Building a business case for corporate fleets to adopt vehicle-to-grid technology (V2G) and participate in the regulation service market

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Abstract

Electric (EV) and Plug-in Hybrid Electric vehicles (PHEV) continue to gain attention and market share, not only as options for consumers but also for corporate fleets. EVs and PHEVs can contribute to lower operating costs through reduced maintenance requirements and enhanced fuel economy. In addition, a fleet of EVs or PHEVs, when parked and aggregated in a sizeable number, can provide regulation services to the grid through the electricity stored in the vehicle's batteries. This opportunity is known as Vehicle-to-grid technology (V2G). This thesis evaluates the economics for V2G-enabled fleets to participate in the regulation services market. In order to build a business case for fleet managers, we constructed a 10-year cash flow model that compares the operating, infrastructure, and capital costs, as well as the revenue opportunities for EVs, PHEVs, and ICEs. To quantify potential revenues, we adapted a tool that the ISO New England has used to simulate the revenues of participants in the regulation market for an alternative energy pilot. We show that ICEs, while having the lowest retail value, actually have the greatest NPV due to their high operating costs and inability to participate in the regulation services market. EVs have the highest retail value, but due to their large battery size are able to provide the most regulation services. The opportunity for V2G is critical for the attractiveness of the EV. PHEVs offer lower V2G revenue opportunity than the EVs but have greater operational flexibility. We determined that V2G revenue potential is driven by the charger capacity and battery size and there are tradeoffs associated with these components. A larger battery and charger will generate more money from regulation services, but their high investment cost may outweigh these benefits. The correct combination of charger capacity, battery size, and state of charge (SOC) is important. If the charger capacity is too large and SOC too high or low, a small battery can be charged or depleted too quickly, hindering its ability to provide regulation services.

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1 Introduction and Motivation

Vehicle-to-Grid technology (V2G) describes a vehicle-connected grid system in which plug-in hybrid (PHEV) and electric vehicles (EV) connect to the electric grid to sell energy storage services to utilities. In a V2G system the vehicle acts as a distributed power resource, providing load and acting as a generation and storage device, through integration with the grid (Guille & Gross, 2009). The common characteristic that enables EVs and PHEVs to participate in 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 due to the fact that 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 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 the batteries in aggregate and model the revenue potential for participating in the frequency regulation market in New England. We then use this financial analysis to assess how the revenue earned through V2G can impact the overall cost of ownership of these vehicles. Finally, we assess if this potential could help promote the adoption of 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). The US dependence on foreign oil, price volatility, and the setting of oil prices by cartels has cost the economy upwards of $5.5 trillion since 1970 and US fuel prices continue to rise (MIT Energy Initiative, 2010). The rise in the cost of fuel affects not only the consumer, but businesses as well. One of the main objectives of a business is to keep its operating expenses low and fleet managers at companies such as Staples, Inc., Frito-Lay, FedEx, and AT&T have recently begun purchasing electric (Ramsey, 2010). A conversation with Mike Payette (Payette, 2011), the fleet manager at Staples, Inc. confirmed a promising future for the adoption of electric vehicles due to their low maintenance and electricity costs and overall favorable acceptance by drivers. While electric (EV) and plug-in hybrid electric (PHEV) vehicles provide lower overall operating costs, they continue to remain more expensive to purchase due to the high cost of batteries and lack of proliferation in the marketplace.

As previously stated, EVs and PHEVs can plug into the grid to charge their batteries. A fleet, when aggregated in a sizeable number, constitutes a new demand load that the electricity system must supply. However, an EV or PHEV can be much more than a simple load due to the fact that bi-directional power transfer is possible when an interconnection is implemented. Given the fact that vehicles remain parked for a large part each 24-hour day, the integration with the grid allows the deployment of EVs to act as a generation resource as well as a storage device for the system operator (Guille & Gross, 2009). In order to maintain a reliable operation, the system operator, commonly known as an Independent System Operator (ISO), contracts out with utilities and other suppliers for the provision of ancillary services. Such services include frequency control, regulation, load following, energy imbalance, spinning reserve, supplemental reserve, non-operating reserve, and standby service.

Many different sources agree that regulation services will be the first step for V2G because (1) it has the highest market value for V2G among the different forms of electric power, (2) it minimally stresses the vehicle power storage system, and (3) battery-electric vehicles are especially well-suited to provide regulation services (Tomic & Kempton, 2007). Regulation uses on-line generation equipped with automatic generation control (AGC) and can quickly change output (MW/min). It tracks the moment-to-moment fluctuations in customer loads and corrects for the unintended fluctuations in generation. Regulation helps to maintain interconnection frequency, manage the differences between actual and scheduled power flows, and match generation to load, or supply to demand (Kirby, 2007).

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 energies, V2G technology is becoming a possible future resource. With V2G the utility offers a *capacity payment* for being an available power source to the grid and an *energy payment* for actually supplying energy to the grid. The capacity payment is for the maximum capacity contracted for the time duration regardless of whether it is used or not. The energy payment is for the actual kWh of energy produced (Kempton & Tomic, 2004a).

In order for vehicles to participate in electricity markets, a vehicle must have the following elements: (1) a power connection to the grid to facilitate the flow of energy, (2) a control or logical connection in order to communicate with the grid operators, and (3) precision metering on-board the vehicle to maintain electricity levels (Tomic & Kempton, 2007). While the utilities will benefit from these energy sources, corporate fleets can also generate revenue through their participation in the service. The V2G market is expected to be worth around $2.9 billion by 2020 (Zpryme, 2010) and corporate fleets are expected to make up a sizeable share of the market.

For the purpose of this project, we built a business case for fleets of V2G-enabled vehicles to participate in the regulation services market. One of the main goals of a company is to increase its profitability. Through our analysis, a fleet manager can use the business case to decide whether it makes economic sense for them to adopt electric and plug-in hybrid electric vehicles in their fleet and participate in the V2G market. Our project consists of three main components: (1) a study of electric (EV) and plug-in-hybrid vehicles (PHEV); (2) an examination of the operational cost savings through operating a hybrid or electric vehicle in lieu of a conventional vehicle; and (3) the prospective additional revenue to be gained through connecting to the electric grid and providing ancillary services.

