UK Power Networks

Charger Use Study

Recharge the Future

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Utility Week Awards 2016 WINNER Utility of the Year

INVESTORS IN PEOPLE Gold

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Author

Tristan Dodson, Senior Consultant, Element Energy, tristan.dodson@element-energy.co.uk 01223 852 496

Senior Editor

For comments or queries please contact:

Jack Lewis Wilkinson, Smart Grid Development Engineer, UK Power Networks, jack.wilkinson@ukpowernetworks.co.uk

Reviewers

Ian Cameron, Head of Innovation, UK Power Networks
Adriana Laguna, Low Carbon Technologies & External Engagement Senior Manager, UK Power Networks
Giulia Privitera, Low Carbon Technologies Delivery Manager, UK Power Networks
Thazi Edwards, Low Carbon Technology & Electric Vehicle Projects, UK Power Networks
Celine Cluzel, Director, Element Energy
Mark Dale, Innovation and Low Carbon Networks Engineer, Western Power Distribution
Esther Dudek, Senior Consultant, EA Technology
Ben Lane, Director, Zap-Map

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Contents

Abbreviations and Definitions

Abbreviation	Meaning
AC	Alternating Current
BEV	Battery Electric Vehicle
CABLED	Coventry and Birmingham Low Emission Demonstrators
CCC	Committee on Climate Change
CCS	Combined Charging System
CLNR	Customer Led Network Revolution
DC	Direct Current
DNO	Distribution Network Operator
DUoS	Distribution Use of System
ED	Electricity Distribution
EHV	Extra High Voltage
EN	Electric Nation
EV	Electric Vehicle
HV	High Voltage
ICCT	The International Council on Clean Transportation
LCL	Low Carbon London
LSOA	Layer Super Output Area. Geographic Area (covering a population of ca. 1,500).
LV	Low Voltage
MEA	My Electric Avenue
NEDC	New European Driving Cycle
NIA	Network Innovation Allowance
OLEV	Office for Low Emission Vehicles
PHEV	Plug-in Electric Vehicle (in the wider sense, i.e. also included range-extended EVs)
PiP	Plugged-in Places
Plug-in time	Time an electric vehicle is plugged-in but not necessarily charging
Rapid public	Public charge points with a maximum charging rate ≥50kW (e.g. Level 3 charging)
Slow/fast public	Public charge points with a maximum charging rate of ≤22kW (e.g. Level 2 charging)
UKPN	UK Power Networks
V2G	Vehicle to Grid
ZM	Zap-Map

Executive Summary

UK Power Networks' EV Readiness Strategy & the importance of load forecasting

UK Power Networks has developed, and is implementing, a strategy to prepare for the electric vehicle revolution; which to an extent, is already taking place in parts of its networks. The strategy has clear objectives that are structured around the ability to facilitate growth in the EV market, whilst ensuring that customers' money is spent efficiently; i.e. the right amount is spent in the right place.

UK Power Networks' objectives	Appropriate investments, policies and standards	Deliver good customer experience	Network readiness
Activity Areas	1 Improve planning and analysis	3 Expand choice and convenience	5 Ensure investment is targeted in the right areas (not stranded)
	2 Develop policies and standards	4 Engage and educate/learn	6 Develop a cost-effective Smart solution toolbox for consumers

The strategy is being implemented using UK Power Networks' three EV Readiness Pillars:

I. **Forecasting** – Given the challenge of identifying where EVs could cluster on its network, and in the absence of smart meter data, UK Power Networks is collaborating with partner organisations and academic institutions to build a comprehensive EV dataset and advanced analytics to pinpoint the neighbourhoods where targeted intervention could be required.

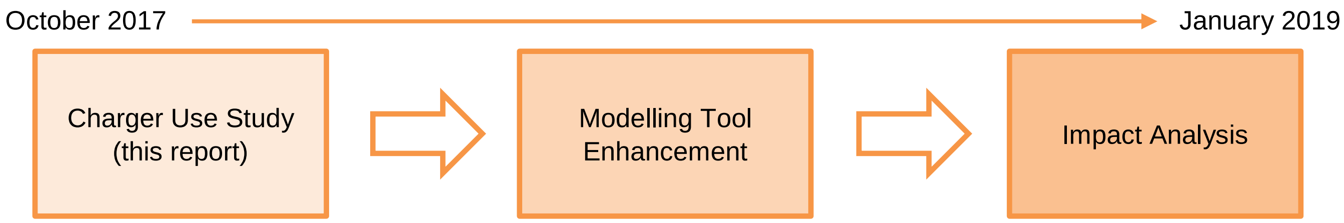
II. **Deploy monitoring and control** – UK Power Networks is investing heavily in developing state of the art active control and monitoring systems for its low voltage network. UK Power Networks' EV analytics steer it to where it needs to deploy network monitoring, and should UK Power Networks discover that the network requires intervention, it will be able to deploy controllable solutions in response.

III. **Deploy smart solutions** – UK Power Networks is investing in both commercial and technical innovations to enable its customers to connect faster and cheaper than ever before. For example, its work with UPS installing smart charging solutions coupled with energy storage has enabled a 270% increase in the number of electric freight vehicles that can operate out of one of UPS's biggest central London depots whilst avoiding the costs and time for traditional upgrades to the network.

At the heart of the first readiness pillar is UK Power Networks' ability to produce accurate and granular forecasts of EV load growth across its networks. UK Power Networks has three main use cases for load forecasts:

1. ***Regulatory Period Settlements*** – Long term load forecasts are used to estimate the level of reinforcement spend needed to accommodate growth over a regulatory period. It is vital that these spend forecasts are made as accurate as possible, to give the regulator, Ofgem, confidence in their projections; so that enough budget can be allocated to reinforcement and flexibility investments over the next regulatory period.
2. ***EHV Reinforcement Planning*** **–** Traditional EHV network reinforcements can take three to five years to complete. They must therefore begin before an asset's firm capacity is breached, to ensure security of supply and avoid network outages. Medium term load forecasts are used here to forecast these firm capacity shortfalls. Granular and accurate forecasts ensure that appropriate reinforcements are made, which facilitate EV load growth, whilst spending bill payer's money efficiently, i.e. the right amount in the right place.
3. ***LV & HV Visibility Deployment*** **–** LV & HV reinforcements take months to complete, so are done reactively. UK Power Networks is aware, however, that the EV revolution means that load may grow rapidly in some areas, as clusters of EVs begin to appear in particular neighbourhoods. The EV Readiness Strategy includes a £30 million project to deploy load monitoring devices in the substations which supply these neighbourhoods, notifying them of when reinforcement or demand side response is required. EV uptake and load forecasts are key here for efficient deployment of the monitoring systems.

The Recharge the Future project plays a key role in UK Power Networks' EV readiness strategy, providing the capabilities to forecast EV load growth on its networks with the high levels of granularity and accuracy needed.



- Investigate EV charging behaviour through literature review, expert consultation and additional data analysis.
- Consolidate findings and propose recommendations for modelling charging behaviour.

- Integrating findings from the Charger Use Study into the Recharge the Future EV Load Forecasting Module.
- Accurately reflect geospatial variations in charging behaviour.
- Develop scenarios to explore future market and policy environments for EVs.

- Use the Recharge the Future EV Load Forecasting Module, in conjunction with the Element Energy Load Growth Model to develop load growth scenarios and conduct impact analysis on the UK Power Networks' network (work carried out by UK Power Networks and Imperial College London).
- Make recommendations for managing charging load.

Figure 1: Diagram of the three work streams that constitute the Recharge the Future project.

In this project, particular focus has been placed in the relationship between location and charging behaviour, to accurately assess the impact of electric vehicles on the need to reinforce specific assets. The goal of this is to allow efficient planning of the network, and a state-of-the-art outlook on investment needs over the next regulatory period, RIIO-ED2 (2023-28), and beyond. To inform the load forecasting model, research has been conducted to quantify the factors that influence charging behaviour and their dependence on location, the findings of which have been made publicly available in this report. This report comprises the first of three project work streams, which are outlined in Figure 1.

Objectives and scope

The aim of the Charger Use Study is to bring together all available data on EV charging behaviour to understand how charging infrastructure will be used in future. Where possible, identified knowledge gaps have been filled through consultation with industry stakeholders and additional data analysis. This looks to identify and quantify the underlying factors that influence EV charging load profiles, such as day of the week, EV specifications, vehicle use cases and location.

This study covers the charging behaviour of battery electric and plug-in hybrid cars, stored overnight at/near user's home (i.e. excluding depot-based cars), across home, work and public charge points. Note that this excludes black cabs and private hire vehicles, which are considered under a separate UK Power Networks NIA project, titled Black Cab Green[1].

The findings from this study will be incorporated into the Element Energy Load Growth Model as the Recharge the Future EV Load Forecasting Module. This will forecast EV load profiles, accounting for geospatial variation in charging behaviour, at each asset across the UK Power Networks licence areas out to the 2030 horizon. The process through which these findings are integrated into the Recharge the Future EV Load Forecasting Module is documented in a separate report, along with the conclusions from the model outputs.

Approach

The Charger Use Study was guided by the following research questions:

- What is the daily charging profile for BEVs and PHEVs in residential, work and public locations?
- What share of a car's annual charging demand is met by different charging locations (i.e. home, work and public charging)? What influences this split?
- How are the above influenced by:
    - Charging location type and rate
    - BEVs compared with PHEVs
    - Battery capacity
    - Managed charging and Time-of-Use tariffs
    - Demographics of the EV owners and their transport needs
    - Transport infrastructure in place
    - Geographic parameters (e.g. road types, urbanity)
    - Time of the year and day of the week

[1] Project documents available from: http://www.smarternetworks.org/project/nia_ukpn_0026

The approach taken to answer these research questions is presented in Figure 2:

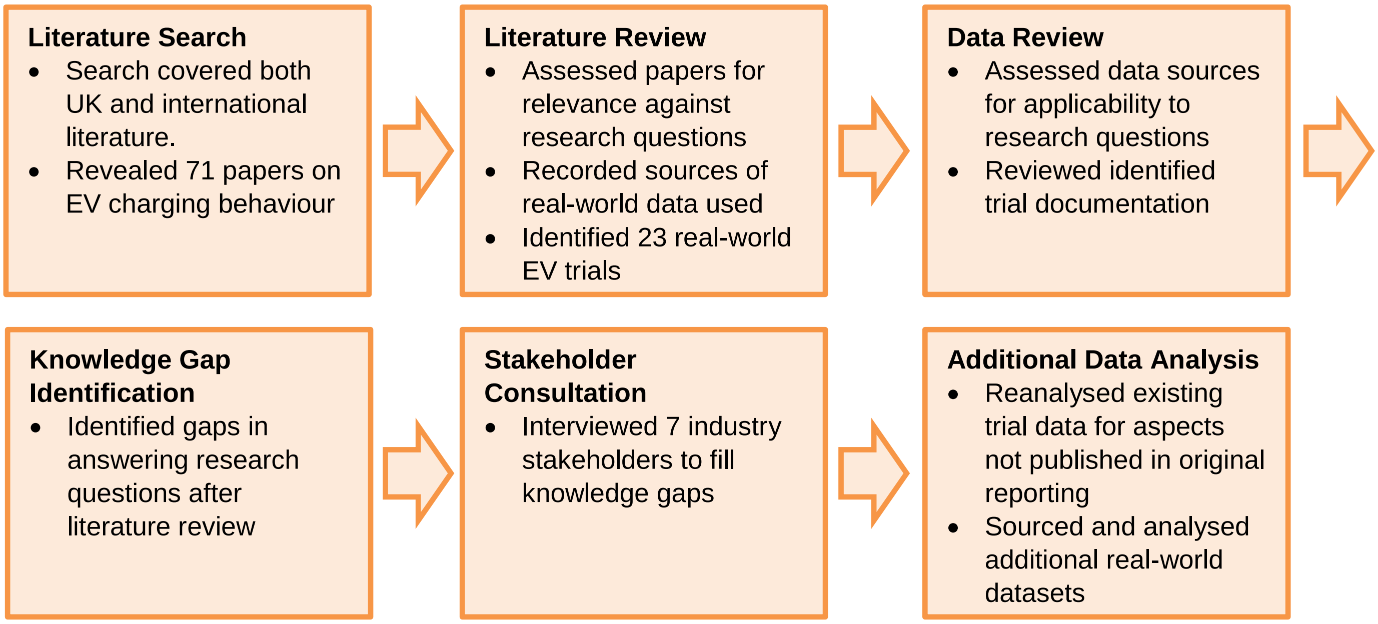


Figure 2: Process followed for the Charger Use Study literature and data review.

During the literature review it was found that the pace of development in the EV sector has meant that many earlier findings regarding charging behaviour have become outdated. For example, older studies involved EVs with low ranges, more limited use cases, and operating in environments with lower availability of public charging infrastructure. Therefore, findings from older studies are not necessarily applicable to current and future charging behaviour, or do not go into the level of detail required to investigate the level of variety that now exists in EVs and their users. Consequently, additional data was sourced and analysed to provide an as up to date view of charging behaviour as possible:

- Western Power Distribution and EA Technology have shared an interim dataset from the ongoing Electric Nation project showing >30,000 home charge events from a wide range of different EVs. In return, UK Power Networks and Element Energy shared the findings from their own data analysis with the Electric Nation team. This pro-active sharing of data between two on-going Network Innovation Allowance projects is a positive example of a way to maximise the value of NIA projects and accelerate their impact;
- Detailed data on usage of the UK's public charging infrastructure was purchased from Zap-Map, who provided a bespoke analysis of 12 months of real time monitoring data from over 3,200 public charge points across the UK. This forms the best available dataset on public charging infrastructure usage in the UK, and this study represents the first time this data has been used to investigate the impact of public charging on the distribution network.

Key findings and recommendations for modelling

The Charger Use Study's findings are grouped by different charging location types. These are classified as home, on-street residential, work, slow/fast public and rapid public charge points. For each one, charging behaviour has been defined by four characteristics: time of charging, frequency of charging, duration & energy delivered, and share of overall charge demand met by that charging location type. For each characteristic, the study has investigated the underlying factors which have the strongest influence, and that should therefore be captured in the modelling of EV charging. Note that the data behind each figure featured in this report are contained within a supplementary appendix, available upon request as per UK Power Networks' Innovation Data Sharing Policy[2].

Home charging is the primary mode of charging for the vast majority of EVs. It is estimated that at present 93% of EVs in the UK have access to charging at home (Systra for the CCC, 2018), which requires off-street parking. This is preferably carried out with a dedicated home charge point, although home charging can be carried out using a domestic 3-pin socket. Data on the take-up of the Homecharge grant provided by the Office for Low Emission Vehicles suggests that only 40% of EVs in the UK Power Networks licence areas have installed a home charge point. Whilst some EV owners may have installed a home charge point without the Homecharge grant, it appears that a large share of EV owners charge from a domestic 3-pin socket, despite EV manufacturers advising against this due to safety risks. It has been found that for EVs with access to charging at home, this accounts for 70-80% of their EV's overall charging demand, however, this figure is highly uncertain as it depends on the type of EV, its usage patterns and availability of other charging infrastructure.

Key Finding: Commuters have a high propensity to plug in their EVs on weekdays between 5pm and 9pm when they arrive home from work, whereas non-commuters spread their charging more evenly throughout the afternoon. Half of commuter charge events begin between 5pm and 9pm compared with only a third for non-commuters.

Time of charging at home has been found to be strongly dependent on when people arrive at home, with little difference observed across BEVs and PHEVs of various battery sizes. Consequently, a noticeable difference is observed for EVs used for commuting compared with non-commuters. Commuters have a high propensity to plug in their EVs on weekdays between 5pm and 9pm when they arrive home from work, whereas non-commuters spread their charging more evenly throughout the afternoon (see Figure 3). At weekends, this evening peak in commuter charging is not observed, and commuters and non-commuters spread their plug-in times similarly throughout the day.

[2] http://innovation.ukpowernetworks.co.uk/innovation/en/contact-us/InnovationDataSharingPolicy.pdf

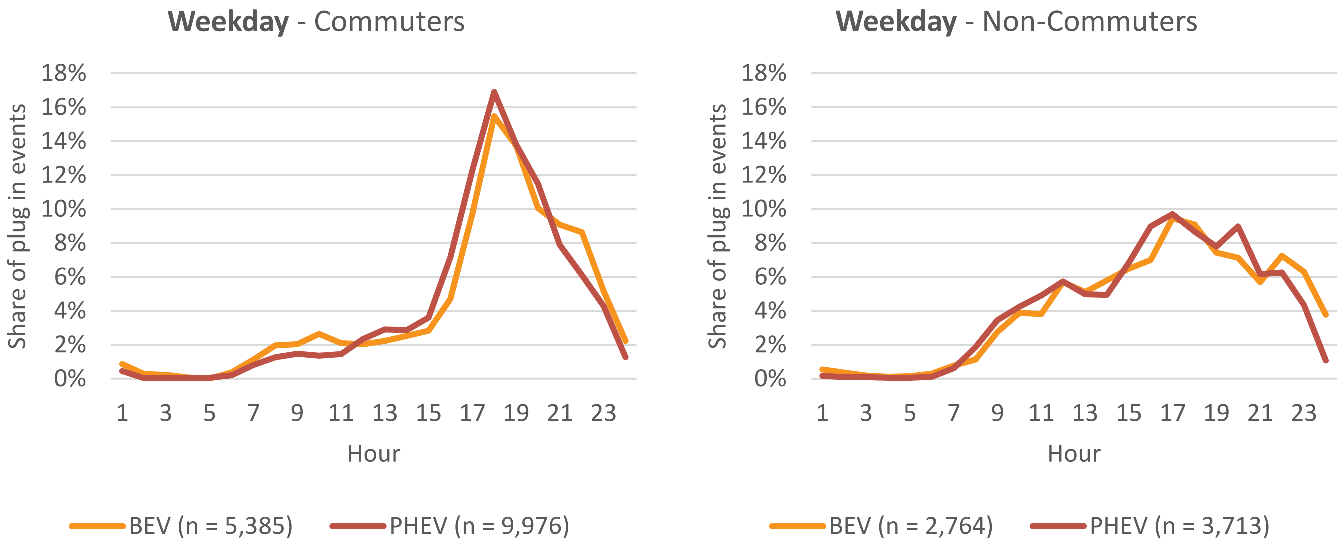


*Figure 3: Average plug-in start time profiles at home for **weekday** charge events for commuters and non-commuters, from the interim Electric Nation dataset. 'n' is the number of charge events in the sample.*

Key Finding: PHEVs plug in at home more often than BEVs.

Interestingly, PHEVs are found to plug in at home more often than BEVs, despite not needing to be charged up to operate (see Figure 4). This suggests that PHEV drivers understand the economic benefit of doing a higher share of driving under electric power but must charge more often than BEVs as their batteries are smaller. However, this finding is based on trial data with early adopter participants who all had access to a dedicated home charge point. Anecdotal evidence suggests that in the UK some PHEV drivers rarely charge and instead complete most of their mileage under fuel power. The reason for this may be that they do not have access to charging at home, or they are company car drivers who are reimbursed for fuel and/or purchased a PHEV to take advantage of favourable company car tax rates.

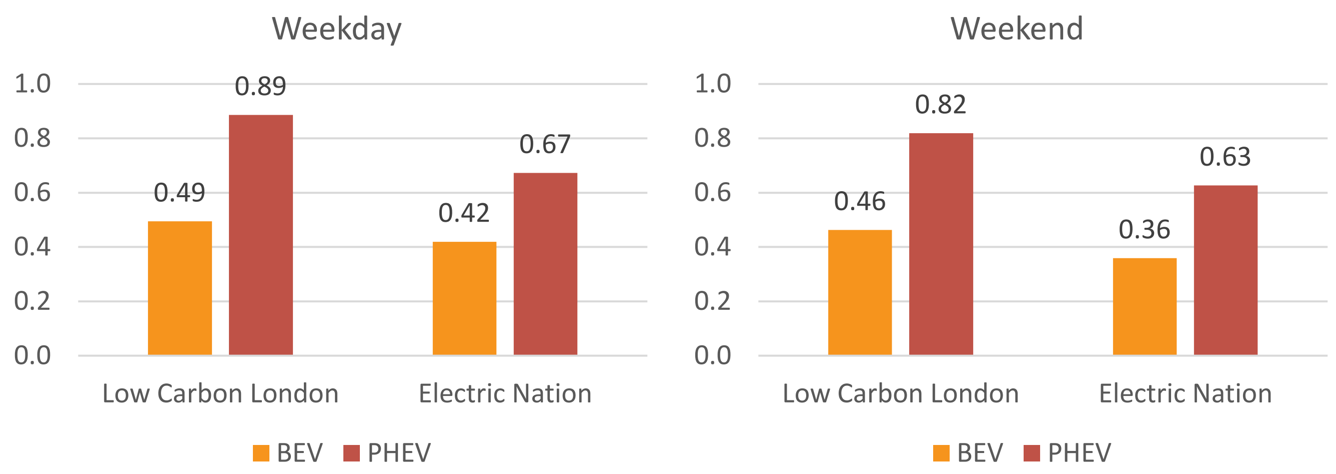


Figure 4: Charge events per day at home charge points, for PHEVs and BEVs, from available literature sources. Note Electric Nation values are from an interim dataset.

Key Finding: EVs with larger batteries are charged less often and with greater kWh per charge.

Battery capacity is also found to have a strong influence on charging frequency. EVs with larger batteries were found to be charged less often for both BEVs and PHEVs, despite all EVs under consideration here having the ability to charge whenever they are at home. The implication of this is that the decision of whether to charge or not is triggered by the EV driver depleting the battery to a particular state of charge, rather than habitually charging under a set routine (e.g. every night). This is supported by the finding that commuters, who generally have higher mileage and so deplete their batteries faster, charge more regularly than non-commuters. However, if these commuters are able to charge at work then their frequency of charging at home is reduced as their state of charge remains higher.

This is further supported by the finding that the average kWh per charge at home is strongly related to the EV's battery capacity (see Figure 5).

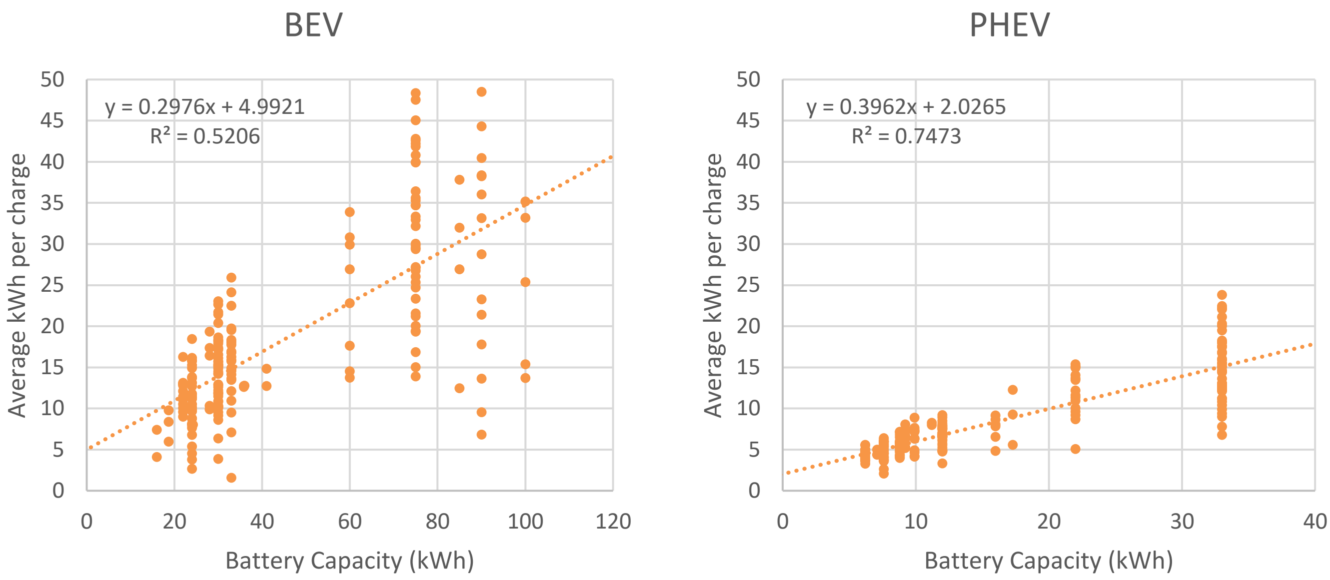


Figure 5: Average kWh per charge for each BEV and PHEV participant in the interim Electric Nation dataset.

It appears therefore that EV drivers currently charge their vehicles with the same mindset as refuelling a conventional car, only when the fuel gauge reads a certain level to minimize the number of trips to the petrol station. A similar finding was made in the My Electric Avenue trial, which reported that most EV users charged their vehicles when the State of Charge was between 25% and 66% (Quiros-Tortos & Ochoa, 2015). This is despite the inconvenience of plugging in being significantly less than visiting a petrol station, and more regular charging reduces the chance of range anxiety. This has implications for the effectiveness of smart charging and vehicle-to-grid which are most effective when EV users plug in as regularly as possible. To maximise the value of these services, EV users may need to be incentivised to change their charging habits, for example, by providing access to lower cost electricity.

Key Finding: Plug-in durations at home tend to be significantly longer than time spent actually charging (e.g. 10 hours plugged in vs 2-3 hours charging), particularly for overnight charging, suggesting a high degree of flexibility exists to shift time of charging.

The average time spent plugged in at home has been found to be approximately 10 hours per charge event. This is significantly longer than the average time spent actually charging which is 2-3 hours depending on charging rate and energy need. The plug-in duration remains similar for both BEVs and PHEVs of various battery sizes. Since a large share of plug-in events occur in the evening, this implies that EVs are generally left to charge overnight but will only draw power for the first few hours. There is therefore significant flexibility to shift this charging load into the overnight off-peak hours. A number of systems for this purpose have been developed, such as simple time-of-use pricing tariffs or more advanced charging management and have been shown to be highly effective at reducing peak charging demand. The My Electric

Avenue trial, for example, deployed a system that dynamically switched off and on residential charge points if a load threshold at the serving substation was reached. This had no noticeable impact on participants' experience of owning an EV, and it was estimated that such a system could save Great Britain's DNOs £2.2bn up to 2050 in network upgrade costs due to EV charging (EA Technology, 2016).

Key Finding: Fully diversified peak charging load at home has been found to be approximately 1kW per EV, however, when small numbers of EVs are considered the highest observed peak is significantly more than 1 kW per EV.

Whilst average peak charging demand was found to be of the order of 1kW per EV (Quiros-Tortos & Ochoa, 2015), the undiversified peak load for a single EV at home could be as high as the charger capacity e.g. 7 kW. Analysis of home charging data from Electric Nation revealed that as the number of EVs charging through a network asset increases, the diversity factor tends towards ~30% for 3 kW charging and ~20% for 7 kW. Consequently, the difference between highest observed peak and average peak has been found to decrease as the number of EVs considered increases. Figure 6 shows the ratio of highest observed peak to the winter average peak, derived from the Electric Nation charging data, which illustrates how this ratio tends to 1 at very high numbers of EVs (e.g. >1000). At 100 EVs, the highest observed peak was twice as high as that suggested by the average winter charging behaviour. A similar reduction in diversity with increasing numbers of EVs was observed in analysis of Low Carbon London data (Aunedi, Woolf, Bilton, & Strbac, 2014).

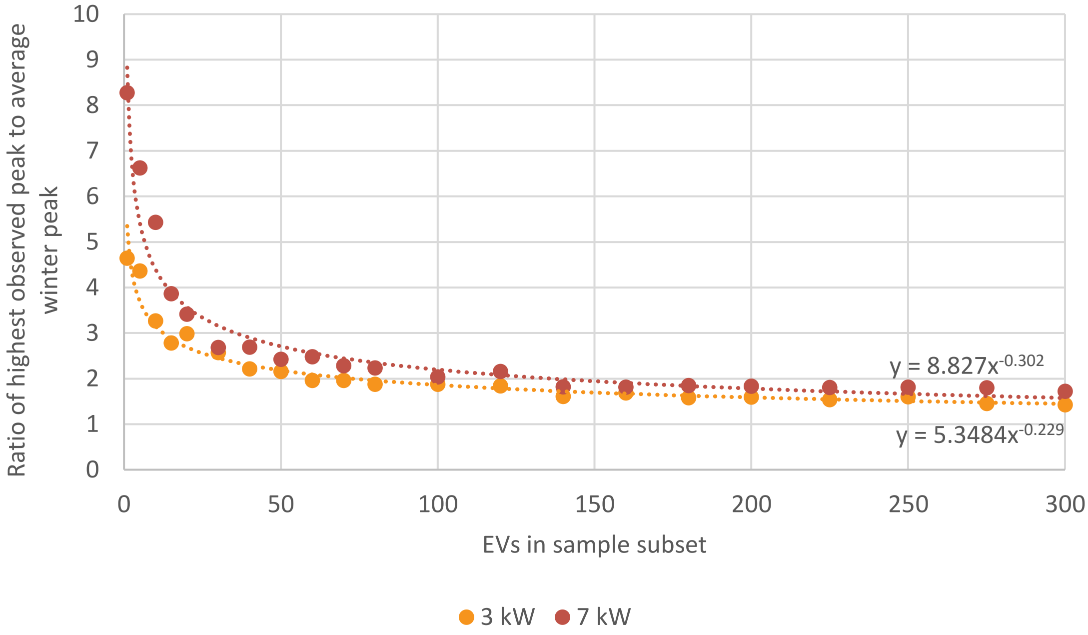


Figure 6: Ratio of highest observed peak to average winter peak for 3kW and 7 kW charging. Element Energy simulation from the interim Electric Nation sample.

Key Finding: Residential on-street charge points are used in a similar fashion to home charge points, with some additional usage in the morning in areas with a high concentration of work places.

Residential on-street charging provides a solution for EV drivers who do not have access to a home charge point. These charge points are publicly accessible but installed specifically in residential areas to act as the primary source of charging for EVs normally parked on-street. To date, their deployment in the UK has been rare, although demand is relatively low as a large majority of EV early adopters have access to some form of home charging. However, in future these charge points are expected to become more common, as EVs will be increasingly purchased by the 27% of car owners who do not have access to off-street parking[3]. This is particularly true of cities, where EVs are needed to support local air quality objectives and off-street parking is even less common. In London, for example, the share of drivers without off-street parking is as low as 6% in some areas, such as Westminster, Tower Hamlets, and Islington (Element Energy; WSP Parsons Brinckerhoff, 2016). In the Netherlands, EV drivers without off-street parking are more common and these drivers have been able to request a charge point is installed at a parking space near their house. These so-called 'demand-driven' charge points show very similar usage patterns to home charge points, with a peak in EV's plugging in seen in the evening (see Figure 7). Plug-in durations are also found to be of the order of 10 hours, of which only 2 hours is needed for charging, as observed for home charging. The peak in EVs plugging in in the morning is attributed to the demand-driven charge points installed in areas with nearby commercial premises which are therefore used during the day by commuters.

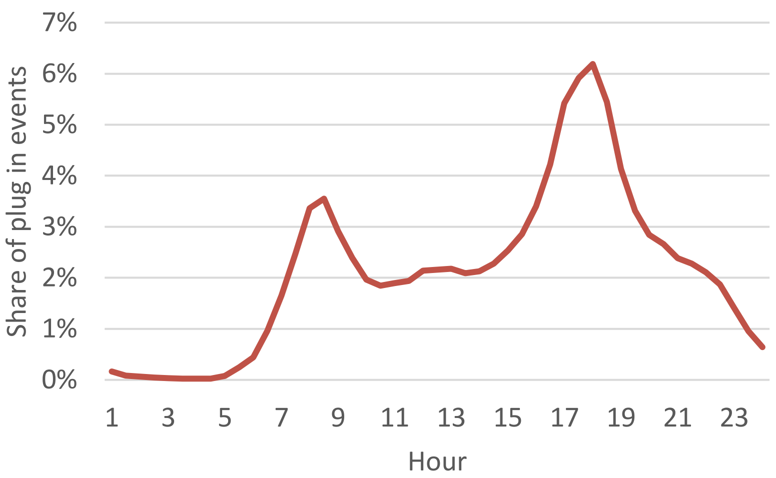


Figure 7: Average weekday plug-in start time profiles for Demand-driven charge points measured by ELaadNL 2012-Feb 2015 (Spoelstra & Helmus, 2015). Sample size = 452,000 charge events (est.).

Uncertainty remains over whether on-street residential charge points will be used in the same way in the UK. To date, all EV trials in the UK have focused on EV drivers with access to off-street parking, but a number of trials of on-street

[3] National Travel Survey, 2009: Table NTS0908 Where vehicle parking overnight by area type, GB, 2009.

residential charging solutions are now ongoing. Several London Boroughs have installed charge points installed in lamp posts, and the city of Oxford is currently trialling different charging technologies for EVs which do not have off-street parking availability. Uncertainty also exists over how behaviour might change as the EV market evolves. Reports from the Netherlands suggest that EVs that rely on on-street residential charge points charge at them more frequently than EVs with home charge points charge at home because it offers a way of securing a convenient parking space. However, the dynamics may change when EVs become more common and multiple vehicles must rely on a single on-street charge point.

Work charging can provide a favourable charging option for EV-driving commuters, particularly if it's provided to employees free of charge. Charging takes place for several hours during the working day and so a charge rate of 3-7 kW is preferred. In general, work place charging has received less attention in the literature compared with home charging, because it is available to fewer EVs, and so data availability is limited.

Key Finding: Most work place charging events begin in the mid-morning around 9am, coinciding with when commuters arrive for work.

Plug-in times at work are concentrated in the mid-morning which coincides with when commuters arrive for work (see Figure 8). A tail of plug-in events is then observed throughout the remainder of the day which could be due to commuters arriving later than usual, charge point use by visitors, or a share of drivers unplugging their EVs to enable their colleagues to charge as well. Charge durations are of the order of 3-4 hours, but findings from the Electric Nation survey suggest that plug-in times are about 6 hours. This is shorter than a full working day and so it appears that at least some EV drivers do unplug well before they leave to go home.

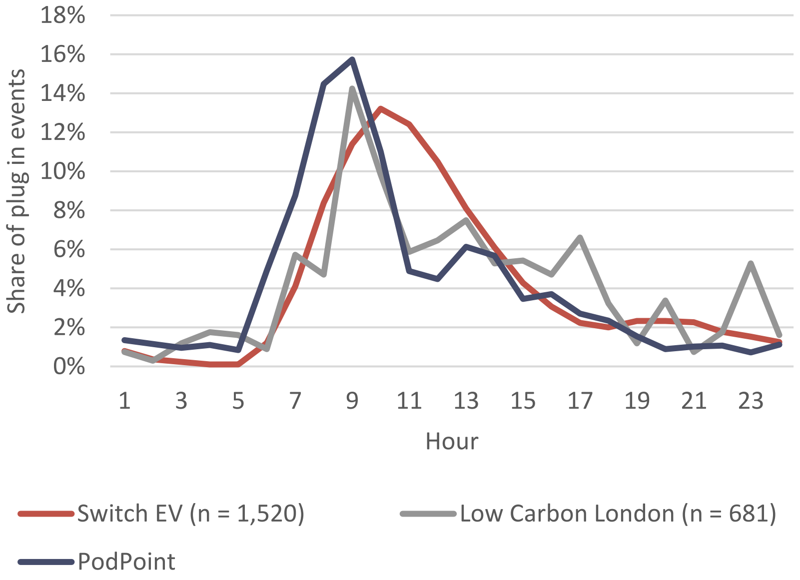


Figure 8: Average plug-in start time profiles at work place charge points, from various data sources. 'n' shows the number of charge events in the sample.

Unsurprisingly very little work place charging occurs over the weekend. Findings from a survey of the Electric Nation participants suggest that PHEVs plug in at work more often than BEVs. This is presumably because for PHEV commuters there is an incentive to also drive their return leg of their commute under electric power to reduce running costs, whereas for BEVs charging at work is not necessary if their range can manage a full roundtrip. Anecdotal evidence suggests that many PHEV owners, particularly company car drivers, purchased a PHEV to take advantage of the favourable tax incentives, such as low Benefit-in-Kind tax, and rarely charge their vehicles. This finding from the Electric Nation study suggests that this is not the case, however, the sample is not necessarily representative of all PHEV drivers, particularly as all participants have access to home charging.

Key Finding: Slow/fast public charge points (≤22 kW) are mostly used during the day, with weekdays showing clear usage peaks around 9-10am, 1-2pm and 6-7pm.

Slow/fast public charging, defined as public charging at a rate of up to 22kW, is found to be used primarily during the day. For weekdays, a large share of plug-in events occur in the early morning around 9am, with secondary peaks occurring in the early afternoon and evening (see Figure 9). The evening peak coincides with a general downward trend in plug-in events and is thus lower than the morning and midday peaks.

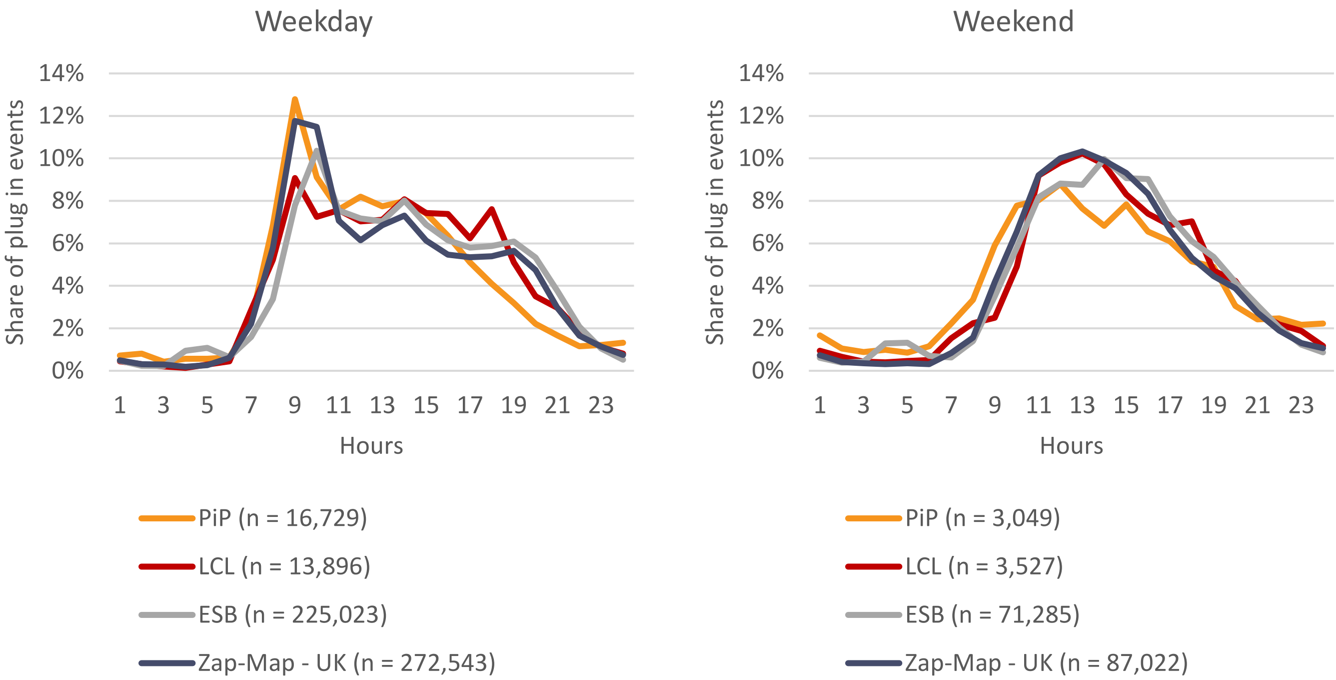


Figure 9: Average weekend and weekday plug-in start time profiles for slow/fast public charging. 'n' denotes number of charge events in sample.

