kinds of infrastructure is marshalled to meet their needs, according to a cost-effective contract for which the service provider takes responsibility. It is a holistic and IT enabled vision, recognisable as the Uber or Amazon world, not the world of regulated commodity energy supply.

You plan your journey in advance or on the fly and the system not only helps plan your journey but reserves the resources you need. Details are downloaded to the vehicle, smartphone or other digital assistant. In the most advanced versions of full-service, the driver does not own the vehicle; it is available for a period as part of an integrated mobility service[27].

All three levels of service have similar core electricity system components: buying electricity when it is at its cheapest, avoiding network constraints in the local distribution system and avoiding exceeding the capacity of the individual building/site supply. However, the potential to schedule charging across different locations is much greater at the full-service level. Also, different locations have different flavours of the constraints: large car parks have much greater diversity across parking bays than a home; balancing the needs of different car park users is not the same as jig-sawing together charging two cars in a home, when both working parents have parental "taxi duties" on return from work, etc. Within these simplified and illustrative concepts of service we distinguish between the business model and the customer offer (which is only part of the business model).

For example, the customer offer might be something like a mobile phone package, whereas the business model would involve the service supplier managing charging to maximise their profit (within the limits of acceptable service delivery).

The ETI does not see exposing variable Time-of-Day (ToD) costs directly to consumers as likely to be effective, except in very simple situations, such as differential day and night tariffs. Unfortunately, the evolution of energy systems makes the likely pattern of electricity costs and carbon contents more fluid than fixed tariffs can capture. The potential for sharp rises and falls in demand and of super-peaks can also be problematic.

Different drivers will value different aspects of these potential services. Not everyone will want the Full Service. We might hypothesize, for example, that there will be different ways of thinking about charging:

- Baseload focused charging – I want to buy as much of my electricity as cheaply as possible; whenever I see cheap electricity, I will fill up as much as possible; I try and avoid expensive electricity, unless I really need to buy it.
- Grazing charging – I like to keep my battery topped up and will charge whenever the opportunity presents; I'm not willing to go out of my way or spend time waiting for charging when there are so many opportunities to charge in my normal day.
- Unplanned charging – I will charge my car whenever I need to, in order to enable my journeys; it's good to set out with a reasonably full battery in the morning but I only fill up when I need to.

These are hypotheses, not based on research. They are intended to illustrate the potential for different expectations and behaviours from different drivers.

Managed charging models have the potential to make significantly better use of system capacity to meet drivers' needs than simple rationing. However, they are complex and have subtle embedded risks, for example that they create service expectations that drive up investment, creating costs which are hard to recover or that they enable wealthier people to buy limited capacity away from vulnerable people. The Section on The Social Dimension discusses some of these issues.

[27] For example, see https://whimapp.com/uk/

CHARGING NEEDS

It is unlikely that market and governance structures developed to manage the existing uses of electricity will be suitable when new classes of use, such as vehicle charging, are added. The governance of the electricity system needs to develop suitable market structures and pricing, so that new assets and operating tools can deliver cost-effective and end-user focused operations. Avoidable additional costs and restrictions on use need to be minimised.

The central theme of this report is that charging management is a critical tool within this new governance, combined with cost allocation methods that are better aligned to the real drivers of costs. Suppliers will then be able to help their customers easily get what they want at the lowest added cost to the supply side.

The Higher and Lower scenarios in Figure 2 imply between 25% and 80% of new car sales in 2030 will be PiVs. This is a significant increase on the 10% to 35% implied in 2025. This will be a mass-market, not very early adopters, such as form the majority of electric vehicle purchasers today.

Consumers have widely different needs and ways of thinking about what they want. Although modern marketing has developed the concept of digital micro-targeting and service customisation, this requires engagement with consumers and the collection of considerable amounts of data. For the purposes of investing in the large-scale infrastructure potentially required to deliver services to different consumers, we will probably need to fall back on more traditional marketing approaches. Traditionally consumers are grouped together, so that consumers within a group have sufficiently similar needs that they can all be satisfied by similar services and delivery mechanisms. These groups are called segments (parts of the total market).

During the 2020's we will only remain on track to meet policy targets if electric vehicles start by capturing the bulk of sales to segments that are attracted to them; then make significant progress with segments that are well-served by them; and leave only segments that are badly served or actively unpersuaded that a rechargeable vehicle is for them. It is the experience of the first 15% to 25% of car drivers in the early to mid-2020's that will set the tone for meeting 2030 goals.

DRIVER SEGMENTATION

From carefully designed consumer research carried out by the ETI CVEI project partners (building on a previous ETI project), we can make informed judgements about the early development of consumer segments. Inevitably the segmentation will change and develop as the market matures, in ways that experience with other consumer products and services tells us are hard to predict. The CVEI analysis was based on a segmentation developed for the Department for Transport. We have also used the segmentation from the previous ETI project as background to this report[28]. More detail on these segmentations is provided in Appendix II.

The segmentations provide clues about the likely characteristics of the owners and drivers of the first few million PiVs in the UK, i.e. those most likely to be driving a PiV by 2030 and contributing to meeting medium term carbon targets. These segments are both based on large samples of consumers with no experience of PiV use. Although they provide useful background on issues that concern consumers, the research carried out with participants in the CVEI Uptake and Charging trials has more authority, since the consumers did have experience with PiVs. Most people make purchase decisions based on what people tell them about their actual experiences, seen from the perspective of their own concerns. Combining the existing segmentations with the CVEI outputs allows us to make judgements about how the market for PiVs might develop.

There are indications from the CVEI project consumer research analysis[29], that most mass-market consumers are driven primarily by the functional attributes of PiVs. How well they meet their needs and their upfront and operating costs are the most important factors. Attitudinal and other factors play a role, but this is less significant. The most appropriate segmentation for charging is therefore functional – what do drivers need from their cars and what does this mean for charging loads in different places?

In order to convert a significant fraction of mileage to electricity, there needs to be uptake of BEVs and PHEVs, especially amongst drivers with higher annual mileage. BEVs are likely to be more suitable for lower mileage drivers and PHEVs for higher mileage ones. However, some wealthy drivers will buy BEVs with larger batteries and some drivers with moderate annual mileage will want the ability to drive long distances, even if only rarely. Individual driver mileage by trip length curves (see Figure 4) is an important factor in the choice between PHEV and BEV, and in the miles accessible to electricity when a PHEV is chosen.
This leads to the four-way outline grouping by vehicle functionality:

1. Increased use of integrated transport services, including BEV taxis and ride hailing services, and access to occasional BEV or PHEV use

2. BEV drivers who do limited mileage, close to home, mostly on short trips (3-8,000 miles per year).

3. PHEV drivers who do significant mileage (12-25,000 miles per year), with a significant number of long distance and motorway trips

4. BEV drivers with quite large batteries who drive the BEV whenever they can but also use other modes of transport, mostly public transport but including ICE vehicles, for much of their travel.

[28] "Who will adopt electric vehicles?: A segmentation approach of UK consumers", Anable, Skippon, Schuitema and Kinnear, Proceedings of the European Council for an Energy Efficient Economy, June 2011

Many longer distance drivers will have a modest increase in their use of integrated transport services when they are visiting cities. Although data from trials shows that mileages are constrained by range, when using current generation BEVs, a minority of drivers have usage patterns that allow very high annual mileages.

The transition to electric vehicles and increasing provision of mobility services will change the pattern of vehicle ownership and trips, including how car owners and users drive. Drivers in the 4 groups above, will not be distributed evenly across the UK, or regions of the UK. Patterns of vehicle purchase and use will be very location specific.

Table 1
Individual vehicular travel

Miles/ person/year	Walk	Cycle	Car /van	Motor cycle	Bus	London Under-ground	Rail	Taxi	Other public	All modes
Urban Conurbation	210	47	3,507	27	447	217	578	65	76	5,175
Urban City and Town	209	65	5,351	39	339	23	535	51	25	6,639
Rural Town and Fringe	184	52	7,395	14	463	31	508	50	90	8,787
Rural Village, Hamlet etc	141	53	8,827	74	404	17	515	53	38	10,122
England average	202	56	5,091	35	398	99	548	57	52	6,538
London	257	62	2,452	25	499	489	825	58	106	4,773

Table 1 shows average annual distance travelled per person by different types of location in England[30]. As well as contributing to the figures for Urban Conurbations, London has been pulled out separately. We can infer that conurbations other than London will fall between London at one extreme and other urban cities. Note that this data refers both to passengers and drivers. Data in previous charts refers to car drivers.

CVEI CHARGING TRIAL PARTICIPANTS

Drivers in the CVEI Charging Trial were distributed across area types as:

Table 2
Location of drivers in CVEI charging trial

ONS Rural/Urban classification	No of Participants	% Participants	England & Wales average %
Urban Conurbation	31	13	36
Urban City and Town	159	64	45
Rural town and fringe	28	11	9
Rural village, hamlet etc	30	12	10

[29] CVEI D5.2 Consumer Uptake Trial Report: Mainstream consumers' attitudes and willingness to adopt BEVs and PHEVs, 2019
[30] Government statistics, based on NTS data

Urban conurbation residents are under-represented amongst trial participants, but the trial did capture the core of drivers likely to contribute most to electric miles in 2030, as can be seen from Table 1.

Participants for both trials were recruited in an identical fashion from the areas within 50 miles around Wokingham and Loughborough (the trial management centres). The age and gender of the cadres were matched reasonably with the demographics of UK drivers. There were three important filters:

- Company car and delivery drivers were excluded for insurance reasons
- Participants were required to have off-road parking[31]
- People with very low annual mileage were excluded

Participants were not made aware of the nature of the trial until after recruitment, in order to minimise enthusiast bias. Very early adopters (Innovators) were screened out by filtering out existing EV drivers or anyone with an intention to purchase an EV. BEV drivers were additionally screened to ensure that the range was likely to meet their needs.

This report draws most heavily on the CVEI charging trial outputs. The Uptake trial was designed to calibrate models of likelihood of PiV purchase, as an input to wider analysis by the CVEI team. Recruitment for the Uptake trial was very similar to the Charging Trial, apart from omitting the check that BEV range would be suitable. The aggregate trip length distribution curves (see Figure 4) for the BEV journeys in both trials were very similar, as were the ICE trip lengths in the Uptake Trial and the PHEV trip lengths in the Charging Trial. Effectively we have sampled from the same population of drivers and their journeys in both trials, even though the individual drivers were not the same people. The difference between trip length distribution in an ICE (or PHEV) and a BEV was also clear; in aggregate drivers do a larger number of shorter and a smaller number of longer journeys when driving a BEV with an effective range of 125 miles (than in an ICEV).

AN ILLUSTRATIVE SCENARIO

Developing detailed scenarios for PiV uptake and use out to 2030 would require models that combine local transport, inter-regional travel, driver vehicle choice, vehicle technology cost and performance, local network capacities, charge point type and location and business models for the management of charging in relation to electricity supply. Elements of these are being developed by various organisations, but models at this level of local detail were beyond the scope of the ETI CVEI project.

To illustrate some of the issues, we can create a very simplified 2030 vehicle uptake, charging and electrification scenario, based on a total PiV uptake between the Lower and Higher lines in Figure 2, but closer to Lower. The scenario is based around four groups (functional segments). Although this is not a granular model, it does not assume an even take up of PiVs across all drivers and locations. It does target drivers who are likely to drive PiVs and whose journeys need to be significantly electrified to meet carbon targets.

- There are 5M rechargeable vehicles on the road: 55% PHEVs averaging 18,000 miles/year, 35% standard range BEVs averaging 5,000 miles/year, 8% long range BEVs averaging 10,000 miles/year and 2% fast-charging taxis averaging 25,000 miles per year.
- PHEVs do 65%[32] of their miles on electricity on average at 3 miles per kWh
- Low mileage BEVs do 3 miles per kWh in the winter and 4.3 miles per kWh in the summer, on average 3.5 miles per kWh.
- High mileage BEVs do 2.8 miles per kWh

The nominal battery capacities of each PiV have been chosen to match the CVEI Uptake Trial findings in terms of range for significant uptake, although they also seem to be consistent with the kind of journeys that drivers make. This simplified scenario assumes that older PiVs, with smaller batteries than typical 2030 models, are owned by drivers with below average mileage requirements. Models available in 2030 will include those with smaller and larger batteries and used PiVs will be bought by drivers whose needs they fit.

The basic energy statistics are in table 3.

In order to simplify the analysis, it assumes that the aggregate for each segment corresponds to a "typical" member of that segment. In reality, owners of the different types of PIVs will show a wide range of behaviours. However, it is the effect of the mass of drivers that behave somewhat like their typical segment representative, that will determine the national outcome.

This scenario is provided to illustrate the issues that might arise in terms of the different kinds of charging infrastructure and contribution to decarbonisation. We know that the real outcome will be different, just not how. In this scenario, PHEVs account for 55% of PiVs but 68% of electric miles. Taxis (including ride-hailing apps), account for 2% of vehicles but nearly 6% of electric miles. Between them, they account for three-quarters of electric miles. This illustrates the importance of functional segmentation to costs of decarbonisation. Both PHEV drivers and BEV taxi drivers have particular charging needs, different to the two BEV groups.

DRIVING & CHARGING BEHAVIOUR

The CVEI project collected very granular data on journeys and charging. More could be done with this data than has been possible within the project or the analysis for this report. This section presents some key findings, in relation to the implications for Smart Charging, especially at home.

Earlier, we suggested that PHEV drivers are likely to recharge more often than BEV drivers. CVEI data and early data from the Electric Nation project confirm this[33].

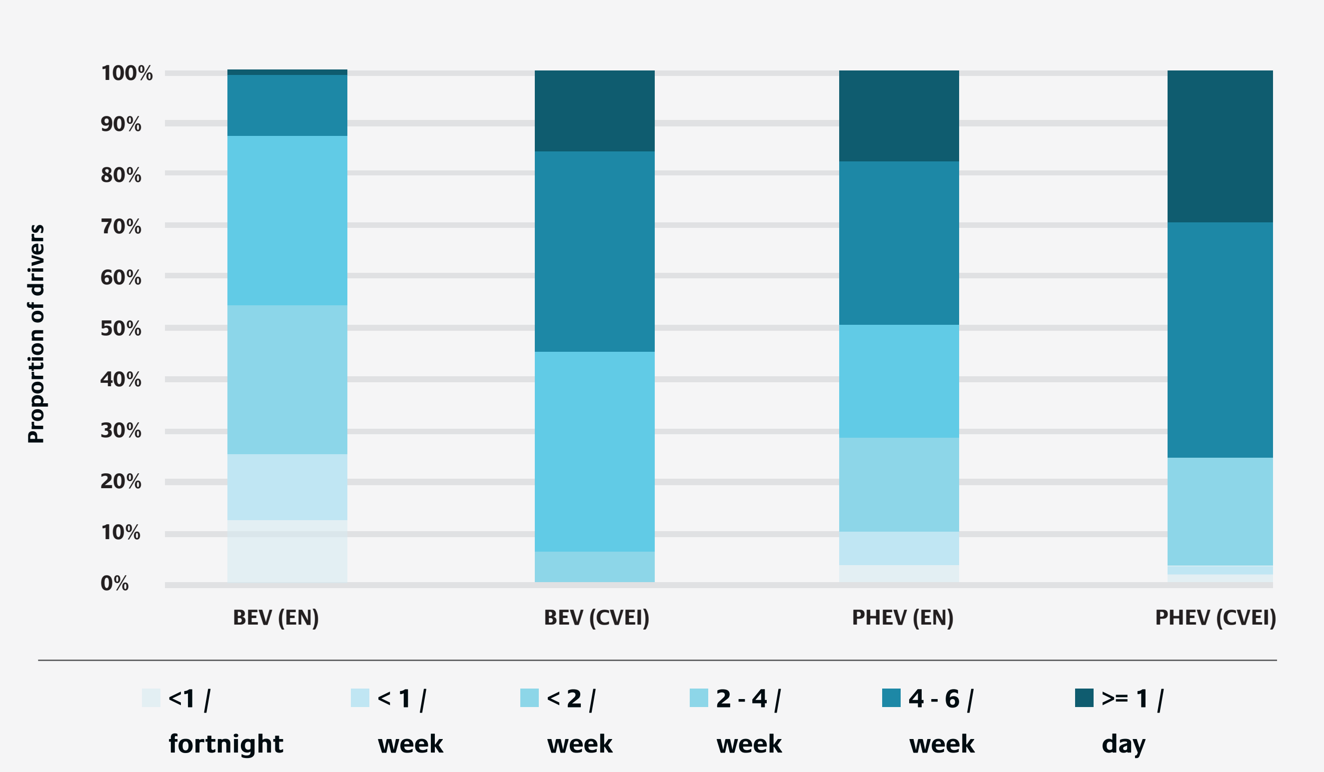
The Electric Nation project is funded via Ofgem through its Network Innovation Allowance scheme. It aims to provide local electricity network operators with the tools to be able to ensure that their networks can cope with the massive new challenge of PiV charging, whilst avoiding replacing cables and substations. It tracked the charging behaviour over many months, of several hundred drivers who have made the choice to buy or lease a PiV, both BEVs and PHEVs. In addition to data gathering, there were also tests of different approaches to charging.

Although Electric Nation participants are very early adopters[34], and therefore not representative of mass-market consumers, we can see that PHEV drivers charge much more frequently than BEV drivers, both in Electric Nation and in CVEI.

Table 3
An illustrative 2030 driving and charging scenario

Category	Vehicles (M)	Average daily mileage	Average/ Maximum daily charge (kWh)	Fleet annual electric mileage (bn miles/year)	Fleet electricity use TWh/year
PHEVs	2.75	50	11/20	33	11.0
High range BEVs	0.4	27	9.5/100	4	1.4
Low range BEVs	1.75	14	4/50	9	2.6
Taxi BEVs	0.1	70	24/60	2.7	0.9
UK	5	-	-	48.7	15.9

Figure 7
Distribution of charging frequency for BEV and PHEV drivers in Electric Nation and CVEI



[31] More than 75% of vehicles outside conurbations have access to off-road overnight parking (see NTS0908)
[32] A realistic target based on 50 miles effective range and analysis of the Charging Trial data; it assumes that vehicle design assists drivers to maximise electricity use, without being too ambitious overall.

[33] Hey, Electric Vehicle Charging Infrastructure Conference, March 2018
[34] Referred to as Innovators, regarded as the first 2.5% of adopters.

A cluster of PHEV drivers, all wanting to recharge fully on several nights a week, would present a significant and reasonably constant weekday overnight energy requirement. By contrast the lower frequency of BEV recharging and the greater battery capacity makes relatively rare coincident charging requirements the most challenging load. A cluster of BEV drivers would represent a more fluctuating overnight energy requirement.

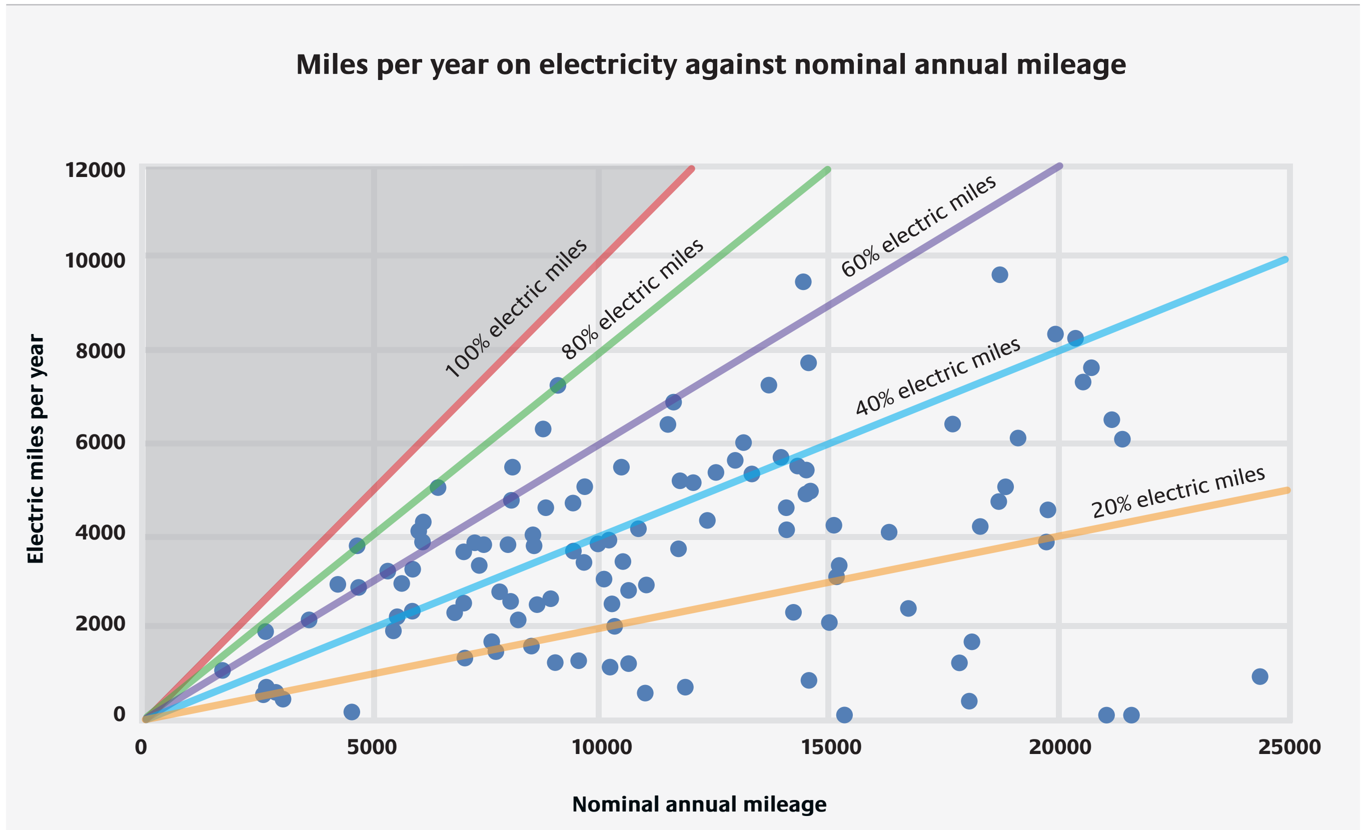
CVEI participants recharged more frequently than Electric Nation participants. It is unclear what drove this:

- Greater mileages in CVEI, requiring more frequent charging, or
- Allowing the battery to discharge more deeply before recharging, with increasing experience and confidence, in Electric Nation.

