Analyzing the Vehicle-to-Grid (V2G) Potential for Electric and Plug-In Hybrid Fleets

By: Kristen Nordstrom and Andres De Los Rios Vergara

Thesis Advisor: Dr. Jarrod Goentzel

Industry Advisor: Clay Siegert, XL Hybrids

Summary: Vehicle-to-grid (V2G) describes a system where electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) can connect to the electric grid to provide ancillary services, such as frequency regulation, to grid operators. This thesis evaluates the opportunities for V2G-enabled EVs and PHEVs to participate in the regulation services market and lower their net costs, making them more cost competitive with conventional vehicles. We build a ten-year net cash flow model for a fleet of delivery trucks to assess the costs and benefits of adopting this technology. To project potential V2G revenue, we utilize a simulation model developed by a grid system operator. Based on exploration of numerous scenarios we determine which combination of factors produce the greatest overall benefit. Our results indicate that EV and PHEV fleets offer lower operating expenses for urban pickup and delivery services. In addition, fleet managers can expect to offset 5-11% of the total cost of ownership with V2G revenue.

Kristen Nordstrom worked as a business analyst for Discovery Communications prior to joining the SCM program. Upon graduation she joined the MITRE Corporation as a Senior Economics / Business Analyst.

Andres De Los Rios Vergara came to the SCM program with seven years of experience in public transportation. Upon graduation, Andres went to Mexico City to work as a consultant on transportation projects.

KEY INSIGHTS

1. Adopting an EV or PHEV and participating in V2G technology can provide savings in overall costs with respect to internal combustion engine vehicles (ICE). Higher capital and infrastructure investments are offset by significant savings in operational expenses.
2. The V2G revenue opportunities with ramp down only regulation service, absorbing excess energy, offset 5-7% of the total fleet cost and with ramp down & up service, both absorbing and providing energy, range from 9-11%.
3. The design mix of charger capacity, battery size, battery state of charge has an important impact on V2G revenue potential. Flexible operations having the ability to adjust fleet operating schedules can realize notable increases in marginal V2G revenue.

Introduction

The common characteristic that enables electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) to participate in vehicle-to-grid technology (V2G) is their re-chargeable battery: the source of all or part of the energy required for propulsion. In theory, V2G could be a viable way to improve the cost-effectiveness (and promote the adoption of) EVs and PHEVs since revenue can be generated through participating in the energy and ancillary services markets. Our study examines the benefits of V2G at a fleet-level perspective, focusing specifically on corporate fleets of grid-enabled electric and plug-in hybrid electric trucks that are used on a daily basis to deliver products and services. We treat their batteries in aggregate and model the revenue potential for participating in the frequency regulation component of the ancillary services market in New England. Through simulation, we determine the revenue potential of V2G in this market. Finally, we assess how this revenue offsets the capital and operating costs to improve the business case for adopting EVs and PHEVs in corporate fleets in the future.

Fossil fuels are currently the main source of energy for on-road transportation in the United States (US). As fuel costs rise, businesses struggle to keep operating expenses low for internal combustion engine (ICE) vehicles. A conversation with the fleet manager for a large home and office delivery company confirmed that its new electric vehicle fleet was attractive due to low energy and maintenance costs and favorable acceptance by drivers. While EVs and PHEVs provide lower overall operating costs, they continue to remain a more expensive capital investment than conventional fossil fuel vehicles due to the high battery costs and lack of scale in the marketplace. An EV or PHEV fleet, when aggregated in a sizeable number, also constitutes a new load that the electricity system must supply.

However, such a fleet also represents a resource for the grid operator. The bi-directional power capability of the EV and PHEV make them well suited to provide ancillary services to the grid. Figure 1 contains a pictorial description of V2G. Fleets of vehicles can connect to the grid to provide services to the utility. The utility is connected to the vehicles as well as to the customers they service.