In order to fully understand the possible opportunities of embracing V2G technology and to build a business case, we performed a thorough review of the available literature on the topic and had several meetings with industry insiders, including a market analyst at the ISO New England (Lowell, 2011), a fleet manager for a prominent office supply store (Payette, 2011), a postdoctoral researcher on the future of the electric grid (Heidel, 2011), an MIT lecturer from the Energy Ventures class (Hynes, 2009), the Director of the Analysis Group for Regional Energy Alternatives (AGREA) (Connors, 2011), and the CEO of Automotive Career Development Center (ACDC) (Van Batenburg, 2011). In addition, we explored the current rate of adoption of electric and plug-in hybrid electric vehicles as well as the factors limiting their adoption, including their high retail cost. In order to build a business case, we broke down each component, for each vehicle type, which adds to the operational costs of the vehicle (e.g. the cost of the battery, yearly maintenance costs, electricity and fuel costs) as well as the lifetime of each component. Finally, we took the appropriate components and built a ten year net present value cash flow model for each vehicle type: an electric vehicle, a plug-in hybrid electric vehicle, and an internal combustion engine vehicle. This cash flow model served as a working tool with the capability to be customized to a specific fleet owner's specifications. In addition to evaluating each of the operational costs, the valuation process also included an examination of the sources of revenue to be gained through participation in V2G, namely regulation services. We simulated the economics of a corporation having hundreds of alternative vehicles and identified implementation strategies for fleet managers.

Throughout this research we worked with XL Hybrids, an MIT startup based in Somerville, Massachusetts. XL Hybrids currently retrofits commercial fleet vehicles into battery electric vehicles through a process called hybrid conversion. Their target customer base consists of fleet owners looking to embrace the benefits of hybrid technology. This project will help prepare XL Hybrids to capitalize on future V2G opportunities when the company offers a plug-in hybrid conversion system starting in 2012. XL Hybrids can use the results of our simulations to build a business case of their own. The working simulation we develop can be used to help them decide if it is economically feasible for them to act as an aggregator, attracting and providing the necessary services for vehicles to participate in the ancillary services market. The final results of our simulations will not only be helpful for XL Hybrids and owner/operators of corporate fleet vehicles, but can also have an impact on efforts to decrease the United States' dependence on foreign oil and reduce the environmental impacts of fossil fuels.

2 Literature Review

Vehicle-to-Grid (V2G) is an innovative technology that is still in its developmental stages. The benefits of V2G are not fully understood, and the literature related to this topic is relatively scarce. The majority of available publications correspond to academic works, such as theses and research papers, lectures, conferences, interviews with pundits, and popular press articles. These resources theorize about the potential applications and benefits of the technology and highlight some short-range experiments employing a few vehicles. The bibliography on V2G and its related research reflects the nascency of this field of study; the first papers date to the late 1990s and most publishing has occurred after 2006. In addition, the literature available on the topic concentrates mostly on passenger cars, contrasting with our corporate fleet scope.

Since V2G is a young and developing technology, the approaches and postulates concerning the field may change. We aimed our efforts at studying the most current literature in order to gain a fundamental understanding of the technology and its related concepts. Through this review, we attempt to document the significant sources of information and identify the necessary knowledge needed to answer our research question and prove our hypothesis.

2.1 An Examination of the Electric and Plug-In Hybrid Electric Vehicle Market

Electric and plug-in hybrid electric vehicles constitute research fields in themselves and we have conducted an extensive investigation on each vehicle type. A research report by Shanker and Steinmetz (2008) from Morgan Stanley hypothesizes that PHEVs will transform the auto industry in the next ten years; mainly due to their favorable fuel economy and reduced emissions. Unlike pure electric vehicles which are powered by an electric motor and battery, plug-in hybrids are powered by an internal combustion engine as well as a battery and electric motor. While hybrid electric vehicles also use an electric motor that is powered by a battery pack, the battery on the PHEV can be recharged from the grid whereas the battery on an HEV is recharged solely through regenerative braking. PHEVs have approximately 20-40 miles of pure electric driving range, but can also drive long-distances due to their gasoline engine (Steinmetz & Shanker, 2008). In contrast, pure electric vehicles have an approximately 100 mile driving range with no engine to expand this range.

Markel and Simpson expand on the key benefits of PHEV technology; PHEVs are not dependent on a sole source of fuel and can achieve dramatic petroleum consumption reductions (Markel & Simpson, 2006b). These authors also note some of the barriers to widespread commercial PHEV production: the battery life, packaging, and cost. An article by Millner et al. notes the barriers of the high expense of lithium ion battery systems, the technology of choice today, which will probably remain so for some years to come (Millner, Judson, Ren, Johnson, & Ross, 2010).

Due to the fact that the battery is the most important component in these systems, more extensive research has been conducted on battery technology. The consulting firm PRTM has widely documented the options as well as the barriers for broad adoption of alternative vehicles (PRTM, 2010b). In a 2010 presentation, they clearly defined the differences between HEVs, PHEVs, and EVs, stating that they expect alternative vehicles to reach a 50% market share in the future, up notably from their current market share of less than 10%[1]. PRTM estimates the battery market to reach $40 billion in 2013 and $95 billion in 2020. PRTM's analysis also evaluates the evolution of battery costs for each type of technology and estimates a 50% reduction in battery prices from 2010-2020, mainly due to projected increases in the scale of operations, technological innovations, design standards, and sources (PRTM, 2010a).

A research report by Morgan Stanley also highlights the benefit of lithium-ion batteries for use in hybrid and electric vehicles due to their high energy capacity (contributing to more efficient packaging) and low "memory effect" leading to efficient charging and discharging times (Steinmetz & Shanker, 2008). The Boston Consulting Group (BCG) ran a study on Batteries for Electric Cars, projecting costs out to 2020. BCG also stresses the fact that battery costs will decline significantly as the production volumes increase,

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[1] These percents include both passenger cars and trucks.

but asserts that the costs of raw materials and standard, commoditized parts, which represent 25% of overall costs, will not change with the increase in volume. Overall, BCG forecasts that the battery cost to consumers will fall from an estimated $1,400 - $1,800 per kWh to $570 - $700 per kWh by 2020; a significant overall reduction in costs (Dinger, et al., 2010).

An article in Technology Review by Peter Fairley also estimates battery costs along a ten-year period, beginning in 2010, and the additional costs of a PHEV over a conventional ICE vehicle. Battery costs are expected to decrease by 50% during this period. The author makes a helpful comparison of battery capacity, electric range (in miles) and projected price for various PHEV and EV. It also estimates the CO_2 emitted per mile driven for each vehicle type. However, as most of the literature reviewed above, these references concentrate on passenger vehicles and include estimates rather than observed measures (Fairley, 2011).

To gain a more fleet-oriented perspective, we conducted an interview with Mike Payette, the Fleet Equipment Manager of Staples, Inc., which has recently added 50 electric trucks to its delivery fleet. The interview offered realistic operating data (e.g. vehicle ranges and types, operating hours, operating and maintenance costs) that form the basis of our fleet assumptions (Payette, 2011). However, further data were scarce and rather static, and no definitive trends or evolution in costs and performance could be definitively discerned.

