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Potential power system and fuel consumption impacts of plug in hybrid vehicle charging using Australian National Electricity Market load profiles and transportation survey data

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ABSTRACT

Future electric vehicle (EV) deployment raises the potential for opportunities and challenges for policy makers in both the electricity and transportation sectors. This paper describes the development of a simple, time based simulation tool for assessing plug-in hybrid EV charging load and gasoline consumption under a range of standard charging infrastructure and charge control scenarios. This tool is intended for use by power system planners and other policy makers in evaluating a range of possible load outcomes arising from EV integration. Australian vehicle trip data from the New South Wales Household Transport Survey is used with the introduced model to assess the impact of EV charging load on the 2011 Australian National Electricity Market load profile. Results are presented which address a gap in existing literature with respect to EV load profiles in the Australian context with findings which include (1) that the provision of non-residential (public) charging infrastructure is beneficial for both vehicle owners and power system load profiles, (2) that fast charging in the residential context represents a significant risk to the power system if not accompanied by charging control, (3) that inappropriate Time-of-Use electricity tariffs may lead to poor outcomes at high penetration levels, and (4) that there are trade-offs between benefits for the power system and the amount of gasoline consumed by the vehicle fleet when charging is restricted to occur overnight. Given the current focus on Time-of-Use electricity tariffs as the primary mechanism for influencing EVs recharging, the finding that inappropriate Time-of-Use electricity tariffs lead to poor outcomes at high penetration levels is significant for long term EV integration planning.

1. Introduction

The potential electrification of private vehicular transport presents an important and interesting challenge at a policy level. In particular, this challenge involves the coupling of two large, historically separate, macro systems (the transportation and power system) through private electric vehicles (EVs). Due to their historically separate evolution, the transport and power systems each have their own participants, business models, supply chains, regulatory and legal structures, geographical scopes, and technical characteristics [1]. The formulation of policy from the perspective of the electricity industry must therefore cross traditional boundaries to consider transportation behaviour when assessing the power system impacts of EV integration.

From the perspective of the electricity industry, EVs have the potential to be a source of value in improving the efficiency of power system operation and investment, improving electric grid performance, and enhancing the penetration of renewable energy sources [2]. These benefits however are offset by the potential for increased costs from power system level impacts in generation and transmission, as well as distribution system level impacts such as thermal limit violations, increased losses, harmonics, and transformer ageing impacts [3]. The most significant single risk factor for the power system from EV integration however is associated with a potentially high correlation between EV charging load and existing system load [4]. Such an outcome may cause deterioration in the efficiency of power system operation and investment resulting in higher costs being borne by society in respect of its electricity supply.

Temporal EV charging characteristics, and by extension the correlation between EV charging demand and existing power system load, are a function of transport vehicle behaviour (where and

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when drivers use their vehicles), the availability of recharging opportunities (where and when drivers have access to recharging infrastructure), and any restrictions on recharging imposed by the electricity industry. While there have been a significant number of studies which have investigated the potential impact of EVs on the power system, many of these have used high level assumptions with respect to vehicle charging and not captured the full diversity of vehicle use and charging behaviour in their analysis [5–7]. Of those studies which have utilised vehicle level transport data, the most common sources of information have been household travel surveys and logged GPS travel profiles. Weiller [7] and Kelly, et al. [9] both used data from the US National Household Travel Survey (US NHTS) to simulate EV charging and produce aggregated fleet level EV charging profiles. Refs. [4,8,9] utilised GPS data from Seattle, Washington and St. Louis, Missouri to respectively assess EV charging load, EV uptake potential, and electricity sector costs and air emissions.

While numerous studies have been undertaken in the US and European contexts, outcomes are specific to the electricity and transport system under investigation. Therefore, Australian specific data is required for studies aiming to inform the Australian policy making process. Paevere et al. [10] investigated variations in spatial EV charging load in the Australian state of Victoria finding an increase of up to 15% in residential household peak electricity demand due to EV charging. Wagner and Reedman [11] modelled EV uptake and associated impacts on spot prices in the Australian National Electricity Market finding the potential for a considerable number of hours with un-served energy by 2030 in the absence of generation capacity expansion. AECOM [12] in a study for the Australian Energy Markets Commission found the potential for significant additional network investment requirements when EV charging is un-managed. These studies however, did not consider gasoline consumption impacts and, with the exception of Ref. [10], did not utilise vehicle level transportation data in establishing EV charging load patterns. This paper seeks to address this gap by introducing a simple simulation tool to establish EV charging load and fuel consumption from vehicle level transport data. This simple simulation tool is then applied to understanding the impact of EV charging on the load profile of the Australian National Electricity Market.

