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Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips ☆

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HIGHLIGHTS

- Study of EV driver recharging habits in the north east of England.
- 7704 electric vehicle recharging events, comprising 23,805 h were collected.
- There was minimal recharging during off- peak hours.
- Free parking and electricity at point of use encouraged daytime recharging.
- Need for financial incentives and smart solutions to better manage recharging demand peaks.

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ABSTRACT

This paper quantifies the recharging behaviour of a sample of electric vehicle (EV) drivers and evaluates the impact of current policy in the north east of England on EV driver recharging demand profiles. An analysis of 31,765 EV trips and 7704 EV recharging events, constituting 23,805 h of recharging, were recorded from in-vehicle loggers as part of the Switch EV trials is presented. Altogether 12 private users, 21 organisation individuals and 32 organisation pool vehicles were tracked over two successive six month trial periods. It was found that recharging profiles varied between the different user types and locations. Private users peak demand was in the evening at home recharging points. Organisation individual vehicles were recharged primarily upon arrival at work. Organisation pool users recharged at work and public recharging points throughout the working day. It is recommended that pay-as-you-go recharging be implemented at all public recharging locations, and smart meters be used to delay recharging at home and work locations until after 23:00 h to reduce peak demand on local power grids and reduce carbon emissions associated with EV recharging.

1. Introduction

The Stern Review (2006) highlighted the future economic costs of the impact of climate change. It recommended that greenhouse gas (GHG) emissions need to be cut by 60–80% by 2050, relative to 1990 levels. The UK Government has set a legally binding target of reducing carbon emissions by 80% by 2050 compared to a 1990 base level in the Climate Change Act 2008 (Department of Energy and Climate Change, 2008). The King Review was commissioned specifically to investigate ways in which the UK could cut carbon emissions from cars and small vans to meet this target. It was concluded that electric drives are needed to replace the internal combustion engine (ICE) for cars and small vans. The battery electric vehicle (BEV/FEV) will form part of this electric drives solution (King, 2008). Estimates have been made regarding the number of EVs on UK roads in future. Arup (2008) forecast that there will be between 0.5 and 5.8 million EVs in the UK by 2030. A higher estimate of between 4.6 and 12.8 million pure battery electric vehicles and between 2.5 and 14.8 million plug-in hybrid electric vehicles on UK roads by 2030 was forecast by National Grid (2011b).

If realised, this EV uptake will lead to a greater demand for electricity. Therefore, there is a need to understand the relationship between the current power demand and generation and the loads that are likely to be placed on electricity infrastructure in future years. The power generation from all major sources during a typical winter day in the UK in 2010 is shown in Fig. 1.

On the typical winter day in Fig. 1, demand increased from a minimum of 30,800 MW at 05:00 h to 46,300 MW at 09:00 h. There was a peak demand of 53,500 MW at 17:30 h. From here it

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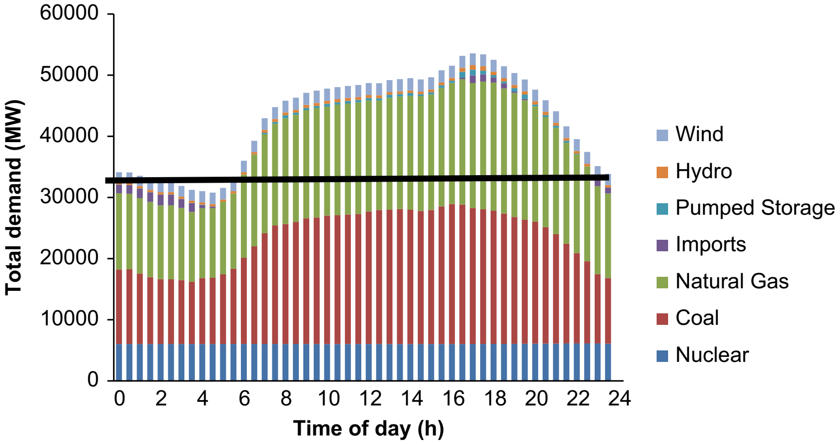

Fig. 1. Power demand in the UK on a typical winter day (National Grid Electricity Transmission, 2011).

decreased by 19,600 MW to 33,900 MW at 00:00 h. In the UK the Economy 7 tariff offers reduced electricity costs during the 7 h of the day where power demand is at its lowest (British Gas, 2012; EDF Energy, 2012). These hours are between 23:00 h and 06:00 h, and represent all power demand bars underneath the horizontal line in Fig. 1. This period of time is defined as 'off-peak' in this study. All other times are defined as 'on-peak'.

Problems might occur if EV drivers recharge during on-peak periods where existing power demand is already high. First, this creates pressure on existing generation sources and may require investment in further power generation capacity. Second, local power grids may be pushed beyond capacity if there is a high demand for EV recharging during on-peak hours (Jansen et al., 2010; Kemp et al., 2010; McCarthy and Yang, 2010).

Ideally, all EV recharging will be managed, in order to spread the total power demand on the UK power network more evenly throughout the day. Off-peak recharging of EVs will ease demand on local power distribution networks. Additionally, less investment in power generation capacity would be required (Kemp et al., 2010).

Another benefit of recharging during the off-peak period is that it can reduce the carbon content of the electricity used to recharge an EV. On a typical winter day, power generation from coal-fired power stations increased from 34% of total generation off-peak to 41% during the on-peak. Coal has a relatively high carbon content (910 gCO_2/kW h), compared to natural gas (390 gCO_2/kW h), nuclear and renewables (0 gCO_2/kW h), and other sources (average of 540 gCO_2/kW h). (Department of Energy and Climate Change, 2012). As power demand increases, the carbon content of electricity therefore increases. For these reasons, the ideal scenario is for EVs to be recharged predominantly off-peak where possible (Kemp et al., 2010; Office for Low Emission Vehicles, 2011).

2. EV recharging

2.1. Overview of EV recharging profiles

The capacity constraints of local power grids to deliver energy and the consequential carbon content of electricity during EV recharging means that understanding drivers' recharging behaviour and how it can be influenced is important.

A recharging profile shows how an EV is recharged over a 24 h period. In future, it is anticipated that smart meters and pricing incentives will be implemented to manage spikes in EV recharging demand profiles. Smart meters are devices that can delay electricity use, including EV recharging. This could be a time-specific delay of several hours, ensuring that an EV is recharged during off-peak periods. Alternatively, they could draw power from the grid when there is either an increase in energy output from renewable energy sources or a drop in total energy demand (Andersen et al., 2009; Kiviluoma and Meibom, 2011; Zhang et al., 2011; Hedegaard et al., 2012). It is important to understand EV drivers' recharging behaviour in order to be able to define the role smart meters and incentives can play in EV recharging demand management.