The morning and evening peaks are found to coincide with very long plug-in events, whereas shorter charge events tend to take place during the day (see Figure 10). The implication is that usage of slow/fast public charge points displays strong bi-modal behaviour. Note that on weekends, the morning peak in plug-in events is not observed which suggests that it is the result of commuters who park and charge on-street while at work. The evening peak is most likely due to EV drivers who charge on-street overnight. These events with long plug-in durations are therefore better described by on-street residential charging behaviour, with slow/fast public charging in this study referring to the shorter duration charging that takes place during the day.

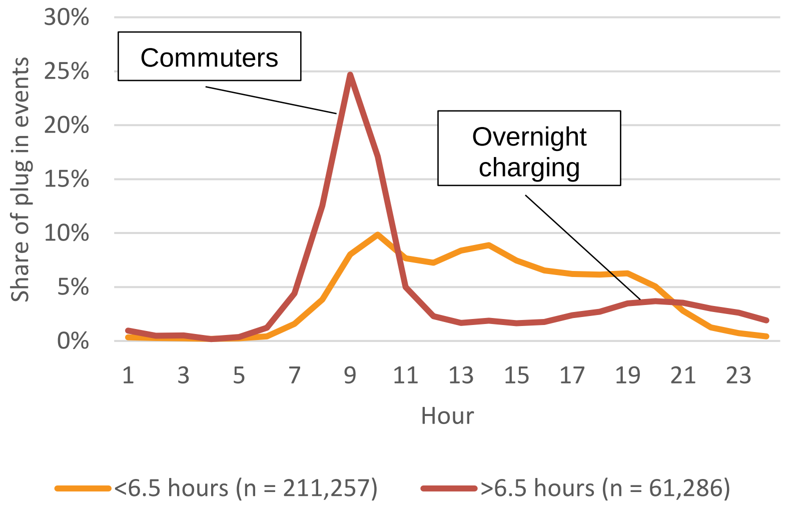


Figure 10: Average weekday plug-in start time profile for slow/fast public charge events <6.5 hrs and >6.5 hrs. Element Energy analysis of Zap-Map dataset.

Key Finding: Plug-in and charge durations for slow/fast public charge points (≤22 kW) are similar at around 2-4 hours**,** suggesting the charge duration and kWh delivered are dependent on dwell time.

The plug-in durations of these shorter day time charge events are found to be of the order of 2-4 hours. This is comparable to the average time spent charging of 3.1 hours recorded during the Switch EV trial (Robinson, Blythe, Bell, Hübner, & Hill, 2013). The suggestion is that dwell time, rather than battery capacity, is the limiting factor to charging duration and kWh delivered. This supports the proposition that slow/fast public charging is mainly used opportunistically to top up batteries, and EV owners will stop charging once they have completed their trip purpose, rather than wait for their EVs to fully charge. Plug-in durations for slow/fast public charging events are therefore primarily dependent on journey patterns, rather than EV specifications, such as powertrain (i.e. BEV or PHEV) and battery size.

Key Finding: Utilisation of slow/fast public charge points (≤22 kW) is very low, with charge points averaging less than one charge event per day.

Given that their usage profile suggests few EVs depend on them, utilisation of slow/fast public charge points is unsurprisingly low. Data from Zap-Map shows that currently on average slow/fast public charge points in the UK are used approximately once every two days, with marginally higher utilisation on weekdays compared to weekends. Although this rate of utilisation would be expected to increase as the number of EVs increases, interim survey data from Electric Nation suggests that individual EV drivers only use slow/fast public charge points about once every four weeks. Frequency is found to decrease with larger batteries, for example, BEVs with a capacity >60kWh average one charge every 7.5 weeks. Therefore, although greater numbers of EVs could increase utilisation rates of slow/fast public charge points, this could be offset by a shift to higher range EVs. However, it is worth noting that all participants in the Electric Nation project had access to a home charge point. Future EV owners who do not have access to a home charge point may choose to better utilise the slow/fast public charging infrastructure, particularly if they do not have ready access to an on-street residential charge point.

Rapid public charge points, defined in this work as public charge points capable of offering a charging rate of at least 50kW, provide a viable method of extending a BEV's usable range, with in-journey charging that minimises additional journey time. They are therefore primarily located near motorways and major A-roads, although increasingly are being installed in cities to provide mid-duty cycle charging for taxis, as well as potentially being used by private BEV owners without easy access to overnight charging. Note that only one PHEV, the Mitsubishi Outlander, is currently compatible with rapid public charge points, although its small battery means that the actual rate it charges at is considerably lower than 50kW. Since PHEVs are not dependent on battery power to drive long distances, it is unlikely that any further PHEV models will be released with rapid charge point compatibility.

Key Finding: Rapid public charge points (≥50 kW) are typically used during the day, and on weekdays show distinct peaks in the morning (9-10am), early afternoon (1-2pm) and evening (6-8pm)

Plug-in times show a similar pattern to slow/fast public charging, with the majority occurring during the middle of the day (see Figure 11). On weekdays, three distinct peaks are observed in the morning, early afternoon and evening, whereas on weekends, only a broad peak centred around the early afternoon is visible.

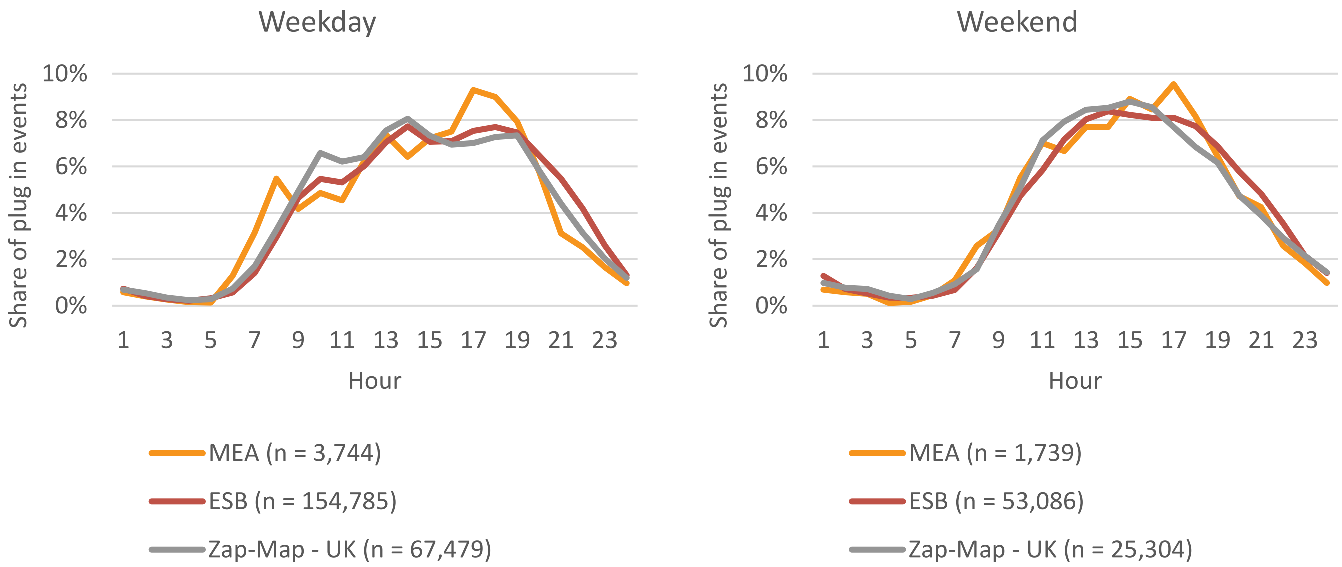


Figure 11: Average weekday and weekend plug-in start time profiles for rapid public charging. 'n' denotes number of charge events in sample.

For weekdays, the morning and evening peaks are attributed to rapid charge events occurring before and after the first and last trips of the day. The midday peak is likely the result of high mileage drivers charging during a lunch break in order to complete their remaining mileage for the rest of the day. This same pattern is found for rapid public charge points regardless of whether they are located near motorways/A-roads or not.

Key Finding: On average, BEVs use rapid public charge points (≥50 kW) once every three weeks, and frequency of charging increases with battery capacity.

Analysis of the interim Electric Nation survey data reveals that BEV drivers use rapid charge points approximately once every 3 weeks, which is a similar frequency to slow/fast public charging. However, unlike slow/fast charging, charging frequency is found to increase with battery capacity. It is proposed that this is because the BEVs with large batteries, such as the Tesla Model S, are more suitable for long distance motorway driving, whereas small BEVs are used more as low mileage city cars and are less likely to be rapid charging enabled.

Plug-in durations at 50 kW rapid public charge points are found to be on average 35-40 minutes. This is comparable to the 30 minutes that Ecotricity recommends it takes to charge a Nissan Leaf from 0-80%, and so suggests that BEV drivers will not leave their vehicles plugged in longer than necessary. This supports the idea that rapid charging is done as quickly as possible to avoid unnecessary delays to journeys. BEVs with smaller batteries actually charge at rates lower than 50kW and so as battery sizes get bigger it is unlikely that rapid charging durations will increase. Larger batteries up to a point enable more energy, and therefore range, to be added in a shorter amount of time. Conversely to slow/public charging, a shift to higher range BEVs may initially increase the utilisation of rapid public charge points, as more BEVs are purchased with long range driving in mind and batteries are large enough to take advantage of the charging rates available. However, higher ranges will also reduce the share of trips which require a mid-journey charge.

Future data

A persistent issue with real world data collected to date is that it considers charging behaviour from early adopters driving first generation EVs, with scarce public charging infrastructure. The findings from existing literature will not necessarily apply to mass market EVs/drivers in future. The study has identified several developments which are likely to have the strongest influence on future charging behaviour and charging load from the perspective of the distribution network:

- Take-up of EVs by mass market consumers and second-hand car buyers
- Shift away from conventional 'refuelling' behaviour (i.e. only charging once a low state of charge is met)
- Multiple EVs per household
- Larger batteries
- Improved public charging infrastructure
- Delayed and managed charging
- Vehicle-to-Grid
- Co-location of battery storage
- Wireless charging
- Mobility-as-a-service

Some of these knowledge gaps will be partly lifted in the coming months or year through dedicated projects, the main ones of which are listed in the table below, along with the topics they are covering.

Table 1: Ongoing and upcoming EV trials which will address some of the knowledge gaps identified during this study.

<table>
<tr><th>Project</th><th>Description</th><th>Knowledge Gap Addressed</th></tr>
<tr><td>Oxford Go Ultra Low Trial (2017-18)</td><td>Trial of charging technologies for EV owners that do not have access to off-street parking (e.g. lamp posts, cable gullies, charging bollards)</td><td>Usage patterns for public on-street CPs aimed at overnight residential charging</td></tr>
<tr><td>ETI CVEI (2015-19)</td><td>Randomised Control Trial measuring how mass-market consumers use/charge BEVs & PHEVs, and how they engage with different managed charging schemes (e.g. user and supplier managed)</td><td>Findings will apply to mass market rather than early adopter EV drivers
Will segment participants by demographics, and quantify behaviour under managed charging and its uptake</td></tr>
<tr><td>Electric Nation (2016-19)</td><td>Evaluating consumer acceptance of smart charging and its impact on charging behaviour, amongst different EV drivers</td><td>Large sample (~600) will allow influence of powertrain, battery size and demographic factors to be reliably explored</td></tr>
<tr><td>Network Impact of Grid-Integrated Vehicles (2017-20)</td><td>Northern Powergrid will monitor the installation and usage of 1,100 V2G CPs to understand their impact on the low voltage network</td><td rowspan="2">Will provide data on:
• Usage patterns of EV owners with a commercially available V2G product
• Effectiveness in handling constraint periods</td></tr>
<tr><td>Innovate UK V2G Demos (2018-21)</td><td>Large Innovate UK funded V2G demonstration project(s)</td></tr>
</table>

The UK Government's Automated and Electric Vehicle's Act, passed in July 2018, gives the Government the power to require charge point operators to share data on usage of public charge points, such as energy consumption, which could also be used to explore charging behaviour with slow/fast and rapid public charge points.

Next Steps

The Charger Use Study is the first work package of the Recharge the Future project and brings together all available data relevant to charging behaviour of EVs in Great Britain. Its findings will be integrated into the Recharge the Future EV Load Forecasting Module to better predict EV charging's contribution to load growth at each primary and secondary substation across the UK Power Networks licence areas. This will provide UK Power Networks with the necessary tools to effectively prepare for mass EV adoption during the next regulatory period, RIIO-ED2 (2023-28), and beyond.

Results from the Recharge the Future EV Load Forecasting Module will feed an impact analysis on the UK Power Networks' network. This will provide estimates of UK Power Networks' required re-enforcement costs resulting from EV charging load. From this, a range of recommendations will be devised for DNOs and policy makers regarding the management of future EV charging load. These results, along with an explanation of the Recharge the Future EV Load Forecasting Module, will be documented in a final project report due to be published in January 2019.

Figures

Tables

1 Introduction

1.1 UK Power Networks' EV Readiness Strategy & the importance of load forecasting

UK Power Networks has developed, and is implementing, a strategy to prepare for the electric vehicle revolution; which to an extent, is already taking place in parts of its networks. The strategy has clear objectives that are structured around the ability to facilitate growth in the EV market, whilst ensuring that customers' money is spent efficiently; i.e. the right amount is spent in the right place.

UK Power Networks' objectives	Appropriate investments, policies and standards	Deliver good customer experience	Network readiness
Activity Areas	1 Improve planning and analysis	3 Expand choice and convenience	5 Ensure investment is targeted in the right areas (not stranded)
	2 Develop policies and standards	4 Engage and educate/learn	6 Develop a cost-effective Smart solution toolbox for consumers

The strategy is being implemented using UK Power Networks' three EV Readiness Pillars:

IV. **Forecasting** – Given the challenge of identifying where EVs could cluster on its network, and in the absence of smart meter data, UK Power Networks is collaborating with partner organisations and academic institutions to build a comprehensive EV dataset and advanced analytics to pinpoint the neighbourhoods where targeted intervention could be required.

V. **Deploy monitoring and control** – UK Power Networks is investing heavily in developing state of the art active control and monitoring systems for its low voltage network. UK Power Networks' EV analytics steer it to where it needs to deploy network monitoring, and should UK Power Networks discover that the network requires intervention, it will be able to deploy controllable solutions in response.

VI. **Deploy smart solutions** – UK Power Networks is investing in both commercial and technical innovations to enable its customers to connect faster and cheaper than ever before. For example, its work with UPS installing smart charging solutions coupled with energy storage has enabled a 270% increase in the number of electric freight vehicles that can operate out of one of UPS's biggest central London depots whilst avoiding the costs and time for traditional upgrades to the network.

At the heart of the first readiness pillar is UK Power Networks' ability to produce accurate and granular forecasts of EV load growth across its networks. UK Power Networks has three main use cases for load forecasts:

4. ***Regulatory Period Settlements*** – Long term load forecasts are used to estimate the level of reinforcement spend needed to accommodate growth over a regulatory period. It is vital that these spend forecasts are made as accurate as possible, to give the regulator, Ofgem, confidence in their projections; so that enough budget can be allocated to reinforcement and flexibility investments over the next regulatory period.
5. ***EHV Reinforcement Planning*** **–** Traditional EHV network reinforcements can take three to five years to complete. They must therefore begin before an asset's firm capacity is breached, to ensure security of supply and avoid network outages. Medium term load forecasts are used here to forecast these firm capacity shortfalls. Granular and accurate forecasts ensure that appropriate reinforcements are made, which facilitate EV load growth, whilst spending bill payer's money efficiently, i.e. the right amount in the right place.
6. ***LV & HV Visibility Deployment*** **–** LV & HV reinforcements take months to complete, so are done reactively. UK Power Networks is aware, however, that the EV revolution means that load may grow rapidly in some areas, as clusters of EVs begin to appear in particular neighbourhoods. The EV Readiness Strategy includes a £30 million project to deploy load monitoring devices in the substations which supply these neighbourhoods, notifying them of when reinforcement or demand side response is required. EV uptake and load forecasts are key here for efficient deployment of the monitoring systems.

The Recharge the Future project plays a key role in UK Power Networks' EV readiness strategy, providing the capabilities to forecast EV load growth on its networks with the high levels of granularity and accuracy needed.

1.2 The Recharge the Future project

The Recharge the Future project consists of three work streams, of which the Charger Use Study is the first (see Figure 12).

- Investigate EV charging behaviour through literature review, expert consultation and additional data analysis.
- Consolidate findings and propose recommendations for modelling charging behaviour.

- Integrating findings from the Charger Use Study into the Recharge the Future EV Load Forecasting Module.
- Accurately reflect geospatial variations in charging behaviour.
- Develop scenarios to explore future market and policy environments for EVs.

- Use the Recharge the Future EV Load Forecasting Module, in conjunction with the Element Energy Load Growth Model to develop load growth scenarios and conduct impact analysis on the UK Power Networks' network (work carried out by UK Power Networks and Imperial College London).
- Make recommendations for managing charging load.

Figure 12: Diagram of the three work streams that constitute the Recharge the Future project.

1.3 Objectives and scope of the Charger Use study

The aim of the Charger Use Study is to bring together all available knowledge on EV charging behaviour to understand how charging infrastructure will be used in future. All findings have been sourced from published literature or derived from analysis of real-world charging data. Where possible, identified knowledge gaps have been filled through consultation with industry stakeholders and additional data analysis. This work looks to identify and quantify the underlying factors that influence EV charging load profiles, such as day of the week, EV specifications, vehicle use cases and location.

The Charger Use Study covers the charging behaviour of battery electric and plug-in hybrid cars, across residential, work and public charge points that are connected directly and indirectly to the LV, HV and EHV distribution networks. Charging of commercial depot-based fleet vehicles, which includes some cars and light goods vehicles, as well as heavy goods vehicles and buses, is not considered in this study, the reasons being:

- These connections are expected to be less distributed by nature, and sporadic as fleet operators choose to electrify their fleet, either partially or fully. The specification and utilisation of the connection is also likely to be highly fleet specific. This makes predicting the date, size, load profile and location of these connections very uncertain.[4]

- These connections must be approved by the network operator, so will not contribute to unplanned capacity shortfalls.

Although motorcycles and some light goods vehicles are stored overnight at home, charging loads from the electrification of these vehicles have not been considered in this study. As of Q1 2018, motorcycles and light goods vehicles accounted for only 3.2% and 10.4% of all vehicles registered in Great Britain, compared with 83% for cars[5]. The energy consumption of motorcycles on a kWh/km basis is considerably lower than that of cars and so even fully electrifying this sector should not contribute to a significant increase in peak load. Plug-in electric light goods vehicles may drive reasonable load growth in future, but their progress in electrification lags well behind that of cars, currently accounting for just 0.11% of total light goods vehicle stock[6]. However, the UK Government's recent Road to Zero strategy includes an ambition to have 40% of new van sales being ultra-low emission by 2030 (compared with 50-70% for cars), and for all new car and van sales to be 'effectively zero emission' by 2040[7]. Consequently, growth in the plug-in light duty vehicle market is expected during the 2020s and its impact on domestic load growth would be a valuable area for further study.

Note that the charging behaviour of black cabs and private hire vehicles is considered under a separate UK Power Networks lead innovation project, titled Black Cab Green.

The findings from this Charger Use Study and Black Cab Green have been used to create the Recharge the Future EV Load Forecasting Module which has been integrated into the Element Energy Load Growth Model. UK Power Networks will use this model to forecast EV load profiles, which accounts for geospatial variation in charging behaviour, at each asset across its three licence areas, out to the 2030 horizon. The process through which these findings are integrated into the Recharge the Future EV Load Forecasting Module will be documented in Recharge the Future's Final Report, along with the conclusions from the model outputs. This report will be published in Q1 of 2019.

1.4 Structure of the report

The subsequent sections of this report are structured as follows:

Section 2 describes the current state and future trends of the EV market relevant to charging. This includes EV driving range, energy efficiency, and charging rate, as well as the various options available for EV charging and associated technologies.

[4] UK Power Networks is intending to investigate the impact of charging commercial EVs through its Network Innovation Competition funding bid, Optimise Prime.
[5] DfT Vehicle Licencing Statistics Table VEH0101: Licensed vehicles at the end of the quarter by body type, available at https://www.gov.uk/government/collections/vehicles-statistics
[6] DfT Vehicle Licencing Statistics Table VEH0130: Ultra low emission vehicles (ULEVs) licensed at the end of quarter by body type, available at https://www.gov.uk/government/collections/vehicles-statistics
[7] DfT (2018) The Road to Zero: Next steps towards cleaner road transport and delivering our Industrial Strategy, available at: https://www.gov.uk/government/publications/reducing-emissions-from-road-transport-road-to-zero-strategy

Section 3 outlines the approach to the broad literature review of charging behaviour, reports the list of sources covered and the knowledge gaps identified in the literature. This section also details the industry experts consulted in attempt to fill these knowledge gaps.

Section 4 describes the additional analysis that was carried out on available real-world charging trial data, to draw out further conclusions not featured in their original analyses and to fill the remaining knowledge gaps.

Section 5 details all the findings from the literature review, consultations, and data analysis that characterise EV charging behaviour.

Section 6 summarises the recommended features of EV charging behaviour, described in Section 5, that should be represented when modelling EV load profiles from the perspective of the distribution network.

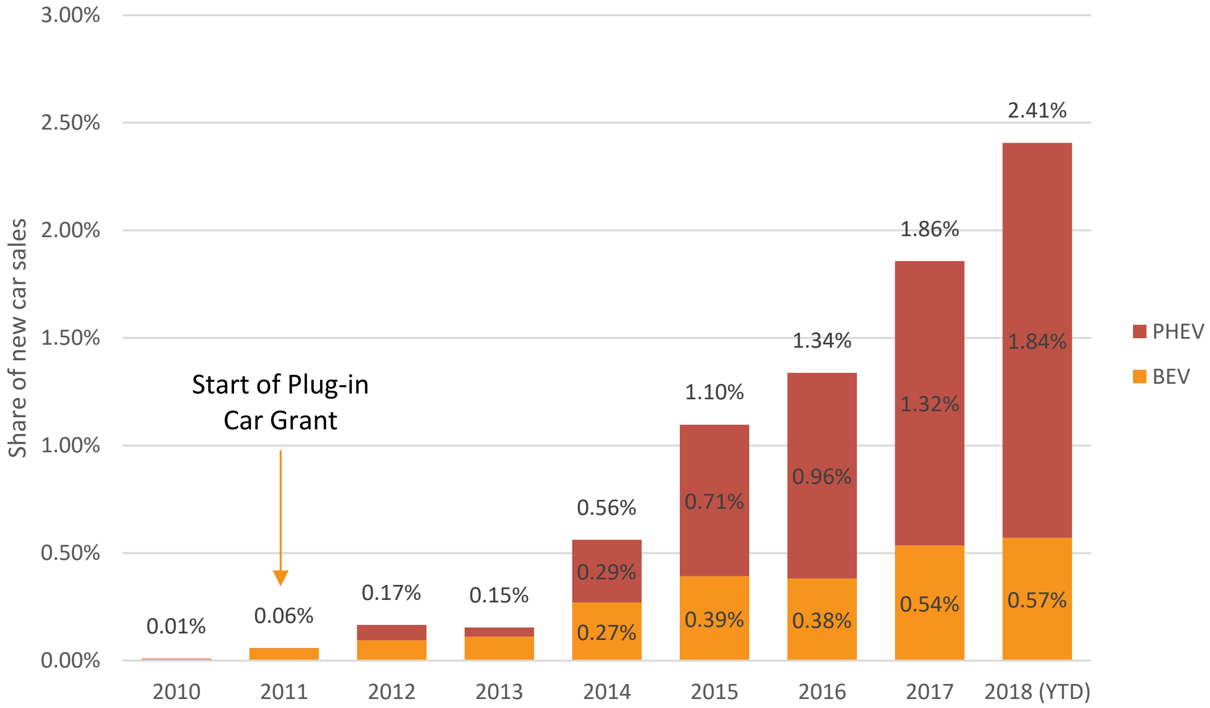
Section 7 highlights the uncertainties in future charging behaviour and lists the ongoing and upcoming studies and trials which will help inform outstanding questions posed by these uncertainties.

2 Electric Vehicle Market in the UK

To provide context to the scale of potential issues that EV charging behaviour may present to the distribution networks, this study included a review of the current EV market, including sales trends, and an outlook for EV and charging technologies. The findings are presented in the following section.

2.1 EV Sales Trends

Sales of plug-in cars in the UK have seen significant growth since the beginning of the decade, but the overall market share remains low in comparison to conventional petrol and diesel models. Figure 13 illustrates the increase in plug-in car market share since 2010, which from January-August 2018 stood at just over 2.4%:



Cumulative Sales, thousand

BEV	0.2	1.3	2.5	5.0	11.7	21.6	31.9	45.5	54.5
PHEV	0.0	0.0	1.0	1.6	9.1	27.8	54.5	88.1	117.0

Figure 13: Shares of car sales which are BEV and PHEV, 2010-2018 YTD (to August 2018). Data collected from SMMT monthly registrations figures of Electric and Alternatively-Fuelled Vehicles[8].

[8] Monthly EV Registrations data: https://www.smmt.co.uk/category/news/registrations/evs-afvs/

Whilst the early market was dominated by BEVs, much of the growth in the plug-in car market has been driven by PHEVs which now make up approximately two thirds of the plug-in cars currently registered in the UK. This is despite the changes made to the UK Government's Plug-in Car Grant in March 2016, which saw the maximum grant value reduce from £5,000 off the purchase price to £2,500 for PHEVs and £4,500 for BEVs.

PHEV sales have been primarily driven by company car buyers, which during Q1-Q3 2017 accounted for 81% of all PHEV purchases (see Figure 14). This is significantly higher than the company car share for all car sales, which over the same period accounted for 57% of purchases[9]. This skew has been attributed to the favourable company car tax rates levied on PHEVs, due to their low type-approval CO_2 emissions figures. For example, a Mitsubishi Outlander PHEV 2.0 3h Auto, which has a list price of £34,805, would attract annual Benefit in Kind tax of £1,809 for a higher rate tax payer, compared with £4,218 for an Outlander 2.2 DI-D 3 Auto (i.e. the equivalent diesel model) which has a list price of £30,129[10].

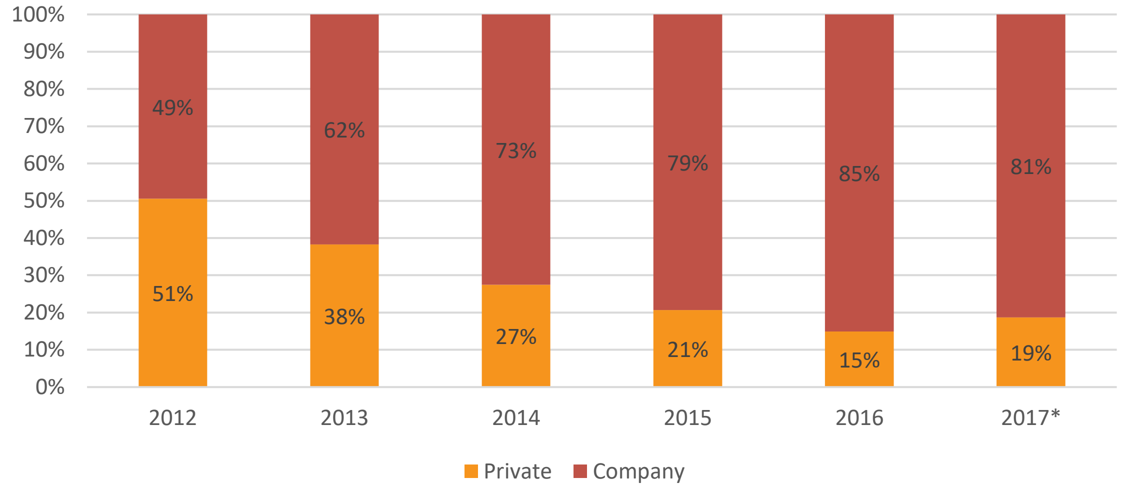


*Figure 14: Proportion of **PHEV** sales made to private and company car buyers[11]. *Note that 2017 data incudes only Jan-Sept 2017. Data provided by the Department for Transport.*

In contrast, BEV sales show a slight skew towards private buyers, with company cars accounting for only 38% of BEV sales during the period Q1-Q3 2017 (see Figure 15).

[9] Company and private cars sales data for Great Britain provided by the Department for Transport.
[10] Prices and tax rates provided by ComCar.co.uk [May 2018].
[11] These figures include Private Hire Vehicles.

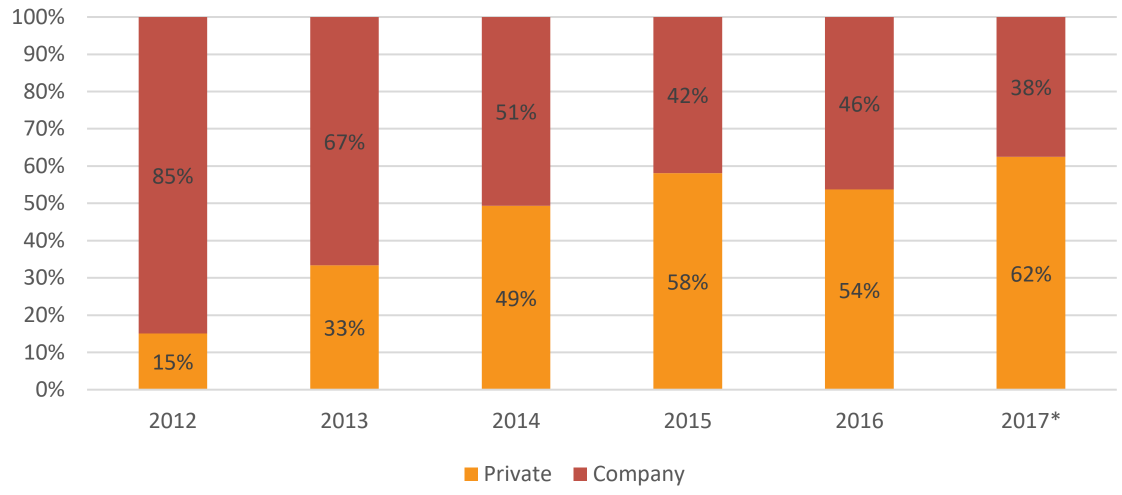


*Figure 15: Proportion of **BEV** sales made to private and company car buyers[11]. *Note that 2017 data incudes only Jan-Sept 2017. Data provided by the Department for Transport.*

BEVs are classed in same company car tax bracket as PHEVs and so receive similar Benefit in Kind tax relief. However, their relatively high upfront price, limited range, and dearth of options in the Executive and other large car segments has made them less popular with company car buyers, who in general have high annual mileages.

2.2 Current and future EV capabilities

When BEVs were first released 2010-13, available models consisted of smaller vehicles with ranges of 100-150km, such as the Mitsubishi iMiev and Nissan Leaf (24kWh), and the Tesla Model S with a range of 400-500km depending on battery size[12]. Figure 16 shows how BEV ranges (as stated under NEDC type-approval) have evolved as additional models have been brought to market. Note that the size classes of small, medium and large, are defined using the Society of Motor Manufacturers' car segment classification scheme, which is described in Appendix A.

[12] Note these ranges are quoted in terms of the NEDC test cycle which is known to be very generous. Under real world driving conditions the range can be expected to be as low 60-70% of the NEDC figure

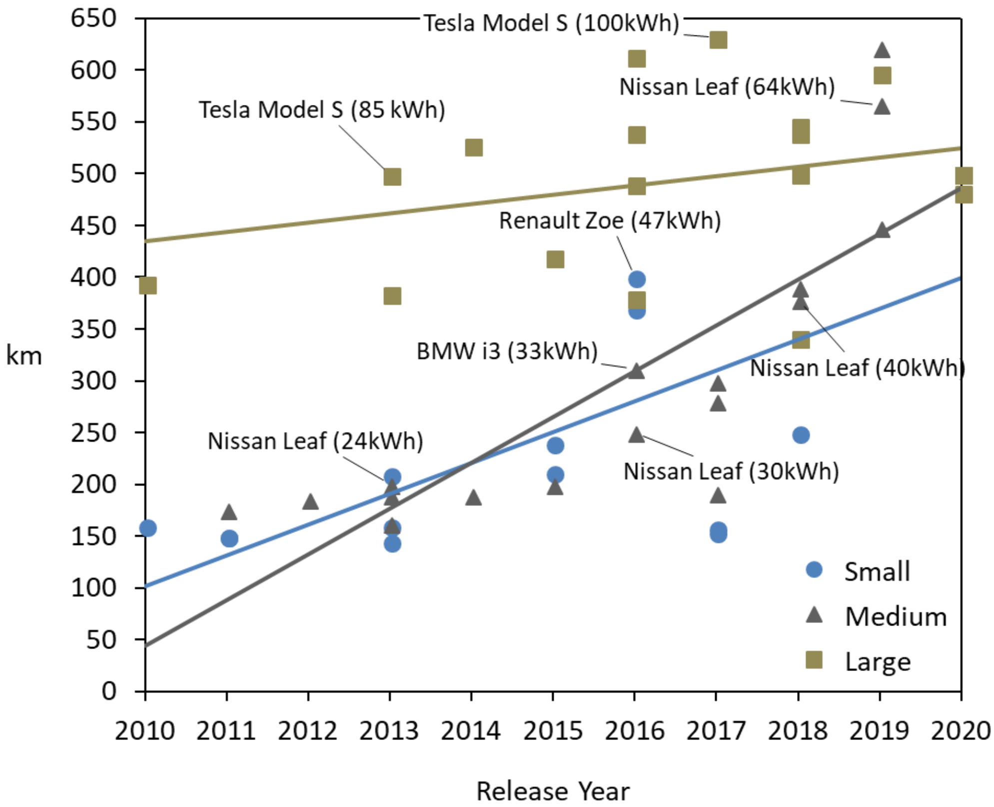


Figure 16: NEDC ranges of current and announced BEVs, grouped by car size.

It is observed that the driving ranges of large BEVs have remained at approximately 500-600km, while the ranges of small and medium BEVs have grown considerably as battery costs have fallen. Based on the vehicles that have been announced for release over the next two years, it appears that both medium and large BEVs will be offered with similar ranges of approximately 500km, and slightly lower range for small BEVs.

Figure 17 shows the equivalent information, but for PHEVs. Here it can be seen that the growth in range has been less marked than for BEVs, with a similar rate for both medium and large segments. A large number of PHEVs previously showed electric ranges around 50km, but recently vehicles have been released/announced offering 60-70km.

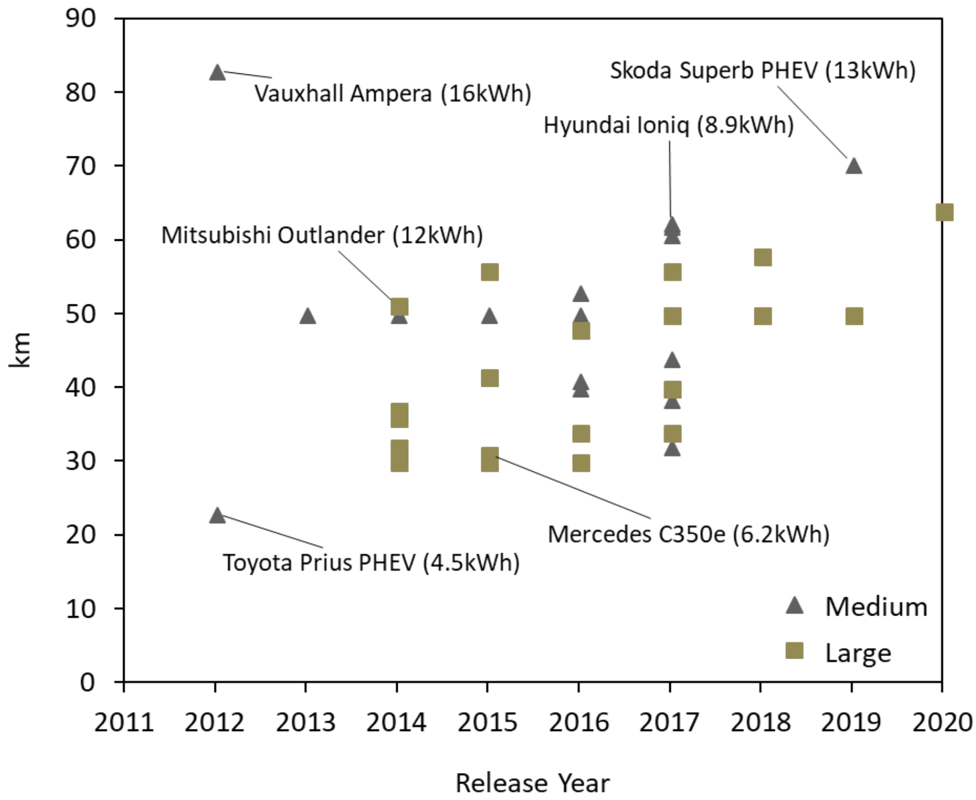


Figure 17: NEDC ranges of current and announced PHEVs, grouped by car size.

Figure 18 presents real-world electricity consumption figures for a range of BEVs, reported by users of the website Spritmonitor.de. This shows how there is a fairly large variation in electricity consumption which is strongly dependent on the size of the EV, the efficiency of its powertrain, and the conditions under which it is driven. For example, consumption can be significantly higher if the vehicle is driven primarily at high speeds on motorways, or in stop-start traffic. For illustrative purposes, kWh of charge can be converted to range added using the average consumption value of all BEVs in the Spritmonitor dataset of 0.164 kWh/km.

