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Can parked cars and carbon taxes create a profit? The economics of vehicle-to-grid energy storage for peak reduction

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ABSTRACT

This article discusses a five-year, hourly economic model of vehicle-to-grid energy storage for peak reduction. Several scenarios are modeled for a participant using a 60 kW-h capacity battery electric vehicle, such as the Tesla Model S or Chevrolet Bolt, in the New York City area using pricing data for the years 2010 through 2014. Sensitivity analysis identifies that variables such as one-way power efficiency and battery lifetime are the major factors influencing the economics of selling electricity back to the grid. Although it is shown that vehicle-to-grid electricity sales can create positive economic benefits, the magnitudes are small due to the cost of added degradation to the vehicle's battery and are not likely to entice the average electric vehicle owner to participate. However, over the five-year period, the potential economic benefits of this technology have shown a promising trend. A carbon dioxide tax is examined as a potential policy measure to encourage vehicle-to-grid adoption. The implementation of a carbon dioxide tax is shown to create additional opportunities for economic gain but, these benefits are dependent on the grid's electricity generation portfolio. Added benefits from the tax are also small in magnitude considering current international carbon prices.

1. Introduction

The first fifteen years of the twenty-first century brought about great technological advances in the personal transportation sector. Since Toyota first introduced the Prius in 1997, automakers have been finding ways to push the envelope of powertrain electrification. Vehicle electrification creates a plethora of technical difficulties but also the hope that transportation energy demand could, someday, be supplied without energy sources that emit harmful air pollutants.

This analysis focuses on a specialized application of electric vehicle technology – vehicle-to-grid (V2G) energy storage. The basic premise of V2G is the capability of bi-directional energy and data flow between electric vehicles and the electricity grid (Fig. 1.1). In V2G, the excess battery capacity available from a participant's vehicle is used to balance the electricity grid. During times of low demand on the electrical grid system, electricity flows from the grid to the electric vehicle, charging the vehicle's battery. During times of high electricity demand, excess battery capacity can be sent back to the electricity grid thereby transforming the participant's electric vehicle from a load to an energy capacity resource for the grid operator. For a review of the concepts, benefits and barriers relevant to V2G implementation, see Sovacool and Hirsh (2008).

Individuals participating in V2G can provide traditional energy storage services by sending electricity from their vehicle's battery to the grid during electricity demand spikes, thereby reducing electrical demand from central generating plants. Participants could also provide ancillary services by communicating to the grid operator that their vehicle's battery capacity is available at a moment's notice if needed (spinning reserves) or by allowing electricity to flow to or from their vehicle's battery in order to maintain the local electricity grid's frequency at 120 Hz (regulation services). In addition to the system benefits created in support of the electricity grid, V2G service provision also has the potential to provide its participants with economic benefits. This paper presents an analysis of the economic benefits of participating in V2G.

The principle focus of previous publications on the subject of V2G

Abbreviations: C_b, capital cost of battery storage [$/kWh]; c_{ch}, charging cost [$/kWh]; $c_{ch,O}$, off-peak charging cost [$/kWh]; c_{CO2}, cost of carbon dioxide emissions [$/kWh]; c_{dgdn}, battery degradation cost [$/kWh]; DoD, depth of battery discharge [%]; $\bar{e}_{MU}$, median lifecycle emissions factor of an electricity generating technology [gCO2eq/kWh]; $E_{S,max}$, maximum battery capacity level, 100% state-of-charge [kWh]; $E_s(t)$, battery capacity level at hour t [kWh]; η, one-way power efficiency [%]; LBMP, location-based marginal price [$/MWh or $/kWh]; L_C, lifetime of the vehicle's battery in cycles; mt, metric ton; NY-ISO, New York Independent System Operator; PHEV, plug-in hybrid electric vehicle; τ_{CO2}, carbon dioxide tax amount [$/mt]; V2G, vehicle-to-grid

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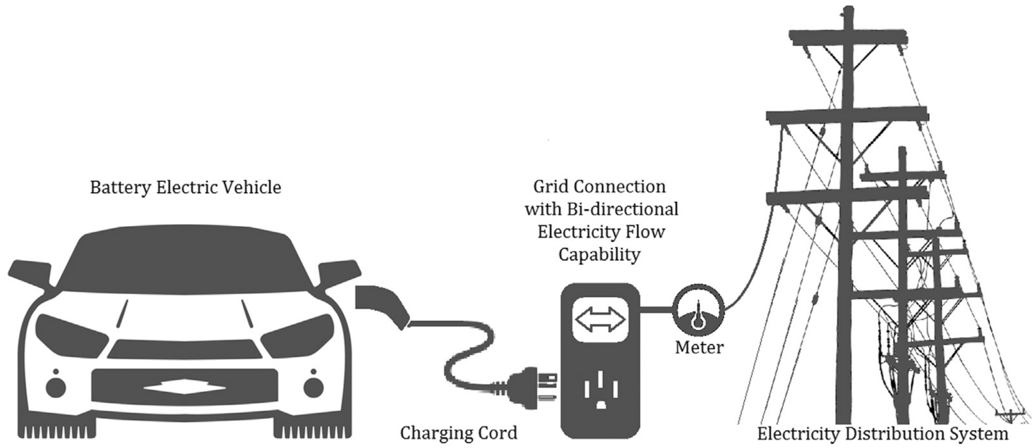

