Economic Analysis of Vehicle-to-Grid (V2G)-Enabled Fleets Participating in the Regulation Service Market

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Abstract-- **Vehicle-to-grid (V2G) describes a system where electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) can connect to the electric grid an participate in markets managed by grid system operators. This paper evaluates the opportunities for V2G-enabled EVs and PHEVs to realize revenues from the regulation market that offset operating costs, making them more cost competitive with conventional vehicles. We built 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 modified and adapted a simulation model developed by a grid system operator. Based on exploration of numerous scenarios we determined which combination of factors produced the lowest total cost of ownership. Additionally, we conducted sensitivity analysis on battery size. Our results indicate that EV and PHEV fleets offer lower operating expenses for urban pickup and delivery services than internal combustion engine vehicles (ICE). In addition, fleet managers can expect to offset 5-11% of the total cost of ownership with V2G revenue.**

***Index Terms*—Vehicle-to-Grid, V2G, Ancillary services, Electric vehicles, Plug-in hybrid electric vehicles, Fleet management, Total Cost of Ownership.**

I. Introduction

Fossil fuels are currently the main source of energy for on-road transportation in the United States [1]. As fuel costs rise, businesses struggle to keep operating expenses low for internal combustion engine (ICE) vehicles and alternatives vehicles (AV) become more attractive due to low energy and maintenance costs and favorable acceptance by drivers. While EVs and PHEVs provide lower overall operating costs, they require more 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 system operator. Vehicle-to-Grid technology (V2G) enables PHEVs and EVs to connect to the electric grid and provide energy services. In a V2G system the vehicle acts as a distributed power resource, acting as a generation and storage device, through integration with the grid [2]. In theory, V2G could be a viable way to improve the cost-effectiveness (and promote the adoption of) EVs and PHEVs through revenue from participating in the ancillary services market.

Our study examines the benefits of V2G at a fleet-level perspective, focusing specifically on corporate fleets of grid-enabled trucks that are used on a daily basis to deliver products and services. To do so, we built a ten year projected cash flow model for each vehicle type that includes: (1) the ownership costs (capital investments, infrastructure costs, and operating costs); and (2) the potential revenue of providing ancillary services, specifically regulation services, in New England. We evaluate the net present values (NPV) of the projected cash flows under various scenarios to provide a better understanding of V2G opportunities and of the business case for adopting EVs and PHEVs in delivery fleets.

This paper also outlines an analytical methodology for further investigation on the topic. The key analytical contributions from our research include: (1) a detailed cost model for corporate fleets that can be customized to include data specific to any company; (2) a projected cash flow model, modular and adaptable to various economic situations; and (3) a simulation tool for V2G revenue, particularly for regulation service revenue[1].

II. Conceptual Framework

We explored two fields central to the development of our research: (a) alternative vehicles, namely EVs and PHEVs, and the benefits they provide to companies adopting them into their operations; and (b) V2G and its relation with ancillary services.

A. Alternative Vehicles

EVs are exclusively powered by an electric motor and battery, and have an approximately 100 mile driving range with no engine to expand this range. PHEVs are powered by an internal combustion engine as well as a battery and electric

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[1] The revenue simulation tool was originally designed by ISO New England. We modified and adapted it for fleets participating in V2G regulation services.

motor. PHEVs have approximately 20-40 miles of pure electric driving range, but can also drive longer distances due to their gasoline or diesel engine. Both have in common the capability to plug into the grid and produce electricity through regenerative braking [3].

AVs have shown to provide operating savings compared with diesel or gasoline ones, not only in fuel costs but in maintenance. Fleet managers estimate that the annual maintenance costs for an electric vehicle are approximately 10% of the total maintenance costs of their diesel counterparts: $250 rather than $2,700. Electric trucks costs upwards of $30,000 more than diesel vehicles, but the expense can be recovered in 3.3 years due to the cost savings through operating these vehicles. However, companies need to be cautious about the accuracy of these numbers due to the fact that part of the savings are due to the relatively low prices of trucks through federal grants provided to the vehicles manufacturer [4].