2.2 Operational Cost Savings

Alternative vehicles have been in use for more than a decade. While these vehicles generally have a greater capital expense, PRTM estimates that by 2012, PHEVs will reach a parity with internal combustion engine vehicles (ICE) in terms of ownership costs, including capital expenses and operating costs (PRTM, 2010b).

Mike Ramsey (2010) presents an analysis of the operational benefits that three companies have achieved by using electric trucks in their commercial fleets. Staples Inc., the Frito-Lay division of PepsiCo, FedEx

Corp, AT&T, and a few other firms have begun employing electric delivery trucks. Currently, FedEx is employing 19 electric vehicles in London, Paris and Los Angeles; and Frito-Lay has ordered 176 electric trucks with the goal of employing 2,000 electric vehicles (half of its total fleet) in the future. These vehicles have shown to provide operating savings compared with diesel or gasoline ones, not only in fuel costs but in maintenance. According to Ramsey, the fleet equipment manager for Staples, Mike Payette, estimates 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 according to Payette 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 (Ramsey, 2010). This situation may change as electric vehicle manufacturers believe their costs are decreasing enough to not have to raise their prices after the federal grants issued to the fleets employing electric vehicles expire (Ramsey, 2010).

Several researchers have attempted to develop models that take into account the variables that drive the costs of alternative vehicles, such as electricity and fuel, spare parts and maintenance costs. These models are usually aiming to determine an average operational cost and compare it to the operational costs of ICE vehicles in order to demonstrate the benefits of adopting alternative vehicles. Dr. Willet Kempton, one of the prominent researchers in the V2G field, together with Leonard Beck developed a spreadsheet model to calculate the savings and earnings from operating electric vehicles and participating in V2G (Beck & Kempton, 2008). Kempton's model considers a ten-year evaluation but makes no adjustments for the time value of money. Further, the model evaluates performance for only one or two passenger vehicles and does not highlight the potential for multiple trucks, vans and other fleet vehicles. This model became a baseline tool for our research. Throughout the course of the project we added various features to create a more extensive working tool.

2.3 Vehicle-To-Grid Technology

In order to understand V2G, one must understand key concepts in electric grid infrastructure. We had access to the class notes from a lecture on the US Electricity Value Chain in an Energy Ventures class and attended a presentation where the instructor explained the components of the electric grid infrastructure. Discussion topics included an explanation of electricity generation, transmission, and distribution, grid operation, regulatory practices, and the requirements for a smart grid (Hynes, 2009). This information helped us more effectively incorporate the utilities and grid operators as well as the ancillary services and regulation markets into our research.

Dr. Tim Heidel believes there are distinct opportunities for V2G: Grid-to-Vehicle and Vehicle-to-Grid. Grid-to-Vehicle involves a very intelligent charging of the vehicle's battery serving as a regulation service; and Vehicle-to-Grid involves the vehicle providing the grid with power. Dr. Heidel is unsure of the prospect for V2G to become a prevalent solution in the near future. While he does not think that the economics are favorable and the electric vehicle market has not gained enough traction to be a notable source of energy, he believes electric vehicles can be utilized as a capacity resource for certain grid services. Batteries can respond very quickly to signals from the grid (at a faster rate than conventional energy resources) and thus will be paid a premium for their rapid response time. Dr. Heidel asserts, however, that a small number of vehicles could saturate the frequency regulation market (Heidel, 2011).

Steven Connors, the Director of the Analysis Group for Regional Energy Alternatives (AGREA) expresses a similar sentiment as Dr. Heidel. He agrees in the potential for Grid-to-Vehicle and the idea of smart variable charging, where the vehicle can adjust to the load and charge only when the grid is able to supply the requested energy. The vehicle is provided with the benefit of participating in regulation services (through ramp down only) as well as purchasing electricity at a lower projected cost. In addition, Like Dr. Heidel, Mr. Connors is unsure of the future of V2G opportunities since the price of regulation services could diminish as the EV market proliferates, affecting the overall monetary benefits of the service (Connors, 2011).

Peterson et al. (2009) examine the economics of battery storage as well as the potential impacts of battery degradation through participation in V2G. They also believe that the market for regulation could be saturated by a small number of vehicles and thus explore the idea of energy arbitrage in lieu of frequency regulation. Arbitrage involves storing energy in the battery during off-peak periods for use in the grid during peak hours. Overall, they see annual profits at around \$140-\$150 per vehicle and around \$10-\$120 per vehicle when battery degradation is accounted for (Peterson, Whitacre, & Apt, 2009b). In their second article Peterson et al. (2009) determined the impact of battery degradation due to driving use and participation in the V2G market. Their results showed promising performance for the batteries as 90% of the original capacity in the battery remained after thousands of driving days (Peterson, Apt, & Whitacre, 2009a).

A paper from the 2010 MIT Energy Initiative Symposium provides good info on the current and project course of the technology and market. The study discusses the background, state-of-the-art, barriers and future of three key areas relevant to our thesis: electrification of transportation, vehicle technologies, and grid infrastructure. Its conclusions are focused on the fact that EVs and PHEVs can help address security, climate, and economic issues associated with oil consumption, but even under the most aggressive deployment scenarios, but vehicles will continue to be dependent upon oil and the ICE for years to come. Increasing the EV penetration rate substantially will require major battery cost reductions and significant build-out of vehicle charging infrastructures. (MIT Energy Initiative, 2010).

Tomic and Kempton map out the three different types of electric drive vehicles (EDVs) that can produce V2G power: battery, fuel cell, and hybrid. The authors also highlight V2G's promise as a back-up source to balance the grid's fluctuations in load and variability in supply (Tomic & Kempton, 2007). Letendre and Kempton had published an earlier article in 2002 that also explained the possible roles that EDVs and ancillary services (spinning reserves and regulation) can play and the benefits that can be gained through V2G. They believe that for battery and fuel cell vehicles, and possibly plug-in hybrids, the net value of this power is over \$2,000 annually per vehicle (Letendre & Kempton, 2002). Guille and Gross (2009) also stipulate the proposed framework for V2G and the possible services that battery vehicles can provide to the grid. Such services include leveling the off-peak load at night as well as storage resources that can charge and discharge energy as needed. The authors also outline the necessary steps to bring V2G to fruition: the communication and control system between the vehicles, their aggregator, and the service operators as well as an incentive scheme between the aggregator and the vehicles (Guille & Gross, 2009).

