Analysis of Electric Vehicle Driver Charging Behaviour and Use of Charging Infrastructure

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Abstract

Estimates suggest that there will be between 0.5 and 12.8 million electric vehicles (EVs) on UK roads by 2030. Power grids could overload if large numbers of these EVs are not recharged off peak, between midnight and early morning. This study investigates the recharging patterns of 12 Private, 21 Organization Individual and 32 Organization Pool users over two successive six month periods as part of the Switch EV trials. EVs were monitored using a data loggers and GPS devices. Recharging locations were identified as Home, Work, Public and Other. It was found less than 10% of recharging took place off peak. Work was the most popular location to recharge, and demand peaked between 09:00am and 10:00am. Private individuals peak recharging occurred on an evening at Home, while Organization Individuals users recharged mostly early morning at Work. Organization Pool users recharging peaked at Work, late afternoon. Smart Meters can delay recharging until off peak hours at Home and Work locations. It is recommended that pay as you go access to non-domestic infrastructure is used for individual drivers. This will encourage them to recharge at Home or Work, where Smart Meters can then shift their recharging to off peak.

Introduction

The Stern Review (2006) suggested that extreme weather events could reduce the global GDP by up to 1% and damages from climate change could amount to 20% of GDP or more if no action was taken to reduce carbon emissions. (Stern, 2006). Following this, the UK set the legally binding target of reducing carbon emissions by 80% compared to 1990 levels (DECC, 2008). The UK government also commissioned the King Review of Low Carbon Cars to investigate ways in which the transport sector could meet future carbon emissions targets. It was concluded that private cars and small vans, which accounted for 13% of global carbon emissions, would need to be completely electrified by 2050. The battery electric vehicle (EV) was identified as part of an electrified transport solution (King, 2008). There are various estimates as to how many EVs will be on UK roads by 2030. A BERR (2008) study forecasts that there will be between 0.5 to 5.6 million (with an additional 2.5 – 14.8 hybrid vehicles). National Grid (2011b) predicts that there will be between 4.6 to 12.8 million by 2030.

The resulting electricity demand for the recharging of these EVs is expected to add to already high peak loads during daytime and evening peak hours. Potentially more power generation would be needed and local grids would need to be reinforced to meet this additional demand. If recharging takes place during on peak periods, there is an opportunity for Smart meters to shift this demand. This would work by offering cheaper off peak electricity rates to drivers who recharge off peak. The Smart Meter would then automatically delay the recharging of the vehicle until off peak hours (Kemp *et al.*, 2010).

Therefore it is important to understand the way in which EV users recharge their vehicles. The aim of this paper is to understand the recharging behavior of EV drivers. One year of recharging data (April 2011 – April 2012) are collected from 31 electric vehicles taking part in the Switch EV trials in North East England.

Recharging infrastructure in North East England

The recharging infrastructure in North East England fits into the wider UK Government strategy for a national EV recharging infrastructure (OLEV Ref). Three pillars of recharging infrastructure are proposed: home pod points, and recharging posts at work and public locations. It is planned that the bulk of EV recharging will take place overnight, with public and workplace posts being used only when necessary. This is due to the need to reduce peak time demand on the power distribution network from EVs.

Charge your car (CYC) is the name of program in North East England that is responsible for the installation of recharging infrastructure. The CYC target is to have 1000 recharging posts installed across the region by May 2013. As of May 2012 (the end of the Switch EV data analyzed for this paper) CYC had installed 91 domestic units and 343 recharging points (both 3kWh and 7kWh) at 268 locations (Charge Your Car, 2012a).

CYC currently provides funding to EV owners in the region for the installation of domestic recharging posts, providing they own their own home and has access to off street parking. EV drivers can access the CYC recharging posts at workplace and public locations using a smartcard. Drivers obtain a smartcard by paying a fixed annual fee of £100 to become CYC members. CYC membership gives drivers unlimited use of parking spaces and electricity at all workplace and public CYC posts (Charge Your Car, 2012b)..

Previous studies into recharging profiles of EVs

The need to understand the load profiles of EV drivers is based both on the potential need for additional power generation capacity and the potential need to upgrade local power grids if recharging occurs during existing on peak periods (Kemp *et al.*, 2010). The power demand profile in the UK on a typical winter day is shown in Figure 1.