In spite of AVs' benefits, there are still barriers to their widespread commercial production: the battery cost. The high expense of lithium ion battery systems, the technology of choice today, will probably remain so for some years to come [5]. However, it is expected that by 2020, battery costs will decrease by 50% mainly due to projected increases in the scale of operations, technological innovations, design standards, and sources [6], [7], [8]. Experts hypothesize that AVs will reach a 50% market share by 2020, up notably from their current market share of less than 10%, which will transform the auto industry, mainly due to their favorable fuel economy and reduced emissions [3], [6].

B. *Vehicle-to-Grid and Regulation Services*

In order to maintain a reliable operation, the Independent System Operator (ISO), contracts out with utilities and other suppliers for the provision of ancillary services. Ancillary services are defined as those services necessary to support the transmission of electric value from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system [9].

Our research focuses on regulation service, the use of on-line generation equipped with automatic generation control (AGC) that can change output quickly (MW/min) to track the moment-to-moment fluctuations in customer loads (demand) and to correct for the unintended fluctuations in generation (supply). Regulation helps to (1) maintain interconnection frequency, (2) manage differences between actual and scheduled power flow between balancing areas, and (3) match generation to load within the balancing area [10].

The deviation between load and generation is known as area control error signal (ACE) and is measured in MW. Fig. 1 depicts the variation in ACE during an hour. The grid is at equilibrium at zero MW and the signals fluctuate around this point. When the ACE is less than zero MW, the grid is requesting energy from its regulation service providers through a process called "regulation up" or "ramp up". When the ACE is greater than zero MW, the grid is providing energy to its regulation service providers through a process called "regulation down" or "ramp down". In traditional resources without storage capabilities, such as coal or gas plants, ramp down is a decrease in generation below certain MW point.

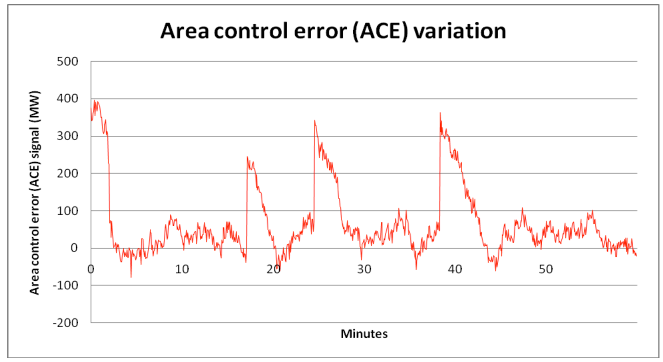

Fig. 1. ACE Signal variation

A regulation provider is compensated via three different payments: capacity payment (for being an available energy or storage source to the grid regardless of whether it is used or not), service payment (for the actual amount of energy [kWh] charged or discharged), and opportunity cost payment (for the revenue foregone by sitting idle rather than generating) [11].

Regulation services have historically been provided by gas, coal, and fuel plants; but as the ISOs are in continual search for cheaper, cleaner, and more reliable resources, new ways to provide these services are being explored. Such examples include renewable energy resources such as hydropower, biomass, geothermal, wind, and photovoltaic cells (or solar energy), as well as grid-scale batteries, compressed air, and flywheels. In addition to these alternative resources, V2G is becoming a possible future option.

In order for vehicles to participate in electricity markets, they must have a power connection to the grid to facilitate the flow of energy, a control or logical connection in order to communicate with the grid operators, and precision metering on-board the vehicle to maintain electricity levels. The re-chargeable battery and bi-directional power capability in EVs and PHEVs make them well suited to provide ancillary services to the grid while parked. Regulation services are a likely the first step for V2G because of high market value and minimal stress on the vehicle power storage system [12].

III. MODEL DESCRIPTION AND CONFIGURATION

We modeled the economics of the investment, infrastructure, and operating costs as well as the potential grid revenues for each type of vehicle (EV, PHEV, and ICE) through a ten year projected cash flow model. The cash flows were based on a standard fleet size and compared using the NPV at a 10% discount rate. The 10% discount rate is based on the 10 year Treasury note, which is yielding around 3%, plus a 7% risk premium due to the fact that this is a high-risk business proposition with a lot of unknown variables. Below we discuss in detail the cost model and the revenue simulation model used to calculate the projected cash flows.