Finally, an article by Sovacool and Hirsh examines the possible barriers, in addition to possible benefits, that surround the adoption of V2G. Such barriers are not specifically related to technology and include social and cultural values, business practices, and political interests. Sovacool and Hirsh imply that these barriers are important to evaluate, on top of the technological issues, for V2G to move forward and become a viable practice in the future (Sovacool & Hirsh, 2008).

A vehicle's battery can charge during low demand times and discharge when power is needed, i.e. when the demand for electricity has outpaced the supply (Kempton & Tomic, 2004b). Kempton defines the economic value of V2G as the revenue that the vehicle owner can obtain through providing V2G services to the grid operator. Some markets only pay for energy, such as peak power and base load power (power that is provided continuously throughout the day). The revenue generated from these services is simply the product of price and energy dispatched. According to Kempton, however, V2G is not suitable for base load power due to the fact that this energy can be provided by large generators at a much lower cost (Kempton & Tomic, 2004b). Other markets pay for spinning reserves and regulation services.

Even though the concept of V2G was developed more than a decade ago, the application of the technology to fleet vehicles is practically nonexistent. We found only one paper in which this issue is explored. Kempton and Tomic evaluate the economic potential of two utility-owned fleets of EVs to provide power for a specific electricity market. They found that V2G power for regulation services is profitable in the four different markets they analyzed: PJM (dispatching to all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia), ERCOT (Texas), CAISO (California), and the NYISO (New York). The article coincides with our research in that the market value of regulation services, the power capacity (kW) of the electrical connections and wiring, and the energy capacity (kWh) of the vehicle's battery are important variables in the regulation service revenues. However, they reach this conclusion through the development of equations for the calculation of V2G revenues, whereas our model uses a simulation tool provided by the ISO New England (Tomic & Kempton, 2007).

Leonard Beck also conducted an economic analysis of regulation services and is in agreement with several of the other researchers that regulation service has the best near-term earnings proposition for V2G vehicles. He employs basic calculations and concepts to prove the benefits of V2G and his main focus is centered on passenger cars. Additionally, Mr. Beck is aware that the future benefits of the technology are uncertain as the potential of the regulation market can change as the market becomes saturated with V2G-enabled vehicles (Beck, 2009).

2.4 Regulation Services and the Electric Grid

This section describes the market for regulation services. An article entitled "Ancillary Services" by Hirst and Kirby (1996) explains these services using a definition from FERC (Federal Regulatory Energy Commission). FERC defines regulation 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" (p. 1) . The authors delineate the six different types of ancillary services: reactive power and voltage control, loss compensation, scheduling and dispatch, load following, system protection, and regulation (Hirst & Kirby, 1996). For the purpose of this project, our analysis focuses primarily on regulation services. A survey of ancillary services defines regulation as "the use of on-line generation that is equipped with automatic generation control (AGC) and that can change output quickly (MW/min) to track the moment-to-moment fluctuations in customer loads and to correct for the unintended fluctuations in generation" (Kirby, 2007). 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 (Kirby, 2007).

V2G is aimed at the EV and PHEV market. Researchers have theorized that V2G-enabled electric vehicles are ideally suited to serve the regulation and spinning reserve markets (Kempton, et al., 2008). The regulation and spinning reserve markets pay primarily for capacity and an immediate reaction time to requests. Batteries in a vehicle can provide energy storage as well as a quick response to either draw power or send energy back into the grid. These unique features of V2G enabled vehicles are essential factors for a grid system operator to consider when determining where to contract these services (Kempton, et al., 2008). In order to participate in V2G, a vehicle must have the following elements: (1) a power connection to the grid to facilitate the flow of energy, (2) a control or logical connection in order to communicate with the grid operators, and (3) precision metering on-board the vehicle to maintain electricity levels (Tomic & Kempton, 2007).

Since our analysis is based on in a region where the ISO New England manages the grid, important references for our work include the ISO New England Manual for Operations (ISO New England, 2008), paying special attention to the market operations and regulation market sections, and conversations with Jonathan Lowell (Lowell, 2011), a principal analyst at the NE ISO specializing in market development. The ISO has employed various pilot programs in regulation services in the past using various technologies. Some of the alternative technologies involved in the past pilots include fly wheels, large batteries, and a residential electric storage heater, which acts like an aggregator. Mr. Lowell stipulated that the regulation market has declined in the past couple of years from $50 million in 2008 to $15 million in 2010, signaling a small market in which it may be difficult to make a business case. In addition, Mr. Lowell covered the three different payments that the ISO contracts out to participants in the pilot programs: a capacity payment (a payment for being an available energy or storage source to the grid), a service payment (a payment for the amount of energy charged or discharged), and an opportunity cost payment (the money you are losing by not generating energy and sitting idle) (Lowell, 2011).

Using the information we have gained through a review of the available literature, we seek to find ways for V2G to work in the corporate fleet environment. We built a business case that will provide fleet managers solid reasons to adopt or not adopt this technology as they plan for the future.

3 Methodology and Model Overview

The economic viability of V2G is based on technological advancement, energy policy, and operations management. The availability of components and equipment, the expertise to bring the system to fruition, and the legislation and regulation that determine the way in which the technology will operate are the backbone of V2G economic model. As previously mentioned, the scope of our research is to assess the business case for corporate fleets incorporating V2G opportunities, and our efforts are focused on developing a projected cash flow model of the topic. No special emphasis is placed on technological advances. In addition, we do not discuss policy matters, possible tax credits and other incentives, which could offset the fleet's operating costs. Rather we assess different operating approaches using the near-term technological and policy context.

In order to evaluate a system, various modeling techniques can be employed. Some projects use physical models that mimic the physical behavior of the real system by providing, for example, a smaller replica of it. However, when a physical model is neither effective nor possible, as in the V2G case, due to its technological and conceptual infancy and high cost of implementation, analysts resort to analytical models. An analytical model is an abstraction of the real system and tries to capture its essence to assess key issues. A great benefit to this type of model is that it measures how the system is affected by these initial parameters without actually implementing the system. The analyst can analyze the project by trial and error in a relatively short period of time, which would be very difficult to implement with a real system due to time and cost constraints. In order for a fleet manager to consider a big change such as V2G, they must be able to achieve a high degree of certainty that their daily operations will not be adversely affected and the efforts required to incorporate this new process will benefit their bottom line. The ability to run a model with various inputs to reflect different scenarios will enable the analyst to be confident in their results and the fleet manager can be secure that their case has been fully vetted.