2.2. Theoretical models of recharging profiles

Previous studies have predicted EV drivers recharging demand profiles, based on assumptions regarding availability of recharging infrastructure and level of recharging demand management available through smart meters. Morrow et al. (2008) made predictions based on individual trip and daily distances from the 2001 US National Household Travel Survey conducted by the US Department of Transportation. This study predicted that there would be one peak in EV recharging demand per day, occurring in the late evening between 20:00 h and 22:00 h. Kang and Recker (2009) on the other hand developed four theoretical recharging scenarios, based on recharging demand assumptions and vehicle use from travel dairies. The *End of travel day* recharging scenario assumed that vehicles were recharged only when the vehicle had completed all of its trips in any given day. *Uncontrolled home* recharging involved drivers recharging their vehicles as soon as they arrive at home on an evening. *Controlled charging* was where drivers were limited to recharging their EVs after 22:00 h. *Publicly available electricity recharging* involved drivers recharging their EVs whenever the vehicle was parked in a public place.

Similar theoretical scenarios were devised by Mullan et al. (2011), who used three independent scenarios when modelling recharging habits. The evening only recharging scenario involved EVs being recharged between 16:00 h and 23:00 h. The night time only recharging scenario involved EVs being recharged between 22:00 h and 7:30 h. The controlled recharging scenario involved the total amount of EV recharging rising from 19:30 h to 02:00 h. Wang et al. (2011) considered four theoretical recharging scenarios. The first involved unconstrained recharging of EVs as soon as they arrive at home. The second scenario assumed all recharging from the first was delayed by 3 h. Scenarios three and four involved smart recharging of EVs. In these scenarios, the EV was recharged only when there was a lower demand on the power grid.

Weiller (2011) highlighted how the time of day a driver recharges the EV can be influenced by location. A model was developed to determine how access to recharging at different locations on time of day can impact on recharging profiles. It was suggested that the accessibility of both home and work based recharging infrastructure will influence their recharging demand profiles. It was predicted that energy demand from recharging at home will increase by between 25.0% and 29.4% if this is the only option available to a driver. However, if workplace recharging infrastructure is provided, it is expected that between 24.6% and 28.7% of recharging will occur at work. Camus et al. (2011), using Portugal as a case study, investigated the impact of EV recharging on electricity prices. It was found that if the political target of 0.7 million EVs was reached, on-peak recharging costs could be three times as much as the off-peak rates. Druitt and Früh (2012) suggested that EV drivers in the UK, if financially incentivised, will recharge vehicles during the off-peak hours to maintain a more consistent power demand on the power generation network.

2.3. *Real world studies*

The CABLED trial took place in the UK, in the cities of Birmingham and Coventry. This trial involved the analysis of real world data from 108 EVs over a one year period. They were tracked using in-vehicle data loggers. All individual drivers were offered a £50 reimbursement for recharging off-peak. Half of drivers had smart meters installed in their homes and were offered significantly cheaper electricity if they used them to recharge their vehicles during off-peak hours. There were 36 non-domestic recharging posts at 12 locations. Six locations were in Birmingham and six were in Coventry. Of these recharging posts, half were completely free of charge to use and at the other half a fee at standard rates was levied for parking. The private users with the home recharging infrastructure completed the majority of their recharging after 23:00 h (Bruce et al., 2012).

A study of domestic EV recharging in two United States cities, San Francisco and Nashville, also highlighted the importance of smart meters and financial incentives. EV drivers in San Francisco have access to smart meters at home and are offered financial incentives to recharge off-peak. EV drivers in Nashville do not have smart meters and receive no such incentives. The domestic recharging profile of drivers in San Francisco peaked at 01:00 h whilst domestic recharging peaked in Nashville at 20:00 h (Schey et al., 2012).

The data from the ECOtality network of recharging posts in the United States offer an insight into how the pricing mechanism can impact usage. Recharging posts where drivers pay standard rates for parking and electricity had an average daily recharging usage that was equivalent to 28% of the recharging usage of the average post that was available for free. This suggests that pricing mechanisms can influence recharging location (Saxton, 2012).

2.4. *Link between EV recharging profiles and CO_2 emissions*

The carbon content of the electricity used to recharge an EV has a direct impact on the subsequent CO_2 emissions per kilometre from an EV journey (Doucette and McCulloch, 2011). A fixed emissions factor for the carbon content associated with the generation of electricity can be applied to electricity transferred into an EV battery to calculate EV emissions (Howey et al., 2011; Pasaoglu et al., 2012; Thomas, 2012). However, using a fixed emissions factor does not take into account the fluctuations in the carbon content of electricity, which depends on the time of day and month of the year that the recharging event takes. This varies between a minimum of 234 $gCO_2/kW\,h$ during the summer ‘off-peak’ and a maximum of 607 $gCO_2/kW\,h$ in winter ‘on-peak’ (Kemp et al., 2010). McCarthy and Yang (2010) use carbon content data for each power generation source at hourly intervals throughout the day to define a typical daily CO_2 profile.

2.5. *Research gap*

The impacts of EV recharging infrastructure design, procedures for user access and adoption of future technologies such as smart meters have been predicted through theoretical studies. However, knowledge from real world trials is limited. In particular, real world studies have not been conducted to investigate the development of a high-density non-domestic recharging infrastructure with fixed-fee membership access on the recharging demand profiles and subsequent carbon content of the electricity supply used to recharge the EV batteries of vehicles driven by different user types.

3. Aim and objectives

The aim of this study was to develop a fundamental understanding of the recharging behaviour of EV drivers in the north east of England. Both private and organisational EV user types and recharging locations were considered.

The specific objectives of this study were to:

- Recruit a sample of EV drivers.
- Identify a study area.
- Track real time usage of EVs.
- Determine the location and time of day of each recharging event.
- Quantify recharging demand profiles and subsequent CO_2 emissions from recharging.
- Quantify impact of user type on the recharging locations used and the time of day of recharging events.

The next section describes the methods adopted in this study of driver recharging behaviour.

4. Methodology

4.1. *Overview*

Data were available from the SwitchEV trials, which started in April 2011 in the north east of England. Switch EV is a £10.8 million EV trial funded by the Technology Strategy Board (TSB) with the aim of understanding the real world use of EVs. There are 44 EVs in total involved in SwitchEV. Both private and organisation drivers leased these EVs for six month periods. Analysis of one year of data from the first two consecutive cohorts of drivers is presented in this paper. The EVs were fitted with data-loggers and GPS devices to allow drivers' driving and recharging behaviour to be monitored. Focus groups were conducted to provide insights into drivers' experiences of EVs.

4.2. *Data collection*

4.2.1. *Driver recruitment*

Drivers were recruited through media campaigns, and had to meet the following conditions:

- Able to pay a £220 monthly fee to lease the vehicles (subject to credit check).
- Satisfy insurance criteria.
- Home owner with off street parking (private individuals only).
- Requirement for access to recharging infrastructure.
- Expectation of at least 2000 miles travelled within the lease period.

The users, who were selected from a pool of applicants by the SwitchEV project managers Future Transport Systems, leased the vehicles for one of the two consecutive six month periods between

March 2011 and April 2012. EVs were leased to three user types; Private users were members of the public, Organisation individual user vehicles were leased to an organisation for use by an individual manager and organisation pool vehicles were leased to organisations for use as pool vehicles (and were available for use by a number of different employees). The number of users in the first two trial periods is shown in Table 1. This study only considers the EV models that are currently commercially available and that fit into the three main user categories.

