Strategies for the uptake of electric vehicles and associated infrastructure implications for
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1 Summary

1.1 Purchasing decisions for electric vehicles

Analysis of international literature on electric vehicle (EV) adoption, and the results of a new UK survey, indicate that high capital on-cost remains the biggest barrier to EV adoption. In the UK, derogation of the London congestion charge and parking charges, combined with early adopter’s “willingness to pay” go some way in bridging the gap in capital on-cost and supporting EV uptake. Outside of the early adopter group, the willingness to pay is zero or negative.

Limited range is the next most frequently stated concern. Drivers place a very high utility on the ability to drive very long distances, even though they realise that such trips are (for the majority) extremely rare. This is a major disutility for Battery Electric Vehicles (BEVs) which will need to balance range and cost of batteries. Plug-in Hybrid Electric Vehicles (PHEVs) do not suffer from this restriction, and P40 PHEV (i.e. with a range of 40 miles in electric mode) could achieve significant market uptake while delivering electrification of the overwhelming majority of vehicle trips.

Recharging infrastructure is mentioned as a concern but with a lower priority.

1.2 Demographics of BEV and PHEV users

The overwhelming majority of EV users (internationally and in the UK) are multi-car families with off-street parking. This is somewhat at odds with the “urban city car model” of electric vehicle adoption, where both parking availability and car ownership is lower (see Figure 1). Fewer than 50% of city centre households have access to adequate parking facilities, rising to 70% for suburban households.

Compared to single car households, multi-car households also have higher disposable income. EV adoption by multi-car households is an effective, rational hedge against the limitations of the new technology.

In the UK, around 90% of all households are in the ‘other urban centre’, ‘suburban residential’, or ‘rural residential’ categories. While a high profile urban centre such as London will play an important role in early EV markets (using congestion charge derogation as an financial incentive), meaningful CO₂ reductions can only be achieved through widespread adoption in the suburban sector (see Figure 2).
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Figure 1: Parking availability and car ownership by area

Figure 2: Parking availability by area type
1.3 The utilisation of electric vehicles

The full technical range of EVs is significantly underexploited in use. On average, between one third to on half of the technical range is actually used i.e. a vehicle with a capability of 100 mile range will on average be used between 33–50 miles. The low utilisation ratio is a rational response to limited recharging opportunities, long recharging times, and concerns over the reliability of new technology.

This utilisation ratio needs to increase if EVs are to achieve their CO₂ reduction potential. There is evidence to suggest that widespread slow charging will have limited effect on increasing the utilisation ratio, but in contrast fast-charging can be very effective in encouraging users to exploit the vehicles’ full potential.

1.4 Electric vehicles and trip types

An extensive statistical analysis of the Department for Transport (DfT) travel database has shown (see graph 3):

- The driving patterns of a significant proportion of the UK population are dominated by relatively low daily distances. For example, half the people in the sample analysed did not exceed 40km (25 miles) on any day of the travel diary week.

- Commuting is the dominant trip purpose, with circa one-quarter of all car trips being undertaken with getting to or from work as the primary reason for travel.

- Around two-thirds of commuting trips are less than 16km (10 miles). This suggests that there are a significant number of commuters with round-trip commutes of less than 20 miles.

- There is an important distinction between the trip types and distance (Figure 4). For example, a vehicle with a utilised range of 100km, would account for over 90% of trips, but only 60% of overall UK car-km.

- Assuming a utilised range of 80km (i.e. the capable range is much higher, between 120km and 240km), 50% of all UK vehicle-km can be undertaken by EVs. The remaining distance is undertaken by a relatively small number of high mileage individuals.

- To achieve an 80% reduction in CO₂, assuming that renewable electricity was used to charge EVs, would require a vehicle with a utilised range of circa 200km (and therefore a capable range between 300km-600km, assuming current behaviour patterns). Battery technology is unlikely to deliver this very high, single charge range in an affordable vehicle.

- Battery swap technology or fast charging stations could provide the extension in range required to accommodate this high mileage sector, although given the limited number of such drivers, alternative means for reducing carbon could be more effective.
Figure 3: Analysis of car-km in the eight most frequent trip types

Figure 4: Comparison of cumulative trip and mileage in the UK
1.5 Daily usage patterns of vehicles

Analysis of the DfT database has shown that the average time spent at a destination (outside of the home and workplace) is 1-2 hours. A slow charge system has limited utility in such circumstances as it would provide a small fractional increase in battery state of charge. In contrast, the average time spent at the workplace is seven hours, indicating that slow charging has merit here.

The probability of vehicles being at home is shown below (Figure 5) where the morning and evening commutes can be identified. There is a strong correlation between vehicles arriving home (potentially requiring recharging) and the evening peak in electricity consumption. If left unchecked, this could be a significant concern (see section 4).

![Figure 5: Probability of vehicles being at home, by time of day](image_url)
1.6 Recharging infrastructures

The technical capabilities of a number of EV recharging infrastructures have been estimated, based on the DfT trip statistics (see Figure 6).

![Figure 6: Recharging infrastructures and contribution to overall UK car-km](chart)

### 1.6.1 Residential recharging

Residential and workplace recharging points are shown to be technically capable of providing the majority of EV accessible passenger km at a much lower cost than publicly available recharging solutions.

An examination of vehicle trip statistics shows the expected correlation between potential domestic EV recharging demand, and evening peak domestic electricity demand. If left unchecked, at large EV uptake this will affect the distribution network and require relatively carbon intensive electricity. However, the UK Distribution Network Operators who were consulted believed that a very simple solution in the form of delay timers would be appropriate. These would prevent charging until the evening demand peak has passed. If provided with an “override button” this solution would be unlikely to discourage potential EV users as the public already accepts daytime/overnight electricity tariff structures provided there is an opportunity to override.

### 1.6.2 Publicly available recharging points

There is a widely held view that a dense and widespread publicly available recharging infrastructure needs to be in place to encourage EV adoption. While a highly visible infrastructure would undoubtedly send strong signals to potential end users, the technical necessity for this recharging solution is questionable, especially given the high cost of this solution (per kWh delivered) when compared to alternatives such as residential and workplace charging.
The cost of an installed publicly available slow charge (low kW) post could range from £6,000 (current prices) to £1,000-£2,000 (at volume). A fast charge (>50kW) charging point could cost between £50,000-£100,000, depending on the necessity for upstream grid reinforcement.

To encourage uptake of EVs, the parking area adjacent to public recharging posts may need to be reserved for EVs only, or even individual drivers. This will result in lost revenues from parking.

The limited time spent at destinations means that slow charge publicly available infrastructure will have very limited utility. Fast charging points will have a higher utility to the end user, and will promote increased use of the vehicles’ technical range. Fast charging plays an important role in removing the time barrier of recharging and there are examples of fast charge points promoting increased utilisation of electric vehicles.

If publicly available recharging posts are to be installed, it is vital that a common standard is agreed to ensure interoperability. This is of particular concern in London, where boroughs risk developing their own networks without sufficient levels of interoperability.

1.6.3 Workplace charging

Workplace charging has an important role in expanding EV uptake in the commuting sector, which accounts for the greatest car-km. Compared with publicly available charging points, the utilisation rate of workplace chargers can be accurately predicted. It will be easier to guarantee a parking spot with recharging facilities without losing revenue, and this is crucial from the end user’s perspective. The cost of a slow charge point in a workplace environment could approach that of a domestic recharging point in new build, and even in retrofit on existing buildings, the cost should be lower than that of a publicly available point.

Given the residence time at the workplace, workplace chargers can be of the slow charge type without suffering significant loss in utility from the user’s perspective.

1.6.4 Battery swap infrastructures

If the goal is to achieve 100% of car-km with EVs, battery swap stations are a logical technical response to limitations in battery technology. The necessity for swap stations could be challenged by improvements in fast charge technology. It is outside the scope of this report to analyse if battery swap infrastructures are the most appropriate approach to reducing carbon in this passenger car sector, or if alternatives (such as PHEVs with biofuels) are more efficient at saving CO₂.

1.7 CO₂ implications

Under a 2030 scenario where the UK passenger car parc includes 15.9 million EVs¹, and these vehicles are responsible for 45% of all car-km travelled, up to 16Mt of CO₂ per year may be saved relative to the baseline (no EVs). This is based on an average grid CO₂ intensity of around 0.14kgCO₂/kWh. This CO₂ saving represents 30% of 2030 baseline emissions from cars in the UK, or around 2.7% of total 1990 CO₂ emissions.

Should EVs be recharged with electricity from marginal plant, the CO₂ savings are reduced to around 5MtCO₂/yr under the uncontrolled charging scenario. This figure may be increased to

¹ Scenario provided by CCC.
around 8.5MtCO$_2$/yr if the peak demand for electricity due to EVs could be offset to correspond to periods of lower overall electricity demands.

1.8 Demonstration/rollout requirements

With its capital city status and derogation of congestion charging and parking charges, London represents an important site for early EV demonstration projects, although there is no reason why other regions and cities cannot provide a similar set of incentives. Interoperability of EVs between boroughs is a concern and should be a key success indicator. The London programme presents an opportunity to vary fast/slow charging availability and overall recharging density, thereby providing vital data on the importance of these issues. Achieving this while ensuring flexibility of vehicle and recharging point use will require extensive standardisation amongst vehicle and recharging post suppliers.

To achieve meaningful CO$_2$ savings requires significant EV adoption in suburban areas throughout the UK. A demonstration project testing the issues surrounding suburban EV use and recharging is required, and the results compared with urban EV projects. A suburban project should focus on domestic recharging. Without the benefits of congestion charging, a suburban project is likely to require significant financial assistance to overcome the capital on-cost of EVs (either capital grants or subsidised leasing of vehicles).

Assuming that the capital on-cost barrier can be removed, domestic recharging can accommodate a sizeable EV uptake. A significant market penetration will need to be achieved before widespread rollout in workplace recharging can be sufficiently low risk.

An indicative rollout programme for EVs in the UK is shown below.
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Figure 7: Rollout of EVs in the UK

A more detailed consideration of pilot schemes and publicly available recharging infrastructure is given in section 8.

1.9 Remaining areas of uncertainty

The issues itemised below must be addressed if we are to proceed with an efficient rollout of electric vehicles in the UK.

- The requirement for public recharging infrastructure as a signal that EVs are a successful technology (as opposed to the technical requirement for charge points).
- The minimum density of public recharging sufficient for it to be no longer perceived as a barrier.
- The increase in vehicle utilisation as a function of slow charge availability versus fast charge availability.
- A business model of public recharging points and the willingness of EV users to pay a significant multiple in electricity price to offset the cost of the recharging point (versus using a domestic recharging point).
- Outside of London and congestion charging, the availability of sufficient fiscal support mechanisms strong enough to address the high on-cost of EVs.
2 Characterisation of EV users

2.1 Introduction

An understanding of why EVs are and will be purchased, and how they will be used, is vital in developing policies supportive of the technology, and predicting the impact this technology will have on carbon abatement. Predicting consumer behaviour in the EV market is challenging as the technology is very distinct from the incumbent, and uptake to date is limited to a very small group of early adopters. As the current study relates to the impact of large scale EV adoption, care is required when using data (which tend to be biased towards early adopters) and extrapolating to the mass market, which has very different requirements.

Much of the available data on EV purchase behaviour and utilisation, comes from a number of trials undertaken in California, set up as a response to the Air Resources Board Zero Emission Mandate. Although ultimately rescinded, at the time of its introduction the ZEM posed a significant challenge to car manufacturers, prompting research into new automotive technologies, and how the buying market responds to these technologies.

Given concerns that these data sources may be biased towards US behaviour, a UK centric survey has also been developed as part of the current project. The survey focused on those who have purchased and use EVs in the UK, and those who have demonstrated significant interest in purchasing EVs. While not designed to provide statistically robust results (sample groups in the UK are too small) the survey represents the first publicly available systematic analysis of UK perceptions of EVs both from the perspective of EV owners and those who have considered EVs. For more information please see section 14.

2.2 Purchasing electric vehicles

Electric vehicles have a number of primary attributes which distinguish them from the incumbent technology. For a prospective buyer, the most important of these are higher capital cost, lower range, lower running cost, “green motoring”, make/model/brand, concerns over recharging infrastructure, and the impact of innovative technology (with regard to maintenance and resale value).

The relative importance of these attributes changes between prospective users. For example, the mass market sees capital cost as the primary factor; concerns over EV range are also rated highly, but see “green motoring” benefits as irrelevant. In contrast, early adopters place a higher value on green motoring, will pay to support new technology, will be much less sensitive to higher capital costs and are more likely to account for lower running costs when deciding on a purchase.

Identifying the most relevant attributes for EV adopters is important for designing effective incentives to promote uptake.

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2 www.arb.ca.gov

2.2.1 Capital cost as the primary factor

When considering a purchase, capital cost is always the primary factor for the mass market. It is commonly stated that the expected lower running costs for EVs could be used to offset a higher capital cost. However, the potential for lower running costs is largely ignored by the mass market\(^4\) i.e. life cycle costing (or Net Present Value) is rarely considered at the point of purchase.\(^5\) Policy makers should not overestimate the effect of an incentive policy which makes the “investment” in an EV net NPV neutral. If there is a requirement to offset higher capital costs with lower running costs, this would have to be undertaken by a third party. This gives support to the model of vehicle leasing, or pay per mile.\(^6\)

The sensitivity to capital costs means that any strategy for significant uptake of EVs (i.e. over and above the relatively small early adopter market) will need to prioritise this issue. Even a significant intervention such as a grant to cover the additional capital cost of an EV (relative to the incumbent) would not of itself be enough to ensure significant uptake. There would remain the significant disutility associated with limited range of EVs.

2.2.2 The requirement for very high range

Most drivers are aware that their daily mileage is relatively low (e.g. less than 30 miles), and this is demonstrated by some of the results presented in chapter 4. Nevertheless surveys of vehicle purchasing behaviour do indicate a deep seated desire for a vehicle which has very high range (100’s of miles) even though this range would be utilised very rarely.\(^7\) The inability to provide this (hardly ever utilised) range requirement is, after capital cost, the most frequently mentioned barrier to EV adoption.

At this time we cannot foresee battery performance improvements and cost reductions sufficient to provide this range while approaching any reasonable level of affordability. The Project Better Place model is one response to this limitation of BEVs (see section 12.4). This barrier also points strongly in favour of PHEVs, with a gasoline/diesel range equivalent to the incumbent.

2.2.3 Willingness to pay

Willingness to pay (WTP) is the capital on-cost that a prospective end-user will consider paying for a product in return for the perceived benefits. The value is not constant, being highest for the “early adopters” of a technology, and lowest (possibly zero or negative) for the mass market. An incentive mechanism designed to support EV introduction needs to reflect the likely WTP of the market it is addressing.

\(^4\) “Driving Plug-In Hybrid Electric Vehicles: Reports from U.S. Drivers of HEVs converted to PHEVs, circa 2006-07”, Kurani et al., UC Davis, 2007. The report refers to purchasing behaviour of BEVs as well as HEVs.

\(^5\) Having said this, there is evidence that higher gasoline prices lead to a greater awareness of the cost of motoring, leading to greater uptake of smaller vehicles.

\(^6\) Useful proxies to this include some mobile phone business models, and the Xerox model of paying per page, not for the machine.

\(^7\) “Projecting use of electric vehicles from household vehicle trials”. Golob and Gould, 1998.
WTP in stated preference surveys tends to be in the low thousands of pounds (or dollars) i.e. a large percentage of the population say they would pay such amounts for an EV or a PHEV. However in stated preference surveys, the WTP is usually overstated, relative to the real costs supported by the market. Nevertheless, WTP figures do provide a useful guide as to the levels of support required by the market. The UK survey developed as part of this work, identified that circa £2000 was representative of the WTP for the early adopter group. As the actual on-cost of BEVs are (at least initially) likely to be much greater than this, extra support will be required to sustain the market.

2.2.4 Availability of recharging infrastructure

The lack of a sufficiently well developed EV recharging infrastructure is identified in surveys as a relevant issue. However it is not identified as a primary barrier (this is overwhelmingly capital cost). This may be due to sample bias, in that most EV trials make provision for recharging thus limiting concerns within the sample group. Nevertheless, the lack of data proving that infrastructure is a primary concern, does bring in to question the prioritisation of this issue by those wishing to support EVs. The widespread and unquestioned view that significant EV uptake requires a priori a high density of (usually public and urban) recharging points, is simply not supported by the evidence and should be challenged. There are many examples of urban recharging infrastructures which have not been followed by significant EV uptake (see section 12).

In contrast, an infrastructure model which relies predominantly on home recharging with some workplace charging (at least in the early stages of uptake) is supported by the limited evidence as being technically sufficient to meeting demand.

Certain EV stakeholders with whom we have consulted, reiterated their view that a highly visible publicly available EV recharging infrastructure is vital in sending a signal to end users that EVs are real and viable. Whether the investment in this can be justified, when there are other (more significant) barriers to uptake, and home recharging would be much more cost effective, has not been proved.

