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A probabilistic approach to combining smart meter and electric vehicle charging data to investigate distribution network impacts ☆

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HIGHLIGHTS

- Working with unique datasets of EV charging and smart meter load demand.
- Distribution networks are not a homogenous group with more capabilities to accommodate EVs than previously suggested.
- Spatial and temporal diversity of EV charging demand alleviate the impacts on networks.
- An extensive recharging infrastructure could enable connection of additional EVs on constrained distribution networks.
- Electric utilities could increase the network capability to accommodate EVs by investing in recharging infrastructure.

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ABSTRACT

This work uses a probabilistic method to combine two unique datasets of real world electric vehicle charging profiles and residential smart meter load demand. The data was used to study the impact of the uptake of Electric Vehicles (EVs) on electricity distribution networks. Two real networks representing an urban and rural area, and a generic network representative of a heavily loaded UK distribution network were used. The findings show that distribution networks are not a homogeneous group with a variation of capabilities to accommodate EVs and there is a greater capability than previous studies have suggested. Consideration of the spatial and temporal diversity of EV charging demand has been demonstrated to reduce the estimated impacts on the distribution networks. It is suggested that distribution network operators could collaborate with new market players, such as charging infrastructure operators, to support the roll out of an extensive charging infrastructure in a way that makes the network more robust; create more opportunities for demand side management; and reduce planning uncertainties associated with the stochastic nature of EV charging demand.

1. Introduction

The UK government passed the Climate Change Act which established a legally binding target of cutting the UK's greenhouse gas emissions by at least 80% compared to 1990 levels by 2050 [1]. In order to make the transition to a low carbon economy, the government published the Carbon Plan in 2011 which sets outs a strategy to achieve the decarbonisation target across sectors. A quarter of the UK emissions come from the domestic transport sector which needs to substantially reduce its emissions by 2050. The Carbon Plan emphasizes the need for a move towards a mass market roll-out of ultra-low emission vehicles such as Electric Vehicles (EVs) to achieve the deep cuts required [2]. It would then be important to investigate the potential impact of a significant take up of EVs on the electricity system in the UK; in particular, this work will focus on the impact on electricity distribution networks of residential uncontrolled and clustered charging of EVs.

Several studies have already looked at the impacts of the uncoordinated charging of EVs on distribution networks. The potential impacts on Low Voltage (LV) distribution networks include voltage variations, transformer and thermal limit violations. However, these studies based their work on estimated rather than actual EV charging behaviour and smart meter data. Most of the charging data used in these previous studies was derived from driving patterns collected in national transportation surveys in order to

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estimate certain aspects of EV usage; such as journey distance and energy used, parking location and time, State-of-Charge (SoC) at the beginning of a charging event and the plug-in time. Some of these studies assumed that the charging starts immediately upon the users' home arrival while others assumed that a large proportion of charging starts from a low SoC. Furthermore, some of the studies considered that users would only charge at home and did not consider the availability of a public charging infrastructure [3–17].

Using the derived charging profiles, the studies demonstrated that the impacts of uncontrolled EV charging in residential areas were detrimental to the operation of distribution networks. Some studies demonstrated thermal limit violations and voltage drops below acceptable limits for EV penetration of 50% [11–13]. One study stated that with 50% EV penetration, there would be significant impacts on the operating conditions of the distribution networks and uncontrolled charging could require major infrastructure upgrades [14]. Another study [15] showed that a 25% penetration of EVs in residential areas would cause considerable voltage dropping below the statutory limit while [16] stated that the distribution network can handle only up to 10% EV penetration without changes in the usual electricity grid operation and planning procedures. One of the studies that focused on British distribution networks found that a 12.5% uptake would cause severe impacts on the transformer and the LV underground cable supplying the households [17]. In this study a probabilistic approach was used to address uncertainties associated with residential loads and EV user behaviour such as plug-in time and SoC. The authors noted that real-world data of EV usage comprising more accurate charge durations, connection times and a reflection on the use of the additional recharging infrastructure (i.e. work, public) could be the focus of further work on the subject and could help improve the probabilistic methods used.