A. Cost Model

The costs are limited to the products and services that a company must pay to operate its fleet. We organized the costs in our analysis into three subgroups: capital costs, infrastructure costs, and operating costs. Operating costs are further broken down into nine components listed in TABLE I. Our model calculates the accumulated operation life of the fleet and its components. For example, when a component reaches its expected life, a cash flow for the purchase and installation of a new part is generated.

TABLE I
CASH FLOW MODEL COST COMPONENTS

Cost	EV	PHEV	ICE
Capital costs	X	X	X
Infrastructure costs	X	X	
Operating costs			
Electricty	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

1) Capital

We assumed that the company purchases new vehicles, originally manufactured to operate as an EV, PHEV, or ICE, in year zero; and thus the capital investment is the cost of the new delivery vehicles.

Through the American Recovery and Reinvestment Act (or “Stimulus Bill”), the federal government offers subsidies for EVs and PHEVs. Some states also offer subsidies. Buyers of plug-in hybrid and electric vehicles benefit from a tax credit ranging from $2,500 to $7,500, depending on the size of the vehicle’s battery. On the low end of the spectrum, vehicles with a 4 kWh battery pack will qualify for a $2,500 tax credit. This credit maxes out at $7,500 for vehicles with a 16 kWh battery pack. An additional $200 tax credit is added for each Kilowatt-hour thereafter the 16 kWh limit [13].

An ICE is assumed at $50,000. EVs and PHEVs take this cost as a base plus and minus the cost of the applicable components. The overall capital investment is equal to the cost per vehicle (less the subsidy) times the fleet size.

2) Infrastructure

Changes in infrastructure depend on the desired charging speed, which is defined by the capacity of the charger (kW/vehicle). Fast charging requires an industrial-type electric service (voltage greater than 208 V and amperage above 15 A). While these factors make fast charging stations more complicated and expensive for the consumer, the government is providing incentives for their implementation. In late December 2010, the federal government continued the tax credit for installation of home-based charging equipment, set to expire at the end of 2011. EV buyers can now claim a credit of 30% of the purchase and costs of the charging equipment, up to $1,000 for individuals and $30,000 for businesses, and these rules are in effect until December 31, 2011 [13].

This up-front cost – accounted for in year zero of our projected cash flow – depends on the fleet size (one charging station per vehicle), the cost of each charging station (depending on the level of charge), and the incentives provided by the government.

3) Operating

The operating costs are organized into nine different components. These costs can be considered as variable costs since they are accrued only during fleet operation (253 days/year), not while sitting idle.

a) Electricity

In our analysis, EVs and PHEVs utilize electricity as energy for propulsion. The ISO New England market features eight "Zones" and nearly 500 "Nodes” each with its own Locational Marginal Price (LMP). Nodal prices vary by time of day, season, and location within the New England region [14].

The cost of electricity also depends on the battery state of charge (SOC) and size of the battery. The electricity necessary to fully charge the batteries is aggregated for the workdays and fleet size. This amount of electricity is affected by the charger efficiency and regenerative braking efficiency. The final amount of energy (including all adjustments) is paid at the LMP, which depends on the location, hour, and day when charging occurs.

b) Diesel

Consumption depends on the number of miles driven per year and the ICE mode efficiency determines how much fuel is necessary to cover this mileage. The cost of fuel per gallon defines the total cost of fuel per year. For the PHEV, the mileage corresponds only to the number of miles operated in hybrid mode. As regenerative braking produces some energy to assist in driving, the fuel efficiency is a specific value for the PHEV. The fuel cost is assumed at $4 per gallon.

c) Battery

We focused our research on lithium-ion batteries. Sources estimate the current cost of lithium-ion battery packs at between $1,000 and $1,200 per kWh [7]. As a consequence of increased manufacturing volume, the impacts of federal subsidies, and technological advancement, batteries for automotive use are expected to follow a descending trajectory, with $500/kWh attainable by 2020, and even greater declines thereafter [1], [8].