2.2.5 Aversion to new technology

While early adopters may pay to support new technologies, the mass market actively avoids this. There are a number of contributory factors: a perception that an innovative technology may be less reliable; that maintenance costs may be higher; or that the technology is not available in the make/model preferred by the buyer. Certainly, the business models of commercial/fleet operators are very sensitive to resale values and if these are untested, this represents an unacceptable risk. Sources suggest the innovation barrier reduces as the technology is taken up by the market, and is no longer an issue once an uptake of 15% of the market has been achieved.

The implication is that incentives will need to be stronger during this market introduction phase, to address the mass market hostility to innovation.

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2.2.6 Demographics

Data from trials and surveys show that EVs are overwhelmingly purchased by multi-car households\(^\text{10}\) (see section 14). These households have higher than average income, education, and have off-street parking. These users understand the limitations of EVs and retain their primary vehicle for longer journeys.

Due to range constraints and the increase in city-based emissions legislation (such as the London “congestion” charge) EVs have been promoted as city-cars. However the demographics of the overwhelming majority of current EV adopters are at odds with this application. City dwellers have more restricted access to parking and single car households are much more common. Finally, meaningful CO\(_2\) reductions will only occur if EVs achieve significant uptake in the sub-urban sector.

2.3 Operating electric vehicles

2.3.1 Underutilisation of technical range

Analysis of how EVs are used shows that only a fraction of the technically capable mileage is commonly utilised. Generally, the utilised daily range is one-half to one-third of the technically capable range.\(^\text{11}\)

It is reasonable to assume that the origin of this is the lack of a suitably widespread recharging infrastructure, combined with the time implications should an unscheduled recharge be required. The graph below compares statistics on battery state of charge (SOC) before, and after an additional fast charger was installed in Tokyo. Beforehand the typical SOC at the end of the working day was circa 60-70%, implying just one third of the potential range was utilised. Following installation of fast charging (additional to the existing six charging points in the metropolitan Tokyo area) on average two thirds of the range was utilised. Fast charging (i.e. not just extra charging points) was seen as vital in achieving this result.

This issue has important implications when estimating electric km’s driven and hence CO\(_2\) savings arising. In the early stages of EV adoption, concerns over infrastructure may limit exploitation of range to circa one third of technical capacity. Longer term this utilisation ratio should increase as users become more familiar with the technology and fast charging infrastructure becomes more widespread.


\(^{11}\) Projecting use of electric vehicles from household vehicle trials”. Golob and Gould, 1998.
2.3.2 Competition with second car in household

When an EV is introduced to a multi car household, it competes with the first car for use on trips. Surveys of usage indicate that for short trips (for which the EV is technically capable) the EV may be used for up to half of these trips. The EV utilisation rate drops off as the trip length increases, and approaches zero at lengths equivalent to the EV technical range. As with the preceding issue, the impact of this is that EV mileage in use may be less than the technical potential range, particularly if the current pattern of EV adoption into multicar households continues.

2.4 Recharging infrastructures

A review of worldwide EV infrastructure projects is given in the appendix, along with EV support programmes. The following issues are important when considering infrastructures.

2.4.1 Charging location

The issue of charging infrastructure location was mentioned above. Publicly available recharging points have been the focus of publicly funded infrastructure projects, and this continues to be the case with the announcement from the Mayor of London. An advantage of publicly available recharging points is that they have high visibility and this may act to encourage uptake. Providing ancillary benefits (such as a reserved parking space) would be highly attractive to a target market.

There are drawbacks to the public infrastructure model. Utilisation rates will be lower than a dedicated home or workplace charger. The cost of installed slow charge (circa 1-2kW) recharging posts are upwards of £5,000 (reducing towards £1,000 with volume), not counting the time required to plan the deployment, acquire planning permission etc. Maintenance of an item of street furniture may also be significant. If recouping these costs through a charging fee,

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12 Tepco R&D centre, Tokyo Electric Power Company. Data relates to Tepco’s own fleet of EVs. The charger can supply at 45kW.
this could result in a cost per kWh of circa £1/kWh. Providing a “free” reserved parking space would also be costly in lost revenue.

As experienced in Tokyo, and shown in chapter 4, publicly available “slow” recharging points will have limited utility to most end users. Fast charging points are required but are significantly more costly both in terms of the charging point itself, and the potential for upstream network reinforcement.

2.4.2 Slow versus fast charging

Slow charging typically refers to a charging rate that can be supplied by a typical single phase supply i.e. in the low kilowatts, with full recharge times measured in many hours. Fast charging may be measured in tens of kilowatts. Given that the current generation of lithium batteries may be recharged at up to 5C then a quick charger could be rated at upwards of 75kW.

Analysis from chapter 4 shows that, when away from the home or office, the average residence time of a vehicle at its destination is around one hour. Under slow charge conditions, this would represent a small fractional increase in battery SOC i.e. a Mitsubishi i-MiEV is nominally charged in 7–14 hours. This “grazing” model of recharging – frequent stops for small increases in SOC, is very different from how we refuel vehicles currently and would require a significant shift in driver behaviour. Instead, evidence suggests that end users will avoid extensive use of slow charge infrastructures (even if they are visible) and instead restrict their daily range.

2.4.3 Interoperability of recharging infrastructures

If an investment in a public recharging infrastructure is to be made, it should be available to a wide range of stakeholders. Two issues to be addressed are: standardisation of the recharging plug and interface with the vehicle, and use of (or at least access to) a common communications and billing system.

By involving boroughs in the deployment of recharging points, the “Electric Vehicle Implementation Plan”, announced by the Mayor of London, runs the risk of inter-borough operability issues. Coordination of early infrastructure is necessary to ensure the investment does encourage uptake.

2.4.4 Vehicle to grid

This is the term given to the use of on vehicle battery capacity to supply power to the grid at times of peak demand. The vehicle fleet would act as a source of distributed generation, providing power efficiently and close to the point of demand. Analysis of vehicles’ daily usage profiles (see section 5) suggests that a large number of EVs could be connected to the grid at times of peak demand.

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14 Assuming a £5,000 post, rated at 2kW charge rate operating four hours per day, 200 days per year. A simple payback of three years requires an additional cost of £1.04. Personal communication with a charging post supplier suggests that this figure is not unreasonable.
15 5C is the charging rate which allows a battery to be recharged in one fifth of an hour.
16 The fast chargers installed by TEPCO in central Tokyo are rated at 50kW.
However there are serious concerns over the cost of achieving this. Using the minimum goals for advanced battery performance generated by the US Advanced Battery Consortium\textsuperscript{17}, the cost of supplying a unit of electricity from an EV is circa $0.15/kWh (this is based on amortisation of the battery cost alone). This is much greater than the current average marginal cost of electricity generation and therefore presents a challenge to the feasibility of vehicle to grid operation. Having said this, electricity prices can be highly variable depending on demand and generation mix (i.e. type of plant). For example, the economics of vehicle to grid operation would be favoured in the future at times of high electricity demand if a significant proportion of this demand were supplied by inflexible low-carbon generators and the costs of electricity from conventional back-up plant were high due to high carbon prices.

\textsuperscript{17} www.uscar.org Target price is $150/kWh of capacity, and target lifetime is 1,000 cycles.
3 National Travel Survey

3.1 Summary

With their inherently higher efficiencies and lower CO₂ emissions (g/km), electric vehicles offer the potential to reduce carbon emissions from road transportation. The extent of the CO₂ savings will be proportional to the total distance driven in EVs relative to overall vehicle-km driven, and the carbon intensity of the electricity used during EV recharging.

To date, sales of electric vehicles have been low due mainly to technical limitations of EVs (in terms of range and performance), limited availability (a lack of choice for consumers), and high capital costs. EV-kilometres therefore currently represent a negligible proportion of overall vehicle-kilometres driven in the UK. The potential for EVs to gain a greater share of overall car-km depends on a number of related factors, including:

- Achieving higher sales of EVs (overcoming the barriers of high capital cost and disutility compared to incumbent vehicles).
- The technical range of EVs and the ratio between the technical range and the range perceived by the EV user, herein termed the usable range ratio.
- Car driving patterns, in particular length of trips and daily distance travelled.
- Charging infrastructure available.

The aim of this work is to estimate the carbon savings possible due to the use of EVs under different charging infrastructure scenarios. For the purpose of this exercise, the focus is on data relevant to the potential for increased overall EV-km in the UK. The main source of data was the National Travel Survey database, from which relevant data were taken and analysed to explore statistics relating to:

- Car ownership and parking availability by area type.
- Trip purpose, length and frequency.
- Car usage in terms of daily distance, number of trips per day, and timing of trips throughout the day and week.

Key conclusions are summarised in the Conclusions section at the end of this section. Some highlights include:

- With today’s EV technology (160km technical range and 110km usable (perceived) range); up to an estimated 50% of total UK car-km could be achieved by EVs under the home charge scenario, which requires no additional infrastructure.
- This contribution rises to over 60% if on-street overnight charging facilities were to be deployed.

See appendix for a comparison of CO₂ emissions between EVs and internal combustion engine vehicles.
• However, to access 80% of car-km with no additional infrastructure, EVs would need a usable range of around 200km.

• Commuting is the trip purpose with the single highest contribution to overall mileage, with commuting trips accounting for around a quarter of all car-km driven.

• Deploying on-street and work place recharging facilities could lead to around an 80% increase in the number of commuter-kilometres that could be achieved by EVs relative to the home charge only scenario. This represents an additional contribution to overall car-km of approximately 8%.

• Of the charging infrastructure solutions considered (i.e. excluding battery exchange), home charging represents the largest opportunity for EVs to contribute to overall car-km driven.

3.2 Objectives of the analysis

This section presents the key findings of research into the driving patterns of car drivers in the UK. Other factors relevant to EV recharging infrastructure strategies such as parking availability are also considered. The primary aim of this task was to investigate car use in the UK in order to answer questions such as:

• Which type(s) of drivers/households may be able to make use of an electric vehicle, given the technical limitations of EVs relative to traditional cars?

• Where are cars kept overnight and where are they parked during the day?

• When do car trips tend to occur and is there a strong correlation between time of day and when cars arrive at certain destinations?

3.2.1 Data sources

Statistics from the National Travel Survey (NTS) formed a central source of data for this analysis. The NTS is a continuous survey of households designed to build a databank of personal travel information for Great Britain. Information is collected via face-to-face interviews and travel diaries, which respondents complete for all trips made over a seven day period. A large range of information is recorded, including personal information (age, gender, working status), details of cars available to the respondent, and full details about trips made (purpose, method of travel, start and end time, distance etc). The sample size varies year-by-year, but as an indication the number of respondent households during 2006 was around 8,300.

Data from the NTS were used to gain an understanding of a range of car use characteristics pertinent to EVs and EV infrastructure:

• Typical trip profiles (common journey purposes, when journeys occur etc).

• Car usage profiles in terms of number of trips undertaken each day and estimations of cars’ total daily distances.

• Where cars are parked, both overnight and during the day when in use, and time parked at different locations.
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- Other geographic and demographic factors that influence car ownership, usage, and availability of parking facilities.

Supplementary data sources include the English House Condition Survey and an Office for National Statistics (ONS) omnibus survey, which included an investigation of attitudes to car use. Further details of the data sources are included in the Appendix.

3.2.2 Overview of results section

The results of trip statistics analysis are presented in section 3.3.1 and section 3.3.2 contains the parking availability and usage analysis. The final results section considers what contribution electric vehicles may make to the overall distance driven in cars in the UK. Supplementary results to these main results presented in section 3.3 are included in section 9.

3.3 Results

3.3.1 Trip statistics

3.3.1.1 Daily driving patterns

Given the relatively limited range of EVs and the typically long recharge times, an individual’s total daily driving distance is a key parameter when considering the potential for EVs to be used in place of incumbent vehicles. In the absence of fast-charge or battery exchange infrastructure, the majority of EV users would be expected to recharge overnight only, which limits EV use to daily driving patterns within the EV range. The following graph indicates how the proportion of car drivers who did not exceed a certain daily distance increases with the kilometres per day figure.
Figure 9: Drivers who do not exceed certain daily distances

This plot was derived from an analysis of 13,390 individuals who had recorded trips as a driver of a car in the 2006 NTS and suggests that approximately two-thirds of people in the survey did not exceed 40 miles (c.65km) per day (as car drivers) on any day of the seven day travel diary week. That is not to say that two-thirds of all drivers never exceed 40 miles per day, it merely presents evidence that the driving patterns of a high number of people are dominated by relatively short trips.

The same data set was used to determine the cumulative contribution of drivers in certain daily distance bands to overall trips and overall car-km. The results are shown in the graph below and suggest that while 80% of all trips were made by individuals who travelled less than 40 miles (65km) a day, these trips accounted for only 44% of the total daily mileage.
These results suggest that if all drivers had access to an EV with an 80km (50 mile) usable range, about 50% of all miles could be undertaken by EVs. From a carbon saving point of view, if EVs could provide zero carbon driving (if they were to be recharged by electricity from renewable sources, for example), then with no additional infrastructure the usable range of EVs would need to be around 200km in order to achieve an 80% reduction in car CO₂ emissions (and all of this range would have to be utilised).

**Key Points**

- Driving patterns of a significant proportion of people are dominated by relatively low daily distances. For example, half the people in the sample analysed did not exceed 40km (25 miles) on any day of the travel diary week. This implies that the majority of trips for many drivers could be done by today’s EVs.

- An important distinction must be made between trips and distance. While drivers with a daily distance below a certain level may account for a significant proportion of all trips, their contribution to overall car-km will be somewhat lower. Although EVs with a usable range of 160km could be used for over 95% of all trips, these trips would only account for around three-quarters of the total car-km.

- Very large CO₂ savings from EVs will only result if a very high proportion of total distance driven becomes electric. These results suggest that EVs will have to be made accessible to high mileage drivers in order to achieve the greatest carbon savings.
3.3.1.2 Trips and mileage by purpose and distance band

A total of 23 distinct trip purposes are defined in the National Travel Survey. Although there is a certain amount of variation in the proportion of trips in each distance band with trip purpose, on the whole a relatively high proportion of trips for a given purpose fall into the lower distance bands, as shown below.

![Percentage of trips by distance band for most frequent trip purposes](image)

Figure 11: Trips by distance band and trip purpose of the eight most frequent trip types

The numbers in brackets indicate the proportion of the total trips that were recorded as the given purpose. There were a total of 764,692 trips (in all distance bands for all purposes) in this data set, which included results from the 2002–2006 surveys. This suggests that commuting trips represented about 22% of all trips and these eight (most frequent) trip purposes plotted above accounted for 77% of all trips.

Key Points

- Commuting is the dominant trip purpose, with over a fifth of all car trips being undertaken with getting to or from work as the primary reason for travel.
- Around two-thirds of commuting trips are less than 16km (10 miles). This suggests that there are a significant number of commuters with round-trip commutes of less than 20 miles.
- Certain trip purposes are dominated by short trips, for example over 90% of food shopping trips (the third most frequent trip purpose) are less than 16km.
The data behind Figure 11 were used to estimate the contribution of the most common trip types to overall car-km driven in the UK (the mid-points of each distance band were taken as average trip lengths for all trips within that band).\textsuperscript{19}

![Estimation of contribution to total annual car-km in the UK](image)

**Figure 12: Contribution of high frequency trip purposes to overall annual UK car-km**

The percentage figures above each column on this plot indicate the contribution that trips of the given purpose make to the overall annual mileage done by car drivers in the UK, and suggest that around 76% of the total distance is due to these eight most frequent trip purposes. Compared to Figure 11, the effect of the greater average trip length of trips in the higher distance bands is clear, with the mid to high distance bands showing far greater prominence in Figure 12. For example, although 67% of all commuting trips were below 16km, trips in this distance bracket account for only 35% of the total distance due to commuting trips.

\textsuperscript{19} The NTS data had a higher resolution than that presented here, as it consisted of 12 distance bands: under 1 mile, 1 to under 2 miles, 2 to under 3 miles, 3 to under 5 miles, 5 to under 10 miles, 10 to under 15 miles, 15 to under 25 miles, 25 to under 35 miles, 35 to under 50 miles, 50 to under 100 miles, 100 to under 200 miles and 200 miles and above. A mean trip length of 250 miles was assumed for the highest category.
3.3.1.3 Timing of car trips

The effects of the widespread roll-out of electric vehicles on the electricity grid depend on when vehicles are charged, which in turn depends on how cars are used in terms of when trips occur. The NTS records when trips begin and end and the following plot shows the daily trip profiles for three common trip purposes. The percentage figure indicates what proportion of trips of a given purpose occurred during the particular time band (note that these time band categories are not all of equal duration).

Key Points

- From the point of view of distance (rather than number of trips), trips in the higher distance bands are more significant when considering overall car-km. For example, although only 5% of trips are for ‘Business’, the characteristics of this trip purpose (a higher proportion of longer trips) means that they account for around 12% of total car-km driven. The opposite is true for a trip purpose such as food shopping, which is dominated by short trips.
- Commuting trips (the most common purpose) account for around a quarter of all car-km driven in the UK.
- Together, trips in the eight most frequent trip purpose categories are responsible for around three-quarters of all car-km.