The most plausible hypothesis is that Electric Nation drivers are generally lower mileage drivers than those in the CVEI trials. Low mileage drivers were selected out during recruitment for CVEI, so that the participants in CVEI represented the population of drivers who drive the bulk of miles. Electricity consumption is a direct measure of conversion of fossil fuel miles to electricity. If we aim to convert many fossil fuel miles to electric miles by 2030, we need to plan to meet these higher charging needs.

The most significant factor in PHEV charging appears to be the proportion of miles driven on electricity.

Figure 8
Estimated electric miles against annual mileage for CVEI Charging Trial PHEV drivers



Within the group of trialists, we have drivers who achieved a relatively high proportion of miles on electricity, and also drivers who hardly drove any miles on electricity. One PHEV driver managed to drive over 3,500 miles during the 8 weeks and only recharge six times, for a total of 12.5kWh, all at home. Figure 8 shows that this is an extreme example.

The PHEV model used has a number of different driving modes, ranging from battery recharge by the engine, through maximum torque, balanced engine and motor use, to maximum electric miles.

It is clear from studying the detail of individual driving and charging patterns that some combination of understanding and motivation led to much lower electric miles than might otherwise have been achieved. Many drivers used battery recharge mode for a majority of their trips – a very inefficient way of using fuel. The chart above (and other analyses in this report) only count electric miles driven on electricity from a charge point; electricity generated from the car engine is counted as fuel, leading to low fuel efficiencies in PHEVs.

Appendix III describes the important role that fleets play in vehicle uptake in the UK. It includes data on the use of PHEVs within fleets. This data shows that the average performance of PHEVs in fleets is not dissimilar to the average of all the charging trial PHEV drivers shown in Figure 8. Small trials with PHEVs show performance closer to that achieved towards the top boundary of Figure 8. It seems that motivation, understanding and vehicle design combine to produce a wide range of outcomes in terms of PHEV electricity and fuel consumption.

There are technical, educational and social factors that could be used to encourage greater vehicle efficiency and electric miles. In combination, these nudges might make a significant difference to the average performance across all PHEV drivers.

This is a critical issue:

- Without PHEVs, a high proportion of miles currently driven on fuel will be inaccessible to electrification until well after 2030.
- Unless PHEVs are driven to deliver significant electricity use, their economics are poor, both for the owner and in terms of public support costs.
- Relatively high mileage PHEVs, driven largely on electricity, could be a significant load; apparently small changes in vehicle design, incentive structures and driver social environment could produce sudden increases in charging load.

The summary results of the CVEI charging trial are attached as Appendix IV. The impact of charging management and implications for electricity supply can be exemplified by the BEV charging during weekdays.

The impact of charging management is dramatic. The impact for PHEV drivers is similar, although there is some evidence of a small requirement to recharge on arrival home in the PHEV Supplier Managed Charging group, but not in the User Managed Charging group.

Figure 9
Average charging power for different charging management schemes

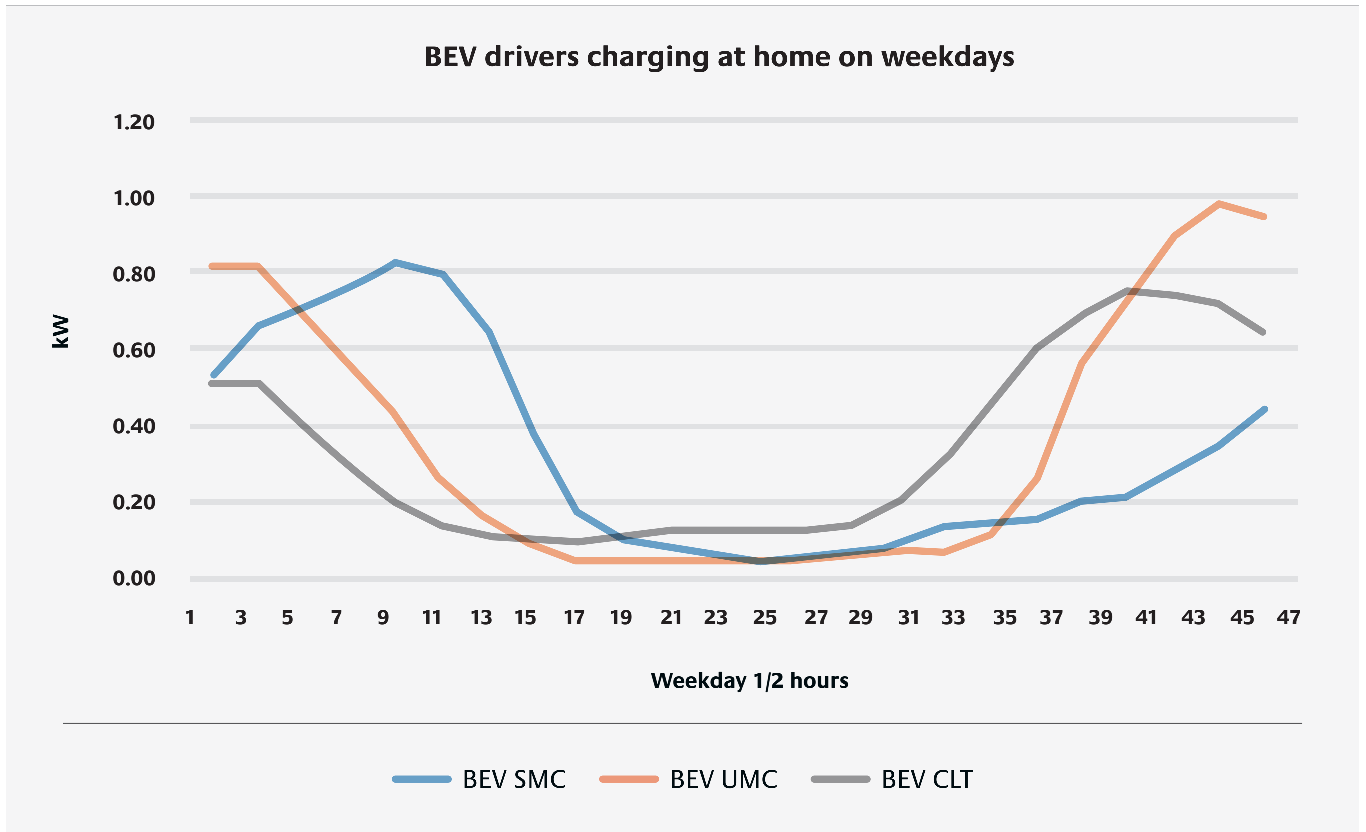
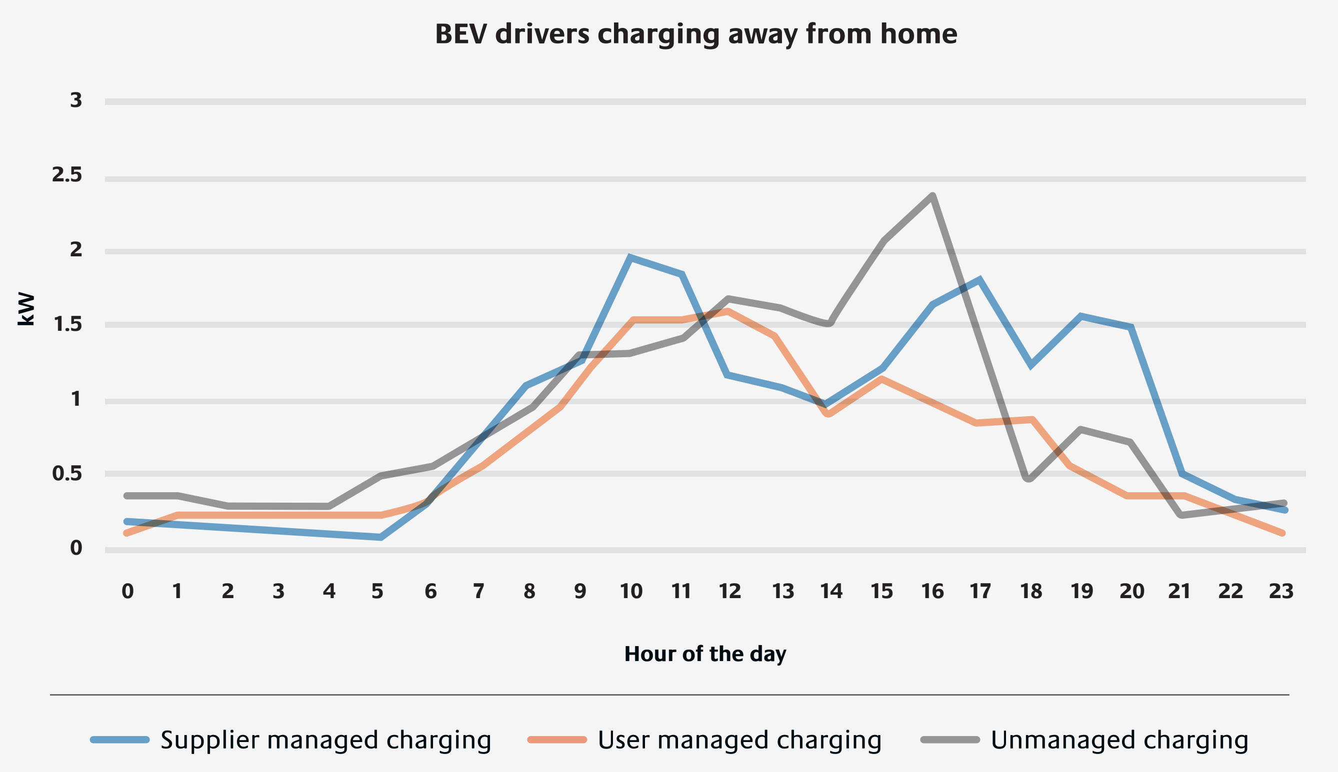


Figure 10
Average charging power away from home (charging away from home was not managed) for different charging management schemes



There is insufficient statistical power (or specific consumer research) to understand whether the differences between the three different charging sub-groups in Figure 10 are significant. PHEV drivers hardly charged away from home, but the sub-group differences seem to be consistent between PHEV and BEV drivers, which suggests that further research would be valuable, especially connecting observed charging behaviours to underlying motivations.

This is the first test of different approaches to charging management with mass-market consumers. Different results would have been produced by different designs of consumer proposition, App design and charging algorithm. Having shown that dramatic differences can be delivered, significantly more work is required to develop real-world "products" that can integrate effectively with the electricity system.

It is very evident that both unmanaged and fixed time tariff charging pose significant risks to the electricity system. Given that the potential scale of PiV charging load is similar to current domestic loads, the scale of peaks in Figure 9 would be problematic for both networks and generation. The ramping rates at tariff boundaries in fixed tariff user managed charging would represent a significant system services demand.

More sophisticated supplier managed charging algorithms than those used in the CVEI trial would spread the load more during the night, to avoid the risks of unexpected early departure with a low range, changes of forecast electricity price and the coincidence of charging peaks between different suppliers.

Depending on how BEVs are recharged, they may present a significant challenge to the electricity infrastructure, even at relatively low rates of uptake. Although diversification will usually mean that the aggregate load on an LV substation is manageable, the random coincidence of arrival times (as shown by Infield) and States of Charge may lead to rare but exceptional peak events. From the perspective of electricity users, events which only happen every few months, but blow the substation circuit fuse, are probably not rare enough.

Even if the substation avoids circuit overload by rationing capacity between charge points, it is possible that some drivers will find that they can no longer go out on some evenings, as they were planning. Since these coincidences will not be predictable, they will be irritating and a possible source of tension between neighbours. Managed charging would encourage drivers to plug in more frequently, as they would be rewarded for making their vehicles available to charge, thus reducing the need for less frequent but larger charging events.

Whereas Infield relied on mathematical modelling to explore the frequency of charging peaks caused by variations in arrival times, we can use real behavioural data to construct a charging load frequency analysis. Five BEV drivers with a range of annual mileages were selected at random from each of the Control and Supplier Managed groups. The last six weeks of charging data for each participant was aligned,

Table 4
Estimated annual frequencies of coincident charging loads

	At any time		During peak	
	4 at once	5 at once	4 at once	5 at once
BEV Unmanaged Charging	9	17	9	17
BEV Supplier Managed	26	17	0	0

as though they were all on the same substation at the same time. This gave a table of half hourly frequency data for combined charging power for both groups of five. Much of the time no-one was charging. It is rare for more than one BEV to be charging in any one half-hour period, very occasionally four or five participants were charging "at once".

Four BEVs charging at once is 30kW and five is 37.5kW. Even out of 150 houses with a diversified peak load capacity of over 300kW, those would be significant additional loads from only five vehicles. Although managed charging removes this load from the existing peak, as more PiVs are bought by users of the same substation, the risk of exceeding the capacity away from peak will rise. More sophisticated managed charging would require an interlink with the substation (probably through Smart Meters) and co-ordination or randomisation between charge point suppliers.

The risk that any managed charging scheme fails to prevent these rare coincident peaks, is an argument for a rationed charging system, at least as a backup. Experience with rationed charging between higher mileage drivers may show that it also creates problems, when several drivers want to charge at once. Consumer research from the Charging Trial points towards a strong underlying concern about not being able to recharge when required. Participants are expressing a rational fear that the system may prevent them from using their vehicle when they have an urgent, probably unplanned, need.

Although the percentage of time when charging might need to be rationed is very small, what will matter to consumers will be:

- Loss of electricity supply if the circuit is overloaded through unmanaged charging, or
- Loss of access to their vehicle if rationing is applied when they discover that they need it.

The findings from Electric Nation are encouraging in terms of the acceptability in principle of rationing, but the detailed data from CVEI should be checked against the detailed data from Electric Nation, to ensure that this finding is consistent with the behaviours of mass-market, high mileage drivers. The matching finding from CVEI is that a majority of drivers prefer managed charging to unmanaged charging; a majority of drivers with experience of Supplier Managed Charging prefer that to User Managed Charging.

Only Supplier Managed Charging is capable of maximising the use of low-carbon electricity, which will be important to decarbonisation by 2030.

CHARGING COSTS AND NETWORK CAPACITY

Network costs for new charging points can be significant, so it makes sense to make best use of existing capacity by managing charging. Managing overnight charging at or near home is the cornerstone of this but managing across different places visited during the "driving day" will also be important. As battery capacity increases, many drivers will find that the charge balance over several days is what matters under many circumstances, not the charge required for each day's journeys. There is an opportunity to provide a high quality but cost-effective travel service to drivers, if the market and technical infrastructure is developed for charging management.

Electricity retailers have a set of costs in supplying their domestic customers, including the margin over input costs that they need to reward their cost of capital. Charge point operators face similar costs, but also need to pay for:

- A charge point and systems to manage it
- Any additional connection costs of the charge point
- Costs of parking space, where the charge point is located in a car park or parking bay.

Charges to users could reflect the value of the "electric miles added", the value of the parking space and any additional services (where the service is travel management). The location business model could have other sources of value, which are discussed in more detail later.

It is currently unclear whether charge points will be provided as shared infrastructure (like the rest of electricity supply or cash points) or as private networks (like mobile phones). Currently they are developing as private networks with incomplete interoperability. In future the charging network could be operated like ATMs, with a charge to use them but services provided on a roaming basis.

This analysis assumes a roaming model, where costs and services are optimised from the perspective of users and taxpayers. As can be seen from the examples, this is by no means inevitable. There are commercial advantages in gaining early options over desirable locations and spare network capacity, as moves by Tesla, Pivot Power and others have demonstrated. Hotels, supermarkets, local authority parking, lamp posts and even domestic properties, all present opportunities for first movers with access to sufficient finance to buy the options.

As part of the CVEI project, Baringa prepared projections of 2030 retailer costs for domestic electricity supply. They later developed this into a full analysis against different 2030 energy scenarios. The cost structures were quite similar between the scenarios (Figure 11).

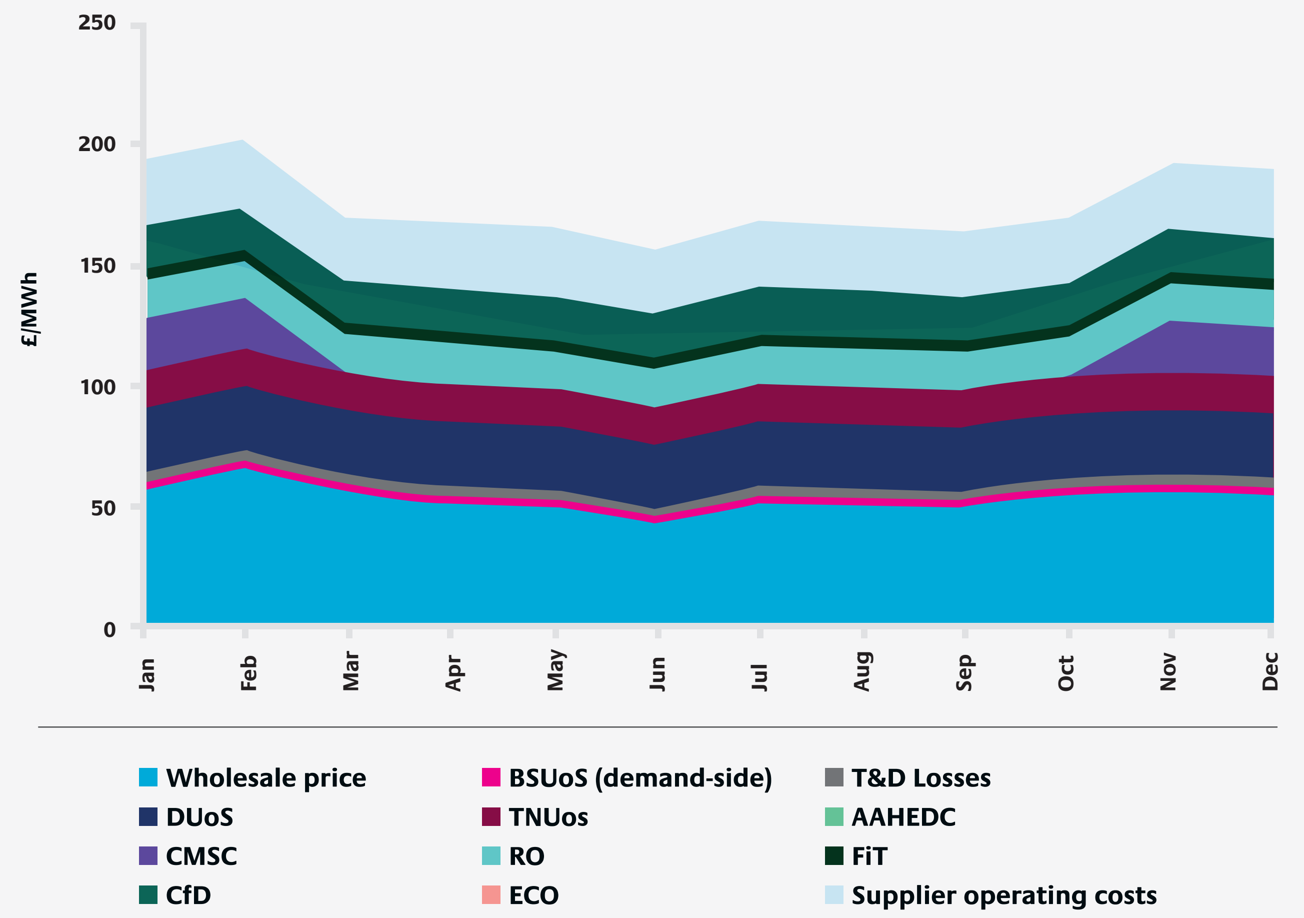
The seasonal impact of Capacity Market Support Charges can be clearly seen, in this chart, along with the scale of Distribution Use of System charges. How these are charged by Time of Day is critical to retailer costs and business models.

This chart and the following ones are based on the National Grid Future Energy Scenario Two Degrees[35]. They have been translated into hourly retailer cost stacks for ETI by Baringa, making assumptions about future investments in networks and the application of market rules[36]. National Grid were not involved in this translation, which was based on published information. Although ETI differs in some respects from National Grid on the most attractive trajectories of the UK energy system out to 2030, we used it as a highly professional and plausible path to meeting carbon budgets to 2030, which has been widely used as a reference.

ETI has published the results of Baringa's work, to support discussions of pricing and charging mechanisms that incentivise reduced investments in generation and network capacity and that reward low carbon generators with higher revenues, or at the very least discourage the use of high carbon capacity to meet vehicle charging needs.

The hourly detail for the simulated first week in January shows the effect of periods of high and low wind generation on wholesale prices. Capacity and transmission charges mean that retailer costs spike during peak periods, although less so at weekends. If distribution use of system (DUoS) was also to be charged on a time basis, this would make these spikes larger, and also reduce the price outside peak periods.

