Journal of Power Sources 195 (2010) 2377–2384

Contents lists available at ScienceDirect

Journal of Power Sources

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

The economics of using plug-in hybrid electric vehicle battery packs for grid storage

Scott B. Peterson [a], J.F. Whitacre [a,b], Jay Apt [a,c,*]

[a] Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[b] Department of Materials Science & Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[c] Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA

ARTICLE INFO

Article history:
Received 7 August 2009
Received in revised form
26 September 2009
Accepted 30 September 2009
Available online 14 October 2009

Keywords:
Electric vehicle
PHEV
Smart grid
Vehicle-to-grid power
Energy arbitrage

ABSTRACT

We examine the potential economic implications of using vehicle batteries to store grid electricity generated at off-peak hours for off-vehicle use during peak hours. Ancillary services such as frequency regulation are not considered here because only a small number of vehicles will saturate that market. Hourly electricity prices in three U.S. cities were used to arrive at daily profit values, while the economic losses associated with battery degradation were calculated based on data collected from A123 Systems $LiFePO_4$/Graphite cells tested under combined driving and off-vehicle electricity utilization. For a 16 kWh (57.6 MJ) vehicle battery pack, the maximum annual profit with perfect market information and no battery degradation cost ranged from ∼US$140 to $250 in the three cities. If the measured battery degradation is applied, however, the maximum annual profit (if battery pack replacement costs fall to $5000 for a 16 kWh battery) decreases to ∼$10–120. It appears unlikely that these profits alone will provide sufficient incentive to the vehicle owner to use the battery pack for electricity storage and later off-vehicle use. We also estimate grid net social welfare benefits from avoiding the construction and use of peaking generators that may accrue to the owner, finding that these are similar in magnitude to the energy arbitrage profit.

1. Introduction

Legislation enacted in 2008 provides a subsidy in the form of tax credits for purchasers of plug-in-hybrid electric vehicles (PHEVs) to increase market acceptance [1]. Subsidies may be economically justified if they support private investments that have social benefits. One suggested benefit has been that PHEVs could provide services to the electricity sector (vehicle-to-grid or V2G services) [2]. These benefits might include peak load shifting, smoothing variable generation from wind and other renewables, and providing distributed grid-connected storage as a reserve against unexpected outages. Hybrid electric vehicles, battery electric vehicles, and plug-in hybrid electric vehicles (PHEVs) rely on batteries located in the vehicle to store energy.

One of the fundamental properties of electricity markets is the lack of cost-effective storage [3]. Without storage, meeting peak demand requires underutilized investment in generators and transmission lines. Because of the costs of meeting peak demand, the difference between daily peak and off-peak costs can vary greatly throughout the year (wholesale markets see this as a price difference; a small but increasing number of retail customers also see this as a price difference). If the difference is small on a given day, single purpose storage facilities either make minimal revenue or sit unused and depreciating. Single purpose battery energy storage facilities have not proven economical except in niche applications such as delaying a distribution system upgrade [4]. A plausible conjecture is that V2G, that relies on dual purpose batteries where the initial capital cost of the battery is not assigned to the off-vehicle electricity use because the battery was purchased for driving, will be more economic for grid support than batteries whose capital cost must be amortized for grid use. With vehicle batteries, if load shifting or peak shaving is not economical the only wasted expenditure is the cost of the controllers and converters, some of which will likely be installed in any case to enable off-peak charging (although additional electronics would be required for V2G). This possibility, along with quick battery reaction times, has made V2G applications to stabilize or slow fluctuations from intermittent sources (such as wind or solar) a subject of research interest [5]. V2G has the potential to diminish the need for rapid ramping of following generators to match variable power sources. Rapidly ramping generators may not be the lowest cost generators, and ramping can lead to increases in pollution [6].

* Corresponding author at: Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA. Tel.: +1 412 268 3003; fax: +1 412 268 7357.
E-mail addresses: speterson@cmu.edu (S.B. Peterson), whitacre@andrew.cmu.edu (J.F. Whitacre), apt@cmu.edu (J. Apt).

0378-7753/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2009.09.070

Nomenclature

List of symbols

kWh	kilowatt hours
$kWh_{Transacted}$	the number of kWh transacted in a given discharge
PHEV	plug-in hybrid electric vehicle
V2G	vehicle-to-grid energy transfer
V2G Deg	coefficient relating battery degradation to battery use
LMP	locational marginal pricing
BOS	Boston, MA
ROC	Rochester, NY
PHL	Philadelphia, PA
NHTS	National Household Transportation Survey
RTP	real time price
TND or T&D	transmission and distribution charge
RTE	round-trip efficiency
RTO	Regional Transmission Organization
ISO	Independent System Operator
NYISO	New York Independent System Operator
ISO-NE	New England Independent System Operator
PJM	Pennsylvania New Jersey Maryland Interconnection LLC
DCH_{eff}	discharge efficiency
CH_{eff}	charge efficiency
LMP_{BUY}	buying price of electricity
LMP_{SELL}	selling price of electricity
LMP_{BUY} (t_{Bx})	buying price of electricity in hour x
LMP_{SELL} (t_{Sx})	selling price of electricity in hour x

