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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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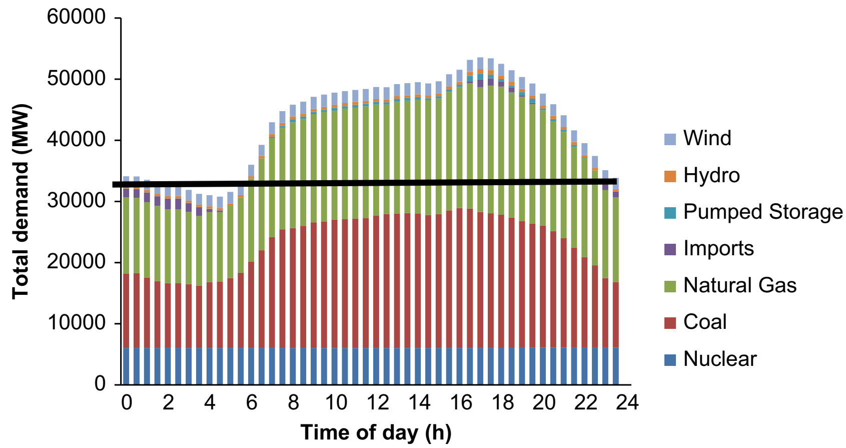

Fig. 1. Power demand in the UK on a typical winter day (National Grid Electricity Transmission, 2011).

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