Energy Policy 87 (2015) 591–603

Contents lists available at ScienceDirect

Energy Policy

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

A cost-benefit analysis of alternatively fueled buses with special considerations for V2G technology

Yosef Shirazi *, Edward Carr, Lauren Knapp

School of Marine Science and Policy, University of Delaware, Newark, DE, USA

HIGHLIGHTS

- We present a robust cost-benefit analysis of various bus technologies.
- Diesel is a low-cost technology at current prices.
- CNG represents slightly higher costs on a marginal bus basis.
- V2G-enabled electric buses are not cost-effective at current prices.
- We identify frequently overlooked costs and challenges to V2G implementation.

ARTICLE INFO

Article history:
Received 19 April 2015
Received in revised form
21 September 2015
Accepted 27 September 2015

Keywords:
Compressed natural gas (CNG)
Cost-benefit analysis
Electric vehicle
Frequency regulation
Temperature effects
Vehicle-to-grid (V2G)

ABSTRACT

Motivated by climate, health and economic considerations, alternatively-fueled bus fleets have emerged worldwide. Two popular alternatives are compressed natural gas (CNG) and electric vehicles. The latter provides the opportunity to generate revenue through vehicle-to-grid (V2G) services if properly equipped. This analysis conducts a robust accounting of the costs of diesel, CNG and battery-electric powertrains for school buses. Both marginal and fleet-wide scenarios are explored. Results indicate that the marginal addition of neither a small CNG nor a small V2G-enabled electric bus is cost effective at current prices. Contrary to previous findings, a small V2G-enabled electric bus increases net present costs by $7,200/seat relative to diesel for a Philadelphia, PA school district. A small CNG bus increases costs by $1,200/seat relative to diesel. This analysis is the first to quantify and include the economic implications of cold temperature extremes on electric vehicle battery operations, and the lower V2G revenues that result. Additional costs and limitations imposed by electric vehicles performing V2G are frequently overlooked in the literature and are explored here. If a variety of technical, legal, and economic challenges are overcome, a future eBus may be economical.

1. Introduction

For decades, school buses have been powered almost exclusively by diesel and gasoline. The long history of mass production and adoption of these vehicles provides for significant economies of scale, as well as predictable performance characteristics and maintenance schedules.

While diesel touts numerous desirable properties as a fuel for heavy-duty vehicles, concerns over volatile petroleum prices, as well as health and environmental externalities have spurred interest in alternative fuels for heavy-duty vehicles (US Department of Energy, 2014a).

A combination of factors—both technological and social—have recently expanded the available fuel technologies for transportation. Compressed natural gas (CNG) in particular is a popular fuel for municipal and commercial fleets in the US due to its low cost, reduced emissions, and domestic extraction (National Research Council, 2010). Major school bus manufacturers, including Thomas Built, Blue Bird and International, offer CNG and/or propane options (Florida Department of Education, 2014).

Battery-electric buses, or eBuses, have also been developed, albeit by more specialty manufacturers. Proterra, BYD, and New Flyer manufacture transit eBuses, while eTrans and TransPower manufacture eBuses specifically for school applications.

Abbreviations: BEV, battery electric vehicle; CBA, cost-benefit analysis; CNG, compressed natural gas; DGE, diesel gallon equivalent; eBus, electric bus; kW, kilowatt; kWh, kilowatt hour; MPGe, miles per gallon equivalent; MW, megawatt; NPC, net present cost; NPB, net present benefit; PJM, a large, independently operated grid in the eastern US; V2G, vehicle-to-grid

* Corresponding author.
E-mail addresses: yshirazi@udel.edu (Y. Shirazi), ecarr@udel.edu (E. Carr), knlauren@udel.edu (L. Knapp).

http://dx.doi.org/10.1016/j.enpol.2015.09.038
0301-4215/

Battery-electric vehicles (BEVs) derive energy from an onboard electrochemical battery, typically of a lithium-ion variety. These vehicles offer zero tailpipe emissions, decreased fuel costs, lower maintenance costs, but higher initial purchase costs relative to diesel counterparts (Electrification Coalition, 2010).

Successful pilot runs have been demonstrated for school eBuses in California (Clements and Nagrani, 2014; Ramsey, 2011; TransPower, 2014). Pilot projects for electric transit buses are also underway in various European cities under the Zero Emission Urban Bus System (ZeEUS, 2015).

1.1. BEVs with vehicle-to-grid (V2G)

If properly equipped, BEVs can perform vehicle-to-grid (V2G) services while not operating routes, receiving payment in return, thereby offsetting a portion of total ownership costs. During V2G, a vehicle's battery provides services to the electrical grid, helping to maintain high quality and reliable electricity for grid customers.

The specific grid service most lucrative for V2G is frequency regulation (Kempton and Tomić, 2005). Frequency regulation (FR) is the contracted availability to provide short bursts of power into and/or out of the electrical grid as directed by the grid operator. Vehicles that provide FR are compensated primarily as a function of total hours of service, amount of service offered (measured as power), and market rates during each hour service is offered.

