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Investigating the Potential to Influence the Electric Vehicle Users' Recharging Behaviour to Reduce Well to Wheel Carbon Emissions

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Abstract

The need to cut carbon emissions from cars and small vans is becoming an increasingly important issue. In the UK, it is anticipated that the electric vehicle (EV) will play a key role in meeting the 80% emissions reduction target in the Climate Change Act 2008. Although there are no emissions at their point of use, the equivalent emissions from an electric vehicle are dependent on the electricity used to recharge the EV's battery. This electricity is generated from coal (910gCO2/kWh), natural gas (400gCO2/kWh), nuclear (zero emissions) and renewables (zero emissions). The contribution of these power sources to the overall energy mix varies depending on the time of day; meaning that the average carbon content varies from an 'off peak' minimum of 366gCO2/kWh at 03:00am to an 'on peak' 466gCO2/kWh at 18:00pm. Therefore, depending on when an EV is recharged, the effective carbon content of the electricity stored in the battery varies. This study aims to quantify the carbon emissions and power demands of electric vehicles when in everyday use, by correlating the times of day when drivers recharge their cars with the carbon content of electricity at that time. Data was collected through the Switch EV trial in North East England, which see 44 electric vehicles employed in the region for three years. Analysis of the behaviour of these drivers over a six month period indicates that the average carbon content of the electricity transferred into an EV during recharging is 436gCO2/kWh. Changes in charging behaviour could lead to a 70gCO2/kWh reduction in emissions.

Keywords: electric vehicles, recharging, energy demand, carbon emissions, CO_2

1 Introduction

The Climate Change Act of 2008 set the UK the target of reducing carbon emissions by 80% by 2050, measured from a baseline of 1990 values (DECC, 2008). Cars and small vans are responsible for 13% of the total carbon emissions in the UK, highlighting the need for emission reductions from these transport modes. It is anticipated that the private vehicle sector will need to be at least partially electrified in order to meet these targets (King, 2008).

The well to wheel emissions (typically measured in gCO2/km) of an EV are determined by calculating the energy use of an EV (kWh/km) over a journey and multiplying this by the carbon produced by the generation of the electricity used to recharge the EV battery (gCO2/kWh). This refers only to the emissions from the energy used to power the vehicle during operational use, not the entire life cycle emissions of the vehicle. This carbon content is based on the mix of power sources that contribute towards the national grid energy mix. This carbon content has been shown to fluctuate, both over 24 hour periods and by time of year. The significance of this is that, depending on when an EV driver recharges their car, there will be a different carbon content of electricity. Also, if a large number of EV users plug in simultaneously, there could be large surges in power demand placed on local power grids. It is anticipated that in future 'Smart Grid' technology will help to control power demand (Kemp et al., 2010).

This study aims to quantify the carbon content of the electricity transferred into an EV battery, based on users' recharging behaviour (when, where and how much power they draw from the grid).

Furthermore, the theoretical maximum and minimum values of this carbon content, based on a continuous, average length recharging event taking place during the best case 'off peak' hours and the worst case 'on peak' hours for the national grid carbon content, will be calculated. These will be compared to the users results to quantify the emissions savings that could be achieved by users switching to 'off peak' recharging. This study forms the initial stages of research into this area, which in the long term will help to inform policy makers of the likely impacts of EV recharging behaviour on emissions and power demand.