The significance of the present work is that it is based on a unique combination of two comprehensive high resolution spatio-temporal real-world data sets of EV driving and charging patterns and residential smart meter data. The use of real-world data avoids the need to make assumptions about the stochastic nature of vehicle use and would minimise uncertainties associated with simulated charging demand. Based on real-world datasets, this paper demonstrates that distribution networks could accommodate higher EV penetrations than previous studies have suggested.

The EV data is collected from the SwitchEV project which trialled 44 EVs in the North East of England between 2010 and 2013. The cars were fitted with data loggers that captured more than 85,000 EV journeys recorded second by second and over 19,000 recharging events recorded minute by minute at more than 650 public and 260 private charging points [18,19]. The smart meter data was collected via the Customer Led Network Revolution (CLNR) project. This is the UK's largest trial of smart grids and it provided domestic load profiles of half-hourly power consumption data collected from nearly 9000 smart meters. In addition, the CLNR smart meter data set [20] is parameterised by socio-economic variables which allow the selection of representative load profiles appropriate to the network customer population under study. The four-year CLNR project also provided network data and extensively validated network models based on existing local distribution networks operated by the regional distribution network operator (DNO), Northern Powergrid.

This work is an elaboration on [21], extended to include the impacts on a generic distribution network to provide broad value and replicability for the whole of the UK. This is in addition to the urban and rural case study networks. A more comprehensive distribution network impact analysis has been undertaken using IPSA2 (steady-state, balanced three phase network) and PSCAD (Electromagnetic transient analysis for voltage unbalance analysis); and a more extensive results and discussion sections. Section 2 describes the EVs' data, the smart meter data and network models used for this study (including network validation). Section 3 describes our modelling framework to study the impact on the distribution network. The results of the study are presented in Section 4; the discussion and conclusions of this work are presented in Section 5.

2. Data

2.1. Electric vehicles trial – SwitchEV project

High resolution spatial and temporal data of EV driving and charging events were collected, processed and analysed during the SwitchEV project. The dataset gave insight and illustrated the stochastic nature of real world behaviour of EV users. The project recruited different types of users- private and fleet drivers. They had access to an extensive charging infrastructure (home, work, public). The majority of vehicles used in the trial are production vehicles available on the market and were provided by Nissan (LEAF) and Peugeot (iOn). A total of 125 different users were recruited for the duration of the project [19]. As a result, the data collected from the SwitchEV trial captured how people would use an electric car in a real-world context.

2.1.1. The electric vehicle is the primary vehicle

Participants on the trial leased the cars for 6 months which allowed them to get familiar with the vehicle. Shortly after the beginning of their 6-month trial, the participants reported that they had trusted the EV to be their primary car. To verify that the EVs were used in an equivalent fashion to primary vehicles, the authors compared the daily mileage of the Switch EV vehicles collected from the data loggers (Fig. 1) and the National Travel Survey (NTS) mileage data in Great Britain (GB) for conventional cars. The Department for Transport NTS data provides information on personal travel on all mode of transport in GB [22]. Daily average distance travelled was not available; however, according to the NTS the average distance travelled per person per year by car/van drivers is 5207 km. It was assumed that drivers could be using their cars 5 times a week and as such it was estimated that the average distance travelled per person per day by car drivers is 20 km. The average daily mileage of the EV drivers on the trial is 38.9 km, almost the double of the national average, suggesting that the electric vehicles on trial were used as the primary vehicle, as reported by the drivers. Fig. 2 shows the responses collected from the post-trial questionnaires regarding the reasons for driving the electric vehicle.

2.1.2. Real and diverse EV usage profiles (charging and driving)

This work focuses on the charging profile of users. The variables recorded during the recharging events include the time, battery current and voltage along with its State of Charge (SoC). These variables are then used to determine secondary variables such as the duration of a charge event and the energy transferred. However, the driving profile (driving behaviour and driving conditions) is also important because it would determine the SoC of the EV battery before it is plugged in for recharging. The driving profile is briefly described in the two following paragraphs.

The SwitchEV trial recorded trips of varying length ranging from less than 1 km to over 100 km; it also recorded the number of trips between two consecutive charging events. Previous work using the SwitchEV data has demonstrated that driving behaviour of users (i.e. speed) and driving conditions such as the topography of the road network and the network conditions (i.e. free flow, congested)

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