Figure 13: When trips occur throughout the day

Morning and evening peaks for commuting journeys are clearly evident. Data on the start times of commuting trips from home show that around 68% of these trips occur between 6am
and 9am. Similarly, approximately 58% of all return commuting trips by car arrive home between 4pm and 7pm. Figure 13 includes typical daily trip profiles for some other common trip purposes, which show peaks in the number of trips around the middle of the day and in the late afternoon / early evening.

While Figure 13 shows the distribution of trips throughout the day for a typical weekday, Figure 14, below shows when the three most common trip types occur through the week.

![Journey purpose by day of week for frequent journey types](image)

**Figure 14: When journeys occur throughout the week**

This graph suggests that the number of commuting trips remains relatively constant during the working week, and falls significantly on the weekend. As may be expected, trips for other purposes such as personal leisure (in this case visiting friends), are more likely to occur on the weekend.

These results suggest that if mass market EV uptake were to occur, and EVs may be used for any trip purpose with an equal probability, then peaks in electricity demand for home recharging would be more likely on weekdays than weekends.\(^\text{20}\)

Figure 15 shows when drivers arrive home, irrespective of journey purpose. This plot was derived from 2006 NTS data and the percentage figures are calculated based on a total of over 65,000 trips arriving home throughout the day.

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\(^{20}\) This is based on the fact that commuting is the most common trip purpose, most commuting trips occur on week days, and commutes lead to the most pronounced evening peak as drivers arrive home.
Figure 15: Timing of trips that end at home throughout the day

This graph shows that the main peaks in terms of drivers arriving home occur between 4 and 6pm and around two hours either side of midday. Around a quarter of all trips that finish at home end in a two hour window in the late afternoon (i.e. a period that corresponds to one twelfth of a full day).

Key Points

- Peaks in when trips occur during the day are observed for a range of trip purposes. There appears a particularly strong correlation between trips occurring and time of day between the hours of 4 and 6pm.

- This late afternoon peak is caused by drivers arriving home and another peak is observed around midday. These results suggest that, as expected, demand for electricity for EV recharging will be far from evenly spread throughout the day.

- With high EV uptake, it is possible that mechanisms to control the timing of EV recharge could be required.

Data on when trips to/from home begin and end were used to estimate the probability of vehicles being parked at home at any given point during a 24 hour period. Trip purposes were divided into two categories: commuting and other. It was assumed that practically all vehicles used for non-commuting trips would be parked at home around the period 1am to 3am. The proportion of cars used for commuting that would not be at home (due to night shift workers) was estimated by assuming that commuting trips made from home in the period 6pm to midnight were due to night-shift workers. Out of all commuting trips from home those in this
period represent around 5%. With starting points of 95% of commuter cars and 100% of other cars being at home in the period 1am to 2am, the probability of cars being at home for the remainder of the day was found by applying the following formula:

\[
\text{Number of cars at home in a given period} = \text{Number of cars at home in previous period} - \text{Number of cars that leave home in period} + \text{Number of cars that arrive home in period}
\]

The numbers of cars leaving and arriving home were estimated from NTS data on when vehicles arrive and leave home throughout the day. For a given sample size, the probability of cars being at home could then be found by dividing the number of cars at home in a given period by the total number in the sample.

![Figure 16: Probability of vehicles being at home by time of day](image)

Cars used for commuting typically follow fairly well-defined usage patterns, hence the relatively low probability of commuting cars being at home during the day. For a large sample of drivers, other trip purposes tend to be more randomly distributed throughout the day, which is reflected by the higher probability of non-commuting cars being at home at any given time during the day.

### 3.3.2 Parking

In the absence of fast-charging facilities and/or battery exchange infrastructure, EVs may mainly rely on slow charging while parked. An understanding of what parking facilities are
available to car-owning households and how they are used is particularly significant in devising strategies for an EV recharging infrastructure. This section presents results relating to parking facilities and household car ownership as a function of area (city centres to rural settlements), what parking facilities are available and used by car-owning households, and average times spent parked for a selection of common trip purposes.

3.3.2.1 Parking facilities and household car ownership

The following graph gives an indication of the proportion of households that have access to adequate parking facilities (either off-street (e.g. garage, driveway), or on-street parking) and the likelihood of a household owning a car by area type.

![Figure 17: Parking availability and household car ownership](image)

This graph suggests a strong correlation between parking availability and household car ownership. For example, city centres, the areas with the lowest parking availability (over 50% of households have no adequate parking facilities), are also the areas with lowest household car ownership (40% of households have no cars). Unfortunately, since these data came from two different sources, it is not possible to say conclusively whether household car ownership and parking availability are linked, but these results certainly suggest they may be.

The English House Condition Survey also gave the breakdown of households by area type and these figures were extrapolated to the UK to estimate where the majority of people (and vehicles) reside.

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21 EHCS is the English House Condition Survey.
22 Parking availability data from English House Condition Survey (EHCS). Household car ownership data from National Travel Survey (NTS).
Figure 18: Parking availability by area type in the UK\textsuperscript{23}

Key Points

- Fewer than 50\% of city centre households have access to adequate parking facilities, while around 95\% of rural households do have parking. However, both household car ownership and parking availability increase with increasing rurality, which suggests that most car-owning households do have access to parking.

- Access to off-street parking is lower in any sort of centre, for example around 40\% of ‘urban centre’ households have off-street parking compared to 70\% of ‘suburban residential’ households. Similarly, the figures are 75\% and 92\% respectively for village centre compared to rural residential households.

- Over half of all households (57\%) fall into the ‘suburban residential’ category, in which almost 80\% of households have at least one car. Over 70\% of these households have access to off-street parking.

- Around 90\% of all households are in the ‘other urban centre’, ‘suburban residential’, or ‘rural residential’ categories. Based on a weighted average, it is estimated that around 65\% of these households have access to off-street parking.

- These results suggest that households that own EVs are likely to have access to off-street parking facilities.

\textsuperscript{23} Based on 2006 estimate of the number of households in the UK (26.5 million), http://www.statistics.gov.uk/STATBASE/ssdataset.asp?vlnk=7678 and EHCS data on the proportion of households in different area types.
A further source of data relating to residential parking comes from the 2005 ONS Omnibus survey.\(^{24}\) In this survey, individuals in households with access to a car were asked about availability and use of parking facilities and the results of the responses are summarised in the following graph.

![Graph showing parking habits](image)

**Figure 19: Overnight parking for car-owning households**

Households with more than one car could give positive responses in more than one category, which means that the sum total of all percentages across parking locations may exceed 100%. These results suggest that around 80% of car-owning households make use of a garage or some other off-street parking facility.

**Key Points**

- According to data from the ONS Omnibus survey, around 80% of car-owning households use a garage or other off-street parking facility.

- The data show that only about half of those households with access to a garage actually use it to park a car overnight. However, this relatively low garage utilisation rate need not be a barrier to home charging of EVs, as most houses with a garage will also have a driveway (or other off-street parking facility).

- This suggests that in a world with mass uptake of EVs, a large proportion of EV owners would be expected to recharge at home and would not require additional infrastructure to keep their vehicles charged at home.

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\(^{24}\) The ONS Omnibus survey is a random probability survey of adults over the age of 16 living in private households in England, Wales and Scotland. A total of 1,238 people were interviewed, with a 68% response rate. For further details see: [http://www.dft.gov.uk/pgr/statistics/datatablepublications/trsnstatsatt/earlierreports/attitudesto caruse](http://www.dft.gov.uk/pgr/statistics/datatablepublications/trsnstatsatt/earlierreports/attitudesto caruse).
3.3.2.2 Average time spent parked at destination

The NTS collects data on many aspects of recorded trips, including purpose, and when trips begin and end. Data from the 2006 survey were analysed to find how long cars remain parked at the destination for a selection of trip purposes. Total time parked was found by taking the difference between when the trip to the destination ended and when the subsequent trip from the same location began. The results of this analysis for five common trip purposes are shown below.

![Mean length of time spent parked at destination for a selection of journey purposes](image)

**Figure 20: Average length of time spent parked at destination**

In the above graph the numbers in brackets indicate the sample size from which the mean values were calculated. Unsurprisingly, cars used for commuting generally spend longest parked at the destination, while average times parked for other purposes are typically between one and three hours. Further details of parking facilities used by commuters are included in Appendix C.

**Key Points**

- Cars used for commuting spend around seven hours on average parked at the workplace. Around three-quarters of commuter cars are parked in private car parks (Figure 41). This suggests that workplace slow charging facilities could be of high value to commuters using EVs.

- Given the relatively low mean times spent parked during the course of other trips, these results suggest that the utility of publicly available slow charging facilities would be extremely limited.
3.3.3 Potential EV contribution to UK car-kilometres

3.3.3.1 Effect of EV range and usable range ratio

This section presents the results of analysis of car use data from the 2006 NTS. Estimations of the potential for EVs are made based on the implicit assumption that all drivers have access to an EV and choose to use it for all trips in a day provided that their daily distance does not exceed the perceived range limit, which is dictated by the vehicle’s technical range and the usable range ratio. This ratio reflects the fact that drivers demand a certain comfort factor when deciding how far to drive a vehicle (few people would be happy to complete a commute with a round trip distance of 50km in an EV with a technical range of 50km for example). It is equivalent to how low drivers of petrol/diesel cars will allow the fuel gauge to fall before feeling the need to refuel. A ratio of one means that the driver will use the full technical range, whereas a ratio of two implies that only 50% of the technical range is used. The usable range ratio for EVs is currently between two and three, though this may be expected to fall as recharging time decreases and availability of recharging facilities increases. With technological advances and higher market penetration of EVs, a reasonable anticipated usable range ratio for most drivers would be in the region of one to two.

![Figure 21: Potential contribution of EVs to total car-km in the UK](image)

The above graph was derived assuming that 80% of all cars are parked off-street (including garages, driveways, and other off-street areas with access to an electricity supply) and 20% of cars are parked on-street. The number of drivers with a daily distance below the perceived range increases with the technical range of the EV, as demonstrated by the shape of the curves. These results suggest that for mass market EVs with a technical range of 100 miles (160km), and a usable range ratio of 1.5, up to 50% of the total annual UK car-km could be

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25 These percentages were chosen based on the results of the parking analysis, presented in section 3.3.2.1. The sensitivity to these figures is considered in section 9.2.
driven with EVs with no additional infrastructure (i.e. home charging only). This figure rises to over 60% if provision were made for on-street charging for car-owning households with no access to off-street parking.

Figure 21 implies that even with EVs with usable ranges of 200km, and with all households having access to home charging, only around 80% of all car-km could be done by EVs. The final 20% of car-km are done by drivers who travel over 200km per day, and although they represent a very small percentage of all drivers, the mileages (being very long) account for a significant proportion of the total.

### Key Points

- With a 160km usable range, EVs could contribute up to 59% of all car-km with no additional infrastructure. This figure rises to 73% with the implementation of on-street recharging points outside the homes of car-owners with no off-street parking.

- Assuming all households could access home-charging facilities, but no other recharging infrastructure were available, EV range would need to increase to around 200km (usable range) in order for 80% of all car-km to be done by EVs.

#### 3.3.3.2 Maximum potential of plug-in hybrid electric vehicles

A similar analysis to that presented above was undertaken for plug-in hybrid electric vehicles (PHEVs) to determine how the electric range of these vehicles affects the contribution they could make to overall car-km.
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The total mileage that could be done in electric mode by PHEVs was estimated based on the assumption that all cars are PHEVs. For a given maximum PHEV electric range, the car-km possible in electric mode were estimated according to the following logic:

\[
\text{Total car-km possible from PHEVs in electric mode} = \text{Sum of daily mileages of drivers whose daily mileage is below PHEV electric range} + \text{PHEV electric range} \times \text{Number of drivers whose daily mileage exceeds PHEV electric range}
\]

This analysis suggests that if all drivers in the UK used PHEVs with an electric range of 40 miles (64km), around 70% of all car-km could be completed in electric mode.

**Key Points**

- If all drivers switched to PHEVs with electric range of 30km, up to 48% of all car-km could be done in electric mode.
- This percentage rises to 63% and 72% for PHEVs with electric range of 50km and 70km respectively.

### 3.3.3.3 Potential impact of alternative infrastructure solutions

The results of the NTS data analysis led to the definition of three general trip purposes: *commuting*, *long*, and *other*. The following figure summarises which trip purposes, as defined in the NTS, fell into each category.
The following graph indicates the proportions of overall mileage that may be accessed by EVs based on an analysis of trips made by car drivers from the 2002–2006 NTS data.

**Figure 23: Potential contribution of EVs to overall mileage with alternative infrastructure solutions**

The percentages in brackets indicate the contribution of all trips in each category to the total distance travelled by car. This graph was derived from data on trips by distance band for each purpose. The proportion of trips in each distance band that may be made by EVs was estimated given the perceived range (c.100km) and data on the percentage of drivers who complete fewer than a certain number of trips per day.
On-street charging infrastructure allows those households with no off-street parking access to EVs. Work charging would include charging facilities at train stations for those commuters whose journeys consist of stages by car and train. It was assumed that such infrastructure would effectively double the range of EVs used for commuting. Provided it achieved sufficient coverage, a battery exchange infrastructure would enable EVs to be used for all car journeys, just as the network of filling stations in existence today gives petrol and diesel vehicles effectively unlimited range.

Note that given the assumption that a battery exchange infrastructure could allow all car-km to be done by EVs Figure 23 could entirely consist of ‘Battery swap’ (i.e. 100% purple shading). However, the graph was derived with an implicit assumption that other charging infrastructure solutions may be deployed first in order to give an indication of the potential of the alternative solutions.

**Key Points**

- Around 40% of commuting car-km could be accessed by EVs with a perceived range of 100km under the home charge scenario. On-street and workplace charging infrastructure increases this to around 72%.

- A significant proportion of total car-km driven remain inaccessible to EVs with a usable range of 100km. A combination of increased EV range and suitable range extension facilities (i.e. charging infrastructure and/or battery exchange networks) will be needed to achieve high EV car-kilometres and deep cuts in CO₂ emissions.
3.4 Conclusions

The carbon savings available from electric vehicle use are directly proportional to the market share EVs can gain in terms of overall car-km driven. This analysis has shown that even with today’s EV technology and no additional infrastructure, over 50% of all car-km driven could be met by EVs, if they were to be available to all drivers. Other key conclusions include:

- Generally, a very high percentage of trips are below 10 miles for the most common trip purposes. The main exception to this rule being business trips, and to some extent commuting.

- Commuting is the trip purpose with the single highest contribution to overall mileage, with commuting trips accounting for around a quarter of all car miles driven.

- The NTS data suggest that two-thirds of drivers rarely exceed 40 miles per day.

- Half of all drivers complete two or fewer trips per day, and 80% do not exceed four trips per day. Although the mean daily distance driven is around 28 miles, there is a very large variation in daily mileages for all drivers.

- On a particular day around 80% of all trips and 44% of the total mileage is due to vehicles that complete a daily distance of less than 40 miles.

- Plots of when trips occur through the day show distinctive peaks for some common trip types. For example, around 30% of car-driving commuters arrive home between 5 and 6pm. This suggests that should EVs achieve significant market penetration, careful management of recharge timing may be required to avoid surges in demand for electricity which could put severe strains on the grid.

- The vast majority of car-owning households have access to either off-street parking or on-street parking near home. Access to parking (including off-street versus on-street) is strongly linked to area type.

- If EVs with a technical range of 100 miles were to fully replace incumbent cars in the UK, the above analysis suggests that up to around 59% of all UK car-km could be done by EVs relying on home-charging only. This figure rises to 73% if on-street charging were available.

- Of the charging infrastructure solutions considered (i.e. excluding battery exchange), home charging represents the largest opportunity for EVs to contribute to overall car-km driven. This suggests that a key priority must be to encourage greater uptake of EVs.
4 Distribution Network Impacts

4.1 Introduction

The existing electrical transmission and distribution system in the UK has been designed for moderate annual load growth. However with the anticipated growth of electrical loads such as plasma TVs, heat pumps and BEVs/PHEVs, the electricity supply system may be required to accommodate significantly larger load and different loading patterns in the future. If the penetration of BEVs/PHEVs in the UK car parc reaches very high levels their impacts on the operation of LV distribution networks, due to the additional demand required for battery charging, may be significant. These issues will depend on both the technical characteristics of the public LV distribution networks that BEVs and PHEVs are connected to, as well as on the timing, location and rate of battery charging required.

The following technical impacts of BEVs and PHEVs have been considered for the purposes of this report:

- Steady-state customer voltage profiles: DNOs have an obligation to supply their customers at a steady-state voltage within specified limits, defined as 230/400V +10/-6% for UK LV distribution networks. In order to achieve that, distribution systems are normally regulated using load-tap-changing transformers at substations and supplementary line regulators and switched capacitors on feeders. Through the application of these devices, customer service voltages may be maintained within statutory regulations during both minimum and maximum loading conditions.

- Steady-state voltage regulation: the voltage deviation between the LV busbars of the MV/LV distribution substation and the end of service (i.e. customers located at the remote ends of the network) must be kept within specific limits. These limits differ between countries and DNOs however in the UK most DNOs allow a maximum of 5-8% voltage regulation. A higher degree of voltage variation is often allowed for rural distribution networks compared to urban and sub-urban distribution networks due to longer, higher-impedance conductors being employed.