This study analyses EV users' recharging behaviour from the Technology Strategy Board (TSB)-funded Switch EV trials in the North East of England . These trials comprise 44 electric vehicles (Avid cue-V, Liberty Electric Range Rover, Nissan Leaf, Peugeot iOn, Smith Edison) which are leased to a combination of private individuals and to businesses, where they are used as fleet vehicles. The data from this study is from the first six months of the Switch EV trials, where six vehicles were leased to private individuals and the rest were integrated into company fleets, with each company having between 1-6 drivers who used the EVs to commute to and from work (Blythe et al., 2011, SwitchEV, 2011). The TSB required the recharging locations to be put into one of three categories: home, work, or other. 'Home' refers to recharging events taking place at the known address of a Switch EV user. All individual drivers and some fleet drivers are covered by this category. Users with access to home based recharging were offered the chance to have a free 'pod point' for recharging the electric vehicle installed in their home. This point can be programmed to recharge the vehicle only at certain times of the day. 'Work' refers to a known recharging point at a place of work. All fleet vehicles in the trial had access to work based recharging. 'Other' covers any location not covered by 'home' or 'work'. This could be a public recharging point, or a vehicle being plugged into any other socket to recharge, including a fleet user recharging at home (home addresses were not known for all fleet users).

2 Methodology

2.1 Data collection

Vehicles used in this trial are Nissan LEAF, Peugeot iOn, Avid Cue-V, Liberty electric cars eRange, and the Smith Electric Vehicle Edison Minibus.

Attitudinal data were collected through pre- and post-driving questionnaires and focus groups. The soft data were collected using an online questionnaire before the delivery of their EV. The driver recruitment process and dissemination of questionnaires is undertaken by Future Transport Systems, the data analysis is largely carried out by Newcastle University. The analysis is based on more than 100 responses from two 6-month trial periods. The number of drivers exceeds the number of vehicles because some of the vehicles are used as pool and fleet vehicles and multiple drivers have access to those vehicles.

The hard data on the cars are derived from the CAN bus of the vehicle and transmitted to a secure database through the use of wirelessly enabled data loggers within the car. This is overlaid with GPS and time data derived from an additional logging unit in the vehicle. The Avid Cue-V vehicles were equipped by Avid Analyticals with a logger that connects to the CAN bus through the vehicles OBD port. The Peugeot iOn vehicles were equipped with loggers provided by RDM.

The loggers have been designed to take some external analogue and digital inputs. These inputs include the GPS and time-stamp data as well as a number of analogue inputs from current-clamps which are attached to various electrical systems of the vehicle to measure current flow and battery drain.

2.2 Power Supply in the UK

Electricity consumed in the United Kingdom (UK) is transferred from the sites where it is generated into the national grid, where it is then distributed transferred into local power grids, which then carry the power directly to the consumer. The total power generation capacity for in the UK in 2010 was 84GW, with and that the main sources of power generation beingare coal (28GW) and natural gas (27GW)., with A furthera maximum 9GW is available from nuclear powered sources, 5GW from renewables and 9GW from other sources (NationalGrid, 2011).

The sources of power generation used to meet demand fluctuate over a 24 hour period, as illustrated in Figure 1.

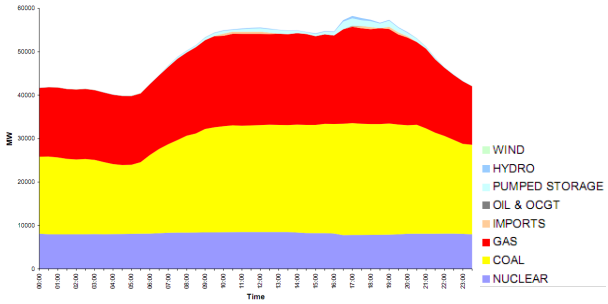

Figure 1: How demand for power is met in the UK

Figure 1 shows that the power provided by nuclear sources remained fixed at approximately 9GW. This value remained consistent throughout the 24 hour period. It can be seen that, during the period of lower demand during the night, coal was used more sparingly, with gas meeting a higher proportion of the total demand.

2.3 Quantifying the carbon content of electricity

To calculate the well to wheel carbon emissions from electric vehicles, previous studies have multiplied the energy used by an EV by a fixed conversion factor to determine the average carbon content of electricity (Arar, 2010, Carroll, 2010). This makes the assumption that, regardless of charging time, the carbon content of the electricity that is being stored in the vehicle and used to drive the vehicle, is constant.