72% of SwitchEV drivers were male and 28% were female. Comparing the sample demographics to the regional demographics; 5% of drivers were 17–25 years old (13% regionally), 16% of drivers were 26–35 years old (12% regionally), 30% of drivers were 36–45 years old (13% regionally), 39% were 46–55 years old (14% regionally) and a further 11% were 56–65 years old (12% regionally). None of the drivers were over 66 years old compared to 16% regionally (ONS QS103EW, 2011).

Compared to regional figures from ONS QS108EW 1 (2011), 63% of Switch EV drivers were married (45% regionally). A total of 11% were single (26% regionally), 19% were living with a partner (11% regionally), 3% separated (2% regionally), 3% were divorced (7% regionally) and 1% widowed (7% regionally).

Considering employment classifications; 91% of SwitchEV drivers were in full-time employment (65% regionally), 6% in part time employment (15% regionally), 3% self-employed (12% regionally) and 1% full time students compared to 2% regionally (ONS QS602EW, 2011).

In terms of earnings; 4% earned £20,000 or less, 32% earned between £21,000 and £40,000, 36% earned between £40,000 and £70,000, 19% earned between £70,000 and £100,000 and 9% earned more than £100,000. This compares to a regional median full-time gross annual earnings of £23,665 (ONS, 2012).

The profile of the SwitchEV drivers was similar to the profile of EV early adopters. In the UK, a government scheme called the ‘Plug-in Car Grant’ offers 25% towards the purchase cost of an ultra-low carbon vehicle (to a maximum of £5000). This scheme is open to all consumers with a UK address. Current data shows that 87% of recipients of the 'Plug-in Car Grant' have been male, working full time (in senior roles or self-employed) or retired and aged 40 years and above (DfT, 2012).

Table 1
SwitchEV driver user types taking part in this study.

User type	Cohort 1	Cohort 2	Total
Private	7	5	12
Organisation individual	11	10	21
Organisation pool	15	17	32

4.2.2. *Study area and recharging infrastructure in the north east of England*

The UK government has funded the development of a national recharging infrastructure, under the Plugged-in-Places (PiP) scheme. PiP started in 2010 with three deployments in London, Milton Keynes and the North East of England (Office for Low Emission Vehicles, 2011).

The PiP scheme in the north east of England, called Charge Your Car (CYC), began in April 2010. As of May 2012 (the final month of the data presented in this study), there were 91 3 kV home recharging points, 268 3 kV public/work recharging posts and eight 50 kV public/work fast chargers (Charge Your Car, 2012a).

Fig. 2 shows the study area and the current locations of non-domestic recharging infrastructure.

Drivers pay an annual membership fee of £100 ($150US) or a monthly membership fee of £10 ($15US) for the use of CYC public and work based recharging posts. Once this membership fee has been paid, there are no additional parking charges or electricity costs incurred at any of the CYC workplace or CYC public recharging posts. Members access these posts via a smartcard control key. All EV drivers are eligible for CYC membership. In addition, any EV driver can have a home recharging point installed at no additional cost, provided they own their home and have access to off-street parking (Charge Your Car, 2012b). All drivers in this study were CYC members, and some had additional CYC recharging points installed at home.

4.2.3. *Recharging data collection*

Each EV was fitted with a data-logger that linked to both the CAN bus of the vehicle and to a GPS device with a timer. The logger was configured to record both digital inputs (GPS coordinates and time) and analogue inputs from electric current clamps attached to parts of the vehicle.

The following key parameters were recorded every second:

- Time of day (hours, minutes and seconds),
- GPS co-ordinates (latitude, longitude, altitude),
- Battery current (amps),

Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Fig. 2. SwitchEV study area within the UK illustrated by the box (left) and the non-domestic recharging infrastructure locations within the North East region study area. The recharging infrastructure locations are indicated by pink circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Battery voltage (volts),
- Battery state of charge,
- Temperature (°C).

Initially, these data were stored on the hard drive of the logger within the vehicle. In order to process these data, they were then sent via GPRS from the data-logger hard drive to a server at Newcastle University, in a binary format.

A recharging event was defined as an event in which the vehicle was stationary and power was being drawn from the electric power system.

From these binary data, the following parameters were calculated:

- Start time of recharging event (defined as the point when the transfer of electricity into the vehicle battery starts),
- End time of recharging event (defined as the point when the transfer of electricity into the vehicle battery stops),
- Energy transferred recharging per second (this is determined by multiplying the battery current by the battery voltage to calculate the energy used per second),
- Vehicle position (from GPS).

This then allowed the following parameter to be calculated:

- Duration of recharge (End time of recharge—start time of recharge).

4.2.4. *Variables of interest*

Each individual recharging event was quantified by the time spent recharging in each hour of the day. This is consistent with previous approaches in this field (Jansen et al., 2010; Axsen et al., 2011; Camus et al., 2011).

The GPS latitude and longitude were used to define the recharging locations. The GPS coordinates of the EV when a recharging event was taking place were compared to the coordinates of known CYC recharging infrastructure. As per TSB guidelines, recharging locations were defined as

- Home—The known home address of a CYC home recharging point,
- Work—The known address of a CYC work recharging point,
- Public—All other public CYC recharging posts, and
- Other—Charge events where the location of the recharging event did not correspond to any of the above locations.

When a recharging event began, the GPS coordinates of the vehicle were cross-referenced against the known GPS coordinates of all CYC domestic, public and workplace posts. If a recharging event was found to take place in close proximity to any of those known locations, then this recharging event was assigned as home, work or public accordingly. If there was no known recharging infrastructure nearby when a recharging event was taking place, the location was recorded as ‘other’. This process was repeated for all recharging events.

4.3. *Methods*

4.3.1. *Aggregation of recharging events*

Once all of the recharging event profiles had been identified, the next stage was to collate these to determine the overall demand profiles throughout the day. Individual recharging events were collated in three separate stages. To quantify the total demand profile for each user, the total of the durations spent in each hour of the day were aggregated to give the total time spent recharging in each hour.

The recharging during each hour of the day was aggregated for all users by both recharging location and user type. This gave 12 profiles; Private user home, private user work, private user public, private user other, organisation individual home, organisation individual work, organisation individual public, organisation individual other, organisation pool home, organisation pool work, organisation pool public and organisation pool other. These recharging profiles were then aggregated by both user type and location separately.

4.3.2. *Recharging data analysis*

The aim of this analysis was to determine whether there was any evidence that different EV user types made use of recharging infrastructure at different times of the day and at different locations.

4.3.3. *Focus groups*

Focus groups were conducted as part of the SwitchEV project. This paper uses the outputs from the focus groups to provide potential explanations behind the recharging profiles once they have been defined. Parts of the focus group discussion related to driver recharging habits. All drivers were invited, via email, to take part. Opinions and comments from EV users in five semi-structured focus groups and three semi-structured interviews were used in this study. Three of these groups had six participants. One group had five participants and one group had three participants. There were three interview sessions. One session had one participant and the other two sessions each had two participants. In terms of EV recharging, drivers were specifically asked “when and where do you recharge your vehicle?”, “What factors influenced your decision?” and “would you recharge your EV differently if you had to pay parking and electricity at standard rates at the public recharging posts”.