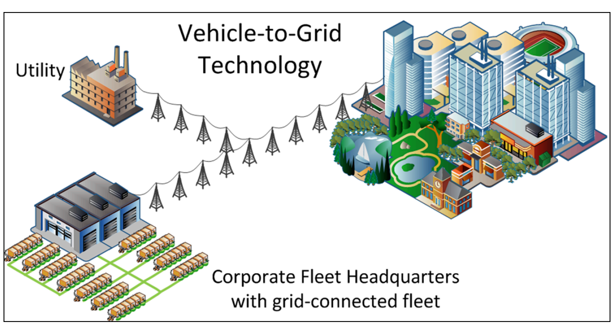

Figure 1: Vehicle-to-Grid Technology Photo Description

Methodology and Model Overview

Due to the nascency of V2G and the high degree of uncertainty in the future of the technology, we used a simulation model to determine the V2G revenue potential for corporate fleets. We combined these revenue projections with the investment, infrastructure, and operating costs for each vehicle type (EV, PHEV, and ICE) using a 10-year net cash flow analysis. Interviews with fleet managers who have deployed EVs and PHEVs yielded realistic investment and cost estimates for the cash flow projections. Table 1 is a breakdown of the different cost components associated with each vehicle type.

Cost	EV	PHEV	ICE
Capital costs	X	X	X
Infrastructure costs	X	X	
Operating costs			
Electricity	X	X	
Diesel		X	X
Battery	X	X	
Controller	X	X	
Charger and wiring	X	X	
Brakes	X	X	X
ICE Engine		X	X
Electric Motor/Generator	X	X	
Maintenance	X	X	X

Table 1: Cash Flow Cost & Revenue Components Table

Working with the ISO New England to understand the market for ancillary services, we decided to focus V2G revenue from frequency regulation (or regulation services). Regulation tracks the moment-to-moment fluctuations in customer load (demand) and corrects for the unintended fluctuations in generation (supply). If the load exceeds the generation, the grid will request an energy resource. If the generation exceeds the load, the grid will request a storage resource. Figure 2 is a depiction of the daily load pattern for a summer day in New England. The difference between actual demand and forecast demand is translated into area control error.

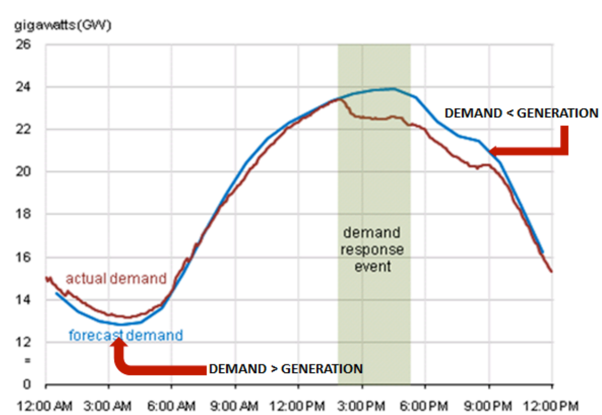

Figure 2: ISO New England Electric Load Fluctuation
Source: (U.S. Energy Information Administration, 2011)

Figure 3 shows the area control error (ACE) signal for an hour-long period from 7 AM – 8 AM. The grid is at equilibrium at zero MW and the signals fluctuate around this point. When the signal is greater than zero MW the grid is requesting energy from its regulation service providers. When the signal is less than zero MW the grid is providing energy to its regulation service providers.