Figure 11
Average monthly domestic retailer cost stack based on Two Degrees Future Energy Scenario and current market structures



[35] Two Degrees, Future Energy Scenarios 2018, National Grid, July 2018
[36] https://www.eti.co.uk/programmes/energy-storage-distribution/2030-electricity-price-time-series

Figure 12
Sample winter hourly domestic retailer cost stack based on Two Degrees Future Energy Scenario and current market structure

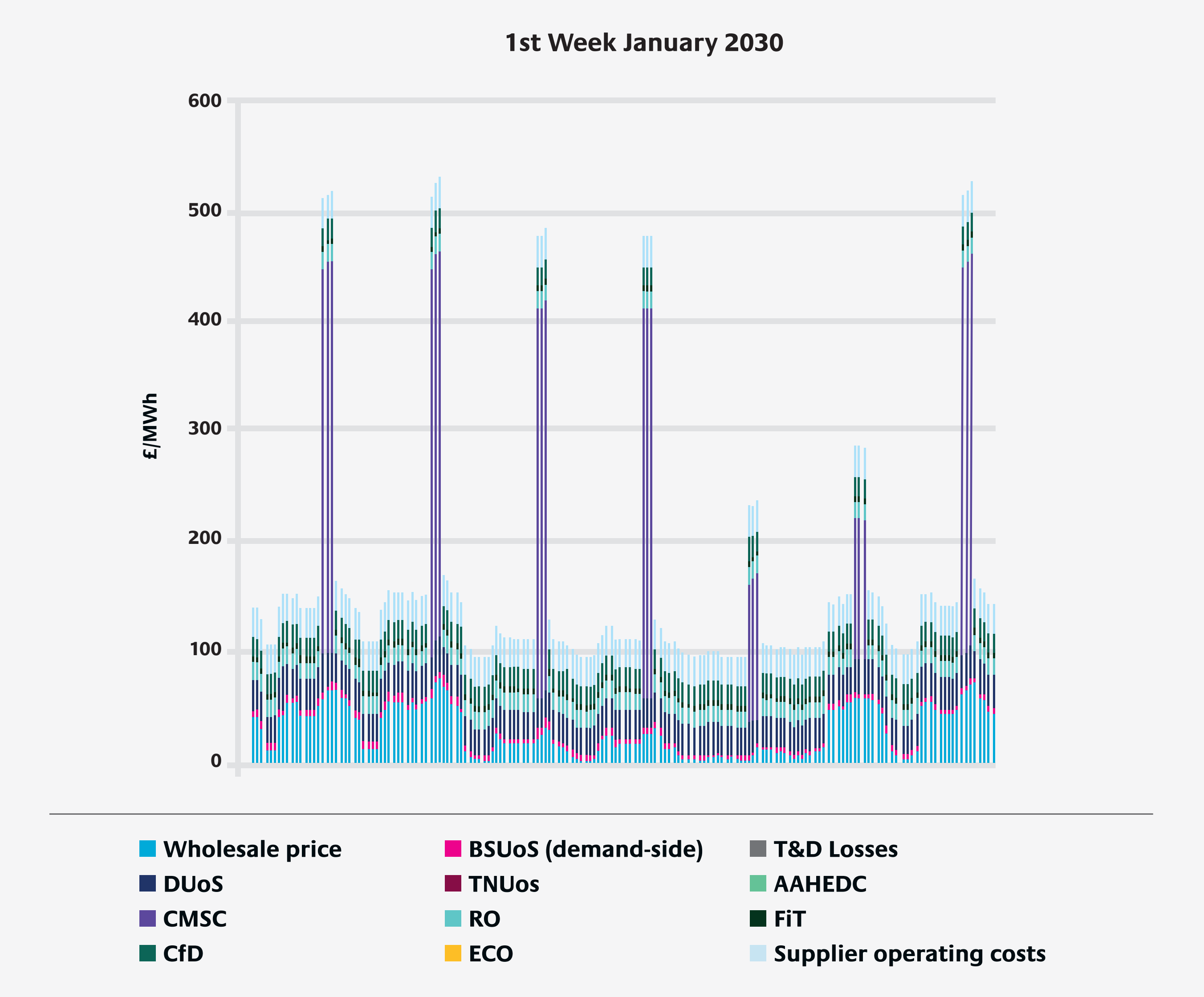
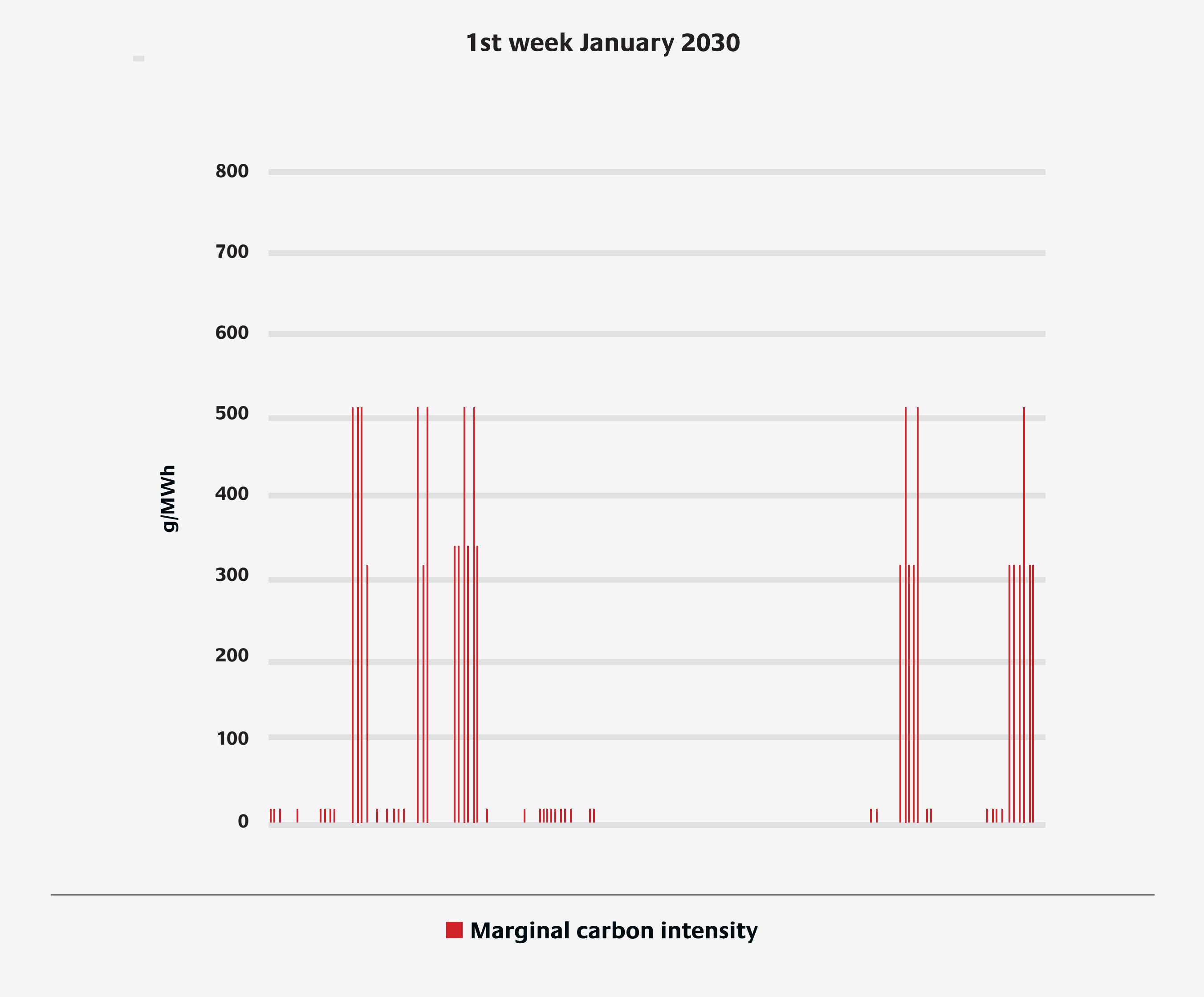


Figure 13
Sample winter hourly marginal carbon intensity based on Two Degrees Future Energy Scenario and current market structure



The carbon intensity of additional electricity to charge vehicles varies significantly.

Charging during peak demand has limited carbon benefit, unless it is windy, or the interconnector is importing[37]. Retailer hourly costs in the current market model do not accurately reflect either distribution network use or carbon intensity.

The general picture for a summer week is similar but with some differences (Figure 14).

Electricity wholesale prices are typically higher in the summer, because of reduced wind availability. Peak prices are significantly less, because of the way that Capacity Market costs are charged out. There are many more hours in this week when charging vehicles would lead to increased carbon emissions than in our winter week. Despite installed PV capacity being 27GW in Two Degrees, midday wholesale price dips in this summer week are infrequent. This is because nuclear capacity is only 8GW in this scenario. Key points from these charts are:

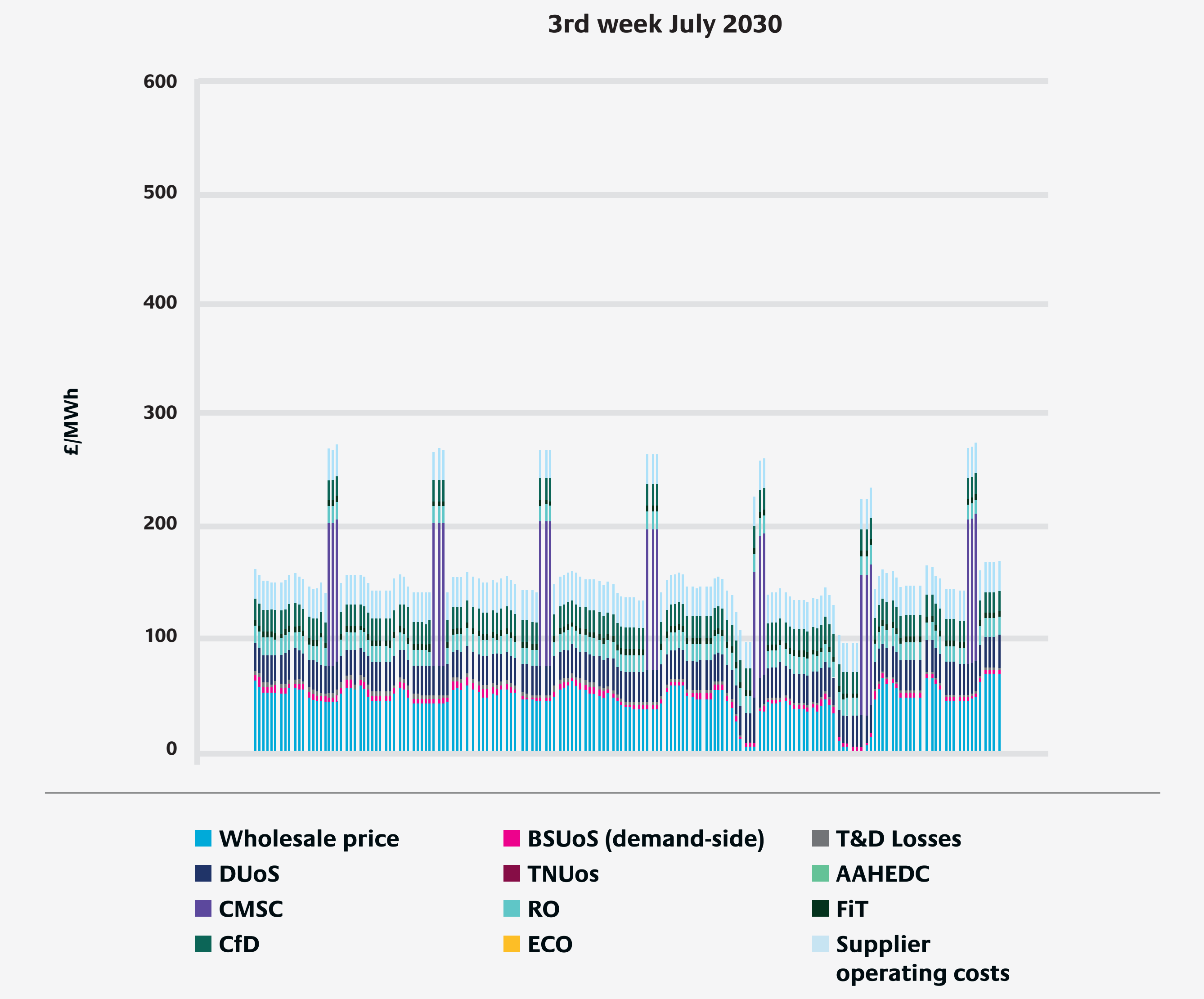
- Wholesale market costs for electricity are a small part of overall costs; in the winter being about the same as support costs (categories CMSC to ECO). Supplier transaction costs are also significant.
- Network costs (categories T&D losses to AAHEDC) are a significant and rising part of the overall costs.
- Current domestic Profile Classes charging mechanisms allocate distribution costs to all supplied energy, whereas capacity and transmission costs fall into the evening peak; if distribution costs were also to be weighted more towards peak load, then the seasonal and daily profiles would be even more pronounced.
- Carbon emissions from the marginal generator vary widely, from low carbon to levels where electric miles have only a modest benefit compared to an efficient ICEV (especially a hybrid ICEV, such as a Prius). The effect of interconnectors is complex, since imported electricity causes no carbon emissions in the UK but may be supplied from low or high carbon generation in the country of origin.
- Wholesale market costs in the current market arrangements are a reasonable but imperfect surrogate for marginal carbon content.

If the intent behind the Ofgem Half Hourly Settlement (HHS) project is delivered by 2030 or HHS is applied to charge points, then there will be strong incentives for charging service providers to avoid the evening peak, especially in winter. Extending cost allocation further, to more closely reflect location and time, would inevitably highlight the extent to which vehicle charging uses distribution network capacity. Currently we have the situation that using existing capacity attracts only the standard charge, whereas installing a significant new distribution connection to a non-domestic location would attract the costs of that distribution investment.

It is only natural that many public charge point installations until now have been installed in sites with lower network costs, effectively using up existing capacity margins. There is limited published information on likely additional network costs to support vehicle charging.

[37] Emissions in other countries from imported electricity do not count against UK targets, although there are strategic risks in relying on this

Figure 14
Sample summer hourly domestic retailer cost stack based on Two Degrees Future Energy Scenario and current market structure



A report prepared for the CCC[38] estimates the number of public charge points likely to be required to support electric vehicle uptake. This considers locations in two categories:

- Destinations or parking based
- En-route or refuelling based for long journeys

It does not consider charging at or near to home or allocate total annual mileage recharging requirements across home, destination and en-route. Destination charging requirements were estimated from data on the location and use of existing public charge points. En-route charging requirements were estimated from refuelling requirements based on travel along major roads between regions of the UK.

Modelling and optimisation in this project are sophisticated and it shows what kind of work might need to be undertaken by network companies, regional authorities and the Highways Agency in planning for public access charging points to support mass uptake of electric vehicles. There will also be commercial interests which will interact with these stakeholders. The recent announcement by Pivot Power is a good example of commercial interests aligned with planning by the System Operator.

The authors of the CCC report did not include network reinforcement costs[39] but did estimate charge point and local connection costs. For en-route chargers they estimated the installed cost, see table 5.

[38] Plugging the gap: An assessment of future demand for Britain's electric vehicle public charging network, Connolly et al, Systra for the Committee on Climate Change, January 2018
[39] See 3.6.10 in the report

Figure 15
Sample summer hourly marginal carbon intensity based on Two Degrees Future Energy Scenario and current market structure

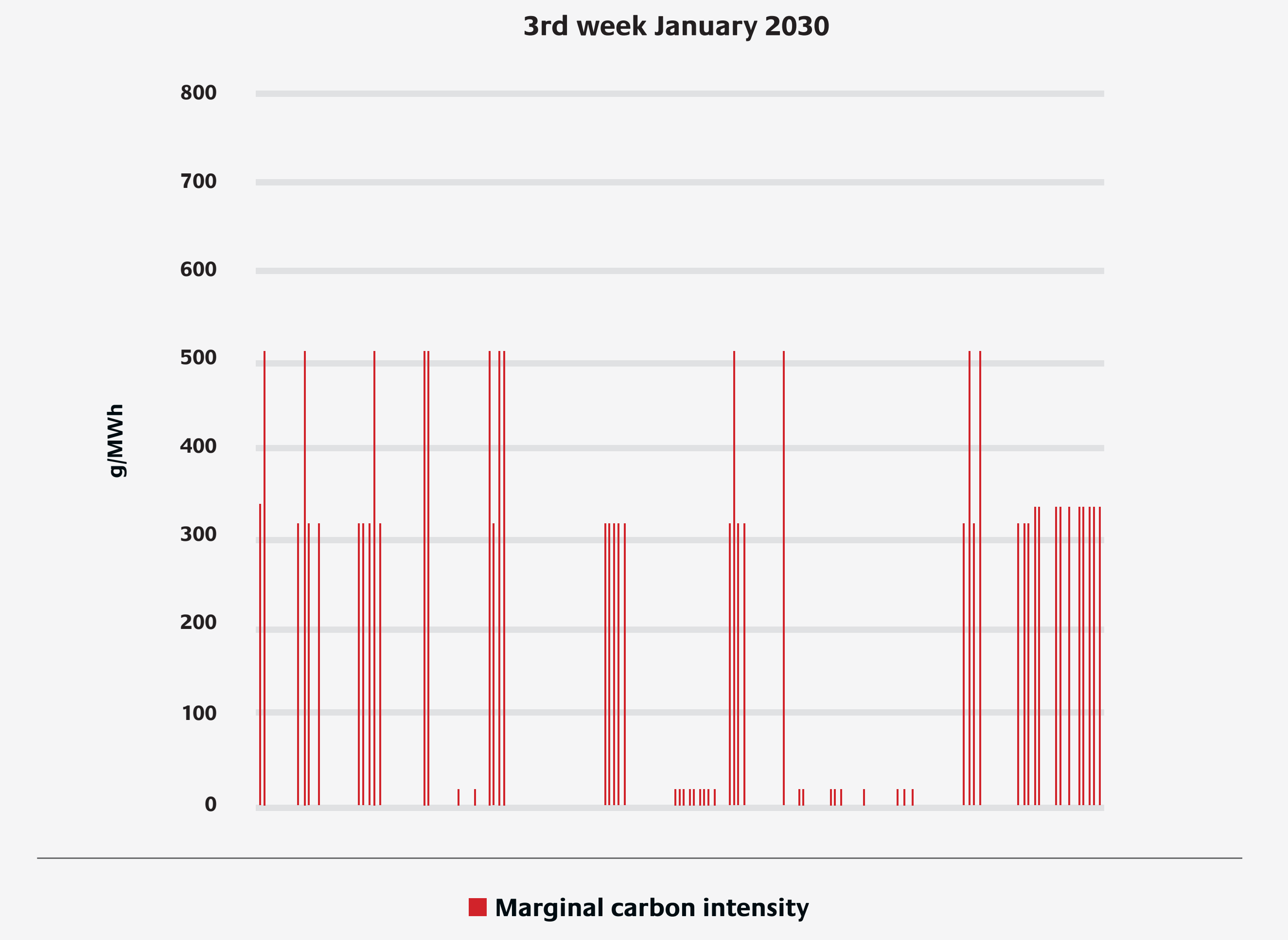


Table 5
Estimated costs of charge point installation and connection

Charger capacity (kW)	Cost of first charger (£k)	Cost of additional chargers (£k)
43	52	34
150	82	64
350	112	94

National Grid reported recently on an internal study which had identified 50 locations in England and Wales close to major routes, where connection to the transmission system would be most cost-effective. They appear to have identified costs of £0.5 - 1bn for installing 50 chargers of up to 350kW capacity at each location. They make the important point that cost effective en-route charging will depend on a coordinated set of investments at good sites, rather than piecemeal installation.

Pivot Power recently announced a £1.5bn project to install batteries and rapid chargers connected to the transmission system at 45 sites, with a capacity to provide system services up to 2GW/3GWh to the TSO, as well as rapid charging.

The National Grid figures imply unit costs of £200k/charge point at current prices. This suggests that capital costs used in the CCC report are underestimated by a factor of at least two. Although charge point costs will fall, especially at large sites, connection costs have less opportunity for reductions.

The Pivot Power proposition introduces the interesting possibility of additional revenues to reward the connection and power electrical costs. Many sites with an existing connection to the transmission system will not be located close to the most attractive locations for recharging. For example, although existing large coal fired power stations may be attractive locations for batteries to provide system services, they will only be able to attract modest additional revenues as recharging locations. The Pivot Power project costs are consistent with the nominal system services and recharging capacities.

While approaches such as those proposed by Pivot Power and the ESO are promising for en-route charging and regional charging close to their sites, it is not obvious that similar opportunities exist for other locations. On the other hand, these other locations have different potential business models. Nevertheless, ETI approaches discussions of destination and near home recharging with a degree of concern about the risk of underestimating network costs as part of the overall business model. Historic connection costs are undoubtedly skewed by cherry-picking of the most cost-effective sites.

We note also that many actors are claiming per driver system services value which is in direct competition to Pivot Power. 3GWh of static batteries is the equivalent of 75,000 Renault Zoes, or 30,000 Teslas, parked at locations with Vehicle-to-Grid (V2G) capabilities. As the System Operator seeks to minimise both the volume and unit costs of system services, the supply of system services is self-cannibalising.

In order of likely importance to drivers we identified the following types of charging locations:

- Up to 7 kW at or close to home (and hotels).
- Up to 50 kW at work and other business destinations (including hotels with conference centres).
- Up to 450 kW en-route on major routes for long distance journey.
- Up to 20 kW at long-stay car parks at transport nodes (stations, airports etc.).
- Up to 100 kW at car parking at destinations such as shopping centres, in cities etc.
- Up to 450kW at refuelling stations, where the purpose of the trip is a bulk, cost-effective charge.

Taxi and delivery drivers will often have a large enough battery to cover a whole day's trips. However, topping up at up to 100kW will be required on occasion. The Energy Saving Trust carried out a trial for Uber, that contains some interesting anecdotal evidence[40].