4.3.4. *Calculating the carbon content of electricity*

The carbon content of electricity over a 24 h period was calculated using the approach described by Kemp et al. (2010) and McCarthy and Yang (2010). This method requires power generation data, a power transmission loss factor and emissions factors for the carbon content of power generation for each power source used to generate electricity.

Typical UK summer and winter electricity generation data at half hourly intervals were obtained from National Grid (2011a). Each half hourly generation level is based on the sum of the total output from the eight energy generation sources. These were coal, natural gas, nuclear, imports, oil and open cycle gas turbine (OCGT), pumped storage, hydro and wind. The average carbon emissions factors for power generation and power transmission loss factor for the period April 2011 to May 2012 were obtained from the Department of Energy and Climate Change (2012). The carbon emissions factors for power generation are shown in Table 2. The power transmission loss factor was quoted as 1.10.

For each half hourly interval, the carbon content of electricity in summer was calculated. The emissions factor for coal was multiplied by the total ‘typical’ summer energy generation from coal in this time interval. This gave the total emissions from coal. This process was repeated for the other seven power sources. Not all sources of power generation have their emissions quoted. Wind and hydro were classified as renewable. Oil and OCGT, imports and pumped storage were classified as ‘other’.

The sum of these eight emissions totals for each power source gave the total emissions. This was then divided by the total output to give the average emissions in this half hourly interval. This process was repeated for each half hourly interval throughout the day to give a typical summer carbon content of electricity profile across a 24 h period. Typical profiles from summer and winter were defined to allow the impact of recharging behaviour on carbon emissions to be compared irrespective of day to day fluctuations in power demand. The process was then repeated for the winter generation data. The summer and winter carbon average content of electricity profiles can be seen in Fig. 3.

The start and finish time of recharging events were used in conjunction with the carbon content profiles to give a summer average and winter average carbon content for each recharging event.

5. Results and discussion

5.1. Descriptive statistics of EV usage

Table 3 shows the average usage statistics for a six month trial period per vehicle user type.

The highest average number of trips per vehicle trial period was made by the organisation pool users, with 520. This was followed by organisation individual (476) and private users (429). In terms of average total distance travelled, private users travelled the furthest (4955 km). This was followed by organisation individual users (4924 km) and organisation pool users (3971 km). The average trip length was highest for private users (11.6 km), followed by organisation individual users (10.3 km) and organisation pool users (7.6 km). The organisation pool vehicles are essentially used more frequently than other vehicle types but for shorter trips.

Halving the annual figures from the 2010 UK National Travel Survey shows that the average distance travelled per six month period in the UK was 4215 km for private vehicles and 3745 km for business vehicles (DfT, 2011). Therefore, the average EV for all user types in this study travelled further than the UK average private vehicle during the trial period.

Table 2
Carbon content of electricity generation in the UK by power source (Department of Energy and Climate Change, 2012).

Source	CO_2 Content (gCO_2/kW h)
Nuclear	0
Coal	910
Gas	390
Other	540
Renewables	0

5.2. Recharging statistics by user type and location

A summary of the total data collected for all drivers in this study is seen in Table 4.

It can be seen that during a six month trial period, the organisation individual users recharged their vehicles most frequently (averaging 124.8 recharging events per user), followed by the organisation Pool vehicles (117.8 recharging events per user) and the private users (109.7 recharging events per user). In terms of locations, work was the most popular location (50.4 recharging events per user), followed by public (32.5 recharging events per user). There was an average of 24.8 home recharging events per user. Other was the least frequently used with an average of 10.9 recharging events per user. This highlights the fact that not all vehicles were recharged on a daily basis.

The average duration per recharging event was greatest for private users (3.4 h). This was followed by organisation individual users (average of 3.2 h per recharging event) and organisation pool users (2.9 h per recharging event). By location, other had the longest recharging duration (3.7 h). This was followed by home and public (both 3.1 h). Work had the lowest average recharging duration (2.9 h).

5.3. Recharging profiles by recharging location

The recharging profiles at each location by time of day can be seen in Fig. 4.

The most frequent recharging period by location was between 09:00 h and 10:00 h at work, where 11.0% of recharging took place. Home and other locations both had an evening peak, with 8.9% of home recharging taking place between 19:00 h and 20:00 h and 9.8% of other recharging taking place between 20:00 h and 21:00 h. Public recharging posts had an early morning peak lasting two successive hours between 09:00 h and 11:00 h during which period 14.0% of the total public recharging occurred.

5.4. Analysis by user type

The total recharging profiles by user type can be seen in Fig. 5.

It can be seen that each of the user types had a different recharging profile. The organisation pool users have a distinct peak between 15:00 h and 16:00 h, which accounts for 8.2% of the total recharging. The private users and organisation individuals both have two peaks. The larger peak for organisation individual vehicles occurred between 09:00 h and 10:00 h, where 10.4% of the recharging took place. This correlates with the time a vehicle

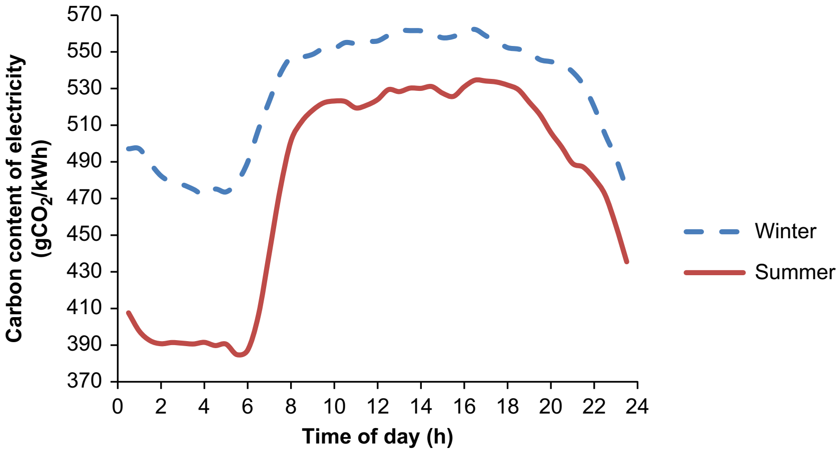

Fig. 3. Seasonal carbon content of electricity in the UK by time of day.

arrives at work on a morning. A second, smaller peak occurred between 19:00 h and 20:00 h, where 4.2% of recharging took place. This contrasts with the private users, where there was a smaller morning peak between 11:00 h and 12:00 h, where 5.8% of recharging took place. This could be due to recharging whilst undertaking leisure activities, shopping and private business. Private users also saw a larger evening peak lasting two consecutive hours between 19:00 h and 21:00 h, during which period 15.0% of their total recharging occurred.