We modeled the economics of the investment, infrastructure, and operating costs as well as the potential grid revenues for each type of vehicle (Electric, Plug-in Hybrid Electric, and Internal Combustion Engine) through a ten year projected cash flow model. We use simulation (See Section 3.2) as the tool to assess the grid opportunities for corporate fleets to adopt this technology.

The costs and revenues for each vehicle were modeled with a standard fleet size and compared using the Net Present Value (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. The NPV analysis provides the fleet manager with a distinct figure of the total overall costs and V2G revenue for the ten year period. Figure 3-1 shows an example of a cash flow model for the PHEV. Appendix 1 presents the cash flow models for the best case scenario[2] of ramp up & down for each type of vehicle: EV, PHEV, and ICE.

Component	Year 0	1	2	3	4	5	6	7	8	9	10
Capital investment	14,850,000										
Infrastructure Cost	0										
Electricty cost		67,405	67,405	67,405	67,405	67,405	67,405	67,405	67,405	67,405	67,405
Fuel cost		1,459,079	1,459,079	1,459,079	1,459,079	1,459,079	1,459,079	1,459,079	1,459,079	1,459,079	1,459,079
Battery replacement costs		0	0	0	0	0	0	0	0	0	487,500
Controller Costs		0	0	0	0	0	0	0	0	0	0
Charger, wiring, switches, adapter Costs		0	0	0	0	0	0	0	0	0	0
Brake Costs		0	0	0	0	0	300,000	0	0	0	0
Engine Costs		0	0	0	0	0	0	0	0	0	0
Electric Motor/Generator Costs		0	0	0	0	0	0	0	0	0	0
Maintenance Costs		1,407,715	1,407,715	1,407,715	1,407,715	1,407,715	1,407,715	1,407,715	1,407,715	1,407,715	1,407,715
Total Costs	14,850,000	2,934,199	2,934,199	2,934,199	2,934,199	2,934,199	3,234,199	2,934,199	2,934,199	2,934,199	3,421,699
Capacity payment		159,062	159,062	159,062	159,062	159,062	159,062	159,062	159,062	159,062	159,062
Service payment		324,303	324,303	324,303	324,303	324,303	324,303	324,303	324,303	324,303	324,303
Total payment		483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365
Regulation revenue after deducting aggregator fee		483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365	483,365
Net cashflow	-14,850,000	-2,450,834	-2,450,834	-2,450,834	-2,450,834	-2,450,834	-2,750,834	-2,450,834	-2,450,834	-2,450,834	-2,938,334
Net Present Value	-30,266,606										

Figure 3-1 Cash Flow Model Example

The next section discusses the theoretical and practical background of the different cost components included in the cash flow model and the appropriate parameters required to model them. The following section describes the simulation tool used to project V2G revenues. The specific parameters we selected for our analysis are given in Chapter 4.

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[2] See Chapter 5 for a description of simulated scenarios and cases.

3.1 Costs Components

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 include nine components listed in Table 3-1. We describe each cost component below.

Table 3-1 Cash flow model cost components

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

3.1.1 Capital

A truck fleet can be classified according to various parameters: weight, purpose, fuel efficiency, etc. Our research characterizes the fleet by the drive train - the set of components that propel the vehicle. In a traditional ICE, the engine is the sole source of propulsion. Adding an electric motor to the drive train drive enables the use of electricity for propulsion and creates three classes of vehicles: Hybrid Electric (HEV), Plug-in Hybrid Electric (PHEV), and Electric (EV) (MIT Energy Initiative, 2010). As depicted in Figure 3-2, each vehicle has a different blend of fuel and electric propulsion. Our thesis considers EVs and PHEVs, since these vehicles are able to connect to the grid.

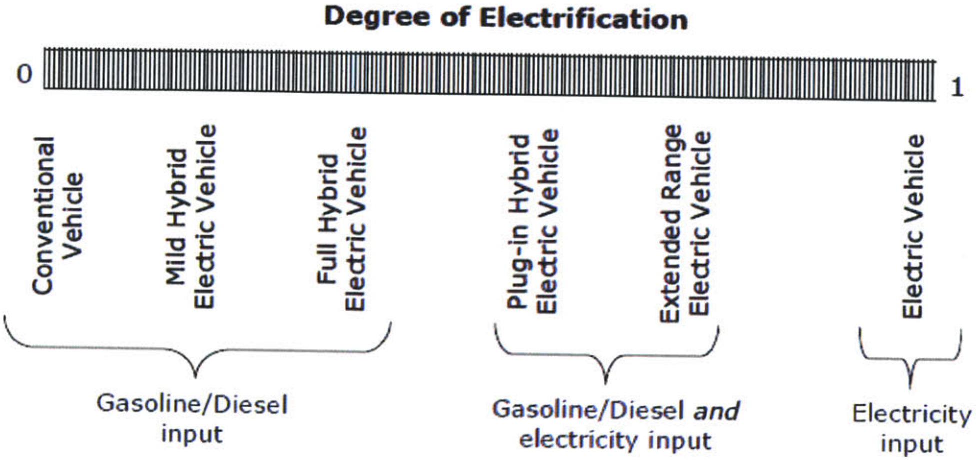

Figure 3-2 Degree of Electrification for Vehicle Types (MIT Energy Initiative, 2010)

A company can lease or purchase a new or used vehicle. In the case of EVs and PHEVs, the vehicle can be manufactured as a hybrid or electric vehicle, or it can be retrofitted to become a hybrid or electric vehicle. For the basis of this thesis 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.

As outlined in the literature review, there are several differences between EV, PHEV, and ICE vehicles. EVs are powered by an electric motor and a re-chargeable battery. These vehicles use the energy stored in the battery as the source for propulsion. PHEVs, in contrast, are powered by an internal combustion engine, an electric motor, and a rechargeable battery. PHEVs have approximately 20-40 miles of pure electric driving range, but can also drive long-distances due to their internal combustion engine (Steinmetz & Shanker, 2008). For example, if a PHEV needs to serve a 100 mile route, it has the ability to travel the first 20-40 miles in full electric mode. Once the battery is drained, it can switch over to hybrid mode for the remaining 60-80 miles. The PHEV also has the “start-stop” functionality. After the vehicle is idle for a specific amount of time, for instance stopped at a red light or in bad traffic, the combustion engine shuts down, improving fuel economy (J.D. Power and Associates, 2011). The batteries on a PHEV can also be charged through regenerative braking.