Here we examine the net revenue that a vehicle owner could receive from V2G energy sales to estimate whether this would provide an attractive incentive for owners to participate in V2G operations as a dual use for the battery pack whose capital cost has been justified largely by transportation. V2G services could be sold in an organized market as ancillary services (spinning reserve and regulation), as energy sales to the grid (running the meter backwards), or their value could be captured as avoided grid electricity purchases (running the meter slower). The first two incur transaction costs and grid costs, while the third does not; it is the third we examine here. Net revenue, as used here, is the net of avoided grid energy purchases from using the energy stored in the vehicle battery pack less the cost of grid electricity used to charge the battery pack and the cost associated with shortening the battery pack's lifetime by cycling for such energy use.

2. Methodology

We examine energy arbitrage (buying low cost power to charge the battery pack and discharging the battery pack at high power price times) with PHEVs assuming that electricity sold will be replenished from the grid later in the evening so the battery pack is be full in the morning. Hourly historical locational marginal pricing (LMP) data were obtained for three cities: Boston (BOS), Rochester NY (ROC) and Philadelphia (PHL). Each city is in a different electricity market and good data from the 2001 National Household Travel Survey (NHTS) of 70,000 households [7] are available to construct driving profiles in each of these metropolitan areas [8]. The three cities have annual mean temperatures that are not far enough from the national average of 11.6 °C to materially affect the modeled battery state of charge: Boston is 10.7 °C, Rochester is 8.7 °C, and Philadelphia is 12.4 °C [9].

LMP data are available for the years from 2003 to 2008 for Rochester and Philadelphia; the first full year of Boston data is 2004. The LMPs (plus a transmission and distribution charge) provided the cost for buying the electricity, and the maximum potential profit for avoiding electricity purchase, or for selling the electricity in the absence of transaction costs. We model a vehicle with a 16 kWh battery pack, as used in Chevrolet's proposed Volt [10].

We model energy arbitrage by owners to offset their own electricity consumption during high priced periods. This simplifies consideration of transaction costs. On the other hand, it ignores possible social benefits such as increased rates of utilization of utility investments or other benefits that might accrue to society if PHEV owners used their vehicles in a widespread fashion for energy arbitrage. Thus, it is an analysis of the economic benefits to individuals providing energy arbitrage services, although we use coarse estimates of the net social welfare to bound additional revenue below.

2.1. Revenue

We calculate the revenue from energy arbitrage based on LMP data from the PECO, Genesee, and Boston nodes of PJM, NYISO, and ISO-NE. These nodes serve Philadelphia, Rochester, and Boston, respectively. LMP data from 2003 to 2008 are used to calculate the maximum revenue possible from energy arbitrage (2004–2008 for Boston). For this model, we assume the PHEV owner is under a real time pricing (RTP) tariff. We add a transmission and distribution (T&D) cost of 7 ¢ kWh^{-1} [11] to the hourly nodal price to estimate the RTP. The net effect of the T&D costs is small given high round-trip efficiency (RTE). We use an RTE of 85% as our base case. The discharge efficiency (DCH_{eff}) and charge efficiency (CH_{eff}) were both assumed equal and the square root of 0.85 so that they result in 85% RTE (our laboratory measurements showed DC–DC energy efficiency of cells only in excess of 95% for discharge/charge cycles). It is assumed the PHEV owner is a price taker. The results therefore estimate the incentive for owners, in a RTP scenario, to choose to use their PHEV for energy arbitrage.

We estimated the profit possible from energy arbitrage by subtracting the degradation cost and the cost of buying electricity from that of selling it to offset the owner's use and multiplying by the number of kWhs transacted and adjusting for efficiency.

$$\text{profit}\,(\$) = \left((\text{LMP}_{\text{SELL}} + \text{T\&D}) \times \text{DCH}_{\text{eff}} - \frac{\text{LMP}_{\text{BUY}} + \text{T\&D}}{\text{CH}_{\text{eff}}}\right) \times \text{kWh}_{\text{Transacted}} - \text{degradation cost} \quad (1)$$

The kWh transacted by a profit-maximizing PHEV owner depends on the percent of the battery pack energy available after driving, the battery pack size, and the marginal cost of degradation associated with additional withdrawal from the battery pack. The variable cost of battery degradation depends on the amount of energy withdrawn. Thus, the objective function for the transaction optimization considers revenue and variable costs (battery degradation), but not fixed costs necessary for using a PHEV for energy arbitrage because the capital cost of the battery pack and charging station are considered here to be sunk costs.

2.2. Degradation cost

Degradation cost was calculated based on the multiple linear regression based on laboratory data from cycling $LiFePO_4$ cells described in [8]. While other chemistries, such as those based on the $Li4Ti_5O_{12}$ anode, have been considered for vehicle use, their low cell voltage, relatively poor energy density, and higher expense per unit energy make their use less likely in the near term. For