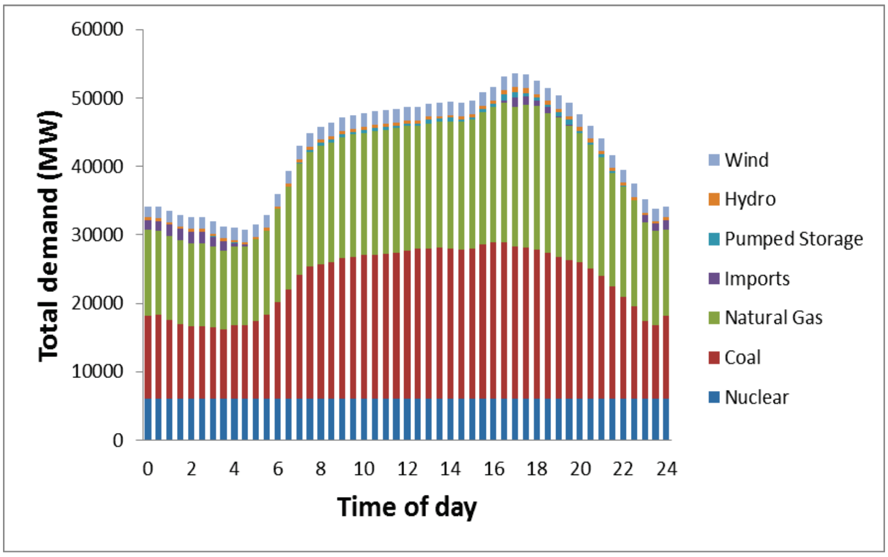

Figure 1 - Power demand in the UK over a 24 hour period (National Grid, 2011a)

It can be seen in Figure 1 that demand peaks at 17:50pm at 53,500MW, and then drops by 19,600MW to 33,900MW by 00:00am. Therefore, the ideal time for EV recharging in terms of minimizing the impact on power generation is between 00:00am and 06:00am. Recharging between 08:00am and 20:00pm adds to an already high demand.

Theoretical profiles have been defined by researchers in this field. Kang and Recker (2009) proposed four theoretical recharging scenarios. '*End of travel day'* recharging assumes that all EVs are recharged immediately upon completion of their daily trips. This produces a high evening load. A similar scenario was '*Uncontrolled home*' recharging. This is where EVs are recharged as soon as they arrive at home on an evening. This produces a similar evening peak. '*Controlled*' recharging made the assumption that drivers were limited to recharging after 22:00pm. This shifted EV recharging loads into the off peak period. '*Publicly available'* recharging saw vehicles recharged whenever they were parked in a public place. Recharging occurred throughout the day during the on peak period in this scenario.

Similar profiles have been defined by Wang *et al.* (2011) and Mullan *et al.* (2011), where a combination of controlled and uncontrolled recharging occurs. These scenarios also suggest that if drivers are given access to recharging infrastructure without it being controlled through smart meters and incentives, recharging will occur on peak. Kiviluoma and Meibom (2011) agree, stating that on peak recharging will occur in any uncontrolled situations, and that incentivizing drivers to switch to off peak recharging through the use of pricing incentives and the provision of smart meters is the only way to shift EV recharging loads to off peak hours.

However, an additional factor that could play a role in influencing the recharging behavior of drivers is the combination of locations at which drivers have the option of recharging their EVs. Predictive models suggest that between 25 – 30% additional load could occur at home on an evening if drivers do not have access to public recharging infrastructure (Weiller, 2011). In future, it is likely that both provision of recharging infrastructure and pricing mechanisms will play a role in defining the recharging profiles of EV drivers (Druitt and Früh, 2012).

Results from the CABLED trials in Birmingham and Coventry suggest that the bulk of EV recharging will be completed at Home, overnight. This trial offered the users limited public recharging infrastructure. There were 36 recharging posts at 12 sites, six in Birmingham and six in Coventry (CABLED, 2012). Furthermore, all drivers were given incentives to recharge off peak. 50% of users were given Smart Meters and financial incentives to recharge off peak at Home. All drivers were offered £50 for recharging off peak (Bruce *et al.*, 2012). This trial shows that, if the bulk of recharging is completed at Home, then it can be switched to off peak. However, it did not show how a high density public recharging infrastructure would impact on the recharging profiles. This was due to the relatively limited infrastructure in place in the region.