Given the jurisdictionally specific nature of power system load profiles and vehicle transport behaviour, Australian power system planners and policy makers require modelling specific to the Australian context. As such, a key contribution of this paper is to present a simple method of simulating temporal EV charging characteristics which is then used to produce results which inform Australian planning and policy processes.

This paper is structured with: Section 2 introducing the modelling methodology; Section 3 introducing a case study of EV charging in the context of the Australian National Electricity Market; Section 4 presenting and discussing the results obtained with respect to the case study; with Section 5 then concluding and discussing future work.

2. Modelling methodology

2.1. EV vehicle modelling parameters

The modelling tool implements a plug in hybrid EV model with a series drivetrain and a petrol internal combustion engine for range extension (All future use of 'EV' will refer to a plug in hybrid EV types). Such a vehicle is modelled using binary Charge Depletion/Charge Sustaining modes of operation in a manner similar to [13–15]. Key vehicle energy consumption parameters include the average current draw from the battery when operating in Charge Depletion mode and the fuel consumption rate when operating in Charge Sustaining mode. The Charge Depletion current draw parameter was established using the ADVISOR vehicle drivetrain simulation software released by the National Renewable Energy Laboratory and described in Markel and Wipke [16]. ADVISOR was configured around a vehicle approximating a General Motors Volt and then simulated over the US EPA Urban Dynamometer Driving Schedule (UDDS) which is designed to be broadly representative of the velocity, acceleration, and breaking seen in urban driving conditions [17]. The average Charge Depletion mode current draw was established from simulated results (average 16.23 A at the nominal battery voltage of 335 V) which translates to a distance based energy consumption rate of 0.17 kWh/km (0.27 kWh/mi) at the average velocity of the UDDS drive cycle (31.51 km/h).

Charge Sustaining mode fuel consumption is taken to be 15.7 km/L which corresponds to the premium gasoline fuel efficiency reported by the US DOE for the Volt [18] and translates to an average fuel consumption rate of 0.033 L/min at the average UDDS drive cycle velocity. These parameters were then applied within the simulation tool presented in Section 2.2 to establish battery SOC and fuel consumption for each vehicle over the simulation time period.

2.2. Modelling Tool

The simulation model tool was implemented using Matlab's Simulink and Stateflow packages with vehicle battery state of charge (SOC) tracked utilising Simulink's internal Li-ion battery model (implemented as a nominal 45 Ah battery at a nominal voltage of 335 V). Battery SOC thresholds of $T_{\text{high}} = 95\%$, $T_{\text{low}} = 30\%$ were applied to provide an effective battery capacity of 65% which is consistent with the Li ion battery control strategy applied in the Volt [19].

Fig. 1 shows a schematic of the developed model tool. Model inputs are on the left had side and are specified in Table 1. Each input is constructed prior to simulation for each vehicle (n) in the N vehicles making up the simulated fleet.

Simulation model outputs are specified in Table 2 and consist of the vehicle SOC, charging power, and fuel consumption for each simulated vehicle during each simulation time step.

A state based control scheme was implemented to establish charging and fuel consumption timing as a function of driving

Table 1
Simulation model input parameter specifications.

$\text{PARK}_{n,t}$	Represents an integer value of 1 or 0 depending on whether the vehicle is parked or driving during time step t;
$\text{INF}_{n,t}$	Represents an integer value which encodes the charging infrastructure available to the vehicle at time step t. $\text{INF}_{n,t}$ can take a value between 0 and 3 depending on whether it can support un-managed, controlled, or V2G charging, respectively;
$\text{CONTROL}_{n,t}$	Represents an integer value of 1 or 0 depending on whether the specified charging control approach allows the simulated vehicle to charge at a particular time/location during simulation time step t; and
$\text{CFG CURRENT}_{n,t}$	$= [V_{\text{supply}}/V_{\text{battery}}] * I_{\text{Charge}} * \eta_c * \Delta t$ Represents the amount of charge received by the battery during one simulation time step (Coulombs/simulation time step). Δt represents the simulation time step used (60 s); V_{battery} represents the vehicle battery bus voltage (335 V); I_{Charge} corresponds to the charging capacity available from the charging infrastructure (Amps); V_{supply} represents the power supply voltage corresponding to the Australian standard singly phase supply (230 V); η_c represents the charging efficiency which is taken to be 88% [6,15].