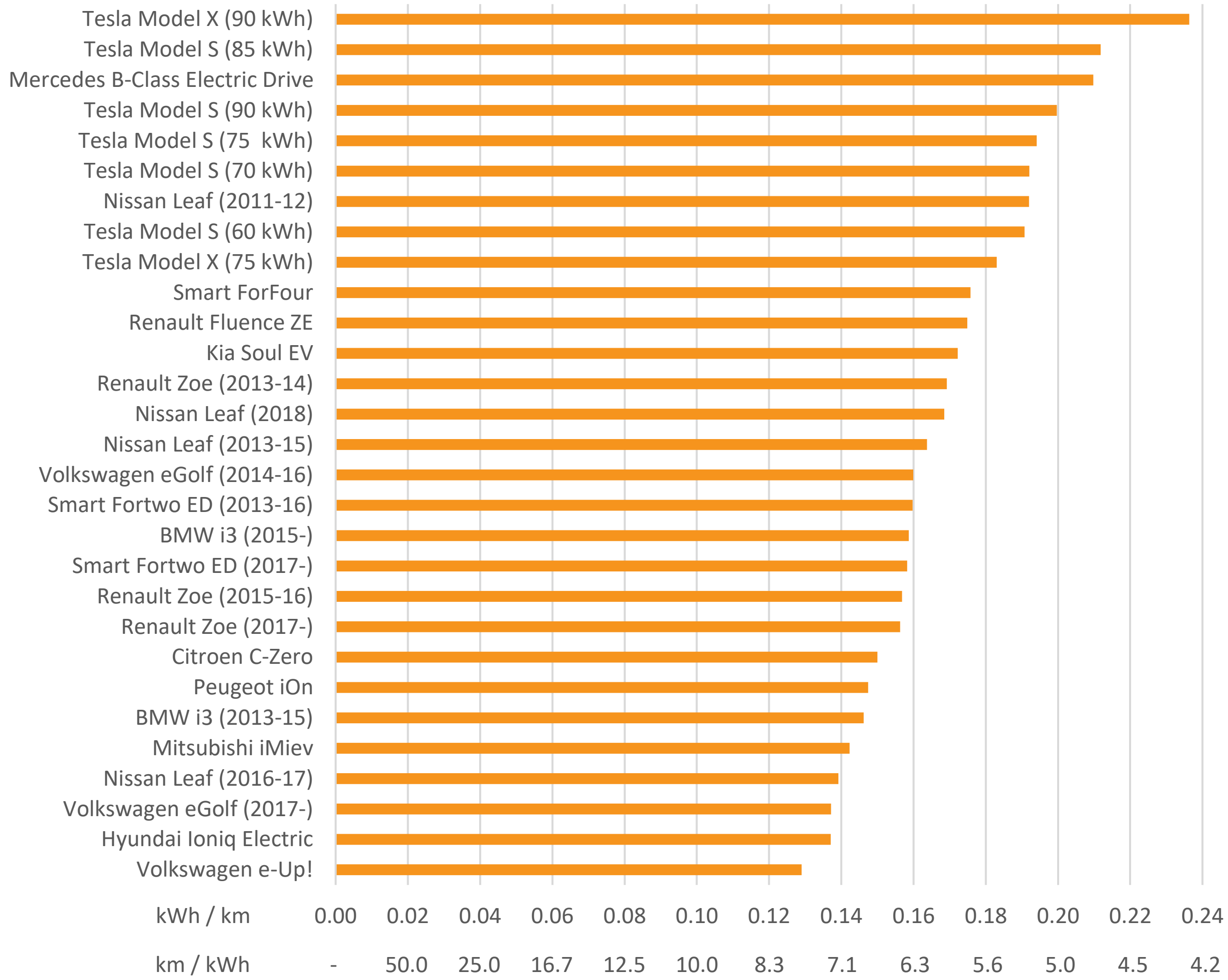


Figure 18: Real-world electricity consumption in kWh/km & km/kWh reported on Spritmonitor.de for a range of BEV models (July 2018)

2.3 Charging Infrastructure

Current EV charging can be categorised into five distinct location types: home, on-street residential, work, slow/fast public, and rapid public. These are summarised in Table 2 then discussed in more detail below.

Table 2: Major location types for EV charging

Location Type	Rate	Typical Usage Pattern	Deployment	Section
Home	3-7 kW	Charging overnight	Highest deployment and usage	2.3.1
On-street Residential	3-7 kW	Charging overnight	Not yet common	2.3.2
Work	3-7 kW	Used by commuters during the working day	Low	2.3.3
Slow/fast Public	3-22 kW	Used for short opportunistic charging during the day	Highest public deployment but low usage	2.3.4
Rapid Public	50kW+	Used during the day to support long journeys and those without home charging	Reasonable but growing quickly	2.3.5

2.3.1 Home

The results of a survey by Next Green Car suggest that at present 93% of EV owners in the UK have access to charging at home (Systra for the CCC, 2018). In most cases, this requires off-street parking and either a dedicated EV charge point or simply a domestic 3-pin socket.

The cost of home charge point is around £800. The cheapest available is currently offered by Rolec at £650 fully installed. However, the Government currently offers a grant of up to £500 for the installation of home charge points through the Electric Vehicle Homecharge Scheme. Depending on specification, and available connection capacity, these charge points are capable of supplying 3-7 kW of power. Charging from a normal 3-pin plug will provide up to 3 kW, however, this option is discouraged by EV manufacturers because the high current demand and long charging duration increases risk of equipment failure.

There are no official central records showing the rate of home charge points that have been installed. However, the price difference between domestic 3 kW and 7 kW charge points is less than £100. It therefore appears likely that for EV owners who install a dedicated home charge point, where possible, 7 kW charge points are preferred. This is supported by discussions with PodPoint and Chargemaster, who have both said that they mostly install 7 kW home charge points.

However, evidence suggests that the installation rate of dedicated home charge points in the UK Power Networks licence areas is likely to be lower than expected. Data provided by the Office for Low Emissions Vehicles show that as of March 2018, approximately 12,500 home charge points had been installed in the UK Power Networks licence areas through the Homecharge grant scheme. Comparing this with an estimated 32,000 EVs registered in the UK Power Networks licence areas[13], it appears that only around 40% of these EVs made use of the Homecharge grant scheme. It is to be expected

[13] Analysis of EV registration data provided by the Department for Transport shows that 24% of Great Britain's EVs are registered in the UK Power Networks licence areas (see Recharge the Future Final Report). As of March 2018, there were 134,686 EVs registered in Great Britain, according to DfT Vehicle Licencing Statistics Table VEH0130: Ultra low emission vehicles (ULEVs) licensed at the end of quarter by bodytype.

that the share of EVs that charge at home is lower in the UK Power Networks licence areas compared with the national average, since the share of car owners in London with off-street parking is 54% and so lower than the national average of 73%[14]. However, this difference does not fully explain the low take-up of the Homecharge grant, particularly as the number of car owners in London with off-street parking is far from saturated with EVs. It is possible that some EV owners installed a home charge point without making use of the grant, and therefore do not appear in the OLEV data. Possible reasons for this could be non-eligibility, lack of knowledge of the grant's existence, or the buyer received a charge point as part of the car purchase. Regardless, the likely significant share of EV owners without a dedicated home charge point either use a domestic 3-pin socket, public charge points or do not charge at all. The latter only applies to PHEVs, which can be run entirely under fuel power and may have been purchased exclusively for their favourable tax incentives. This is particularly true of company car drivers who are charged low company car tax on PHEVs and may be reimbursed for their fuel use and not electricity.

Future expectations:

Charging Rate

The rate at which an EV charges is limited by two factors:

1. The maximum rate at which the charge point can supply power.
2. The rate at which the battery can accept charge.

When charging from an AC power supply, as provided by all home charge points, the EV's on-board charger first converts this to DC before feeding the power supply to the battery. In most cases, the on-board charger is limited to 3.6 kW or 7 kW in order to save cost. There are currently very few EVs available with higher rated on-board charger. The premium Tesla Model S and Model X BEVs are fitted with 11 kW chargers, with an option to increase this to 22 kW, while the Renault ZOE is capable of accepting 22 kW as standard or up to 43 kW AC with the Quick Charge Option. However, these charging rates are only achieved with a three-phase power supply which is currently rare for domestic connections in the UK. In the absence of a three-phase supply, it is unlikely that the rate of home charging will increase above 7 kW as this would add cost to the vehicle and would be more likely to overload the 60-100A supply fuses usually fitted in UK homes, particularly if other appliances are running. Furthermore, even with the largest battery capacities of 100 kWh, 7 kW would provide a full charge in 14-15 hours which could conceivably still be done overnight. Note that the vast majority of EVs will have battery capacities considerably smaller than this.

Time of Use Tariffs

To encourage EV users to charge their vehicles outside of peak times, it is expected that electricity suppliers will offer time-of-use tariffs with electricity charged at a lower cost during off-peak times. At present, there are only two examples of time-of-use tariffs aimed at EV charging: TIDE from Green Energy and Octopus Energy Go. TIDE supplies electricity at 6.4p/kWh from midnight to 7am, and Octopus Energy Go offers electricity at 5p/kWh during a 4-hour window overnight. Octopus Energy also offers a dynamic time-of-use tariff, Agile, where prices are updated daily in line with wholesale electricity prices. In all three cases, a smart meter is required to record accurate half-hourly electricity usage. Economy 7 tariffs also provide a route to accessing low cost electricity overnight for 7 hours. About 18% of domestic users in GB are under Economy 7 and 10 rates (Economy 10 adds 3 hours of off-peak times during the day), covering 26% of the domestic demand (Element Energy, 2013).

[14] Analysis of National Travel Survey 2009: NTS0908 Where vehicle parked overnight by area type, GB, 2009

At present EV owners can access these low electricity prices by scheduling charging during the cheaper hours. There are already several home charge points on the market which offer a delayed/scheduled charging, where the charge point will not begin drawing power until a specified time, even if the EV is plugged in. Many of the EVs themselves also provide this functionality through the vehicle infotainment system and/or a smartphone app. Systems have also been trialled whereby charging under a dynamic time-of-use tariff is automatically optimised to minimize the cost to the user. For example:

- The Electric Vehicle Intelligent Infrastructure trial (2011-13) in Gothenburg, Sweden deployed smart controllers in EVs which received charging schedules based on electricity prices and grid capacity.
- The Mobility House EV Smart Charging trial (2014-15) in Germany installed smart charge points at the homes of 11 Renault ZOE owners. Each day the charge points designed optimum charging plans in response to that day's electricity prices.

While no commercial solutions exist, it is likely that similar systems will be developed if more dynamic time-of-use tariffs are made available.

Managed Charging

To further ensure that charging takes places at optimal times, systems are also being developed to enable EV charging to be automatically controlled with minimal user input. This would allow an EV user to plug-in their car when convenient, for example when they arrive home after a journey, but cede control of the timing and charge rate of the charging process. This could be for a range of purposes:

- **To avoid exceeding a property's capacity limit**. This could occur if charging is done at the same time as other high-power appliances are in use, such as ovens or tumble dryers. There are already several charge points available which regulate the charging rate to limit overall property demand, by communicating with either a smart meter or an additional meter installed in the property's main distribution cabinet.
- **To avoid exceeding capacity limits at various network assets**, for example primary and secondary substations and LV feeders, in order to avoid or postpone costly network upgrades. UK Power Networks is currently investigating potential models to implement this function through its Network Innovation Allowance-funded Smart Charging Architecture Roadmap project[15]. This will develop architecture representations specific to each option, including detail at the point of customer connection or interaction with charging infrastructure, and outline the requirements between the substation and the internal systems and processes that a DNO may need. The study will consider the possibility that there are differences in smart charging models and the architectural requirements between urban, suburban and rural areas.
- **To shift charging to when electricity prices are lowest**, for example when demand is low or generation is high. This is similar to dynamic time-of-use pricing, but the tariff structure does not need to be defined in advance. Instead, an external actor with control over a large number of EVs/charge points could actively shift charging to maximise revenues/savings, which could then be shared periodically with participating EV users. For example, an electricity supplier could shift charging to when wholesale prices are lowest and return a portion of the savings made to customers, depending on how much charging flexibility they have provided. In addition, variable DUoS pricing could also be implemented to enable DNOs to manage network constraints through electricity pricing.

[15] More information on UK Power Networks' Smart Charging Architecture Roadmap is available here: http://www.smarternetworks.org/project/nia_ukpn0034

- **To provide grid services**. For example, the charging rate of a large pool of EVs could be ramped up or down to provide frequency response. Aggregating the response of a large number of EVs enables the capacity thresholds set by National Grid for each grid service to be met e.g. Enhanced Frequency Response requires a minimum of 1 MW of response to be made available. Intelligent aggregation would also ensure that grid services are not provided at the expense of other network requirements, such as local constraints on the LV network. A portion of the grid service revenues could then be shared with participating EV users.

Managed charging products are likely to incorporate a combination of the functions listed above, to take advantage of a range of revenue streams. To facilitate this either the charge points or the EVs will be required to have some communication functionality which can report on the current charging condition and respond to third party control commands. This communication capability is already built into some charge points and EVs, and potential systems are in trial phase.

It is expected that use of managed charging will become widespread during the 2020s as a method of reducing the cost of charging, thereby improving the economic proposition of owning an EV. As such, the UK Government's Automated and Electric Vehicles Bill 2017-19, which is presently progressing through Parliament, could mandate all charge points to have smart charging capability which can receive, transmit and react to information such as by adjusting the rate of charging or discharging.

Vehicle-To-Grid
Vehicle-to-grid is conceptually similar to managed charging but is extended to bi-directional power flow. This enables power to also flow out of the battery and back into the grid to provide a greater range of balancing services. This has the potential to boost grid service revenues for the EV user, although concerns have been raised over faster battery degradation from increased charge cycling. There are also additional hardware requirements on top of those needed for managed charging. To enable bi-directional flow, the charge point or EV must be fitted with a grid-tied inverter which converts DC power flow from the battery to AC at the correct voltage and frequency for use in the grid.

Currently all EVs with a CHAdeMO DC charging socket are capable of providing bi-directional power flow, if paired with a V2G-enabled charge point. This includes all Nissan Leaf, Nissan e-NV200 and Mitsubishi Outlander models with rapid charging capability. In principle, EVs with the current generation of CCS DC charging sockets also have the necessary hardware to provide bi-directional power flow, but the standard does not yet enable it.

At present, the feasibility of V2G technology remains under investigation, but it is receiving widespread attention in the UK and elsewhere. To date, a number of large trials have already taken place to explore V2G's real world potential. For example, Nissan have partnered with Endesa to develop a V2G-compatible charge point. This was tested with a fleet of 10 Nissan e-NV200 vans in Denmark, with each vehicle reported to earn approximately €1,300/year in grid service revenue[16]. This trial has been extended to the UK, with an aim of installing 100 V2G charge points across the country serving both private and company fleet EVs. The UK is planning to be at the forefront of V2G technology and in February 2018 the UK Government, via Innovate UK, announced the award of £30m in funding to V2G research, feasibility, and demonstration projects (see Section 7.2.5). UK Power Networks is supporting several of these projects via its

[16] http://time.com/4901153/diplo-interview/

TransPower project, which covers demonstration of V2G on over 650 vehicles. TransPower will consolidate learnings to understand the impact of V2G technology on the electricity network and value of the benefits from providing local grid services.

However, the feasibility of deploying V2G at home is as yet uncertain. Its business case relies on the revenues gained from providing grid services offsetting the higher charge point capital cost and potential cost of faster battery degradation. For example, Drive Electric recently announced plans to release the first commercially available V2G charge point which they expect to cost £8,000-£9,500 and provide revenues of £300-£800 per year[17]. Although capital costs are expected to fall, and revenues increase due to more renewable generation deployment, V2G may be better suited to commercial customers who are more willing to accept longer payback times, drive more regular duty cycles, and have multiple vehicles charging per site.

2.3.2 On-street Residential

For EV drivers that do not have access to a home charge point, a potential option is to charge regularly at a nearby publicly accessible charge point. For convenience, this would need to be located at the vehicle's home location and used for an extended period of time to provide a full charge. This makes them distinct from other forms of public charge point, such as in retail car parks, which are used opportunistically when a car is away from home.

The need for on-street residential charging is greatest in areas with low levels of off-street parking and is therefore a strong focus for cities. Historically, charging provision for EV drivers without off-street parking has been met with dedicated on-street charging posts. However, these carry a very high capital cost of the order of £7,500, due largely to the cost of ensuring asset resilience and installation (Cambridge Econometrics and Element Energy for the European Climate Foundation, 2018). These provide a charging rate of 3-7kW. OLEV currently offers a grant to Local Authorities covering 75% of the capital cost of installing residential on-street charge points, up to a maximum of £7,500.

Future expectations:

Coverage

The density of on-street residential charge points is currently low, which is unsurprising given 93% of existing EV owners having access to some form of home charging (Systra for the CCC, 2018). However, 27% of car owners do not have off-street parking[18], with particularly low rates in some urban areas. For example, in several London MSOAs, such as Westminster, Islington, Hackney, Tower Hamlets, as few as 6% of car owners have off-street parking (Element Energy; WSP Parsons Brinckerhoff, 2016). Therefore, as rate of EV penetration rises, it is expected the share of EV drivers without access to home charging will also increase. For many of these future owners, on-street residential charging will be a favourable solution for meeting their charging needs and the rate of installation will grow accordingly.

New Technologies

The cost of providing residential on-street charge points is expected to fall as new innovative charging solutions are developed. This is a necessity as costs are an order of magnitude greater than home charge points and would quickly

[17] https://www.drive-electric.co.uk/driveelectric-launches-vehicle-grid-charging-service-uk-homes-workplaces/
[18] National Travel Survey, 2009: Table NTS0908 Where vehicle parking overnight by area type, GB, 2009.

exhaust OLEV's £4.5m budget for its on-street residential charge point grant scheme. Adding charge points to existing street furniture with electrical connections, such as street lights, is gaining significant interest. This has the potential to reduce costs considerably. Ubitricity, for example, has developed a charge point which can be retrofitted to an existing street light for £300-£400 (Edwards, 2015). The user is required to purchase a smart cable, at a cost of ~£400, which has a built-in meter to monitor electricity usage and handle billing. Several London Boroughs (Richmond, Hounslow, Westminster, Wandsworth, Lambeth and Kensington & Chelsea) are currently installing the technology. These trials are necessary to understand potential barriers for these types of charge points, for example, the limits of the available charging rate and suitability of street light locations relative to parking bays. Innovate UK is also funding feasibility studies (in 2018) and demonstration (from early 2019) of new on-street charging solutions through its *Electric vehicle charging for public spaces* competition.

Charging Rate
As for home charging, it is not expected that charge rates higher than 7kW will be common. Although public charge points are installed offering 22kW 3-phase supplies, this rate is unnecessary for overnight charging which is likely to make up the bulk of usage for charge points in residential areas. Street furniture grid connections are also unlikely to be capable of supplying high power charging. The Ubitricity street light socket, for example, is rated at 4.6kW.

2.3.3 Work

Charge points installed at workplaces can be used by commuters to charge EVs throughout the working day. It is estimated that 25% of EV users have access to charging at work (RAC Foundation, 2017). Workplace charge points are typically more expensive than home charge points, but cheaper than publicly accessible charge points as they do not incur the same permitting costs. Chargemaster offers a two-socket work place charging post for £795 (excl. VAT)[19], providing up to 7kW. While the charge points are funded by the employer, OLEV's Workplace Charging Scheme provides £300 per socket, up to a maximum of 20 per application. For many of these EV drivers, the cost of electricity is also covered by the employer and so is an attractive charging option.

Future Expectations:

Charging Rate
Workplace charge point rates are 3-7kW as this is sufficient to provide enough charge if EVs plugged-in throughout a typical 8-9 hour working day. It is possible that higher rated charge points will be installed in future as commercial sites are more likely to have higher connection capacities than residential properties. However, since 7kW is already sufficient for commuters this will only provide additional benefit for visitors whose dwell time at the site is only a few hours. The employer would also incur higher capital costs and potentially connection upgrade costs, and so the incentive is limited.

Managed Charging and Vehicle-to-grid
As noted in Section 2.3.1, workplace charging could be well suited to providing grid balancing services. Since charging times are likely to be significantly shorter than work days, businesses may be able to offer a highly flexible storage load throughout the day. Since a large number of EVs would be located at a single site and will have more routine usage patterns the complexity of aggregating charging load is likely to be reduced. Business may also show a greater

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[19] https://chargemasterplc.com/2017/09/05/chargemaster-launches-new-low-cost-powercharge-workplace-charger/

willingness to accept the commercial proposition, even if payback times are several years. V2G has already been demonstrated with commercial fleets, for example, Nissan and Enel's V2G trial in Denmark with a fleet of 10 e-NV200 vans operated by the utility Frederiksberg Forsyning. This led to the Innovate UK funded e4Future Project, led by Nissan, which aims to install 1,000 V2G charge points in the UK for use by commercial fleets.

2.3.4 Slow/fast Public

In this context, slow/fast public charging consists of publicly accessible charge points intended for EVs to use while they are away from home. This could include charge points in supermarket, retail and public car parks or on-street charge points in shopping or leisure areas. They are unlikely to be the primary mode of charging, and instead used opportunistically to top-up between trips legs. This intended usage makes them distinct from on-street residential charge points despite the charge points themselves being similar.

Future Expectations:

Charging Rate

Slow/fast public charge points are currently installed with supply capacities up to 22kW 3-phase AC. As discussed in Section 2.3.1, most EV models are only capable of accepting up to 7kW. Since most mainstream EVs are unlikely to be fitted with on-board chargers capable of accepting higher AC power than 7kW, it appears unlikely that higher power slow/fast public charge points will be installed. Figure 19 shows the evolution in the numbers of available 3 kW and 7-22 kW public charge point connectors and illustrates how 7-22 kW charge points are now being installed in far greater numbers than 3 kW points. In 2017, for example, 5.5 times as many 7-22 kW public connectors were added as 3 kW connectors.

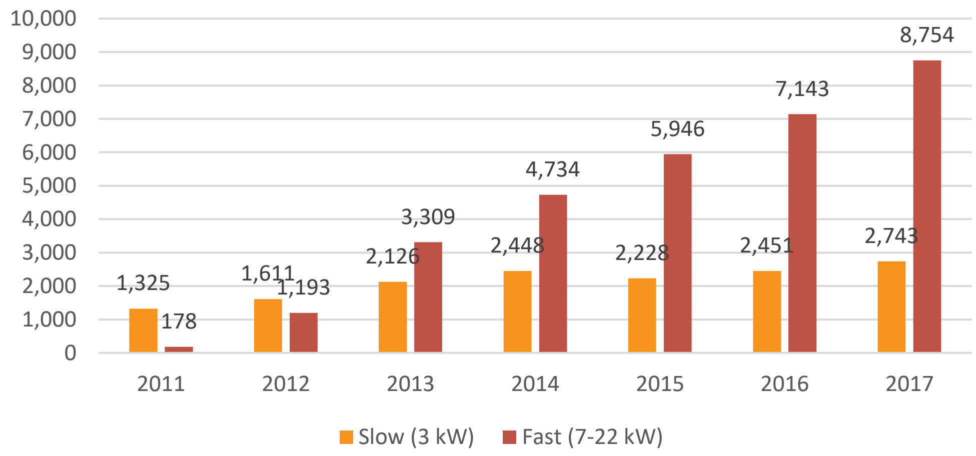

Figure 19: Number of slow and fast public charge point connectors available in the UK[20].

[20] Data provided by Zap-Map, available from https://www.zap-map.com/statistics/

2.3.5 Rapid Public

These are defined as publicly accessible charge points capable of supplying at least 50kW. These are intended to minimise charge duration and are therefore suitable for in-journey charging, as well as offering a potential charging option for EV drivers without access to a home charge point. Consequently, most rapid public charge points are located on or near major highways, where journey distances are more likely to exceed the range of the EV. Rapid charging is primarily aimed at BEV users, who do not have an on-board internal combustion engine they can be used to extend range. Currently, only one PHEV, the Mitsubishi Outlander, is compatible with rapid charge points, however, the rate at which it charges is significantly lower than 50kW due to avoid damaging the small 12kWh battery. It is unlikely that further PHEVs will be released with rapid charging capability as its utility to PHEV drivers is limited, and rapid charging tariffs have been specifically designed to discourage their usage[21].

Future Expectations:

Charging Rate

Nearly all rapid public charge points installed are rated at 50kW, apart from Tesla Superchargers, compatible only with Tesla cars, which can supply up to 145kW (although the cars themselves can only accept 120kW). However, charge point and car manufacturers have announced plans to install rapid charge points capable of supplying up to 350kW. For example:

- PodPoint will begin installing 150kW charge points in the UK during 2018[22]. Chargemaster have also said they intend to expand their network to several thousand rapid charge points across the UK, many of which will include 150kW units[23].
- Ionity, a joint venture between BMW, Mercedes, Ford and Volkswagen, plans to install 'ultra-rapid' charge points at 400 sites across Europe, including UK, by the end of 2019. Each site will include about six charge points with initial capacity of 150kW but with the intention of upgrading these to 350kW in future.[24]
- Tesla will begin rolling out V3 of their Supercharger charge points by the end of 2018, which they have stated will provide 200-250kW[25].
- E.ON and CLEVER have announced a plan to install ultra-rapid charge points every 120-180km along Europe's motorways. They will install at the first 180 sites across seven countries, including UK, by the end of 2020. These sites will initially offer 150kW charging, with the potential to later upgrade to 350kW.[26]
- Porsche have stated that their upcoming Taycan (previously called Mission E) will be capable of 350kW charging, and they installed the first 350kW charge point at one of its Porsche Centres in Germany in July 2017[27].
- At present, only Tesla cars and the Hyundai Ioniq Electric are capable of charging at >50kW, however, a number of upcoming BEVs will also be able to take advantage of these higher rapid charge rates. For example, the

[21] https://www.greencarguide.co.uk/2016/07/ecotricity-ev-charge-fee/
[22] https://pod-point.com/electric-car-news/150kw-rapid-chargers
[23] https://chargemasterplc.com/2018/03/02/one-million-public-ev-charging-sessions-per-year-2020-polar-network/
[24] https://electrek.co/2018/02/06/map-ionity-ultra-fast-charging-network/
[25] https://electrek.co/2018/06/06/tesla-pushes-supercharger-v3-expansion-batteries-solar/
[26] https://www.eon.com/en/about-us/media/press-release/2017/eon-and%20-clever-are-creating-an-electric-highway-from-norway-to-italy.html
[27] https://electrek.co/2017/07/14/porsche-350-kw-ev-charging-station/

Jaguar I-Pace, Hyundai Kona Electric, and Kia Niro EV will be able to accept 100kW DC, and the Audi e-tron 150kW DC.

Co-location with battery storage and renewable generation

The current cost of installing a 50kW rapid charge point is ~£30,000 (Cambridge Econometrics and Element Energy for the European Climate Foundation, 2018), but this is highly dependent on the connection costs which may include grid upgrades. High grid upgrade costs are likely to become an even greater issue as more charge points are added per site, and with higher power capacities. Installing batteries at the rapid charging sites is a method of avoiding these costly grid upgrades. The batteries act as a buffer, charging at a low rate during off-peak times or when on-site renewable generation is available, and then discharging to support the grid connection when demand exceeds the site's capacity limit. This enables the charging site to access low cost electricity, while the revenues could also be supplemented through using the batteries to provide grid services.

Tesla have previously stated an aim to install battery storage and solar panels at all of their Supercharge sites and have already installed their Powerpacks at some select sites, for example, South Mimms Service Station in UK. In May 2018, Pivot Power and National Grid released plans for a £1.6bn investment to install rapid charge points alongside 50MW batteries at 45 sites across the UK, which would connect directly to the Transmission System[28]. The initial aim is to install these at 10 sites over the following 18 months.

[28] https://www.businessgreen.com/bg/news/3032674/future-proof-pivot-power-unveils-plans-for-gbp16bn-battery-based-ev-charging-network

3 Literature Review

3.1 Research Questions

The literature review was directed with a view to answering the following research questions:

- What is the daily charging profile for BEVs and PHEVs in residential, work and public locations?
- What share of a car annual charging is done at different charging locations (i.e. home, work and public charging)? What influences this split?
- How are the above influenced by:
  - Charging location type and rate
  - BEVs compared with PHEVs
  - Battery capacity
  - Managed charging
  - Demographics of the EV owners and their transport needs
  - Transport infrastructure in place
  - Geographic parameters (e.g. road types, urbanity)
  - Time of the year and day of the week

3.2 Literature Review Approach

Relevant literature was identified by searching Science Direct with the search term *(("Electric vehicle" OR EV OR "electric car") AND (charging OR "time of charge" OR "plug-in time" OR "peak time" OR "peak demand") AND (data OR trial))* in the Title, Abstract and Keywords fields. Literature published before 2009 was removed from the search.

The abstract of each result was then reviewed for relevance with regard to answering the research questions. This process yielded 71 literature sources, the content of each was explored in more detail, and their relevance for answering each of the research questions was recorded.

Any real-world data sources, such as EV charging trials, which were mentioned in the literature sources were also recorded, and where available that data along with any accompanying project reports was also sourced. The project reports were also reviewed and their relevance to each research question was recorded in the same manner as for the other literature sources.

Table 3 and Table 4 show the real-world data sources identified during the literature review. In each case, the dataset has been graded in terms of how relevant its age, size and availability are for answering the research questions.

While the list of data sources is substantial, the related studies often do not answer the research questions of interest, either because they have a different focus or lack the data needed. Another issue is the level of relevance of the datasets e.g. quite often the vehicles are not representative of current and future EVs. For these reasons, the review was supplemented by a substantial new data analysis, as well as a consultation with industry stakeholders.

Table 3: List of identified EV charging datasets collected in UK and Ireland. Colour code illustrates relevance to answering research questions. Red = low, amber = medium, green = high[29].

Project / dataset	Region	Date	Size	Data availability
CABLED	Birmingham and Coventry	2009-12	110 ULEVs (BEV, PHEV and H2 FC)	1 paper showing average charge profile
Switch EV	NE England	2010-13	44 EVs	2 papers with detailed analysis
Plugged-in Places	National	2010-13	4,000 CPs across UK	Detailed datasets and project reports available
Low Carbon London	London	2010-14	72 residential, 54 commercial, 491 public CPs; 30 EVs	Detailed datasets and project reports available
CLNR – EV Trial	NE England	2014	143 EVs	Detailed datasets and project reports available
My Electric Avenue	London, Southampton, Sunderland	2012-15	200 Nissan Leafs	Detailed datasets and project reports available
LCL (Smart EV)	London	2013-15	68 EVs, 52 public CPs	Detailed datasets and project reports available
Rapid Charge Network	National	2014-15	40 EVs, 74 rapid CPs	1 paper with detailed analysis
ESB ecars	Republic and Northern Ireland	2011-ongoing	>500 public CPs	Monitoring data from Nov 2016-July 2018

[29] Criteria for evaluating project relevance: Project end date >2015 = high, 2013-15 = medium, <2013 = low; Project size >100 EVs/CPs = high, 40-100 EVs/CPs = medium, <40 EVs/CPs = low; Data availability: raw monitoring data = high, detailed analysis = medium, limited analysis or none = low.

Table 4: List of identified EV charging datasets collected in Rest of World. Colour code illustrates relevance to answering research questions. Red = low, amber = medium, green = high[29].

Project / dataset	Location	Date	Size	Data availability
Pecan Street Smart Grid	Austin, Texas	2010	33 EVs	1 paper, low data
BMW/Vattenfall EV Trial	Berlin, Germany	2011	79 Mini EV prototypes	1 paper, limited relevance
Western Australian EV Trial	Australia	2010-12	11 fleet EVs	Detailed project report, and 1 paper
Test An EV	Denmark	2011-12	2,400 EVs	1 paper with low levels of data
ARCHIMEDES EV Trial	Aalborg, Denmark	2011-13	80 EVs	Project report, some data
The EV Project	USA	2011-13	12,500 public and home CPs, 8,650 EVs	Detailed monitoring reports, and 1 paper
CROME	France / Germany	2011-13	121 EVs	Project report and 1 paper with some relevant data
Victorian EV Trial	Australia	2010-14	120 private, 50 commercial EVs, 200 CPs	Project report and paper containing detailed analysis
Green eMotion	Denmark, Spain, France, Ireland, Italy	2011-15	2,682 home, work and public CPs, and 1,362 participants	Large amount of data contained in project report but often aggregated over all project years
Jump Smart Maui	Hawaii, USA	2011-17	200 Nissan Leafs, 44 rapid CPs	None
ChargeTO	Ontario, Canada	2015-17	30 EVs	Project report, some data
BMW iChargeForward	San Francisco, USA	2016-18	>250 BMWi3s	Detailed project report
ELaadNL	Netherlands	2009-ongoing	>7,000 CPs	3 papers with detailed analysis
CPUC Load Reporting	USA, California	2012-ongoing	~20,000 EVs	Detailed annual reports

3.3 Consultation with Industry Stakeholders

Several organisations were contacted as part of the research, with a view to discuss either future trends/technology, understand existing data in light of the research questions and/or address a data gap from the literature review e.g. workplace charging. The table below summarises who was consulted and the focus of the exchange. The findings of the consultation are integrated in Section 5.

Table 5: List of industry stakeholders consulted

Company / Stakeholder	Type	Why / key focus
EA Technology	Research / Consultancy	Home charging behaviour observed in the My Electric Avenue and Electric Nation trials
ELAN Project (Norway)	Research / Consultancy	Early vs mass market, charging price, urban/rural
Fastned (Netherland, UK, Germany)	CP operator	Rapid charging, pricing impact
FleetCarma	Technology provider	Managed charging
Nissan	EV OEM	V2G, Charge price impact, battery capacity, future seasonal effects
Open Energi	Technology provider	Battery storage at rapid charging sites
PodPoint	CP operator	Workplace charging
Robert van den Hoed (Amsterdam University of Applied Sciences)	Research / Consultancy	On-street public charging, pricing
Zap-Map	Data provider	Public charging network usage and geographic distribution
Zero Carbon Futures	Research / Consultancy	Rapid charging network, pricing impact

4 Additional Data Analysis

For many of the EV trials, the accompanying analysis had not focussed on answering the research questions of this study. Therefore, to fill some of the identified data gaps, additional analysis was carried out on available raw trial data. Where trial data was insufficient, additional data sources not featured in the literature review were sought and analysed. This included an interim dataset from the ongoing Electric Nation trial, and a public charge point monitoring dataset from Zap-Map. Table 6 shows the datasets analysed and the charging locations they covered. In each case, the dataset is discussed in more detail below the table, describing the trial, data quality and analysis carried out.

Table 6: Available EV charging datasets further analysed. Region, age and size graded for relevance. Red = low, amber = medium, green = high.

Dataset	Acronym	Region	Date range	Size	Monitoring	Home	Work	Slow/fast Public	Rapid Public	Comment
Plugged-in Places	PiP	UK nationwide	2010-13	31 Home CPs, 115 Work CPs, 602 Slow/fast Public, 81 Rapid Public	CPs	✓	✓	✓	✓	Large number of public charge points but EV numbers low during period so few charge events.
Low Carbon London	LCL	London	2013-14	52 home CPs, 21 work CPs, 393 Public CPs	CPs	✓	✓	✓	✓	Small EV sample size precludes reliable disaggregation by participant characteristics.
My Electric Avenue	MEA	London, Southampton, Sunderland	2013-15	224 Nissan Leafs (24 kWh)	EVs + home CPs	✓			✓	Includes EV monitoring data but can only distinguish home and rapid public charging.
ESB ecars	ESB	Republic and Northern Ireland	Nov 2016 - July 2018	591 Public CPs	CPs			✓	✓	Very recent data with large number of charge events. Can enable further disaggregation of public charge points. But data for Ireland so not necessarily applicable to GB.
Electric Nation	EN	UK	Apr 2017-Feb 2018[30]	402 BEVs and PHEVs	CP + EV	✓				Preliminary data available. Home charge point monitoring and survey data received for partial sample block. The only dataset allowing influence of PHEV/BEV and different battery sizes to be reliably inferred.
Zap-Map	ZM	UK and UK Power Networks licence areas	Mar 2017 - Mar 2018	2,816 slow and 413 rapid public CPs	CPs			✓	✓	The best available dataset for public charging, due to very large sample size. Does not show kWh delivered, as only plug-in time recorded.

[30] This is an interim trial dataset. Final trial data will cover January 2017-December 2018.

4.1.1 Plugged-in Places (2010-13)

The Plugged-in Places programme was initiated by the UK Government in 2010 to support the installation of charging infrastructure in 8 regions across the UK[31]. Charging data was collected from all charge points from all charge points in the Plugged-in Places areas that were funded through the programme. This resulted in a publicly available dataset covering 988 home, work and public charge points monitored from August 2010 to December 2012. Some analysis of the data has been carried out by OLEV (Office for Low Emissions Vehicles, 2013), however, their definition of rapid public charge points included those rated at 22 kW, whereas in this present report rapid charging is classified as at least 50kW (see Section 2.3.5). Consequently, the dataset has been re-analysed to incorporate this difference. As for Low Carbon London, charge points were considered rapid if they showed a charge event with a rate >25kW. In addition, charge events were also discarded using the same filtering criteria as for Low Carbon London residential charge point data (see Section 4.1.1). Any charge points that featured only 1 charge event were also removed from the sample. The composition of the resulting sample in terms of charge point types is shown in Figure 20, which shows that it is heavily weighted towards slow/fast public charge points.

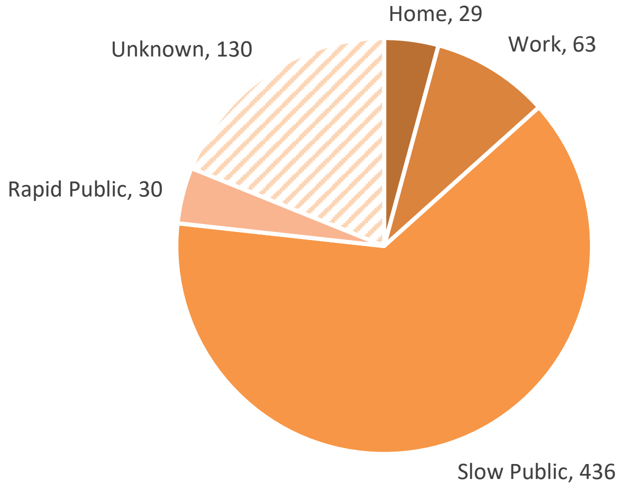

Figure 20: Number of each charge point type in the cleaned Plugged-in Places dataset Source: Element Energy analysis of the Plugged-in Places dataset.

4.1.2 Low Carbon London (2013-14)

Low Carbon London, led by UK Power Networks, included a programme of trials in London which investigated Demand Side Response (DSR) and distributed generation, electrification of heat and transport, and network planning and

[31] For more information on the Plugged-in Places programme see https://www.gov.uk/government/publications/plugged-in-places

operation[32]. This included several trials of EVs which recorded power, timing and duration of charging events. Three sets of monitoring data covering home, public and work charge points were available.

Home Charging Data

This contained monitoring data from 52 home charge points at 10-minute resolution, collected between January 2013 and June 2014. The breakdown of cars used by participants is shown in Figure 21, which reveals they are heavily weighted towards BEV drivers. The largest battery size featured is 24 kWh in the Nissan Leaf participants. This is considerably smaller than the latest BEVs available today which feature batteries from 35 kWh to 100 kWh.

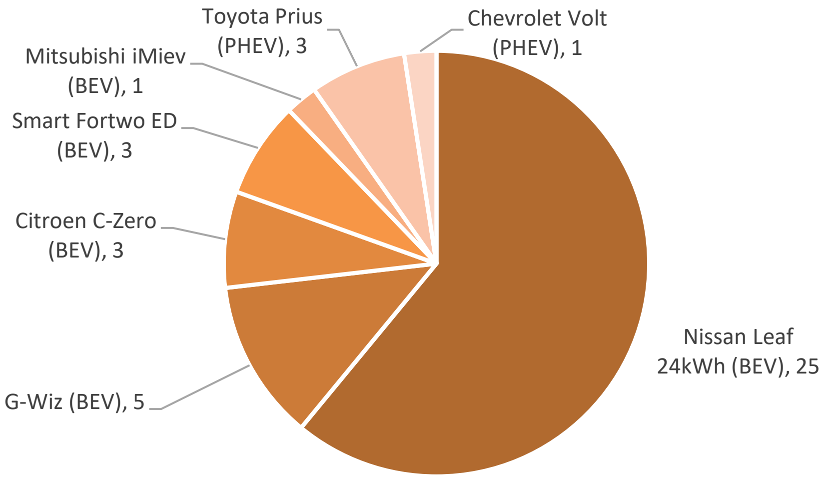

Figure 21: EV models driven by participants in the Low Carbon London home charge point monitoring dataset. Note that the dataset does not provide the EV models charged at 11 of the 52 home charge points.

In addition to the vehicle model, data on participants commuting habits is also available. Of the 41 participants for which data is available, 26 of them use their cars for commuting.