There have been previous studies that have quantified the fluctuations in carbon content of electricity grids (McCarthy and Yang, 2010, Mullan et al., 2011). The approach taken is to calculate the proportion of the total power demand that is met by power source, and then multiply this proportion by the grams of carbon produced per kilowatt energy generated by the power source. This gives the average carbon content per kilowatt hour of power generated.

There are several assumptions that were made when calculating the carbon content of electricity drawn from the power grid at a specific location at any given time of day. Firstly, each kilowatt hour of electricity must be assumed to have the same carbon content. This is because individual units of energy cannot be tracked as they are transferred through a power grid, from their point of generation through to their point of use. Therefore, in this study it was assumed that the carbon content of the electricity that is drawn from the grid, regardless of the recharging point, has the overall grid average carbon intensity.

These proportions were then used to calculate the average carbon content of the electricity:

$C_{total} = T_{loss} \times [(P_{coal} \times C_{coal}) + (P_{gas} \times E_{Gas}) + (P_{nuc} \times C_{nuc}) + (P_{ren} \times C_{ren}) + (P_{other} \times C_{other})]$

Where:

C = carbon content of a given electricity source (gCO_2/kWh)

T_{loss}= Average transmission loss factor for the national grid (1.09)

P = Proportion of total energy generated by a given power source

Subscripts indicate the source of power generation:

coal = coal-fired

gas = natural gas

nuc = nuclear power

ren = renewable sources of energy

other = energy from other sources

total = cumulative value for all power sources

The proportions were calculated using the following formulae:

$E_{Total} = E_{coal} + E_{gas} + E_{nuc} + E_{ren} + E_{other}$

$P_{coal} = E_{coal} / E_{total}$

$P_{gas} = E_{gas} / E_{total}$

$P_{nuc} = E_{nuc} / E_{total}$

$P_{ren} = E_{ren} / E_{total}$

Where:

E = Energy generated by a given electricity source (kW)

Power source	gCO_2/kWh
Coal	910
Natural gas	400
Nuclear	0
Renewables	0

Table 1: Carbon content of energy generation in the UK by power source. The transmission loss factor to be applied to these figures is 1.09 .

Table 1 shows carbon emissions factors from the Department for Energy and Climate Change (DECC) for power generation in the UK.

It can be seen in Table 1 that the carbon content varies between the power sources, with a maximum of $870gCO_2/kWh$ for coal, and no carbon emissions from renewable energy and nuclear power.

Energy power generation source data was obtained through ELEXON, the company responsible for

the buying and selling of electricity in the UK through the New Electricity Trading Arrangements (NETA). These data give point values for the power generation from all power sources contributing to the national grid energy mix, on a half hourly basis, for the duration of the trial. Due to the lack of a UK carbon emissions factor (See Table 1) for all power sources, any electricity that was not generated from coal, natural gas, nuclear or renewable was classified as 'Other '.

3 Results and Discussion

The fluctuations in the carbon content of electricity over an average 24 hour period are shown in Figure 2.

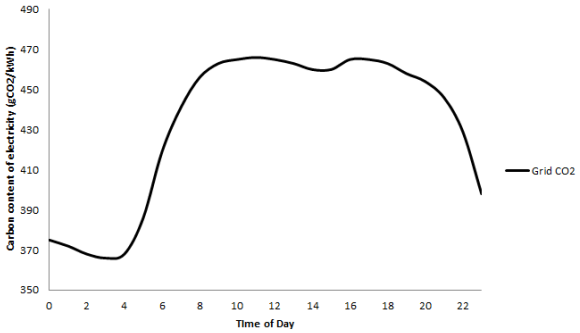

Figure 2: average carbon content of electricity over a 24 hour period

It can be seen in Figure 2 that the carbon content is highest between 08:00am and 18:00pm, with average value of 465gCO2/kWh over this period. This then drops off to lower carbon content between 00:00 and 05:00 with a minimum of 364gCO2/kWh at 4:00am.