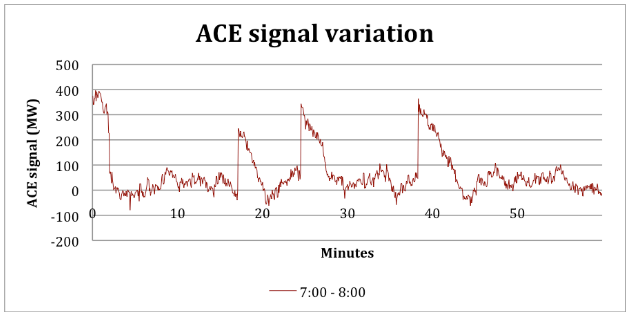

Figure 3: ACE Signal Variation
Source: ISO New England, 2008

The market for regulation services comprises three different payments: a capacity payment, a service payment, and an opportunity cost payment. The capacity payment is based on the maximum capacity contracted from the vehicles, regardless of whether it is used or not. The service payment is based on the absolute sum of ramp up (discharging of the battery) and ramp down (charging of the battery). The opportunity cost payment compensates for revenue the provider forgoes by not generating energy while participating in the service.

We modified a simulation tool from the ISO New England that models the regulation services market. We altered the tool to meet the needs of an urban delivery fleet, i.e. to specify which hours the V2G resource is available and to ensure the vehicle's batteries are completely charged for departure the next morning.

Preliminary Results and Sensitivity Analysis

Our analysis projected cash flows for a 250-vehicle fleet that provides pickup/delivery services over routes 70 miles in length. We considered two different approaches for providing regulation services to the grid: (1) "ramp down" V2G, where the vehicle only responds to signals when supply exceeds demand, and thus only absorbs energy from the grid; and (2) "ramp up and down" V2G, where the vehicle responds to positive and negative signals and the battery both charges and discharges energy as requested. We then compared the total overall costs, including the capital investment, infrastructure, and operating costs for each vehicle. Following this analysis, we compared the total cost of ownership – investment and operating cost less V2G revenue – over the ten-year period. Table 2 shows the results our base case scenario for "ramp up and down" vehicle-to-grid.

METRICS	EV	PHEV	ICE
Capital & Infrastructure Investment ($)	$27,770,000	$14,850,000	$12,500,000
Operating Cost ($)	$6,302,709	$18,059,959	$20,698,377
V2G Revenue ($)	$3,257,213	$304,820	$0
Total Cost of Ownership ($)	**$30,815,496**	**$32,605,139**	**$33,198,377**

Table 2: Ramp Up and Down V2G Base Case Results

While the EVs had higher upfront investment, their operating costs were significantly lower than PHEVs and ICE vehicles, resulting in the lowest cost of ownership over the 10-year period. It was surprising that the EVs also had much higher V2G revenue than PHEVs under the base case assumptions.

Anticipating that these base case assumptions may not be producing the best results, we conducted sensitivity analysis to determine how different configurations affected revenue and cost. We considered three discrete options for each of several key parameters in configuring EVs and PHEVs, as shown in Table 3 and Table 4. The values highlighted in red were the base case assumptions.

Electric Vehicle	
Parameter	**Scenario**
Battery size (kWh)	Dynamic
Charger size (kW)	6.24 / 19.2 / 30
SOC (%)	20 / 30 / 40
Regulation duration (h)	12/14/16
Regulation period (h)	20-8 / 18-6 / 16-4

Table 3: Electric Sensitivity Analyses Variables

Plug-in Hybrid Electric Vehicle	
Parameter	**Scenario**
Battery size (kWh)	3.9 / 10 / 20
Charger size (kW)	1.92 / 6.24 / 19.2
SOC (%)	30 / 50 / 70
Regulation duration (h)	12/14/16
Regulation period (h)	20-8 / 18-6 / 16-4

Table 4: Plug-in-Hybrid Electric Sensitivity Analyses Variables

Among all combinations of the parameters considered in the sensitivity analysis, we determined the configuration of battery size, charger capacity, battery state of charge, and 12-hour regulation period that produced the lowest total cost of ownership, labeled as "Net Cost" in Table 5. The best configuration for EVs and PHEVs under both "ramp down" V2G and "ramp up and down" V2G are provided in Table 5 along with the associated costs. The 10-year costs are further broken down into units that may be more familiar with fleet managers – cost per mile and cost per vehicle per day.