In the US city of Nashville, EV drivers do not have access to off peak tariffs and financial incentives to recharge off peak. Their Home recharging peaks at 20:00pm. EV drivers in San Francisco have access to smart meters and cheap domestic electricity use off peak. Their home recharging peaks at 01:00am (Schey *et al.*, 2012). This further backs up the role of Smart Meters in shifting domestic recharging from evening to overnight.

Data from the US also suggests that the use of non-domestic recharging infrastructure is based on the pricing mechanism. Posts in the ECOtality network that involve users making a one off payment for parking and recharging their EV have an average usage rate of 28% compared to the average post offering free parking and electricity (Saxton, 2012).

Methodology

Overview

Switch EV is an EV trial in North East England, funded by the Technology Strategy Board (TSB) Low Carbon Vehicle Demonstrator Program (LCVD). The aim of Switch EV is to understand the real world usage of EVs. Individual drivers and organizations typically lease an EV, at a cost of £220 per month, for a six month trial period. Data from each vehicle are collected and processed from in-vehicle loggers and GPS devices.

Driver Recruitment

The EVs were leased to three user types. Private individuals are members of the public. Organization Individuals are individual managers within an organization. Organization Pool involves the EV being used as a pool car for a group of individuals within an organization.

These users were recruited through media campaigns. There were various conditions drivers had to meet. They had to be able to pay a monthly fee to lease the vehicles (subject to credit check) and meet insurance criteria. Private Individuals had to own a house with off street parking. All Organization users had to agree a recharging solution for their EV. All users were expected to have a minimum usage expectation of 2,000 miles.

As well as driver type, Switch EV drivers had access to a range of recharging options. All drivers in this study were members of CYC. This gave them all access to the CYC posts across the region. All Private Individual users had pod points installed at their home address. All but one of the Organization Individual and Organization Pool vehicles had CYC recharging posts installed at their work premises.

A summary of the user types taking part in the successive six month cohorts that are presented in this paper can be seen in Table 1.

Table 1 - Summary of user types in this study

User Type	Cohort 1	Cohort 2	Total
Private	7	5	12
Organisation Individual	11	10	21
Organisation Fleet	15	17	32

Data collection and processing

Every EV in this trial was fitted with a data-logger. This logger connected to the controller area network (CAN) Bus of the vehicle and to an external GPS and timing device. This allowed the start time, end time, energy transferred and location to be determined. The recharging locations were defined by comparing the GPS coordinates where a recharging event took place to a list of known recharging CYC recharging posts in the region. Home was a known home address of a Switch EV driver. Work was a known workplace address with a CYC posts. Public was any other CYC post that is not at a workplace. Other was a recharging event at any location that was not covered in the other categories. For each individual recharging event, the total demand per hour of day was recorded. Hourly intervals have been used previously by Jansen *et al.* (2010), Axsen *et al.* (2011), Camus *et al.* (2011) and Weiller (2011). These were then aggregated based on recharging location and user classification.

Results and Discussion

Recharging profiles by recharging location

The total and percentage of hours of recharging, for all users, is shown in Table 2.

Table 2 - Total recharging by location

Location	Total hours	%
Home	4839	22
Work	8738	39
Public	7020	31
Other	1908	8

All	22505	100

Work was the most popular recharging location. 8,738 hours (39%) of all recharging took place at Work. This was followed by Public locations, with 7,020 hours (31%) of recharging. Home accounted for 4,839 hours (22%) of recharging. 1,908 hours (8%) of recharging events took place at Other locations. The total recharging demand by time of day for each location can be seen in Figure 2. The percentage of recharging at each location by time of day is shown in Figure 3.