A considerable amount of analysis was carried out on the original sample (Aunedi, Woolf, Bilton, & Strbac, 2014), however, this focussed on the diversity of charging load. For this present study, the data has been re-analysed to specifically understand the influence of powertrain, battery size, commuting and day of the week. The publicly available project dataset consists of current and voltage measurements of the trial's residential charge points at 10-minute resolution. As a first step, the monitoring data for each charge point was run through an algorithm to identify each charge event, and record its start and end times, as well as kWh delivered. The resulting charge event dataset was cleaned in a similar manner to the original study, discarding events that:

- Delivered <0.1 kWh
- Had an implied rate (kWh delivered / duration) of <0.1 kW

[32] Low Carbon London project reports are available from http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/. The residential, public and commercial charge point monitoring raw data is available from the Greater London Authority Datastore: https://data.london.gov.uk/dataset/low-carbon-london-electric-vehicle-load-profiles.

Work Charging Data
This dataset included 10-minute resolution current and voltage meter data from 21 work place charge points, used by company cars, pool cars and public fleet cars, collected from January 2013 to March 2014. This data was re-analysed in a similar manner to the residential charge points, with a view to comparing weekend and weekday charging behaviour. From this data, 681 charge events were identified. However, the applicability of this data is limited since the sample size is very small and no information is provided on the car types using the charge points, such as their powertrain type or where else they charge.

Public Charging Data
This dataset contains charge event data from 393 public charge points, measured from July 2012 to May 2014. Each data point shows the plug-in start and end time, and the kWh delivered. The original analysis is detailed (Aunedi, Woolf, Bilton, & Strbac, 2014), but unfortunately does not consider the difference between slow/fast and rapid public charge points. It was therefore necessary to re-analyse the dataset to understand the difference in usage between the two charge point types. The capacity of each charge point is not shown in the publicly accessible data, and so charge points showing a maximum observed charge rate greater than 25kW were marked as rapid, with the remainder as slow. Although 25kW is significantly lower than the 50kW capacity of a rapid public charge point, battery capacities at the time were generally too small to accept 50kW. Using a threshold of 25kW ensures that any 22kW charge points are not erroneously identified as rapid.

4.1.3 My Electric Avenue (2012-15)

Between 2012 and 2015, Scottish and Southern Energy Power Distribution and EA Technology investigated the impact that clusters of EVs could have on local electricity networks through the My Electric Avenue trial[33]. Clusters consisting of 10 neighbours were monitored while testing smart charge points that could switch off if the load on the local feeder surpassed a particular threshold. The trial included 100 cluster participants, and a further 100 participants spread across the country. All participants drove a 24 kWh Nissan Leaf. The trial data that was publicly available included:

- All charge events recorded by the cars, logged as the times the car started and ended a charge and the kWh delivered.
- Voltage and current measurements, at 10-minute resolution, for each home charge point.
- Information on each participant, such as their start and end date in the trial, and their location.

Since the purpose of the trial was to gauge the effectiveness of actively switching off charge points to protect the local grid, the resulting analysis was more concerned with the observed loads rather than the factors that contributed to them (Quiros-Tortos & Ochoa, 2015). The dataset was therefore re-analysed to explore the impact of day of the week and urbanity. Although the charging events recorded by the EV included no information on where the charge took place, home charge events were identified by cross-referencing with the charging data recorded by the home charge point. From the remainder of charge events, rapid public charge events were assumed to be where the charge rate was >10kW. Note that the Nissan Leaf 24kWh is unable to charge at more than 6.6kW with an AC supply, which was only available as an optional extra, and therefore any rate higher than this will be with a 50kW DC rapid charge point. Compared with other available datasets, this one is unique in that it provides charge data as monitored from the EV. This enables share

[33] http://myelectricavenue.info/

of charging at different charging location types to be explored, although it is not possible to distinguish between slow/fast public and work charging.

4.1.4 ESB ecars (2016-18)

This dataset consists of status data for all public charge points in ESB's ecars network in the Republic of Ireland and Northern Ireland at a 5-minute resolution. This includes over 500,000 charge events recorded across 591 public charge points. This data has not been provided by ESB directly, but instead gathered by a third-party through monitoring the status of charge points as listed on the ecars Charge Point Map[34]. The data is freely available from http://www.cpinfo.ie/data/archive.html, and updated monthly. For the purposes of this study, the data analysed covered the period November 2016 – July 2018. Plug-in and plug-out events were identified from changes to each charge point's status to and from "Occupied" or "Partially Occupied". The sample includes 496 charge points with a maximum capacity of ≤22kW, designated as 'slow/fast', and 94 with a capacity ≥43kW which we designated as 'rapid'.

Figure 22 and Figure 23 show the distribution of plug-in durations of slow/fast and rapid public charge events. For slow/fast public charging there are very few events with durations beyond 16 hours, however, 1.3% of events identified are longer than 24 hours with the longest lasting for nearly 16 days. Similarly, for public rapid charging there are very few plug-in durations longer than 2 hours, but 0.8% are longer than 3 hours, with the longest nearly 7 days. These events were excluded from the analysis as they have a disproportionate impact on the mean durations and are considerably longer than the maximum time an EV can draw power for.

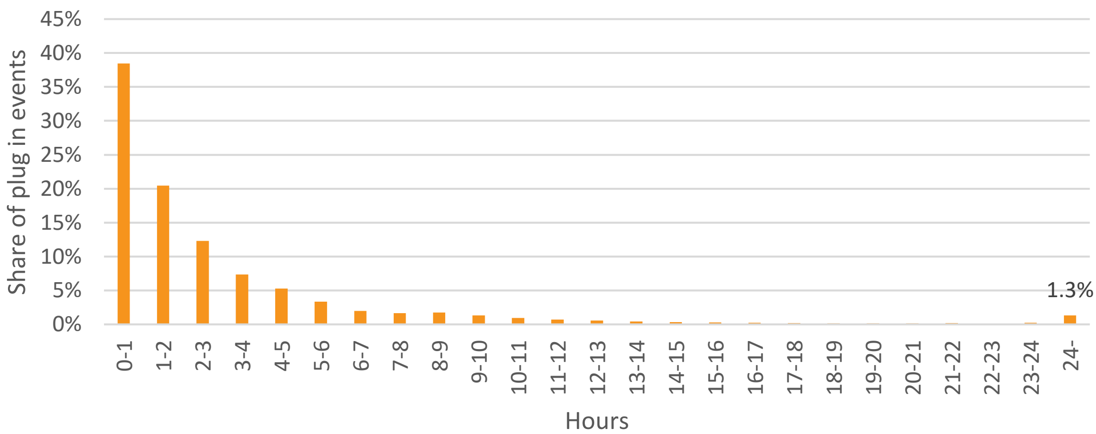

Figure 22: Distribution of plug-in durations for the slow/fast public charge events in the ESB ecars monitoring dataset.

[34] https://www.esb.ie/our-businesses/ecars/charge-point-map

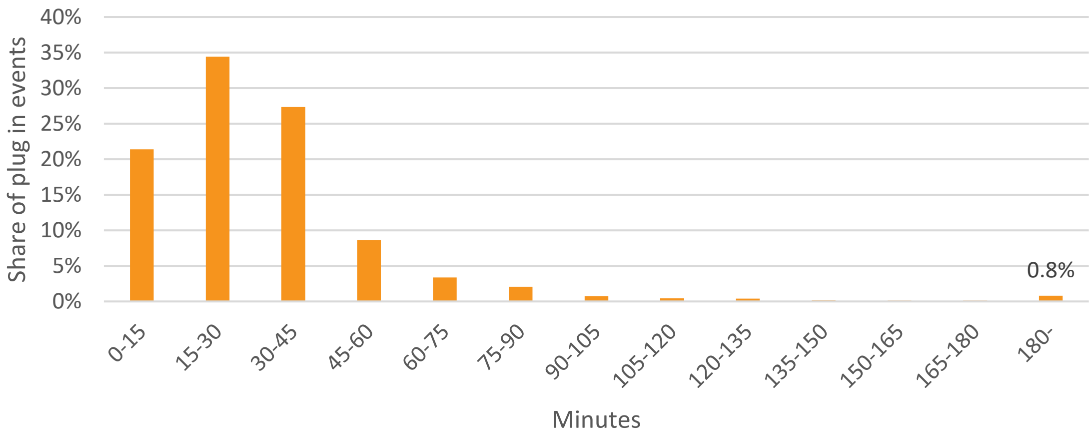

Figure 23: Distribution of plug-in durations for the rapid public charge events in the ESB ecars monitoring dataset.

4.1.5 Electric Nation (2017-18)

The Electric Nation Project, a Network Innovation Allowance project led by Western Power Distribution in partnership with EA Technology and DriveElectric, follows on from the findings of the My Electric Avenue project, and aims to understand how the use of 'smart' chargers could act as an alternative to costly network upgrades. With respect to understanding charging behaviour, this project goes beyond My Electric Avenue in two key ways: the number of EVs is considerably larger with a targeted participant sample of up to 700 (compared with 200 in My Electric Avenue); participating EVs include both BEVs and PHEVs with a wide range of models and battery sizes. As a result, this is the largest trial of its kind in the UK to date.

Despite the project running until mid-2019, Western Power Distribution helpfully shared an interim dataset of charge events recorded by the smart charge point. These charge points have been installed in each of the participant's homes and are capable of automatically reducing charge rate and/or delaying charge start times in response to the load on the local electricity network. In addition, data on each of the participants was also shared, including the EV model they used, whether they used it for commuting and had access to work charging, and their level of urbanity. The sample included 578 participants, although those that showed less than 7 days' worth of data were excluded, which left 195 BEVs and 207 PHEVs (see Figure 24 and Figure 25). Note that the sample included 60 BMW i3 range-extended electric vehicles with battery capacities of 22 kWh or 33 kWh. Despite being based the BMW i3 BEV, these have been included in the PHEV sample since they are powered by both fuel and electricity.

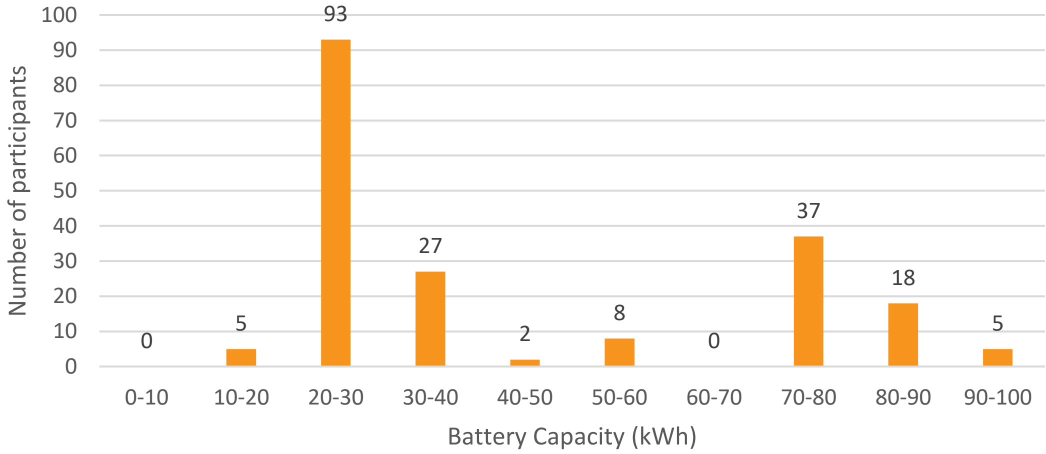

Figure 24: BEV participants in the Electric Nation Apr 2017-Feb 2018 sample, by battery size. Each battery size bin includes upper bound. Source: Element Energy analysis of the interim EN dataset

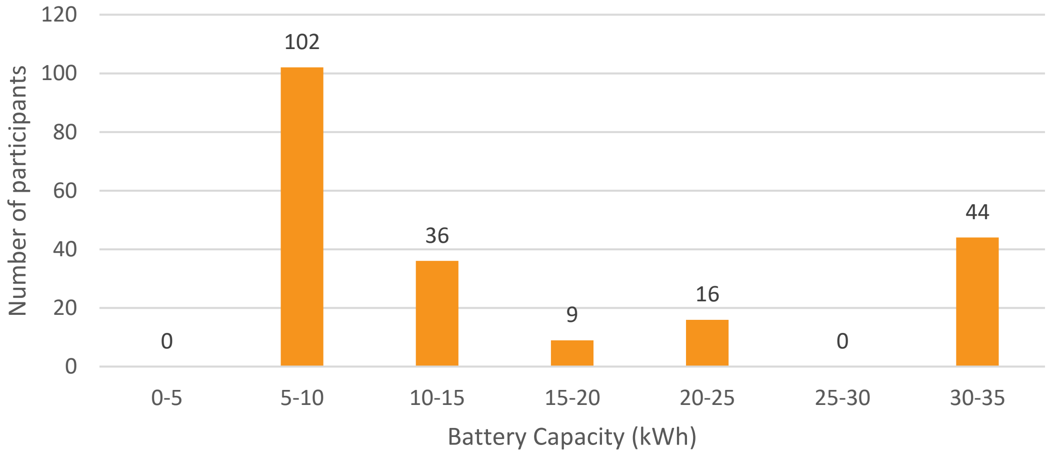

Figure 25: PHEV participants in the Electric Nation Apr 2017-Feb 2018 sample, by battery size. Each battery size bin includes upper bound. Source: Element Energy analysis of the interim EN dataset

The charge events data shows both the timestamp of when the car plugged-in and plugged-out, as well as when the EV starting drawing power. This enables charge events where the user has chosen to use their EV's delayed/scheduled charging function to be identified. The sample included 33,796 charging events, but before being analysed was cleaned to remove the following outliers:

- Events with a plug-in duration >50 hours

- Events that consumed <0.1 kWh

In addition, the kWh consumed in each event was capped at the battery capacity of that specific participant's EV.
The data shared also included responses to participant surveys, enabling the influence of participant characteristics on charging behaviour to be investigated. For example, using these survey answers it was possible to identify which participants used their vehicles for commuting and of these who had access to work place charging, and whether they were located in an urban or rural area. Note that participants that reported their location as 'Mixed/semi-rural' were classed as rural.

Whilst the value of this dataset is high, given its large sample and diverse composition, it must be stressed that this is interim trial data which has not yet undergone rigorous quality checking by the project team. For example, EA Technology have cautioned that they have experienced some problems with communication black-outs with charge points which could result in charge events being missed in this dataset. In some cases, the charging data is stored locally in the charge point and so some of these black-outs will not be present in the final trial data. Regardless, a more detailed analysis which will attempt to correct for these issues will be carried out by EA Technology once the trial has ended and fully disseminated to the industry.

4.1.6 Zap-Map (2017-18)

In the absence of high-quality data on UK public charge point usage, an additional dataset was purchased from Zap-Map. The Zap-Map website features a map of all public charge points in the UK, and in December 2016 started showing live charging status data for some of the charge points, which they have subsequently rolled out for most of the major networks. They have consequently collected a large dataset of public charging events and were able to provide 12 months of detailed charging data from 2,816 slow/fast public charge points and 413 rapid public charge points across the UK up to 31st March 2018. At the time of the analysis, this covered 40% of all slow/fast public charge points and 32% of rapid public charge points installed in the UK. This is the largest and most up-to-date dataset of UK public charging infrastructure usage currently available, and the study represents the first time that it has been analysed in this manner. Due to the commercial sensitivity of the raw data all analysis was carried out by Zap-Map, with only the outputs of this made available. This output data included the following fields:

- Number of charge events
- Mean utilisation in terms of events per day per charging device
- Distribution of plug-in durations
- Plug-in start time profiles

And each of these fields was disaggregated by the following dimensions:

- Slow/fast public and rapid public
- UK and UK Power Networks licence area only
- Urban and rural (as defined by LSOA's 2011 Census definition)
- Located by trunk road or not
- Weekend and weekday

Note that not all charge points produced 12 months of data, as many were added to the data stream during the collection period, while the data resolution also changed from 15 minutes to 5 minutes. This makes the results unsuitable for comparing seasonal differences in charging behaviour. Furthermore, no data was available on kWh supplied during charge events or when charging, rather than simply being plugged in, actually took place. However, to our knowledge this remains the most comprehensive dataset of public charging behaviour in the UK to date.

5 Charger Use Findings

This section outlines the findings from the literature review, stakeholder consultation and additional data analysis for each of home, residential on-street, work, slow/fast public and rapid public charge points. These findings will be integrated into the Recharge the Future EV Load Forecasting Module which will be used to enhance the Element Energy Load Growth Model, the process of which will be documented in a separate report along with the conclusions from the modelling.

For each charging location type, charging behaviour is characterised by:

- Time of charging
- Charging frequency
- Charge duration and/or kWh per charge
- Share of charging at location

Where possible, for each of these characteristics the impact of the following factors, as observed in the literature, is discussed:

- Day of the week
- Powertrain i.e. PHEV vs BEV
- Battery capacity
- Commuter status
- Urbanity

For home charging, this study also investigated the impact of diversity on peak load, and its relationship with the number of EVs charging.

Season is also expected to have an impact on charging behaviour since EV electricity consumption is known to be higher during the winter compared with summer. This is due to greater need for battery and cabin heating during Winter, and reduced battery performance at low temperature. However, there is not yet enough available data to show how charging behaviour changes throughout the year. Although some trials collect data over the course of a year, the samples do not necessarily remain consistent. Note that seasonal differences will be included in final analysis of Electric Nation trial data, due in mid-2019.

The underlying data in each figure are available in a supplementary Appendix, available upon request.

5.1 Home

5.1.1 Time of charging

Charging start times are strongly dependent on the day of the week. Figure 26 shows the average plug-in start time profiles observed in literature and derived from available data. Plug-in start time is the time at which the vehicle is plugged in, which is not necessarily the same as when it starts charging. These profiles show the share of plug-in events which start in each hour of the day.

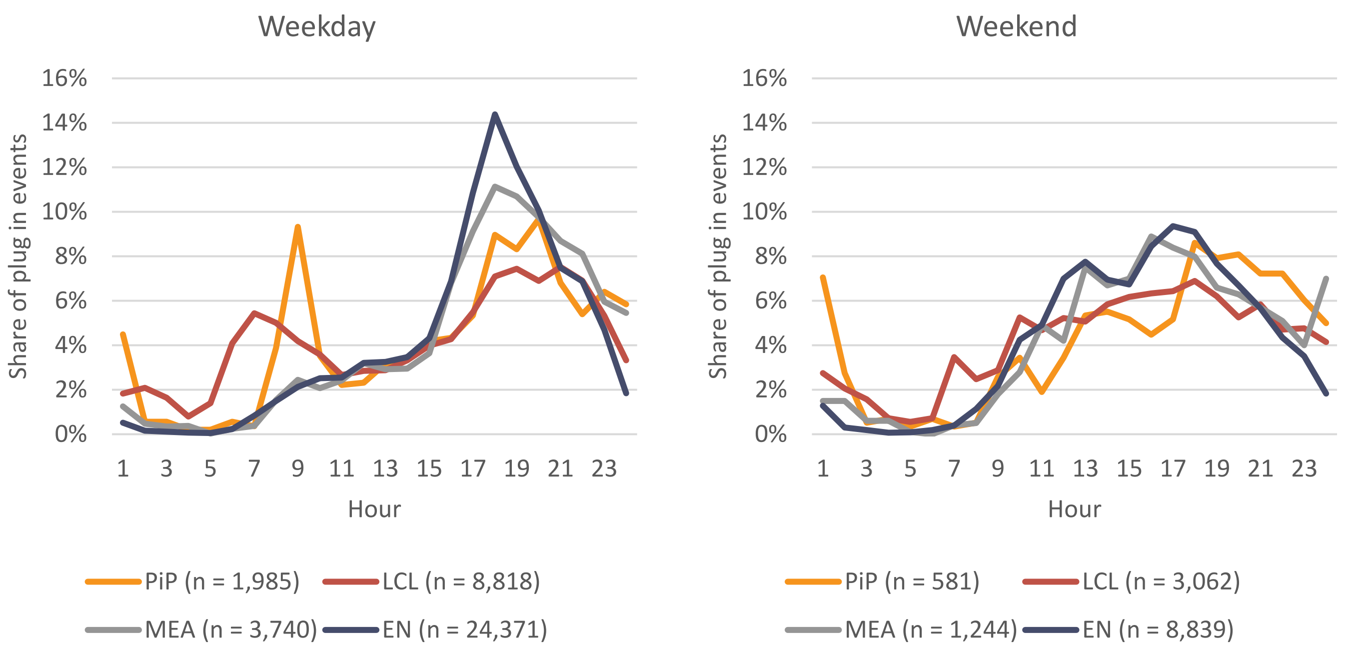

Figure 26: Average plug-in start time profiles at home for weekday and weekends. 'n' is the number of charge events in the samples. Note: the EN dataset is not final (trial on-going)

On weekday, all data sources show a strong peak in plug-in events occurring in the evening between 6pm and 8pm, with far fewer plug-in events starting during the middle of the day. It is proposed that this is because most EV drivers tend to plug in at home after their last trip of the day, which in most cases will be arriving home from work or the school-run. On weekends plug-in events are spread more evenly throughout the day, resulting in a considerably broader evening peak occurring slightly earlier in the day. Note that in both Low Carbon London (LCL) and Plugged-in Places (PiP), a morning peak is also observed on weekdays. Reasons for this are not provided, but it may be a result of EV drivers forgetting to plug in the previous evening, and so attempt a quick morning charge before starting their daily driving or plug in to pre-condition the vehicle during very hot or cold weather. However, this morning peak is not observed in more recent datasets, My Electric Avenue (MEA) and Electric Nation (EN).

Low Carbon London and Plugged-in Places also displays a slightly later evening peak than the other data sources. This is likely a consequence of differences in the sample make-up, for example Low Carbon London focussed purely on London, whereas the other trials included participants from elsewhere in the UK. This is illustrated by the fact that 44% of the Low Carbon London participants reported using their cars for commuting, compared with 77% in Electric Nation. The Electric Nation data shows that using the EV for commuting has a strong influence on charge times during the week. Figure 27 illustrates how the time of commuter plug-in events on weekdays are concentrated in the evening, which presumably coincides with when commuters arrive home from work. For non-commuters, the weekday plug-in start time profile shows a much broader peak, which is similar to the average weekend profile shown in Figure 26. This suggests that the evening peak observed on weekdays is primarily due to commuters.

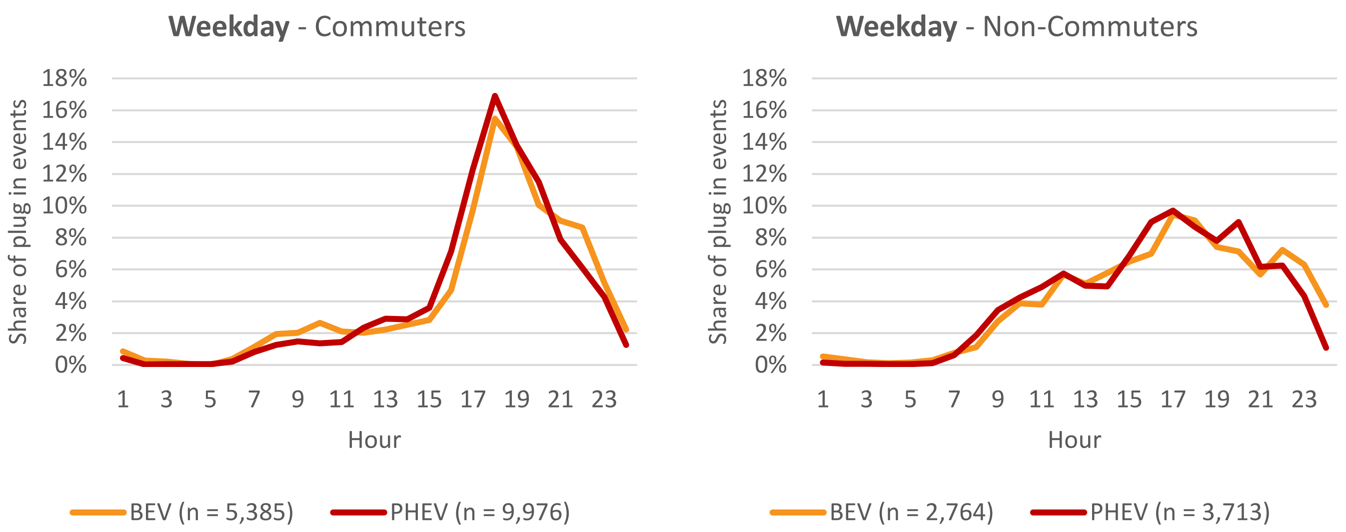

Figure 27: Average plug-in start time profiles at home for ***weekday*** *charge events for commuters and non-commuters, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

Figure 28 shows the equivalent comparison between commuters and non-commuters but for weekend plug-in events. The profiles appear very similar to one another, with no strong evening peak visible for commuters. This is unsurprising given that most commuters will not be travelling home from work during the weekends.

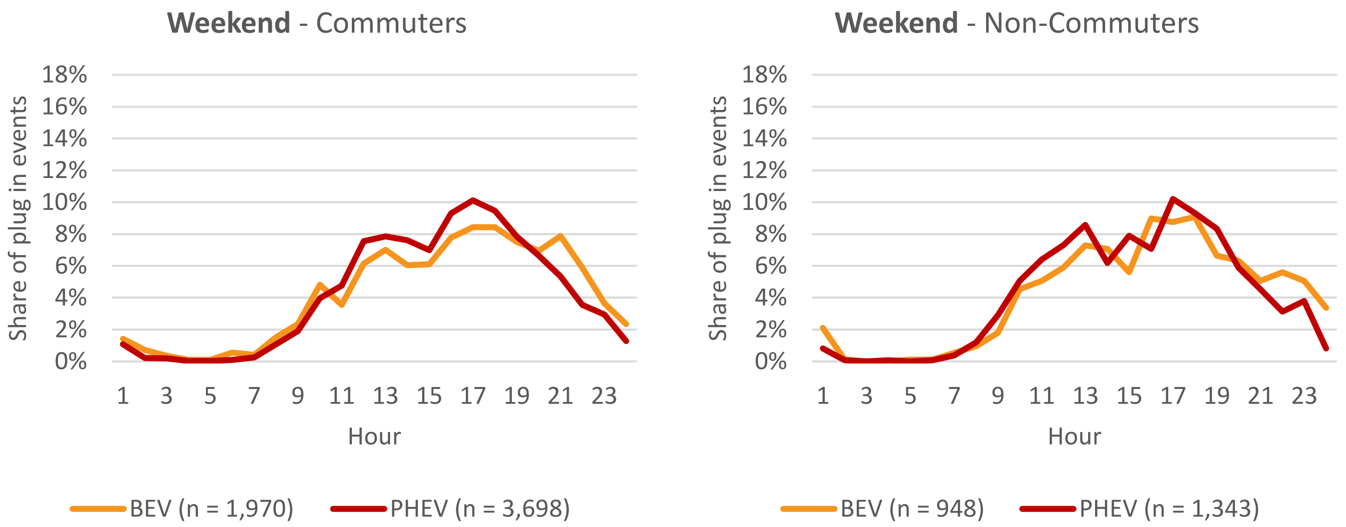

Figure 28: Average plug-in start time profiles at home for ***weekend*** *charge events for commuters and non-commuters, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

Figure 27 and Figure 28 also reveal that there is very little difference between the plug-in start times of BEVs and PHEVs, with very similar profiles observed in all four cases. This is supported by findings from the Victorian EV Trial in Australia which also observed no significant difference between the charge start times of BEVs and PHEVs (Khoo, Wang, Paevere, & Higgins, 2014).

Figure 29, Figure 30 and Figure 31 illustrate the influence of battery size, which in general shows no discernible trend with plug-in time. This was also observed in the Victorian EV Trial (Khoo, Wang, Paevere, & Higgins, 2014). Figure 30 shows some weekday variation across battery size between non-commuters: both BEVs with medium and large batteries and PHEVs with small batteries display a more concentrated evening peak. However, at this level of disaggregation the sample sizes are relatively small. For example, there are only 12 non-commuter BEVs with batteries between 30kWh and 60kWh. This would require further analysis with the full sample, once the trial is complete, to confirm whether a trend exists.

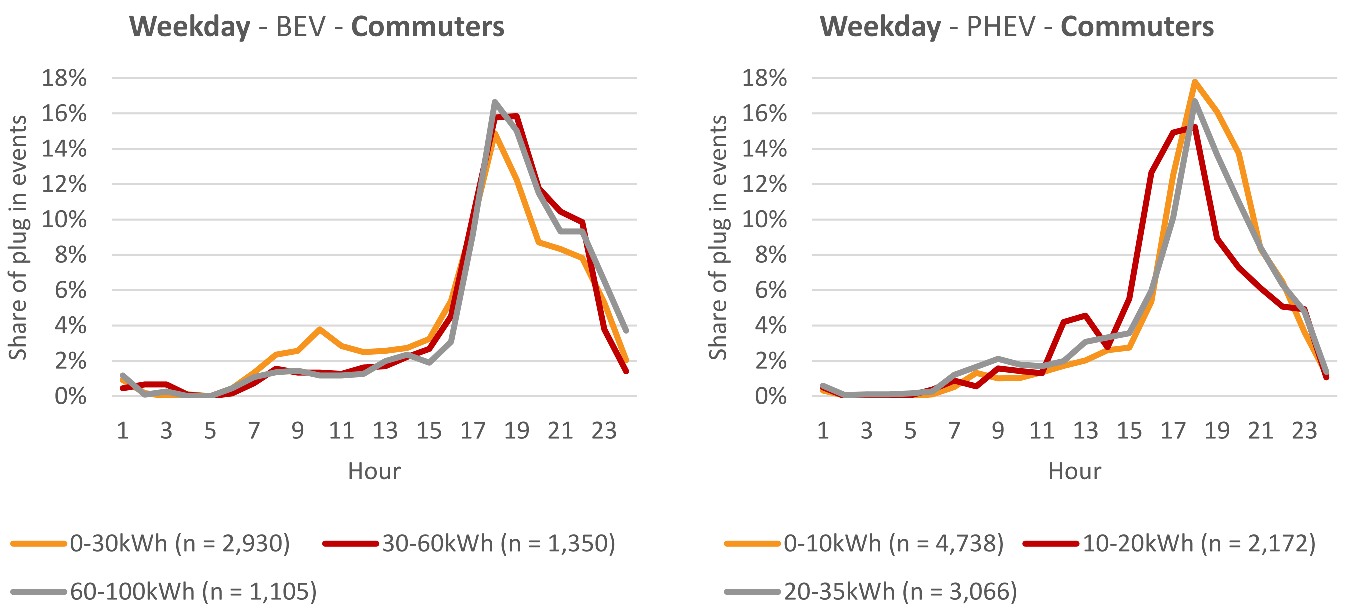

*Figure 29: Average plug-in start time profiles at home for **weekday** charge events for **commuters**, grouped by battery size, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

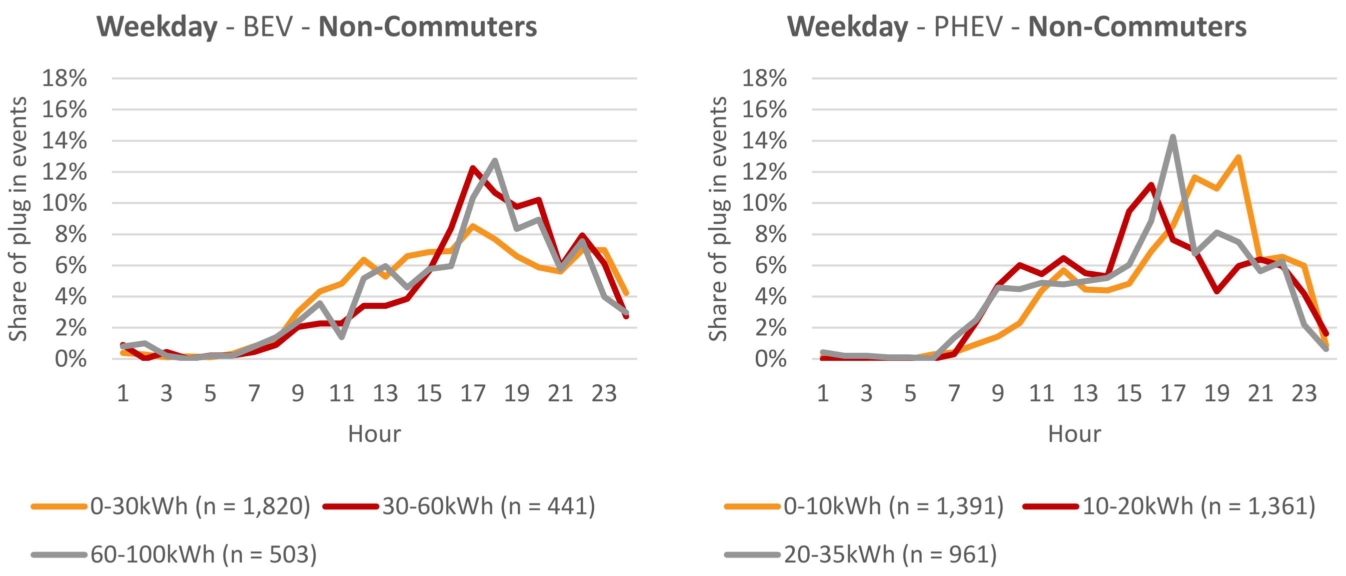

*Figure 30: Average plug-in start time profiles at home for **weekday** charge events for **non-commuters**, grouped by battery size, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

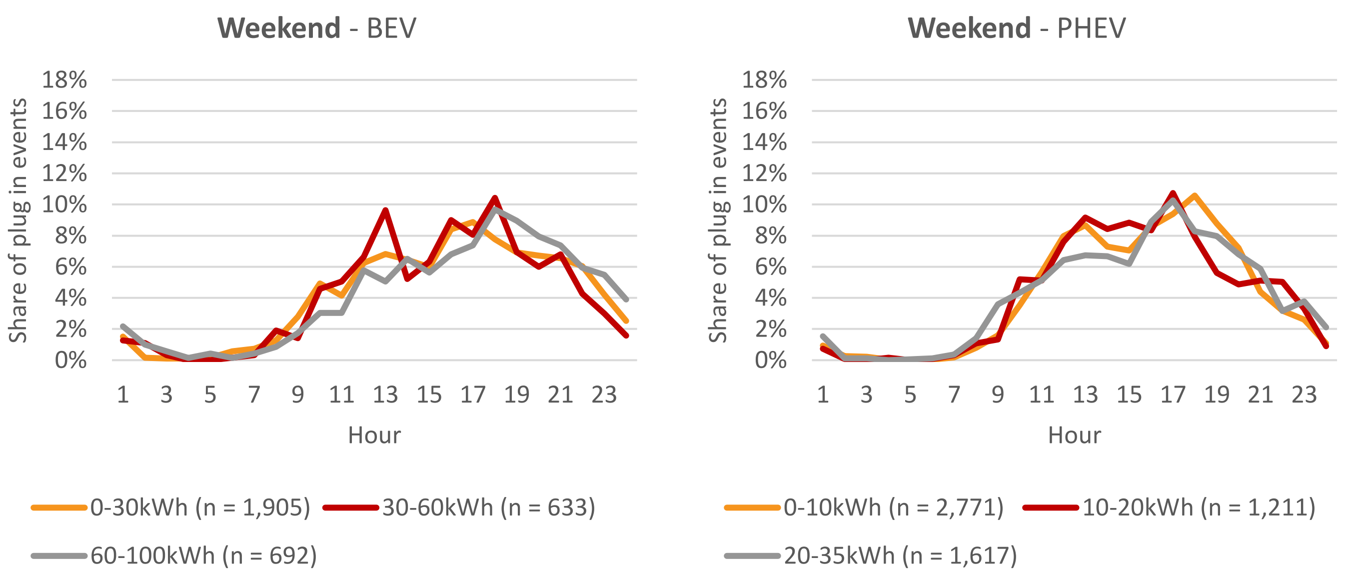

*Figure 31: Average plug-in start time profiles at home for **weekend** charge events, grouped by battery size, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

Figure 32 reveals that having access to work charging has no influence on commuters' plug-in start times.

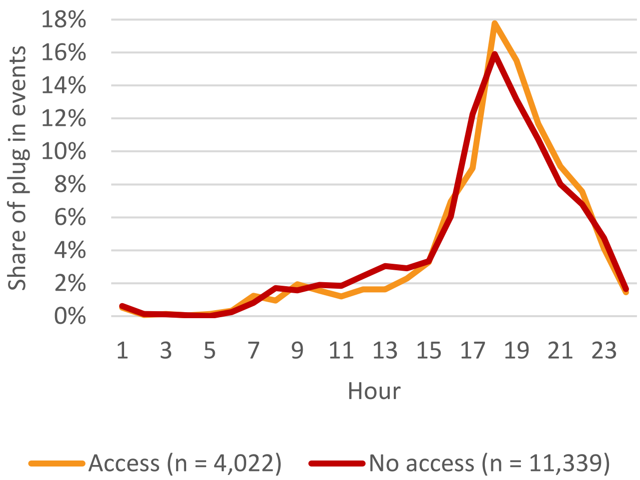

*Figure 32: Average plug-in start time profiles at home for **weekday** charge events, comparing commuters with and without work charging access, from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

Similarly, Figure 33 and Figure 34 demonstrate the minimal impact of urbanity on plug-in time. For the comparisons shown, the profiles are near identical, other than non-commuters on weekdays for whom the evening peak comes slightly later for urban EVs. However, the reason for this is that the urban non-commuter sample is skewed by 2 of the sample's 31 participants who contribute 13% of the charge events, and these are concentrated in the evening around 7pm.

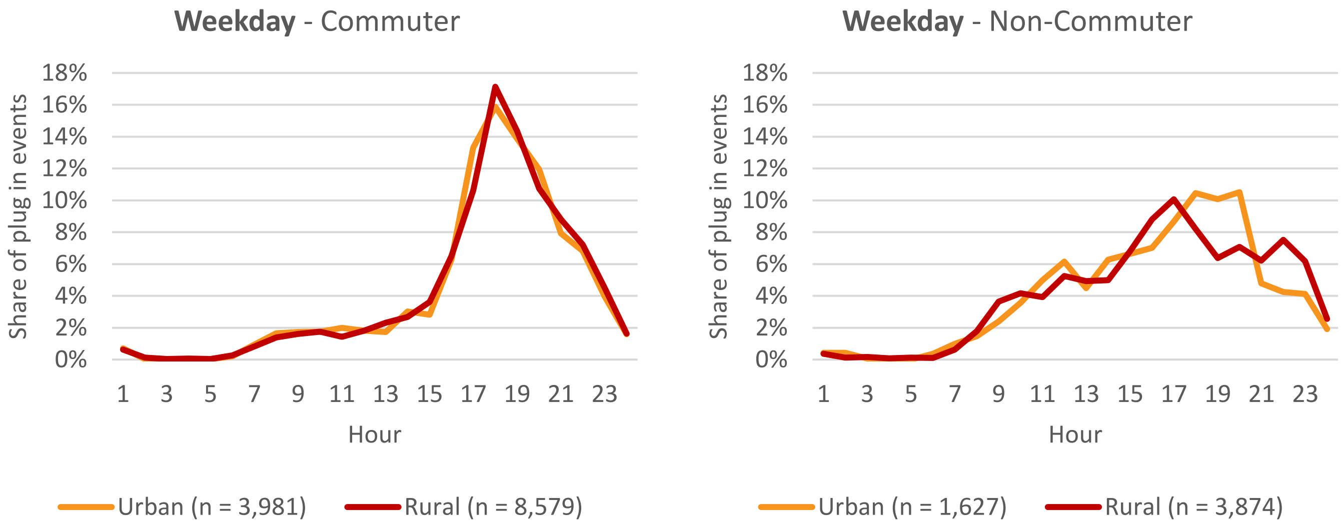

*Figure 33: Average plug-in start time profiles at home for **weekday** charge events, comparing urban and rural participants from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

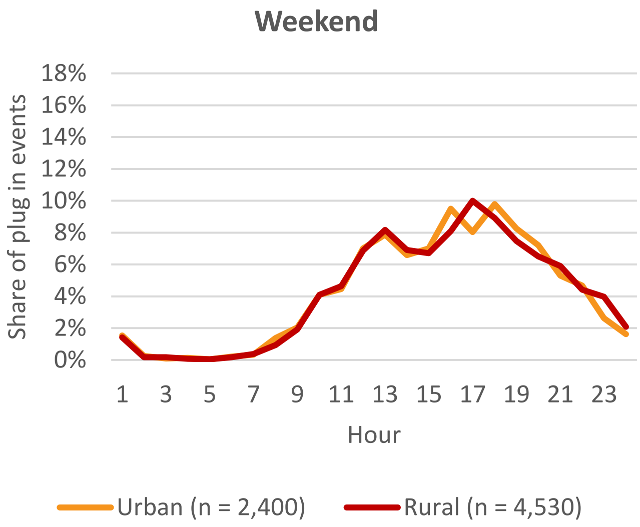

*Figure 34: Average plug-in start time profiles at home for **weekend** charge events, comparing urban and rural participants from the Electric Nation dataset. 'n' is the number of charge events in the sample.*

In general, only factors which are linked to journey times i.e. day of the week and commuting have a significant influence on the plug-in start times. This is unsurprising given that charging cannot (yet) be carried out while a vehicle is in use, and it is most convenient to plug-in at home immediately after arrival. Because of this many early modelling studies generated charging profiles from travel statistics, before actual charging data was readily available, but it is only recently that the strength of this assumption has actually been explored. For example, it was noted during an analysis of data during the Green eMotion Ireland trial that participants showed a *preference to recharge their vehicle immediately following the last journey of the day* (Weldon, Morrissey, Brady, & O'Mahony, 2016). Conversely, analysis of data from the Japan Automobile Research Institute (JARI), which monitored 234 privately owned BEVs in Japan, found that only 45% of home charge events occurred immediately after the last trip of the day (Xiao-Hui Sun, 2015). However, the vast majority of charge events which were delayed later began after 11pm which is when off-peak electricity prices become available. Furthermore, the data only recorded the time that charging started, rather than plug-in time, and so it is possible that a larger proportion of EV users were plugging in immediately after returning home and using their vehicle or charge point's charge delay or scheduling function.