One of the main characteristics that separate plug-in hybrid electric and electric vehicles from ICE vehicles is the regenerative braking process. In an ICE, the energy that is used to stop the vehicle dissipates into the air as heat. In contrast, when the vehicle is braking, the electric motor on a PHEV and EV acts as an electric generator and kinetic energy can be converted into electric energy and stored in the battery. Thus, braking can provide energy (in the form of electricity) for future use at zero cost to the driver. In effect, the regenerative braking process provides the driver the benefit of purchasing less electricity than is required for full operation. Figure 3-3 depicts the regenerative braking process.

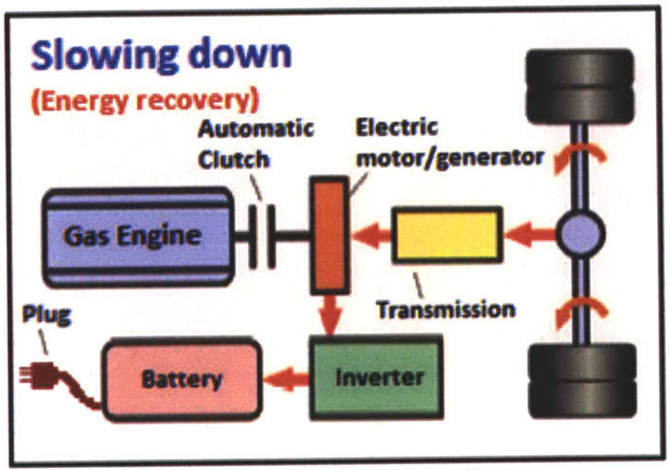

Figure 3-3 Regenerative Braking Process
(Jcwinnie, 2010)

In order to determine which components to include in the cash flow model, we made use of the literature concerning the different vehicle types as well as the interview with Mike Payette, the Fleet Equipment Manager for Staples, Inc. Mr. Payette operates a fleet of over two thousand delivery vehicles, including over 50 electric delivery trucks (Payette, 2011). Figure 3-4 shows one of the electric vehicles currently employed by Staples.

Figure 3-4 Staples' Electric Vehicle
(Auto parts marketplace, 2010)

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 (Berman, 2011). An additional $200 tax credit is added for each Kilowatt-hour thereafter the 16 kWh limit (Center for Sustainable Energy California, 2010). Some states such as California, Delaware, and Georgia, offer additional incentives. For our thesis, no additional state incentives were included. While outside the scope of this research, it is worth mentioning that a driver or a company that converts a vehicle into a plug-in hybrid or electric vehicle receives a tax credit equal to 10% of the conversion cost, up to a maximum credit of $4,000 for a $40,000 conversion. These credits are only available until December 31, 2011. Individual states, such as Colorado and Florida, provide additional incentives, such as rebates and state tax credits (Berman, 2011).

The overall capital investment is equal to the cost per vehicle (less the subsidy) times the fleet size. Other components, such as the battery, controller, controller, charger, brakes, engine and electric motor are already included in the vehicle price and are only applicable cost factors when they reach their maximum lifespan.

3.1.2 Infrastructure

The charging infrastructure will play a key role in consumer acceptance of alternative vehicles, especially those with a high electrification requirement, and the standards for EV-to-grid communication are still undergoing revision. Because the electrification requirements of EVs are still unclear, it is difficult to determine how much or what type of infrastructure is needed to support EVs. There is agreement that the lack of public infrastructure will impede EV market penetration but disagreement on timing and degree of public support for its development (MIT Energy Initiative, 2010).

Changes in infrastructure depend on the desired charging speed, which is defined by the capacity of the charger (kW/vehicle) (Section 3.1.3 discusses chargers in more detail). Fast charging requires an industrial-type electric service (voltage greater than 208 V and amperage above 15 A). According to Craig Van Batenburg, CEO of ACDC (Automotive Career Development Center), fast charging produces a high energy loss, which is converted directly into heat. This heat could harm the battery pack and related electronics and cooling equipment must be used to cool down the system (Van Batenburg, 2011).

While the above 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 (Berman, 2011).

Accounted for in year zero of our projected cash flow, this up-front cost 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.

3.1.3 Operation

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

3.1.3.1. Electricity

In our analysis, EVs and PHEVs utilize electricity as energy for propulsion. EVs are propelled solely by electricity, whereas PHEVs are able to run a pre-determined number of miles in only-electric mode, and automatically switch over to hybrid mode[3].

The electric grid is a network of high-power transmission lines and "last mile" distribution lines that deliver energy to residential and commercial customers. 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. For example, the price of electricity may be trading at $63 per Kilowatt-hour in Cambridge, Massachusetts, and the same hour the price could be $58 in Maine. In Cos Cob, Connecticut, electric prices in the summer can range from $3 to over $300 per Kilowatt-hour in a single day, while winter prices may only top out at $270 (Saran & Siegert, 2009). Table 3-1 depicts the LMP, in dollars per MWh, for each hour of the day, for the week between May 1, 2008 and May 7, 2008. The prices are for the Massachusetts hub and are most likely lower than the prices set in urban settings, such as Boston.

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 (Described in Section 3.1.3.6). The final amount of energy (including all adjustments) is paid at the LMP, which depends on the location, hour, and day when charging occurs.