Each of these locations has a different driver proposition, business model and operating model. The network implications of each are also different. Shared asset business models, for example car hire or Zipcar, would have some combination of charging by the driver during use and recharging on return to base. Charging at base would be part of the asset owner business model.

The central proposition of this whole report is that managed charging within and between locations will both give superior driver experiences and minimise what will inevitably be significant network extension and reinforcement costs. En-route charging is not responsive to management, as drivers need to refuel here and now, nevertheless the Pivot Power project shows how imaginative and entrepreneurial thinking can lead to synergistic economies. A framework for driver focused charging management will unlock these kinds of opportunities for other locations.

Although the electrification of heating will require network reinforcements, and inevitably interact to a significant extent with vehicle charging, this will happen later. Work by ETI on Smart Heat strongly suggests that many of the market and technical elements required to manage vehicle charging will be critical to managing heating in future[41].

Charging management therefore represents an opportunity to lay the foundations for future innovation and success in further decarbonisation and economic growth for the UK.

[40] Electric Private Hire Vehicles in London: on the road, here and now, Lewis-Jones et al, Energy Saving Trust, March 2017
[41] Developing Whole–Systems Analysis to Explore Future Great Britain Energy System Challenges Case Study: Facilitating Markets for Mass Deployment of Hybrid Heat Pumps in Localised Areas, ESC, 2019

BUSINESS MODELS

Each charge point location will have a specific consumer proposition, cost structure and additional value possibilities for the location owner. Nationally, the operation of charging will impact on the utilisation of generation and transmission assets and the extent to which new investments in system services and low carbon generation are required and economically efficient.

Currently we are concerned with ensuring access by PiV drivers to sufficient convenient and cost-effective charging that does not compromise the security of the local network, right at the grid edge. By 2030 the scale of vehicle charging will be enough to impact on the profile of national demand. With unmanaged charging based on plug-in on arrival, this will drive additional requirements for capacity and almost inevitably this will not be low carbon capacity. With managed charging, not only will network security be protected and additional network investments be minimised, but better use will be made of generating capacity, especially low carbon capacity. These public goods of reduced costs to drivers, homeowners and businesses and lower carbon emissions will require policy led changes to market and technical infrastructure, especially soft infrastructure such as codes, standards, rules, governance and agencies.

PiV charging is the latest and largest electrification and decarbonisation challenge to existing ways of governing and operating the electricity and fossil fuels industries[42]. Systems are now required to deliver charging management to the benefit of all stakeholders. They need to reasonably reflect the underlying costs to serve, given the scale of additional investments potentially required. The CVEI project is a first step in understanding the response of mass-market consumers to charging management based on value and costs. Electric Nation has been examining the response of very early adopters to charging management based on rationing.

There are a very wide range of stakeholders for electric vehicle charging, including:

- Landowners and tenants, as an adjunct to parking – for example retail footfall or employee retention at offices.
- Vehicle OEMs – as sales support and after sales services.
- Local Authorities – as part of spatial planning, transport, clean air and decarbonisation policies.
- Network companies – in terms of network load and serving societal needs.
- Energy Service Company (ESCos) – in order to capture revenues from charging, including sales at petrol station forecourts by existing petrol retailers.
- Highways England (and equivalents in other UK nations) – in terms of mission requirements and own vehicle fleet operations.

Some examples can illustrate how business models might be applied in different situations.

DOMESTIC CHARGING OFF-STREET

Homeowners and landlords install charge points to provide this new essential domestic service requirement. Vehicles were already parked on the property, so there is no added cost for parking. Provided the rating of the supplier fuse is not exceeded, the individual property is just using more electricity than before, typically 1.5 to 3 times as much. Within the current market arrangements, it is probably slightly cheaper to switch to Economy 7, provided that the bulk of charging is expected during off-peak hours (typically midnight to 7am).

Apart from this Time-of-Day tariff, there is no penalty or incentive for avoiding peak network usage periods or making use of additional low carbon generation capacity. As the technical capability to ration electricity usage starts to become widespread, EV drivers in congested areas will pay the same unit costs for network use as EV drivers in uncongested areas, but they will get less service for this. This will hit people who want or need to recharge to go out in the evening. In principle they have a justification for an immediate network upgrade at no additional cost and arguably for an interim payment to compensate for the

Table 6
Current electricity tariffs

Tariff	Peak rate	Off-peak rate	Standing Charge
Sample Economy 7 cost	15.2p/kWh	7.1p/kWh	18.9p/day
Sample electricity-only cost	12.6p/kWh	12.6p/kWh	18.9p/day

[42] Fossil fuels are beyond the scope of this report but a world with significant EV uptake and stringent requirements on vehicle efficiency will require a different and increasingly fragile supply chain as discussed in An affordable transition to sustainable and secure energy for light vehicles in the UK, Batterbee, ETI, November 2013

reduced service.

It is not obvious why people without EVs (likely to have lower average incomes) should contribute to the costs of network upgrades for EV drivers. It is difficult to see how it would be acceptable to force EV drivers onto an Economy 7 tariff, unless they could very obviously save money. By 2030, Smart Meters in principle could enable more flexibility in how these questions are addressed.

An alternative model would be for distribution network charges to energy suppliers to reflect time (and possibly location) of usage. That would create an incentive to manage charging away from peak and to charge those who need to recharge at peak at a rate which justifies network reinvestment. If the network constraint is reached, even with this cost signal, then there is a much stronger case for a payment to reflect the under provision.

Where a visitor needs to use the charge point, it is unclear how this could be addressed. Although 20 - 100kWh, at current rates is only £2.50 to £12.50, this may still be enough to cause tension between the visitor and the host, especially where the meter is on pre-pay mode. Similar issues may arise when there are multiple drivers in the household and the cost of all refuelling falls on the bill payer, or where some shared renter “housemates” are drivers and others are not. In principle the charge point and Smart Meter could cooperate to split the bill, but the current market and technical structures do not readily enable this, for example by automatically charging the driver and crediting the household.

PARKING INTEGRAL TO RETAILER

Where retailers have their own parking, potentially shared with others on the same retail park, the purpose is to enable and encourage footfall. In some locations retailers currently charge for parking, with a refund or reduced rates for customers who make a minimum purchase. Some retailers already provide a small number of charge points, which appear to be a brand support and marketing proposition, consistent with other elements of branding visible at these locations.

As recharging becomes a normal part of a shopping trip, retailers will need to decide what charging resource to provide and on what basis. Typical commercial parking charges at similar locations range from £2 - 10 per visit. A “Zoe fast-charge” at £16 (nominal 50p/kWh) would be a very significant additional cost and potential customer benefit. However, many customers will judge the value of the benefit in relation to their current state of charge, their medium-term journey plans and the availability of cheaper electricity elsewhere, especially at home. Reduced cost charging for shoppers will become another factor in the business mix. By 2030 there will be significant numbers of PiVs located in retail parking. How many drivers will be motivated to recharge there is unclear, but some of them certainly will. With a large number of drivers, the location can share the network connection and power electronics between vehicles, so that only cabling, switching and IT is required to be installed for each vehicle bay. That makes added services such as Vehicle-to-Grid (V2G) potentially attractive[43], especially if the location can provide the services through an aggregator rather than acquiring the skills etc. for themselves. Arguably V2G services will have a relatively low value, since many locations will compete to provide them at marginal cost.

Charging management at these locations will then be mostly about sharing the site overall charging capacity between vehicles and managing charging to minimise costs and maximise the provision of system services.

EN-ROUTE RAPID CHARGING

There is a footfall argument for these locations also, even though they are primarily service stations on major routes. From the point of view of the customers, there is an opportunity to rest within the journey and take a comfort and food break. From the perspective of the location, there are various retail opportunities, including fuel.

Without access to the cost and revenue models for such locations, it is not possible to comment in any detail on the impact of switching from liquid fuel to electricity.

Currently many service stations, especially on busy routes, have several recharging points. These appear to have been provided within the existing parking and network capacity of the location, i.e. at marginal cost. The site owner benefits from marginally increased footfall and any revenues from the charge point provider.

Pivot Power have constructed a business model which implies additional sites, located where network costs are minimised close to major routes. In addition, such sites are likely to attract customers from local towns. Their business model includes spreading the connection and power electrical costs across the provision of system services to the ESO and recharging services to drivers. They are likely to be price setters for charging, rather than price takers.

LONG-STAY CITY CENTRE / PARK & RIDE PARKING

Long-stay car parks are free-standing businesses, not mechanisms for attracting footfall. They may enjoy support from the local area as important facilities, but this is supportive to their business model, not central. Station and airport car parks have similarities to long-stay car parks; they are not discussed in detail, although large long-stay car parks at tourist airports have an obvious V2G opportunity. Operators will have extensive data on the distribution of parking times through the day, which will determine how much charge they are able to provide and their likely costs and revenue potential from system services. Depending on how much charge each vehicle requires, they may have significant opportunities for capacity sharing and asset utilisation optimisation. They can use pricing of both parking and charging as mechanisms for co-maximisation of revenues.

It is very unlikely that there is significant spare network capacity in existing long-stay car parks. They do not have high power loads per vehicle.

Operators with significant numbers of parking places in different locations will need to decide whether they will enter the recharging business in their own right, or partner with a charge point provider. Each approach has its advantages and disadvantages.

WORKPLACE CHARGING

Where businesses provide employee and visitor parking, they will need to decide on their recharging strategy. This will be a new question, since almost no employers provide refuelling facilities onsite. As employees increasingly travel to work with PiVs, providing recharging facilities may become critical to individual employee attraction and retention. It will also be increasingly important to branding and the experience of visiting suppliers, customers and partners.

The costs of providing recharging facilities will be very location dependent.

MOBILITY SERVICES

Several companies are already in the business of providing public charge point services. These currently split broadly into installers, operators and vehicle OEMs. Only a charge point operator has the primary mission to secure long term revenues from providing charging to drivers.

Charge point operators must currently be seeking to acquire long term options over locations for charging, especially those where there is spare network capacity and the possibility of parking at no cost to the operator, in return for a share of charging revenue. Hotels, hospitals, workplaces, car parks, shopping centres, etc. should all be under investigation.

The charts for domestic retail cost stacks (Figure 11 et seq) show distribution as a variable charge cost (i.e. per kWh). In commercial settings it may well be a fixed cost or charged at different costs and/or capacities at different times. The charts also show that elements of cost at the transmission connection are highly time dependent and seasonal. The marginal carbon intensity of electricity varies between effectively zero, up to levels which do not justify vehicle electrification or occasionally those where it would be better to use liquid fuel.

By inspection, minimising costs and emissions involves managing charging over hours and a few days. Only mobility service providers who have access to the management of domestic and public charging in a region will be able to deliver this. This does not necessarily involve owning the charging assets, but it does involve being able to schedule and control charging across locations, based on the needs and typical behaviours of many thousands of drivers.

This extension of commercial ownership of energy use across multiple locations is completely alien to the current market environment, while it also appears vital to the public goods of cost-effective decarbonisation and electric vehicle uptake.

Charging service providers may also have a business relationship with integrated Mobility-as-a-Service providers. Some companies are working to provide integrated public and private transport services in cities, while others are working to provide seamless trips, on a door-to-door basis. The evolution of these markets in different situations is almost impossible to predict, other than they are likely to be significantly different from today by 2030.

[43] Modulating charging to provide services such as frequency response is also possible, sometimes named V1G

THE SOCIAL DIMENSION

Personal mobility is important to all of us. In an equitable society basic needs are considered and met – decency and fairness are important to UK citizens. When a major change is about to happen, we need to discuss the potential impacts on vulnerable people and how they might be mitigated. Access to mobility will change for everyone as a result of electrification combined with digitisation and there are choices about which costs and benefits might be socialised, and which should remain the responsibility of individuals.

If we look to how the costs of the introduction of 'clean energy' have been socialised it gives us some pointers on what should be avoided. The introduction of Feed-in-Tariffs for the owners of small-scale renewable energy installations (solar panels on roofs for instance) pays out £500million each year; this is disproportionally paid to wealthier households and "roof rental" businesses, who can afford the installation costs. However, the costs of this and other climate change schemes are recovered via domestic energy bills. This approach disproportionately hits the poorer in our society harder, as paying for energy is a larger proportion of their outgoings, and they are unlikely to be able to access the funds needed to benefit from Feed-in-Tariffs. Tenants with electric heating are especially vulnerable.

In the case of vehicle electrification roll-out to the mass market, it is likely that this will happen first in groups where the increased costs associated with owning an electric vehicle are not considered by the purchaser to be significant. Appropriate charging infrastructure improvements will be needed to ensure these drivers have access to a range of charging options – this is necessary to encourage them to see that owning a PiV is a feasible option for their lifestyle.

The costs associated with electricity network upgrades and installation of charging points will need to be socialised in some way; adding this cost uniformly across electricity bills may not be the fairest solution. The assumption will no longer hold, that electricity provides a similar range of services across all bill payers and the costs should therefore be shared. Earlier we discussed tying the costs more closely to the service to ensure that revenue signals would justify increased investment, here we go further and argue that not tying costs to the customers who benefit is inequitable.

As more people choose to use a PiV, the need for a liquid fuel infrastructure will decrease, filling station numbers and competition between them will reduce, resulting in higher prices at the pump and longer journeys to the petrol station. The poorer in our society who tend to own older, cheaper cars and are unable to afford a new PiV, would find themselves having to pay more to run these fossil fuel cars. Expecting them to pay more for fossil fuel to run their cars and at the same time expecting them to pay more on their electricity bills to fund a PiV charging infrastructure they cannot access would be doubly unfair. There are also likely to be other costs, such as congestion charges and fuel taxes, which are designed to disincentivise fossil fuel vehicle use.

Considering how all parts of society might transition through any roll-out scenario must therefore be a part of the planning and policy development process. No doubt a wide range of potential issues will emerge and require consideration, but two examples are included, to illustrate the nature of the process.

Priority Services Customers

Vulnerable people are currently able to register for Priority Services with their electricity supplier or Network Operator. This provides them with additional support in the case of a power cut. This can range from providing welfare in the form of meals, drinks, warmth and phone charging points, to ensuring that critical medical equipment has a temporary electrical supply.

Increasing the reliance of consumers on the electricity supply to also include their transport needs should be properly considered. A vulnerable person, in the event of a power cut would currently have the option to use their fossil fuelled car to go to a place with a supply. When they are also relying on a vehicle to be charged by the electricity system this creates additional scenarios where they are likely to need outside help.

In light of this, the current priority service responses would need to be reviewed, and resilience of this system to an increased number of requests reviewed. For example, a kidney dialysis patient with a BEV might not be able to get to hospital during a power cut, even if the hospital is running on standby power.

Charging Management & Location

In earlier sections we argued that the potential scale of investment in generation and networks to support charging justified stronger time and location cost signals, at least to charging service providers and electricity retailers. Such cost signals would encourage better use of existing capacity.

However, this could penalize people with constraints on when and where they can charge. Imagine a person on shift work on low wages with no off-street parking. They may have very limited access to public transport during unsociable hours. Not only may they have to pay a premium to charge where they can park but they may also find that they tend to charge during higher cost hours.

If pricing reflects the availability of low carbon electricity, they may also have added uncertainty about the size of their recharging bill in any month. They may find not only that their heating bill depends on how cold it is but that their recharging bill depends on how windy it is while they are asleep.

Historically these kinds of challenges are often met with solutions that are relatively expensive and hard to target. Identifying these issues early and stimulating creative thought will find better solutions than postfix "sticking plasters". For example, in many places on-street parking requires a resident's permit. A smart charging system can differentiate access and costs between people, so that vulnerable people can be protected from high and unpredictable costs, while still paying in relation to their use of the system. In one sense this is an integrated transport system planning issue – how do the combination of options meet collective needs at good performance and acceptable cost?

Earlier we argued that some combination of electric miles and electric vehicle ownership would be important as the top-level metrics of progress. It is very likely that the first few percent of electric vehicle owners will be disproportionately people on above median incomes. If electric vehicle use comes to be seen as the domain of the better-off and the poor, we may develop a sense of exclusion of "the middle". Electric vehicle ownership has to be seen as a realistic medium-term aspiration for most people, otherwise there will not be enough support and enthusiasm for it[44].

Also, it should be part of a wider drive to a more environmentally friendly and healthy system of mobility. As discussed in the Introduction, walking, cycling, railways, trams, etc. should all be part of local spatial planning activities.

How these important social issues should be handled is outside the scope of a technical report on charging management. However, the technical solutions need to be informed by thought about these broader social issues and technical creativity can contribute to delivering better outcomes.

[44] See for example https://inclusivev.eu/

REFERENCES

These additional references are provided as background reading

1. Electric Vehicles: Towards an Excellent User Experience, Transport Systems Catapult, 2018

2. EA Technology Ltd, "My Electric Avenue Summary Report," [Online]. Available: http://myelectricavenue.info/sites/default/files/documents/Summary%20report.pdf.

3. UK Government, Automated and Electric Vehicles Bill, London, 2017-19.

4. Energy Systems Catapult, "Energy Systems Architecture Methodology: Enabling Multi-vector Market Design," Energy Technologies Institute, Loughborough, 2017.

5. G. Day, "Enabling Efficient Networks for Low Carbon Futures," Energy Technologies Institute, Loughborough, 2016.

6. EA Technology Limited, "Consultation on the Interim Solution for Domestic Managed Electric Vehicle Charging," EA Technology Limited, Capenhurst, 2018.

7. National Grid, "Electricity Transmission Network Charging," National Grid, 2018.

8. Element Energy, "Rapid charging network study," 26 June 2015. [Online]. Available: http://content.tfl.gov.uk/rapid-charging-network-study.pdf. [Accessed 11 June 2018].

9. N. Storer, "How will the growth of electric vehicles impact the grid?," November 2017. [Online]. Available: http://www.electricnation.org.uk/wp-content/uploads/2017/11/14-How-will-the-growth-of-electric-vehicles-impact-the-grid.pdf. [Accessed June 2018].

10. M. Dale, N. Storer and D. Hollingworth, "Electric Nation overview presentation," 2017. [Online]. Available: http://www.electricnation.org.uk/wp-content/uploads/2016/08/104060-Electric-Nation-BA-2017_final-low.pdf. [Accessed April 2018].

11. Office for Low Emission Vehicles, "Lessons Learnt from the Plugged-in Places Projects," Her Majesty's Stationery Office, London, 2013.

12. eMobility ICT Interoperability Innovation Group, "Electro mobility - Interoperability Challenges," 23 June 2015. [Online]. Available: http://xwp4f3h137o27oft81jv1nyh.wpengine.netdna-cdn.com/wp-content/uploads/sites/5/2015/11/eMI3-Electro-Mobility-Interoperability-Challenges-v1.0.pdf. [Accessed May 2018].

13. SAE, "Automated Driving: Levels of Driving Automation are Defined in New SAE International Standard J3016," [Online]. Available: https://www.smmt.co.uk/wp-content/uploads/sites/2/automated_driving.pdf. [Accessed 13 June 2018].

14. ELEXON, "Enabling customers to buy power from multiple providers," ELEXON, 2018.

15. T. Seymour, Avoid piecemeal approach to EV charging urges National Grid, Bauer Consumer Media Ltd, 2018.

[45] A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldie-Scot, Bloomberg NEF, March 2019

APPENDIX I – BATTERY TECHNOLOGY

There is a very considerable investment in battery research and development globally by both commercial and public-sector investors. PiV battery development is a very large part of this and the state of the art has been advancing rapidly. The ETI has chosen to invest in novel static electricity storage technology at a utility scale, recognising the limited opportunity for any ETI added value in vehicle batteries.

We have attempted to keep up with vehicle battery developments by the usual means, including using expert consultants to inform our vehicle projects at key points. The scale up of vehicle battery production and the commercial value of real-life battery performance data make it challenging to stay abreast of every relevant development, although overall trends and issues are reasonably clear.

This Appendix aims to provide background information to readers who are less familiar with batteries, not cutting-edge information on the current state of the art. There are ongoing innovations at every level of battery technology but the largest contribution to cost reduction at present is probably supply chain scale up and competition for the rapidly growing global market for vehicle batteries. Automated six-sigma manufacture is therefore a key competitive capability. Battery manufacturers are trying to identify which chemistries are likely to be most sustainable as scale up occurs.

The key performance parameters of a vehicle battery pack (in priority order) are:

1. Cost of range ($/kWh).

2. Space and weight claim for range (lbs or kg /kWh).

3. Recharge time without loss of battery capacity (% loss per cycle at any given recharge rate).

4. Safety (typically temperature at which runaway occurs but there are issues to do with the cell and pack design).

5. Suitability for second use (with and without remanufacture).

6. Design for recycling.

Battery Basics

EVs currently use specific types of Lithium-ion (Li-ion) batteries to power them.

The three primary components of a lithium-ion battery are the positive and negative electrodes and an electrolyte. Generally, the negative electrode is made from carbon or graphite, the positive is made from a metal oxide and the electrolyte is composed of lithium salt in an organic solvent.

In an EV several Li-ion cells are assembled together in a module and a number of modules are assembled along with the controls, cooling and protection systems in a battery pack. So, for example in a BMW i3, 8 modules, each containing 12 cells, are combined in the battery pack of the vehicle – making a total of 96 cells.

The energy flowing into the battery pack, as it is charged from the grid, and from the battery pack, as it is discharged to power the vehicle, causes heating of the battery pack. The faster the flow of energy the greater the heating effect seen. The performance of Li-ion battery cells is greatly impacted by their temperature, fast charging is not possible below 5ºC and the cells begin to degrade quickly when their temperature exceeds 45ºC. Cooling of the battery cell pack is therefore needed to allow rapid charging and discharging and avoid damaging the battery.

The energy density of a battery is the amount of energy stored per litre of volume. Increasing the energy density of a battery cell results in a smaller battery pack and less space taken up on board the vehicle.