5.5. *Impact of user type on recharging profiles at each location*

This section explores how each of the user types makes use of the recharging infrastructure at the different locations. The recharging profiles of each user type at home are presented in Fig. 6.

It can be seen that all of the drivers made use of home recharging infrastructure in a similar way, with peaks for all users occurring on an evening shortly after 18:00 h. Based on discussion from the focus groups, this is likely due to drivers plugging in their vehicles as soon as they arrive home at the end of the working day. This behaviour was predicted in recharging scenarios in previous research (Kang and Recker, 2009; Mullan et al., 2011; Wang et al., 2011). The recharging profiles of each user type at work are presented in Fig. 7.

It can be seen that there was similarity between the work recharging profiles between private and organisation individual users. The early morning peaks suggest that these user types follow similar commute behaviours. However, neither of the recharging profiles for these user types displayed similarity with organisation pool recharging profiles. The organisation pool users relatively had a smaller peak occurring in the evening at 17:00 h rather than at 09:00 h as seen by the private users and the organisation individual users. Furthermore, there were several peaks throughout the day. The evening peak for organisation pool vehicles suggests that they are plugged-in at the end of the working day, once their daily trips are complete. This result is significant because many of the early adopters of EVs are organisations purchasing vehicles for pool use. This creates a need to develop a fundamental understanding of the barriers to delaying this end of working day recharging.

The recharging profiles at public locations by each user type can be seen in Fig. 8.

It can be seen that there were differences in the way in which the three user types make use of public recharging infrastructure. The organisation individual users revealed an early morning peak in demand. This was similar to the way in which they made use of the work recharging posts. The organisation pool users saw a late afternoon peak in demand at public locations. A similar pattern was observed at work locations. The private users recharging at public locations did not peak at approximately 09:00 h as it did at work. Instead, their recharging at public locations peaked at 20:00 h. It was revealed through focus groups that some drivers with access to a home recharging post instead make use of public posts near their home address on an evening. This could be because they have already paid a fee for parking and electricity through their CYC membership.

The recharging profiles at other locations by user type are presented in Fig. 9.

Table 3
Descriptive statistics of average EV usage over a six month trial period.

	Private	Org Ind	Org Pool
Average total trips/vehicle	429	476	520
Average total distance (km)/vehicle	4955	4924	3971
Average trip length (km)/vehicle	11.6	10.3	7.6

Table 4
Average EV recharging statistics for a six month trial period.

	Average number of recharging events				Average event duration (h)			
	Private	Org ind	Org pool	All users	Private	Org ind	Org pool	All users
Home	41.6	26.3	17.4	24.8	3.1	3.0	3.2	3.1
Work	36.9	51.3	54.9	50.4	3.6	3.6	2.4	2.9
Public	18.8	38.5	33.7	32.5	3.2	2.7	3.3	3.1
Other	12.4	8.7	11.7	10.9	3.7	3.6	3.7	3.7
Total	109.7	124.8	117.8	118.5	3.4	3.2	2.9	3.1

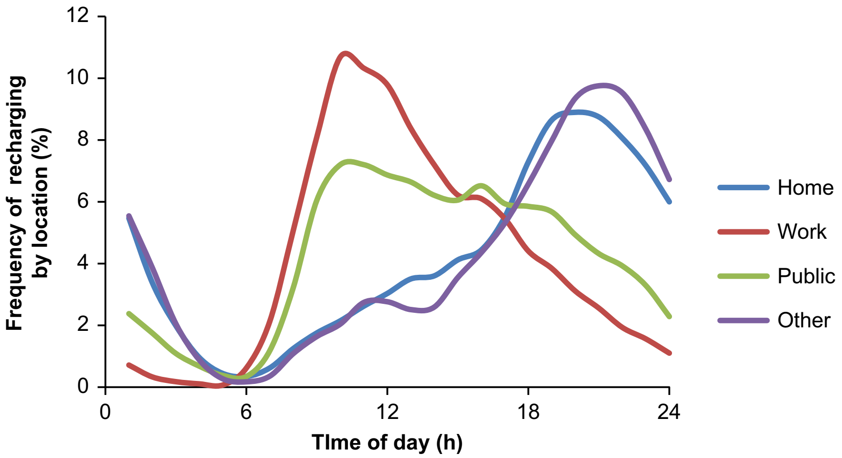

Fig. 4. Recharging profiles at home ($n=1610$ recharging events), work ($n=3278$), public ($n=2110$) and other ($n=706$) locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

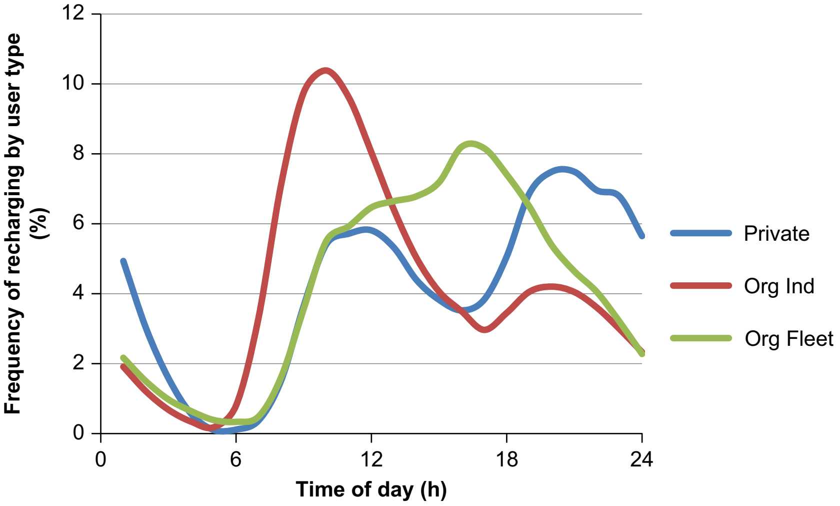

Fig. 5. Recharging profiles for private users ($n=1316$ recharging events), organisation individual users ($n=2620$) and organisation pool users ($n=3768$).

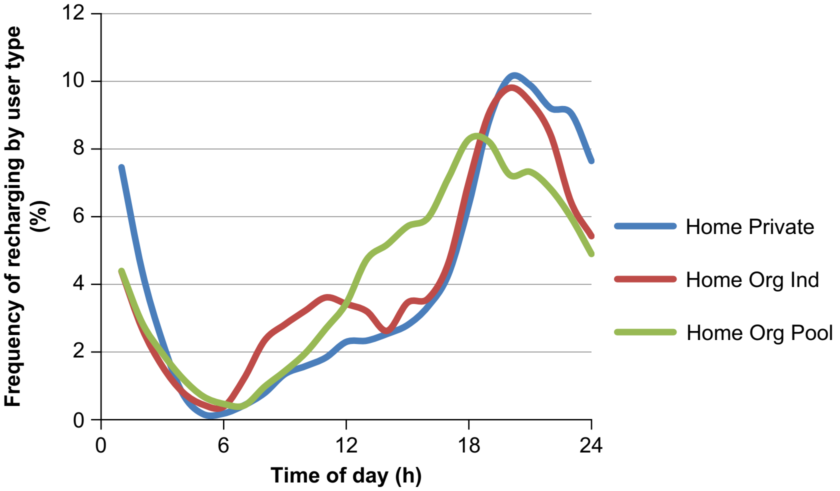

Fig. 6. Recharging profiles at home for private users ($n=449$ recharging events), organisation individual users ($n=553$) and organisation pool users ($n=558$).

