Energy 94 (2016) 715–727

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Estimating the grid payments necessary to compensate additional costs to prospective electric vehicle owners who provide vehicle-to-grid ancillary services

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ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form
8 November 2015
Accepted 13 November 2015
Available online 18 December 2015

Keywords:
Electric vehicles
Lithium batteries
Vehicle-to-grid
Ancillary services
Battery degradation

ABSTRACT

The provision of ancillary services in the smart grid by electric vehicles is attractive to grid operators. Vehicles must be aggregated to meet the minimum power requirements of providing ancillary services to the grid. Likely aggregator revenues are insufficient to cover the additional battery degradation costs which would be borne by an existing electric vehicle owner. Moreover, aggregator revenues are insufficient to make electric vehicles competitive with conventional vehicles and encourage uptake by prospective consumers. Net annual costs and hourly compensation payments to electric vehicle owners were most sensitive to battery cost. The fleet provided firm fast reserve from 1900 h for 0.42 h, up to 2.7 h in the best cases. At best, likely aggregator revenue was 20 times less than the compensation required, up to 27,500 times at worst. The electric vehicle fleet may not be large enough to meet the firm fast reserve power and duration requirements until 2020. However, it may not be until 2030 that enough vehicles have been sold to provide this service cost-effectively. Even then, many more electric vehicles will be needed to meet the power level and duration requirements, both more often and for longer to enable participation in an all-day, everyday ancillary services market.

1. Introduction

The two aims of this paper are to quantify: first, the battery degradation costs when EV (electric vehicles) are used both to satisfy travel demand and to provide V2G ancillary services; and second, the payments necessary from a power aggregator to compensate two group of consumers. The first group comprises existing EV owners who, by the end of the vehicle service life, will want to be left no worse off than if they had not participated in V2G. The second group represents prospective buyers who will compare the costs of EV ownership to that of a conventional vehicle. The motivation for including this second consumer group is that V2G is justified often on the basis that vehicles spend about 95% of their lifetimes stationary [1] and that the revenues from such participation can reduce the costs of ownership [2].

V2G may be used to store electricity generated off-peak which is returned to the grid during peak hours. Net social welfare benefits arise due to avoided construction of peaking generating plant [3]. A recent analysis of the V2G power capacity of a car park showed that ‘peak-shaving’ and regulation services returned the largest economic value, while spinning reserve could not be delivered profitably [4]. V2G can smooth the variations in output from generating plant using renewable energy sources. For example, EV providing V2G through high power connections reduced excess generation (and associated carbon dioxide emissions) from non-wind facilities and increased the efficiency of the power system [5]. Vehicle-to-building (V2B) is a local variation of V2G which exploits the relationship between commuter and employer. Here, vehicles discharge to the building directly to shave the short peaks in demand which reduces costs to the facility [6]. V2B has a role in the residential context where it can reduce energy costs to the home, provide back-up power and maintain power quality [7].

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http://dx.doi.org/10.1016/j.energy.2015.11.029
0360-5442/

V2G may be most cost-effective for owners of plug-in vehicles which participate in the short-duration, high-value power market of ancillary services. Specifically, vehicle owners receive two payments: one for the contracted capacity; and the other for the energy delivered. These capacity payments are the basis for V2G competitiveness because they augment the relatively low energy payments, which alone would render V2G unprofitable. The attractiveness of this scheme is dependent on the power level of the connections, vehicle battery capacity and the value of ancillary services [8]. The vehicle owner can benefit from a greater return when both ancillary services and peak power demands are met with V2G, than when each service is provided individually [9].

The UK National Grid uses ancillary – reserve services and frequency response measures – services to balance demand with supply and to maintain the quality of electricity service, respectively. Examples of reserve services include fast reserve and STOR (short term operating reserve). STOR is the extra power necessary, either when actual demand exceeds that forecast, or to account for unavailability of generating plant. Frequency response mechanisms, such as firm frequency response and frequency control by demand management, are used to counter the real-time changes in system frequency when demand and supply are not matched. Frequency falls when demand exceeds supply and can be remedied by either increasing supply or reducing demand. Firm frequency response is a supply-side measure where a minimum 10 MW is injected to the system to counter a fall in frequency. Frequency control by demand management involves interrupting services to customers for no more than 30 min.[1]

Of the ancillary services, firm fast reserve and firm frequency response may be met best by V2G. The 'firm' relates to the contract which providers enter into with National Grid to provide services on a consistent basis. Both services are attractive to V2G participants because of the two – energy and capacity – payments. Moreover, the time between a dispatch instruction and the duration that power must be fed into the system are short: specifically, firm fast reserve must be provided for a minimum of 15 min and start within 2 min of receiving a dispatch instruction [10]; and secondary frequency response must be provided within 30 s of an event and sustained for 30 min [11].