Battery Costs

Both BEVs and PHEVs are more expensive vehicle technologies than the internal combustion engine. The additional costs of an EV are related to battery and motor components. Reductions in Li-ion battery costs over recent years have led to the increase in availability of affordable, mainstream low carbon vehicles.

Back in 2010 prices for Li-ion battery packs were around $1000/kWh, but by the end of 2017, the cost of a Li-ion battery pack had dropped to $209/kWh[45]. Further reductions in battery costs are expected to be seen as the EV industry focus on driving out costs and a target of $100/kWh battery pack is expected to be reached by the mid 2020s. Many of the cost reductions seen already have been through incremental improvements, for example improving costs as production is scaled up, and reduction in costs associated with raw material as battery chemistry is improved.

Moving below $100/kWh will be challenging as raw material costs become a limiting factor. If we consider current battery chemistry using Li-ion batteries the cost of the raw materials alone is around $46/kWh. With the current Li- ion battery technology the price for a battery pack of $100/kWh is considered feasible, but to drop significantly below this, new chemistries with cheaper materials will be needed.

As the number of EVs increases so will demand for raw materials such as cobalt and lithium, and costs of these would therefore be expected to rise. This increase in raw material cost could speed up the adoption of low-cobalt battery chemistries, or advances in alternative battery chemistries.

Battery Chemistries

Lithium batteries are characterised by the chemistry used in

[45] A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldie-Scot, Bloomberg NEF, March 2019

the cathode of the battery cell. Early Li-ion EV batteries used a lithium-cobalt-oxide chemistry. Following on from this, oxides of manganese, nickel and iron were used.

Nickel-cobalt-manganese (NCM) batteries are currently the most used for EV batteries. The ratio of nickel, cobalt and manganese is designated by numbers, so NCM111 contains equal parts of all three components. Cathodes with lower ratios of cobalt and higher nickel content are favoured due to the current increase in the price of cobalt, with a number of reduced cobalt ratio batteries being introduced to the market. This also brings an increase in the cell energy density. NCM 811 is expected to be introduced by 2020 with a number of battery manufacturers showing this on their roadmaps, and small-scale manufacture (in the inert atmosphere plant this chemistry requires) has already been proven.

NCA (nickel-cobalt-aluminium) is used by Tesla in their current vehicles. It has high energy density, but a lower thermal runaway temp (150ºC) than NCM batteries (200ºC) making the NCA battery a higher fire risk.

Lithium-titanate batteries have the usual lithium cathode as described above but replace the graphite in the anode of the battery cell with lithium-titanate crystals. This creates a much larger surface area at the anode and the resulting battery cell is much quicker to charge and is able to withstand more charging cycles than standard battery cells. It has the added benefit of being the safest Li-ion battery with a high thermal runaway temperature.

Solid state battery technology has solid electrodes as per other batteries, but it has a solid conductive material in place of the conventional liquid electrolyte. This technology removes the need for some of the expensive raw materials such as cobalt and provide an increase in energy density of around 2.5 times that of current Li-ion batteries. The removal of a liquid solvent as the electrolyte also reduces the risk of battery pack fire.

BATTERY CAPACITY & TIME TO CHARGE

Currently consumers can re-fuel their ICE vehicles in a matter of minutes, and en-route charging of EVs at service stations and on motorways is often compared unfavourably to the speed of charging achievable with liquid fuels. There has been a focus by manufacturers of vehicles and charge point providers on quick charging, so charging your car in the time it takes to have a break at motorway services and grab a coffee, say around 20-30 minutes, is achievable.

However, there is an impact on battery life if fast charging is done too frequently, as charging causes the battery to heat up and degrade, and the faster the charger the faster the increase in heat. With persistent fast charging, battery capacity will be reduced which impacts on range of the vehicle. In response to this vehicle manufacturers are in some cases restricting the number of fast charges which can be done in one day via the car's management software. Drivers on long distance journeys are impacted as the second or third charge on a journey take progressively longer times. It seems very plausible that some battery packs will be more optimised for ability to resist fast charging and others for cost, space and weight claim. Although the ideal solution would combine all three, it may well be that vehicle manufacturers offer two models at similar prices: one that has a much larger range but cannot be fast charged and another that has a smaller range but can be fast charged without loss of life. Over time, the design choices of vehicles, investments in networks and driver behaviour and vehicle purchases would co-evolve. The optimum vehicle designs would vary significantly from country to country and region to region within countries.

BATTERY PACK DESIGN & THERMAL MANAGEMENT

How battery cells are produced, combined to form modules, and then these modules assembled into battery packs provides opportunity at each stage to reduce costs, improve battery density and ensure safe operation.

The interest in module and pack design options is increasing in the car industry, with a focus on efficient design and structure of the pack to ensure cells are not subject to external shocks and vibration, are cooled adequately and packed tightly to increase energy density. So, for example, by mounting more cells per module, there is both a decrease in the need for connecting components and a reduction in the space taken up.

In order to prolong the health of a battery pack it is necessary to remove the heat that is generated during charging and during use. There are 3 common battery thermal management methods used today:

- Air cooling – either naturally or by fan.
- Oil cooling – by flooding the battery with a dielectric oil which is then pumped out to a heat exchanger system.
- Water cooling – by circulation of water-based coolant through cooling passages within the battery structure.

Some vehicle manufacturers use air cooled batteries (e.g. Nissan Leaf). These are not able to remove heat as quickly from the battery pack as liquid cooled systems (e.g. Tesla). Whilst the air-cooled option is cheaper to install, it is not as effective. With air-cooled systems, batteries are more likely to suffer from overheating during charging which impacts long term battery capacity and costly battery replacement is needed sooner.

Maintaining a consistent temperature through a battery pack is also important as hot spots within a pack due to patchy heat removal can cause damage and, in the worst case, fires. Research into the best methods for battery cooling has identified that cooling applied to the battery tabs (where the electricity flows in and out of a battery) is more efficient at maintaining a consistent temperature across the pack than surface cooling. As cells start to degrade, the way that current is managed within the battery pack becomes important, otherwise a point failure can translate into progressive and severe degradation.

BATTERY MANAGEMENT & CONTROL

Each vehicle has a battery management system which monitors battery health, temperature and power flow over time and identifies failing cells. The management system also manages charging and provides information to the vehicle about State of Charge (i.e. range) and battery pack health. In principle this can be very sophisticated, managing the charging and discharging loads on individual modules or even cells, to maximise performance and life.

Within a module, which is made up of a number of battery cells, the lifetime of the battery is limited by the performance of the weakest cell within a pack; by using more sophisticated battery pack management and controlling the current through each module an even performance can be managed, extending the overall life of a battery pack.

MANUFACTURING

Manufacturers are pursuing different strategies, with some opting to manufacture everything from the active materials to finished battery packs in-house. Others prefer to buy electrode active materials or electrode rolls from external suppliers and simply manufacture the cells in-house. Whichever option is chosen the growth of electric vehicles will require a dramatic scale up in the current Li-ion battery supply chain.

The worldwide capacity to manufacture Li-ion batteries currently stands at around 131 GWh per year, this is set to swiftly increase to over 400 GWh by 2021 with 73% of the global capacity by that time concentrated in China. Looking out to 2030, global EV battery demand is expected to exceed 1,500 GWh, creating not just a huge scale up task but also driving up demand, and price of key raw materials.

REUSE AND RECYCLE

The performance of an EV battery declines over time, and drivers will notice they get fewer miles of driving per charge and so have to plug in more frequently. Typically, in a family car this would be after around ten years use and a replacement battery would be sought. Whilst these batteries have lost too much of their capacity to continue powering an electric car, they can be reused in a variety of ways which require a lower capacity. These batteries can find a second use powering car-charging stations, storing electricity from solar panels or wind turbines, and storing energy for homes and grids.

As the number of electric vehicles on our roads increases so does the need to find alternative uses for these batteries at scale. The first generation of Li-ion car batteries are now reaching the end of their life powering vehicles and in 2018 it was expected that around 55,000 of these batteries would be retired. By 2025 a total of 3.4million packs are expected to have been made available to the second use market.

This second use can extend the battery life by a further seven to ten years and generating revenues from this second life battery market has the potential to help reduce prices for EVs even further. Once batteries have reached the end of their second life and are not able to even meet these lower capacity demands they will move into the recycling market where the valuable raw materials used to make them will be recycled.

Scaling up and proving second use and recycling will lag scale up of first use. This will be complicated by different chemistries, cell designs, battery pack assemblies and battery pack management systems, including cooling systems.

APPENDIX II – CONSUMER SEGMENTATION

ETI has worked with two related segmentations for drivers of PiVs:

- A segmentation developed for our Consumers and Vehicles project, available from the ETI Knowledge Zone as "Identification of Relevant Consumer Segments", Anable et al, TRL, April 2011, and
- A segmentation developed for the Department for Transport (DfT) and used to segment participants in the CVEI project. This was reported as "Survey of consumer attitudes to plug-in vehicles", Element Energy, October 2015. This report is unpublished but the segmentation, and how it was used, is described in the CVEI project reports.

Both surveys used large populations, representative of UK drivers. Both surveys oversampled enthusiasts, in order to ensure statistically robust representation of their views. Both surveys were largely with respondents who had no or very limited experience of PiVs and are therefore Reported Preference surveys, i.e. not based on actual experience. The psychological distance of CVEI participants was reduced by actual experience of PiVs. In the Uptake Trial, this was four days each with an ICE, BEV and PHEV VW Golf. In the Charging Trial it was around eight weeks with either a BEV or PHEV VW Golf.

Although the DfT segmentation is more recent, it is not clear how much mass-market views of PiVs developed between 2011 and 2015. The CVEI project used it because it was more recent, and the statistical data was available to map CVEI participants into the segments with a degree of robustness.

The ETI segmentation can be summarised as in figure 16.

This segmentation was also reported by Anable, Skippon, Schuitema and Kinnear in "Who will adopt electric vehicles?: A segmentation approach of UK consumers", Proceedings of the European Council for an Energy Efficient Economy, June 2011. The DfT segmentation can be summarised as in figure 17.

Although these two sets of segments differ significantly, they are related. Car Loving Rejecters is a good fit to Image Conscious Rejecters and Unmet Needs a reasonable fit to Willing Pragmatists.

In the main body of the report, the ETI segmentation is used, because a very detailed report on it is available to download. Although DfT kindly shared the Element Energy report with ETI, it is not available for download.

Figure 16
Reported Preference segmentation from ETI Consumers & Vehicles project

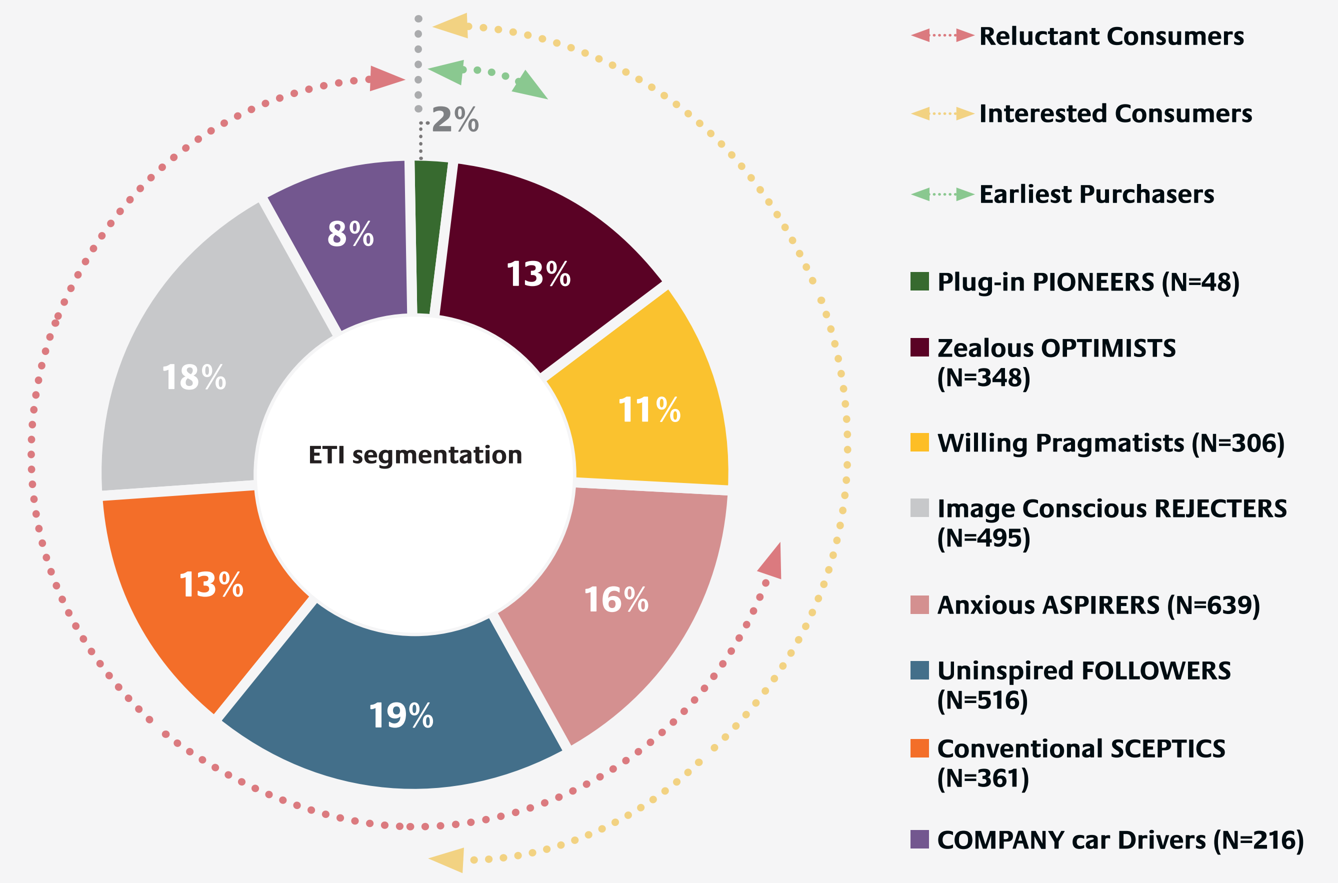
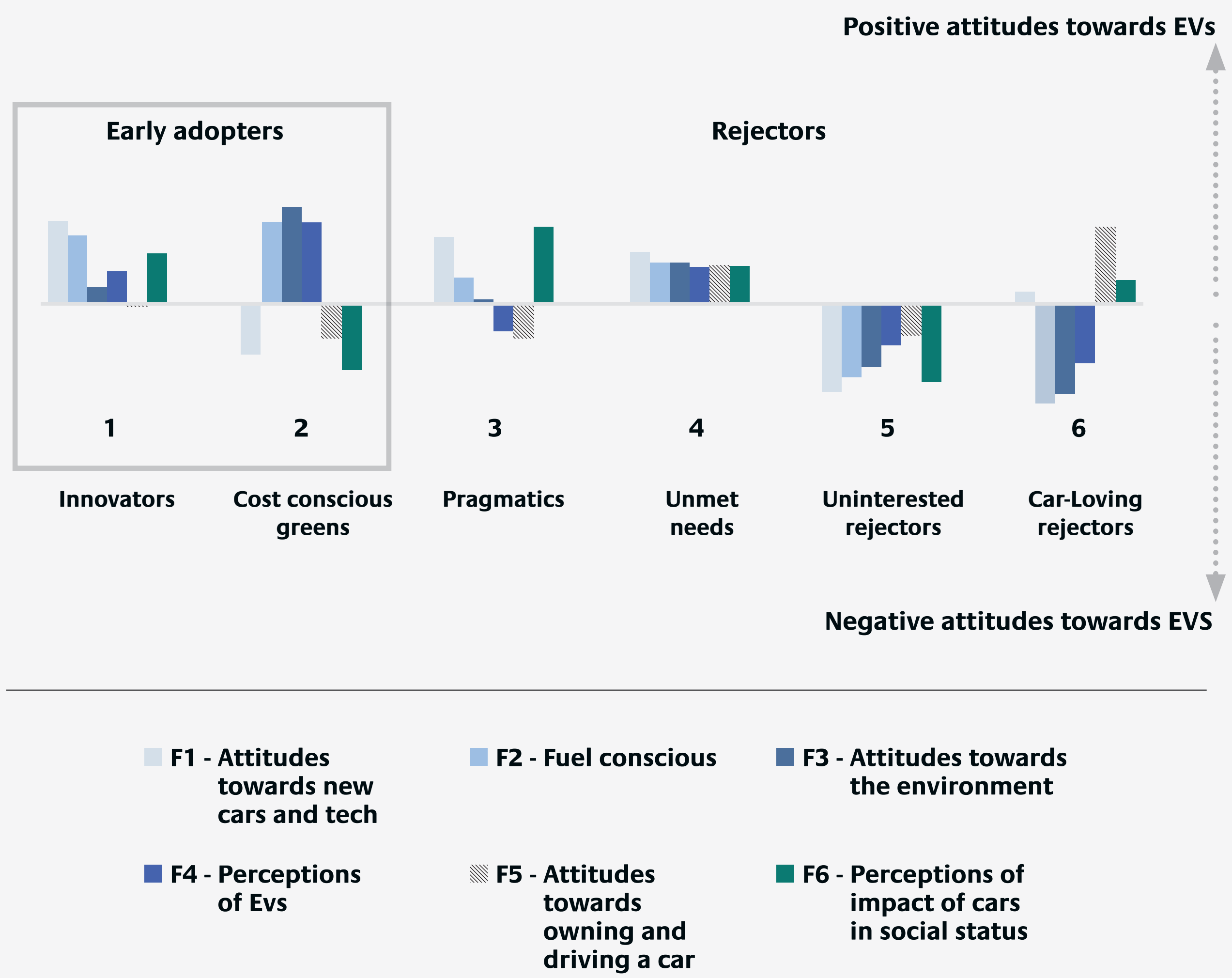


Figure 17
Reported Preference segmentation from ETI Consumers & Vehicles project

	Potential early adopters		Probable late adopters		Probable rejecters	
	1 Innovators	2 Cost conscious greens	3 Pragmatists	4 Unmet needs	5 Uninterested rejectors	6 Car-loving rejectors
Car ownership & driving	› Owns one car › Skew towards medium cars, high % of large › High spend on new cars (all >£20k) › Strongly links cars to status	› Owns one car › Medium car prevalence. Low large › 10% spend >£20k in new cars › Does not link cars to status. Not particularly like cars and driving	› Owns one car › Medium car prevalence. Low large › 10% spend >£20k in new cars › Strong links cars to status. Doesn't particularly like cars and driving.	› Owns two or more cars › Similar small/ medium/large split › 25% spend >£20k in new cars › Links car to status. Like cars and driving	› Owns one car › Medium car prevalence. Low large › 10% spend >£20k in new cars › Does not link cars to status. Does not particularly like cars	› Owns one or two cars › Strong skew towards large, high % medium › 40% spend >£20k in new cars › Links car to status. Very much likes cars and driving
Driving patterns	› High annual mileage › Very frequent long trips	› Average annual mileage › Infrequently long trips	› Average annual mileage › Frequently long trips › Predominately urban	› High annual mileage › Frequently long trips	› Lowest annual mileage › Infrequently long trips	› Highest annual mileage › Frequently long trips
Attitudes towards new tech	› Very interested – enthusiast	› Not interested	› Interested	› Interested	› Not interested at all	› Interested in new cars, but not that much in new tech
Fuel use conscious	› High WTP for lower running costs	› High WTP	› Relatively high WTP	› Relatively high WTP	› Do not see benefits in changing fuel from oil	› Do not see benefits in changing fuel from oil
Green attitudes	› Inclined towards green	› Greenest - deeply believes in the impact of his/her individual action	› Neutral - feels moral obligation to reduce GHGs, but doesn't see problem as priority	› Positive	› Negative	› Least green
Attitudes towards EVs	› Positive	› Positive	› Negative	› Positive	› Negative	› The most negative
Home Charging access	› All	› High majority	› Majority	› Nearly all	› High majority	› Very high majority
Income	› High	› Medium	› Low	› High	› Low	› High
Employment	› Highest (85%)	› Low (50%)	› High (70%)	› High (70%)	› Lowest (50%)	› High (70%)
Age	› Young		› Youngest		› Oldest	
Gender	› High male predominance (65%)	› 50/50	› 50/50	› High male predominance	› Slight male predominance	› High male predominance
% sample	› 2%	› 20%	› 21%	› 19%	› 20%	› 17%

Figure 18
Main factors in DfT segmentation



Notes: The six factors are presented as standised scores (i.e.zones) which indicate the number of standard deviations each respondent differed from the mean response (with a z-score of 0)

Care is required in interpreting the real-world implications of these Reported Preferences. For example, the attitudes of some Tesla drivers are a good fit to the ETI Image Conscious Rejecters segment. A Tesla is an attractive car to them, even if it is not an ICE. The Unmet Needs DfT segment were identified on the Rejector side of the uptake scale, even though they are the only segment of any size that has entirely positive attitudes about car ownership and PiVs. The related ETI Willing Pragmatists segment would be very interested in a PHEV, provided it had sufficient electric range and its overall characteristics fitted their needs.

The authors of this report would advocate a significant degree of caution in using Reported Preference segmentations and especially in taking simple messages from complex data. The ETI segmentation is reported in sufficient depth that an experienced consumer researcher can form hypotheses about how different consumers might approach the reality of living with a PiV. The CVEI choice experiment provides real-world data that can be related back to the DfT segmentation.

APPENDIX III – UK FLEETS

Fleets are an important route for entry of new vehicles into the UK parc. In the year to August 2018 1.57 million new cars were sold in the UK. 52% of these were fleet sales, 4% direct business sales and 44% private sales[46]. In recent years, fleets have accounted for more than two-thirds of PHEV sales.