5.1.2 Charging frequency

Figure 35 compares the available data on weekday and weekend charging frequency and reveals that currently on average EVs charge about once every two days, with a marginally higher frequency on weekdays. However, note that for all the available datasets there was no information available on whether there were any communication outages, which would therefore show up as days without charging. Since the existence of communication outages is known for the Electric Nation data (see Section 4.1.5), it should be recognised that they may also be present in the other data sources.

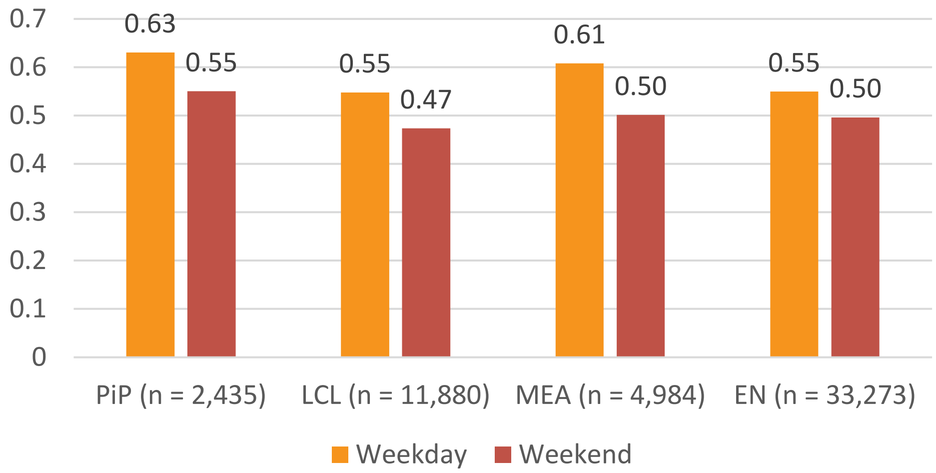

Figure 35: Charge events per day at home charge points, from available data sources. 'n' is the number of charge events in the sample.

Figure 36 compares the charge events per day for BEVs versus PHEVs from both Low Carbon London and interim Electric Nation datasets and finds that PHEVs are charged significantly more often than BEVs[35]. This was previously found to be the case during the Pecan Street Smart Grid Demonstration Project in Austin, USA, and was attributed to the smaller batteries in PHEVs and the desire to minimise fuel usage (Harris & Webber, 2014). The implication is that BEV drivers are choosing to charge only when their battery reaches a low state of charge, in a similar fashion to refuelling a conventional car. However, note that in Norway, which is a more advanced EV market, it found that the gap between BEV and PHEV charging frequency is lower. It is estimated from the Norwegian EV Owners Survey 2016 that BEV owners charge at home on average 0.7 times per day compared with 0.83 for PHEVs (Figenbaum & Kolbenstvedt, 2016). Average annual mileage for the survey participants was 15,500 km for BEV owners and 15,200 km for PHEV owners, which is marginally higher than the UK average of 13,200 km[36] does not fully explain the greater charging frequency. It is therefore possible that in future, in a more advanced market where consumers are used to driving EVs, that more will habitually plug-in every day regardless of state of charge.

[35] Note that interim Electric Nation dataset may include days where communication was lost with some of the charge points and so charge events were not recorded. Caution must therefore be taken with these initial charging frequency findings.
[36] DfT Road Traffic Statistics Table TRA0201: Road Traffic (vehicle kilometres) by vehicle type in Great Britain

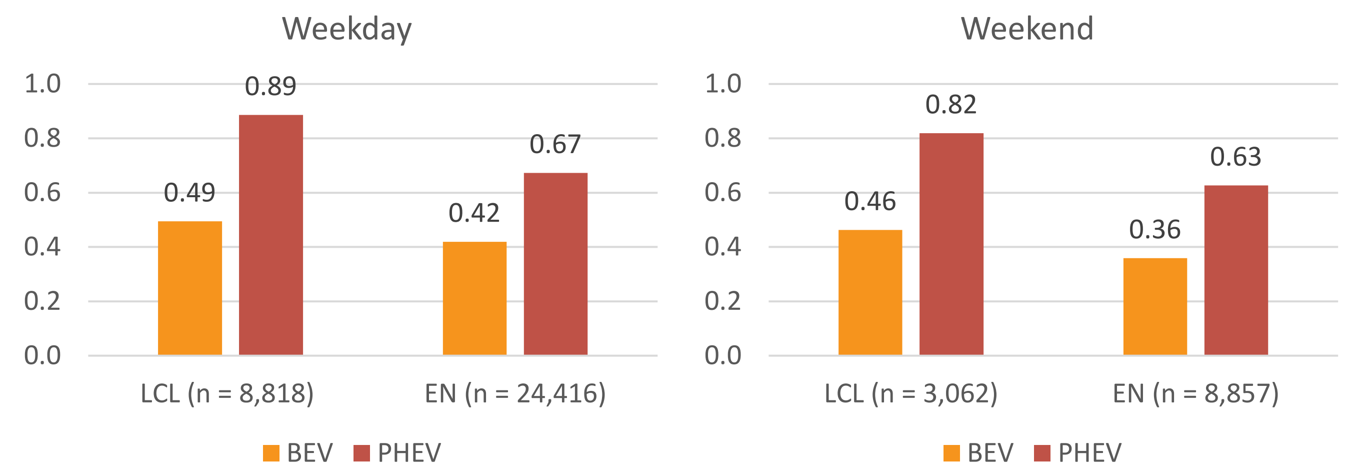

Figure 36: Charge events per day at home charge points, for PHEVs and BEVs, from available literature sources. 'n' is the number of charge events in the sample.

However, anecdotal evidence suggests that in the UK a significant number of PHEV drivers rarely charge and instead complete most of their mileage under fuel power. The reason for this may be they do not have access to charging at home, or they are company car drivers who are reimbursed for fuel and/or purchased a PHEV to take advantage of favourable company car tax rates. These drivers are unlikely to be covered in EV charging trials, which tend to be carried out with early adopters and require participants who do charge so that they generate a sufficient amount of charging data. All participants in Low Carbon London and Electric Nation, for example, has access to a home charge point. A recent analysis by website HonestJohn.co.uk of real fuel consumption figures submitted by car owners found that the average miles per gallon achieved by some plug-in hybrids, such as the Mercedes C-Class C350e, BMW 330e and Volkswagen Golf GTE, was <40% of the official type-approval figure[37,38]. This is considerably lower than the average 83% achieved by all cars in the HonestJohn.co.uk sample, as well as the 70% identified by the ICCT for all cars sold in Europe in 2016[39]. This can be partly explained by the shortcomings of the type-approval process which over predicts electric range, and thus inflates PHEVs' assumed share of driving under electric power and the official fuel consumption figure, but this still indicates that PHEVs in the HonestJohn.co.uk sample are driving a lower share of mileage under electric power than expected. However, the size and composition of the HonestJohn.co.uk PHEV sample is unknown, and other studies have found that on average PHEVs drive a large share of mileage under electric power. For example, in Norway, where electric vehicles are now owned by the mass-market, the Norwegian EV Owners Survey 2016 reported that the PHEVs averaged 55% of their mileage under electric power (Figenbaum & Kolbenstvedt, 2016). This suggests

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[37] HonestJohn.co.uk, 5th June 2018: "Ninety-eight per cent of hybrid cars can't match their advertised MPG", available from: https://www.honestjohn.co.uk/news/real-mpg/ninety-eight-per-cent-of-hybrid-cars-can-t-match-their-advertised-mpg/
[38] It is not known whether real world fuel consumption has been compared with NEDC or WLTP type-approval figures in the analysis by HonestJohn.co.uk
[39] ICCT, 5th November 2017: "Real-world vehicle fuel consumption gap in Europe at all-time high", available from: https://www.theicct.org/news/EU-real-world-vehicle-fuel-consumption-gap-all-time-high

that in future, at least, when PHEV penetration is higher, owners will attempt to charge their vehicles. However, this may not be possible for drivers without access to off-street parking who are likely to make up a larger portion of EV owners as EV market share increases.

Figure 37 illustrates the influence of battery size on charge frequency for both BEVs and PHEVs, as observed in the interim Electric Nation data. These should be considered preliminary findings as the analysis does not consider the impact of possible data outages (see Section 4.1.5). This information was unavailable in the interim data but will be included in the final trial data analysis. However, comparison with more recent findings by the project team are consistent with those presented here. In general, the larger the battery, the less often drivers charge, although note that there is high variability for PHEVs with batteries ≤10 kWh. This is unsurprising since drivers aren't dependent on charging to use their PHEVs, and frequency of charging will therefore depend on how much they want to drive under electric power. Note that for PHEVs with a battery capacity >20 kWh, the frequency of charging is similar to BEVs with battery capacities ≤30 kWh. In the sample, all the PHEVs in this case are 22 kWh or 33 kWh BMW i3s with range extenders. Although range extenders run off both electricity and fuel, and so for the purposes of this analysis have been classed as PHEVs, they differ in that without the engine they work as fully functioning BEVs. There is no mechanical link between the engine and wheels, and the engine's only purpose is to charge the battery when the state of charge approaches zero. For true PHEVs, the engine can directly power the wheels and will operate in conjunction with the battery and motor during times of high power demand, e.g. fast acceleration or hill climbing. Frequently operating a range extended BEV, such as the BMW i3 Rex, on fuel power alone is not recommended as running on the low power engine will bring performance penalties compared with running on battery power. It is therefore unsurprising that charging frequency with these vehicles is so similar to their BEV-only counterparts.

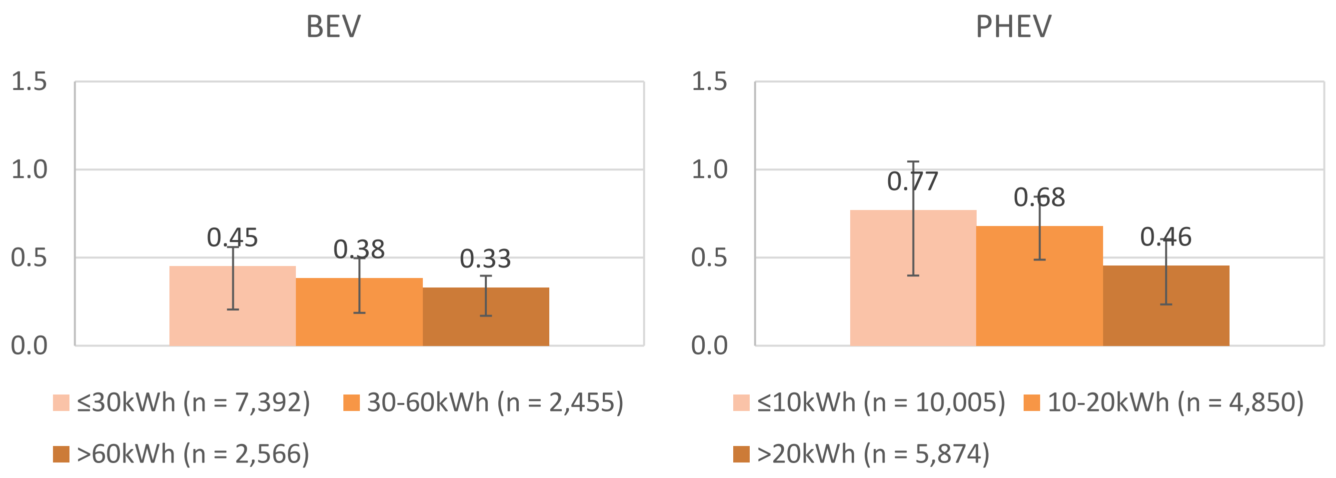

Figure 37: Average charge events per day at home charge points, for BEVs and PHEVs grouped by battery size, from the interim Electric Nation dataset. Error bars show upper and lower quartiles. 'n' is the number of charge events in the sample.

In Figure 38 and Figure 39 the difference in charging frequency for commuters and non-commuters is explored, using the interim Electric Nation dataset. For weekday charging, the frequency appears greater for commuters compared to non-commuters, unless they have access to charging at work. This is as expected, since commuters tend to have higher mileage and will use their vehicles more regularly, and so have greater charging need. But if these commuters have access to charging at work, then their need for charging at home is relieved somewhat.

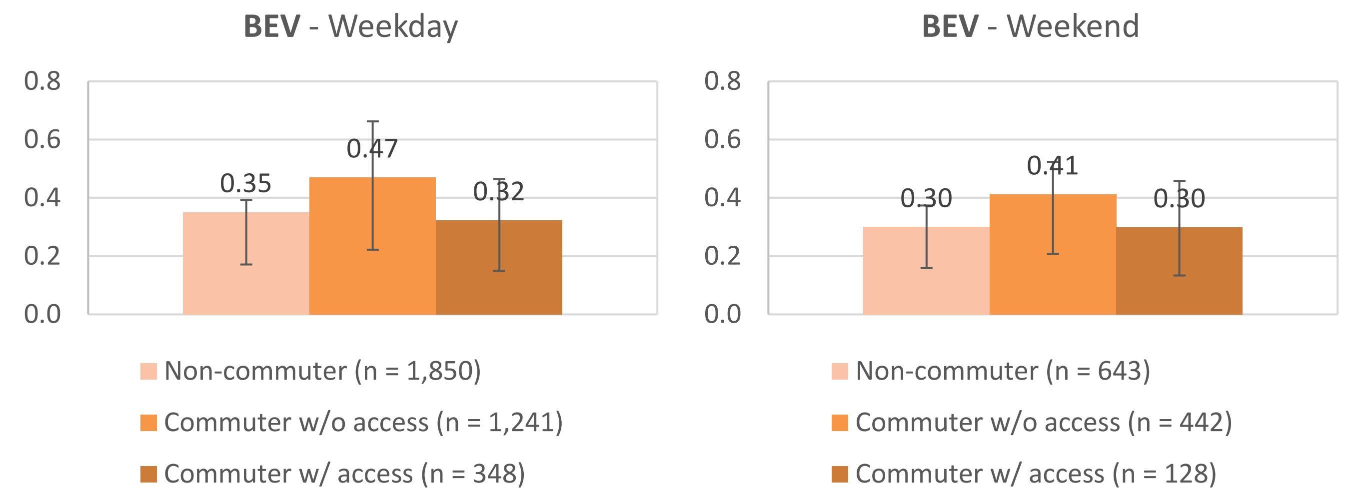

Figure 38: Average charge events per day at home charge points, for BEV commuters with and without work charging access and non-commuters, from the interim Electric Nation dataset. Error bars show upper and lower quartiles. 'n' is the number of charge events in the sample.

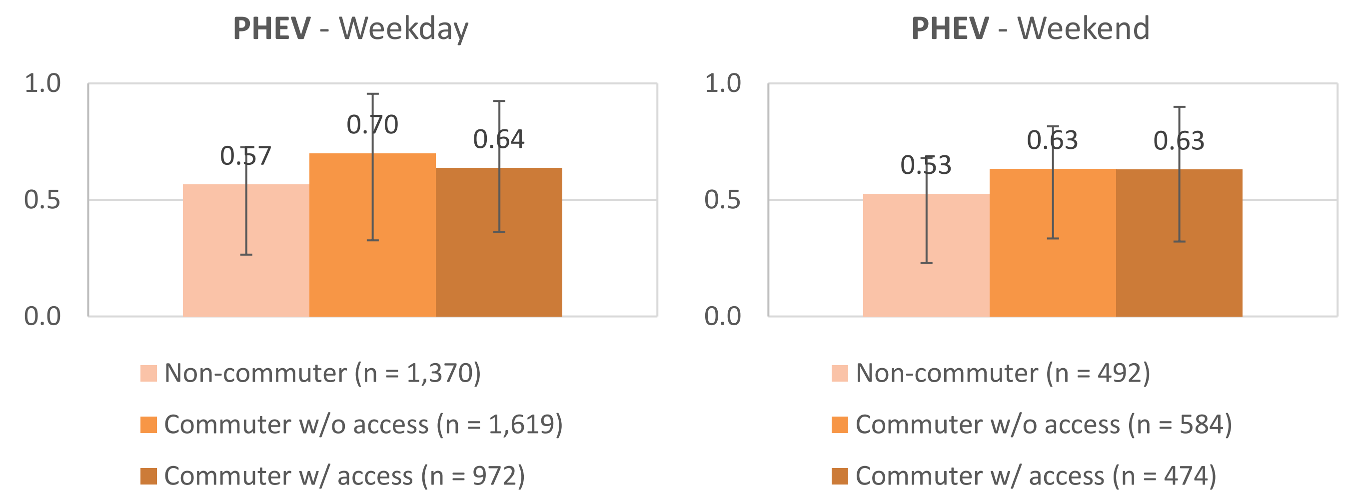

Figure 39: Average charge events per day at home charge points, for PHEV commuters with and without work charging access and non-commuters, from the interim Electric Nation dataset. Error bars show upper and lower quartiles. 'n' is the number of charge events in the sample.

However, the weekday trend between commuters and non-commuters is also visible on weekends, where the influence of commuting should be much reduced. It may be that due to their higher mileages, commuters are more likely to enter the weekend with a low state of charge, and consequently are more likely to encounter a need to plug-in. It is worth noting that the average battery size of the BEV commuters with access to work charging is 56 kWh, compared with 42 kWh and 44 kWh commuters without work charging and non-commuters respectively. Given that battery size appears to have a strong influence on home charging frequency, this will also contribute to the reduced frequency of this group in Figure 38. Note that the average PHEV battery size is 16 kWh for all three groups.

5.1.3 Charge duration and/or kWh per charge

Figure 40 compares the average time spent plugged in and drawing charge at home, from available data sources. This illustrates that EVs usually require only 2-3 hours to charge during both weekends and weekdays but remain plugged-in for considerably longer. This is supported by findings from the Switch EV trial, which reports an average home charge duration of 3.1 hours (Robinson, Blythe, Bell, Hübner, & Hill, 2013).

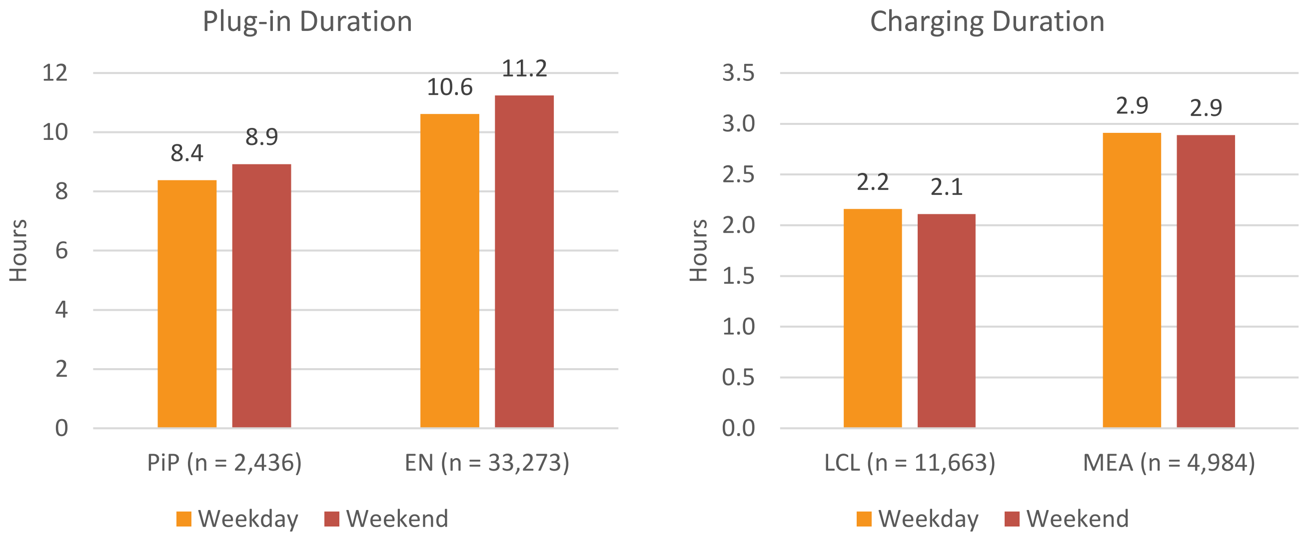

Figure 40: Average plug-in and charge durations for weekdays and weekends from available data sources. 'n' shows the number of charge events in the sample.

Figure 41 and Figure 42 explore plug-in durations in more detail and demonstrates clear bi-modal behaviour with both long and short lengths. A similar feature is observed for slow/fast public charging, which is discussed in Section 5.4.3.

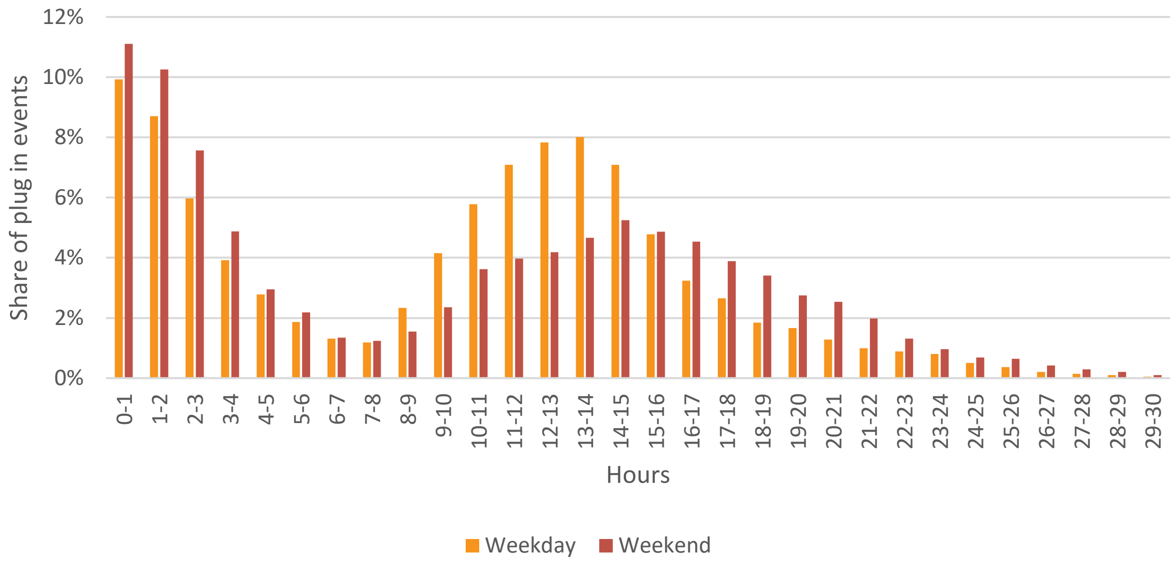

Figure 41: Distribution of plug-in durations from the interim Electric Nation dataset.

Figure 42 shows the plug-in start time profiles for events with plug-in durations for each of the two modes i.e. greater than and less than 7 hrs. For plug-in events >7hrs, most start in the evening, whereas those <7hrs primarily begin during the day, suggesting that the longer mode is primarily due to overnight charging, and the shorter mode is from top-up charging during the day.

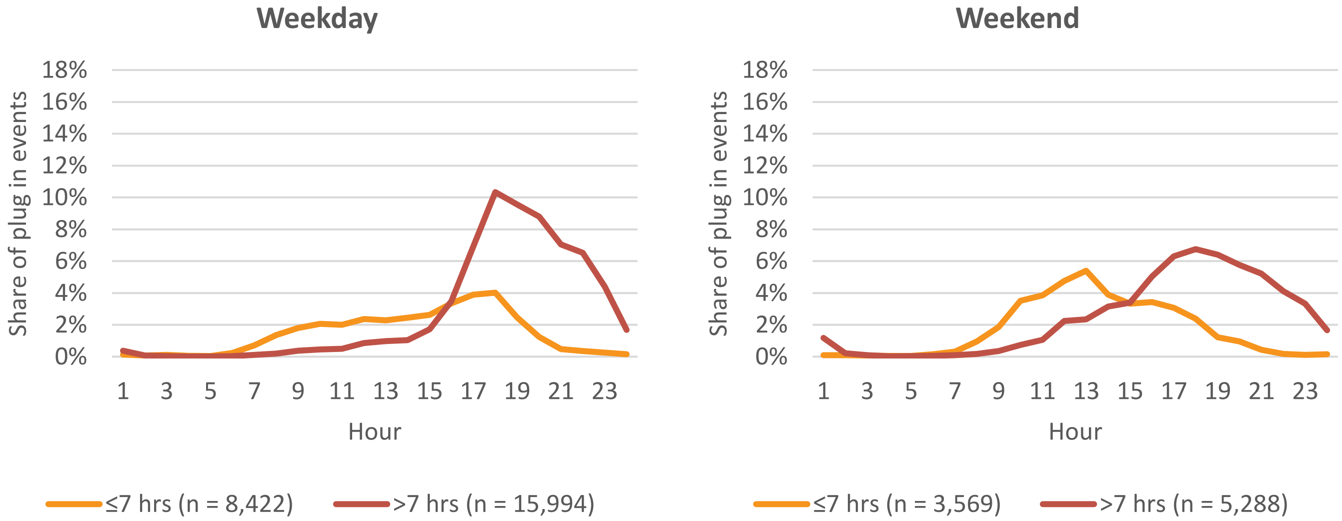

Figure 42: Plug-in start time profiles, grouped by plug-in duration, from the interim Electric Nation dataset. 'n' shows the number of charge events in the sample.

Figure 43 displays the influence of powertrain and battery size on plug-in duration. It can be seen that PHEVs show marginally shorter durations, while there is no clear trend visible with battery size. Likewise, commuting and urbanity also show no clear influence on plug-in duration.

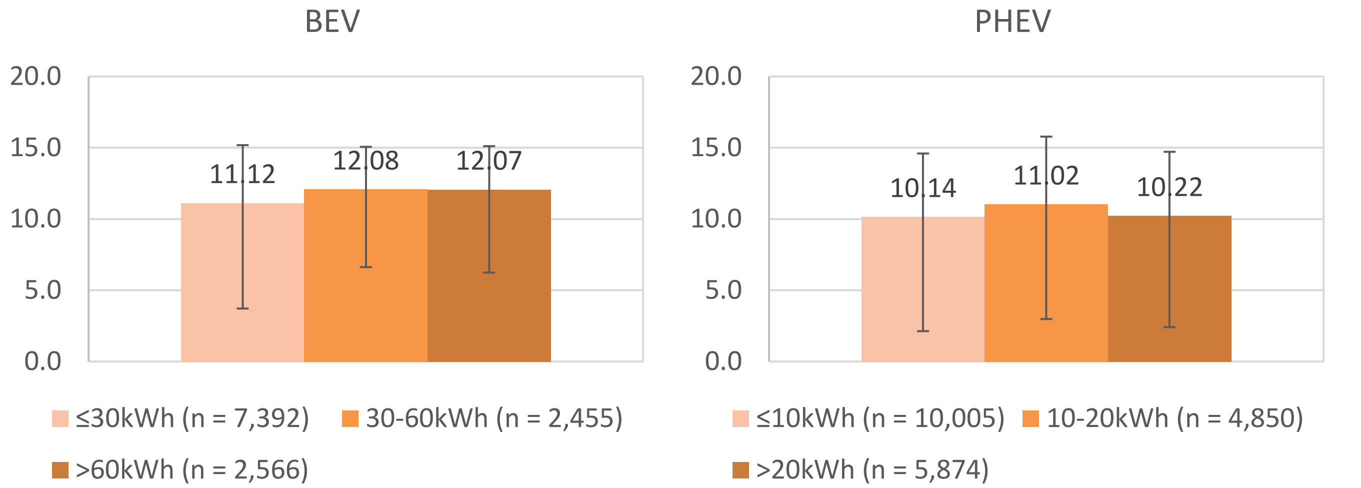

Figure 43: Average plug-in durations for BEVs and PHEVs, grouped by battery size, from the interim Electric Nation dataset. 'n' shows the number of charge events in the sample. Error bars show upper and lower quartiles.

Detailed data on duration actually spent charging is limited, however, energy delivered per charge event can be used as a proxy. Figure 44 shows that there is a strong correlation between average kWh per charge for each EV and the EV's battery capacity.

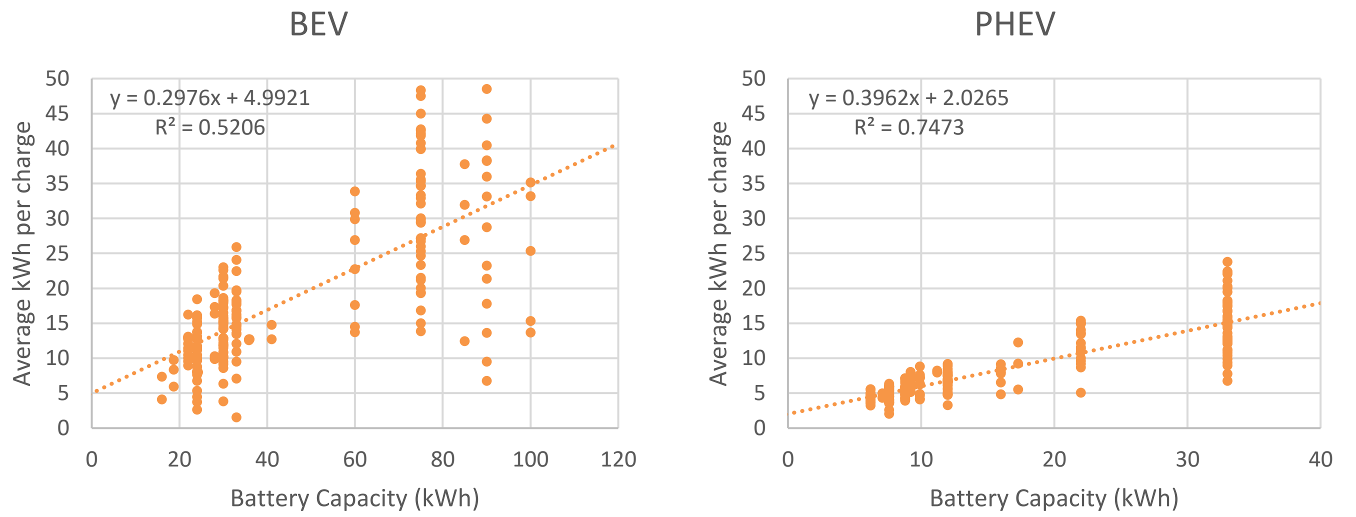

Figure 44: Average kWh per charge for each BEV and PHEV participant in the interim Electric Nation dataset.

For both BEVs and PHEVs, the average kWh per charge increases with battery capacity. This is likely a result of the lower charging frequency for EVs with larger batteries (see Figure 37). PHEVs show a stronger correlation with battery capacity than BEVs, which is probably because PHEVs are more often fully charged from a fully depleted state.

The observation that kWh per charge is primarily related to battery capacity rather than daily energy consumption implies that the decision of EV users of whether to charge or not is strongly influenced by their battery's state of charge. A similar finding was made in the My Electric Avenue trial, which reported that most EV users charged their vehicles when the State of Charge was between 25% and 66% (Quiros-Tortos & Ochoa, 2015). The decision to recharge is therefore made in a similar manner to refuelling a conventional car, even though recharging more regularly, for example every night, would reduce chances of range anxiety being experienced in return for only a small increase in inconvenience. However, it may also be that users are limiting charging frequency in accordance with the advice of some manufacturers to avoid keeping EV batteries at an excessively high state of charge for long periods to limit battery degradation.

A comparison of average kWh per charge for commuters and non-commuters finds that for both BEVs and PHEVs, commuting has no significant impact. On average, commuter and non-commuter BEVs have similar kWh per charge (15.8 kWh vs 14.3 kWh) and show a similar trend across battery sizes (see Figure 45).

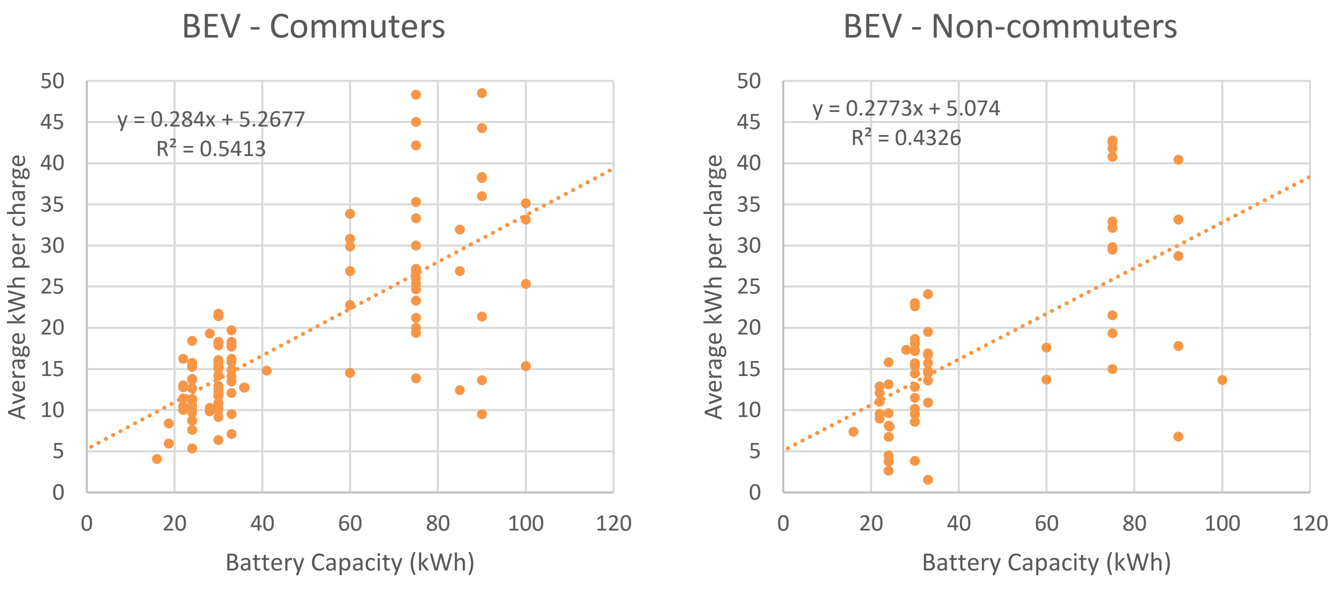

Figure 45: Average kWh per charge for each commuter and non-commuter BEV participant in the interim Electric Nation dataset.

Likewise, for PHEVs the average kWh per charge is very similar for commuters and non-commuters (7.5 kWh vs 7.1 kWh), with the same dependence on battery size (see Figure 46). Since commuters have a higher daily mileage, it could be expected that they would also show greater kWh per charge. But because they also show a higher charging frequency, it is more likely that their higher mileage manifests itself as more often reaching the state of charge that triggers each EV driver's decision to plug in.

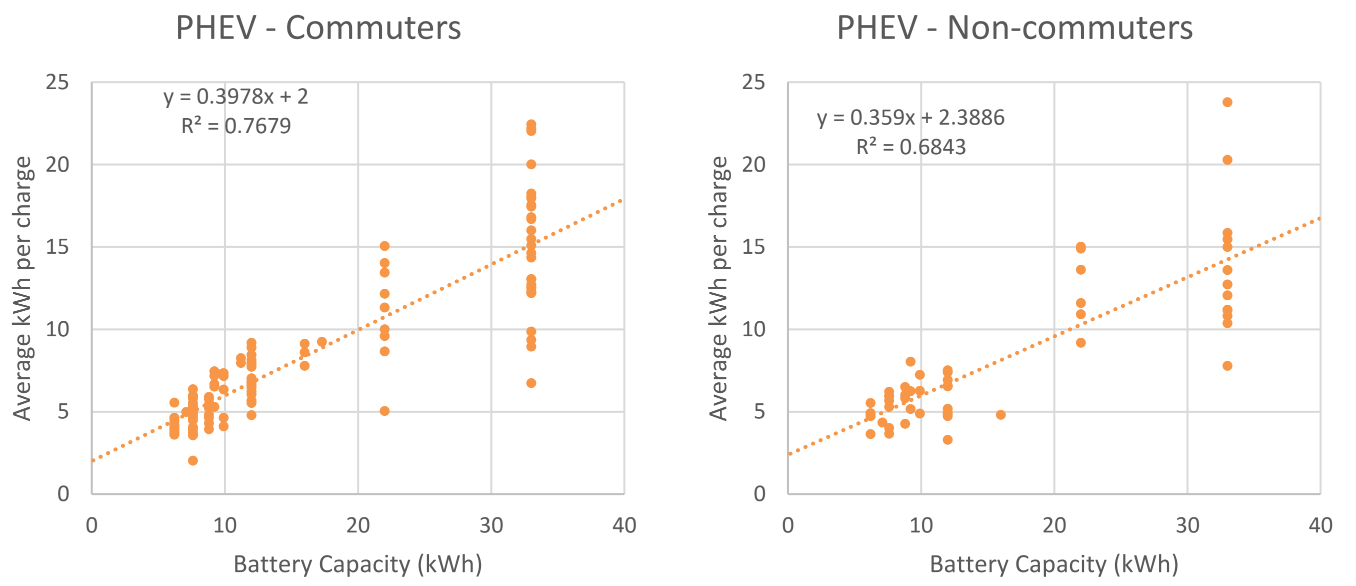

Figure 46: Average kWh per charge for each commuter and non-commuter PHEV participant in the interim Electric Nation dataset.