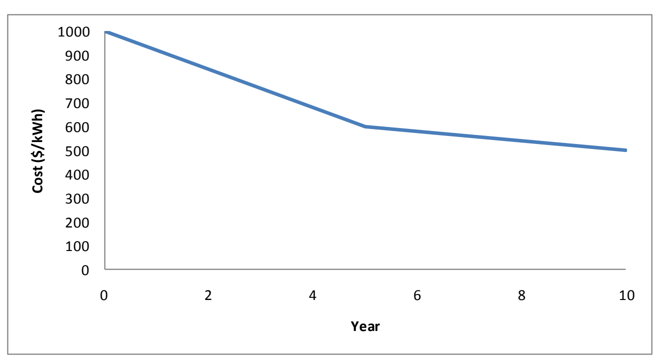

Fig. 2. Estimates of electric-vehicle battery costs reductions.

Battery life is usually measured in terms of cycle stability. Cycle stability corresponds to the number of times a battery can be charged and discharged before being degraded to 80% of its original full charge capacity [7]. However, not all cycles harm a battery to the same extent. Deep cycles, which drain the battery to a low point or high depth of discharge (DOD), are more harmful to cycle life than draining to a low DOD. Fig. 3 depicts the expected cycle life performance of a lithium-ion battery as a function of the DOD. When a battery has a high DOD the cycle life decreases significantly.

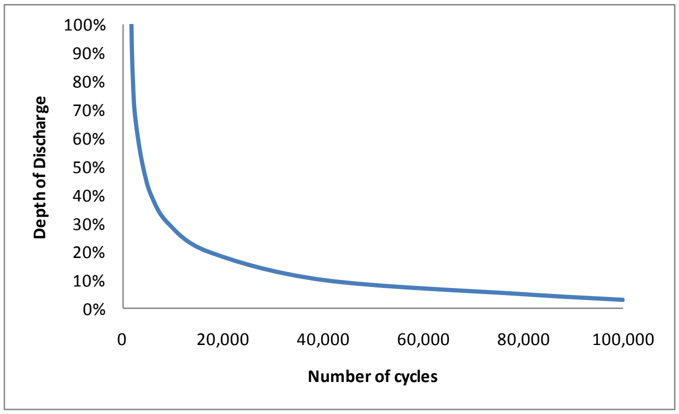

Fig. 3. Cycle life of a lithium-ion battery.

A question that remains is whether or not participation in V2G will also degrade battery life. Reference [15] argues that using vehicles' batteries for V2G energy incurs approximately half the capacity loss compared to the rapid cycling that is encountered while driving. The percent capacity lost (per normalized Wh or Ah processed) is quite low: 0.006% for driving support and 0.0027% for V2G support. The analysis shows that several thousand driving/V2G days incur substantially less than 10% capacity loss, regardless of the amount of V2G support used.

Our cash flow model assumes that the battery is drained to a given state of charge (SOC), a parameter in the model, and then re-charged each workday. According to the average depth of discharge, the battery will last a certain number of cycles.

Unlike ICEs or PHEVs, which can stop at any gas station to fill up their tanks, EVs are able only to run the number of miles corresponding to the amount of electricity stored in the battery. Due to the limited charging infrastructure, we assume these vehicles are able to recharge only when they get back to the garage. For this reason, it is extremely important to design the battery according to the expected mileage. EVs' battery size was calculated as

$$BS_{EV} = \frac{\left(AVMMILE + \left(0.2 \times AVMILE\right)\right) \times KWHM}{\left(1 - STCH - \left(1 - BEFF\right)\right) \times \left(1 + REGEN\right)}, \qquad (1)$$

where *AVMILE* is the average miles per vehicle per day (70 miles), *KWHM* is the electric mode efficiency (0.8 kWh/mile), *STCH* is the minimum state of charge, *BEFF* is the battery efficiency (90%), and *REGEN* is the percentage of electricity gained by regenerative braking (14%). The term "$0.2 \times AVMILE$" in (1) adds an additional 20% to the average miles per day. Since 70 miles is a daily average, some trucks can travel more than 70 miles in a given day. Including this percent adds a buffer to the mileage range. The battery size for the PHEV is a fixed value that we manipulated in the simulation runs, taking on three different values: 3.9, 10, and 20 kWh.

d) Controller

The controller is a computer that controls various parts of the vehicle, such as the battery, motor, and brakes. The objective of the controller is to provide an efficient use of the energy stored in the batteries. It uses algorithms previously loaded in the computer to determine the flow of energy. Controllers are valued at $1,500 apiece.

e) Charger

There is no standard amount of time required to charge a battery; instead, charging times are mainly a function of the amount of power the charger can deliver and the battery capacity, although charging times also vary according to battery chemistry.