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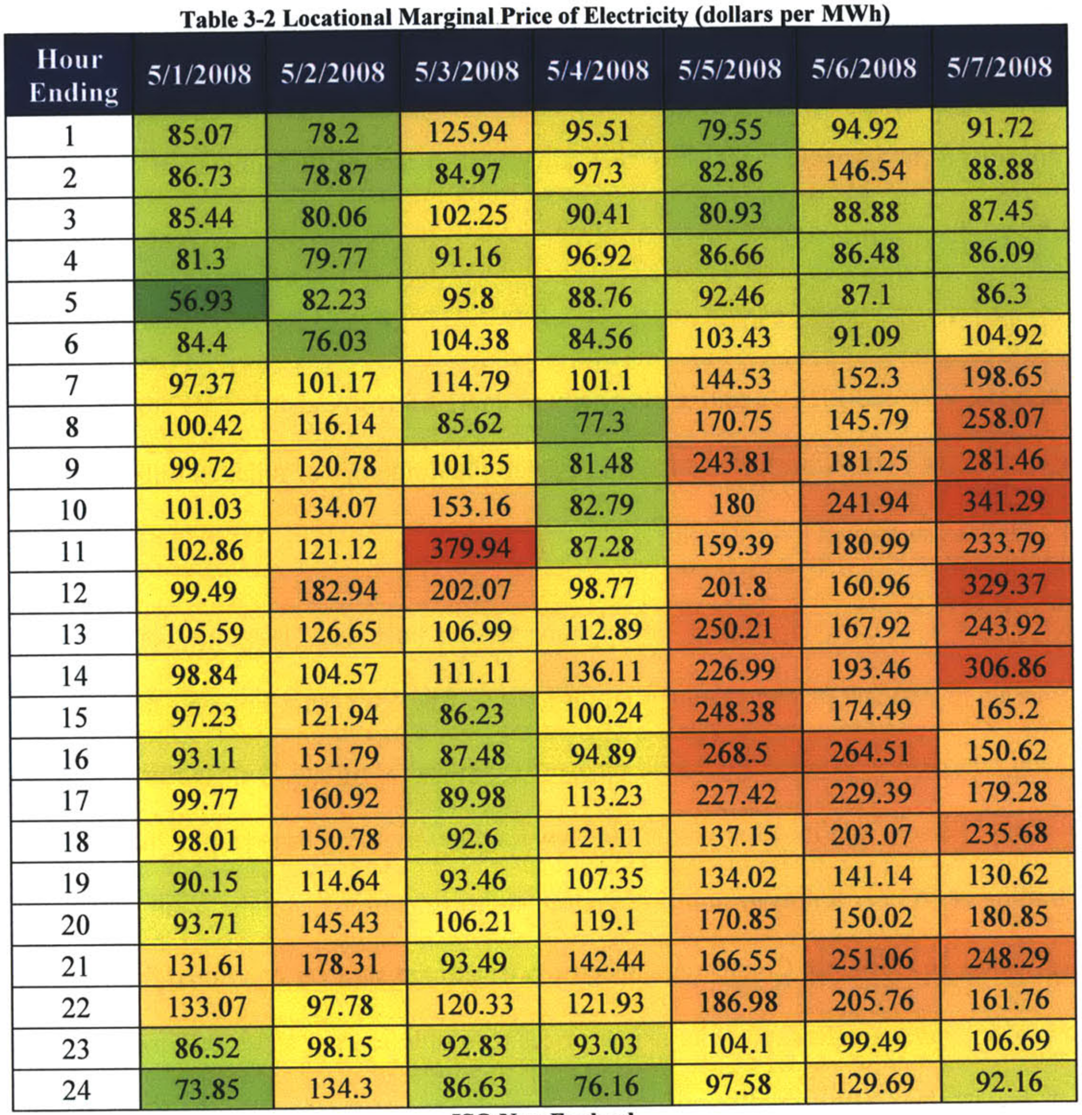
[3] When PHEVs cease operating in only-electric mode, they do not switch over to a pure diesel mode. During this period, the regenerative braking produces some electricity that the vehicle employs to assist some phases of driving.

Table 3-2 Locational Marginal Price of Electricity (dollars per MWh)



Hour Ending	5/1/2008	5/2/2008	5/3/2008	5/4/2008	5/5/2008	5/6/2008	5/7/2008
1	85.07	78.2	125.94	95.51	79.55	94.92	91.72
2	86.73	78.87	84.97	97.3	82.86	146.54	88.88
3	85.44	80.06	102.25	90.41	80.93	88.88	87.45
4	81.3	79.77	91.16	96.92	86.66	86.48	86.09
5	56.93	82.23	95.8	88.76	92.46	87.1	86.3
6	84.4	76.03	104.38	84.56	103.43	91.09	104.92
7	97.37	101.17	114.79	101.1	144.53	152.3	198.65
8	100.42	116.14	85.62	77.3	170.75	145.79	258.07
9	99.72	120.78	101.35	81.48	243.81	181.25	281.46
10	101.03	134.07	153.16	82.79	180	241.94	341.29
11	102.86	121.12	379.94	87.28	159.39	180.99	233.79
12	99.49	182.94	202.07	98.77	201.8	160.96	329.37
13	105.59	126.65	106.99	112.89	250.21	167.92	243.92
14	98.84	104.57	111.11	136.11	226.99	193.46	306.86
15	97.23	121.94	86.23	100.24	248.38	174.49	165.2
16	93.11	151.79	87.48	94.89	268.5	264.51	150.62
17	99.77	160.92	89.98	113.23	227.42	229.39	179.28
18	98.01	150.78	92.6	121.11	137.15	203.07	235.68
19	90.15	114.64	93.46	107.35	134.02	141.14	130.62
20	93.71	145.43	106.21	119.1	170.85	150.02	180.85
21	131.61	178.31	93.49	142.44	166.55	251.06	248.29
22	133.07	97.78	120.33	121.93	186.98	205.76	161.76
23	86.52	98.15	92.83	93.03	104.1	99.49	106.69
24	73.85	134.3	86.63	76.16	97.58	129.69	92.16

ISO New England

3.1.3.2. Diesel

Currently, fossil fuels are almost the exclusive source of energy for the transportation system in the United States (US) and the price of fuel is volatile. The US dependence on foreign oil, price volatility, and the setting of oil prices by cartels has cost the economy upwards of $5.5 trillion since 1970 (MIT Energy Initiative, 2010). Our cash flow model shows the cost of diesel to assume up to 65% of the operating costs for the ICE and 60% for PHEV. Figure 3-5 exhibits the behavior of diesel real prices in recent years according to the US Energy Information Administration.

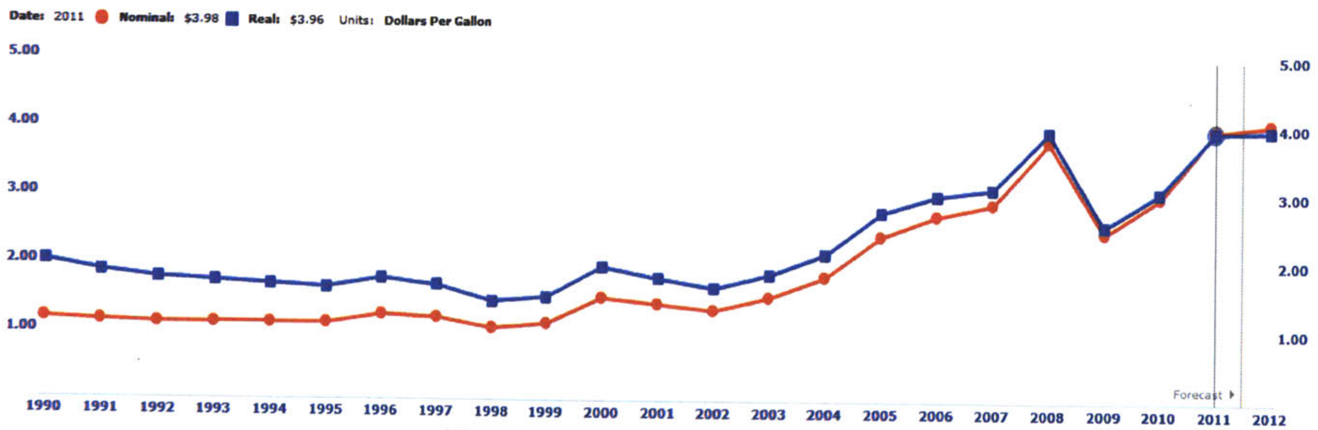


Figure 3-5 Retail price of diesel fuel
(U.S. Energy Information Administration, 2011)

Overall, 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.