Figure 47 and Figure 48 explore the influence of urbanity on average kWh per charge, and the correlation with battery capacity. For both urban BEVs and PHEVs, the average kWh per charge is marginally higher than for their rural equivalents. Given that rural car owners drive ~10% further per year than urban drivers[40], and thus have a greater annual kWh demand, the reverse might be expected. This is therefore indicative that rural EV drivers have a greater charging frequency at home. The reason for this may be that rural drivers are more likely to drive longer distance journeys and so feel greater pressure to charge to ensure they can complete their next journey.

[40] Derived from Element Energy analysis of the National Travel Survey 2006-08

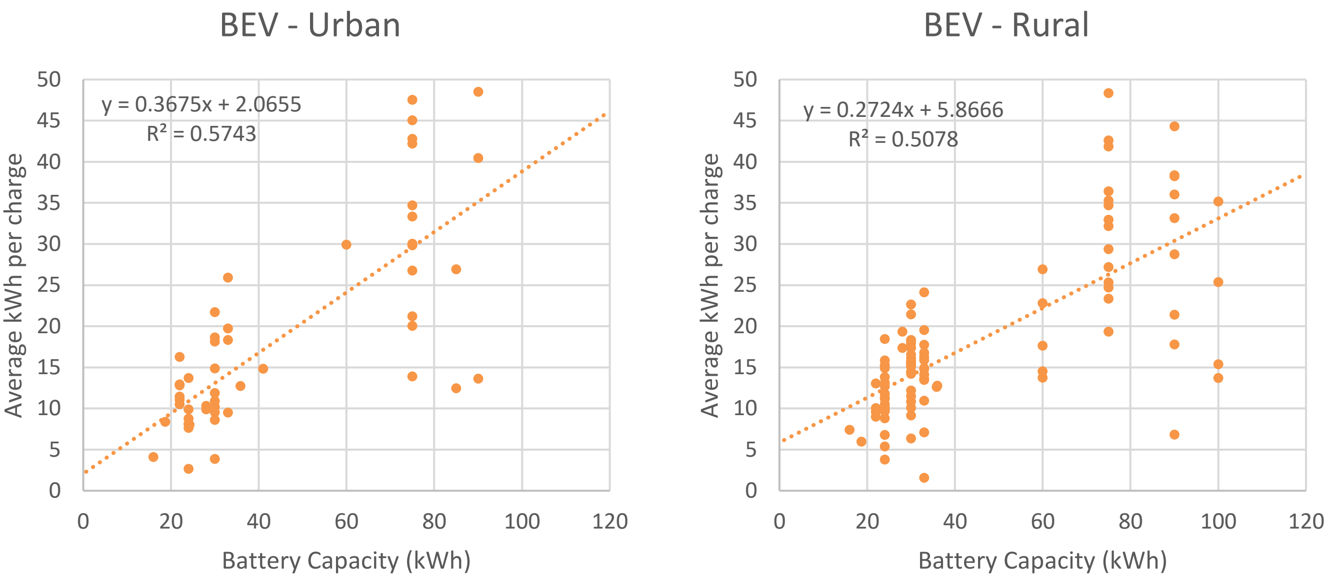

Figure 47: Average kWh per charge for each urban and rural BEV participant in the interim Electric Nation dataset.

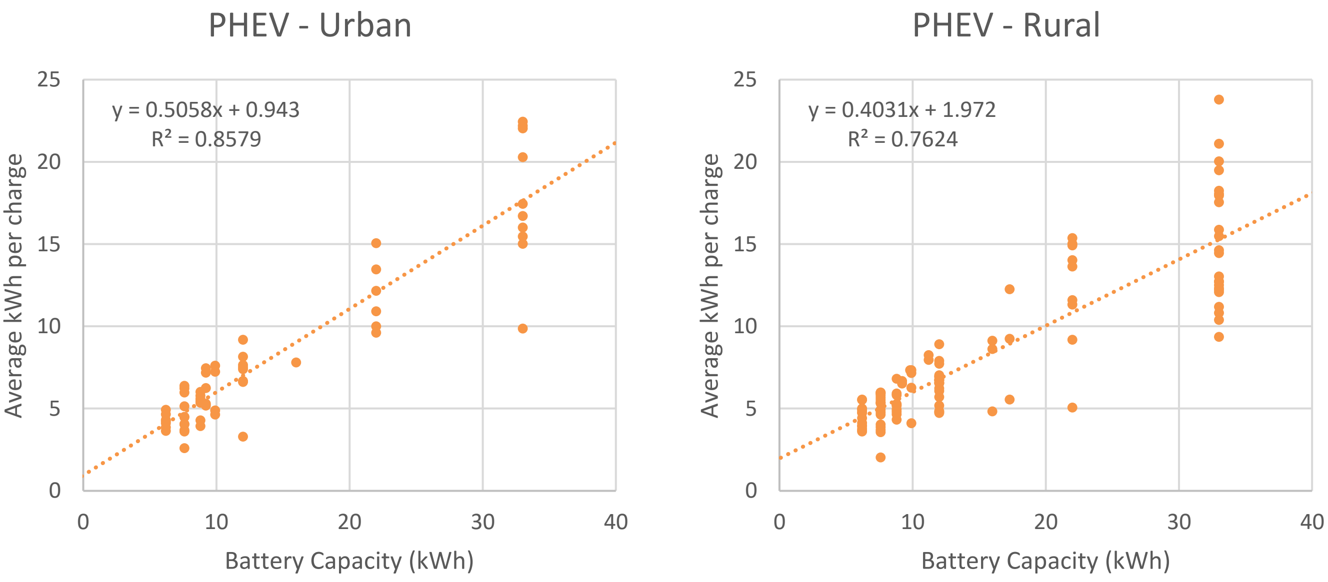

Figure 48: Average kWh per charge for each urban and rural PHEV participant in the interim Electric Nation dataset.

5.1.4 Share of charging at location

To establish the share of EVs' charging demand met by charging at home, data on both the amount of charging at home and overall energy demand of individual EVs must be collected. This limits the applicability of most of the known EV trials, which usually monitored only the home charge point, rather than the EVs themselves. Figure 49 presents the relevant data points identified during the literature review and subsequent data analysis which both show home charging provided an average of 70-80% of the participating EVs' energy demand.

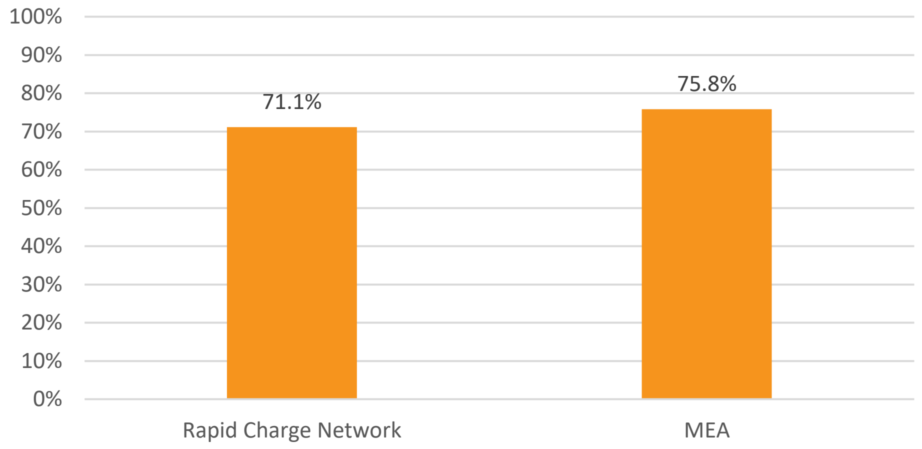

Figure 49: Average share of kWh delivered by home charging from available literature data.

However, for both Rapid Charge Network and My Electric Avenue, only BEVs with battery sizes up to 24kWh were considered, and the Rapid Charge Network study specifically selected EVs that frequently used rapid charge points. Share of charging at home is expected to be highly dependent on individual circumstances of an EV, and so these findings are not necessarily indicative of all EVs with access to home charging. For example, an EV with ready access to public and work charging may do less charging at home, while PHEVs may do a higher share as they are not dependent on other forms of charging to operate. Likewise, larger batteries may also increase the share of home charging, since the range is more likely to be enough to meet a full day's driving need.

5.1.5 Diversity of peak load

The charging load observed at a network asset is the aggregate of the individual loads from the EVs charging at each of charge points connected. Depending on the asset under consideration, these charge points may be connected directly to the asset, or indirectly via downstream network assets. When considering an asset with a large number of charge points connected, such as a primary substation, the diversity in demand will be low as the aggregate behaviour of the EVs tends towards the average. However, when considering an asset with a small number of charge points connected, such as a secondary substation, each charge point contributes a larger share to overall charging demand. Therefore, deviation from average behaviour by a single EV can have a large impact on the asset's charging demand profile. For such an asset, considering only average charging behaviour risks underpredicting peak demand. For example, the My Electric Avenue project estimated that at 100% EV penetration, the diversified peak load per EV would be approximately 1.1 kW (Quiros-Tortos & Ochoa, 2015). However, for a single EV/charge point the peak demand could be as high as 3.3 kW (i.e. the maximum charging rate of the EV model used). This is the so-called undiversified peak. Increasing the number of EVs considered reduces the probability that they are all charging during the peak period and the observed peak per EV will tend towards the average diversified figure. This is quantified as the diversity factor, the ratio of diversified to non-diversified peak:

$$diversity\ factor = \frac{highest\ observed\ peak}{maximum\ possible}$$

The impact of diversity was analysed during the Low Carbon London trial (Aunedi, Woolf, Bilton, & Strbac, 2014), in which the relationship between the diversity factor and number of EVs was explored for residential charging demand. This assumes that each charge point was used by one EV, and so EVs and charge points can be considered interchangeably in this case. The result is shown in Figure 50, and reveals that as the number of EVs connected to an asset increases, the diversity factor tends to a value of about 20%.

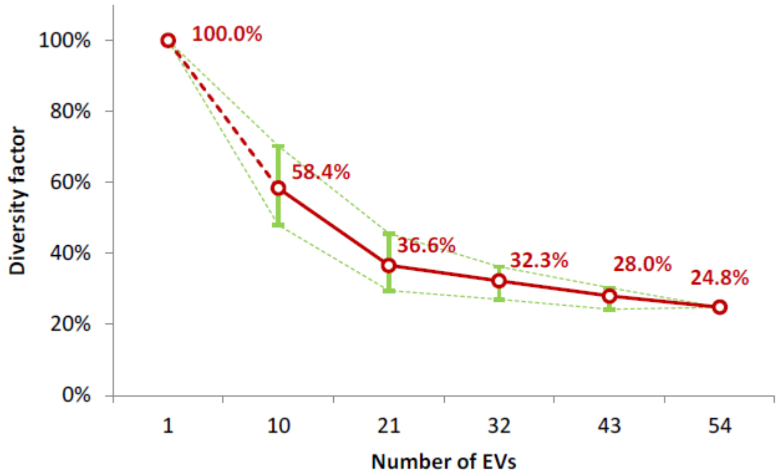

Figure 50: Ratio of diversified to non-diversified peak demand from home charging, estimated from Low Carbon London charging data (Aunedi, Woolf, Bilton, & Strbac, 2014).

However, the Low Carbon London diversity factor analysis was limited by a sample size of only 54 EVs, and so exploring the diversity factor for larger numbers of EVs was not possible. Consequently, the method employed for the Low Carbon London analysis has been applied to the interim Electric Nation dataset which provides access to a much larger sample size. This analysis focussed on winter charging, as this is when peak loads are expected to be largest. The sample was therefore filtered to include only charge events that took place in December, January and February, which reduced the number of EVs to 377. From this sample, subsets of EVs were randomly drawn 50 times, for subset sizes of 5 to 300 EVs, and the highest observed peak load across the 50 draws was recorded. Note that the load profiles were simulated from the charge event data using the plug-in start times, kWh delivered and charge rate. This approach allowed the charging rate to be varied to investigate its impact on diversity. This analysis also assumed that delayed charging was not used for any charge event i.e. charging began as soon as vehicles were plugged in. The highest observed diversity factors for each sample subset size is shown in Figure 51. This reveals that as the number of EVs connected to an asset increases, the diversity factor tends towards ~30% for 3 kW charging and ~20% for 7 kW.

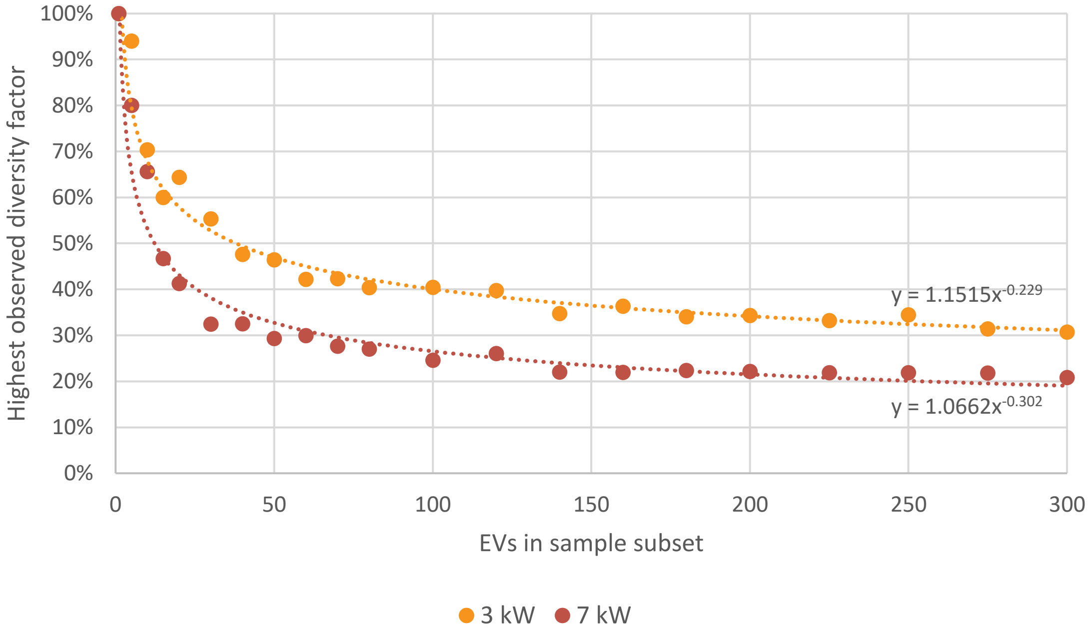

Figure 51: Highest observed diversity factor for different numbers of EVs. Results simulated from Winter charging behaviour of Electric Nation participants for 3 kW and 7 kW charging.

The purpose of this analysis was also to explore how the highest observed peak load compared with that predicted by average charging behaviour. This was so that the peak loads predicted by the Recharge the Future EV Load Forecasting Module could be corrected for diversity. Therefore, for each sample subset draw, the highest observed peak was also compared with the average winter peak. This was based on a load profile simulated from average winter charging behaviour observed in the Electric Nation sample. This was simulated for both 3 kW and 7 kW charging rates, and the resulting profiles are presented in Figure 52. These show a peak load just before 8pm of 0.84 kW and 0.65 kW per EV under 7 kW and 3 kW charging, respectively.

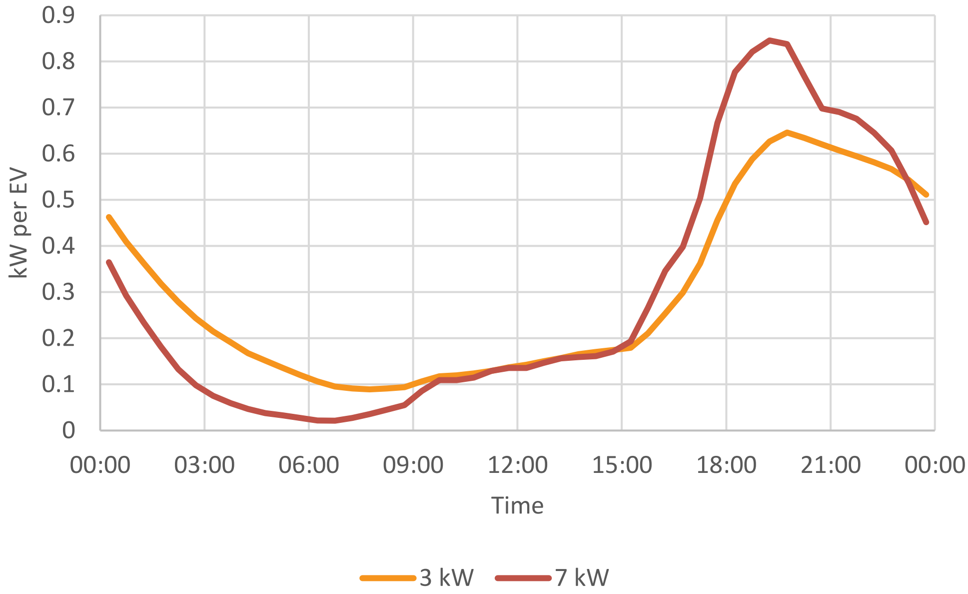

Figure 52: Average winter EV charging load profile (kW per EV), at different charging rates. Element Energy simulation from the interim Electric Nation sample.

For each sample subset size, the highest observed peak across all 50 draws was compared with the relevant average winter peak load. This ratio as a function of sample subset size is plotted in Figure 53, and like the diversity factor, is found to decrease as the number of EVs in the sample subset increases. At very large numbers of EVs this ratio appears to tend to 1, for both 3 kW and 7 kW charging, suggesting that the peak load tends to the seasonal average when fully diversified. However, note that this relationship is only valid for home charge points that are used by just a single EV. The introduction of multiple EV households would be likely to alter the relationship between diversity and number of EVs, as some EVs in the sample could not be charged at the same time.

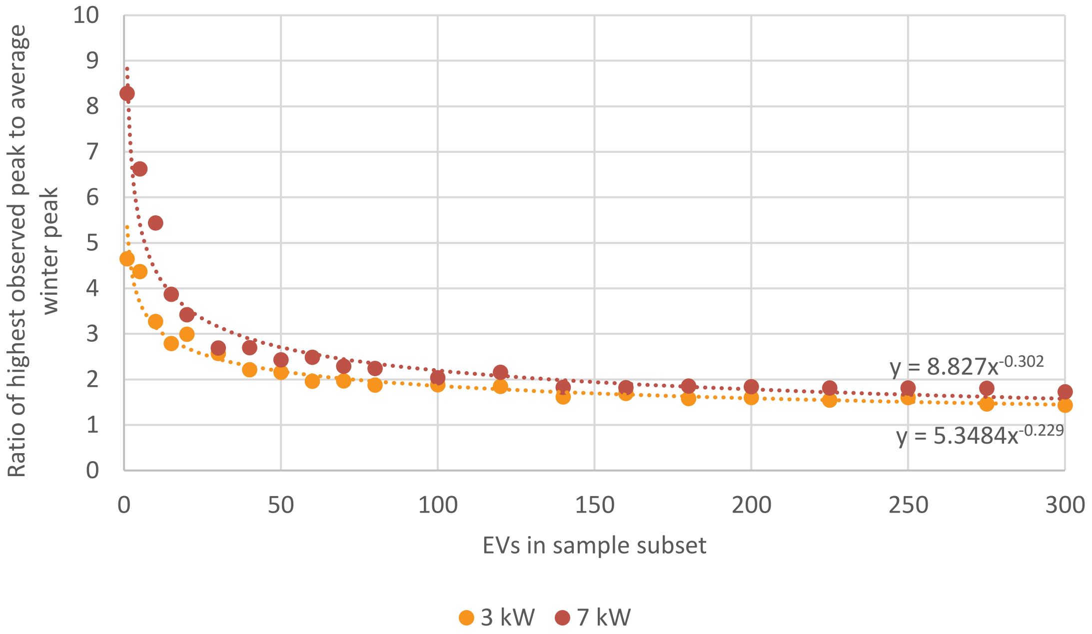

Figure 53: Ratio of highest observed peak to average winter peak, at different charging rates. Element Energy simulation from the interim Electric Nation sample.

Note that this analysis only considered days where all EVs in the sample subset were present in the trial. At large sample subset sizes there are a limited number of days where this is the case and so the statistical power of the sample is reduced. It would therefore be valuable to repeat this analysis on the full trial dataset, once it is completed.

5.2 Residential On-Street

Since the vast majority of current EV drivers in the UK have access to charging at home (see Section 2.3.1), usage of residential on-street charge points as the primary source of charging remains comparatively rare. Whilst EV trials in the UK have generated a large amount of information on home charging, little data is publicly available on the use of residential on-street charge points.

In the Netherlands, availability of off-street parking is comparatively low, and so many public charge points have been installed under the EVnetNL network to encourage EV uptake. Installations are classed as either:

- 'Demand-driven': installed due to a request from an EV owner without off-street parking.
- 'Strategic': sited near public facilities and strategic locations by local and regional governments.

In addition, all public charge points are monitored by ElaadNL, which has generated a comprehensive dataset of public charge point use. Whilst it is not possible to categorically define each charge point as either residential on-street or merely slow/fast public, it seems reasonable that a 'demand-driven' charge point would be most closely associated with residential on-street charging.

A comparison of the plug-in start time profiles of strategic and demand-driven charge points in Figure 54, reveals that the shape of the demand-driven profile is very similar to the home charging profile (see Figure 26) with a primary peak appearing in the early evening between 5pm and 7pm. A smaller secondary peak is also observed in the morning. Since the reverse trend is seen for the strategic charge points, this is presumably a result of some overlap between the strategic and demand-driven use cases. Note that the shape of the strategic charge point profile is very similar to that of slow/fast public charge points in the UK (see Section 5.4.1)

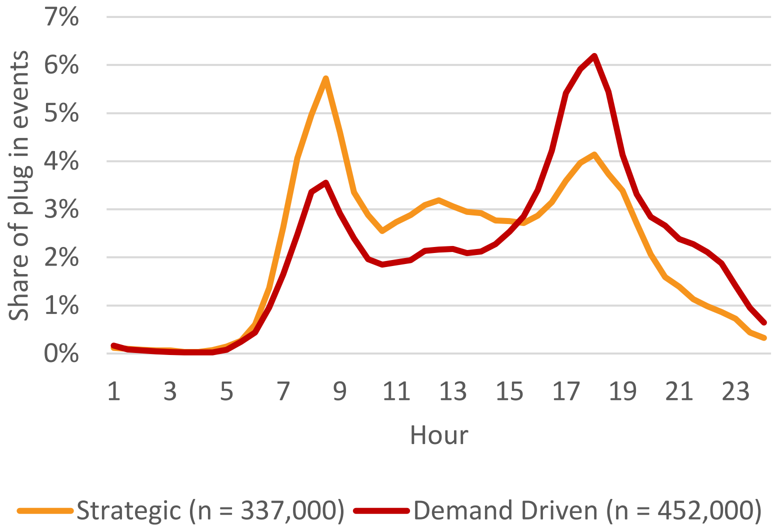

Figure 54: Average weekday plug-in start time profiles for Strategic and Demand-driven charge points measured by ELaadNL 2012-Feb 2015 (Spoelstra & Helmus, 2015). 'n' shows the estimated number of charge events in the sample.

The morning peak observed for demand-driven charge points are the result of those that are located in areas with a high density of workplaces[41]. This peak can therefore be attributed to commuters arriving at work and using these demand-driven charge points during the day.

Figure 55 compares the time spent charging with the time spent plugged-in across the EVnetNL network. Similar to home charging, the plug-in duration is significantly longer than the charge duration, and both are of the same order of duration as for home charging. The suggestion therefore is that use of residential on-street charge points is very similar to home charge points, with the majority of charge events occurring overnight.

[41] Stated during discussion with Robert van den Hoed, of the Amsterdam University of Applied Sciences, which analyses the ElaadNL data.

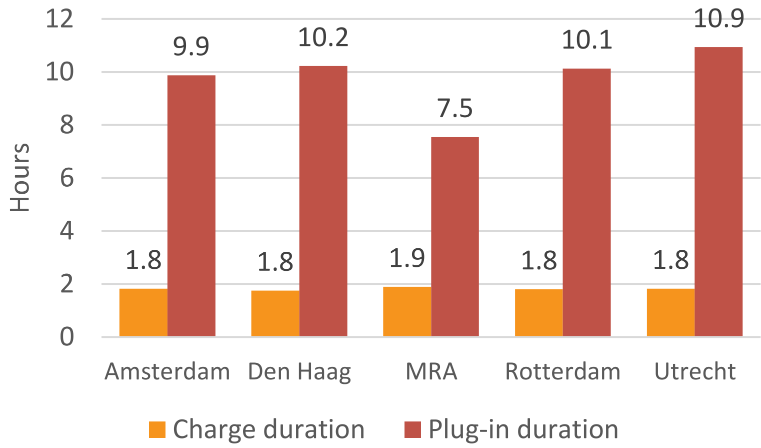

Figure 55: Average plug-in and charge durations for charge points across five regions in the EVnetNL network (Wolbertus, Hoed, & Maase, 2016).

However, it was noted by Robert van den Hoed that charging frequency for residential on-street charge points is potentially greater than home charging, since charging enables an EV user to secure a convenient parking space, which is particularly valuable in populated areas with little off-street parking. It remains to be seen whether this behaviour will be maintained over time. In future, it may become more common for multiple EVs to rely on a single on-street residential charge point. On the one hand, this would encourage EV drivers to charge as often as possible as they will not know when the charge point will next be vacant. However, there is likely to be less opportunity to charge and so EV drivers may be forced to charge less often. From a charge point's perspective, this would manifest itself in the average charging duration.

5.3 Work

5.3.1 Time of charging

Figure 56 shows the average plug-in start time profiles for charge events at workplace charge points observed from available data sources and literature. Other than Plugged-in Places, there is a clear peak in plug-in events between 8am and 10am. For the Switch EV trial, this was attributed to commuters plugging in at the end of their journey to work (Robinson, Blythe, Bell, Hübner, & Hill, 2013), and since the morning peak is more distinct in the PodPoint and Low Carbon London profiles, it's likely that this reason holds for these datasets as well. Indeed, the plug-in start time profile provided by PodPoint was measured during 2017 from 44 workplace charge points, installed specifically for charging commuter EVs.

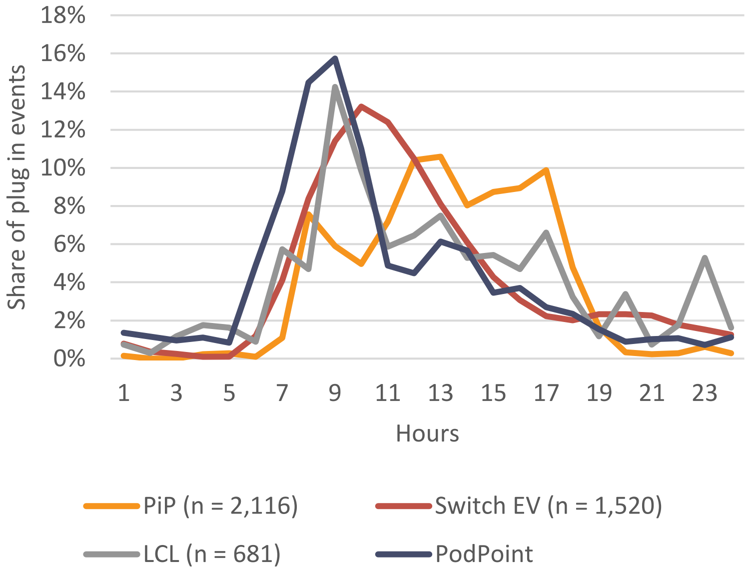

Figure 56: Average plug-in start time profiles at work place charge points. 'n' shows the number of charge events in the sample.

For Plugged-in Places, the profile shows a small peak of plug-in events occurring in the morning, but the majority take place during the middle of the day. However, the type of cars using these workplace charge points is not known, and it may be that these are primarily used to charge depot-based vehicles. These are more likely to be charged when they return to the workplace during the middle of a duty cycle or at the end of the day. A similar profile was observed for 'pooled' cars in the Switch EV trial. These are cars used by employees, but which must remain stored at the employer's site for tax reasons. They are therefore not used for commuting purposes and can be considered depot-based. Note that charge events from these vehicles are excluded from the Switch EV profile in Figure 56, since charging of depot-based EVs are not in the scope of this study.

Information available on the major influencers of charging time is extremely limited. Investigating the difference between weekend and weekday charging times is not possible due to the very small sample size of weekend charge events at work (see Section 5.3.2).

Analysis of the Switch EV trial data suggests that urbanity has a negligible influence on work charging start times (Neaimeh, et al., 2015).

5.3.2 Charging frequency

Figure 57 shows the average number of charge events per day for workplace charge points, on weekdays and weekends, that were observed in the literature. In both Low Carbon London and Plugged-in Places, workplace charge points are used considerably more on weekdays compared with weekends, as expected.

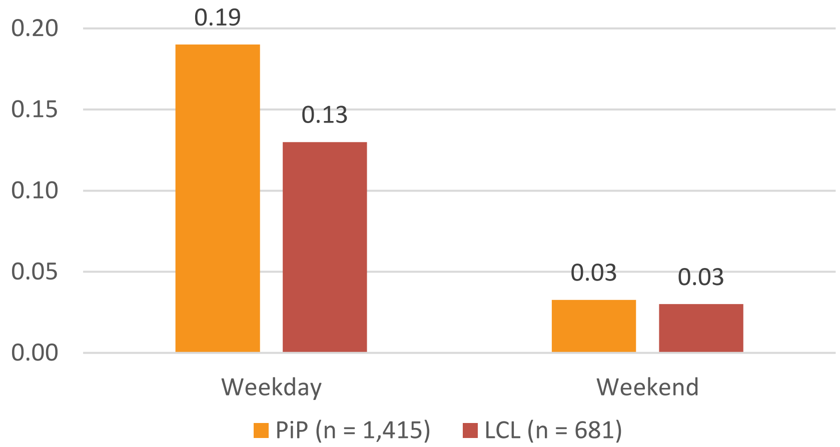

Figure 57: Charge events per day per work charge point. 'n' shows the number of charge events in the sample.

Comparison between sources is of limited value, because the charging frequency will depend on the level of utilisation of the charge points in question, which in turn will depend on the number of EVs using them. Both Low Carbon London and Plugged-in Places suggest quite low levels of utilisation, with fewer than one charge events occurring per week on average per charge point. However, these data points were measured between 2011 and 2014 when there were fewer EVs on the roads. PodPoint have stated that the average usage rate of their workplace charge points is about once per day, suggesting that now EVs are more common, the utilisation of work charge points has increased.

The Electric Nation survey asked participants who had access to work place charging how often they charge at these charge points. On average, PHEV drivers reported plugging in 0.61 times per day, which was more often than BEVs at 0.39 times per day. Unlike BEVs, the short electric range of PHEVs means that commuters would be less likely to be able to do both legs of their commute under electric power. Despite being able to drive the remainder under fuel power, this finding suggests that these PHEV commuters are still charging at work to increase the share of their driving they do under electric power. BEVs on the other hand are less likely to need to charge at work to complete their commute round trip and so do so less often. Note, however, that these values are self-reported and there is some uncertainty over whether participants included weekends or not when considering how many times they plugged in per day.

5.3.3 Charge duration and/or kWh per charge

Figure 58 shows the average charge times observed in the available data sources. Note that for Plugged-in Places, the charge points recorded plug-in and plug-out times, rather than when charging actually occurred (Office for Low Emissions Vehicles, 2013). Switch EV (Robinson, Blythe, Bell, Hübner, & Hill, 2013) and Low Carbon London reveal an average charge duration of 3-4 hours. However, Plugged-in Places data suggests that the plug-in duration is considerably longer and implies that employees leave their cars plugged-in for the entire working day even though they need significantly less time to actually charge. It is unclear whether this behaviour would change when multiple EV drivers share a single charge point. EV drivers may be expected to take it in turns to charge throughout the day, requiring each driver to vacate the charge point once charged to allow another employee to plug in.

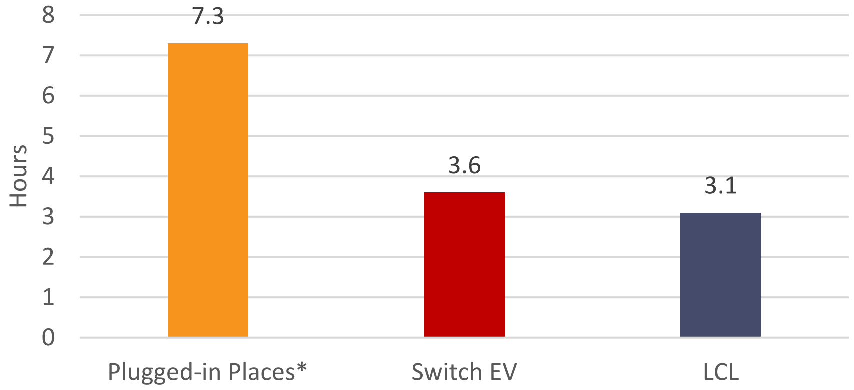

*Figure 58: Duration of charge events at work charge points. *Denotes plug-in duration rather than time spent charging.*

The Electric Nation survey provides a more recent view of work charging durations. The average participant reports charging for 4.9 hrs at work. It is not clear whether participants are referring to time spent plugged in or drawing power, although the former is more likely since they would be less aware of when their car finishes charging. This suggests that plug-in durations are now lower, compared with during Plugged-in Places, and may be a result of more than one EV now sharing some work charge points, so EV drivers choose to vacate the charge point before the end of the working day.

The average kWh per charge recorded in Low Carbon London was 8.9 kWh, and comparison with the average charging duration suggests that the majority of these took place at 3 kW charge points. Since plug-in duration appears much longer and therefore dwell time is not a limiting factor, it seems fair to assume that shifting to a higher charge rate would more likely reduce charge duration rather than increase kWh per charge. This is supported by PodPoint reporting an average of 9.3 kWh per charge, which compares well with the Low Carbon London figure, despite being measured more recently when 7 kW work charge points are more common.

5.3.4 Share of charging at location

Very little information was identified in the literature showing the share of charging carried out at work charge points, due to the limited number of studies which monitored the charging of individual EVs rather than at charge points. The utility of the few examples identified is limited. The Rapid Charge Network study found 3.4% of charging was supplied by work charge points (Blythe, et al., 2015), however, it is not known how many EVs in the trial had access to work charging or were used for commuting. Analysis of the My Electric Avenue data revealed that 19% of kWh were supplied by charge points other than home or public rapid ones. However, it is not known what share work charging contributes to this, and again how many of these EVs had access to work charging.

It is obvious that from the perspective of an individual EV, the share of charging carried out at work will be zero if the car is never used for commuting or the workplace does not provide access to work place charging. However, to establish the typical share of charging for a commuter with access to workplace charging, and the factors that influence this, monitoring of the EVs themselves is necessary.

5.4 Slow/fast Public

5.4.1 Time of charging

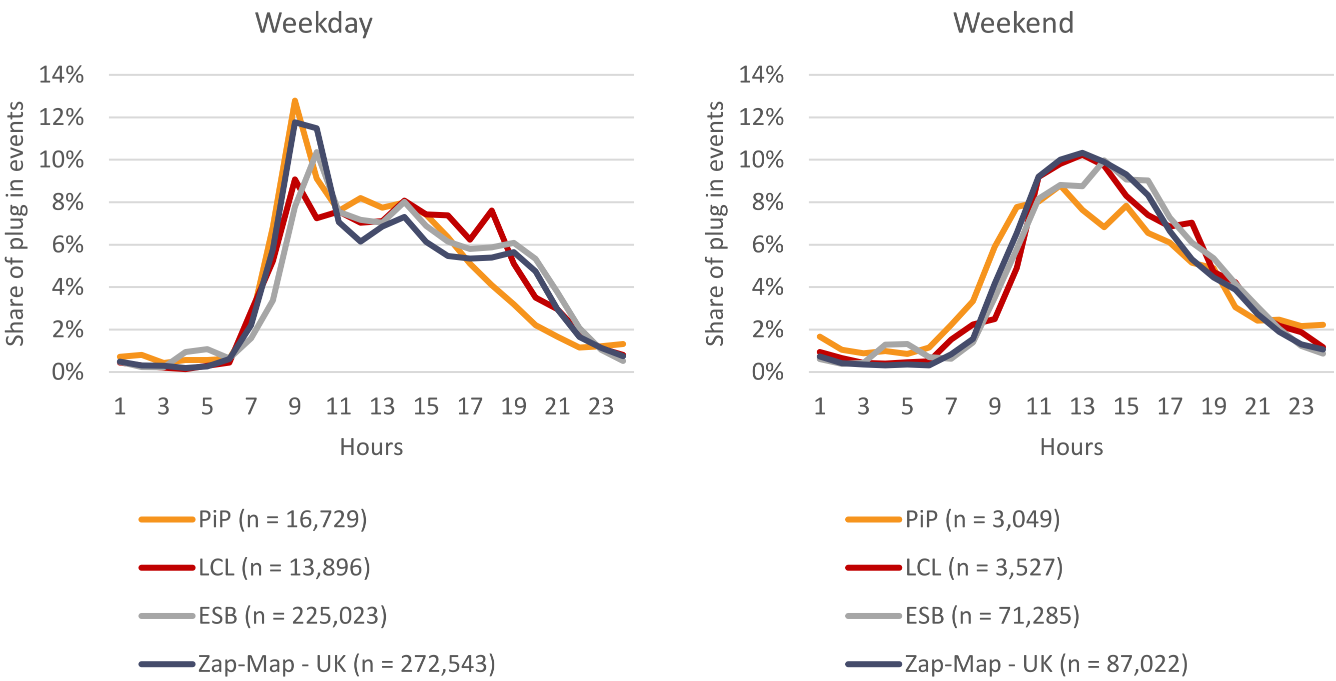

Figure 59: Average weekend and weekday plug-in start time profiles for slow/fast public charging. 'n' denotes number of charge events in sample.

The plug-in start time profiles in Figure 59 show strong agreement between available data sources, and a clear difference in profile shape between weekdays and weekends. On weekdays there is a large peak in the morning, a secondary peak 1pm-3pm, and then there is a gradual tail off of events into the late evening. At weekends the profiles show a much broader peak around midday, with no early morning peak observed. This suggests that the early morning peak is the result of commuters who park and charge in public car parking spaces.

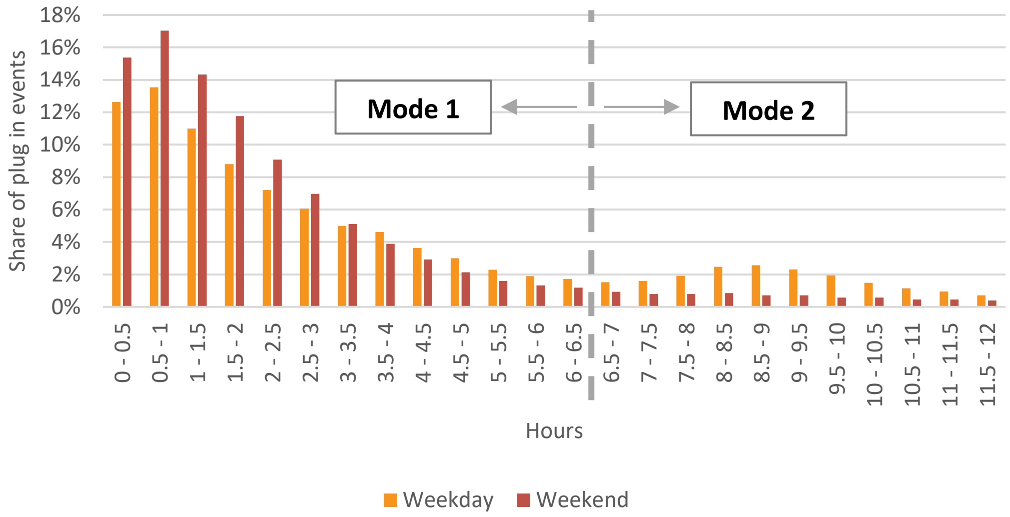

Figure 60: Distribution of plug-in durations for slow/fast public events in UK-wide Zap-Map sample.