This backs up previous studies, suggesting that the carbon content of electricity is lowest on a night time (00:00am – 06:00am), and that this would therefore be the most 'sustainable' time for EV users to recharge.

An overall summary of the six months of data can be seen in Table 2.

Location	Total energy (kWh)	% Energy	Average gCO2/kWh
Overall	12,437	100	436
Home	3,212	26	420
Work	5,143	41	445
Other	4,083	33	430

Location	Average duration	Average energy
	(h)	(kWh)
Overall	1.8	3.4
Home	2.2	5.1
Work	1.6	2.7
Other	1.7	3.4

Table 2: Summary table for Switch EV recharging behaviour over the previous 6 months

Table 2 shows that work based recharging was the most frequently used, with 5143kWh of electricity transferred at work, followed by 4083kWh of energy transferred at other locations, and finally 3212kWh transferred at home. Given that in this first cohort 37 out of the 43 vehicles were integrated into various organisations' fleets with access to company recharging points, and of these 29 vehicles did not have access to home based recharging, it was expected that the majority of the recharging would take place at 'work' and 'other' locations.

The average recharging time was 1.8 hours, with home recharging being the longest, averaging 2.2 hours, followed by other locations at 1.7 hours and work at 1.6 hours. Using the overall average recharging time, the minimum and maximum theoretical values for average carbon content were calculated as 366gCO2/kWh and 465gCO2/kWh respectively.

It can be seen that, overall, home based recharging was the most carbon efficient with an average carbon content of 420gCO2/kWh, and the least carbon efficient recharging location was at work with an average carbon content of 445gCO2/kWh.

Overall, the average carbon content of energy transferred throughout the first cohort of the trial is 70gCO2/kWh above the theoretical minimum value and 29gCO2/kWh below the theoretical maximum value. This suggests that, overall, the EV users did not recharge at times of the day where the carbon content of electricity is low. Throughout the trial, approximately 870kgCO2 could have been saved by drivers changing their recharging habits, which is a reduction of 16%. The overall energy transferred throughout the day, along with the carbon content at that time of day, can be seen in Figure 3.

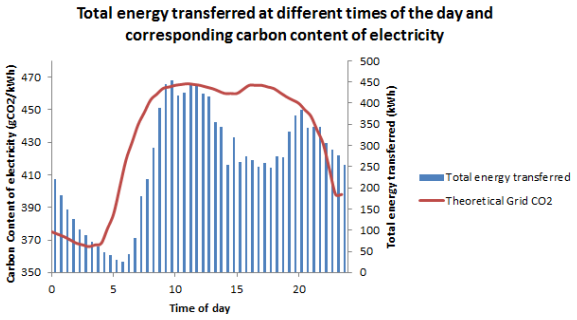

Figure 3: Total energy transferred from grid to recharge EVs and the average carbon content over a 24 hour period

As illustrated in Figure 3, 66% of the recharging activity took place during the 8:00am – 18:00pm time period, and this coincides with the times of day when the carbon content of electricity is at its highest. The time period 00:00am – 06:00am, when the electricity has its lowest carbon content, accounted for 7% of the total recharging activity. This is despite the fact that this accounts for 25% of the day.

In terms of location, the average percentage of the total energy transferred by time of day for each of the recharging locations (i.e. the total percentage for each location is 100%) is shown in Figure 4.