Fleet sales can be broken down into company fleets for use by employees, vehicles leased to private individuals and vehicles for hire. Company cars are typically provided to individual employees, either as part of their overall remuneration or in order to perform their job. Often there is a combination, with business travel being a significant part of the overall mileage. Staff who make sales, provide field service etc. often have company cars. Technical staff frequently have vans, in order to carry tools and materials to work sites.

Only a minority of company car and van fleet vehicles are used on a return-to-base or pool vehicle basis. Typically, employees park their car or van at home (or a hotel) overnight. Where vehicles are operated on a return to base cycle, there is clearly an opportunity to recharge at base. Otherwise refuelling will occur at overnight locations and the sites of meetings and technical work, including locations where the employer has offices and facilities. The CVEI project looked at some van and light vehicle fleets to get a better understanding of factors which are likely to affect uptake and charging[47].

Company cars are broken down between “user choosers” and cars specified by the fleet manager for specific roles. Although there may appear to be a clear line between user chooser vehicles, where the primary aim is employee retention, and specified vehicles, the reality is probably more ambiguous.

Unsurprisingly, company car annual mileage tends to be higher than average – estimated at 18,000 miles per year against a private car average of 7,500 miles per year. Across all ownership, petrol cars average 6,500 miles per year and diesel 10,100 miles per year[48].

How PiVs will be taken up by the fleet markets and how they will be driven and charged are therefore both important questions:

- The availability of used PiVs will depend significantly on sales by fleets.
- The driving and charging patterns of fleet drivers will be important to real-world electric miles and decarbonisation, since they are typically high mileage drivers.

It is too soon to say what impact fleets might have on these factors over the next ten years, however it remains an important question for further research and improved statistical reporting.

PERFORMANCE OF PHEVS IN FLEETS

There is a growing discussion about fleet vans and cars amongst companies involved in their supply and use. The Lombard PHEV trial report provides a valuable illustration of the issues[49]. The Miles Consultancy collect information on fuel usage for their customers, to help them manage their fleets. They report that the overall performance of PHEVs in fleets suggest that drivers are not maximising electric miles[50]. The reasons for this are unclear. Comparing their report with the Lombard trial report and our data suggests that this is due to some combination of the characteristics of the PHEVs that were in service at the time, driver motivation and understanding, and journey patterns.

[46] SMMT car registrations data
[47] CVEI D6.1 - Fleet Study: Case Studies, TRL. 2017
[48] https://www.racfoundation.org/motoring-faqs/mobility
[49] PHEVs: The future of your fleet?, Lombard, February 2018
[50] New analysis of plug-in hybrid car mpg and emissions is expected to spark debate on their suitability for fleet operation, The Miles Consultancy, September 2017, https://themilesconsultancy.com/new-analysis-plug-hybrid-car-mpg-emissions-expected-spark-debate-suitability-fleet-operation/

Figure 19
Fuel efficiency of drivers in CVEI charging trial compared to data from The Miles Consultancy and Lombard

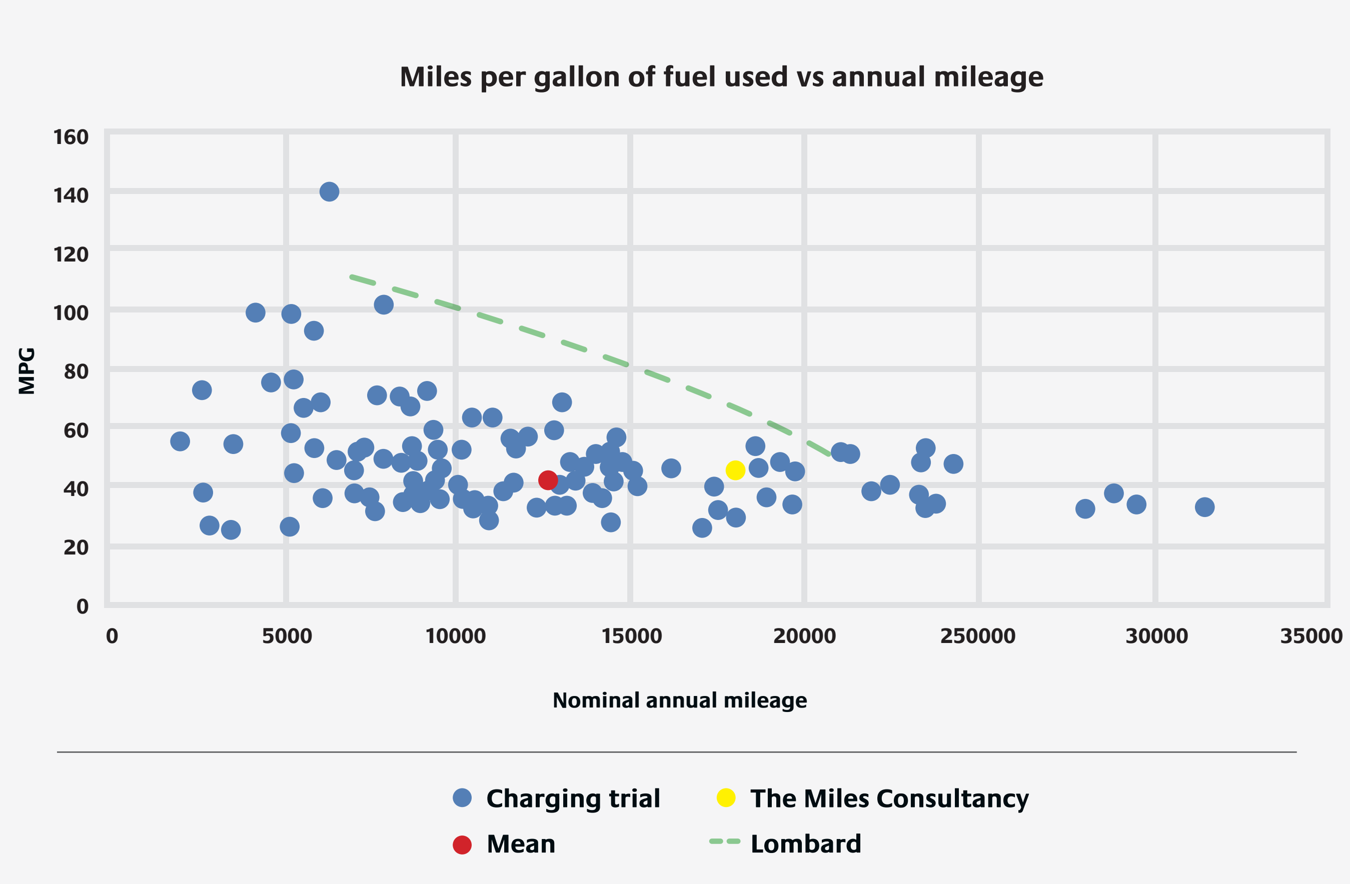


Figure 19 shows the CVEI PHEV driver data plotted as residual fuel use (in mpg) against annual mileage, which is the typical presentation for fleet managers. Overlaid on this is the line provided by Lombard, based on a small-scale trial with enthusiasts; Lombard intend this as guidance in estimating the economics of switching fleet car drivers to PHEVs, based on their individual annual mileages. This line matches the highest performance of drivers in the CVEI charging trial. The yellow point represents the average residual fuel consumption across fleets of PHEVs, as reported by The Miles Consultancy. This matches the average across all CVEI PHEV drivers, shown in red.

As discussed in the main report, the difference between the average performance of real-world fleet drivers and the Lombard trial or the CVEI "high performers" is significant. There is little point in switching to a PHEV, if its carbon emissions are similar to, or worse than, a large diesel car. Equally, charging loads and patterns derived from existing fleet drivers may be completely misleading and underestimate the requirements of future PHEV drivers. Apart from some striking anecdotes about PHEV drivers who returned their vehicle with the charging lead still in its wrapper, or trials where some drivers forgot to plug-in, there is little hard evidence on why some drivers do far more electric miles than others. Most PHEVs purchased in the UK are bought by fleets. There is no strong published evidence on the electrification achieved by private purchasers of PHEVs, although it would be surprising if it were not significantly better than the fleet average.

INDICATIONS FROM CVEI

Other than the reward points for patterns of charging, CVEI PHEV drivers were deliberately not given any incentive or encouragement to maximise electric miles. They therefore represent in some ways the population of fleet drivers or secondary drivers of a privately purchased PHEV. That is validated by their residual fuel consumption being very similar to that published by The Miles Consultancy (although we don't know the effect of annual mileage and mileage patterns).

It is very striking from studying individual driver's journey data, how many miles "lower performing" PHEV drivers did where the battery was being recharged from the engine. Even "higher performing" drivers seemed to start driving in this mode, before switching to driving on electric miles after a few days experience with the vehicle.

This might be regarded as odd behaviour, since recharging the battery uses more fuel than just driving on the engine and costs much more than driving on electricity. One reason for using the engine to keep the battery topped up, would be to ensure that maximum power is always available. However, the extent of this behaviour and the typical end-of-journey State of Charge don't match this explanation. Misunderstandings and lack of interest in how to operate the car seem more likely causes.

There is a natural experiment, in that the cohort of PHEV drivers were split between 3 different charging management sub-groups – User Managed Charging (UMC), Supplier Managed Charging (SMC) and Non-Managed Charging (NMC) – and were briefed at two different centres. One might expect that the level of engagement with the car and its operation would tend to be UMC > SMC > NMC. One might also see differences caused by the briefing between the two centres. We can therefore test for both motivation and understanding.

Separating out the different charging regimes (see Figure 20) shows that motivation might have had a modest effect. The User Managed charging group have a slightly higher tendency to maximise electric miles than the other two groups, and the Control group (NMC) have a slightly higher tendency to drive very few electric miles. Although these inter-group differences are not pronounced, they might be explained in terms of engagement and motivation, consistent with the expected ordering.

Since the participants were recruited and briefed by two different centres, using a small number of staff, we can compare differences between the two groups.

Some combination of recruitment method and the briefings clearly had a modest effect on the proportion of miles driven on electricity.

Since the PHEV model can be driven in different modes, this might be due to small differences in briefing; alternatively, it could be due to the underlying motivations of the participants.

We might make two inferences based on this analysis:

- The design of the drive train controller, regenerative braking controls, and User Interface for PHEVs is likely to have a significant effect on overall efficiency and the proportion of miles driven on electricity.
- As PHEVs penetrate the market, they are likely to be driven by people who have been provided with them as company or fleet cars or to be driven by secondary drivers, whose motivation and understanding is less than the primary driver.

Companies that provide fleet cars and vans to their staff and specialist fleet car providers have the skills and tools to increase the proportion of miles driven on electricity across their fleets and reduce fossil fuel consumption (including through efficiency increases). In the Recommendations section, it is suggested that government is likely to harness this capability through results-oriented policy measures. Unless fleets are used in this way, it is hard to see how PHEV driving performance will reach a sufficient proportion of electric miles and therefore how the UK can deliver sufficient decarbonisation of cars and vans to meet the Fifth Carbon Budget.

Figure 20
Estimated electric miles against annual mileage, by charging group

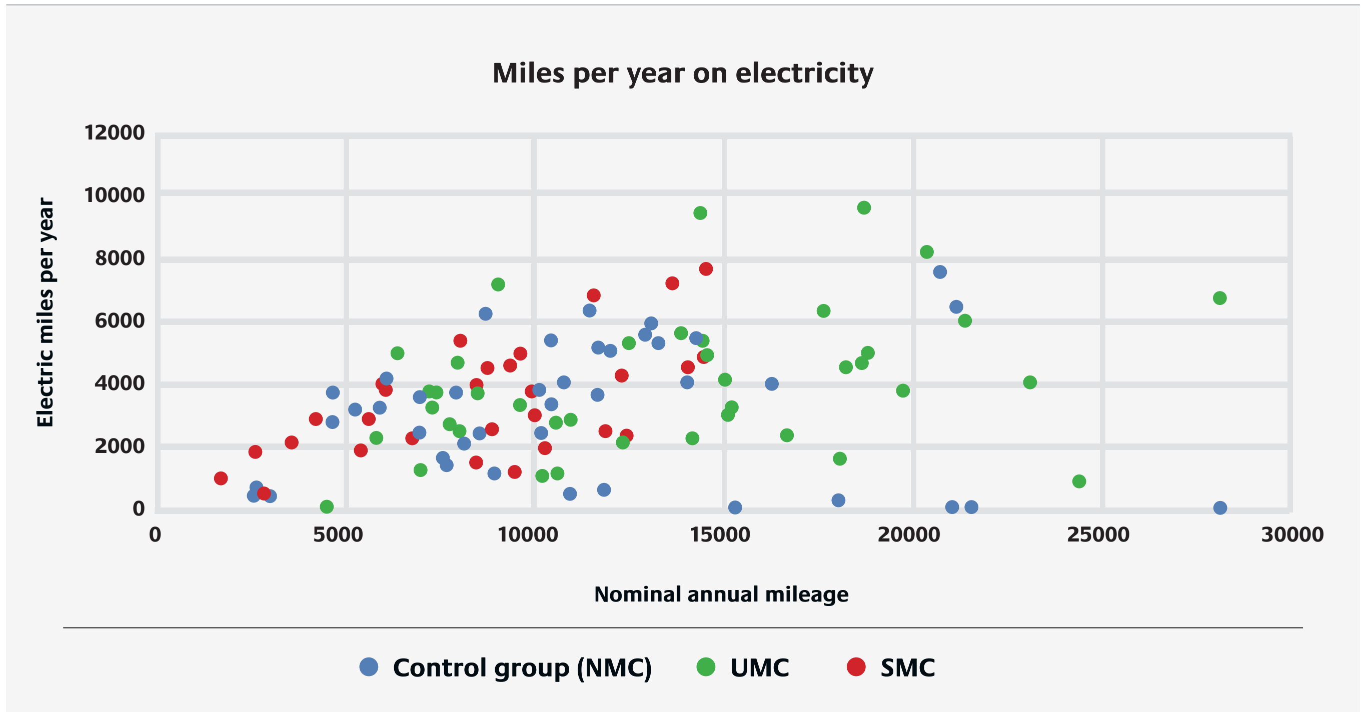


Figure 21
Estimated electric miles by recruitment centre

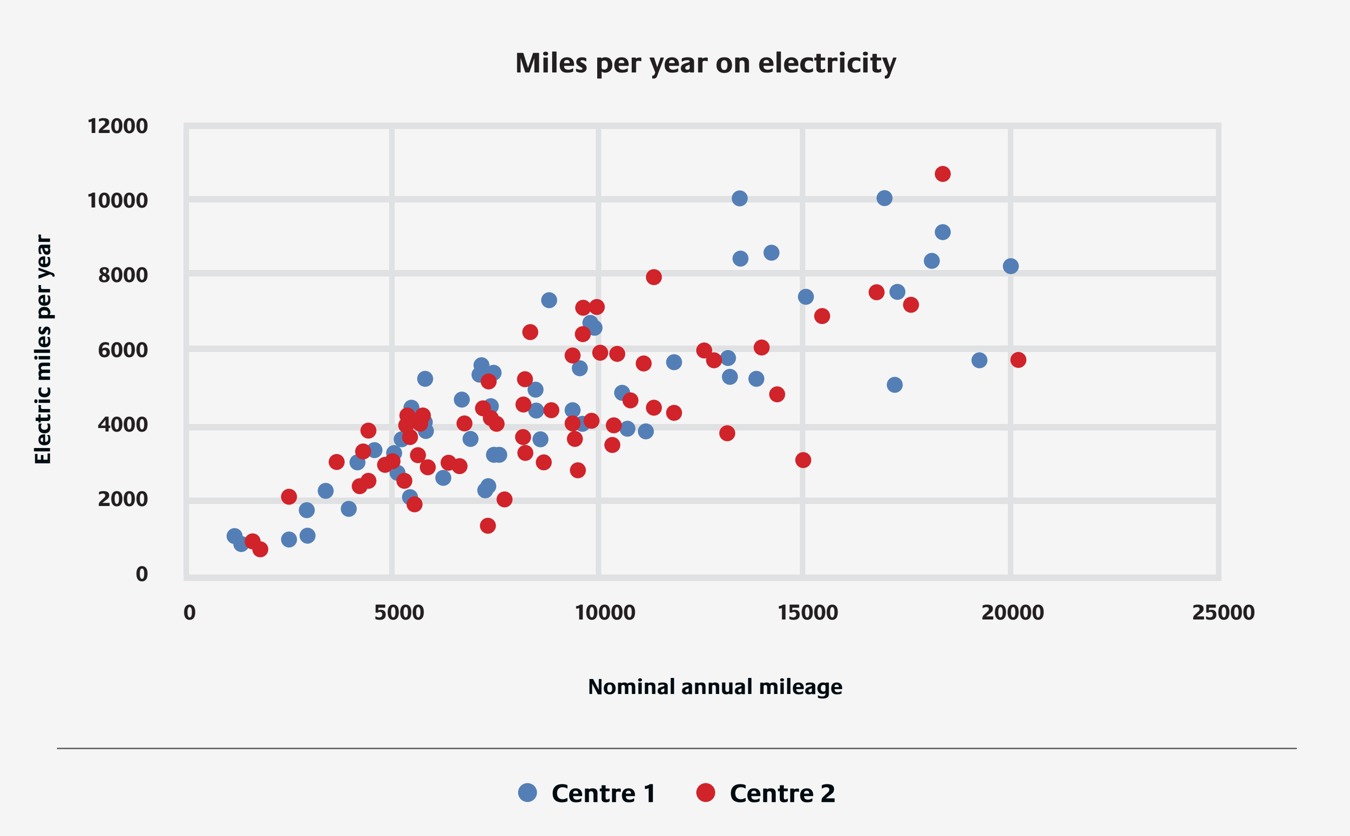


Table 7
Charging amounts in CVEI Charging Trial

Daily average	Weekday Home kWh	Weekday Away kWh	Weekend Home kWh	Weekend Away kWh	Fraction at Home
BEV NMC	7.08	3.37	6.36	3.93	65%
BEV UMC	7.30	4.06	5.87	1.65	70%
BEV SMC	7.53	3.91	6.43	4.16	63%
PHEV CTL	3.87	0.69	3.00	0.28	88%
PHEV UMC	4.07	1.61	2.89	0.40	78%
PHEV SMC	4.18	0.97	3.08	0.57	83%

APPENDIX IV – CHARGING RESULTS

The results of the charging trial are presented as a series of charts. The average charging power for each half hour of the day is plotted for different vehicles, charging management models and Home or Away charging location.

The PHEVs used in the trial had a nominal 3.5kW charging power and the BEVs had 7.5kW for the Home charge point and higher capacity charging at suitable Away charge points.

Participants were given access to the Polar charge point network, the most extensive public network in the UK. Charging Away was mostly free but participants needed to do some charging at Home, in order to earn reward points.

The charging power levels of the PHEVs are lower than BEVs on average, as less miles were driven on electricity than in the BEVs. We would expect miles driven on electricity to be much higher in well-managed fleets and for PHEV chargers to be typically rated at 7.5kW. We would also expect battery ranges to increase for both BEVs and PHEVs. The miles driven on electricity will rise faster with range for PHEVs, as BEVs are only modestly limited by current battery range (for the 2030 driver group identified in our example scenario).

Future charging patterns will therefore be different for both BEVs and PHEVs.

The Control groups were given an app that enabled them to see the State of Charge, but otherwise were left to charge however they wanted. The User Managed Charging groups were able to use the app to set when Home charging started and finished, against a Time-of-Day reward points "tariff". The Supplier Managed Charging groups were able to use the app to request a target State of Charge by a certain time. Their reward points depended on how much flexibility the supplier had to charge at a low cost. Although most PiVs have an interface that enables drivers to set when the car charges, without a tariff there is limited motivation for them to do so. If they are on an Economy tariff, they may well choose to charge on the low tariff. However, Economy tariffs are not especially attractive in terms of the potential cost savings as against the risk that the bill will actually be higher, due to the increased costs of daytime use.