Figure 60 shows how plug-in durations of slow/fast public charge events from the Zap-Map data are distributed across half hourly bins. For weekday charging there is a secondary peak around 9 hours which is not observed for weekend charging. This suggests on weekdays charging behaviour at slow/fast public charge points is bi-modal. To investigate this further, plug-in start time profiles were separately generated for weekday charge events greater than and less than 6.5 hours, in an attempt to isolate the charging modes.

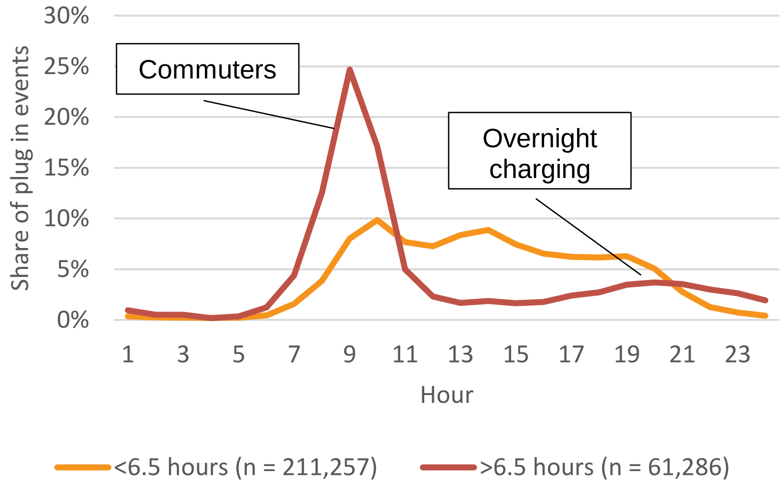

Figure 61: Average weekday plug-in start time profile for slow/fast public charge events <6.5 hrs and >6.5 hrs. Element Energy analysis of Zap-Map dataset.

The plug-in start time profiles in Figure 61 demonstrate clear bi-modal behaviour, with charge events >6.5 dominated by mid-morning charge events along with a broad secondary peak in the evening. This strengthens the proposition that the morning peak observed for weekday slow/fast public charging in Figure 59 is due to commuters who then leave their cars plugged in for the duration of the working day. It is proposed that the secondary evening peak is due to EV drivers using slow/fast public charge points to charge their cars overnight, and in fact these charge points would be better classified as on-street residential.

Since all available data sources are measured from the charge point, no information has been found on the influence of battery size or powertrain on time of slow/fast public charging.

Figure 62 shows the plug-in start times across different location groups, as provided by the Zap-Map data analysis. It can be seen that there is very little difference between the profiles in urban and rural locations, for both weekdays and weekends. This is consistent with the findings from the Switch EV project (Neaimeh, et al., 2015). Furthermore, the profiles from the UK Power Networks licence area closely mirror the UK-wide profiles suggesting slow/fast public charge point usage is unaffected by location. Note that there is high volatility in the UK Power Networks area rural profiles due to the comparatively small sample size, but the same basic trends observed for the location groups are still visible.

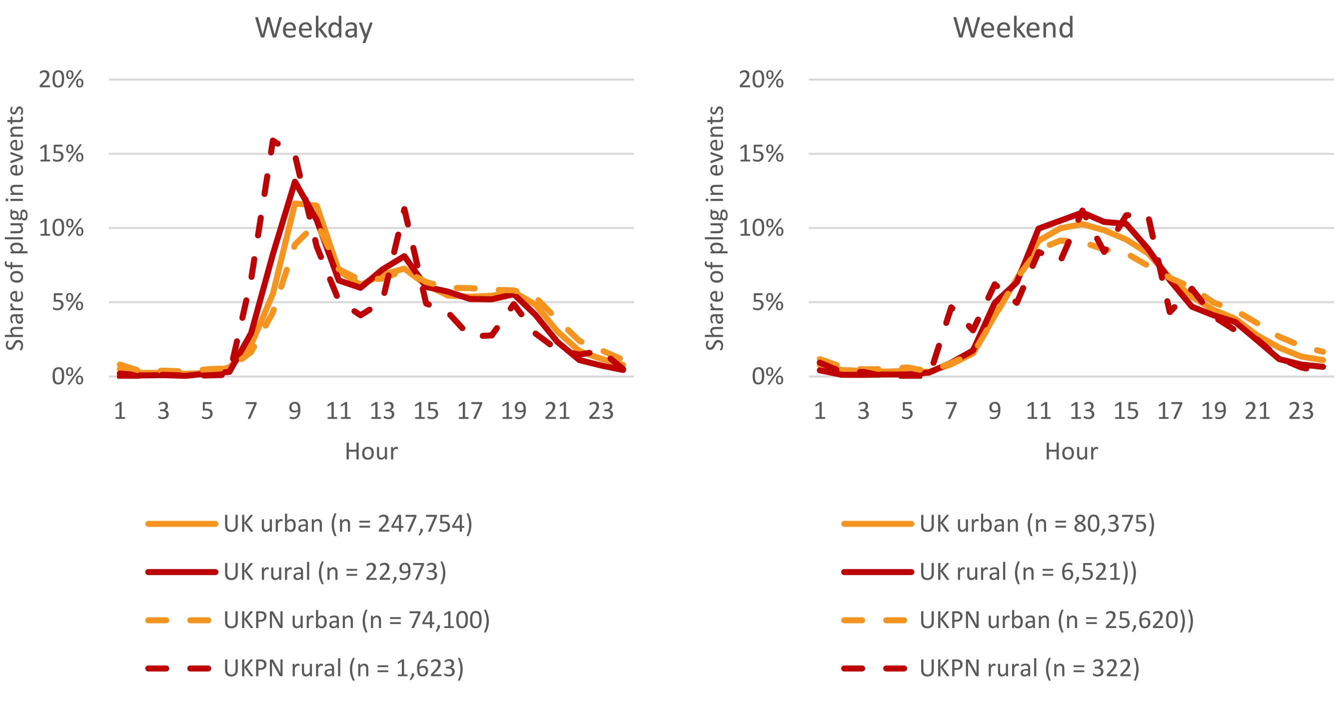

Figure 62: Average weekend and weekday plug-in start time profiles from Zap-Map data for slow/fast public charging, shown separately for urban and rural locations at UK-wide and UK Power Networks licence area levels. 'n' denotes number of charge events in sample.

5.4.2 Charging frequency

Average charging frequency for each slow/fast public charge point is highly dependent on the ratio of EVs to charge points. Figure 63 shows the average number of times each slow/fast public charge point is used per day, and in general reveals a fairly low level of utilisation. It can be seen that there is significant variation between literature sources, but much of this variation is likely a consequence of when and where it was measured. Plugged-in Places and Low Carbon London were pre-2015, when there were fewer EVs available to use these charge points (see Figure 13). Zap-Map and ESB data were collected far more recently and hence show higher levels of charge point utilisation, however, it is worth noting that the ESB charge points are free to use. Despite the differences in samples, all show a clear pattern of fewer charging events occurring on weekends compared with weekdays. ESB and Zap-Map show a similar weekend to weekday ratio of 75% and 80% respectively.

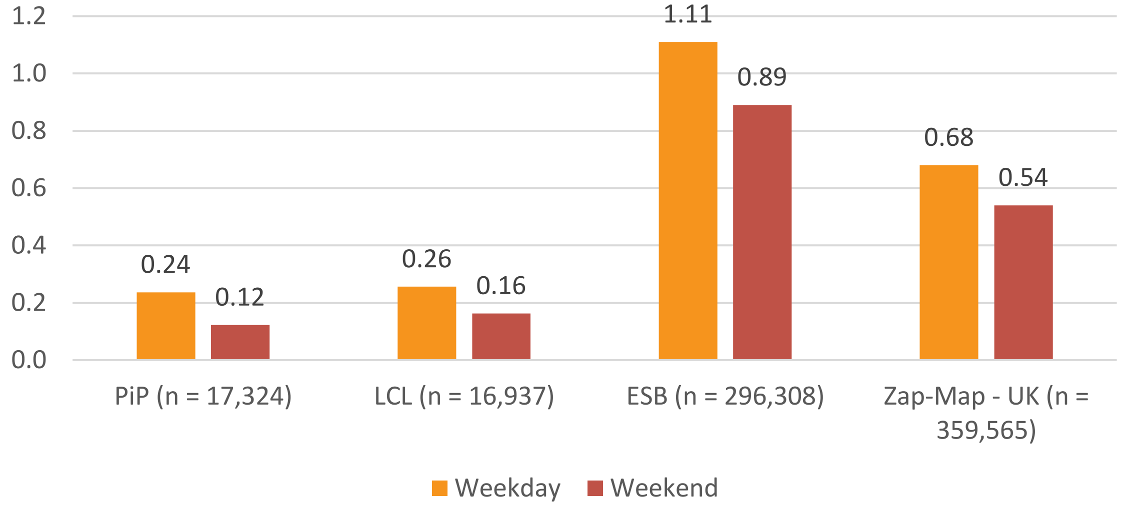

Figure 63: Average charge events per day per charge point. 'n' shows the number of charge events in the sample.

Figure 64 illustrates how charging frequency differs across different regional groups in the Zap-Map data. At a UK level, the charging frequency is very similar between urban and rural slow/fast public charge points. Urban charge points within the UK Power Networks licence area also show similar usage levels, however, rural is considerably lower. However, it is worth noting that the UK Power Networks rural sample consists of only 26 charge points, compared with 649 in the urban sample. It is therefore likely to be highly dependent on the specific EVs in the areas surrounding the charge points.

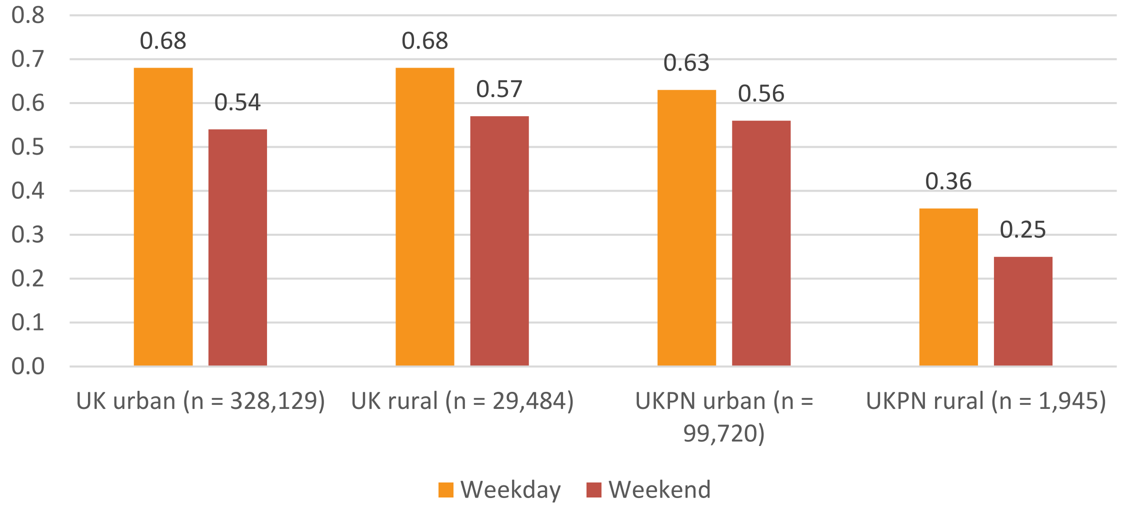

Figure 64: Average charge events per day reported in Zap-Map sample for different location groups. 'n' is the number of charge events in the sample.

There is very limited data available on the frequency of slow/fast public charging from an EV's perspective, although it appears to be quite rare. Low Carbon London reports that 82% of participants used a public charge point less than once per month (Aunedi, Woolf, Bilton, & Strbac, 2014).

The Electric Nation survey asked participants how often they charge at different public charging locations. Although it didn't explicitly ask them the charge point rate, it is assumed that charge point located at supermarkets, car parks and on-street fall under the slow/fast public classification. On average participants reported charging at these locations rarely, at a combined frequency of 0.038 times per day. PHEVs charge marginally less often than BEVs at 0.036 and 0.040 times per day respectively. Frequency also appears to decrease with battery size, for example BEVs with a battery capacity of ≤30 kWh reported charging on average 0.053 times per day compared with 0.019 time for capacities >60 kWh. Likewise, PHEVs with a capacity ≤10 kWh charge 0.047 times per day versus 0.026 time for PHEVs >20 kWh.

5.4.3 Charge duration and/or kWh per charge

Duration of slow/fast public charge events is fairly consistent across the available data sources, with Figure 65 showing that other than Plugged-in Places EVs remained plugged in on average 2-4 hours. Durations also appear similar between weekdays and weekends. Zap-Map data suggests weekday charge durations last approximately 30% longer than weekends, however, as discussed in Section 5.4.1, use of slow/fast public charge points on weekdays is bi-modal, with a minority of plug-in events lasting throughout the working day. Excluding these charge events would be expected to reduce the average plug-in duration closer to the weekend figure.

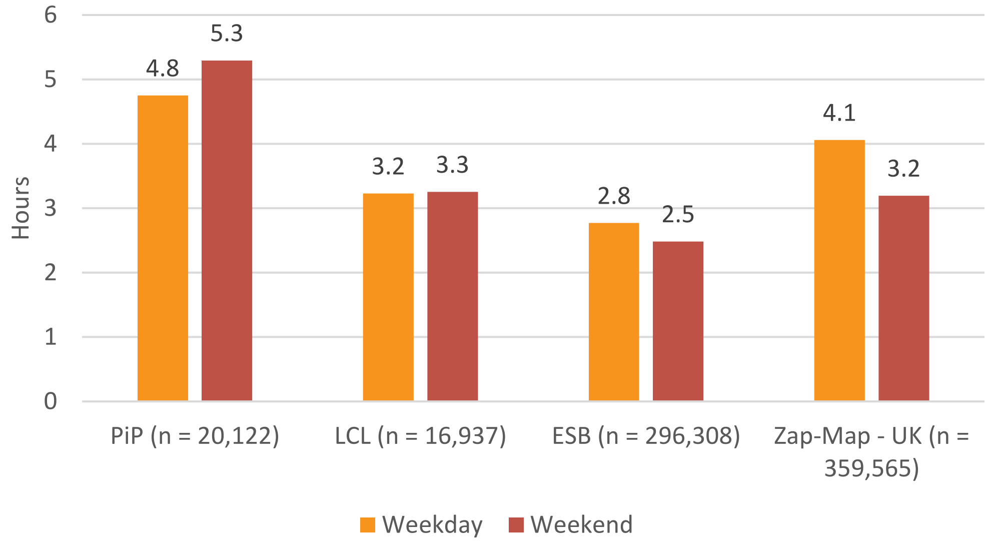

Figure 65: Plug-in duration of charge events at slow/fast public charge points. 'n' denotes number of charge events in sample.

The data sources shown in Figure 65 provide only the time spent plugged-in, rather than time spent drawing charge. The Switch EV trial instead measured time spent charging and recorded an average duration of 3.1 hours (Robinson, Blythe, Bell, Hübner, & Hill, 2013). Although caution should be taken when comparing between trials, the similarity between the plug-in durations in Figure 65 and charge duration reported by Switch EV implies that dwell time rather than battery capacity is the limiting factor to charge time. This supports the proposition that slow/fast public charging is primarily used opportunistically to top up battery states of charge, and owners will stop charging when they have completed their trip purpose as opposed to waiting for the battery to be fully charged. This is further supported by the observation that durations have remained similar between Low Carbon London (2012-2014) and the collection of the Zap-Map and ESB ecars data (2017-18), despite the availability of 7 kW public charging increasing. This suggests that plug-in duration at slow/fast public charge points has a low dependence on charge rate and therefore kWh need.

Furthermore, in the Electric Nation survey, participants reported charging at supermarket, car park and on-street charge points, (assumed to all be slow/fast public) for an average duration of 2.2 hours. This remains fairly consistent across BEVs and PHEVs, as well as battery sizes, implying that these factors have little influence on charge duration.

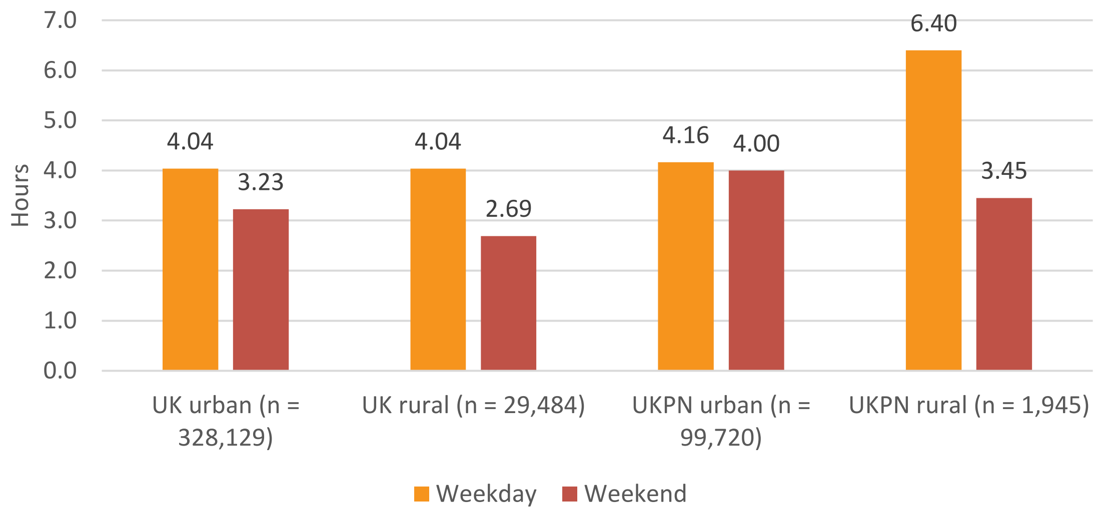

Figure 66: Average plug-in duration reported in Zap-Map sample, for different regional groupings. 'n' denotes number of charge events in sample.

Comparison of plug-in durations across different regional groupings (Figure 66) in the Zap-Map dataset reveals very similar weekday values for urban and rural locations at a UK-wide level, as well as urban locations within the UK Power Networks licence area. Plug-in events at rural locations within the UK Power Networks licence area appear to last much longer, however, note that the sample size for weekday charge events is only 1,623 measured from 16 charge points, and about 40% of these are >6.5 hrs starting between 6am and 10am. This sample is therefore dominated by long commuter charges (see Section 5.4.1) and is likely not representative of all rural charge points in the UK Power Networks licence area.

At all regional groupings shown in Figure 66, weekend plug-in durations are lower than weekday, although the relative differences are not consistent.

Figure 67 shows the distribution of kWh delivered per charge at slow/fast public charge points recorded during Low Carbon London. The average value is 7.2 kWh but note that the results show a long tail with over ~3.5% of charge events supplying >25 kWh. At the time of the trial, the Tesla Model S and Roadster, were the only EVs available with a battery capacity greater than 25 kWh, and apart from during the last quarter of the monitoring period (Q2 2014) there were fewer than 56 of these vehicles registered in the whole of Great Britain[42], with 192 added in Q2014. These vehicles therefore made up a very small proportion of the 3,186-11,126 licenced over the same period in the UK[43], and are unlikely to be

[42] DfT Vehicle Licencing Statistics Table VEH0120: Licensed cars at the end of the quarter by make and model, available at https://www.gov.uk/government/collections/vehicles-statistics
[43] DfT Vehicle Licencing Statistics Table VEH0130: Ultra low emission vehicles (ULEVs) licensed at the end of quarter by body type, available at https://www.gov.uk/government/collections/vehicles-statistics

responsible for all charge events measured >25kWh. This makes the validity of these high kWh charge events questionable. If charge events >25 kWh are excluded then the average kWh per charge drops to 5.9 kWh.

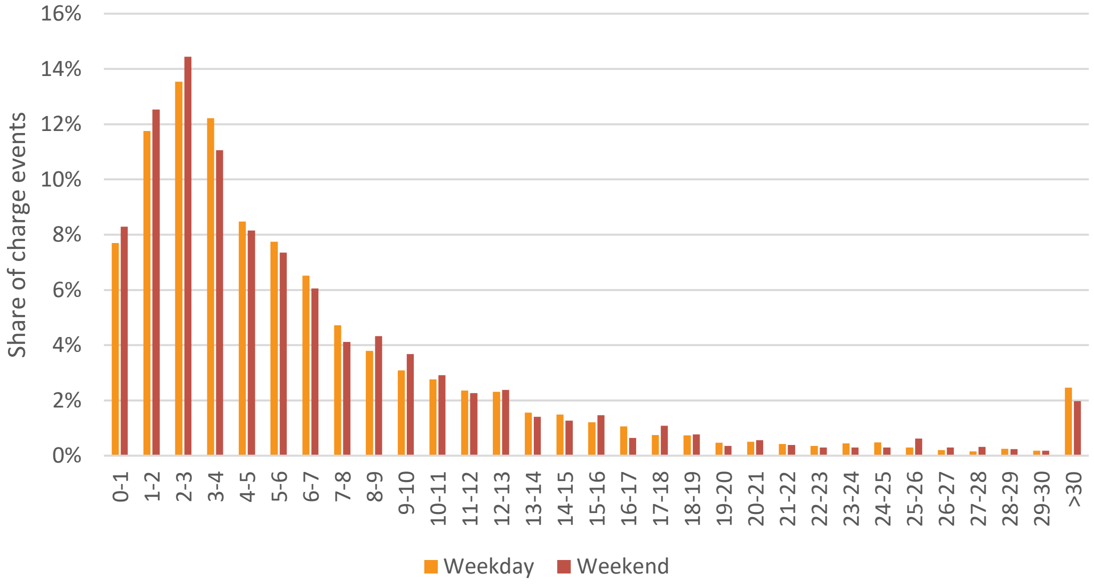

Figure 67: Distribution of kWh per charge at slow/fast public charge points measured during Low Carbon London.

5.4.4 Share of charging at location

Similar to workplace charging, quantifying the share of charging at slow/fast public charge points requires studies in which EVs are monitored and slow/fast public charge events can be identified. The Rapid Charge Network trial provides the only example to date where this was possible and reported 3.5% of total kWh charging demand was supplied by public charging points with a capacity of <22 kW (Blythe, et al., 2015). As stated in Section 5.3.4, 19% of charging demand in the My Electric Avenue trial was not met by home or rapid public charging, but it is not known how this was apportioned between work and slow/fast public charging, nor how this varied for different EV characteristics.

However, the share of an EV's charging demand met by slow/fast public charge points is expected to be highly dependent on availability of charge points at the regular destinations of EV trips. While slow/fast public charge point coverage remains quite low, the share is likely to vary significantly between EVs. The relevance, therefore, of older studies in this respect is likely to be limited in describing future charging behaviour.

5.5 Rapid Public

5.5.1 Time of charging

Figure 68 shows the weekend and weekday plug-in start time profiles for all rapid public charge events in the My Electric Avenue, Zap-Map and ESB ecars datasets[44]. On weekdays, the Zap-Map profile shows three distinct peaks in the morning, evening and midday. The midday and evening peaks are visible in the ESB profile, although the morning peak is less pronounced, and My Electric Avenue also shows three peaks although the profile is skewed towards evening charging. Note that My Electric Avenue consisted of only 24 kWh Nissan Leafs and so this evening peak is possibly a consequence of its limited range requiring an evening rapid charge to complete a day's driving need.

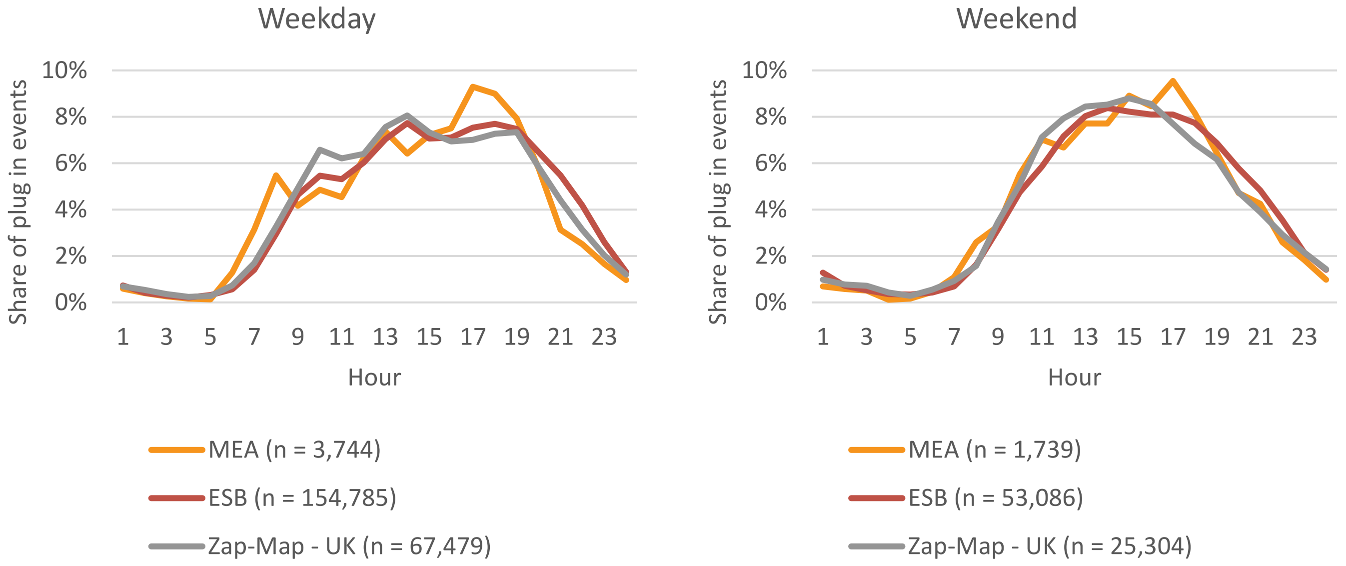

Figure 68: Average weekday and weekend plug-in start time profiles for rapid public charging. 'n' denotes number of charge events in sample.

Fastned stated that the same triple-peak behaviour is observed in their own network. The morning and evening peaks are attributed to charging before and after the first and last trips of the day respectively. The midday peak is likely the result of high mileage drivers charging during a lunch break in order to complete their remaining mileage for the rest of the day. Weekends show a much smoother trend with a broad peak centred on mid-afternoon. There is a similar trend observed for slow/fast public charging, although the peaks are less pronounced on weekdays when very long charge events are removed (see Figure 60 and Figure 61).

The purpose of rapid public charge point is primarily to provide fast in-journey charging to minimize the inconvenience of driving long journeys with BEVs with limited range. To provide this effectively, these charge points should therefore be

[44] Plugged-in Places and Low Carbon London also provide data on rapid charge event timing, however, the number of events in each sample is too small to provide a reliable profile shape.

located on or very near trunk roads on which most long-distance journeys are driven. However, more recently rapid charge points have also been installed away from trunk roads, particularly in urban areas, to provide opportunistic charging while cars are parked, or charging solutions for EVs without access to home charging or vehicle with long urban duty cycles. Transport for London, for example, recently announced the installation of 100 rapid charge points in London, with a target to install 300 by 2020, aimed in part at providing rapid charging for electric taxis[45]. It might therefore be expected that the usage profiles of rapid charge points differ depending on whether they serve trunk roads or not. However, Figure 69 demonstrates that the plug-in start time profiles of rapid public charge points near trunk roads are very similar to the remaining rapid public charge points, for the UK-wide Zap-Map sample.

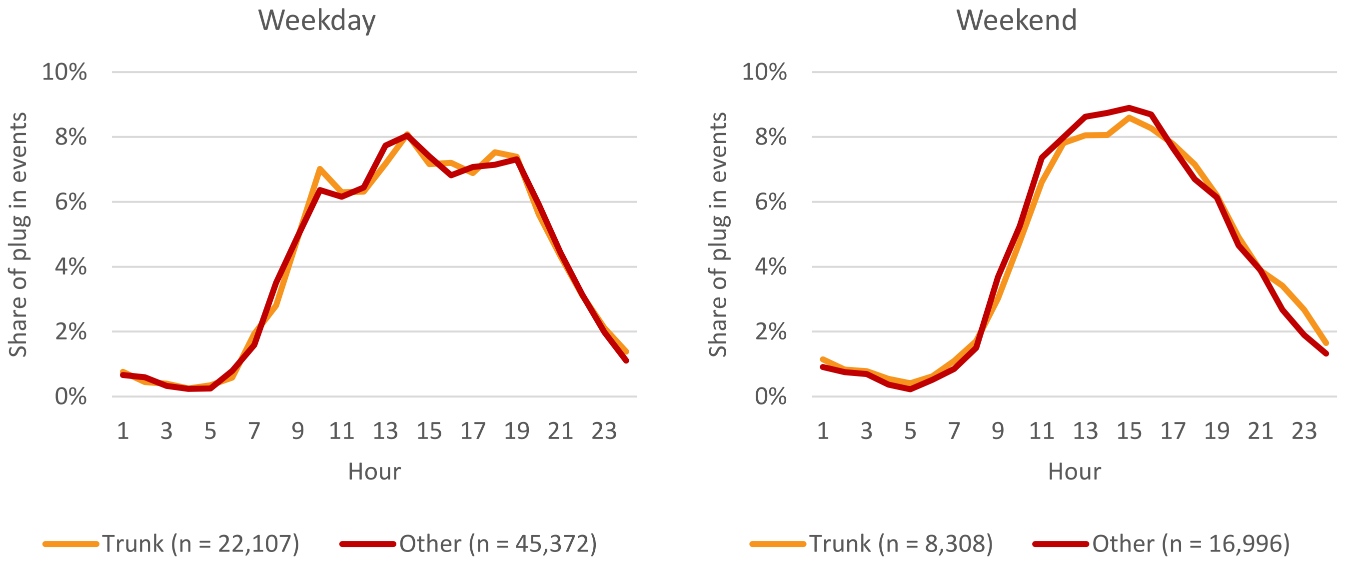

Figure 69: Average weekday and weekend plug-in start time profiles for all rapid public charge points in the UK Zap-Map sample, grouped by proximity to trunk roads and elsewhere. 'n' denotes number of charge events in sample.

Figure 70 presents, from the Zap-Map dataset, the difference in the time of rapid public charging for urban and rural locations across the UK and in the UK Power Networks licence area. Rural charging in the UK sample shows a similar profile to the ESB data in Figure 68, with a less pronounced morning peak on weekdays. The sample covering the UK Power Networks licence areas is measured across only 72 urban and 17 rural charge points resulting in more volatile profiles. For these rural charge points in particular, the plug-in start time profiles are likely to be skewed by a small number of regular users.

[45] https://tfl.gov.uk/info-for/media/press-releases/2017/april/tfl-drives-forward-18-million-electric-vehicle-scheme

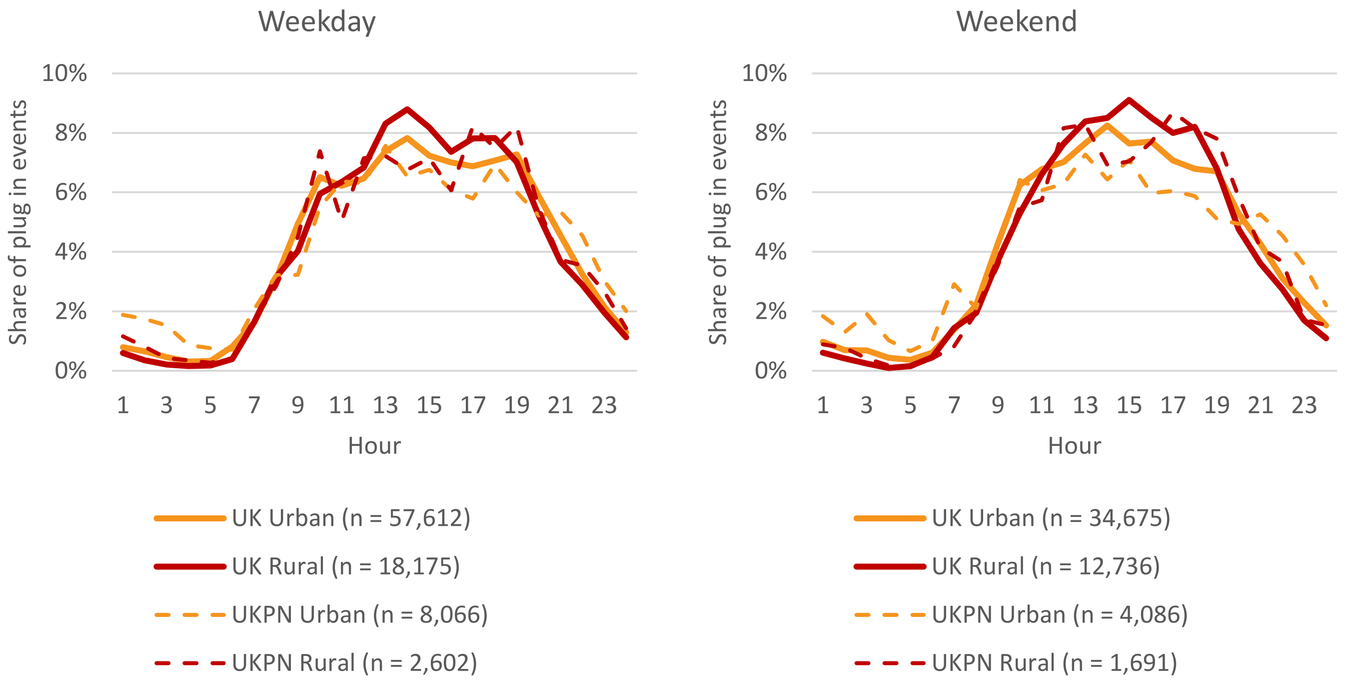

Figure 70: Average weekend and weekday plug-in start time profiles from Zap-Map data for rapid public charging, shown separately for urban and rural locations at UK-wide and UK Power Networks licence area levels. 'n' denotes number of charge events in sample.

5.5.2 Charging frequency

As for slow/fast public charging, utilisation of rapid public charge points will be highly dependent on the number of EVs available to use them, specifically BEVs since nearly all PHEVs are incompatible with rapid charge points (see Section 2.3.5). This is illustrated in Figure 71, where the average number of charge events per day per rapid charge point is found to be significantly lower during Plugged-in Places (2010-2012), when there were far fewer rapid charge points and BEVs capable of using them, than observed in the ESB ecars and Zap-Map datasets from 2017/18.

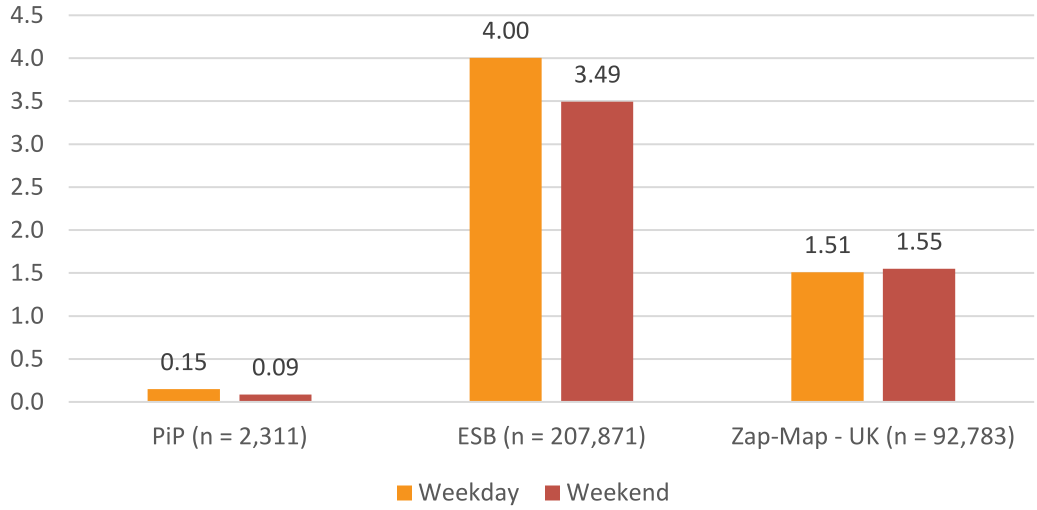

Figure 71: Charging events per day per rapid public charge point, as observed in available data sources. 'n' shows the number of charge events in the sample.

ESB ecars charge points show much higher average utilisation than those in the Zap-Map dataset, however, this is likely a consequence of these charge points being free to use. Whilst there are still some free-to-use charge points in the UK, the vast majority now require a subscription and/or fee per kWh or minute. The ESB ecars charge points also show a higher level of utilisation on weekdays, whereas Zap-Map shows the frequency of charging remains very similar.

A comparison of rapid public charge points at trunk and other locations (Figure 72), shows that utilisation at trunk road sites is slightly lower. However, it is worth noting that the trunk road sample does not include charge points installed at motorway service stations as part of the Ecotricity Electric Highway network which are arguably the most prominently positioned rapid public charge points serving long distance journeys. The true charging frequency at trunk road rapid charge points is therefore likely to be higher, reducing the difference to charge points in other locations.

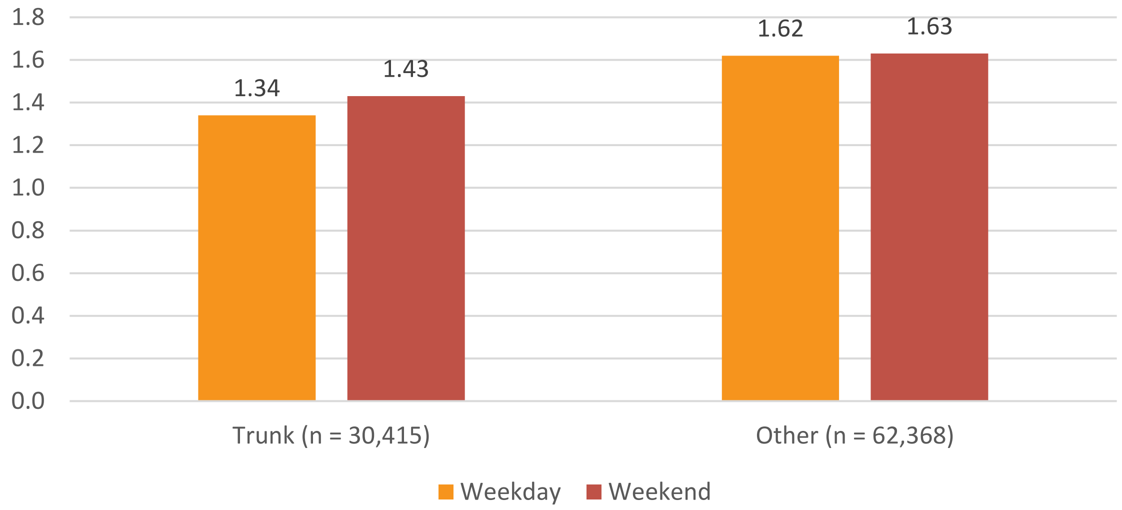

Figure 72: Charging events per day per rapid charge point for trunk and other locations in the Zap-Map dataset.

Figure 73 shows the average charging frequency at urban and rural locations at UK-wide and UK Power Networks licence area levels. For the UK sample, charging frequency is very similar in both urban and rural areas, but is in general lower in the UK Power Networks licence area, particularly in rural locations. However, as noted in Section 5.5.1, the UK Power Networks rural sample is limited to only 17 charge points.