Overwhelmingly, contributions to the V2G discussion quantify the benefits of such services to the power grid or system operator. The premise of current V2G models is that a vehicle, or group of vehicles, competes in a market to provide ancillary services. Common assumptions of these models include that vehicle batteries are charged fully both at the start of the day and at the time of grid disconnection [12] and charged and discharged at fixed rates [13]. Additional assumptions are that vehicles connect: opportunistically [14], based on widespread charging infrastructure; during the daytime only, such as in the V2B scenario [6]; or during the night-time only [12], such as in the 'valley-filling' approach.

Providing V2G services may accelerate the degradation of EV batteries leading to the need for more frequent replacement [15], with associated costs borne by vehicle owners. Consequently, this work adopts their perspective and considers firm fast reserve (non-balancing mechanism) only as it can provide also some short term frequency control. The work in this paper is set in the UK context where the minimum requirements to provide firm fast reserve ancillary services to the National Grid are a: ramp rate of 25 MW min^{-1}; a total power of 50 MW; a duration of service of 15 min; and the service must be in place within 2 min of receiving a request from National Grid [10]. Satisfying these power and energy criteria requires the participation of multiple EV through a power aggregator. Appropriate charging infrastructure, metering, and communications system must exist to support the V2G interaction, the costs of which may not be borne by the vehicle owner alone.

In general, the existing V2G research makes assumptions on one or more of vehicle efficiency, consumer behaviour and battery degradation. Where powertrain modelling is not present, studies are based on either a constant vehicle energy use per distance travelled [16] or battery state of charge dropping linearly with distance travelled [13]. Driver behaviour influences the probability of vehicles being connected to the grid. However, works which do not incorporate real-world travel data make assumptions on at what time and for how long vehicles may be connected. For example [13], assumed normal distributions for vehicle arrival and departure centred around peak driving hours of 0800 h and 1800 h. In contrast, this work uses models of both EV powertrains and battery degradation, paired with national travel survey data to determine the costs to the vehicle owner which need to be compensated by V2G ancillary service provision.

The method presented is flexible and applicable in different national circumstances. There are three bases which support this statement. First, the vehicle market is global. For example, the Nissan Motor Company reported the Nissan LEAF as the best-selling EV, accounting for 45% of the market, having sold 110,000 units globally between December 2010 and June 2014 [17]. Second, similar driving behaviour has been observed in different national travel surveys. In the US, the peaks in trip start times occurred at 0700 h and 1700 h [18]. Third, ancillary services are a power system requirement which is independent of whether the system operates through markets or remains part a vertically-integrated structure. Indeed, the number of studies investigating V2G ancillary services illustrates a demand for such services across regions and countries.

2. Method

The cost calculation method has three principal elements which addresses assumptions in others' models of energy demand by EV on the grid. The first is an empirically-derived battery degradation model. The second is a validated powertrain model simulated over the NEDC (New European Driving Cycle) to give per second current flows through battery pack while driving. The third is a comparison with the costs associated with the equivalent conventional vehicle to reflect the choices faced by prospective EV owners. Together these form a system which both quantifies and internalises the cost burden on the vehicle (and battery) owner when providing V2G services.

The UKNTS (UK National Travel Survey) [19] provided realistic patterns of vehicle availability for the grid. The UKNTS consists of 1.1 million trips (years 2008–2013). The median velocity, distance travelled and duration are 29 km h^{-1}, 11 km and 0.38 h, respectively. The highest frequency of trip start times in the morning and afternoon occurred at 08:00 h and 15:00 h, respectively; the mean trip interval was 7 h. The probability distribution for vehicle activity in any hour of the day is given in Ref. [15].

The UKNTS trip distribution, coupled to opportunistic charging, represents the best case for vehicles to participate in V2G services for two main reasons. The first is that if a vehicle is connected to the grid whenever it is stationary, the battery pack is only depleted by the energy used to deliver the immediate preceding journey. Therefore, the pack will have a high state of charge for meeting grid demands when connected. The second reason is that a vehicle that is always connected when stationary maximises its availability to the grid. Opportunistic charging removes the need to assume specific driver behaviour. However, the driver may choose to charge

[1] The range of reserve services are described online at http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/.