Kempton and Tomić (2005) conducted the first cost-benefit analysis (CBA) for a V2G-enabled vehicle. The battery-electric version of a Toyota RAV4, a compact sport-utility vehicle, was found to generate $411 in monthly revenue and $213 in monthly profit providing FR services to the California-area grid.

More recently, Noel and McCormack (2014) present the economics of operating a school eBus with V2G capabilities in PJM, the electrical grid across thirteen states in the eastern US. Their analysis advances the limited literature regarding V2G economics by considering new FR pricing regimes in the aftermath of the 2012 implementation of US FERC Order 755, and by explicitly accounting for environmental externalities. The authors report that a 24-seat V2G-capable eBus yields a $6,070 lower net present cost (NPC) per seat than a 32-seat diesel counterpart over an expected 14-year life. The higher purchase price for the eBus is more than offset by V2G revenues, as well as lower fuel, maintenance and externality costs.

However, Noel and McCormack (2014) overlook several substantive issues that are addressed in the current study. Such omissions, including driver salary, electrical losses from V2G, nontaxable diesel-fuel for school districts and reduced V2G availability during cold weather, skew the findings of that paper in favor of the V2G-enabled eBus.

The present analysis fills considerable literature gaps by identifying nuanced technical, regulatory, and economic challenges imposed by V2G-enabled vehicles. In addition to incorporating oft-overlooked inputs in the cost-benefit calculations, this analysis provides more robust assumptions and includes an additional alternative fuel (CNG) for a three-way analysis. The present analysis is also the first of its kind to highlight the importance of operating temperature impacts on expected V2G revenue generation.

1.2. Temperature and V2G

Previous attempts to estimate V2G revenue rely on applying an average price for FR derived from a simple average of all hours over some previous period (Kempton and Tomić, 2005; Noel and McCormack, 2014). Such approaches do not represent actual price conditions fleet operators are likely to expect for their fleets. Because V2G participation for fleet vehicles exhibits recurring and predictable availability with respect to time of day (business hours) and ambient temperature (due to constraints in battery performance at extreme temperatures), average prices are best computed from prices that prevail only during these conditions.

Of particular concern are low ambient temperatures. During extremely low temperatures, FR prices can spike to one-hundred times higher than average, greatly increasing average FR prices. However, V2G during these hours may not be possible due to thermal limitations of the lithium-ion cells.

Like many fleet vehicles, school buses are parked outside, exposed to ambient conditions. Outside of narrow optimal temperatures (roughly 10–30 °C), lithium-ion cells suffer degraded performance, longevity and/or efficiency (Reid, 2007; Pesaran et al., 2013). Thermal management systems can alleviate some shortcomings outside of this range, but only with increasing efficiency penalties. Much below freezing (below −5 to −10 °C), typical lithium-ion batteries are only able to operate under limited power, if at all, due to reductions in power capacity as well as programmatic cut-offs designed to preserve long-term battery longevity (Pesaran et al., 2013; Zhang et al., 2011; personal experience with University of Delaware V2G fleet). However, the exact ambient temperature cutoff for these batteries varies by a myriad of factors including cell chemistry, form factor, arrangement of cells within the vehicle, and others (Samadani et al., 2013).

1.3. Outline

We investigate the costs and benefits of V2G-enabled school buses compared to CNG and diesel counterparts using a Monte Carlo-based NPC framework in two distinct scenarios. The first scenario adopts the framework and vehicles of Noel and McCormack (2014), consisting of a marginal addition of a single small school bus to an existing fleet. Both Noel and McCormack (2014) and this analysis compare a Type C diesel bus with a smaller TransTech eBus, using current prices for bus purchase costs. However, the present work differs in that it re-specifies inputs with more realistic values, enhances the model with previously omitted factors, and includes a CNG bus for a three-way comparison.

The second scenario analyzes the NPC implications of establishing and operating an entire fleet of large school buses of a specified technology (either eBus, diesel or CNG). Importantly, it assumes a projected eBus purchase price benefitting from the significant future price decreases anticipated in coming years. The diesel and CNG in this scenario, however, do not benefit from any advancements in cost or performance. As a result, this scenario structurally favors the V2G-enabled eBus.

For both analyses, findings represent optimistic accounting of eBus costs due to the several additional challenges identified but not accounted for explicitly in the analysis. The additional challenges to eBus implementation are discussed qualitatively in Section 4.5, and should be carefully considered when interpreting the results presented here and in related studies. These additional factors, often unacknowledged in V2G literature, further deteriorate V2G-enabled eBus economics in real world implementation.

2. Methods

2.1. FR pricing with temperature considerations

We estimate FR pricing from hourly time-series data in the PJM market during 2012–2014 (PJM, 2015b), incorporating limitations in bus route timing and temperature availability. To address these limitations, we isolate prices for those hours outside of normal school bus operating hours (5–8 AM and 2–5 PM) on school days using a local academic calendar, and all hours of non-school days.

We also calculate potential V2G revenue with an imposed cutoff temperature ranging from 0 °F (−18 °C) to 50 °F (10 °C) using U.S. NOAA National Climatic Data Center temperatures for