- Steady-state voltage unbalance: for ease of deployment, it is anticipated that the majority of BEVs and PHEVs will charge using single-phase power from either household sockets or charging points. This fact, along with BEV/PHEV growth being...
consumer-driven and not centrally planned by DNOs, may result in unbalanced voltages in the electrical distribution system. The maximum allowable voltage unbalance present in UK distribution networks is 1.3% although short-term deviations (less than 1 minute) may be allowed up to 2%.28

- Thermal loading: transformers and network line components (e.g. overhead lines and underground cables) have a thermal rating determined by the maximum current-carrying capacity of the component. BEV/PHEV charging may cause an increase in the overall current flowing in the network, bringing system equipment closer to its thermal limits. In particular, this is anticipated to be a significant constraint for distribution networks that are already operating close to capacity. In such circumstances network reinforcement might be necessary.

- Network load losses: BEV/PHEV charging will change the electrical power flows in the distribution system and hence also have an effect on system load losses. This can have a positive effect for peak shaving scenarios (assuming “vehicle to grid” functionality) or, more likely, a negative effect where system load losses are increased due to the additional current flowing in the network.

- Other power quality issues, such as harmonics, voltage fluctuations or flicker. These issues have been examined in detail in a report for the California Energy Commission29 and it was concluded that for BEV chargers complying with international guidelines based upon IEC 1000-3-4, they should not be a cause of concern. Thus, for the purposes of this report these issues have not been further investigated.

4.2 Overview of modelling approach

This section describes the modelling approach employed to investigate the potential impacts of BEVs and PHEVs on public electrical distribution networks. Results are based on two LV distribution network models:

- (i) a UK generic LV distribution network that has been adopted by UK DNOs as being representative of an urban UK LV distribution network30; and
- (ii) an existing sub-urban LV distribution network that is operated by E.ON Central Networks31.

In addition, load data by the UK Energy Research Centre (UKERC) have been used which describe half-hourly trends in residential UK customer demand depending on the season (winter, spring, summer and autumn) and on the day (weekday, Saturday and Sunday).32

4.2.1 Distribution network modelling

The LV distribution network models described here were modelled using the power systems simulation package PSCAD™/EMTDC™ as multi-grounded three-phase four-wire systems. Using suitable equivalent models of network components, PSCAD™ is capable of representing and simulating a power distribution system, with neutral wires and system grounding explicitly represented. This makes PSCAD™ a useful tool for the analysis of unbalanced multi-grounded four or five-wire LV distribution systems.

4.2.1.1 UK generic LV distribution network

The UK generic distribution network contains six 11kV feeders, each supplying eight 11/0.4kV 500kVA ground mounted distribution transformers and 400V substations. Simulation results described here focus on just one 400V substation of the distribution network, which represents a 1.2km long urban underground cable LV distribution system serving 384 evenly-distributed customers. Maximum and minimum domestic load figures were taken from Electricity Association sources, which show that, including diversity of demand, the minimum and maximum demand figures of each domestic single-phase load are 0.16kVA and 1.3kVA respectively. Moreover, in consultation with two major UK DNOs, an annual increase of 1% was assumed for all customers in the network up to 2030. Finally, in accordance with the BEV/PHEV penetration scenarios developed by Element Energy, the number of households with an BEV/PHEV in the distribution network is assumed to be 128.

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32 UKERC Data: [http://data.ukedc.rl.ac.uk/browse/edc/Electricity/LoadProfile/data](http://data.ukedc.rl.ac.uk/browse/edc/Electricity/LoadProfile/data), last accessed: 2009.
4.2.1.2 UK Existing LV Distribution Network

The network under study comprises a single 11/0.4kV 500kVA distribution transformer and four 400V outgoing feeders with a total length of 1,588m. The remote end of the second feeder has an open link point to a feeder from another LV network, which in the event of a fault may be closed. For the purposes of this report, however, the network is assumed to be radial. In total, there are 198 single-phase customers taken from 400V three-phase street mains; each customer is assumed to use a 30m long service cable. The total load (customer loads and public street lighting) is measured at approximately 450kVA during maximum and approximately 75kVA during minimum loading conditions. Similarly to the UK generic LV distribution network, an annual increase of 1% was assumed for all customers up to 2030. Finally, in accordance with the BEV/PHEV penetration scenarios explained previously, the number of households with an BEV/PHEV in the distribution network is assumed to be 66.
4.2.2 Load Modelling

Load modelling for both networks was based on extensive load data provided by the UK Energy Research Centre (UKERC), which describe half-hourly trends in UK household demand depending on the season (winter, spring, summer and autumn) and on the day (weekday, Saturday and Sunday).\(^{34}\) As an example, Figure 26 illustrates typical UK residential customer demand for a winter day. As it can be seen, maximum demand is observed between 17:30 and 19:30, while minimum demand occurs between 01:00 and 06:30.

Figure 26: Typical UK residential customer demand on a winter day

4.2.3 Charging scenarios

The study has employed three different scenarios with regards BEV/PHEV charging:

- Home charging, whereby customers slow-charge their BEVs/PHEVs once they arrive at home (“uncontrolled charging”).

- 80-20 home and opportunistic charging, whereby 80% of the customers slow-charge their BEVs/PHEVs once they arrive at home and 20% of the customers fast-charge their BEVs/PHEVs using fast-charging points.

- 60-40 home and opportunistic charging, whereby 60% of the customers slow-charge their BEVs/PHEVs once they arrive at home and 40% of the customers fast-charge their BEVs/PHEVs using fast-charging points.

Throughout the simulations home charging was represented as a 1.3kW load and fast charging as a 9.6kW load.

These scenarios were employed to determine the timing, location and amount of battery charging required, which are critical points when considering the potential impact of BEVs/PHEVs on the electrical distribution system. In addition, the authors discussed these scenarios with two major DNOs in the UK in order to understand their concerns and include them when developing the models.
4.3 Simulation Results

The three charging scenarios were simulated on both case study LV distribution networks using loading conditions for all seasons (winter, spring, summer and autumn) and days (weekday, Saturday and Sunday). This resulted in 72 different tests being simulated, with the aim being to identify worst-case scenarios and to quantify allowable BEV/PHEV penetrations with regards the LV distribution network constraints under consideration (steady-state customer voltage drop, steady-state voltage regulation, steady-state voltage unbalance, transformer and cable thermal loading and network losses). The following is a brief summary of the key findings arising from the simulation work. A more detailed description of the simulation results can be found in section 10.

When considering the scenarios provided by Element Energy with respect to the two case study networks, it was found that the only technical constraint which raised real concerns was the transformer thermal loading as shown in Figure 27.

Key Point

- It must be noted that the two case study networks, although representative, do not cover all potential network configurations and loading conditions in the UK and therefore the results derived through simulation are informative but should not be interpreted as being valid for all UK LV networks.
Figure 27: 100% home slow-charging scenario for the UK existing LV distribution network during winter

Under the three devised simulation scenarios, overloading of the 11/0.4kV distribution transformers supplying the two LV networks under study has been found to be the most likely limiting network constraint to BEV/PHEV charging. This is because, for the case study networks, these transformers are already operating close to their ratings (500kVA) under maximum loading conditions even before any BEVs/PHEVs have been connected to the system. Taking the assumed 1% annual increase into account, along with the additional electrical demand due to BEV/PHEV charging, the 11/0.4kV distribution transformers of both case study networks can potentially exceed their kVA ratings as explained below.

For the UK existing LV distribution network, exceeding the rating of the distribution transformer has been observed only under the worst-case simulation scenario (winter day, 100% home slow-charging) shown in Figure 42. During peak loading conditions in the network (17:30 to 20:00), the loading of the transformer has been estimated at approximately 550kW, which exceeds its rating by approximately 10%. However, it should be noted that for relatively short periods (such as the two hours of overloading observed here), it is not uncommon for DNOs to operate their transformers above their ratings by 10-15%, particularly on cold winter evenings. Hence, it is possible that the 10% of overload observed during these two peak hours due to BEV/PHEV charging could be accommodated without any network reinforcement, i.e. without asset replacement.
For the UK generic LV distribution network, exceeding the rating of the distribution transformer supplying the network has not been observed during the summer or spring, but it has been observed under all three scenarios for both autumn and winter. Transformer overloads are more frequent in this particular LV distribution network due to two main parameters: (i) the network is more heavily loaded prior to BEV/PHEV connection compared to the UK existing LV distribution network under study; and (ii) the number of BEVs/PHEVs in the network is significantly increased (128 compared to 66) due to more customers being supplied, hence the additional load required due to BEV/PHEV charging is also increased.

For winter, however, simulation results have shown that under all three devised scenarios network reinforcement would be required to accommodate the additional electrical load due to BEV/PHEV charging. This is because during maximum loading conditions the network is already operating at maximum capacity due to the projected customer load growth by 2030. Under the worst-case simulation scenario (100% home slow-charging), the loading of the distribution transformer supplying the network can reach as high as 690kW (38% above its rating), with the transformer operating above its thermal limits for up to four and a half hours per day (17:00 to 21:30). Meanwhile, for the 80-20 home and opportunistic charging scenario, the loading of the distribution transformer can reach as high as 665kW (33% above its rating) and the transformer is overloaded also for up to four and a half hours per day (17:00 to 21:30). Similar results were obtained for the 60-40 home and opportunistic charging scenario shown in Figure 44, where the loading of the distribution transformer can reach as high as 640kW (28% above its rating). These findings suggest that for densely populated urban areas, exceeding the thermal limits of the transformer supplying the network is the most likely limiting network constraint for accommodating BEVs/PHEVs.
**Key Point**

- When considering the Generic UK LV network, simulation results showed that the 11/0.4kV transformer becomes overloaded in autumn and winter under all three charging scenarios.
4.4 Discussion

Given that the case study networks cannot adequately represent all UK LV network configurations and loading conditions the key factors affecting the network constraints have been considered in order to provide a broader understanding of how certain network attributes affect their ability to accommodate BEV/PHEVs.

The key factors of LV distribution networks that have been identified through simulation as having an effect on the technical impacts under investigation are shown in the table below. This also describes the specific circumstances which are anticipated to cause the most severe adverse effects.

<table>
<thead>
<tr>
<th>Key Factors</th>
<th>BEV/PHEV TECHNICAL IMPACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Customer Voltage Drop</td>
</tr>
<tr>
<td>Network symmetry</td>
<td>Asymmetrical</td>
</tr>
<tr>
<td>Network topology</td>
<td>Radial</td>
</tr>
<tr>
<td>Network length</td>
<td>Long</td>
</tr>
<tr>
<td>Distribution substation voltage</td>
<td>Low</td>
</tr>
<tr>
<td>Network lines</td>
<td>High R, Low X (^1)</td>
</tr>
<tr>
<td></td>
<td>High R, High X (^2)</td>
</tr>
<tr>
<td></td>
<td>High R (^3)</td>
</tr>
<tr>
<td>Distribution transformer</td>
<td>-</td>
</tr>
<tr>
<td>BEV/PHEV battery power factor</td>
<td>Leading</td>
</tr>
<tr>
<td>Network location of BEV/PHEV charging</td>
<td>Clustering, remote end (^4)</td>
</tr>
<tr>
<td>Phase location of BEV/PHEV charging</td>
<td>Clustering at same phase</td>
</tr>
<tr>
<td>Network loading conditions</td>
<td>Maximum</td>
</tr>
</tbody>
</table>

Table 1: Key factors relating to potential technical impacts on LV distribution networks due to BEV/PHEV charging: voltage drop, voltage regulation and voltage unbalance

\(^1\) Assumes leading load and BEV/PHEV battery power factors (i.e. importing VARs)

\(^2\) Assumes lagging load and BEV/PHEV battery power factors (i.e. exporting VARs)

\(^3\) Assumes unity load and BEV/PHEV battery power factors

\(^4\) Assumes uniform BEV/PHEV penetration

\(^5\) Assumes unity load power factor
### Table 2: Key factors relating to potential technical impacts on LV distribution networks due to BEV/PHEV charging: cable and transformer thermal limits and network losses

1. Assumes leading load and BEV/PHEV battery power factors (i.e. importing VARs)
2. Assumes lagging load and BEV/PHEV battery power factors (i.e. exporting VARs)
3. Assumes unity load and BEV/PHEV battery power factors
4. Assumes uniform BEV/PHEV penetration
5. Assumes unity load power factor

When comparing the results from the UK generic LV distribution network and the existing LV network, significant differences were observed with regards the BEVs/PHEVs that can be accommodated. These differences may be attributed to technical characteristics such as the number and location of customers, their consumer demands, length and impedance of lines and distribution substation voltages. These differences illustrate that generic networks are often quite different from real networks and therefore results carried out on generic networks alone must be treated with caution. This emphasises the need for specific impact studies to be performed by DNOs on their LV networks in order to assess BEV/PHEV penetration limits within each LV distribution network.

A more detailed description of the type of LV distribution networks that are most likely to be affected by BEV/PHEV charging, taking each LV distribution network constraint into account can be found in section 10.
4.5 Demand Side Management

The simulation results described above have been based on the assumption that the preferred time for customers to charge their vehicles is immediately after returning home. This assumption was based on two factors:

(i) convenience since customers will already be near their vehicle; and

(ii) security since customers may want to use the vehicle again later that day and will therefore prefer to charge the battery as soon as possible.

As shown in the graphs above, typical daily journey profiles and residential customer demand profiles (Figure 26) are closely matched and as such the impact of BEV/PHEV charging on the LV distribution network during peak loading conditions will be more pronounced. Hence, BEV/PHEV charging during off-peak periods (such as overnight charging) should be implemented through direct load control or encouraged, for example through dual rate tariffs or through more advanced variable electricity tariffs related to the total electrical demand in the network. The development of smart-meters, in particular, may allow customers to automatically select BEV/PHEV charging times and electricity tariffs for demand side management purposes.35

Figure 29 illustrates the worst-case simulation scenario (winter day, 100% home slow-charging) for the UK generic LV distribution network under two different electricity tariffs:

(i) standard tariff, where the cost for the consumer is kept the same throughout the day; and

(ii) dual tariff, where electricity costs are assumed to have significantly dropped after 11pm.

Assuming a standard tariff scenario, the loading of the distribution transformer has been estimated during peak loading conditions (17:30 to 19:30) at approximately 680kW, which exceeds its rating by 35%. Thus, network reinforcement would be required in order to accommodate the additional electrical load due to BEV/PHEV charging.

Assuming a dual tariff scenario, however, where 65% of the customers charge their BEVs/PHEVs after 11pm in order to take advantage of the reduced electricity rates could significantly change the electrical demand in the network. Under this assumed scenario, the loading of the distribution transformer has been found during peak loading conditions (17:30–19:30) to exceed its rating by 20%, which might under certain circumstances be acceptable to the DNO.

**Key Point**

- The adoption of direct or indirect Demand Side Management techniques has the potential to facilitate high penetrations of BEV/PHEVs without the need for network reinforcement.

**Figure 29:** 100% home slow-charging scenario for the UK generic LV distribution network during winter – standard and dual electricity tariffs scenarios
4.6 Network Reinforcement Costs

According to the scenarios investigated in this study, the only network reinforcement likely to be required in the future in order to accommodate BEV/PHEV charging would be that in some cases the 11/0.4kV distribution transformers supplying the LV distribution networks where BEVs/PHEVs would be connected might need to be replaced. In consultation with two DNOs, the full costs associated with replacing a typical distribution transformer were estimated in the region of £20,000–£30,000.

The numbers of ground mounted distribution transformers in the UK network are estimated by Electricity Network Association (ENA) at 149,000, together with 285,000 pole mounted transformers. Not all of these transformers, however, would need to be replaced, with the most vulnerable ones likely to be located in urban or sub-urban areas where BEV/PHEV uptake is anticipated to be high and where distribution transformers are already operated by DNOs close to their thermal limits.

Assuming that 30% of the distribution transformers in the UK electrical distribution system would need to be replaced, the associated costs of accommodating 15.9 million BEVs/PHEVs would be in the region of £2.6bn–£3.9bn. However, it should also be noted that these are pessimistic projections, as they do not include any DSM schemes.

4.7 Conclusions

The simulation results showed that the case study networks could accommodate reasonable levels of BEV/PHEVs and that the first technical constraint encountered was the thermal rating of the 11/0.4kV transformer. This constraint was encountered when approximately a third of the customers connected to a section of LV network owned a BEV/PHEV.

The case study networks are representative of real UK LV networks but they by no means exhaustively represent all possible LV network configurations and loading conditions. It is clear that some networks that are particularly weak and/or heavily loaded will experience thermal and voltage control problems even at relatively modest levels of BEV/PHEVs. Table 1, section 4.4, is intended to assist in identifying the types of networks that are vulnerable and which network constraints are likely to be met.

It is possible that excessive voltage drop may be experienced on long radial rural LV networks or heavily loaded urban networks with clusters of BEV/PHEVs at their remote ends. If voltage drop problems are encountered they could be solved by moving the tap position at the 11/0.4kV transformer, by reconfiguring the network or by re-conductoring some of the network.