There was a strong similarity in the way in which all user types made use of recharging at other locations, with these recharging profiles being similar to the home recharging profiles.

5.6. Carbon content of electricity to recharge EV

In all cases this analysis firstly estimated the average carbon content of electricity during EV recharging (gCO_2/kW h) for the actual recharging events based on their duration and the time of day at which they occurred. Second, assuming an average recharging duration of 3.1 h (see Table 4), the CO_2 levels at the most (maximum) and least (minimum) carbon intensive 3.1 h period of the day for summer and winter profiles were calculated.

The carbon contents of electricity during EV recharging events when the summer and winter CO_2 profiles are applied to the recharging data are shown in Fig. 10.

The average carbon content of electricity during EV recharging in winter was 543 gCO_2/kW h. This was 19 gCO_2/kW h below the maximum value of 562 gCO_2/kW h and 71 gCO_2/kW h above the minimum value of 472 gCO_2/kW h. On the other hand, for the summer period the average was 505 gCO_2/kW h. This was 29 gCO_2/kW h below the maximum value of 534 gCO_2/kW h and 119 gCO_2/kW h above the minimum value of 386 gCO_2/kW h.

However, the average carbon content of electricity during the off-peak hours was 482 gCO_2/kW h in winter, compared to 392/kW h in summer. If all recharging was completed off-peak, the carbon content of electricity used to recharge an EV could be reduced by approximately 11% in winter and 22% in summer if on-peak recharging was switched to off-peak (depending on precise start and finish times of the recharging events).

The carbon content of recharging an EV was generally higher in winter and lower in summer across all events monitored. This was expected, as the higher demand for power in winter creates additional demand for power which is met predominantly through generation from coal (National Grid, 2011a).

The carbon content of electricity during EV recharging by user type can be seen in Fig. 11.

The average carbon content of electricity during EV recharging by user type were; 535 gCO_2/kW h in winter and 495 gCO_2/kW h in summer for private users, 543 gCO_2/kW h in winter and 505 gCO_2/kW h in summer for the organisation individuals and 545 gCO_2/kW h in winter and 510 gCO_2/kW h in summer for organisation pool users. The recharging profiles of the private users coincided with the times of day where the carbon content is lower than the recharging profiles of either of the organisation vehicle user types.

The carbon content of electricity during EV recharging by location is presented in Fig. 12.

The average carbon contents of electricity during recharging in winter by location were; 533 gCO_2/kW h at home, 550 gCO_2/

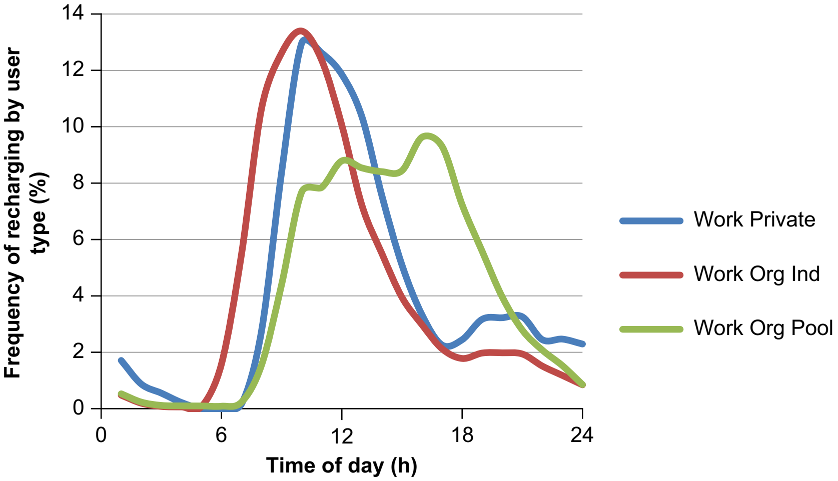

Fig. 7. Recharging profiles at work for private users ($n=443$ recharging events), organisation individual users ($n=1077$) and organisation pool users ($n=1758$).

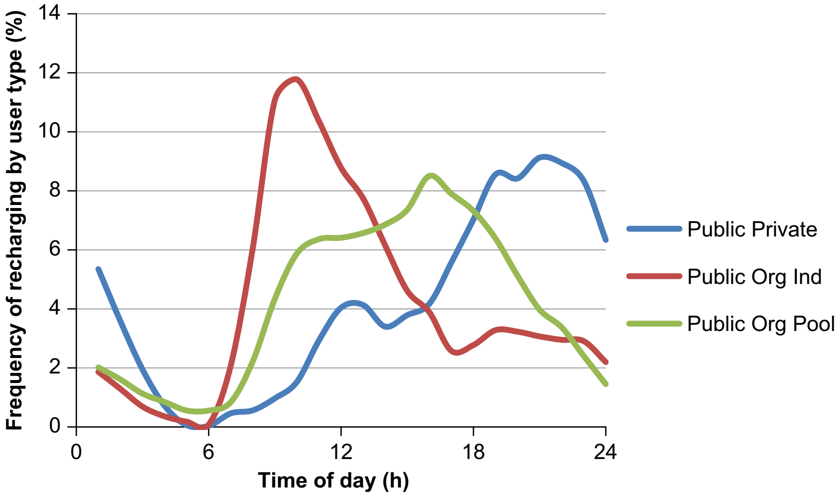

Fig. 8. Recharging profiles at public locations for private users ($n=225$ recharging events), organisation individual users ($n=808$) and organisation pool users ($n=1077$).

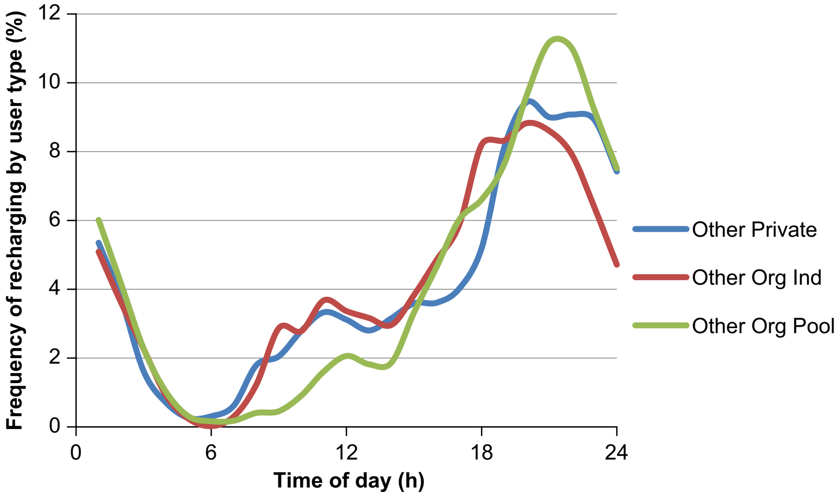

Fig. 9. Recharging profiles at other locations for private users ($n=149$ recharging events), organisation individual users ($n=182$) and organisation pool users ($n=375$).

kW h at work, 544 gCO_2/kW h at public locations and 531 gCO_2/kW h at other locations. In summer, the average carbon content was: 492 gCO_2/kW h at home, 515 gCO_2/kW h at work, 507 gCO_2/kW h at public locations and 489 gCO_2/kW h at other locations. Therefore the recharging profiles at home coincided more closely with the times of day when the carbon content of electricity was lower, relative to the work and public recharging posts.