Level 1[2] charging is performed through a regular household plug, requiring no infrastructure change. However, the time to fully charge the battery is significant if the battery is large. Level 2 charging charges the battery faster but not all homes and businesses have wiring that would support this level. Upgrades could cost anywhere from $500 to $2,500, depending on the wiring already installed in the home. Finally, Level 3 charger charges the battery at the fastest rate, but it is still in its experimental stages and no final standards have been determined. Depending upon its configuration, Level 3 charging could provide an 80% recharge for a 30 kWh battery in less than 10 minutes. This technology is proposed for use on roadsides, as the equivalent to an "EV gas station," and is expected to cost somewhere between $25,000 and $50,000 per unit [1].

f) Brakes

Diesel delivery trucks require an annual brake change whereas the electric trucks can go up to five years before needing new brakes (primarily due to the face that regenerative braking puts less stress on the brakes). When the vehicle is braking, the electric motor on a PHEV and EV acts as an electric generator to convert kinetic energy into electric energy and store it in the battery. Since the motor performs some of the stopping force, the brakes do not wear out as fast. Brake replacement can reach $1,200 per vehicle [4], [16].

g) ICE Engine

Both PHEVs and ICEs utilize diesel engines. Diesel engines are far more complex than electric motors given the high number of moving parts and fluids that intervene in the combustion process. The cost of ICE engines, although very variable, can be around $5,000.

h) Electric Motor/Generator

[2] Level 1 chargers support up to 2.4 kW, Level 2 up to 19.2 kW, and Level 3 up to 250 kW. We used four different chargers to be manipulated in the simulation runs: 1.92, 6.24, 19.2, and 30 kW.

Electric motors are present in EVs and PHEVs. Electric motors need less maintenance and are far less complex than diesel engines, they last much longer, and the training required to operate them is minimal. Electric trucks also don't need the urea exhaust-cleaning system of diesels, which costs about $700 a year to maintain [4]. The cost of an electric motor can be around $2,000.

i) Maintenance

The average maintenance costs for the EVs are $250 per year per vehicle, and the ICE maintenance costs are approximately $3,400 [16]. The maintenance cost for the PHEV is an average of the costs for EVs and ICEs, weighted by the percentage of miles driven in each mode.

B. Revenue Simulation Model

In order to calculate the opportunity for V2G revenue, we simulated fleets of EVs and PHEVs participating in the regulation services market. First, we simulated the ramp down only approach. Under this approach the fleet only responds to the ISO signals that request energy storage. Experts predict that ramp down only will be the first step for V2G regulation services [17], [18]. Following the ramp down only approach, we simulated the ramp up & down approach. In this scenario the fleet responds to both charging and discharging signals from the ISO. Since the ICE does not have the capability to connect to the grid, it is not included in revenue projections.

The ISO New England provides participants with a market-based system for the purchase and sale of the regulation service. Generation owners submit unit-specific offers to provide regulation, and the ISO utilizes these offers to calculate an hourly real-time regulation clearing price (RCP). This clearing price is then used to determine the time-on-regulation credits (Capacity Payment) and regulation service credits (Service Payment) awarded to providers of regulation. Providers of regulation also receive compensation for regulation opportunity cost (Opportunity Payment).

TABLE II
CASH FLOW MODEL REVENUE COMPONENTS

Revenue	EV	PHEV	ICE
Capacity payment	X	X	
Service payment	X	X	
Opportunity cost payment			

ISO New England provided us with a simulation tool that they use to estimate revenues for the provision of regulation services. This simulation was originally developed for resources different to V2G, so we modified and adapted the tool to our context. It is a deterministic simulation that processes historical data using standard rules and procedures to calculate payments. We were also provided with ACE and RCP historical data.

1) Capacity payment

The capacity payment is for the maximum capacity contracted for the time duration (regardless of whether it is used or not). Capacity is calculated according as

$$Cap = RCP \times TRM \ , \tag{2}$$

where *RCP* is the regulation clearing price in dollars per Megawatt and *TRM* is the time-on-regulation in Megawatts. *TRM* in turn is defined by

$$TRM = \mathrm{Reg} \times \frac{MR}{60} \ , \tag{3}$$

where the *Reg* is regulation capability, the amount of power that the participant, the corporate fleet in this case, is able to provide to the ISO for regulation and *MR* is minutes of regulation, the total time during the hour that the participant is able to provide the service [11].