It should also be noted that the widespread use of high power fast charging points could cause a whole range of network constraints to be reached very quickly if not carefully planned. Although this is a concern the provision of fast charging points would be centrally planned by the relevant DNOs. High power fast charging points are being considered up to 60kW which are likely to require three phase connections and direct connections to the 11/0.4kV transformer using dedicated infrastructure. This would mitigate against many of the risks associated with fast charging points.

Many of the concerns relating to the impacts of the growth of BEV/PHEVs on the LV distribution network arise when a large number of vehicles require charging at the same time as the peak domestic load. These technical impacts may in some cases lead to LV network reinforcement. However, Demand Side Management could have a key role to play in avoiding the need for network reinforcement by reducing peaks in charging demands. This could be achieved through direct or indirect means by using control signals or tariff incentives.
5 CO₂ implications

5.1 Introduction

The primary motivation for encouraging uptake of electric vehicles is to reduce emissions from the transport sector to help meet the UK’s carbon reduction targets. The CO₂ savings that come about from EVs will depend on:

- The proportion of all car-km done by EVs (which will be a function of factors such as EV uptake and usable range).
- The difference in CO₂ emissions (g/km) between ICE vehicles and EVs (which will depend on advances in ICE vehicle technology and the carbon intensity of the electricity used to recharge EVs (most likely grid CO₂ intensity)).

This chapter explores the potential CO₂ savings under certain scenarios in 2030. The key assumptions are laid out in section 5.2, results are discussed in section 5.3 and the principal conclusions are given in section 5.4.

5.2 Assumptions

The assumptions made in deriving the results presented in the following section are outlined below. Rather than being an attempt to forecast any future scenarios, this analysis should be regarded as a theoretical exercise, which is intended to give an insight into what EV uptake could mean in terms of future carbon savings. This insight should lead to better understanding of the key issues and therefore facilitate informed decision-making.

The CO₂ saving potential of EVs has been estimated for the year 2030, by which time it is possible that EVs could have achieved significant market penetration. One EV uptake scenario provided by the CCC shows 15.9 million EVs in the UK car parc by 2030. According to estimations of distance covered by EVs, these vehicles will be responsible for around 232 billion car-km in 2030, which represents 45% of all car-km (see table below).
### Table 3: Key assumptions in CO₂ implications calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed value</th>
<th>Data source / Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual car-km in 2030</td>
<td>508 billion km</td>
<td>Based on 2007 car-km value of 404 billion (DfT data) and an annual growth rate of 1%.&lt;sup&gt;37&lt;/sup&gt;</td>
</tr>
<tr>
<td>Average emissions from ICE vehicles</td>
<td>100gCO₂/km</td>
<td>The CCC believes that emissions from new cars in 2020 can be reduced to below 100gCO₂/km, which could lead to average fleet emissions (new and old cars) of 130gCO₂/km in 2020.&lt;sup&gt;38&lt;/sup&gt; Based on typical car lifetimes, an average fleet emission factor of 100gCO₂/km in 2030 is assumed here.</td>
</tr>
<tr>
<td>Average energy required by EVs during recharge (i.e. energy delivered to battery)</td>
<td>8kWh</td>
<td>This is based on EVs travelling 40km per day on average (a typical daily distance) and an energy demand of 0.2kWh/km for EVs, which is a relatively conservative average figure.</td>
</tr>
<tr>
<td>EV recharge efficiency</td>
<td>90%</td>
<td>This represents a relatively optimistic view of the efficiency of the recharging process (energy from grid electricity into energy stored in the battery).&lt;sup&gt;39&lt;/sup&gt;</td>
</tr>
<tr>
<td>Recharge power</td>
<td>1.33kW</td>
<td>Typical value for battery recharging.</td>
</tr>
</tbody>
</table>

The carbon impact of driving EVs depends on the CO₂ intensity of the electricity used during recharge, which is assumed to be grid electricity. Redpoint Energy provided CO₂ intensity forecasts for 2030, which gave:

- i) Average CO₂ emissions from electricity generation.
- ii) CO₂ emissions from marginal plant.

CO₂ intensities in terms of tonnes per MWh were given for each hour of the day for every month of the year. A distinction was also made between business days and non-business days. These data were appropriately weighted to derive average hourly CO₂ intensities across

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<sup>38</sup> Committee on Climate Change report (December 2008): *Building a low-carbon economy - the UK's contribution to tackling climate change*, p.267.

all days and months. Grid electricity CO$_2$ intensity was then found by applying an 8% transmission and distribution loss factor.\textsuperscript{40}

An overall average CO$_2$ intensity for electricity used to recharge EVs throughout the day was derived based on the average hourly CO$_2$ intensity data and an estimation of the probability of demand for electricity from EVs occurring in each hourly period. This probability was calculated based on data from the National Travel Survey concerning when vehicles arrive home, and recharge times, which were derived based on the assumptions summarised in the table above. For a given number of EVs, the number that demand electricity in each hour was estimated according to the following formula:

$$\text{Number of EVs that demand electricity in period} = \text{Number of EVs that plug in to charge in period} + \text{Number of EVs still charging (that were plugged in during a previous period)}$$

An estimation of the number of EVs that plug in to recharge was derived directly from National Travel Survey data on when vehicles used for all trip purposes arrive home throughout the day. Except where a charge delay is applied, an implicit assumption is that all EVs begin charging immediately upon arriving home.

\textsuperscript{40} This is a typical average figure for UK electricity transmission and distribution.
5.3 Results

The following graph shows the resulting charging and grid CO₂ intensity profiles based on the methodology described above.

![Graph showing the resulting charging and grid CO₂ intensity profiles](image)

**Figure 30: Likelihood of demand for electricity from EVs and grid CO₂ intensity by hour of day**

Based on the grid electricity CO₂ intensity data presented here, there is very little variation in the average intensity with time of day. This suggests that in the case where electricity demands from EVs are not additional, the overall carbon impact of EVs would be independent of time of day (given this average grid intensity profile).

With the assumptions presented in section 5.2 and an average grid CO₂ intensity of 0.14kgCO₂/kWh, EVs charged from non-marginal electricity would have a CO₂ impact of around 30g/km. However, assuming that EVs represent an additional load on the grid, in-use emission factors should be calculated based on the marginal grid CO₂ intensity. As the solid blue line on Figure 30 shows, there is significant variation in the marginal CO₂ intensity with time of day. Furthermore, the highest marginal CO₂ figure is concurrent with the peak in probability of EVs demanding electricity when no charge delay is applied.

The steady increase in probability of EVs demanding electricity through the afternoon and early evening is a reflection of the typical driving profiles of most drivers, with a peak around 6pm. Figure 30 shows the likelihood of demand for electricity from EVs based on uncontrolled charging, i.e. EV users are expected to plug in their vehicles upon arriving home. However, an opportunity exists to manage this demand in an intelligent manner. The arrows on Figure 30 indicate how the demand signal could be offset to avoid simultaneous peaks in demand and CO₂ intensity. Various practical options for managing demand currently exist, for example simple timers at charge points combined with time-of-day electricity tariffs could be effective in smoothing peaks in demand.
In this analysis a delay was applied which allowed the peak in demand for electricity to be matched to the trough in carbon intensity, as shown in the following graph. This is a simple representation of the general principle of demand management; in reality a more nuanced approach may well be desired.

![Estimation of proportion of EVs that demand electricity by hour of day based on journeys arriving home: 10 hour charge delay](image)

**Figure 31: Effect of delayed charge on charge probability–grid intensity relationship**

Based on electricity from marginal plant, the average in-use CO₂ emissions of EVs range from around 65 to 80g/km, depending on the charge delay time. The following figure summarises the carbon savings possible from EVs in 2030 with no charge delay applied for two separate cases:

- **Case 1** Demands from EVs are non-additional (average CO₂ intensity figure applies).
- **Case 2** Demands from EVs are additional (and therefore supplied by marginal plant).
**Assumptions**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual car-km:</strong></td>
<td>508 billion</td>
<td></td>
</tr>
<tr>
<td><strong>Proportion of all car-km done by EVs:</strong></td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td><strong>Average emissions from ICE vehicles:</strong></td>
<td>100g/km</td>
<td>5 MtCO₂/yr (10% of baseline emissions)</td>
</tr>
<tr>
<td><strong>Average emissions from EVs in Case 1:</strong></td>
<td>30g/km</td>
<td></td>
</tr>
<tr>
<td><strong>Average emissions from EVs in Case 2:</strong></td>
<td>80g/km</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 32: CO₂ savings possible from EVs when demands are non-additional (Case 1) and when demands are additional (Case 2)**

The baseline case corresponds to all car-km being undertaken by ICE vehicles (no EVs). These results suggest that even with a relatively high contribution to overall car-km from EVs (45%), and with a grid CO₂ intensity of the order 0.14kgCO₂/kWh, the emission reductions achievable with EVs are fairly modest, at 16MtCO₂/yr (which represents less than 3% of total UK CO₂ emissions in 1990, or 15% of 1990 road transport CO₂ emissions).

Assuming that electricity demands from EVs would be met by marginal plant, the effect of delaying the peak demand from EVs was investigated by varying the charge delay time from zero to twelve hours. The results suggest that the carbon savings could be increased by a factor of around 1.8 with a sufficient delay, as shown below.
Effect of charge delay time on total annual carbon savings

<table>
<thead>
<tr>
<th>Charge delay time (hours)</th>
<th>CO₂ saved (MtCO₂/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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<tr>
<td>2</td>
<td>2</td>
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<td>8</td>
<td>8</td>
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<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 33: Effect of charge delay time on carbon savings due to EVs

5.4 Conclusions

- Under a scenario where the UK car parc includes 15.9 million EVs, and these vehicles are responsible for 45% of all car-km travelled, up to 16Mt of CO₂ per year may be saved relative to the baseline (no EVs). This is based on an average grid CO₂ intensity of around 0.14kgCO₂/kWh. This CO₂ saving represents 30% of 2030 baseline emissions from cars in the UK, or around 2.7% of total 1990 CO₂ emissions.

- Should EVs be recharged with electricity from marginal plant, the CO₂ savings are reduced to around 5MtCO₂/yr under the uncontrolled charging scenario. This figure may be increased to around 8.5MtCO₂/yr if the peak demand for electricity due to EVs could be offset to correspond to periods of lower overall electricity demands.

- CO₂ savings are relatively modest even when nearly half of all car-km are done by EVs. This is because the savings are directly related to the difference in g/km between ICE vehicles and EVs. The above analysis suggests that a low grid carbon intensity is required for EVs to offer substantial emissions savings.

- EVs are not zero carbon in use. Zero carbon EVs may only be achieved with a source of CO₂-free electricity. Based on the forecast grid CO₂ intensity data (for 2030), the in-use carbon impact of EVs could range from 30g/km to around 80g/km (depending on whether demand from EVs is additional or not and on recharge time). For comparison, the anticipated average vehicle emission figure for new ICE cars sold in 2020 is 100g/km.
6 Appendix: CO$_2$-saving potential of electric vehicles

The following analysis compares the carbon emissions from typical electric vehicles currently available to typical emissions from traditional cars.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EV energy demand (kWh/km)</strong></td>
<td>0.20</td>
<td>Conservative figure based on quoted figures from EV manufacturers$^{41}$</td>
</tr>
<tr>
<td><strong>Grid electricity carbon intensity (gCO$_2$/kWh)</strong></td>
<td>500</td>
<td>The long-term average carbon intensity is 0.43kgCO$_2$/kWh. A figure of 500g/kWh includes adjustment for a charging efficiency of 85%</td>
</tr>
<tr>
<td><strong>CO$_2$ emission from EV (g/km)</strong></td>
<td>100</td>
<td>g/km = (kWh/km) x (g/kWh)</td>
</tr>
</tbody>
</table>

Table 4: Estimation of carbon intensity of EVs (gCO$_2$/km)

Even with today’s grid carbon intensity and a relatively conservative estimation of an EV’s energy demand, the in-use carbon emissions are comparable with the most efficient new petrol or diesel vehicles, and well below the average new car emissions of 165gCO$_2$/km in 2007.$^{42}$ Since the majority of carbon emissions from vehicles arise from the in-use phase of their lives, lifecycle analyses show that electric vehicles still offer CO$_2$ savings compared to petrol or diesel cars when whole-life impacts are considered. See, for example the BERR report investigating the scope to switch to electric and plug-in hybrid vehicles.$^{43}$


## Appendix: Estimates of recharging infrastructure costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (£)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Public Slow Charge Point (2009)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution network extension</td>
<td>£574</td>
<td>2m x £287/m. From SSE</td>
</tr>
<tr>
<td>Recharging post</td>
<td>£4,000</td>
<td>Indicative of current price for smart recharging post.</td>
</tr>
<tr>
<td>Civils</td>
<td>£1,000</td>
<td></td>
</tr>
<tr>
<td><strong>Total capital cost</strong></td>
<td>£5,574</td>
<td></td>
</tr>
<tr>
<td>Maintenance cost per annum</td>
<td>£200</td>
<td>Maintenance cost is £429-£759 per street light (SSE); therefore assume a 400 cost is incurred, every two years.</td>
</tr>
<tr>
<td><strong>Public Slow Charge Point (at volume)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution network extension</td>
<td>£574</td>
<td>will not change at volume.</td>
</tr>
<tr>
<td>Recharging post</td>
<td>£1,000</td>
<td>Volume price for smart recharging post.</td>
</tr>
<tr>
<td>Civils</td>
<td>£1,000</td>
<td>will not change at volume.</td>
</tr>
<tr>
<td><strong>Total capital cost</strong></td>
<td>£2,574</td>
<td></td>
</tr>
<tr>
<td>Maintenance cost per annum</td>
<td>£200</td>
<td>Maintenance cost is £429-£759 per street light (SSE); therefore assume a 400 cost is incurred, every two years.</td>
</tr>
<tr>
<td><strong>Slow charge (off street residential)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital cost</td>
<td>£50</td>
<td>Assumes 13A extension cable, weatherproof plug; simple timer</td>
</tr>
<tr>
<td><strong>Slow charge (workplace car park)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital cost (upper bound)</td>
<td>£2,574</td>
<td>Represents likely upper bound i.e. retrofit, small numbers per installation. Cost as per public slow charge point.</td>
</tr>
<tr>
<td>Capital cost (lower bound)</td>
<td>£50</td>
<td>New build; residential type plugs; civils included in building cost.</td>
</tr>
<tr>
<td><strong>Fast charging points</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of fast charger</td>
<td>£40,000</td>
<td>$40k to 80k for a 60kW to 120kW fast charge (Aerovironment posicharge). Norvik minit charger costs $35k for a 34kW; 125k for a 250kW.</td>
</tr>
<tr>
<td>315kVA to 1000kVA transformer</td>
<td>£39,100</td>
<td>This is the max quoted by SSE for a ground mounted transformer.</td>
</tr>
<tr>
<td>LV network extension</td>
<td>£14,350</td>
<td>assuming 50m times £287/m</td>
</tr>
<tr>
<td><strong>Total capital</strong></td>
<td>£93,450</td>
<td>Worst case, assuming new transformer required. May not be the case at strong points in LV networks, e.g. supermarkets, in which case the cost is that of the charger alone.</td>
</tr>
</tbody>
</table>
8 Appendix: Public charging infrastructure pilot schemes

Whilst home charging is likely to be the most important method for EV recharging, some level of publicly available charging infrastructure will be required to encourage and support EV uptake. The collection of evidence of the relative benefits of types of charging points will depend on EV drivers providing information on how vehicles were used before and after the infrastructure becomes available. Data may be collected via surveys and the robustness and reliability of the results will increase with sample size. For this reason it is important to focus any pilot schemes in areas with reasonably high levels of EV ownership and use. At present, London is the UK’s leading city in terms of EV uptake and infrastructure rollout. At the time of writing out of a total of 200 UK recharge points, 166 were in London. Furthermore, the Mayor of London has committed to providing 25,000 charge points by 2015 to support a target of 100,000 EVs as soon as possible. Although the majority of these charge points are likely to be in workplaces (and therefore not publicly available), some will be on-street, in town centres and other key areas.

The rollout of charging infrastructure provides a unique opportunity to assess the benefits of infrastructure in terms of encouraging EV use. Additional publicly available charging infrastructure may lead to additional EV use in two ways:

1) By expanding the potential market for EVs – i.e. EVs will become a viable choice (in terms of fulfilling typical daily driving requirements) for a greater number of drivers.

2) Existing EV owners may enjoy increased utility from their vehicles as the number of trips possible may increase with suitable infrastructure.

Evidence relating to the benefits of charging infrastructure could be gathered by surveying EV drivers who make use of new charge points. For example, through collection of data on the technical characteristics of the vehicle, how the vehicle was used before charge point installation and any changes as a result of access to charge points. Such data would provide evidence to show how infrastructure availability impacts EV users’ driving habits and the impact, if any, on purchasing decisions.