5.7. Further discussion

The recharging demand profiles, for each of the user types studied, did not follow the strategy outlined by the Office for Low Emission Vehicles (2011), which predicted that the bulk of recharging would take place at home, overnight. All of the recharging profiles, regardless of user type and location, showed minimal recharging during the off-peak hours. This may require a policy rethink and possibly the use of interventions and incentives to manage peaks in recharging demand, where possible.

The recharging behaviour observed in this study could be explained by the fact that drivers were not subject to controlled recharging conditions. It had been predicted that uncontrolled charging behaviour would lead to higher energy demand during peak hours (Kang and Recker, 2009; Mullan et al., 2011; Wang et al., 2011). SwitchEV can be compared to other real world studies under different conditions to put these results into context and make recommendations regarding EV recharging infrastructure in future years.

There are some important differences in the outcomes of SwitchEV when compared to the CABLED study. One is that SwitchEV reveals more off-peak recharging at work and public recharging locations relative to home. There are differences in recharging infrastructure provision and access between CABLED and SwitchEV. CABLED drivers had access to 36 public recharging posts at 12 locations across Birmingham and Coventry, a ratio of one public post for every three vehicles on trial. Half of these were levied a standard parking rate for their usage. This compares to five public/work posts for every SwitchEV vehicle. SwitchEV drivers also had unlimited access to non-domestic recharging infrastructure through the CYC membership scheme (CABLED, 2012; Charge Your Car, 2012a).

The extra provision of recharging infrastructure for SwitchEV drivers is likely to have increased the amount of recharging during the on-peak periods. The membership scheme makes use of non-domestic recharging posts more attractive. Pay-as-you-go posts have a 28% usage rate compared to those that are available at no cost (Schey et al., 2012). In the case of the north east of England, the CYC membership scheme charges users a fixed annual rate for unlimited parking and electricity. Focus group discussions indicate that drivers use of the CYC parking and recharging is influenced by the fact that they view them as a ‘free’ resource. This was because there was no additional out of pocket cost at the point of use. Free parking at the point of use is perhaps a bigger incentive than free electricity. Some drivers reported that it was cheaper for them to pay the monthly lease cost for an EV and the subsequent CYC membership fee than it was for them to pay to park their current petrol/diesel vehicle.

As seen in the CABLED project, providing drivers with limited non-domestic recharging infrastructure, half of which sees standard parking rates applied, saw the bulk of EV recharging taking place at home. However, this does not mean that it should be recommended that a limited amount of non-domestic recharging infrastructure should be installed. Non-domestic infrastructure is considered important for the EV to develop a mass market appeal (Office for Low Emission Vehicles, 2011; Molmen, 2012). This presents the issue that although recharging infrastructure is considered a requirement for long term growth in the EV market, in future its use may need to be optimised through pricing policies if local power grids are pushed beyond capacity.

Smart meters have been suggested as a mechanism for switching recharging behaviour to off-peak hours (Kiviluoma and Meibom, 2011; Mullan et al., 2011; Wang et al., 2011). The evening peak in recharging demand at home is one that could be shifted into the off-peak hours via the use of smart meters and financial incentives. This has been demonstrated by Bruce et al. (2012) and Schey et al. (2012).

User types are also important. For private and organisation individual users, the high peaks in recharging demand at work on a morning should be managed. It is recognised that work recharging could be attractive to drivers, and if drivers feel that they need to recharge during the day at work, then this could be controlled using smart meters to delay some of this recharging to reduce the morning peak demand. Alternatively, unless drivers feel that this recharging is necessary for them to complete their daily trips, it could be completed at home. Then it could subsequently be delayed into the off-peak hours using smart meters and financial incentives. Not all of the organisation individual drivers had home infrastructure installed. This should be targeted as key to EV infrastructure development; otherwise some drivers may have little choice but to recharge on-peak at work or public locations.

In focus groups, organisation pool users indicated that their EVs must be recharged during the day for operational purposes. For example, the vehicle may need to make unplanned trips, requiring company policy to dictate that an EV must always be plugged-in to a recharging post when on-site. Furthermore, some local government departments have a rule that vehicles must be parked in an official depot overnight. Therefore, this rules out domestic recharging of these EVs, but not overnight recharging. There is still scope for some of this recharging to be switched to off-peak. Their

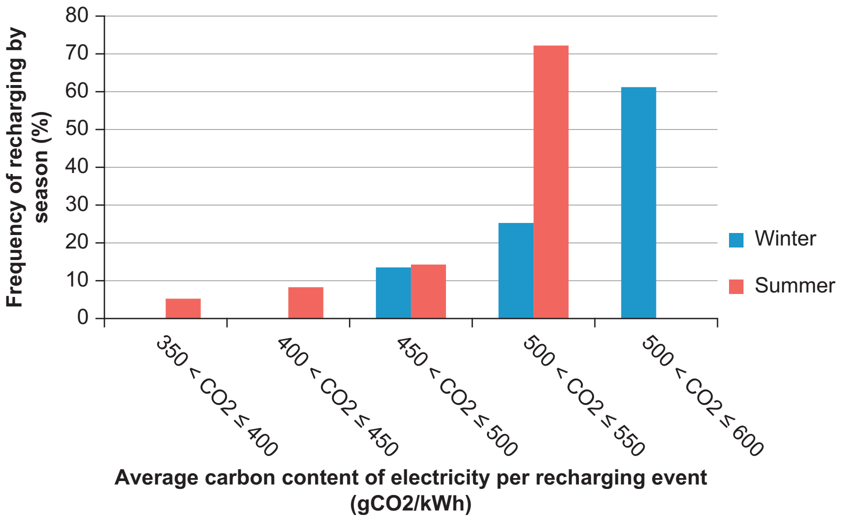

Fig. 10. Typical winter and summer day average carbon content of electricity during EV recharging ($n=7704$ recharging events).