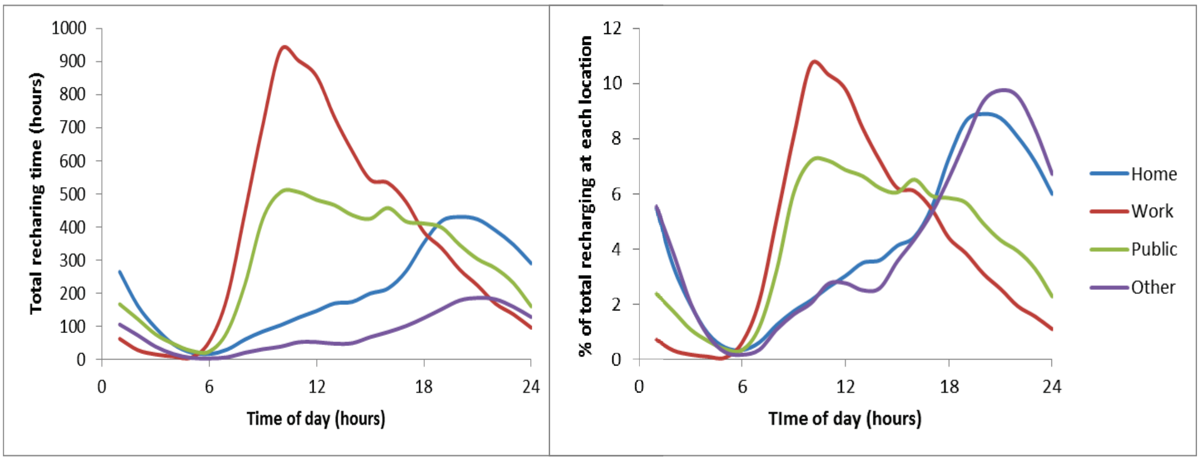

Figure 2 (left) – Total recharging demand by location
Figure 3 (right) – Percentage recharging for each location

It can be seen in Figures 2 and 3 that the largest recharging peak was at Work, with 934 hours of recharging (11% of Work recharging) taking place at the peak between 09:00am and 10:00am.This was the largest peak of any location, in both absolute terms and in terms of the percentage of recharging at a location. Home and Other profiles were similar in percentage terms, suggesting that drivers make use of Other locations in the same way that they make use of Home. They both had evening peaks. Home peaked between 19:00pm and 20:00pm, where 431 hours of recharging took place (8.9% of total Home). Other peaked between 20:00pm to 21:00pm, where 186 hours of recharging took place (9.8% of total Other). The demand for Public recharging infrastructure was spread more evenly between 09:00 and 18:00, with a variation of less than 2% of total Public recharging per hour of recharging in this period. The peak time for recharging at Public locations was between 09:00am and 11:00am, where two successive one hour periods in which 506 hours of recharging took place (7% per hour, and 14% in total, of the total Public recharging).

These results illustrate a need for a shift in recharging behavior. In total, across all profiles, 7.2% of recharging took place during the off peak period between 00:00am and 06:00am. As seen in Figure 3, the Home and Other recharging profiles present the best opportunity to recharge a vehicle at night. It is likely that these vehicles are plugged in as soon as they arrive at their Home location in the evening. This is an area in which ITS technologies such as Smart Meters can be used to delay these events until the off peak period.

Table 3 – Total and percentage of recharging for Switch EV user types

User type	Total hours	%
Private	4722	21
Organization Individual	7139	32
Organization Pool	10644	47
All	22505	100

Table 3 summarizes the total recharging hours for the three use types in Switch EV, and the percentage of recharging each user type contributed to the overall total. Private users contributed 4,722 hours (21%) to the total recharging that took place. Organization Individual users contributed 7,139 hours (32%). Organization Pool users contributed 10,664 hours (47%).

Table 4 – Private user recharging by location

Location	Total hours	%
Home	1703	36
Work	1525	32
Public	862	18
Other	632	13
All	4722	100

It can be seen in Table 4, the private users recharged primarily at Home, with 1,703 hours (36%) of their recharging taking place at this location. 1,525 hours took place at Work locations (32%), 862 hours (18%) at Public recharging posts and 632 hours (13%) at Other locations.

Table 5 – Organization individual user recharging by location

Location	Total hours	%
Home	1220	17
Work	3189	45
Public	2212	31
Other	519	7

All	7139	100

Table 5 shows that the Organization Individual users recharged predominantly at Work, with 3,189 hours (45%) of their recharging taking place at this location. Public contributed to 2,212 hours (31%) of their total recharging, and 519 hours (7%) took place at Other locations. 1,220 hours (17%) of their recharging took place at Home.

Table 6 – Organization Pool user recharging by location

Location	**Total hours**	**%**
Home	1916	18
Work	4024	38
Public	3947	37
Other	757	7
All	10644	100

The Organization Pool user recharging breakdown by location is shown in Table 6. Their recharging is done predominantly at Work and Public, with 4,024 hours and 3,947 hours (38% and 37%) respectively taking place at these locations. 757 hours (7%) of recharging took place at Other locations and 1,916 hours (18%) took place at Home.