Ideally, pilot schemes should be coordinated so that results of alternative infrastructure solutions may be compared. Any charging infrastructure pilot scheme should aim to offer maximum utility to EV users, however the most appropriate charge point design will depend on location, in particular the anticipated length of stay in given parking locations (see section 3.3.2). By taking a coordinated approach in terms of survey questions, evidence collected through different pilot schemes (with alternative infrastructure designs) could be used to assess the relative merits of different infrastructure solutions. In particular, the following aspects merit further investigation:

- The typical EV range used (as a percentage of technical range) in areas with home charging only compared to areas with on-street fast charge points, areas with workplace charge points, and areas with supermarket/shopping centre charge points.

- The utilisation of charge points as a function of charge point type and location.

Source: [www.newride.org.uk](http://www.newride.org.uk).
• The effect of alternative incentives (e.g. free parking, free charging, dedicated EV parking (and recharging) spots) on charge point utilisation.
9 Appendix: Supplementary NTS analysis results

9.1 Daily driving patterns – further analysis

The data used to plot Figure 9 (which included daily data on the number of trips per day and total daily distance for 13,390 individuals) were combined for the whole travel week, leading to a data set with 46,146 data points, where each data point represented a car driver for a particular travel day. This data set was analysed to find the number of trips per day and typical distances covered by car drivers. In the following graph frequency (in terms of the number of occurrences of a given number of trips per day) is indicated by the size of the bubble plotted and the figures on the chart area show the mean daily distance for the given number of daily trips.

![Graph: Daily distance by number of trips per day for car drivers](image)

**Figure 34: Mean daily distance and number of trips per day for car drivers**

The above graph shows that the majority of drivers completed two trips per day (or below). Each data point in the data set represents how many trips a certain individual completed and what the total distance of those trips was for a particular day. Half of all these data points fall into the one or two trips per day categories.

While Figure 34 gives an insight into the relative frequency of different numbers of daily trips, and shows the average distances travelled for car drivers who complete a certain number of trips per day, it conceals the spread of data behind these mean values. The following plot shows the range of daily distances recorded for 1–12 trips per day. The mean values are represented by blue squares.
Figure 35: Range of daily distances recorded for car drivers by number of trips per day

The key observation from this graph is that there is a very large spread of daily distances about the mean values, particularly for the most common number of trips per day (e.g. six and below).

In order to estimate the contribution that EVs could make to overall car-km driven, an understanding of the contribution to overall mileage from cars with daily distances below certain levels is required. Although Figure 34 shows that the vast majority of individuals (cars) completed six or fewer trips per day, and that the mean daily distances for these categories are in the region 30–60km, this information alone cannot be used to find the contribution that cars driven less than a certain daily mileage make to overall car-km. This point is illustrated by the following example.

The daily distances of five cars, each of which completes two trips per day are given below. Three scenarios are considered: one where the daily distances of all cars are close to the mean value, and two further cases where the spread about the mean increases.
The mean daily distance for all cars is the same in each scenario. However, the contribution to the total mileage from cars that travel less than 40 miles per day varies considerably depending on the spread of data about the mean value.

Although the vast majority of drivers fall into daily trip number categories with average daily distances under 40 miles, this does not mean that most mileage comes from drivers doing less than 40 miles per day, as illustrated by section 3.3.1.1.
9.2 EV contribution to UK car-kilometres – sensitivity analysis

Figure 21 in section 3.3.3.1 is derived assuming that all car-owning households in the UK have access to either off-street or on-street parking, with an 80:20 split between the two. Given a lack of data on the precise value of this ratio, the sensitivity of the results to this figure was tested and the results are presented below.

![Diagram showing the effect of assumptions on parking availability on possible EV contribution to overall car-km in the UK (usable range ratio = 1)](chart)

**Figure 36: Sensitivity to parking assumptions of contribution EVs could make to UK car-km**

With the assumption that 80% of vehicles can be parked off-street overnight, the contribution that EVs could make to total car-km (given widespread deployment and a usable range of 100 miles) was 59%. This figure falls to 44% if only 60% of EVs could be parked off-street.
9.3 Further car ownership, usage and parking results

Figure 37 shows that car ownership is lowest in London and other urban areas. Car ownership in general and second car ownership levels both increase with increasing rurality.

Figure 37: Household car ownership by area type

Figure 38: Household car ownership by household income
This graph shows a general trend of increasing distance driven for households in less urban areas, which is consistent with expectations.

9.3.1 Further parking results

Figure 40 gives an indication of the most common parking locations, which is an important consideration when considering the roll-out of EV recharging infrastructure. As discussed in section 3.3.1.2, commuting is the most common trip purpose and single largest contributor to overall car-km driven. Workplace recharging facilities (and recharging points at train stations, for example) would expand the market for EV use by commuters. Figure 41 shows that around three quarters of commuters who drive to work park in private car parks.

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45 The ‘vehicle 1’ title comes from an arbitrary allocation of numbers to vehicles in households when the NTS is conducted.
Figure 40: Where cars are parked after final stages of journeys

Figure 41: Where cars are parked at work
10 Appendix: Distribution network analysis

10.1 Simulation results

The three charging scenarios were simulated on both case study LV distribution networks using loading conditions for all seasons (winter, spring, summer and autumn) and days (weekday, Saturday and Sunday). This resulted in 72 different tests being simulated, with the aim being to identify worst-case scenarios and to quantify allowable BEV/PHEV penetrations with regards the LV distribution network constraints under consideration (steady-state customer voltage drop, steady-state voltage regulation, steady-state voltage unbalance, transformer and cable thermal loading and network losses).

In order to simplify this analysis, unity power factors were assumed for the electrical loads and BEVs/PHEVs connected to the distribution network. However, if leading or lagging power factors were assumed, the amount of additional electrical load that can be accommodated due to BEV/PHEV charging would change, although not sufficiently to also change the order of the most likely limiting network constraints.

Regarding steady-state customer voltages, the additional demand on the distribution system due to BEV/PHEV charging has been found to affect customer voltage profiles but not to an unacceptable degree. The statutory limit of 230/400V -6% was not found to be exceeded under any of the simulated scenarios. This is mainly because distribution substation voltages are set by DNOs during minimum loading conditions near to the top statutory voltage limit (230/400V +10%) to allow for downstream voltage drop during maximum loading conditions. For both case study LV distribution networks, the distribution substation voltage under both minimum and maximum loading conditions is approximately 250V and this allows customer voltages to be maintained within statutory limits. Under the worst-case simulation scenario (winter day, 100% home slow-charging), single-phase customer voltages at the remote ends of the two case study LV distribution networks were computed at approximately 236V for the UK generic distribution network and 239V for the UK existing LV distribution network, which are both well above the lower statutory limit of 216.2V.

Steady-state voltage regulation has been found to be a more likely cause for concern, with the additional electrical load due to BEV/PHEV charging exaggerating the voltage drops across network feeders. Under the worst-case simulation scenario (winter day, 100% home slow-charging), the voltage deviation between the LV busbars of the distribution transformer and the end of service has been found during peak loading conditions to be approximately 6% for the UK generic LV distribution network and 4.7% for the UK existing LV distribution network under study. As previously mentioned, common statutory voltage regulation limits are not employed by DNOs for all UK LV distribution networks, with different voltage deviations allowed for different networks. While the 4.7% maximum voltage deviation observed in the UK existing LV distribution network would be allowed for all types of UK LV distribution networks, the 6% maximum voltage deviation observed in the UK generic LV distribution network can be characterised as high and might be unacceptable for some network types. However, as the network supplies 384 customers, most DNOs would allow a higher degree of voltage deviation, typically 7-8%. Hence, these findings suggest that voltage regulation has the potential to cause concern for DNOs if large numbers of BEVs/PHEVs are connected to
distribution networks where the voltage deviation between the distribution transformer and the end of service is already approaching statutory limits.

For voltage unbalance studies, the impact of connecting BEVs/PHEVs on only one phase of each of the two case study LV distribution networks was considered. For LV distribution networks with uniform demand across the three phases, loading conditions in the distribution network were found to have no influence on the amount of unbalanced BEVs/PHEVs that may be accommodated. It has been found that it is the amount of additional unbalanced load due to BEV/PHEV charging that will determine whether the voltage unbalance factor exceeds statutory limits, independent of network loading conditions. This is in contrast to the other LV distribution network constraints under consideration, where maximum loading conditions represent the worst-case scenario with regards the allowable BEV/PHEV penetrations in the electrical distribution system. Hence, voltage unbalance statutory limits could potentially be exceeded at any time, day and season, depending only on the amount of unbalanced electrical load added to the distribution system due to BEV/PHEV charging.

For the UK generic LV distribution network, simulation results suggest that approximately 48kW of unbalanced load may be accommodated on one 400V feeder before the voltage unbalance statutory limit of 1.3% is exceeded. Meanwhile, for the UK existing LV distribution network under study, this figure drops to 41kW mainly due to higher impedance cables being used. For home slow-charging and assuming an electrical load of 1.5kW per BEV/PHEV (i.e. 240V/13A connection), up to 32 BEVs/PHEVs may be accommodated on one phase of a 400V feeder on the UK generic LV distribution network and up to 28 BEVs/PHEVs for the UK existing LV distribution network. Both cases represent extreme scenarios and hence voltage unbalance is not anticipated to be a significant LV distribution constraint for home slow-charging. For fast charging, however, and assuming an electrical power of 9.6kW for each fast-charging point, only five BEVs/PHEVs may be charged on one phase for both case study LV distribution networks. This figure may appear small, however in practice the fast-charging points are anticipated to be planned by the local DNO and hence it is highly unlikely that all connections will be located on the same phase.

Cable thermal limits were found to be the least likely limiting network constraint due to BEV/PHEV charging in the two case study LV distribution networks. This is because for both networks under study, relatively low-impedance underground cables are used in order to avoid excessive voltage drops during maximum loading conditions. These cables contain high current capacity conductors, which even under maximum loading conditions have been found to be well within their ratings. Considering the worst-case simulation scenario (winter day, 100% home slow-charging), the most congested line in the UK generic LV distribution network under maximum loading conditions has been found to operate at approximately 55% of its rating, while for the UK existing LV distribution network under study this figure rises to 70%. Hence, current flows in both case study LV distribution networks have not been found to have significantly increased due to BEV/PHEV charging and thus for such networks it is unlikely that cable thermal limits will cause concern for DNOs.

Under the three devised simulation scenarios, overloading of the 11/0.4kV distribution transformers supplying the two LV networks under study has been found to be the most likely limiting network constraint to BEV/PHEV charging. This is because these transformers are already operating close to their ratings (500kVA) under maximum loading conditions even before any BEVs/PHEVs have been connected to the system. After consultation with the two
DNOs, an annual increase of 1% by 2030 for all customers of both networks has been assumed. Taking this annual increase into account, along with the additional electrical demand due to BEV/PHEV charging, the 11/0.4kV distribution transformers of both networks under study can potentially exceed their kVA ratings as explained below.

For the UK existing LV distribution network, exceeding the rating of the distribution transformer has been observed only under the worst-case simulation scenario (winter day, 100% home slow-charging) shown in Figure 42. During peak loading conditions in the network (17:30 to 20:00), the loading of the transformer has been estimated at approximately 550kW, which exceeds its rating by approximately 10%. However, it should be noted that for relatively short periods (such as the two hours of overloading observed here), it is not uncommon for DNOs to operate their transformers above their ratings by 10-15%, particularly so on cold winter evenings. Hence, it is possible that the 10% of overload observed during these two peak hours due to BEV/PHEV charging could be accommodated without any network reinforcement, i.e. without asset replacement.

![Scenario 1 - Slow Charging @ Home](image)

**Figure 42: 100% home slow-charging scenario for the UK existing LV distribution network during winter**

For the UK generic LV distribution network, exceeding the rating of the distribution transformer supplying the network has not been observed during the summer or spring, but it has been observed under all three scenarios for both autumn and winter. Transformer overloads are more frequent in this particular LV distribution network due to two main parameters: (i) the network is more heavily loaded prior to BEV/PHEV connection compared to the UK existing LV distribution network under study; and (ii) the number of BEVs/PHEVs in the network is
significantly increased (128 compared to 66) due to more customers being supplied, hence the additional load required due to BEV/PHEV charging is also increased.

Figure 43 shows the 100% home slow-charging simulation scenario during autumn. Transformer overloads do not exceed 10% of the transformer’s rating and thus, for reasons explained above, it is possible that the additional electrical load due to BEV/PHEV charging could be accommodated without network reinforcement. The other two scenarios (80-20 and 60-40 home and opportunistic charging) during autumn have produced similar results, with a slightly lower peak during maximum loading conditions in the evening due to more BEVs/PHEVs being charged during the day at fast charging points.

![Scenario 1 - Slow Charging @ Home](image)

**Figure 43: 100% home slow-charging scenario for the UK generic LV distribution network during autumn**

For winter, however, simulation results have shown that under all three devised scenarios network reinforcement would be required to accommodate the additional electrical load due to BEV/PHEV charging. This is because during maximum loading conditions the network is already operating at maximum capacity due to the projected customer load growth by 2030. Under the worst-case simulation scenario (100% home slow-charging), the loading of the distribution transformer supplying the network can reach as high as 690kW (38% above its rating), with the transformer operating above its thermal limits for up to four and a half hours per day (17:00 to 21:30). Meanwhile, for the 80-20 home and opportunistic charging scenario, the loading of the distribution transformer can reach as high as 665kW (33% above its rating) and the transformer is overloaded also for up to four and a half hours per day (17:00 to 21:30).

Similar results were obtained for the 60-40 home and opportunistic charging scenario shown in Figure 44, where the loading of the distribution transformer can reach as high as 640kW
(28% above its rating). These findings suggest that for densely populated urban areas, exceeding the thermal limits of the transformer supplying the network is the most likely limiting network constraint for accommodating BEVs/PHEVs.

![Diagram of Scenario 3 - Home and Fast Charging - 60:40](image)

**Figure 44: 60-40 home and opportunistic charging scenario for the UK generic LV distribution network during winter**

Finally, load losses are a quadratic function of the electric current, with the largest load losses observed during peak loading conditions of the LV distribution network. When considering the contribution of BEV/PHEV charging to system load losses, it is necessary to consider both worst-case scenarios (i.e. the periods when system load losses are increased the most), as well as their overall contribution throughout the day.

As seen in Figure 42 for Scenario 1, power flows in the UK existing LV distribution network may be increased by up to 10% between 18:00–20:00. This causes system load losses during this period to increase by approximately 20%, from around 50kW to 60kW. For this scenario, where higher peaks were observed in the network current flows for specific periods of the day, the contribution of BEV/PHEV charging to system load losses was exaggerated compared to Scenarios 2 and 3 where electrical demand is more widely spread throughout the day.

For the UK generic LV distribution network where the number of BEVs/PHEVs is significantly increased (128 compared to 66), the increase in system load losses due to BEV/PHEV charging is more pronounced. Considering Scenario 1 (Figure 43), power flows in the network have been found to increase by up to 30% between 19:00–20:00, thereby also increasing system load losses during this period by approximately 70% (from around 35kW to 60kW). For Scenarios 2 and 3, however, the largest increase in system load losses has been found to
occur between 17:30–20:00, where a maximum increase in losses of approximately 15% was observed.

10.2 Impacts on different LV network types

10.2.1 Customer Voltage Drop

Subsequent to the recent European Voltage Harmonisation, the nominal UK steady-state voltage for customers supplied by public LV distribution networks is now 230/400V. The majority of existing LV distribution networks in the UK, however, have remained unchanged and are still operated to supply 240/415V. As a result, and in particular for urban and suburban LV distribution networks, customer voltages can often be located well above the lower statutory limit of 230/400V -6%, even under maximum loading conditions.

The following two types of LV distribution networks are anticipated to be the most vulnerable regarding steady-state customer voltages dropping below their statutory limits (230/400V -6%):

- Sparsely populated rural LV distribution networks with a load density of 0-1.0MVA/km², which are commonly radial networks with overhead lines covering long distances with relatively low current capacity conductors. For such networks, excessive customer voltage drops may be initiated by relatively small penetrations of BEVs/PHEVs due to the high impedance of the conductors used and because customer voltages during peak loading conditions are often close to the statutory lower voltage limit. Moreover, due to the small number of customers being connected to the network, the additional electrical demand from BEV/PHEV charging affects the total electrical demand in the network more significantly compared to a network with high number of customers and where load diversity is high.

- Densely populated urban LV distribution networks with a load density of ≥4MVA/km², which are commonly ring or meshed networks supplied by underground cables with relatively high current capacity conductors. For such networks, excessive customer voltage drops could be observed due to the potentially large number of customers with a BEV/PHEV installed, particularly so if clusters of these units are connected to the distribution system. Under a worst-case scenario, BEV/PHEV clustering at the remote ends of the network would cause their allowable penetrations to be significantly reduced compared to uniform penetration scenarios.