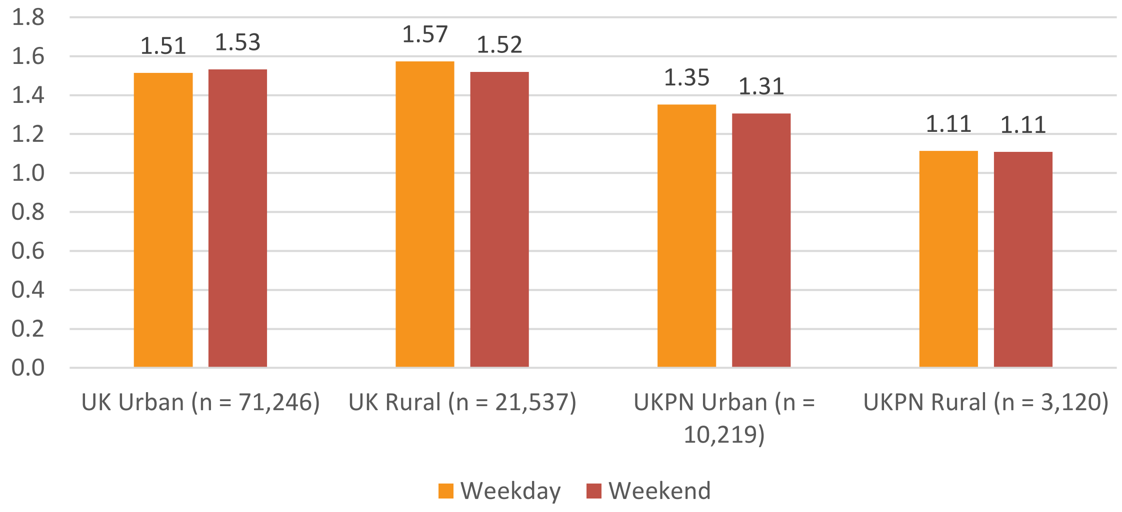

Figure 73: Charging events per day per rapid charge point for different regional groupings in the Zap-Map dataset. 'n' is the number of charge events in the sample.

From the perspective of EVs, identification of rapid charge events in the My Electric Avenue trial data found that each participant did on average 0.047 rapid charges per day on weekdays and 0.055 on weekends. This corresponds to about 1 rapid charge every three weeks. This is very similar to findings from the Norway EV Owners Survey 2016 which found BEV drivers rapid charge on average 0.05 times per day (Figenbaum & Kolbenstvedt, 2016).

This is supported by the available Electric Nation survey data, which asked participants how often they charge at motorway service stations and petrol stations. Assuming all these to be rapid charging gives an indication of how different EV characteristics impact charging frequency. BEV drivers reported charging on average 0.07 times per day, although BEVs with larger batteries appear to use rapid charge points more often. For example, BEVs with batteries larger than 60 kWh used these charge points on average 0.12 times per day, compared with 0.055 for batteries ≤30 kWh. This is likely because small BEVs are used less often for long journeys on motorways, and for some models rapid charging is available only as an optional upgrade (e.g. Renault Zoe, Nissan Leaf 24kWh, VW e-Golf 24kWh).

5.5.3 Charge duration and/or kWh per charge

The purpose of rapid public charging is to increase battery state of charge as quickly as possible to minimize inconvenience. Consequently, average charging durations, shown in Figure 74 are significantly shorter than for slow/fast public charging which is between 3 and 4 hours, and show no variation between weekends and weekdays.

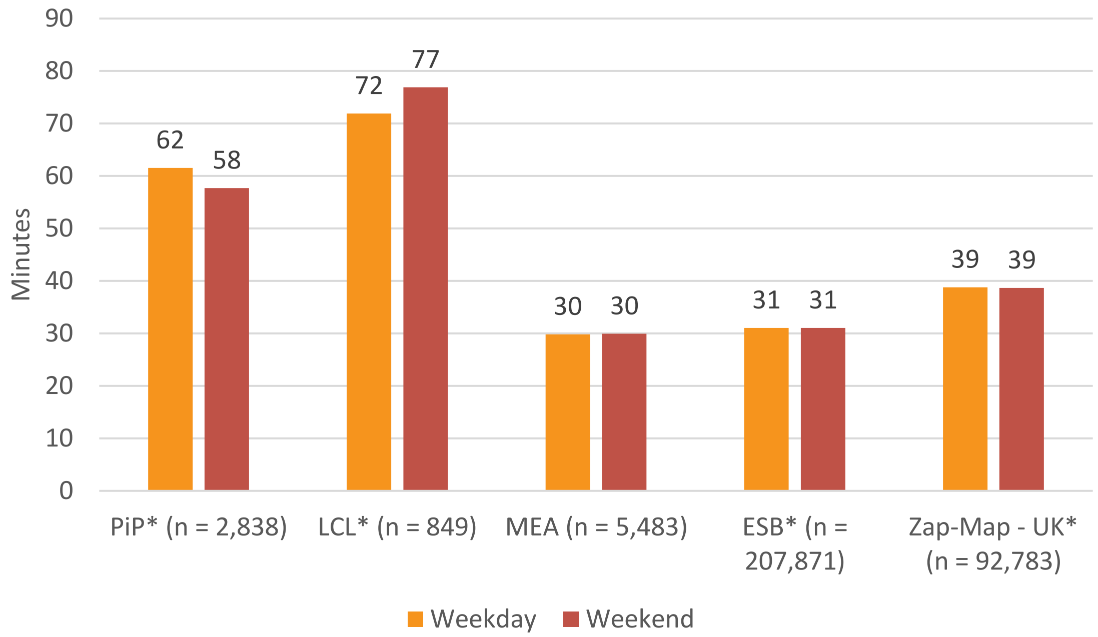

*Figure 74: Average charging duration of rapid public charging events from available data sources. 'n' denotes number of charge events in sample. *Denotes plug-in duration rather than time spent charging.*

My Electric Avenue shows an average time of 30 minutes, which incidentally is the exact time that Ecotricity suggests it takes to charge from 0% to 80% state of charge[46]. This is based on the rapid charging times of both the 24 kWh and 30 kWh variants of the Nissan Leaf, which have been shown to have the same duration (Herron & Coleman, 2017). Figure 75 shows how the rate of change in state of charge for the 24kWh Nissan Leaf is near identical to the 30kWh version. For batteries of this size, the charging rate is limited to less than the 50 kW available to avoid damaging the battery. During My Electric Avenue, which featured only the 24 kWh Nissan Leaf, the average rate of charging at rapid public charge points was only 23 kW.

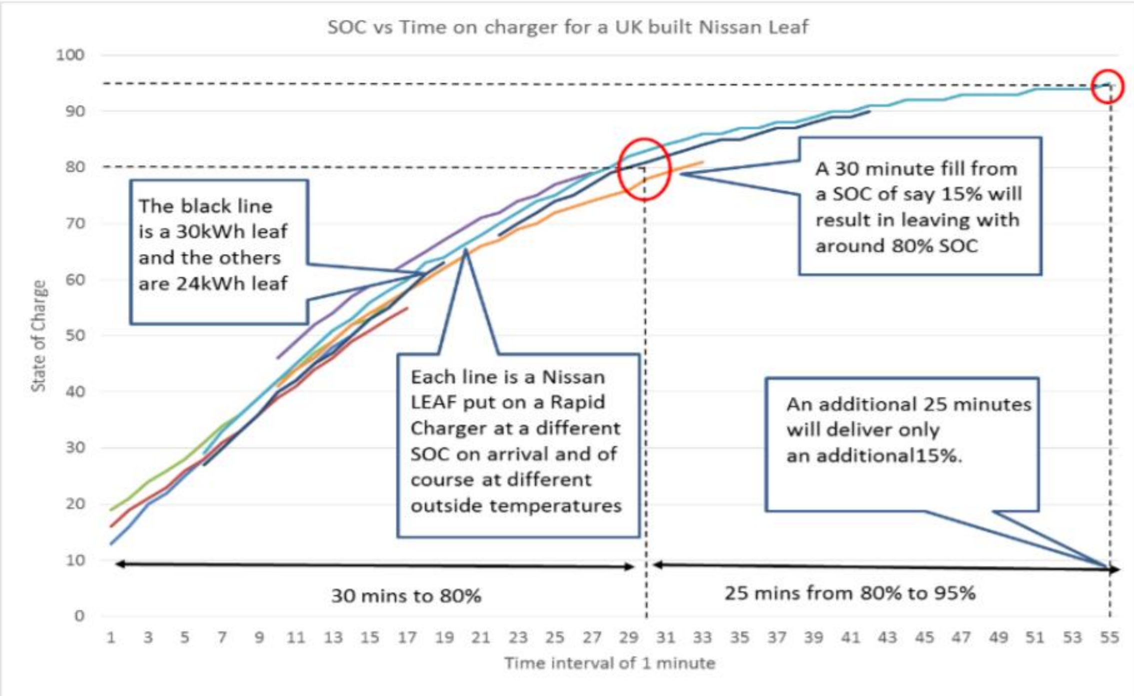

Figure 75: State of Charge vs Time profiles recorded for 30kWh and 24kWh Nissan Leaf models charging at 50kW rapid charge points (Herron & Coleman, 2017).

The similarity between the average charge time from My Electric Avenue and the average plug-in durations reported in Zap-Map and ESB suggests vehicles are rarely left plugged in without charging. Note that the resolution of the ESB data is 5 minutes, and Zap-Map is 5 or 15 minutes depending on when it was recorded. At durations of around 30 minutes, such low resolutions are likely to impact data accuracy.

46 https://www.ecotricity.co.uk/for-the-road/ev-faqs/charging-faqs

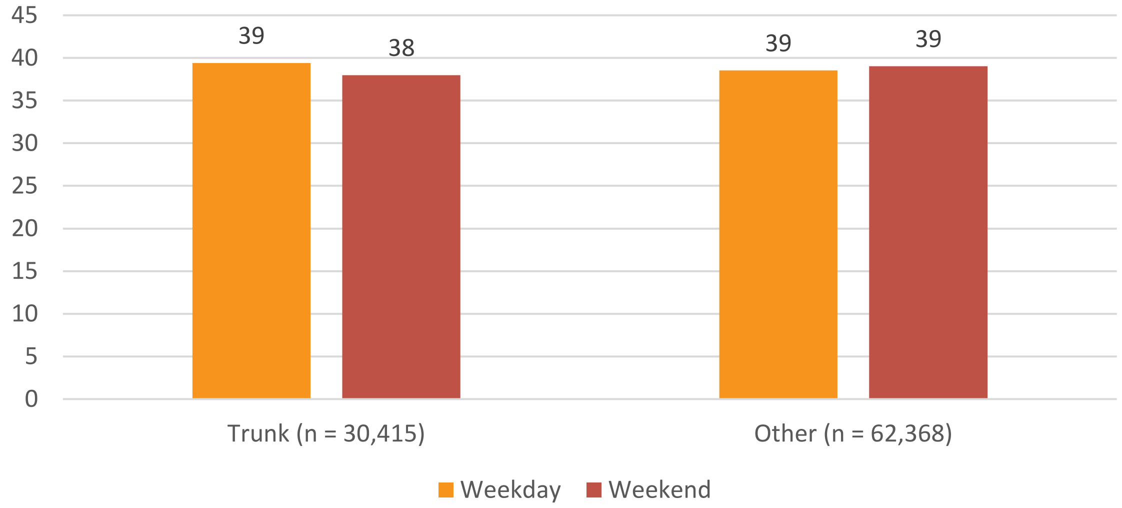

Figure 76: Average plug-in duration of rapid public charging events at trunk road locations and elsewhere, from the UK-wide Zap-Map sample. 'n' denotes number of charge events in sample.

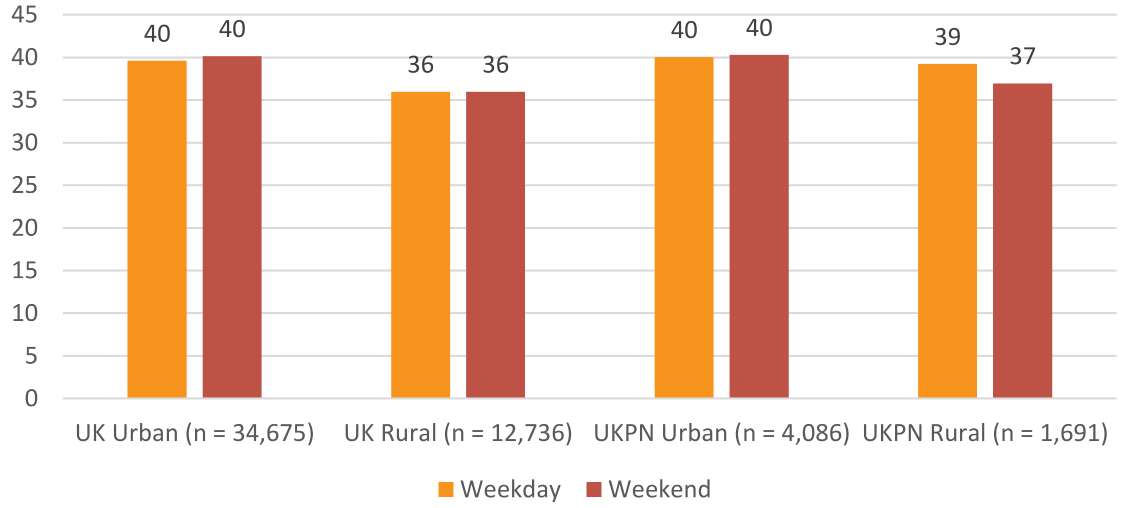

Figure 77: Average plug-in duration of rapid public charging events from the Zap-Map dataset, for different regional groupings. 'n' denotes number of charge events in sample.

Figure 76 and Figure 77 demonstrate that rapid charging plug-in durations are broadly independent of location, with a slight skew towards longer charging events in urban locations.

5.5.4 Share of charging at location

Share of charging at rapid public charge points for each BEV will be dependent on both the availability of rapid charging and the frequency of long distance journeys. During the Rapid Charge Network trial, it was found that most of rapid public charging events took place when daily mileage was larger than 100km, and in total 15.9% of charging demand was met by rapid public charging (Blythe, et al., 2015). However, in this trial participants with a high need for and access to rapid public charge points were purposefully selected, and so this figure is likely to be an overstatement for the average BEV owner. During My Electric Avenue, 9.2% of charging demand was identified as coming from rapid charging which may offer a more realistic average figure.

However, in both cases rapid public charging was available for free (e.g. from the Ecotricity Electric Highway motorway charge points) and so some EV drivers may have rapid charge unnecessarily as a way of reducing their electricity costs. Furthermore, the BEVs used in these trials had relatively short ranges compared to BEVs available today, and so their need for rapid charging could have been larger. Owners of longer ranges BEVs today may be more content with delaying a charge until the end of their journey, if they can charge their car while it is parked at their destination, where the cost is also likely to be lower. However, the availability of long range BEVs may also open up new buyer segments with high mileages, whose need for rapid charging would be greater.

5.6 Delayed and Managed Charging

5.6.1 Time-of-Use Tariffs

Time-of-Use tariffs have been shown on multiple occasions as an effective tool in shifting charging load into off-peak periods. For example, the Low Carbon London Smart EV trial, monitored the engagement of 10 EV drivers with a Time-of-Use tariff that offered 20% electricity price discount between 9pm and 7am. Of the 10 EV drivers, 7 of them actively shifted their charging to off-peak times despite overall cost savings being well under £10/year. Despite the small sample size, it was concluded that the belief that there is a saving to be had is enough to shift participants to charging off-peak, even if actual savings are modest (UK Power Networks, 2014).

Similarly, in California, since 2012 state regulators have required the largest private electric utility companies to continually assess the degree to which EVs necessitate electricity network upgrades, which includes an evaluation of how successfully Time-of-Use tariffs shift charging to off-peak times. So far, they have found that fewer than 0.2% of the state's 334,000 EVs have resulted in a network upgrade and concluded that Time-of-Use tariffs have been highly effective in facilitating this rate (Allison & Whited, 2017). For EV drivers, on average 79-84% of their household electricity demand is off-peak depending on utility area, compared with 70-78% for those without EVs. Some EV drivers have separate meters for their home charge points, and show 88-93% of charging demand is off-peak.

Even without specifically testing the effectiveness of Time-of-Use tariff engagement, several trials have observed participants actively delaying their charging in order to take advantage of lower cost off-peak electricity:

- In the Switch EV trial there was a noticeable peak in home charging load observed just after midnight. This was attributed to some EV drivers employing home charge points with built in timers (Neaimeh, et al., 2015), presumably to take advantage of low price electricity on an Economy 7 tariff. This was seen for both urban and rural participants (see Figure 78).

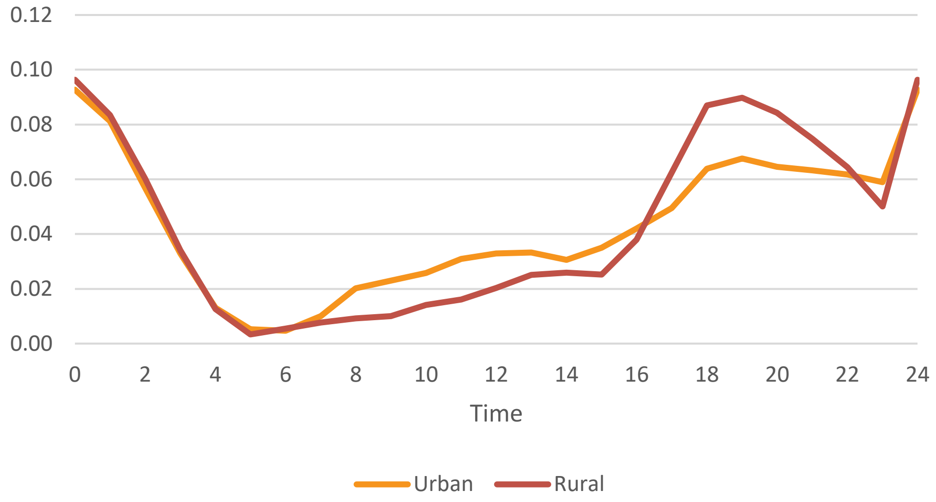

Figure 78: Normalized average home charging demand profiles from the Switch EV trial (Neaimeh, et al., 2015).

- As mentioned in Section 5.1.1, a large proportion of EV drivers in a trial run by the Japan Automobile Research Institute (JARI), delayed charging until after 11pm which is when off-peak electricity prices became available (Xiao-Hui Sun, 2015).
- FleetCarma's ChargeTO smart charging trial took place in Toronto, Canada where a Time-of-Use electricity pricing structure is present. During the control period where charging was left unmanaged, it was found that a share of participants used a delayed-start function on their charge point or EV to begin charging after 7pm to coincide with the start of off-peak electricity prices (FleetCarma, 2017).
- The interim Electric Nation data reveals that 15% of the recorded home charge events were delayed by at least 10 minutes between the time of plugging in and charging. For both BEVs and PHEVs, most of these delayed charge events started just after midnight (see Figure 79). Charge delaying was more common for BEVs, with 24% of BEV charge events delayed compared with 9% for PHEVs. The cause of this behaviour is unknown, but it appears likely that it was due to the presence of Economy 7 tariffs. This will be investigated by EA Technology during the trial analysis phase and included within project reporting.

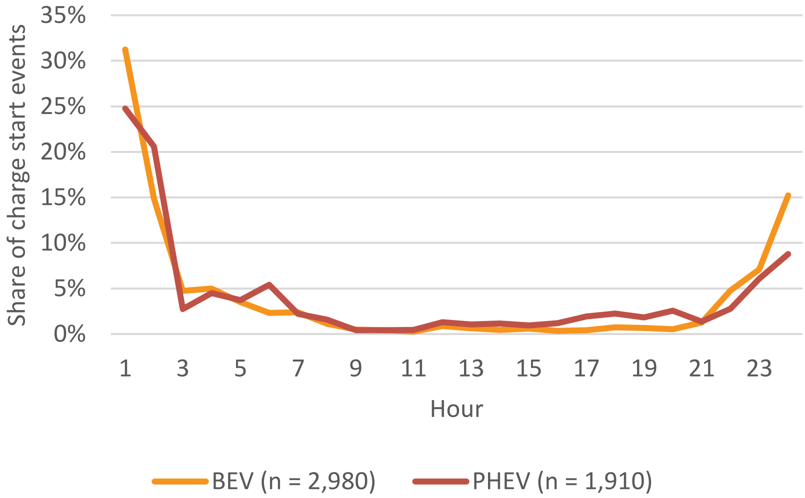

Figure 79: Charge start time profile of charge events delayed by at least 10 minutes after the plug-in time, in the interim Electric Nation dataset. 'n' denotes number of charge events in sample.

5.6.2 Managed Charging

As demonstrated in Section 5.1.3, plug-in durations at home are significantly longer than the required charge durations and so there is considerable flexibility in when EVs charge. Several trials have investigated systems which actively manage charging and found them to be effective in reducing peak charging load.

- The Low Carbon London Smart EV trial, also included the test of an Active Network Management (ANM) system, installed at 62 slow/fast public charge points, which restricted power supply to the charge points when demand at the connected substation was high. The trial demonstrated that this ANM system successfully provided real time distribution network load management, with minimum impact on EV users (UK Power Networks, 2014). However, it was noted that such a system is highly dependent on the probability that there is a sufficient volume of EVs charging to provide a suitable level of system availability. It is also uncertain whether consumers would accept reduced charging rates from public charge points if the cost was related to time spent charging.
- FleetCarma's ChargeTO trial piloted a managed charging system, whereby participants could set the time that they needed their EVs to be charge by when charging at home. The system would then actively shift their charging time to avoid overloading the local grid, but without negatively affecting their charging experience. The key to this was accounting for each participant's battery state of charge when deciding which charging events to shift. Participants also had the option to opt-out for 24 hours. This system was shown to reliably reduce peak charging load by 50%, and on average 85% of the EV load could be shifted 1-2 hours later when needed. In addition, 97% of the participants said that the system had either a neutral or positive impact on their vehicle usage and had little to no effect on their day-to-day driving activities (FleetCarma, 2017).
- My Electric Avenue trialled the Esprit load management system, which was specifically designed to deal with the impact of EV clusters on the low voltage network. When the load at a substation reached a certain threshold, the system would sequentially switch off and on connected home charge points to reduce the load without unduly penalising one connected EV user. It was reported that there was *"no statistically significant difference in opinion*

towards the ownership or use of EVs between the trial participants who experienced frequent and regular curtailment of their EV charging and those who experienced very little, infrequent curtailment" (EA Technology, 2016). It was also estimated that the system could provide savings of approximately £2.2bn to Great Britain's DNOs by 2050 compared with conventional network reinforcement methods.

- Electric Nation is currently trialling two smart charging systems (GreenFlux and CrowdCharge). The aim of this trial is to evaluate the reliability and acceptability to EV owners of a smart charging system and the influence these have on charging behaviour, in order to answer questions such as:
    - Would charging restrictions be acceptable to customers?
    - Can customer preference be incorporated into the system?
    - Is some form of incentive required?
    - Is such a system 'fair'?
    - Can such a system work?

  The customer trial began in 2017 and will continue until the end of 2018. Full results will be published during 2019.

In addition to these trials, UK Power Networks' Smart Charging Architecture Roadmap Project, running from April 2018 to February 2019, is exploring the systems architecture (such as technology, assets, information flows, standards, business functions and commercial arrangements) which is required to facilitate smart charging for residential customers. The project will identify a range of potential models for smart EV charging, to understand the architecture requirements needed to support each of those models. The project will develop architecture representations specific to each option, including detail at the point of customer connection or interaction with charging infrastructure, and outline the requirements between the substation and the internal systems and processes that a DNO may need.

This project is building upon the findings of previous and ongoing projects that have focussed on specific parts of smart charging solutions, such as the link between charging points and substations, to determine an architecture that details the full smart charging landscape. This architecture will then be assessed on its ability to support the various smart charging business models that the project identifies. The geographical focus will be Great Britain, but the project is drawing on international experiences of smart charging where appropriate. The study is also exploring potential differences in smart charging models and the architectural requirements between urban, suburban and rural areas.

6 Recommendations for modelling charging behaviour

As outlined in Section 1, the findings of this literature review are intended to be used to model EV charging in the Recharge the Future EV Load Forecasting Module. This will provide UK Power Networks with a more accurate forecast of EV charging load at each network asset across their licence areas. This following section details the aspects of EV charging behaviour which should be captured in this model:

Home

Characteristic	Finding	Section	Page No.
Time of Charging	Commuters show a large peak on weekday evenings (5-9pm), but broader profile on weekends centred around 4-5pm.	5.1.1	61
	Non-commuters show a similar broad profile centred around 4-5pm on both weekdays and weekends.	5.1.1	61
Charging Frequency	EVs charge marginally less often per day on weekends compared with weekdays.	5.1.2	66
	PHEVs charge more often than BEVs, and for each powertrain charging frequency decreases as battery size increases.	5.1.2	67
	Commuters charge more often than non-commuters, although if commuters have access to charging at work then their charging frequency decreases.	5.1.2	69
Charging Duration	Plug-in duration is usually significantly longer than time spent charging and so does not restrict charging duration.	5.1.3	71
	Average kWh per charge is highly dependent on battery capacity.	5.1.3	73
	For an EV with the same sized battery, rural drivers tend to have a greater kWh per charge than urban drivers.	5.1.3	75
Share of Charging	For EVs with access to home charging, 70-80% of charging demand is provided at home.	5.1.4	77

Residential On-Street

Characteristic	Finding	Section	Page No.
Time of Charging	On-street residential charging displays similar profile to home charging, although for charge points in areas with a high concentration of business premises there is also a secondary morning peak.	5.2	82
Charging Duration	Average plug-in duration is significantly longer than time spent charging, which is similar to home charging.	5.2	82

Work

Characteristic	Finding	Section	Page No.
Time of Charging	Plug-in times are concentrated in the mid-morning, around 9am, and coincide with when commuters arrive for work.	5.3.1	83
Charging Frequency	Very little weekend charging occurs at work, since few commuters travel into work at weekends.	5.3.2	84
	PHEV drivers plug in more often than BEV drivers	5.3.2	85
Charging Duration	Plug-in duration is longer than charge duration, and so does not act as a limit to kWh delivered.	5.3.3	85
	Average kWh per charge is about 9 kWh, and appears independent of charging rate.	5.3.3	86

Slow/Fast Public

Characteristic	Finding	Section	Page No.
Time of Charging	Weekday charging shows a strong morning peak and secondary peaks in the early and later afternoons. The morning peak is attributed to commuters, and the evening peak to overnight charging.	5.4.1	87
	On weekends, plug-in times are spread more broadly throughout the day with a peak around 1pm.	5.4.1	87
Charging Frequency	Charging events occur ~25% more often on weekdays compared with weekends.	5.4.2	90
	For an individual EV, charging frequency is low (e.g. once every 4 weeks) and decreases with increasing battery size.	5.4.2	91
Charging Duration	Plug-in durations have a similar length to charge durations at 2-3 hours and appear independent of powertrain and battery size.	5.4.3	92

Rapid Public

Characteristic	Finding	Section	Page No.
Time of Charging	On weekdays, plug-in start profiles shows three distinct peaks in the morning (9-10am), early afternoon (1-2pm), and evening (6-8pm). On weekends, only a broad peak centred around the early afternoon (1-3pm) is visible.	5.5.1	95
Charging Frequency	Rapid public charge points are used a similar number of times on both weekends and weekdays.	5.5.2	98
	BEVs use rapid charge points fairly infrequently (e.g. once every 3 weeks) but those with larger batteries use them more often.	5.5.2	100
Charging Duration	Plug-in durations with 50 kW charge points last on average 35-40 minutes.	5.5.3	101

7 Future Considerations, Opportunities and Projects

7.1 Future uncertainties

A persistent issue with real world data collected to date is that it considers charging behaviour from early adopters driving first generation EVs, with scarce charging infrastructure. The findings from existing literature will not necessarily apply to mass market EVs/drivers in future. The following developments are likely to have the strongest influence on future charging behaviour and charging load from the perspective of the distribution network:

- **Take-up of EVs by mass market consumers**, who are likely to be less concerned with minimizing impact on the electricity grid and place a higher value in convenience.
- **Shift away from conventional 'refuelling' behaviour**, in which cars are only refuelled when their fuel reserve reaches a certain level. The reason for this is that refuelling a conventional car has an associated inconvenience and so drivers minimize the number of times they must visit a petrol station. However, the inconvenience of plugging in an EV at home is significantly lower, and so drivers may begin seeing plugging in every night an acceptable trade off to reduced range anxiety.
- **Multiple EVs per household** could add an additional dimension to the decision of when to charge, as EVs may have to share home charge points. This would mean that owners would have to choose which EV to charge, which could result in individual EVs being charged less often to accommodate the second EV, or more often as free access to the home charge point is no longer guaranteed. This would also have an effect peak on diversity, as a charge point serving multiple EVs would be used more often. This would likely close the gap between average and highest observed peak. At present, 44% of households in England that own a car or van own more than one[47].
- **Larger batteries**: if the decision to plug in at home continues to be driven primarily by state of charge (see Section 5.1.3), then larger batteries and consequent higher ranges could result in less frequent and longer charges.
- **Improved public charging infrastructure**: higher charge rates and better coverage of public charge points could provide a viable charging solution for EV drivers who do not have access to charging at home. This is likely to push more charging demand into the middle of the day, with EVs charging by 'grazing' on slow/fast public charging while parked between trips and/or periodically driving to a rapid charge point in a similar manner to driving to a petrol station (so called 'gorging'). Alternatively, installation of high power rapid charging hubs could enable EVs to charge in a similar manner to how conventional cars refuel by visiting petrol stations.
- **Delayed and managed charging**: a range of products are likely to be rolled out to encourage EVs to charge during times that put least strain on the electricity grid, for example static and dynamic time-of-use tariffs and smart charging (see Section 2.3.1). Although individually these systems have proved successful, in a world where they are all freely available, consumer preference for each is not yet known.
- **Vehicle-to-Grid** has the potential to generate revenue for EV owners through supply services to the grid such as frequency response and local flexibility services, as well as behind meter load management and energy trading. This may encourage participating EV drivers to plug-in as often as possible to maximise service provision. There is also uncertainty around the range of services that bi-directional charging will be used for. For example, EV batteries could be used for electricity price arbitrage where the battery is charged with cheap off-

[47] National Travel Survey, 2014 and 2015: Table NTS9902 Household car ownership by region and Rural-Urban Classification: England, 2002/03 and 2014/15

peak electricity, and then discharged during peak times to either sell electricity back into the grid at a higher price or power a connected property to avoid these peak prices. This would change the shape of property's load profile and could potentially turn it into a net exporter of energy during certain times of the day. Furthermore, the added cost and complexity of Vehicle-to-Grid charging may limit its use cases and customer segments, for example, depot-based EVs over residential consumer.

- **Co-location of battery storage** with rapid charge points would help shift peak loads into off-peak periods and could also be used to provide grid services such as frequency response. The decision of whether to install batteries and/or renewable generation alongside rapid charging points and how much capacity is needed is extremely site specific, and will be a trade-off between battery costs, available grid service revenue and grid upgrade costs avoided.
- **Wireless charging** has the potential to reduce the driver's influence on when their EV is charged. For example, installation of a wireless charging pad at home could result in EVs charging whenever they are parked at home.
- **Charge point sharing**, where private charge points are made available to other EVs while not in use, could shift charging load into times when it is traditionally low. For example, services such as Bookmycharge provide the ability for EV drivers to reserve charging time at other people's home charge points in return for a fee, and would be expected to shift charging load into the day time when the charge point is less likely to be in use by the owner. Another potential provider of such a service is depots who may look to rent out their charge points while their EV fleet is out, thus making use of an underutilised asset. Centralising charging in this manner could provide DNOs with more control over when and where charging on their networks takes place.
- **Mobility-as-a-service**, including car clubs and autonomous taxis, would shift the charging decisions away from the vehicle owners to the fleet operating entity. In this case, charging would no longer take place at drivers' homes, and would rely either on public infrastructure or centralized depots. Charging behaviour would also be based more strongly on cost factors.

7.2 Upcoming and on-going trials

There are several trials in the near-term horizon and will look to answer some of the uncertainties listed in Section 7.1:

7.2.1 Electric Nation

Lead Partner(s): Western Power Distribution, EA Technology, Drive Electric

Timeframe: 2016-19

Description:
The Electric Nation project is described in Section 4.1.5. Although an interim trial dataset was made available for this study, the trial is ongoing, and the results of the final analysis are planned for release in April 2019.

Knowledge gaps addressed:
In addition to confirming some of the initial findings presented in this report, the analysis will look to evaluate the effectiveness of the managed charging system tested as part of the trial, and will include the effect of time of use tariffs alongside smart charging.

7.2.2 Consumers, Vehicle and Energy Integration Project

Lead Partner(s): The Energy Technologies Institute, TRL, Baringa, Element Energy, Cenex

Timeframe: 2015-19

Description:
This project is specifically focussed on EV attitudes and usage of mass-market consumers, and therefore provides valuable guidance on future EV charging behaviour. The project features two randomised control trials with participants who have had limited prior experience of EVs. The first will explore attitudes towards PHEVs and BEVs, and includes 200 participants who will each be given a multi-day test drive of the conventional petrol, PHEV and BEV variants of the Volkswagen Golf. The participants will be surveyed both before and after the trial to understand how their attitudes towards EVs may have changed, to provide an understanding of how vehicle purchasing behaviour may change as more mass-market consumers gain experience on EVs. The second trial consists of 240 participants, who will be given either a BEV and PHEV, and will test engagement with various managed charging schemes. The attitudes towards these schemes will be quantified, to evaluate the effectiveness of managed charging on a future energy system. The findings from the project are due to be published in March 2019.

Knowledge gaps addressed:
Charging behaviour of mass-market EV drivers and preferences for different managed charging schemes.

7.2.3 Oxford Go Ultra Low Trials

Lead Partner(s): Oxford City Council, Oxfordshire County Council

Timeframe: 2017-18

Description:
The purpose of this project is to test charging solutions for EV drivers who do not have access to off-street parking. It is considering six different charging technologies, used by 20 EV drivers and 10 car club EVs, over a 12-month period. Technologies include street lamp sockets, charging bollards, and cable gullies between the home and EV.

Knowledge gaps addressed:
Effectiveness and usage patterns of on-street residential charging technologies.

7.2.4 Vehicle to Grid - Network Impact of Grid-Integrated Vehicles

Lead Partner(s): Northern Power Grid, NUVVE

Timeframe: 2017-20

Description:
Consists of a phased roll-out of 1,100 Vehicle-to-Grid charging sites, which will be monitored throughout the project to assess their impact on the low voltage network.

Knowledge gaps addressed:
Impact of Vehicle-To-Grid on charging load from a distribution network perspective and influencing factors behind consumer behaviour with Vehicle-to-Grid.

7.2.5 Innovate UK projects

Innovate UK has provided £30m in funding for a range of Vehicle-to-Grid research, feasibility and real-world demonstration projects. The demonstration projects, summarised in Table 7, will generate real-world data with most running from 2018 to 2021.

Table 7: Summary of the V2G demonstration projects funded by Innovate UK in 2018.

Name	Funding	Main Partners	CP Type	Key points
PowerLoop	£3.1m of £7m project	Octopus Electric Vehicles, Open Energi, UK Power Networks	Home	• 135 charging points • London and surrounding areas
e4Future	£6m of £9.9m	Nissan, National Grid, Imperial College, NUUVE, UK Power Networks, Northern Powergrid	Home & Work	• 1,000 charging points • Assess impact of V2G on whole system level
Sciurus	£3.1m of £4.8m	Ovo Energy, Indra Renewable Technologies, Nissan	Home	• Develops grid balancing platform aimed at residential customers • Aiming to consist of 1,000 Nissan Leaf drivers over two-year period.
Bus2Grid	£0.8m of £2.4m	SSE, BYD, UK Power Networks, University of Leeds	Work	• 30 electric buses • Installing V2G units at London bus garage • Multi MW demonstrator
SMARTHUBS demonstrator	£1.4m of £2.2m	Flexisolar, Flexitricity, Turbo Power Systems	Car Park	• 150 V2G enabled EVs • 6 sites (car parks) • Assess which services are accessible for V2G
V2GO	£3m of £4.1m	EDF, Fleet Innovations, Upside Energy	Work	• Focus on commercial fleets (Royal Mail, UPS, DPD) • At least 100 EVs
E-Flex	£3.7m of £5.3m	Cisco, E-car club, TfL, GLA, NUUVE, Cenex	Work	• Focus on urban fleets (delivery, car sharing, police, health care) • 200 EVs
EV-locity	£3.9m of £5.6m	Honda, Honda, E-car club	Car Park	• 100 EVs connected and parked at an airport • Car maker agnostic

UK Power Networks is supporting its participation in these V2G demonstration projects through its TransPower project[48], which will also look to consolidate learnings to understand the impact of V2G technology on the electricity network and value of the benefits from providing local grid services.

Innovate UK is also funding feasibility studies (in 2018) and demonstration (from early 2019) of wireless charging, on-street charging solutions and rapid charging hubs. The competition deadline being in August 2018, the winners are not known at the time of writing this report.

In addition to these EV charging trials, the UK Government's Automated and Electric Vehicles Act 2018 may require charge point operators to share data on usage of public charge points, for example energy consumption and geographic information[49]. Although it is not clear exactly what form this data will take or who will have access to it, this may lead to the generation of additional sources of data to inform on the usage of public charging points.

[48] For more information see: http://www.smarternetworks.org/project/nia_ukpn0033

[49] Documents relating to the Automated and Electric Vehicles Act 2018 are available from here: https://services.parliament.uk/Bills/2017-19/automatedandelectricvehicles/documents.html

8 Next Steps

The Charger Use Study is the first work package of the Recharge the Future project. Its findings, summarised in Section 6, will be used to inform the creation of the Recharge the Future EV Load Forecasting Module, which predicts the growth in EV charging load. This will be integrated into Element Energy Load Growth Model, used to forecast load growth at each primary and secondary substation across the UK Power Networks licence areas. This will represent a significant improvement to the prediction of EV charging's contribution to network load growth and provide UK Power Networks the necessary tools to effectively prepare for mass EV adoption during the next regulatory period, RIIO-ED2 (2023-28), and beyond.

The Recharge the Future EV Load Forecasting Module will accurately reflect geospatial variations in charging behaviour. As noted throughout this report and summarised in Section 7.1, there exist some knowledge gaps and uncertainties surrounding how charging behaviour might change in future. Consequently, a number of scenarios will be developed alongside the model to explore possible future market and policy environments for EVs. These will explore the impact, for example, of different levels of ULEV uptake, charging frequency and rate, adoption of delayed and managed charging, and public charging infrastructure coverage.

The development of the Recharge the Future EV Load Forecasting Module and accompanying scenarios will be documented in a follow-up report, due to be published in 2019 Q1. This report will present load growth results for each of the scenarios generated by the module. These results will feed an impact analysis on the UK Power Networks' network, to be carried out by UK Power Networks and Imperial College London, which will estimate UK Power Networks' required re-enforcement costs resulting from EV charging load. From this, a range of recommendations will be presented for DNOs and policy makers regarding the management of future EV charging load.

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Appendix

A. Description of car segments

Figure 80 illustrates the UK Society of Motor Manufacturers A-I segmentation scheme. An additional Sub-Mini S segment is also shown. Small cars are defined as segments S, A & B. Medium cars are segments C, D & I. Large car are segments E, F, G & H. Note that the example cars shown are conventional ICEs as these are the highest selling examples in each segment.

Figure 80: Passenger car segments as defined by the Society of Motor Manufacturers. The numbers in parenthesis are the segment market share in 2017.