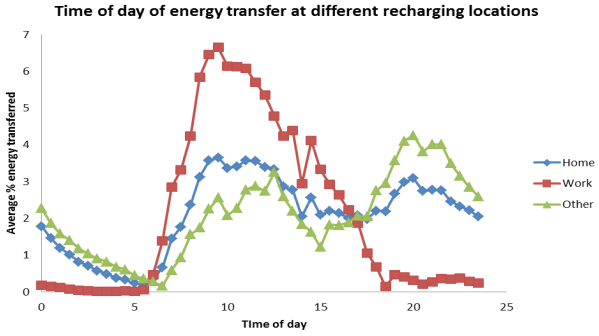

Figure 4: Total energy transferred at different times of day by recharging location

As shown in Figure 4, an average of 0.2% of the work recharging took place between 18:00pm and 6:00am. The percentage of work based recharging increases from 06:00am, rising to a maximum of 7% at 09:30am.The 'home' and other recharging locations show less variation throughout the day. Both follow a similar shape, with an increase from less than 1% of the total recharging at 06:00am to a maximum of 3.8% for home and 3.2% for other recharging locations. These profiles then decrease to 2.1% recharging at 17:00 and then rise to an evening peak of 4.6% for other and 3.1% for home. Both the work and other events then decrease between 0:00am and 6:00am, when the carbon content of electricity is at its lowest .

Figure 4 explains why work based recharging was the least carbon efficient of the three locations overall, with a lower % of recharging taking place during the 00:00am – 6:00am 'off peak' time period than either home or other recharging locations.

With regard to other recharging locations, if a driver did not have access to an EV recharging point at home, they were advised not to plug their vehicles directly into a socket for safety reasons. However, given the similarity between the home and other recharging profiles between 18:00pm and 06:00am, it could be speculated that some of the other recharging events taking place between these hours were fleet users recharging at home using a standard three-point plug or at public recharging points near their homes. This is backed up by previous studies which suggest that over 70% of vehicles arrive back at home by 19:00pm on a working day (Weiller, 2011).

Overall, this analysis suggests that the behaviour observed by drivers in this Switch EV cohort lead to the well to wheel carbon emissions from the EVs being closer to the maximum than minimum values. In particular, the lack of recharging in the 00:00am - 06:00am period, even amongst users with specific EV recharging infrastructure installed at home, is increasing the well to wheel emissions of EVs. This could be due to the fact that 37 of the 43 vehicles in this trial were leased to organisations rather than individual users, and that of these users there was no specific EV recharging infrastructure installed in the home. This could also be down to a lack of driver education on the subject, with drivers being unaware of the implications of their recharging behaviour. However, the average energy use of an EV is approximately 0.2kWh/km, and the average vehicle in the UK emits 173gCO2/km (Blythe et al., 2010). In comparison, the EV well to wheel emissions from these trials were an average of 87gCO2/km, with potential for this figure to be reduced further if driver recharging behaviour shifts toward night time recharging.

4 Conclusion

The vehicles in these trials were not recharged at the most sustainable times of day, and subsequently the average carbon content of 436gCO2/kWh of electricity transferred to the

vehicles was closer to the maximum theoretical value of 465gCO2/kWh than the minimum value of 366gCO2/kWh.

Most of these vehicles were based in company fleets, and more energy was transferred during work based recharging than at any other location. Recharging at work also took place predominantly during office hours (07:00am – 18:00pm). Therefore the reason the average carbon content of electricity transferred is close to the maximum value is that fleet vehicles are generally recharged at work during office hours. The shorter average recharging times could be due to the operational requirements of the vehicle i.e. the fleet managers like the vehicle to have as much charge as possible in the battery at any given time.

The frequencies of the home and other recharging events suggest that drivers plug their vehicles in once they arrive at home at the end of a working day and allow the vehicle to recharge itself. The vehicles will automatically cut-off the power supply once their batteries are fully recharged. Less than 2% of the energy transferred during home based recharging events took place during the off peak hours between 00:00am and 06:00am. Drivers could improve the carbon content of the electricity that they use to power their cars by programming their home pod points to begin recharging at 00:00am. It is not known at present whether these points are being programmed to recharge at certain times or not.

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Andrew Robinson is a PhD researcher studying electric vehicle recharging behaviour and subsequent carbon emissions. Andrew is analysing the recharging patterns of electric vehicle drivers involved in the Switch EV trials using data from on-board vehicle loggers, and interviewing drivers on their recharging habits.