There are clear differences in the amount of time spent by EV drivers recharging at each location depending upon the usage type of the vehicle. The Home recharging infrastructure was used most by the Private users, contributing 36% of the total recharging. Organization Individuals and Organization Pool users spend 17% and 18% of their time recharging at Home. Overall, Work was the most widely used recharging location, contributing 32% from Private Individual recharging, 45% from Organization Individual recharging and 38% from Organization Pool recharging. The Public recharging infrastructure was used more by the Organization individual and Organization Pool (31% and 37%) than the Private users (18%). Other locations were used the least across all three user types, with 13% of Private users recharging, 7% of Organization individual users recharging and 7% of Organization Pool users recharging taking place at Other locations.

Given the distribution of recharging by location, as seen in Figure 3, this could present problems for infrastructure planners in the future. Both Work and Public recharging infrastructure were used predominantly during the peak hours between 09:00am and 18:00pm. The potential to use Smart Metering in homes to shift recharging from evenings to off peak has been identified, both in this study and in the literature (Kiviluoma and Meibom, 2011;

Mullan *et al.*, 2011; Wang *et al.*, 2011; Zhang *et al.*, 2011; Druitt and Früh, 2012). However, even if all Home recharging in this study was shifted to off peak hours, 74% of the total recharging would still have taken place during the on peak hours.

The provision of unlimited parking and electricity at all CYC Work/Public posts once an annual membership fee has been paid may be contributing to the relatively high proportion of recharging observed at these locations. This is backed up by data showing that public recharging infrastructure that does not offer unlimited parking and electricity free of charge only has 28% of the usage that those offering free parking and electricity have (Saxton, 2012). This suggests that ITS combined with pricing incentives can offer a potential solution to shifting recharging from Work/Public posts to off peak, Home based recharging.

Therefore it is recommended that, in future, all Public recharging infrastructures are priced such that drivers will not use it unless they feel they need to. Ideally, most of the recharging would be shifted to domestic locations. This is where intelligent systems such as Smart Meters can shift recharging to off peak, overnight.

Conclusions

To date, 8,724 recharging events were recorded from the Switch EV trial vehicles, totaling 22,505 hours of recharging. 4,722 hours charge events were completed by Private users, 7,139 hours by Organization Individual users and 10,644 by Organization Pool users.

In terms of location, Home and Other recharging locations saw a recharging peak in the evening. Work recharging peaked early morning, and Public recharging had a smaller peak early morning and remained at a similar level throughout the day. 72% of total recharging took place between 08:00am and 20:00pm. This current recharging profile is not beneficial to power generation, distribution or emissions. This creates an opportunity for ITS based technologies. In particular, the findings of this study support the introduction of Smart Meters.

Once a vehicle is connected to recharging infrastructure, Smart Meters can delay the recharging until off peak hours. Smart Meters are used in conjunction with price incentives. Drivers are offered cheaper rates to allow the meter to delay their recharging until off peak hours. This will reduce the CO_2 impact of EV recharging and balance demand with capacity.

Most Home recharging occurs in the evening. Smart Meters could delay this until after midnight. Some Work recharging could also be shifted in this way, provided a vehicle is parked at work overnight. Once a vehicle has completed its daily trips, Smart Meters could delay the remainder of the recharging until off peak hours. Public recharging presents a problem. It is not desirable to have vehicles parked at Public posts when they are not recharging. This may prevent a driver needing to recharge from doing so. However, it is recommended that access to public posts be changed from the membership scheme to a pay as you go system. This reduces the usage of public recharging infrastructure (Saxton, 2012). This would shift Public recharging to Home or Work locations, where Smart Meters can delay the recharging until off peak.

In terms of user types, the Private users recharge the most at Home, and therefore are the easiest recharging pattern to shift as it can be delayed for several hours once the vehicle arrives home on an evening. Organization Pool users also present an opportunity to shift recharging, by delaying all recharging after the end of the working day until midnight using Smart Meters. Organization Individuals use Work most frequently, but can take vehicle Home. Their early morning recharge at Work could be shifted to Home, provided they have access to recharging infrastructure. Alternatively this could be delayed using Smart Meters to overnight recharging at Work.

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