10.2.2 Voltage Regulation

Voltage regulation might be of concern for LV distribution networks where the voltage deviation between the LV busbars of the MV/LV distribution substation and the end of service is already high prior to customers connecting any BEVs/PHEVs. For such networks, the additional electrical demand due to BEV/PHEV charging may cause steady-state voltage regulation to exceed statutory limits. As previously mentioned, these statutory limits differ according to the technical characteristics of the LV distribution network under consideration, such as number of customers, maximum and minimum total load, length and impedance of network feeders etc. In general, however, a higher degree of voltage variation is allowed for rural distribution networks where network lines cover long distances with relatively low current capacity conductors.
For similar reasons as for excessive customer voltage drop, the following two types of LV distribution networks are anticipated to be the most vulnerable with regards steady-state voltage regulation:

- Sparsely populated rural radial LV distribution networks, where statutory limits may be exceeded by relatively small penetrations of BEVs/PHEVs for two reasons: (i) due to the high impedance and extensive length of the conductors used; and (ii) due to BEV/PHEV charging affecting the total electrical demand in the network more significantly compared to a network where load diversity is high.

- Densely populated urban LV distribution networks, where statutory limits may be exceeded due to the potentially large numbers of customers with a BEV/PHEV installed, particularly if clustering is considered.

### 10.2.3 Voltage Unbalance

For ease of deployment, it is anticipated that the majority of BEVs and PHEVs will charge using single-phase power from either household sockets or charging points. Simulation results have indicated that the amount of unbalanced electrical load added to the distribution system due to BEV/PHEV charging will determine whether the voltage unbalance factor has exceeded statutory limits, independent of network loading conditions. Hence, although rural distribution networks are weaker compared to urban and sub-urban distribution networks due to the higher impedance conductors used, the small number of customers typically connected on such networks suggests that voltage unbalance statutory limits are unlikely to be exceeded.

For urban and sub-urban distribution networks, where BEV/PHEV penetrations are anticipated to be higher, the consumer-driven (and not centrally-planned) growth of BEVs/PHEVs may result in unbalanced voltages in the electrical distribution system. However, simulation results have shown that the amount of unbalanced BEV/PHEV charging that may be accommodated on two case study LV distribution networks is sufficiently high so as not to pose considerable concern for DNOs, particularly so if home slow-charging is considered. If, as anticipated, the distribution of BEVs/PHEVs on the electrical network is random as regards the split between the three phases, the net unbalance caused by the introduction of BEVs/PHEVs to the distribution network should remain similar to current levels.

For fast charging problems might arise, however it is anticipated that fast charging points will be centrally planned by DNOs in order to ensure balance with regards their phase connection. This is in line with simulation results presented here that have shown that the number of unbalanced BEVs/PHEVs that may be fast-charged on the two case study LV distribution networks is significantly reduced compared to slow-charging due to the much higher electric current flows.

### 10.2.4 Transformer Thermal Limits

For densely populated urban and sub-urban distribution networks (such as the two case study LV distribution networks presented here), exceeding the ratings of the 11/0.4kV distribution transformers that supply them has been found to be the most likely limiting network constraint to the connection of BEVs/PHEVs. This is because these distribution transformers are in some cases already operated by DNOs close to their ratings under maximum loading conditions (a concept known as “asset optimisation”) even prior to any BEVs/PHEVs being connected to the network. As a result, the additional electrical demand due to BEV/PHEV charging could
potentially cause them to exceed their kVA ratings during peak network loading conditions. However, if this occurs for relatively short periods (commonly less than two hours) and by a small margin (typically 10-15%), network reinforcement might not be necessary. Typical ratings for distribution transformers employed in such networks in the UK range from 300-800kVA.

For rural distribution networks, where smaller transformers are used (typically 50-200kVA), the following parameters must be taken into account to determine the effect of BEV/PHEV charging:

(i) transformer loading prior to any BEVs/PHEVs connected to the distribution network; and

(ii) the total increase in electrical demand during maximum loading conditions due to BEV/PHEV charging.

For heavily loaded networks, it is likely that replacement of the distribution transformers will be required in order to accommodate the increased electrical power flows.

10.2.5 Cable Thermal Limits

Similarly to transformer thermal limits, the increase in electrical power flows due to BEV/PHEV charging might cause cable thermal limits to be exceeded for distribution networks with heavily loaded lines that are already operating close to capacity. Simulation results, however, have shown that densely populated urban and sub-urban distribution networks are unlikely to be affected due to the high-current capacity conductors used, which even under maximum loading conditions are operating well within their thermal ratings. Cable thermal limits are more likely to be of concern for DNOs in rural distribution networks, where network lines with low current capacity conductors are typically employed in order to reduce costs. For such networks, the increase in electric current for a particular network line must be examined by considering the timing, location and amount of BEV/PHEV charging required.

Moreover, while BEV/PHEV clustering has no effect on transformer thermal limits, it is very important when considering cable thermal limits. Although a network line may be able to operate without its thermal limits being exceeded for a specific BEV/PHEV penetration distributed uniformly, it may not be able to do this if the BEV/PHEV units are concentrated in one location and connected to a single feeder (“hot spot”).

10.2.6 Network Losses

BEV/PHEV charging will change the electrical power flows in the distribution system and hence also have an effect on system load losses. Since load losses are a quadratic function of the electric current, largest losses occur during peak loading conditions of the LV distribution network. Heavily loaded meshed urban and sub-urban LV distribution networks are anticipated to be the most vulnerable with regards load losses. For such networks, it is necessary to consider both worst-case scenarios (i.e. the periods when system load losses are increased the most), as well as the overall contribution of BEVs/PHEVs throughout the day in order to determine whether system load losses have increased to unacceptable limits. In all the cases, EV/PHEV charging will have a negative effect, with system load losses increasing due to the additional current flowing in the network. Hence, demand side management techniques may
need to be employed by DNOs in order to manage demand for BEV/PHEV charging and thus ensure that system load losses remain within acceptable limits.

On the other hand, if “vehicle to grid” functionality is considered, BEVs/PHEVs may have a positive effect by providing network loss reduction (“peak shaving”) as an ancillary service. However, it is likely that the electrical power from the vehicle would need to be consumed locally and not exported back to the electrical grid due to the significant difference that exists in the wholesale and retail price of electrical energy.
11 Appendix: Overview of data sources

11.1.1 National Travel Survey
The National Travel Survey (NTS) has been run continuously in Great Britain since July 1988, following ad hoc surveys conducted since the 1960s. The NTS is designed to monitor long-term trends in travel patterns and provides detailed information on households, vehicles owned by participating households, individuals, and trips undertaken by all participants.

Full details of the survey can be found in technical reports published on the Department for Transport website:

http://www.dft.gov.uk/pgr/statistics/datatablepublications/personal/methodology/ntstechreports/

11.1.2 English House Condition Survey
The English House Condition Survey (EHCS) is a national survey of housing in England commissioned by the Department for Communities and Local Government. It operated continuously between 2002 and April 2006, when it was merged with the Survey of English Housing to form the English Housing Survey. To give an idea of sample size, the 2007 EHCS results are based on a sample of around 15,600 households. Data for the EHCS are collected through a number of component surveys, including an Interview Survey, Physical Survey, Market Value Survey and Private Landlord Survey. The relevant data for this work related to parking provision and was collected as part of the Physical Survey. Full details of the EHCS are published on the Department for Communities and Local Government website:

http://www.communities.gov.uk/housing/housingresearch/housingsurveys/englishhousecondition/

11.1.3 Omnibus Survey
The ONS Omnibus Survey is a regular multi-purpose survey of a random sample of adults over the age of 16 living in Great Britain. Questions relating to transport and car use were included in the August 2005 survey by the ONS on behalf of the Department for Transport. The results are published on the DfT website:

http://www.dft.gov.uk/pgr/statistics/datatablepublications/trnstatsatt/earlierreports/attitudestocaruse
12 Appendix: International EV infrastructures

12.1 Japan

As reviewed by Ahman, the Japanese government began support for battery electric vehicles in the 1970s, with a commercialization plan that coordinated effort from government agencies, companies, and municipalities towards removing barriers. However, after ten years oil markets were stable and technical progress had been slow, so little activity resulted. In the 1990s environmental concerns re-emerged and a more aggressive market expansion plan was issued – with the intent of 200,000 EVs on the road by 2000. In 1997 the scope was diluted to incorporate other ‘clean energy’ vehicles, and new targets and comprehensive programmes for RD&D, infrastructure and market support defined.

![Figure 45: Outline of historic Japanese Government programmes supporting electric vehicles (Ahman, Energy Policy (2006) 34 433–443)](image)

Considering support for infrastructure, the ECO-Station project was set up in 1993 to create 1,000 EV charging stations by the year 2000. However, by 2006 only 36 stations were established. Reasons proposed for this failure are diverse and include the high cost of recharging stations, limited funds for municipalities, other choices available (CNG, LPG, methanol also qualified as clean energy). Also important was progress in development of hybrid electric vehicles, which better met the requirements of suppliers and consumers. The development of HEVs was an important but originally unintended spillover from the battery electric vehicle programme (no government support was targeted at HEVs). A conclusion is that despite a carefully coordinated effort, Japan failed to stimulate a BEV market – although the completely unintended creation of an HEV market was a valuable benefit.

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Electric Vehicles
Strategies for uptake and infrastructure implications

Figure 46: Sales of eco-vehicles in Japan (TEPCO, statistics from the Japan Automobile research institute)

12.2 Switzerland

Figure 47: Image of a Park & Charge point in Switzerland

Sixty-one recharging stations were installed throughout the canton of Ticino in Switzerland, with parking places reserved for EVs. Between 1997 and 2001 a total of 88,000kWh of energy was supplied by 30 recharging stations monitored for research purposes, with an average supply per day of 93kWh, corresponding to the energy consumption of 13 EVs. More than half
of the EV owners made use of the reserved parking places for EVs, typically at least once a week, for around two hours. Seldom do owners make a special trip to recharge, more commonly owners take advantage of the recharging opportunity during the time their vehicle occupies a reserved parking place. Some owners make use of dedicated spots without recharging their vehicles. The energy supplied by a given recharging point is highly sensitive to the patterns of a minority of users.

### 12.3 France

#### Figure 48: French-type public charging station

During the 1990s EdF provided EV recharging points in France. This included 200 points at 51 locations in Paris. Access was controlled by chip-cards acquired from EdF. Although Peugeot claim to have sold 10,000 EVs in France during the 1990s, the infrastructure deployment appears to have been unsuccessful – as evidenced by the lack of public information on these sites. However this does not appear to have dented recent enthusiasm for a fresh wave of recharging infrastructure deployment in France (again installed by EdF – see below).

### 12.4 Project better place

Project Better Place offers a transformational approach to electric vehicle ownership and recharging. Better Place’s innovative solution to the challenges of recharging facilities, high battery costs, and limited range is through a single framework that:

i. Installs public charge spots prior to the cars being marketed.
ii. Pays for and own batteries – charging a monthly subscription based on mileage.
iii. Provides geographically dispersed battery switch stations, which allow depleted batteries to be replaced within a couple of minutes with charged batteries, thereby providing unlimited range.
iv. Provides in car information on the need and potential opportunities for recharging/swapping.

Better Place claims to have raised $200 million in venture capital commitments and to have entered into agreements with Renault - Nissan on EV design, and is planning to roll out infrastructure in Israel, California, Denmark, Ontario, Hawaii, Australia and Japan. These regions have a combination of limited support for conventional automobiles, a stated strategic
intent to pursue electric vehicles, and/or consumer priorities that are consistent with EV designs and economics, (e.g. low daily mileage or environmental focus). The company hopes to serve 35,000 vehicles in 2011, split equally between Israel and Denmark.

For the Better Place approach to be deployed at scale, there would need to be a great degree of coordination between car manufacturers, battery suppliers, and policymakers. This would involve agreement on design specifications. There would also need to be limited opposition from incumbent providers (i.e. oil companies) who might be threatened by the new technology. The images below indicate current designs for recharging and battery switch infrastructure.

![Better Place 3–4kW recharging facilities in a demonstration project](image)

**Figure 49: Better Place 3–4kW recharging facilities in a demonstration project**

![Schematic of battery swap station infrastructure](image)

**Figure 50: Schematic of battery swap station infrastructure**

Better Place declined to provide details of likely capital and operating investments or expected tariffs for the UK and it was outside the scope of this study to assess the costs and benefits of this business model in any detail. A few points are noteworthy however.
1. Unusually for the EV market, the company intends to target high mileage consumers, which it defines as those that refuel their petrol/diesel cars at least once a week. This is essential for the business case to be viable (see point 3).
2. The cost of an EV without the battery is broadly equivalent to the internal combustion engine (ICE) vehicle cost. As Better Place retains ownership of the batteries, the barrier of high capital cost of EVs is overcome.
3. Under the Better Place business model, profit comes from the differential between the cost of financing the infrastructure (including batteries) and the per-mile rate paid by subscribers. Better Place may be able to offer drivers a competitive rate relative to ICE vehicles given the high efficiency of EVs (and relatively high fossil fuel prices).
13 Appendix: Current EV policy summary

13.1 Australia

In November 2008, Australia’s Federal Government announced a $6.2 billion plan, A New Car Plan for a Greener Future, to make the automotive industry more economically and environmentally sustainable by 2020. While no specific funding for EV development was included, an initiative was announced that could relate to EV development, the Green Car Innovation Fund (GCIF). This initiative includes a $1.3 billion 10-year Green Car Innovation Fund which will encourage the production of low-emission, fuel-efficient vehicles and components. Lobbying is underway for the first electric car approved for sale in Australia, the Mitsubishi i-MiEV, to access the $500 million Green Car Innovation Fund.

13.2 Canada

Canada is the eighth largest auto producer in the world and the third largest exporter. The automotive industry represents 12 percent of manufacturing GDP and 24 percent of manufacturing trade. But, the government of Canada has not been engaged in the electric vehicle infrastructure policy process, and there are no strong federal policy or financial incentives in support of EVs. Canada is taking steps to address the gaps in EV production. The Mitsubishi MiEV will be on the streets of British Columbia before the end of 2009. The Ontario government recently passed legislation that allows low-speed vehicles to operate on city streets but there are no funding models tailored to EVs.

13.3 China

On January 23, 2009, the Ministry of Finance and the Ministry of Science and Technology jointly issued the Interim Measures for the Financial Support for Energy Efficient-New Energy Vehicle Pilot Application and Promotion, a measure to promote new energy vehicles, the construction of infrastructure and the maintenance of these vehicles. The subsidies are directly given to the purchasers (mainly government entities and state-owned enterprises), rather than the manufacturers or auto parts (e.g. battery) producers. Electric vehicles are one of the three types of new energy vehicles identified by this set of measures. Specifically, public service electric vehicles and small-sized commercial electric vehicles with a maximum electric power ratio ranging from 30% to 100% will be offered rebates up to RMB 60,000.

13.4 Denmark

The Danish Government has publicly supported the introduction of Better Place in Denmark and promotes Denmark as the ideal test-country for environmentally friendly modes of transportation. The Danish government has been very receptive to the technology, even declaring that all new cars sold by 2025 should be EVs. In addition, EVs defined as cars powered exclusively by a battery are exempt from the very high Danish vehicle registration tax of 180% until the end of 2012.

13.5 European Union

The European Green Cars Initiative (EGCI), a public-private partnership announced by the European Commission on 26 November 2008, provides funding for R&D as well as industrial
innovation and risk taking for the production of fuel-efficient cars. The EGCI will be funded by
the Community, the European Investment Bank, industry and Member States' contributions
which will amount to at least EUR 5 billion (EUR 1 billion from the Seventh Framework
Programme for Research (FP 7) and from the private sector; and EUR 4 billion through loans
from the European Investment Bank). On March 12 2009, the European Investment Bank
approved EUR 3 billion in loans for European car and truck manufacturers (BMW, Daimler,
Fiat, PSA Peugeot-Citroen, Renault, Volvo Cars, Scania and Volvo Trucks).

13.6 France

The Automobile Pact (Pact Automobile), a EUR 7.3 billion stimulus measure, includes EUR
200 million for innovative and green collaborative projects with the goal to boost battery
manufacturing and the production of electric vehicles and hybrids. The Zero Emission
Vehicles national strategy priorities (launched February 9, 2009) include EUR 200 million for
research and development of hybrid and electric vehicles, incentives to build industrial
consortiums to develop EVs, funds to set up a working group to develop a national EV
strategy, and market creating or “bulk-buying” incentives. In addition, consumer-based
incentives provide vouchers for buyers of cars that have low CO₂ emissions.

13.7 Germany

In November 2008, the German government announced a road map for e-mobility that will
establish a framework for the technological development (materials, components, cells,
batteries, cars, infrastructure etc.) of EVs and, together with experts from industry and
science, will help create a market for EVs. The four involved ministries plan to spend
altogether EUR 225 million to support regional EV projects and R&D centres. In addition, the
Federal Ministry of Education and Research provides EUR 21 million in funding for the
framework of “lithium ionic battery LIB 2015” an alliance of the private sector and academic
institutions.

13.8 Japan

In May 2007, the Ministry of Economy, Trade and Industry (METI), announced the
“Development of a High-Performance Battery System for Next-Generation Vehicles,” which
will develop batteries for the commercialization of EVs. The aim is for half of cars to be eco-
friendly by 2020. Drivers who replace cars that are 13 or more years old (about 13% of cars)
with a new eco-friendly vehicle are eligible for a subsidy of 250,000 yen. This, along with the
US$3.7 billion stimulus package, hopes to increase the sale of new, more environmentally
friendly cars by 1 million.

