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Electric vehicle charging choices: Modelling and implications for smart charging services

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ABSTRACT

The rollout of electric vehicles (EV) occurring in parallel with the decarbonisation of the power sector can bring uncontested environmental benefits, in terms of CO_2 emission reduction and air quality. This roll out, however, poses challenges to power systems, as additional power demand is injected in context of increasingly volatile supply from renewable energy sources. Smart EV charging services can provide a solution to such challenges. The development of effective smart charging services requires evaluating pre-emptively EV drivers' response. The current practice in the appraisal of smart charging strategies largely relies on simplistic or theoretical representation of drivers' charging and travel behaviour. We propose a random utility model for joint EV drivers' activity-travel scheduling and charging choices. Our model easily integrates in activity-based demand modelling systems for the analyses of integrated transport and energy systems. However, unlike previous charging behaviour models used in integrated transport and energy system analyses, our model empirically captures the behavioural nuances of tactical charging choices in smart grid context, using empirically estimated charging preferences. We present model estimation results that provide insights into the value placed by individuals on the main attributes of the charging choice and draw implications charging service providers.

1. Introduction

1.1. Context

In a context of a progressively decarbonised power sector, electric vehicles (EV) can bring significant reductions in CO_2 emissions from road traffic (IEA, 2009). Moreover, EVs' roll out improves air quality in urban areas.

However, EVs bring both challenges and opportunities for power systems. Amongst the challenges that large EV penetration may bring there is the potential increase of peak power demand if charging operations occur in coincidence of current demand peaks. Amongst the opportunities there is the possibility to use EV as flexible loads that can provide balancing services to grids with large shares of intermittent or fluctuating renewable energy generation (Kempton and Letendre, 1997; Kempton and Tomić, 2005). In order to fully exploit the potential of EVs as a flexible load smart charging strategies need to be implemented.

Smart charging can occur in a centralised way via aggregators or through decentralised control architectures (Galus et al., 2012). In the centralised framework EV owners do not have transactions in electricity markets, because of the low power of a

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single transaction (Bessa and Matos, 2012). In this centralised framework EV load aggregators act as an intermediary between vehicle owners and grid markets and contract power demand from several EVs. In the decentralised framework, individual EVs respond to market information made available to them. Typically, a static or dynamic price signal is used to incentivise a particular charging behaviour (Galus et al., 2012). An example of a static price signal is time-of-use tariffs that would incentivise charging overnight, similar to current time-of-use domestic tariffs for electricity.

The typical aggregator based approach to charging demand management implies direct control. This means that control actions are imposed on electric vehicles without the involvement of the electric vehicle owners (Galus et al., 2012). Such actions must, however, respect the constraints imposed by owners' travel needs. Thus the aggregator must collect charging requirements from each member vehicle. Sundstrom and Binding (2011) formalise the requirements that EV users communicate to the aggregator in terms of an energy requirement and a timing requirement. The energy requirement specifies the battery level required by the end of the charging operation while the timing requirement specifies the time by which the charging operation must be completed.

Under this scheme, users directly affect the flexibility of the controls that can be imposed on the charging operation through their charging preferences. Therefore it is in the interest of the operator to incentivise charging preferences that allow for more flexible operation. Contracts regulating the service provision could include the option for users to override the control imposed by the aggregator.

However, even in a decentralised framework, a central entity might provide these pricing signals to owners of electric vehicles (Galus et al., 2012). From this perspective, the centralised and the decentralised frameworks overlap.

1.2. Contributions

Despite the importance of users' behaviour in the context described, current smart charging strategies largely rely on simplistic or theoretical representation of EV charging and travel behaviour. The main contribution of this paper is a charging behaviour model that bridges the gap between the representations of charging behaviour used in integrated transport and energy system analyses for the appraisal of smart charging strategies, and the representations used in charging behaviour studies.

In integrated transport and energy system analyses, charging behaviour is represented either through charging behaviour scenarios (Koyanagi and Uriu, 1997; Kang and Recker, 2009; Axsen and Kurani, 2010; Mullan et al., 2011; Weiller, 2011; Dong et al., 2014) or theoretical models (Waraich et al., 2009). The former are not policy sensitive and thus are not suitable for assessing the response of EV drivers' to smart charging services. The latter are policy sensitive, but they are not estimated empirically. The absence of strong empirical foundations may lead to weak behavioural realism of the responses to smart charging services.

Empirical evidence from charging behaviour literature shows that charging behaviour is heterogeneous amongst drivers (Franke and Krems, 2013; Zoepf et al., 2013). Such heterogeneity is related to differences in driving patterns, individual attitudes towards risk in dealing with limited range vehicles, and idiosyncratic preferences (Franke and Krems, 2013; Zoepf et al., 2013). However, the charging behaviour literature does not provide operational models of charging behaviour that can be used to analyse driver's response to smart charging services, because the response of drivers to pricing of charging services in smart grid contexts has yet to be addressed.

In the present work we develop a random utility model for charging behaviour that is empirically estimated using discrete choice analysis. Because we model jointly activity-travel scheduling choices and charging choices under the activity-based demand modelling paradigm, our charging behaviour model is well suited to be implemented as a module in integrated transport and energy model systems. However, unlike previous charging behaviour models applied in such model systems, ours captures the behavioural nuances of tactical charging choices in smart grid context. It can do so because the trade-offs involved in tactical charging choices in smart charging contexts are captured empirically by model estimation using discrete charging choice experiment data. Our discrete choice experiment were specifically designed to elicit drivers' charging preferences in smart charging contexts

In addition, another significant contribution is the introduction of the concept of *effective charging time* (ECT) as a dimension of charging choice. The definition of ECT (see next section) makes it possible to use the same representation of charging choice independent from the charging service under analysis.

1.3. Literature review

1.3.1. Approaches for the appraisal of smart charging strategies

As, Daina et al. (2017) point out in a recent review, by and large the current practice for the appraisal of smart charging strategies assumes predefined charging scenarios and exogenous EV use patterns (Koyanagi and Uriu, 1997; Kang and Recker, 2009; Axsen and Kurani, 2010; Mullan et al., 2011; Weiller, 2011; Dong et al., 2014).

The use of predefined charging scenarios prevents analyses that are sensitive to electricity pricing, because the charging behaviour is set using rules. It also limits the representation of users' behaviour heterogeneity. The reliance on exogenous travel patterns implies that travel patterns are independent from the charging decisions. However, if individuals are flexible in their travel choices, ruling out an interdependence between travel and charging choices may lead to biased estimates of EV