Figure 22
Average weekday half-hourly charging load at home across BEV sub-groups

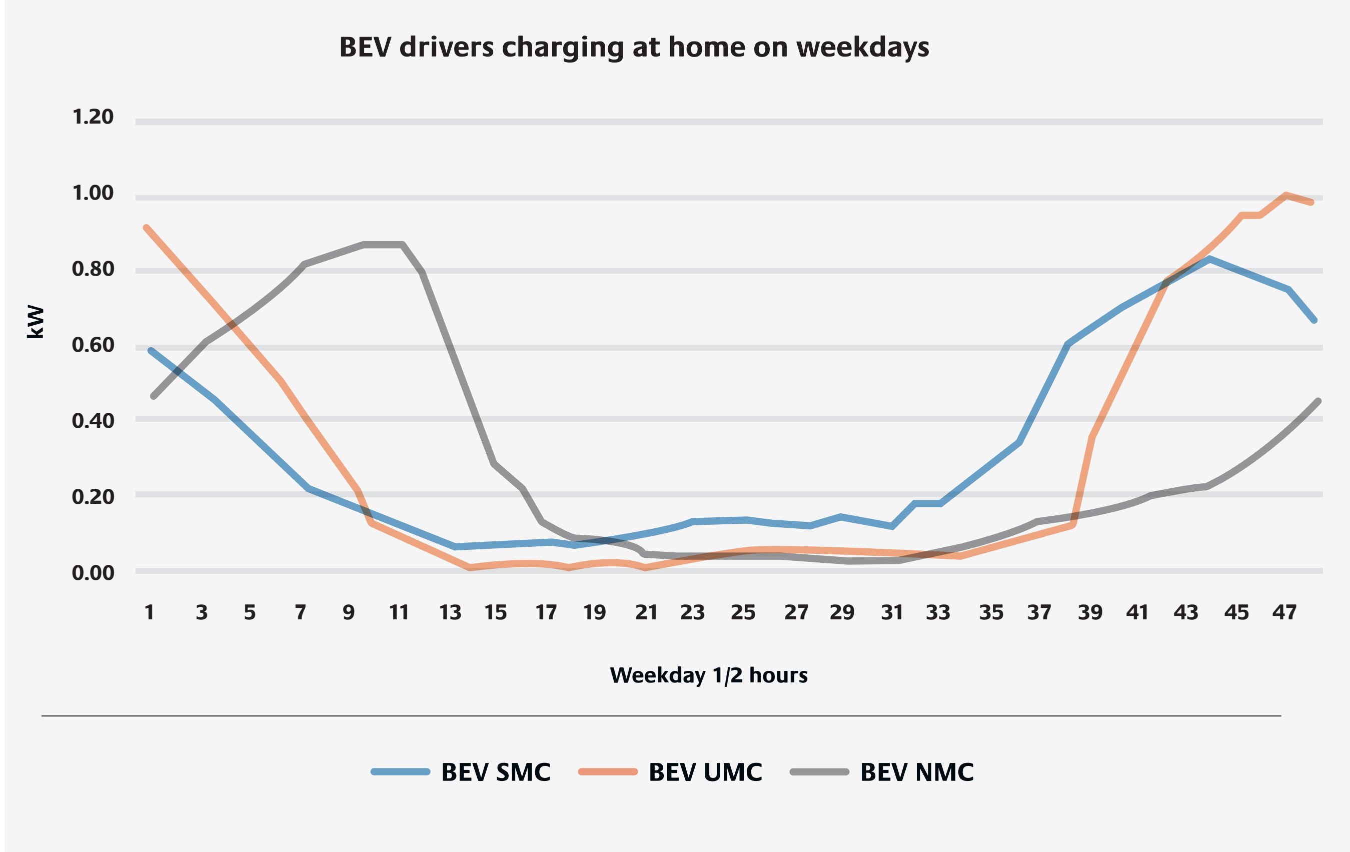
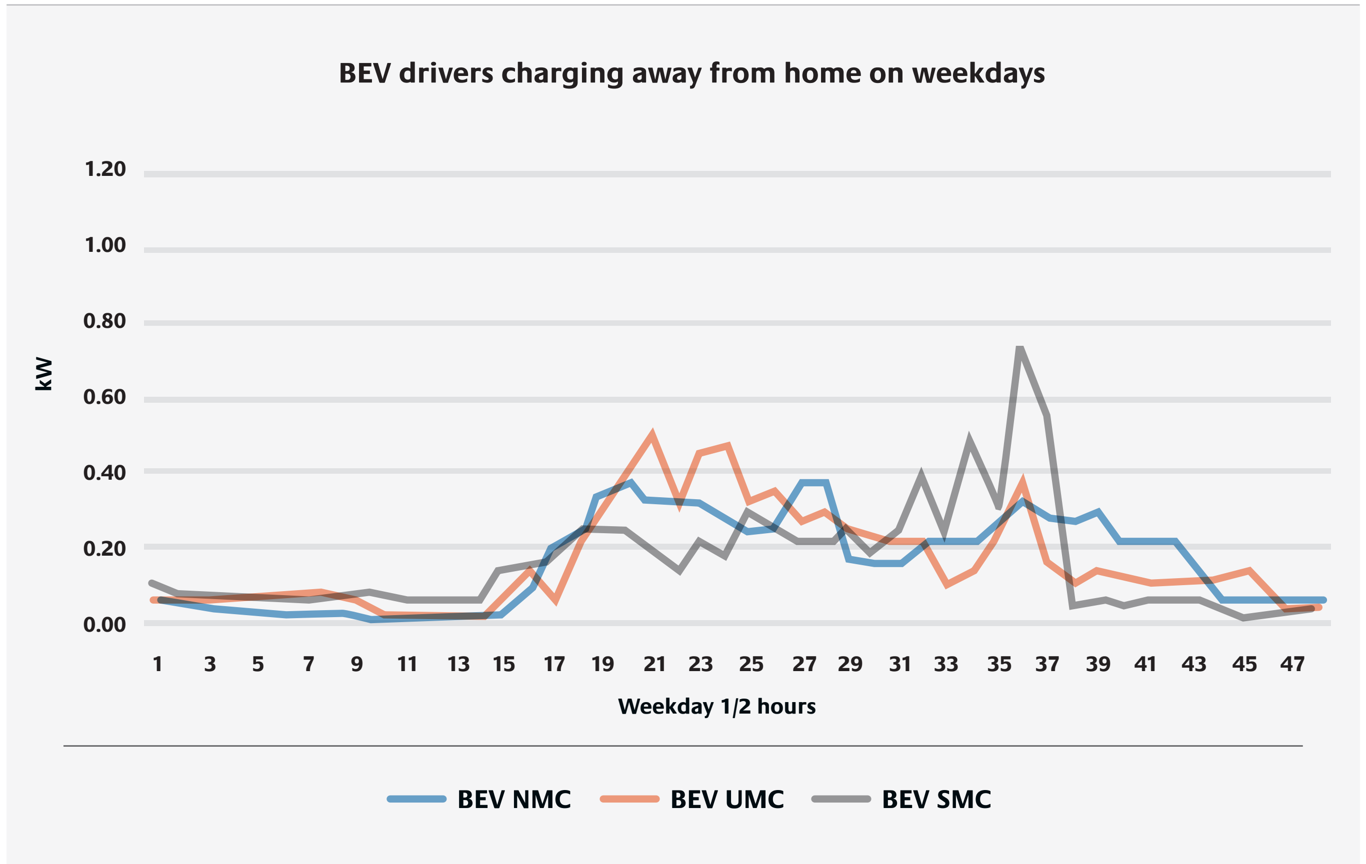


Figure 23
Average weekday half-hourly charging load away from home across BEV sub-groups



The Away data is noisier than the Home data, so should be interpreted with caution. The charts have been normalised, so that the area under all curves is the same as the SMC group.

There is a clear response to the charging management model:

- The Control group plug in on arrival and start charging
- The User Managed group set the charging to start at the tariff boundary
- The Supplier Managed group leave plenty of time for charging overnight, so suppliers could smooth the peak out, if that was desirable

The risk of super-peaks, due to charging, is very apparent. Fixed time schedule tariffs and poorly thought-through supplier management could both become problematic, as PiV uptake increases.

Even when Away charging is free, uptake is limited. It was not part of this study to examine Away charging, so the combination of convenience and access that may have limited Away charging is unclear. However, it does sound a cautionary note against the assumption that drivers will want widespread public charging. Charging at home, at work and en-route on long journeys each have a clear rationale.

Charging at other locations may be limited by what drivers choose, rather than accessibility or cost.

Weekend charging differs from weekday charging in ways that are easily related to the pattern of people's lives.

Figure 24
Average weekend half-hourly charging load at home across BEV sub-groups

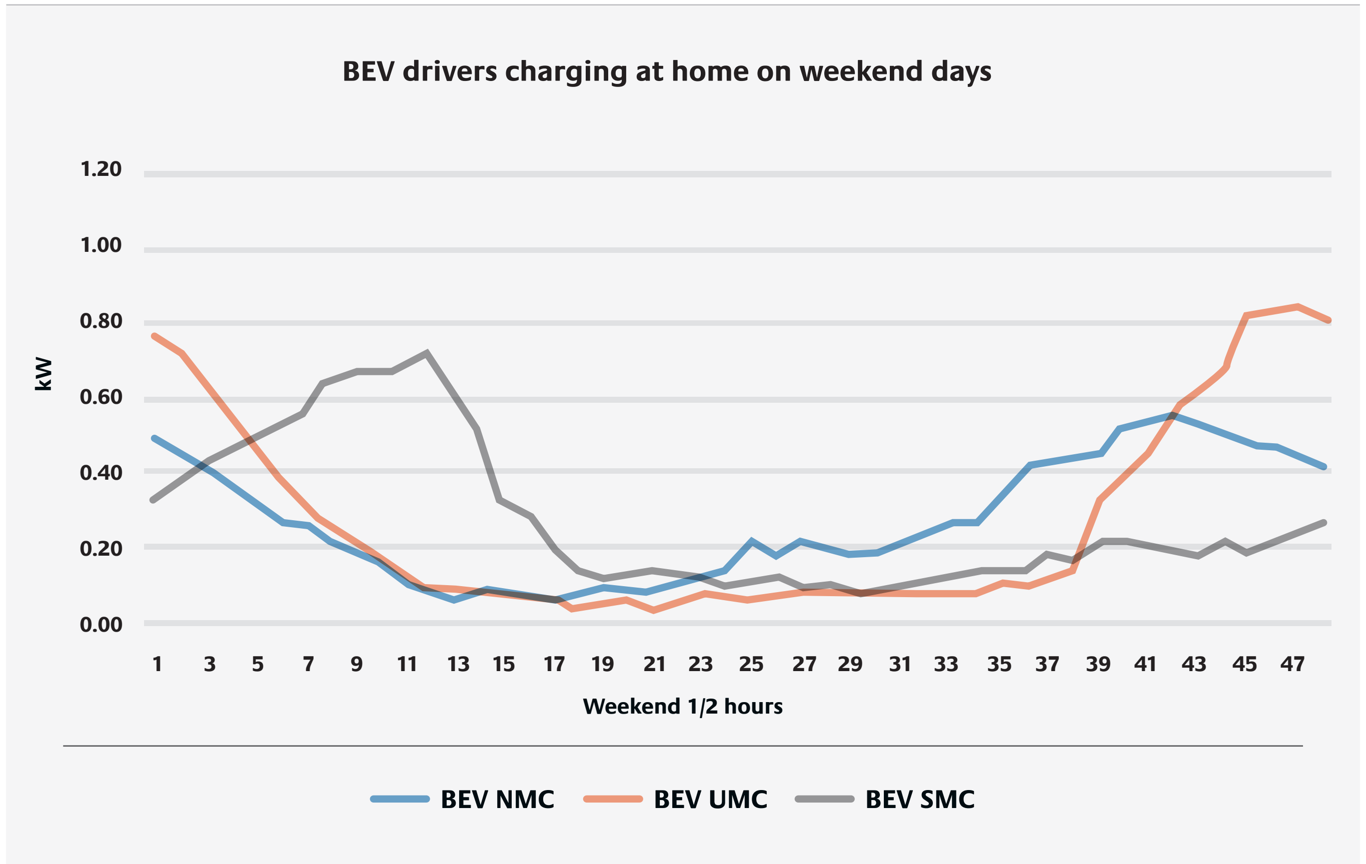


Figure 25
Average weekend half-hourly charging load away from home across BEV sub-groups

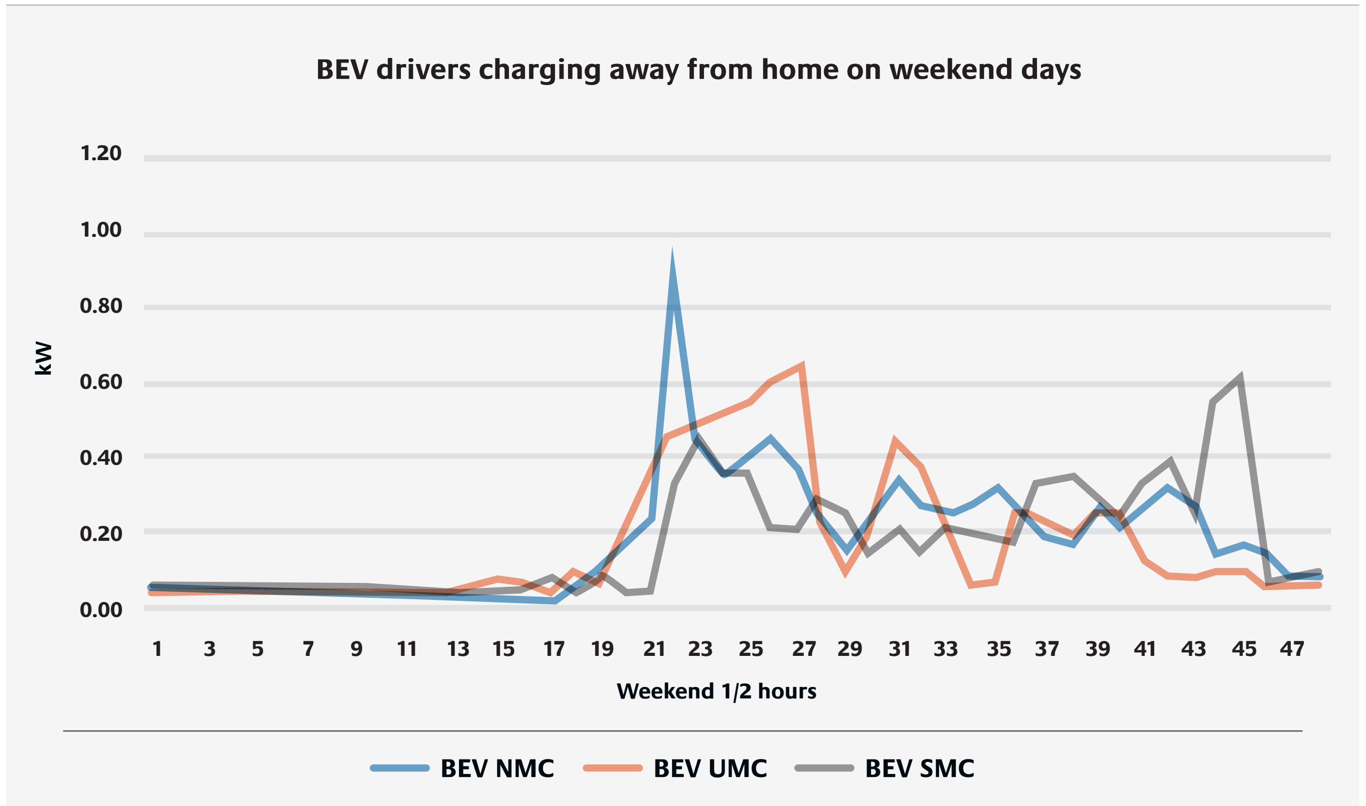
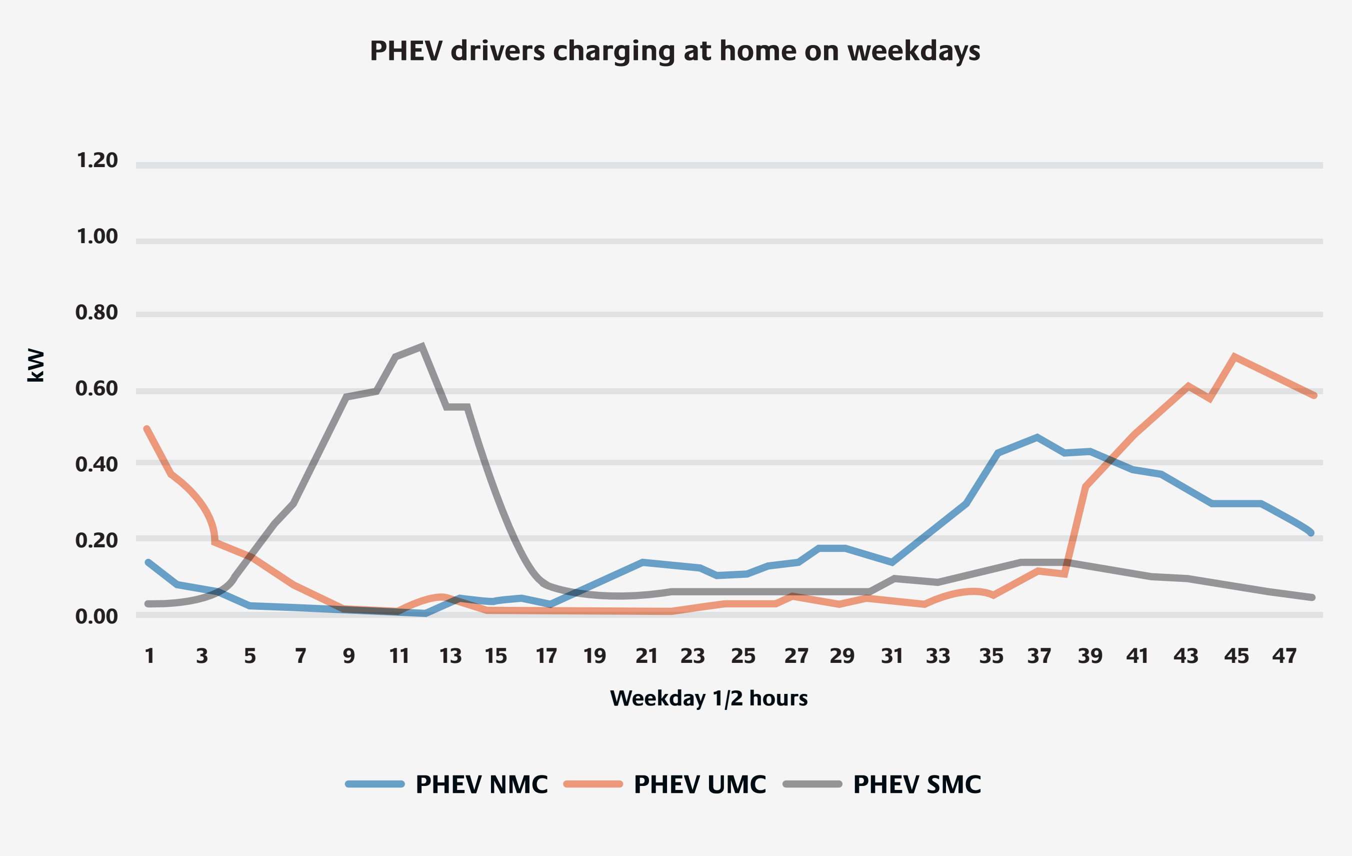


Figure 26
Average weekday half-hourly charging load at home across PHEV sub-groups



The general shape of charging curves for PHEV drivers is similar to BEV drivers. However, PHEV drivers charge much less away from home, as we expected. PHEVs with longer range and higher power chargers would show broader charging curves, with higher peaks. We might also expect that motivated individual purchasers and well-managed fleets will have a higher fraction of miles on electricity than our participants on average. That would also broaden the peaks and increase the Control and User Managed peaks.

Figure 27
Average weekday half-hourly charging load away from home across PHEV sub-groups

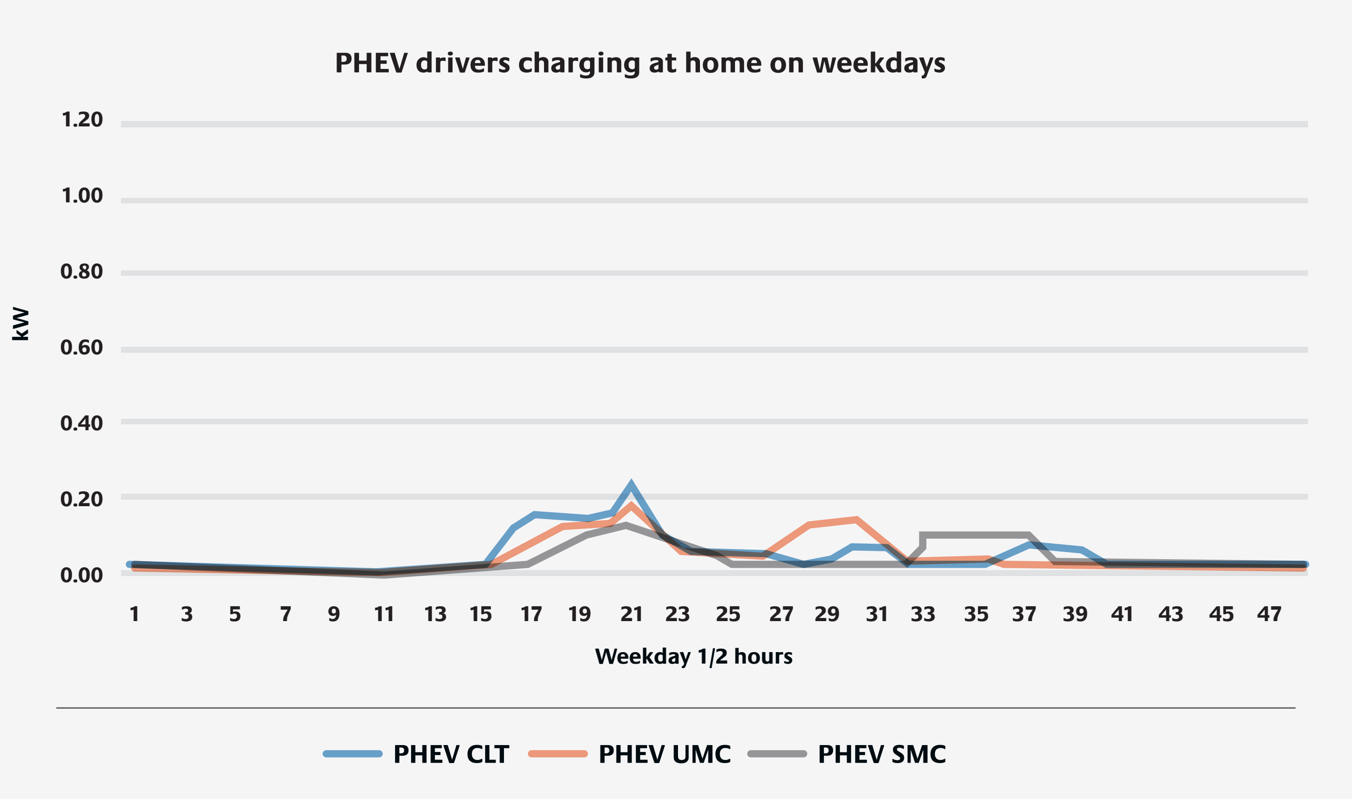


Figure 28
Average weekend half-hourly charging load at home across PHEV sub-groups