As anticipated, the base case configuration underestimated the V2G revenue opportunity for PHEVs. With a larger battery and charger, the V2G revenue for PHEVs is closer to EVs.

The highest state of charge (SOC) was not attractive for EVs since a larger, more expensive battery would be required for fleet operations. For PHEVs, a higher SOC at the end of the day means the vehicle is driving more miles in hybrid mode, increasing its fuel consumption. Also, our analysis of ACE signals 66% are positive (ramping down or providing energy) and 34% are negative (ramping up or requesting energy). This means that a battery with a low SOC would generate the higher revenues as it can respond to the higher number of positive signals. These factors offset the tradeoff that a high depth of discharge diminishes the life of the battery.

Charger capacity is as or more important than battery size as a driver of V2G revenue. While high capacity chargers require larger investment, they also provide the largest revenue stream from regulation services. It is important to appropriately match charger capacity with battery size and SOC.

The timing for connection to the grid also has a large impact on revenue. Our analysis showed that the average regulation clearing price was 42% higher between 6AM and 8AM than between 6PM and 8PM, which means benefits for managers with flexibility in start time for fleet service operations. Also, revenues can increase by up to 30% for each additional hour parked; and the increment in costs due to an additional hour less than 0.2%.

Conclusions

Our results show that EVs and PHEVs offer lower operating costs compared with ICEs even without V2G revenue. Adding in the V2G revenue, the EV and PHEV fleets lower the total cost of ownership by 7-12% compared with the ICE fleet.

Given our assumptions, the V2G revenue potential for fleets is significant enough to pursue. According to our calculations, an EV/PHEV can earn $700-900 per year performing "ramp down" regulation services, resulting in a 5-7% reduction in cost. Further, an EV/PHEV can earn $1200-1400 per year with "ramp up and down" regulation services, resulting in a 9-11% reduction in cost.

Though the economics of V2G are still being explored and the future of the market rests heavily on technological innovation, fleet managers can hasten the transition to EVs and PHEVs and expect to significantly reduce the total cost of ownership with V2G revenue.

BEST CASE		Ramp Down – V2G		Ramp Up & Down - V2G		ICE
		EV	PHEV	EV	PHEV	
Battery size (kWh)		99	10	99	20	n/a
Charger size (kW)		19.2	19.2	19.2	19.2	n/a
SOC (%)		30	30	30	30	n/a
Regulation period		20:00 - 8:00	20:00 - 8:00	20:00 - 8:00	20:00 - 8:00	n/a
10 year total	Cost	$ 32,529,037	$ 32,723,614	$ 32,747,383	$ 33,032,631	$ 33,198,377
	V2G Revenue	$ 2,268,780	$ 1,758,834	$ 3,499,284	$ 3,124,115	$ -
	Net Cost	$ 30,260,257	$ 30,964,780	$ 29,248,099	$ 29,908,516	$ 33,198,377
per mile	Cost	$ 0.735	$ 0.739	$ 0.740	$ 0.746	$ 0.750
	V2G Revenue	$ 0.051	$ 0.040	$ 0.079	$ 0.071	$ -
	Net Cost	$ 0.683	$ 0.699	$ 0.661	$ 0.676	$ 0.750
per vehicle per day	Cost	$ 51.43	$ 51.74	$ 51.77	$ 52.23	$ 52.49
	V2G Revenue	$ 3.59	$ 2.78	$ 5.53	$ 4.94	$ -
	Net Cost	$ 47.84	$ 48.96	$ 46.24	$ 47.29	$ 52.49
V2G Revenue per vehicle/year		$ 907.51	$ 703.53	$ 1,399.71	$ 1,249.65	$ -
Reduction in TCO from V2G		7.0%	5.4%	10.7%	9.5%	0.0%
Savings vs. ICE		8.9%	6.7%	11.9%	9.9%	n/a

Table 5: Best Case Scenario Results