2) Service payment

The regulation service is a payment for the actual amount of energy (kWh) charged or discharged. It is calculated by

$$Svc = RCP \times RSM \times CSR \tag{4}$$

where *RCP* is the regulation clearing price, *RSM* is the regulation service megawatts (the sum of absolute values of the differences in regulation provided between successive four second samples during an hour), and *CSR* is a dimensionless capacity-to-service ratio calculated by the ISO such that the total revenues received for time-on-regulation megawatts (TRM) and regulation service megawatts (RSM) is split equally between the two services. The CSR is set equal to 0.1 [11].

3) Opportunity cost payment

The opportunity cost payment is intended to compensate resources belonging to the wholesale generation market for the revenues they forego by participating in the regulation market instead of the wholesale generation market. A corporate fleet providing regulation services is not considered such a resource, so that no opportunity cost payment is calculated.

4) Total yearly payment

The revenues calculated by the ISO simulation tool are limited to only four weeks of the year, one week per season. The simulated weeks are assumed to have five business days. As our cash flow model is set up in terms of years, so that the results of those four weeks were extrapolated to the whole year. Our model assumes 253 workdays per year, which means that the year has 50.6 5-day weeks (253/5). We also assume that the four seasons of the years have the same number of weeks. In that case, we find that every season has 12.65 5-day weeks (50.60/4). This is the factor we used to extrapolate the revenues of the four simulated weeks to the entire year.

IV. Results and Sensitivity Analysis

Our analysis projected cash flows for a 250-vehicle fleet that provides pickup/delivery services over routes averaging 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 first ran these approaches modifying the most important parameters to determine how they affect ownership costs. The manipulated parameters were battery size; charger size; state of charge (SOC) when plugging into the grid; and regulation period. We chose three different values for each parameter according to the component availability in the market and the current practices by corporate fleets. TABLE III presents the analyzed values for each parameter. Parameters in TABLE III apply for both ramp up & down and ramp down approaches. We do not define parameters for ICEs since they cannot plug into the grid and generate revenues.

TABLE III
EVALUATED PARAMETERS' VALUES

Parameter	EV	PHEV
Battery size (kWh)	85 / 99 / 118	3.9 / 10 / 20
Charger size (kW)	6.24 / 19.2 / 30	1.92 / 6.24 / 19.2
SOC (%)	20 / 30 / 40	30 / 50 / 70
Regulation period	16-4 / 18-6 / 20-8	16-4 / 18-6 / 20-8

Among all combinations of the parameter values, we determined that the configuration that produced the lowest total cost of ownership, i.e. the best combination. TABLE IV and TABLE V show the results of the best combination of parameters for the ramp down and ramp up & down approaches, respectively.

For EVs, the configuration is the same for both ramp up & down and ramp down approaches. For PHEVs, all parameter are equal except the battery size. The 10-year costs are further broken down into units that may be more familiar with fleet managers – cost per mile, revenue per vehicle per year, reduction in cost due to V2G revenue, and savings with respect to ICE.

TABLE IV
RAMP DOWN BEST COMBINATION RESULTS

Parameter		Ramp Down – V2G EV	Ramp Down – V2G PHEV	ICE
Battery size (kWh)		99	10	n/a
Charger size (kW)		19.2	19.2	n/a
SOC (%)		30	30	n/a
Regulation period		20:00 - 8:00	20:00 - 8:00	n/a
10 year total	Cost	$32,529,037	$32,723,614	$33,198,377
	V2G Revenue	$ 2,268,780	$ 1,758,834	$ -
	Net Cost	$30,260,257	$30,964,780	$33,198,377
per mile	Cost	$ 0.735	$ 0.739	$ 0.750
	V2G Revenue	$ 0.051	$ 0.040	$ -
	Net Cost	$ 0.683	$ 0.699	$ 0.750
V2G Revenue per vehicle/year		$ 907.51	$ 703.53	$ -
Reduction in costs from V2G		7.0%	5.4%	0.0%
Savings vs. ICE		8.9%	6.7%	n/a