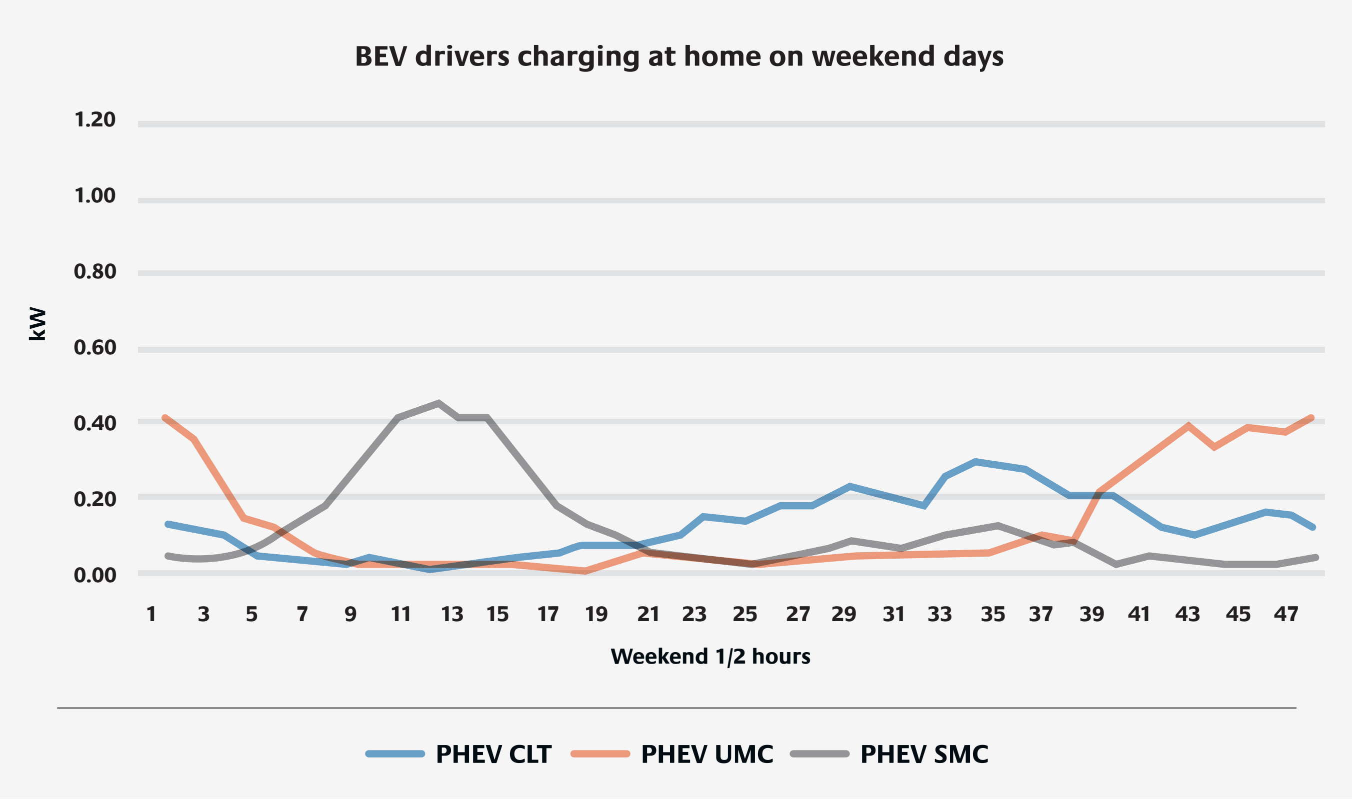
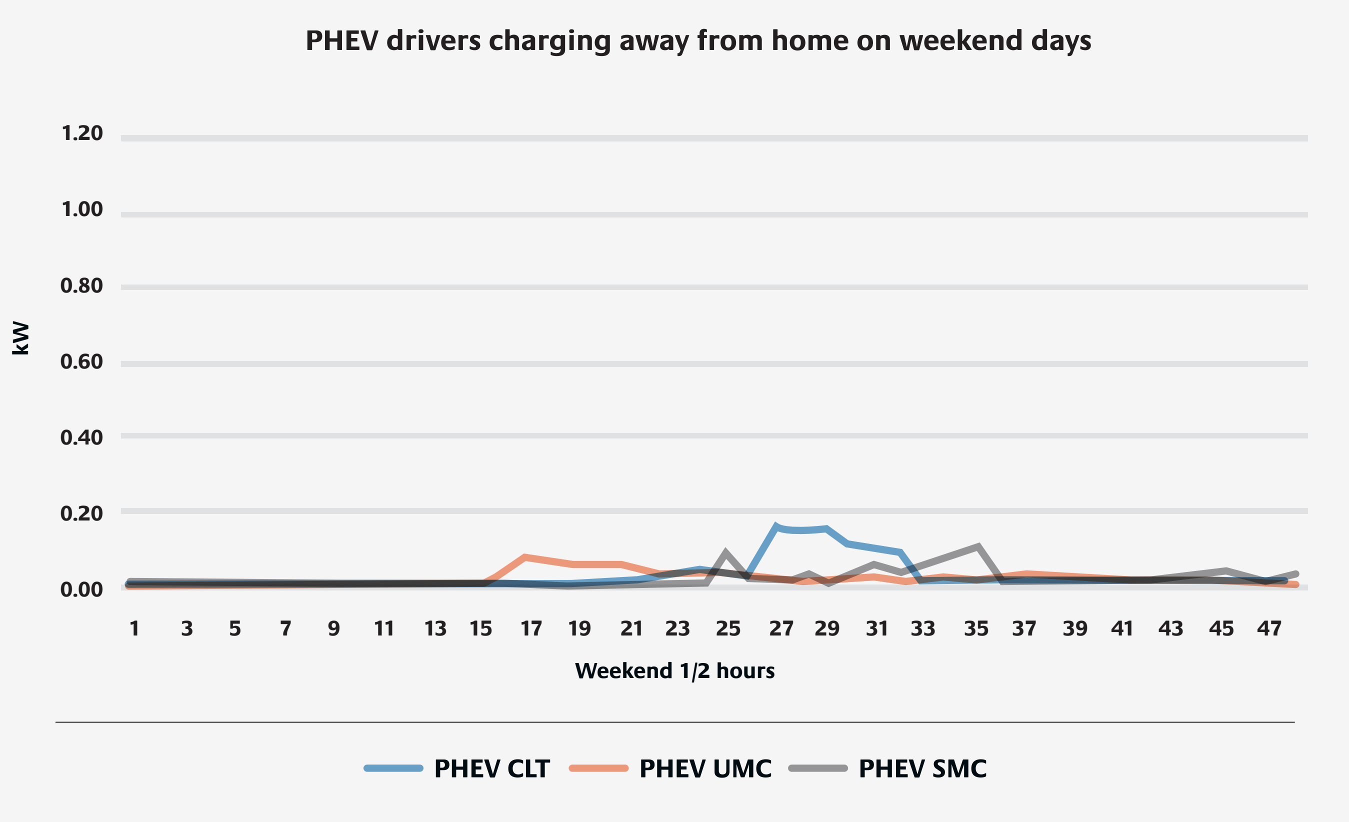


Figure 29
Average weekend half-hourly charging load away from home across PHEV sub-groups



The pattern of weekend charging for PHEV drivers is as might be expected, having seen the charts for BEV charging.

APPENDIX V - UNCERTAINTIES AND ASSUMPTIONS

Extensive consumer use of text messaging came as a surprise to many mobile telephone industry experts. There is no reason to believe that any of us are able to predict the evolution of consumer use of electric vehicles.

Electric vehicle deployment in the UK is still very much at the early adopter stage. Otherwise it is virgin territory, whose future shape is unknowable. Anyone with experience of consumer product and service development knows that suppliers and the market co-evolve over time to meet the expected and unexpected needs of consumers. Although we can map out the mountains, plains and rivers of this virgin territory, we cannot be certain how it will be occupied.

To follow through on the metaphor above, ETI believes in mapping out the territory, planting experimental fields of crops, surveying for minerals and so on. We can offer evidence and analysis that might shape strategies about future land use, however we are also very clear that the future is uncertain, especially where consumers are concerned. That is why we have invested significantly in mass-market consumer research (not just observations of early pioneers) and why our tools are designed to generate multiple plausible scenarios under uncertainty.

Within the field of vehicle electrification, there are a range of perspectives of which we identify the most significant as:

PHEV OR BEV (OR EVEN FCV)?

From one perspective, PHEVs are a distraction. They have limited electric range and combine the added costs and complexities of a mechanical internal combustion engine (ICE) with an electric BEV. Once batteries are small enough, cheap enough and sufficiently resistant to fast charging, then only a network of high-powered chargers is required for BEVs. The only issue is timing. Until battery development has advanced dramatically and the charging network has been built, then PHEVs have a role to play.

Our consumer research shows that PHEVs are attractive to some key high-mileage segments. The CVEI data analysis shows that a significant proportion of mileage of these high-mileage drivers is potentially accessible to electrification by PHEVs (but not BEVs). Until recently the range of available PHEV models was less well-developed than BEV models, but PHEV sales have overtaken BEV sales in the UK (and other countries also). The alternative purchase for most PHEV owners would be an ICE, not a BEV. A PHEV owner is likely to be much readier to buy a BEV at the point where its performance and economics match their needs than someone with experience only of ICE vehicles.

This is important because PHEV drivers will see recharging a majority of nights at home as critical. They may well be high-mileage and therefore high electric mileage drivers, using a lot of electricity. They will be price-sensitive, because they can usually use petrol when electricity is too expensive. They will be willing on occasions to pay up to 45p/kWh for electricity, although the cost and convenience of parking will probably be a material consideration. Recharging at home on an overnight electricity tariff with a high annual mileage will be the core of their cost/benefit analysis for vehicle ownership.

BEV drivers will typically have a much higher electric range than PHEV drivers in relation to their typically lower annual mileage. Since they have no alternative to electricity, they will pay within reason whatever cost is required to enable their journey patterns. It is very unclear what balance they will adopt between grazing and baseload charging. Grazing would involve keeping the battery topped up whenever the opportunity presents; baseload charging would involve adding a significant charge whenever and wherever it is cheap and convenient.

Typically, BEV owners will drive fewer miles per year than PHEV owners and their cost/benefit analysis depends on access to cheap electricity. Whereas a PHEV owner often cannot afford to use electric miles to find cheap electricity, this is more attractive to a BEV owner.

For the purpose of exploring the issues, we have assumed that, at least out to 2030, PHEVs will be a critical element of the path to UK transport decarbonisation. The timing of a switch to BEV market dominance after 2030 is very uncertain. Fortunately, PHEVs and BEVs are largely synergistic in the market, although PHEVs need further development before they can deliver their potential. Fleet managers are well placed to drive real-world performance of both, given the right incentives.

The CVEI project also examined pathways for Fuel Cell Vehicles (FCVs), operated on hydrogen. These are essentially electric vehicles, where the power is supplied from a fuel-cell, supplied from a hydrogen tank. Typically, these would also include regenerative braking and a battery to smooth the electricity supply. In some variants, the battery is larger, and can be recharged using a plug. This report does not discuss them, as it is focused on 2030. However, FCVs may be an important part of the longer-term transport mix; if the supply of cost-effective low-carbon hydrogen is scaled up to a level where millions of vehicles could be powered by fuel-cells, then there are important segments where FCVs might be the successful solution.

DESTINATION, EN-ROUTE OR AT-HOME CHARGING?

Consumer research finds that many prospective electric vehicle owners see being able to recharge at home as an advantage, compared to having to find a petrol station[51]. It also finds that the availability of public charging points adds to consumer confidence that they will be able to charge their vehicles and complete journeys. Analysis of travel patterns shows that over 10% of UK overall light vehicle fuel consumption is on or close to motorways. En-route rapid charging at sites similar to current motorway service stations is therefore very important. A higher than average proportion of miles on long-distance journeys may

[51] A review of consumer preferences of and interactions with electric vehicle charging infrastructure, Hardman et al, Transportation Research Part D, 62, 2018, pp508-523

be driven by those most likely to have an electric vehicle by 2030.

There are therefore different arguments for each location for vehicle charging. This report is based on a view that the arguments for at home and en-route charging are compelling and for destination charging are relatively strong, especially work-place charging. There is, however, the caveat that the use of destination charging by mass-market consumers is very unpredictable, once they have access to better electric vehicles than today, properly priced overnight managed charging, and a network of en-route fast chargers.

By destinations, we mean locations away from homes (and hotels), where vehicles are parked for significant periods of time during the trip patterns of normal daily life. Rapid recharging points on major routes during long journeys are a special case, described as en-route charging.

During the charging trial, the majority of charging events and electricity supply occurred at the home charging points. This was despite free access to the largest network of public charging points.

Nevertheless, the use of non-home charging points by BEV drivers was also significant. How different consumers respond to the location and costs of public charging points is likely to be complex.

On most nights of the year, the UK electricity system is significantly underused, both generation and networks[52]. Managing a large part of recharging overnight is therefore a very attractive first option, which would improve utilisation and effectively supply low carbon electricity at a low marginal cost to society. This requires people to recharge at or near home (and other places that they sleep). However, there needs to be some mechanism that enables people to wake up to a charge that more than meets their likely needs that day, while avoiding starting charging during the peak window, except for those who need a recharge to go out that evening.

This report makes the case that the cost, utilisation and business models of different charging points are important considerations and that the location of the bulk of cost-effective charging and of sufficient fast or rapid charging to enable in-day journeys are both critical.

RATIONING OR SERVICE?

One can see charging management as a way of protecting the electricity system from short-term and localised overload. Where a cluster of electric vehicles develops on a single domestic substation, some means is required to prevent the circuit fuse blowing and cutting off maybe up to 50 homes until a field engineer can replace the fuse. Technical solutions are being developed to enable charge points to be instructed to reduce and increase loads in response to signals from the substation[53]. Each connected vehicle gets a share of the capacity by being able to charge at full capacity for say 15 minutes, and then waiting until its turn comes again.

A different model involves domestic electricity suppliers paying more or less for access to peak network capacity and scheduling when vehicles charge to meet drivers' needs in the most cost-effective way, subject to a fall-back to a hard capacity limit.

Each of these has advantages and disadvantages. Rationing can be seen as fair and it avoids wealthier drivers being able to buy limited capacity away from poorer ones. It maximises the use of the network when it is loaded. It is simpler to explain and operate than service-based charging. Rationing cannot maximise the use of low-carbon electricity without significant risk of driver dissatisfaction.

Service-based charging applies the available capacity to meet the underlying needs of drivers. Someone who needs a charge to go out on a social occasion takes precedence over someone who won't need the car until the next morning. The costs that each pays (indirectly through their suppliers) reflect the value they place on this time slot and enables the DNO to make the case for greater investment, based on increased value (and revenue). Reading between the lines, the charging trial consumer research is persuasive that drivers have an underlying concern about getting home with limited remaining range and then being prevented from charging. The experience of forced rationing might reinforce this, creating a strong negative perception around PiVs that would then be hard to reduce.

This report considers both models, although the service-based model is likely to be a greater enabler of innovation and cost-effective investments in the longer term. Further experimentation with both models and mass market consumers is desirable, along with development of the market and technical architectures that each requires. There are potential complications with both rationing and charging management.

FAST CHARGING OR TRICKLE CHARGING?

Within our current electricity system there is plenty of capacity and time for the bulk of charging by 2030 to be at a slow rate, several hours for a full charge. Never quite fully discharging batteries and keeping charge rates low, especially when they are nearly empty or nearly full, maximises battery life. We can see however that it is both possible and often desirable to recharge batteries rapidly. The Renault Zoe for example has a fast charge mode when 80% charge is provided by a 43kW (50kW nominal) charger in 1 hour 40 minutes. That is an average charge rate of over 20kW. This fast charge can only be used again once the battery has cooled down.

The fastest charging stations coming into use are rated at 350kW. If we scale to the Zoe, that would imply an actual charge of 275kWh (or 800 miles) in 1 hour 40 minutes or perhaps 160 miles in 20 minutes. That is clearly a persuasive consumer proposition! However, this would imply a 330kWh battery, more than three times the size of the Tesla battery pack.

If the battery pack was more resistant to aggressive charging, then a Tesla-sized battery that could be mostly recharged in 20 minutes would be able to take advantage of 350kW charging.

This report assumes that battery technology and vehicle design for battery cooling will slowly develop, in response to drivers' needs, and critically to the availability of 350kW charging. However, such battery packs are currently larger, heavier and more expensive than typical EV batteries. We have therefore assumed that access to managed trickle charging is key to EV adoption at least out to 2025, probably to 2030, and quite possibly well beyond.

An alternative scenario would have competition between similar vehicles at similar costs, where vehicles using current automotive battery chemistries have significant ranges, but the battery life depends on limiting charge rates. Vehicles using alternative chemistries (that already exist) have only a fraction of the range but can be recharged aggressively without unacceptable loss of battery life, although considerable development will be required[54]. These vehicles would need external cooling to manage the heat from losses during recharging. Although many days could be managed with overnight charging, using the limited range, there would be a need for an extensive network of fast charging stations. Even with fast charging, drivers are unlikely to spend a large part of their lives waiting for a charge, so these would need to be mostly located where people park for other reasons, as well as on major long-distance routes. This report does not discuss the role of these low range but fast-charge vehicles. This is partly because they are not yet available in the market and partly because they would require a significantly more expensive infrastructure.

PIV UPTAKE OR ELECTRIC MILES?

PiV uptake is important to wealth creation and the sense of progress as a society with the electrification of transport. However, decarbonisation requires miles on fossil fuels to be converted to miles on electricity. PiV uptake by low-mileage drivers will deliver fewer electric miles than PiV uptake by high-mileage drivers. Both metrics are therefore important as indicators of the use of taxpayers' and electricity customers' money. However, PiV sales are very tangible whereas electric miles require more complex data collection and analysis. We assume that clear statistics will be collected on both, targets will be set for both and value for money for support costs will be judged against a balance of both. Therefore, the report considers the recharging needs of high mileage drivers, who will need to contribute most to decarbonisation out to 2030. Based on ETI system modelling, ETI recommends a target of at least 50bn electric miles per year by 2030, with less than 35bn electric miles being a strong signal of problems in delivering Carbon Budgets. Cars are currently driven about 250bn miles per year in total across the UK.

Current low-mileage drivers will also benefit from integrated transport systems that include flexible access to shared vehicles, both self-drive and with a driver.

ELECTRIFICATION OR DECARBONISATION?

In some countries, continued use of coal fired power stations to provide system services means that unmanaged electric vehicle charging risks many electric miles being driven on high-carbon electricity. Although this probably still amounts to a real overall carbon saving, even accounting for the higher embedded carbon in electric vehicles, it is an expensive way to decarbonise.

In the UK, we need to make better use of low carbon generation rather than installing additional fossil fuel capacity to meet peak recharging loads. By 2030, the amount of electricity used in vehicle charging will be significant and therefore the operation of the generating mix and especially signals for further investment in low carbon generation will depend to some extent on charging management. The large flexibility in when vehicles are charged is a low marginal cost and high marginal benefit contribution to the economics and carbon performance of the electricity system. Firing up additional gas-turbine capacity to meet additional recharging load is less attractive than using wind or nuclear electricity better. Summer days when the sun is shining present an opportunity to maximise electricity use during peak PV output.

We assume that the short-term imperative is electrification but that this will switch by 2030 to decarbonisation and the cost-effective delivery of Carbon Budgets.

This Appendix has set out the key assumptions as context for the rest of the report. These are only assumptions, based on a current best view of the evidence. As mass-market adoption takes off and new evidence becomes available, assumptions must be reconsidered. The Recommendations are for collecting additional evidence and extending system modelling tools to consider real-world driving, charging and mass-market consumer segmentation. Where strong evidence is available, it should be considered, where it is not, it needs to be gathered.

[52] Substations currently operating close to their thermal limits may still be unable to cope with the additional load, especially during the summer
[53] SBRI - Smart Meter load control device trial, BEIS, October 2018

[54] Enabling Fast Charging – A Battery Technology Gap Assessment, Ahmed et al, Idaho National Laboratory, June 2017

ABBREVIATIONS

AAHEDC – Assistance for areas with high electricity distribution costs

BEV – Battery Electric Vehicle

BSUoS – Balancing Services Use of System

CfD – Contract for Difference

CMSC – Capacity Market Supplier Charge

DfT – Department for Transport

DUoS – Distribution Use of System

ECO – Energy Company Obligation

ESCo – Energy Service Company

ESO – Electricity System Operator

FiT – Feed-in-Tariff

ICEV – Internal Combustion Engine Vehicle

ICE – Internal Combustion Engine

Li-ion – Lithium-ion

NCA – Nickel-Cobalt-Aluminium

NCM – Nickel-Cobalt-Manganese

NMC – Non Managed Charging (also referred to as unmanaged charging and experienced by the Control Group)

PHEV – Plug-in hybrid electric vehicle

PiV – Plug-in vehicle

RO – Renewables Obligation

SMC – Supplier Managed Charging

T&D – Transmission and Distribution

TNUoS – Transmission Network Use of System

UMC – User Managed Charging

V2G – Vehicle to Grid

ABOUT THE AUTHOR

Andrew Haslett
Chief Engineer

Andrew Haslett joined ETI as Strategy Director in April 2008 and was appointed Chief Engineer in January 2014 until 2018. He is a Fellow of the Royal Academy of Engineering, the Institution of Chemical Engineers and the Royal Society for the encouragement of Arts, Manufactures and Commerce.

Credits to:
Jonathan Wills, Liam Lidstone, Deborah Stubbs, Rebecca Sweeney-Haines.

Energy Technologies Institute
Charnwood Building
Holywell Way
Loughborough
LE11 3AQ

01509 202020
eti.co.uk
info@eti.co.uk
@the_ETI

energy technologies institute