13.9 Spain

Spain’s auto sales have decreased 7.1% in the past year. The Competitiveness Plan of the
Automobile Sector, worth EUR 800 million will provide aid to the sector, including loan aid,
with EUR 1110 million going to new technology. Other plans will aim to replace older cars with
more environmentally friendly ones. A main objective is to have one million hybrid and EVs on

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47 The four ministries are: Federal Ministries of Economics and Technology, of Transport,
Building and Urban Affairs, of Environment, Nature Conservation and Nuclear Safety and of
Education and Research.
the road by 2014 through pilot projects such as Project Movele in Madrid, Barcelona, and Seville.

13.10 United Kingdom

In October 2008, Secretary of Transportation Geoff Hoon committed to providing £100 million in funding to accelerate the emergence of greener vehicles through research and development projects as well as green vehicle procurement programmes. Earlier this year, Secretary Hoon announced that additional funding of £250 million will be available for consumer incentives and the infrastructure development to promote the adoption and commercialization of ultra low emission road vehicles in the UK. In London, Mayor Boris Johnson established the London Electric Vehicle Partnership to plan, develop and set up the infrastructure for electric vehicles, including the funding 100 electric vehicle charging spots.

13.11 United States

In 2007, the Energy Independence and Security Act established the Advanced Technology Vehicles Manufacturing Loan Program (ATVMLP). Under that programme, Congress authorized $25 billion in direct loans to eligible applicants for the costs of reequipping, expanding, and establishing manufacturing facilities in the U.S. to produce advanced technology vehicles, and components for such vehicles. In addition, the American Recovery and Reinvestment Act of 2009 established $400 million in transportation electrification grants to set up the infrastructure for electric vehicles. At the state level, a number of programmes have been in place. Most prominently, the state of Michigan has offered up to $335 million in tax credits for the development of advanced battery technology.
14 Appendix: Survey of EV owners and EV considerers

Uptake of new consumer technologies occurs in stages whereby the technology progressively satisfies the (evolving) needs of different buyers, starting with the early adopters and proceeding to mass market. Early models of electric vehicles and recharging infrastructure must meet the needs of early adopters, before mass market penetration begins.

In this context, the study sought to quantify to what extent current electric vehicles and recharging facilities satisfy the needs of those who have purchased electric vehicles and those who recently considered purchasing electric vehicles. Online questionnaires were developed for domestic and commercial users and considerers of EVs. The online approach met the project needs for efficiency and economy.

Drive Electric Ltd holds a database of EV owners and those who have expressed an interest in owning EVs (considerers). This database has grown over recent years through individuals choosing to leave their contact details on the Drive Electric website, permitting follow on contact. It should be recognised that historic sales and current demand for electric vehicles among householders and commercial operators are vanishingly small when compared with conventional petrol/diesel vehicles.

Four questionnaires were designed by Element Energy tailored for:

I. Household EV owners.

II. Commercial (fleet) EV owners.

III. Householders considering owning an EV.

IV. Commercial (fleet) operators considering owning one or more EVs.

The survey methodology, which included a series of choice experiments, was adapted from previous successful Element Energy surveys for early adopters for microgeneration technologies. Element Energy and Drive Electric worked together to optimise the questionnaires to elicit maximum response. EV owners and considerers were invited to participate in the study by completing the questionnaires, which were made available online by Drive Electric. The respondents were asked to choose which survey (i.e. I-IV) was more appropriate.

Responses were collected over three weeks beginning 16th March 2009. Questions focussed heavily on understanding charging infrastructure requirements, (so not, for example vehicle purchasing patterns), so limited geographic or socio-demographic data was collected. No regional or socio-demographic weightings were applied to correct results.
14.1 Questionnaires

The four questionnaires followed very similar formats. Questions were asked about existing EVs and usage (for owners) or potential usage (for considerers), recharging behaviour, daily mileage, possible recharging locations, and the challenges and benefits of driving EVs. A final set of questions was a choice experiment, whereby respondents were asked to make trade-offs between additional expenditure and additional battery range. For example, the questionnaire for domestic EV owners is shown below.

![Questionnaire Example](image)

Figure 51: Survey of Household EV owners: description of existing EVs and charging pattern
**Figure 52: Survey of household EV owners: mileage, challenges and benefits**
Figure 53: Survey of household EV owners - Part 3 - Choice Experiments

14.2 Sample sizes

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household EV owners</td>
<td>36</td>
</tr>
<tr>
<td>Commercial (fleet) EV owners</td>
<td>11</td>
</tr>
<tr>
<td>Householders considering owning an EV</td>
<td>215</td>
</tr>
<tr>
<td>Commercial (fleet) operators considering owning one or more EVs.</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>278</td>
</tr>
</tbody>
</table>

Table 5: EV owner and considerer survey: sample sizes

As shown above, the majority of respondents were householders claiming to be considering EV purchase (215 respondents in this category). By way of comparison, a sample size of 150 early adopters of microgeneration technologies was a sufficiently large sample size to provide statistically significant and meaningful insight into early adopter behaviour in that sector. Although some caveats remain, this would suggest that the sample of household EV considerer respondents is sufficient for results to be meaningful.

The numbers of respondents that are domestic EV owners or commercial (fleet) owners or considerers are much smaller. This is inevitable given the paucity of these groups within the
UK market. The responses from these groups are shown for completeness. The small sample sizes imply that the responses from these groups must be treated with caution as small differences lead to high percentage changes in responses. For this reason, in the subsequent graphs both percentages and overall sample size are shown where possible.

### 14.3 Characteristics of EV owners and considerers

Current EV owners and considerers clearly represent a specific segment of car buyers. As an example nearly all EV owners and considerers that responded were male. This may present a challenge if EVs are targeted at two car households where the lower mileage vehicle driver is female.

The overwhelming majority of householders with EVs (Figure 54) have access to a non-EV car. A similar result is seen for commercial operators. This mitigates the risk that early adopters will be heavily constrained by the range disutilities of an electric vehicle – i.e. a petrol/diesel vehicle would be used for longer journeys.

![Diagram showing access to other vehicles](image)

**Figure 54: Access to /use of another car (household EV owners - Base = 36)**

### 14.4 Usage of electric vehicles

Many households with EVs, and nearly all commercial EV owners use their EVs every day. Some householders use their EVs only occasionally or up to four days a week.
Owners and considerers were asked about daily mileage requirements and journey purposes. Household EVs are most commonly used for travelling 10–20 miles/day. Fleet EVs are most commonly used for travelling 21–40 miles/day. A minority of EVs are used for daily mileages of 40 miles per day or more. In contrast, many EV considerers have daily mileages greater than 40 miles, and some have a requirement for daily mileage in excess of 80 miles. These potential users would require distributed recharging infrastructure.
14.5 Recharging patterns for existing EV owners

Although household EV owners primarily recharge their EVs at home (Figure 57), and commercial EV owners primarily recharge their EVs at company premises (Figure 58), householders sometimes recharge EVs at work and commercial EV owners sometimes recharge EVs at drivers’ homes. Figure 57 also indicates that some householder EV owners also recharge elsewhere.

![Figure 56: Estimation of overall daily mileage (household EV owners base = 36, household EV considerers base = 194, fleet EV owners = 10, fleet EV considerers = 16)](image)

- **Figure 56**: Estimation of overall daily mileage (household EV owners base = 36, household EV considerers base = 194, fleet EV owners = 10, fleet EV considerers = 16)

- **Figure 57**: Where EVs are recharged (EV household owners, base = 36)
Interestingly, current users of EVs seem to solve the recharging challenges associated with multiple users. More than half of household (Figure 59) and commercial (Figure 60) EVs are driven by more than one person.
### 14.6 Potential locations for recharging electric vehicles

The locations of recharging infrastructure for householders can be identified by understanding journey lengths and journey types, or by asking preferences. The results from an analysis of journey lengths and journey types are broadly consistent with the results of the NTS, i.e. distances for commuting (Figure 61) and visiting friends and family (Figure 62) can be short or long, whereas distances for school runs and shopping are relatively short.

On average, EV considerers have longer journeys than EV owners, for commuting, for visiting friends and family, and for school runs. Requirements for shopping journeys of EV owners and considerers are similar. Taken together, these responses suggest that household considerers of EVs have similar driving patterns to car users generally, EV owners typically have lower mileages than the population overall.
Together these results indicate that workplace recharging would offer the highest benefit. The demand for school or shopping based recharging infrastructure would be much lower. This is fully consistent with a high perceived value for workplace recharging facilities shown below.
Notwithstanding the small sample sizes, this divergence between the journey lengths of EV owners and EV considerers is reproduced in the commercial sector.

![Graph showing estimated mileage for the main purpose of the EV](image)

Vertical axis shows percentage of respondents within group. Numbers indicate absolute number of responses in given range.

**Figure 63: Estimated mileage for the main purpose of the EV (commercial EV owners base = 6, commercial EV considerers base = 7)**

Many owners and considerers think that recharging points at public car parks, on street, at friends and family driveways, and petrol stations, would be beneficial.

<table>
<thead>
<tr>
<th></th>
<th>Workplace recharging</th>
<th>Public car parks</th>
<th>On street recharging</th>
<th>Driveways of friends, family, clients, suppliers.</th>
<th>Petrol Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household EV owners</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Household EV considerers</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Commercial EV owners</td>
<td>Not asked</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Commercial EV considerers</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>Not asked</td>
<td>+++</td>
</tr>
</tbody>
</table>

**Figure 64: Utility of alternative charging locations**

### 14.7 Barriers to EV ownership

Respondents were asked to assess the relative disutilities of EV ownership. The figures below show the results for each respondent type and for each challenge. Among barriers to EV ownership, owners and considerers consistently state that high price, limited range and lack of recharging points are major barriers. Lack of choice among vehicles and time required to
recharge are moderate barriers. Limited power and performance, unfamiliarity and inconvenience of recharging are perceived as low barriers to EV ownership.

<table>
<thead>
<tr>
<th></th>
<th>High Price</th>
<th>Limited Range</th>
<th>Time to charge</th>
<th>Inconvenience of recharging</th>
<th>No recharging points</th>
<th>Lack of power or performance</th>
<th>Unfamiliarity</th>
<th>Lack of choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household EV owners</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Household EV considerers</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Commercial EV owners</td>
<td>+++</td>
<td>+++</td>
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<td>+++</td>
<td>++</td>
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<tr>
<td>Commercial EV considerers</td>
<td>+++</td>
<td>++</td>
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<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Figure 65: Relative importance of EV disutility factors

14.8 Drivers of EV ownership

EV owners were asked to assess the merits of low running costs, green motoring, and supporting new technology. It was found that all three are considered very high or high benefits by more than half of all respondents. Green motoring ranks highest, closely followed by technology support and lower running costs. Other surveys have shown that green motoring and supporting new technology are low priorities for the mass market, so these aspects would appear to differentiate the EV owners from the mass market. These attributes were valued both by household EV owners and commercial EV owners.

14.9 Value of additional range

Two choice experiments were used to quantify respondents’ willingness to pay for additional range. In the first experiment respondents were asked how much they would pay for additional range. In the second experiment, respondents were asked how much range they would expect for a given on-cost. The two approaches were used to check the consistency of responses. Results from both approaches were broadly similar, though not identical. A similar finding was observed in the study of domestic microgeneration systems.
Figure 66: Response to the question: ‘If the price of £12,000 for an electric vehicle with a range of 40 miles were acceptable to you, how much extra would you be willing to pay to have a 60 mile range?’ from fleet owners/considerers

Figure 67 shows the responses from household EV owners and EV considerers to the first question. Within the limitations of the experiment, it is not meaningful to show error bars. However it would appear that owners and considerers have similar willingness to pay, although owners would appear willing to pay slightly more for range than considerers.
Figure 67: Response to the question: ‘If the price of £12,000 for an electric vehicle with a range of 40 miles were acceptable to you, how much extra would you be willing to pay to have a 60 mile range?’ from household owners/considerers

The data indicate that the willingness to pay of commercial respondents and householders is similar. Again, there is a tendency for owners to be willing to pay more than considerers.

<table>
<thead>
<tr>
<th>Median willingness to pay for additional 20 miles range</th>
<th>Household</th>
<th>Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV owner</td>
<td>£1,200 (equiv. £60/mile)</td>
<td>£1,000 (equiv. £50/mile)</td>
</tr>
<tr>
<td>EV considerer</td>
<td>£900 (equiv. £45/mile)</td>
<td>£900 (equiv. £45/mile)</td>
</tr>
</tbody>
</table>

Figure 68: Median results of responses to the question: ‘If the price of £12,000 for an electric vehicle with a range of 40 miles were acceptable to you, how much extra would you be willing to pay to have a 60 mile range?’
Figure 69: Additional range expected from paying an additional £2,000 (households)

Figure 70: Additional range expected from paying an additional £2,000 (commercial)
The experiments narrow the median willingness to pay for owners and considerers to the range £45–£111/mile. To our knowledge this is the first time this willingness to pay has been estimated for UK-based household and fleet EV owners and EV considerers. The willingness to pay can be fed into consumer uptake models for electric vehicles (see for example, Element Energy for EST (2006) “A new vehicle purchase model for low carbon vehicles”).

Given that purchase price and limited range are already barriers, and that there is a low willingness to pay for additional battery range, EV uptake cannot be incentivised simply by selling vehicles with larger batteries if consumers are required to meet the higher capital costs.

### 14.10 Willingness to pay for extended battery range for PHEV

The survey used two choice experiments to examine whether EV owners are willing to pay extra for PHEVs relative to petrol/diesel only vehicles. In the first choice experiment (Figure 72) consumers were offered a PHEV with a 20 mile range on battery. In the second choice experiment (Figure 73) consumers were offered a PHEV with a 40 mile range on battery. Consumers were asked to identify the price they would be willing to pay for these vehicles, relative to a conventional (i.e. petrol or diesel) vehicle costing £12,000. Again the purpose of asking two questions was to understand consistency, and to allow some flexibility if initial survey estimates proved either optimistic or pessimistic.

As with the answers to the questions on battery only vehicles, these figures show there is a wide distribution of willingness to pay, indicating that neither EV owners nor EV considerers act as a homogeneous group in terms of their willingness to pay for plug-in hybrid vehicles. Replicating the findings on EVs, owners of EVs are willing to pay slightly more for PHEVs than considerers of EVs.
Figure 72: Results of responses to the question: ‘How much extra would you pay for a plug-in hybrid with a range on electric only of 20 miles, compared to a £12,000 standard petrol vehicle?’

Figure 73: Results of responses to the question: ‘How much extra would you pay for a plug-in hybrid with a range on electric only of 40 miles, compared to a £12,000 standard petrol vehicle?’
The results of the data above highlight a significant challenge for PHEV adoption and battery sizing. Even among owners and early adopters of EVs, the willingness to pay for battery range on a PHEV is considerably below typical battery supply costs.

### 14.11 Conclusions from surveys of EV owners and considerers

A total of 278 EV owners and considerers that had previously registered on Drive Electric’s website responded to an invitation to participate in an online survey on EV infrastructure requirements. The majority (215) of respondents were householders that had recently considered EV purchase but had not (yet) purchased an EV. The views of 16 commercial EV considerers and 36 household and 11 commercial EV owners were also captured. The results
provide some quantitative and up-to-date insights into the requirements for EV recharging infrastructure.

EV owners and considerers form a distinct subset of the overall population of vehicle users – for example they are mostly male, and care about supporting electric vehicle technology and 'green motoring'. However a wide range of answers to several questions indicates that these early adopters are not a homogeneous group.

Focussing on issues around recharging, the survey reveals that:

- Nearly all EV drivers have access to an alternative non-electric vehicle – reducing range constraints.
- Most EVs are driven by more than one person – indicating that drivers are able to coordinate recharging requirements.
- Most EVs are used every day – indicating that daily recharging facilities are important.
- EV drivers tend to have shorter commuting, social and school journeys than EV considerers. EV considerers more closely resemble the wider population of drivers, i.e. many have long daily journeys that would benefit from additional recharging opportunities.
- The high price and limited range of EVs, and lack of recharging points are considered high or very barriers for the majority of EV owners and considerers.
- Home and work place charging are the most important recharging locations for both household and commercial EVs. Additional recharging facilities on street, at petrol stations, public car parks, supermarkets, and in the driveways/garages of friends and family are all considered to offer moderate or high benefits.

The study provided a first order estimate of the willingness of household and commercial EV owners and considerers to pay for battery capacity. To our knowledge this is the first time such a metric has been derived for early adopters of EVs in the UK. There was a wide range of responses, i.e. sample heterogeneity. To give an approximate idea of scale, median willingness to pay for extended mileage is £45–£111 per additional mile of range. This is obviously lower than current battery costs. Willingness to pay for battery range in PHEVs is consistent (median values £35–£45 / mile battery range). This suggests that EV early adopters do not markedly differentiate the benefits of battery range in EVs against battery range in PHEVs.