TABLE V
RAMP UP & DOWN BEST COMBINATION RESULTS

Parameter		Ramp Up & Down - V2G EV	Ramp Up & Down - V2G PHEV	ICE
Battery size (kWh)		99	20	n/a
Charger size (kW)		19.2	19.2	n/a
SOC (%)		30	30	n/a
Regulation period		20:00 - 8:00	20:00 - 8:00	n/a
10 year total	Cost	$32,747,383	$33,032,631	$33,198,377
	V2G Revenue	$ 3,499,284	$ 3,124,115	$ -
	Net Cost	$29,248,099	$29,908,516	$33,198,377
per mile	Cost	$ 0.740	$ 0.746	$ 0.750
	V2G Revenue	$ 0.079	$ 0.071	$ -
	Net Cost	$ 0.661	$ 0.676	$ 0.750
V2G Revenue per vehicle/year		$ 1,399.71	$ 1,249.65	$ -
Reduction in costs from V2G		10.7%	9.5%	0.0%
Savings vs. ICE		11.9%	9.9%	n/a

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. Additionally, EVs' bigger batteries and chargers produce higher revenue than PHEVs given their ability to provide and store more energy, as well as the possibility to offer higher regulation power. As expected, the ramp up & down approach produces much higher V2G income than ramp down alone, but it is less than double.

In the best case, PHEVs can produce up to $1,250 per vehicle per year in V2G revenues, which would allow them to offset ownership costs by up to 9.5% and diminish expenses by 10% with respect to ICEs. On the other hand, EVs can produce up to $1,400 per vehicle per year in V2G revenues, which would allow them to offset ownership costs by up to 10.7% and diminish expenses by 12% respect to ICEs.

Given that batteries currently are the single most expensive component in EVs and PHEVs, we conducted additional sensitivity analysis on battery capacity to determine how different sizes affected revenue and cost. We projected cash flows for one kWh incremental values between four and 20 kWh for PHEVs for both ramp down and ramp up & down approaches. We found that the best size among these incremental options is 16 kWh in both cases. Total ownership cost is reduced a further 0.37% and 0.43% under the ramp down and ramp up & down approaches, respectively, around $120,000 over the 10-year period for our 250-vehicle fleet.

We also discovered that charger capacity, rather than battery size, had more impact on V2G revenue. Evaluating results from several scenarios, we discovered that the V2G revenue often scaled up at nearly the same rate as the charger capacity, e.g. increasing the PHEV charger capacity by a ratio of 3.25 (from 1.92 to 6.24) typically tripled the revenue. At the same time, the incremental revenue from increasing battery size led to much smaller gains in revenue, e.g. increasing the in battery size by a ratio of 2.5 (from 3.9 to 10) led to only a 6% increase in revenue. However, there are diminishing returns when considering the total cost, as the 30 kW (Level 3) requires much higher investment. A 19.2 kW charger offers the best return on investment for both EVs and PHEVs.

The SOC also plays a role in the balance between revenue and cost. The highest 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 showed that 66% of them 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.

The timing for connection to the grid also has a large impact on revenue. Our analysis showed that the average regulation clearing price between 6AM and 8AM was 42% higher than between 6PM and 8PM, which means benefits for managers with flexibility in start time for fleet service operations. Electricity costs (LMP) are lower during this period, which would reduce operating costs as well. Also, revenues can increase by up to 30% for each additional hour connected.

V. Conclusions

Adopting EVs or PHEVs and incorporating V2G technology can provide savings in overall costs with respect to ICEs. Based on our analysis, significant savings in operating expenses and incremental revenue from grid services offsets higher capital and infrastructure investments.

V2G revenue potential for fleets is significant enough to pursue. According to our calculations, an EV/PHEV can earn $700-900 per year per vehicle performing ramp down regulation services, resulting in a 5-7% reduction in cost. Further, an EV/PHEV can earn $1250-1400 per year per vehicle with ramp up & down regulation services, resulting in a 9-11% reduction in cost.

The design mix of charger capacity, battery size, and battery state of charge has an important impact on V2G revenue potential. Flexible operations and the ability to adjust fleet operating schedules can realize notable increases in marginal V2G revenue.

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.

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