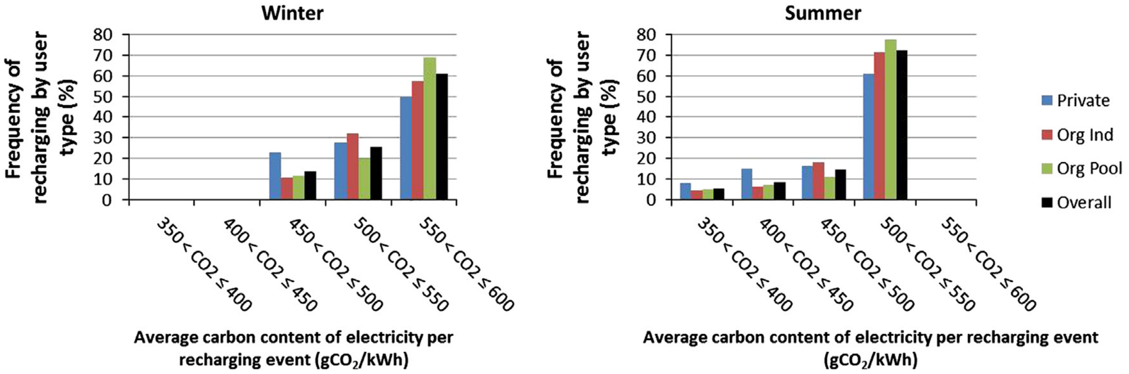

Fig. 11. Carbon content of electricity used to recharge EV for private users (n=1316 recharging events), organisation individual users (n=2620) and organisation pool users (n=3768) in winter (left) and summer (right).

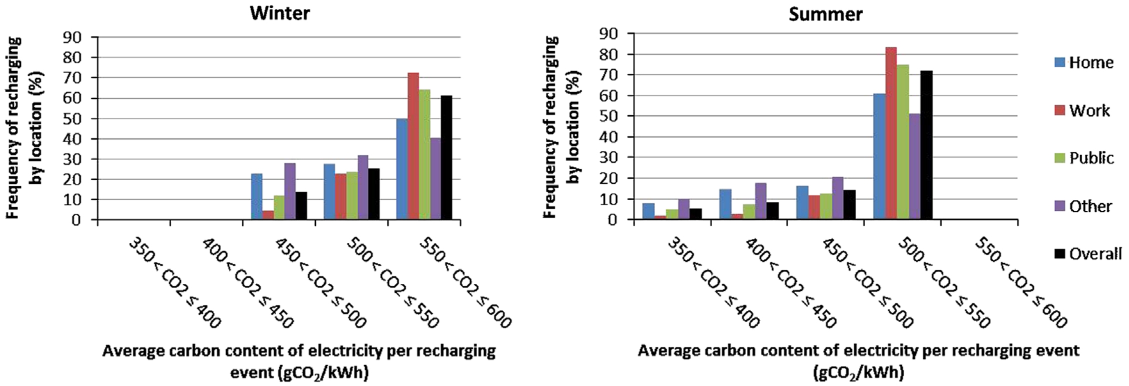

Fig. 12. Carbon content of electricity used to recharge EV at home (n=1610 recharging events), work (n=3278 recharging events), public (n=2110 recharging events) and other (n=706 recharging events) locations in winter (left) and summer (right).

evening peaks at work locations could theoretically be shifted using smart meters and financial incentives in the same way as home evening peaks are shifted. This evening peak occurs once daily trips are completed, so there should be no operational reasons for not delaying this recharging into the off-peak hours. Focus groups and interviews revealed that some pool users would be interested in using this technology. It is advised that recharging posts at workplaces utilise smart meters to allow the evening peak demand to be shifted to off-peak. However, it is acknowledged that it may not always be practical for all workplace recharging to be delayed. This is highlighted by the fact that the average recharging duration at work was 2.9 h, and it may be that the EV requires an on-peak recharge to complete the desired number of daily trips.

Current work involving the final two cohorts of SwitchEV drivers is exploring mechanisms to incentivise overnight recharging by offering to reimburse a percentage of electricity costs to those users recharging off-peak. This final phase will quantify the impacts of this scheme and make recommendations that can help maximise the effectiveness of smart recharging management.

To investigate alternative payment methods that may better help manage the demand for the public charging infrastructure, from July 2013 the CYC scheme will change from a subscription basis to a pay-as-you-charge flat rate. This rate will be set by the post host and is expected to be approximately £3.50 ($4.75) per recharging event (including parking). This will enable the impacts of the change in payment method on recharging behaviour to be studied and help the region to develop an economic assessment and long-term business case for the future fees to be levied for use of the current and future public charging infrastructure.

6. Conclusions

In total 23,805 h of recharging took place in the first year of SwitchEV during 7704 recharging events. A total of 7.2% of the time spent recharging took place between 00:00 h and 06:00 h, 34.1% between 06:00 h and 12:00 h, 37.7% between 12:00 h and 18:00 h, and 30.3% between 18:00 h and 00:00 h. This is not in line with government plans where the majority of drivers should recharge during off-peak periods. Consequently, the average carbon content of electricity during EV recharging was 505 gCO_2/kW h. However, when applying the typical winter day profile, the average carbon content of electricity during EV recharging was 543 gCO_2/kW h, 19 gCO_2/kW h below the maximum and 63 gCO_2/kW h above the minimum. In summer, this is 29 gCO_2/kW h below the maximum and 120 gCO_2/kW h above the minimum value. Therefore EVs in this study could have being recharged with electricity with an average carbon content that was 22% lower in summer and 11% lower in winter if the recharging was switched from on-peak to off-peak.

In terms of location, home and other recharging profiles were not significantly different, with a peak of 8.9% of total demand occurring between 19:00 h and 20:00 h. Recharging at these locations can therefore be shifted to off-peak using smart meters and/or financial incentives. Work had a peak of 11.0% of total demand occurring between 09:00 h and 10:00 h, whereas public recharging posts had a flatter profile, with a peak of 14.0% of total demand occurring between 09:00 h and 11:00 h. This highlights the need for smart solutions to optimise this recharging during the working day. Smart solutions could be used to balance some of the loads at the work morning peak throughout the working day, although not all. This is because some companies and local authorities require vehicles to be recharging at all times and the vehicles may be required to complete multiple trips in a working day. Smart management of fleet vehicle usage could be part of a future recharging demand management solution. The home evening peak in recharging occurred after the daily trips had been completed. This could be shifted into the off-peak hours using a combination of pricing incentives and smart meters.

Giving EV drivers access to a significant public recharging infrastructure with CYC membership access did not encourage the off-peak recharging plan outlined by Office for Low Emission Vehicles (2011). It is thought that this is due to the lack of smart meters and incentives to recharge off-peak, along with what is perceived as ‘free’ parking and electricity. SwitchEV saw more on-peak recharging compared to previous studies where there has either been limited public infrastructure or a pay-as-you-go payment mechanism for use of the parking space and recharging post.

In terms of policy recommendations, it is recognised that more public infrastructure is required to improve the market appeal of the EV. It is recommended that smart metering and/or financial incentives are installed at both home and work locations, where vehicles are often parked overnight. This would allow recharging demand peaks that currently occur between 17:00 h and 20:00 h to be shifted into the off-peak hours. Further work is required for the region to develop a long term, sustainable recharging infrastructure that both generates a business case yet manages recharging loads.

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