Fig. 1.1. Simplified Vehicle-to-Grid (V2G) Schematic. With V2G technology, electricity can flow either from an electric vehicle's battery back to the utility grid to reduce the energy requirement from central generating units or from the grid to the vehicle's battery to regulate the frequency on the local utility network. The point of connection to the grid is required to have communication ability between the participant's vehicle and the central grid operator for V2G to work.

economics has been in three areas: the analysis of smart charge/discharge algorithms to maximize revenue across all applications of V2G technology (Ma and Mohammed, 2014; Rotering and Ilic, 2011; Saber and Venayagamoorthy, 2009; Sortomme and El-Sharkawi, 2010); ancillary service provision, particularly regulation, as the principle money-making strategy for V2G (Han et al., 2011; Kempton and Tomić, 2005a; Peterson et al., 2009a; Quinn et al., 2009; Tomić and Kempton, 2007); and fleet-level analysis of V2G implementation (Debnath et al., 2014; Sioshansi and Denholm, 2008, 2009). Rather than focus on complex participation algorithms, this analysis takes an approach that is meant to represent the realistic method that an intelligent individual would use if presented an opportunity to participate in the market. Past research has shown that very low profit potential exists for V2G storage services for peak reduction (Debnath et al., 2014; Kempton and Tomić, 2005a; Peterson et al., 2009a; Sioshansi and Denholm, 2009; White and Zhang, 2010). However, it is important to note that many of the past research articles focused on plug-in hybrid electric vehicles (PHEVs) as their central vehicle technology (Peterson et al., 2009a; Quinn et al., 2009; Rotering and Ilic, 2011; Sioshansi and Denholm, 2009; White and Zhang, 2010). While PHEVs can use all of their battery capacities for V2G service provision – due to their possession of a backup powertrain – PHEVs simply do not have enough battery capacity onboard to allow sufficient storage dedication to V2G. The introduction of larger capacity battery electric vehicles, such as the Tesla and Chevrolet Bolt, allows for an analysis of pure electricity arbitrage using V2G, rather than energy arbitrage between transport fuels. This paper presents an example analysis of the economic benefits created by a V2G participant using the 60 kW h model of the Tesla Model S. Coincidentally, the Chevrolet Bolt also offers a 60 kW h battery pack, so this analysis can approximate the magnitude of economic benefits generated by the Bolt as well.

As alluded to above, ancillary services, such as frequency regulation, have been an area of interest for many researchers in the past decade. These markets utilize a capacity payment mechanism which rewards participants for simply being available to provide services if they are called upon. It is possible to be paid to provide services like regulation and spinning reserves without ever being dispatched to discharge the V2G-ready vehicle's battery. The ancillary services markets are certainly the best for avoiding added degradation to the vehicle's battery, however, literature has shown that it would take only a small portion of the vehicle fleet to saturate these markets (Kempton and Tomić, 2005b). For this reason, this paper focuses on V2G energy storage for peak reduction rather than ancillary services.

Specifically, this analysis asks the question: “Can the everyday, informed participant derive any economic benefit from V2G energy storage service provision using solely large-capacity battery electric vehicles after ancillary service markets are saturated?” The answer to this question is central to the development of the large-scale market for V2G technologies. The following analysis has two parts. The first part estimates the trend in economic benefits of V2G energy storage during the years 2010 through 2014 using the Tesla Model S. The second part investigates the impact that a simple, $50 per metric ton carbon dioxide tax would have on the benefit trends derived in the first part. Sensitivity analysis is then conducted on key model assumptions and variables.

2. Methodology

A five-year economic model was constructed using top-of-the-hour increments for pricing data and calculations. The five-year model consists of the total number of work hours for the years 2010 through 2014 based on the federal holiday schedule. The analysis is driven by hourly location-based marginal pricing (LBMP) data for electricity delivered within the participant's zone of the electricity grid. Three scenarios of V2G storage provision provide breadth and flexibility of the economic model. To create additional functionality, model users also have the ability to select their commute distance, beginning time of their workday, duration of their workday, and electricity selling prices (when applicable).

2.1. Vehicle-to-grid scenarios

Three scenarios of V2G participation were constructed: a work-hour price-taker scenario, an arbitrage-guided scenario with perfect information, and a user-defined electricity selling price scenario. In the results section, all three scenarios are compared to a simulated normal commute. The normal commute consists of daily energy use during the drive to and from the participant's workplace with the participant charging their vehicle during off-peak hours.

There are four basic steps in the V2G scenarios. First, the user charges their vehicle at home during off-peak hours in order to capture low electricity prices. Second, they commute to work and connect their vehicle to the grid at a parking area near their place of work. Third, energy flows from the participant's battery to the grid if the specified V2G conditions are met. Energy flow controls, simulated using logical operators, prevent the battery from discharging beyond the capacity required to complete the afternoon commute. Finally, after work, the participant disconnects from the grid, drives home and reconnects to a grid connection point at home. Again, energy flows from the participant's battery to the grid if the specified V2G conditions are met. The