3.1.3.3. Battery

Of utmost importance to a fleet operator is the ability to run their operations without interruption. A fleet manager, faced with the decision of whether or not to purchase electric vehicles for their fleet, wants to be certain that their operations will not be interrupted by a vehicle running out of energy. Moreover, they would want to ensure that the battery size for the electric vehicle corresponds to the number of miles driven. Thus, the battery selection becomes one of the most important decisions in an electric vehicle.

Although there are several different types of batteries, we focused our research on lithium-ion batteries. Absent a major future technological breakthrough in battery chemistry, Li-ion batteries will most likely be the battery technology of choice for the near future (MIT Energy Initiative, 2010). Lithium-ion batteries, widely known through their use in laptops and consumer electronics, dominate the current EV market. For further reading on lithium-ion chemistry and its properties, please consult Dinger, et al., 2010 and Peterson, Apt, & Whitacre, 2009a.

The cost of the battery is perhaps the biggest deterrent for the commercial viability of electric cars. Sources estimate the current cost of lithium-ion battery packs at between $1,000 and $1,200 per kWh (Dinger, et al., 2010). Actual cost data from manufacturers is not publicly available, however, because of proprietary restrictions (MIT Energy Initiative, 2010). This significant cost, even when distributed over the life cycle of the vehicle, can easily be more than the cost of the electricity. Figure 3-6 shows the estimated breakdown of the battery cost in terms of materials, R&D, labor, etc.

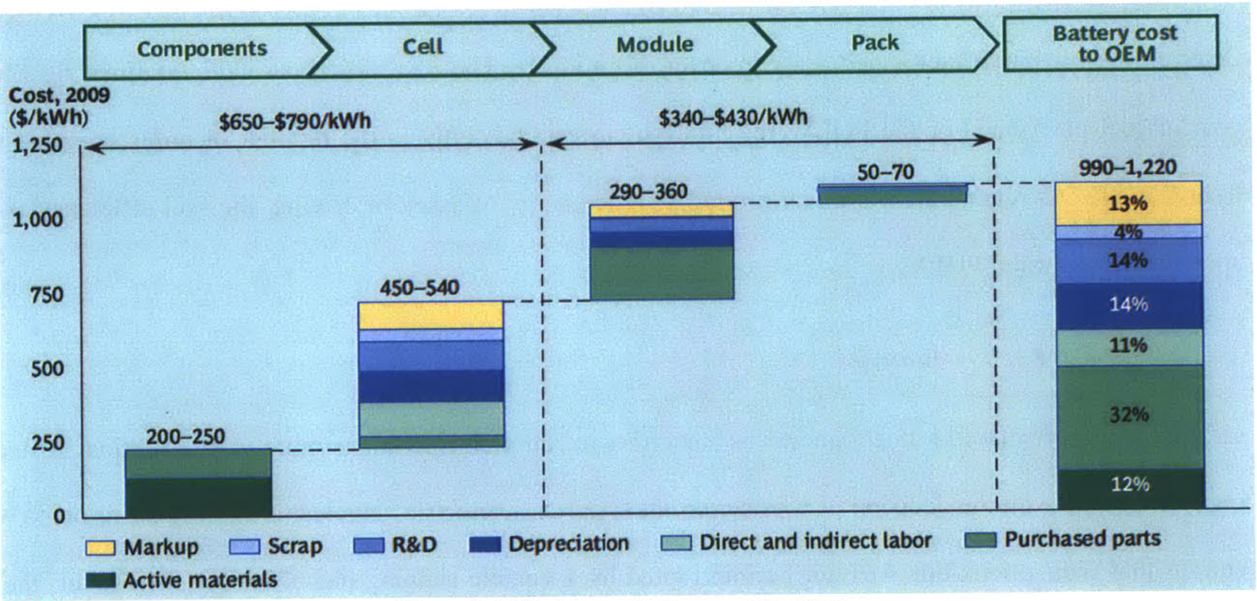


Figure 3-6 Electric car battery cost breakup
(Dinger, et al., 2010)

Nevertheless, significant cost reductions are anticipated for lithium-ion batteries. 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 (MIT Energy Initiative, 2010), with $500/kWh attainable by 2020, and even greater declines thereafter (Fairley, 2011).

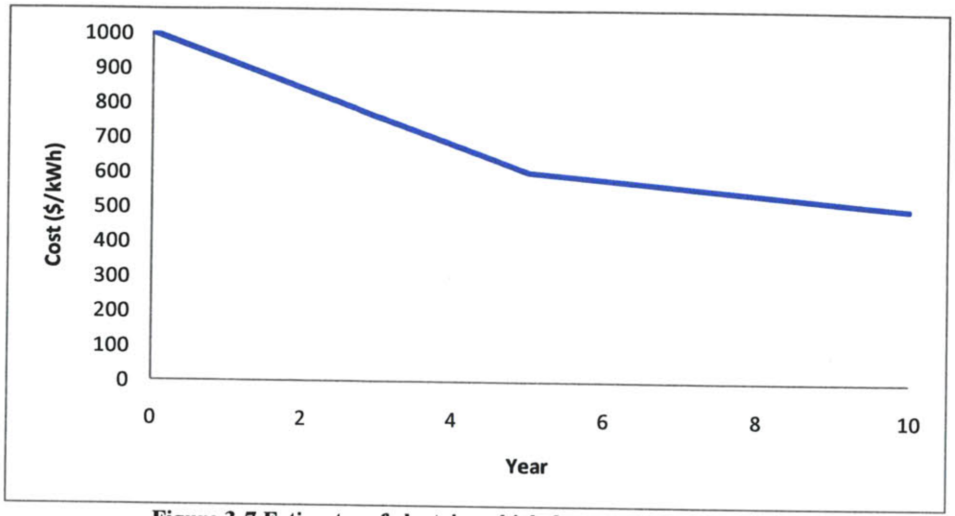


Figure 3-7 Estimates of electric-vehicle battery costs reductions (Fairley, 2011) and adapted by authors

Another important factor is the life span of the battery. There are two ways of measuring battery life span: overall age and cycle stability. Overall age is the number of years a battery can be expected to remain useful. However, this metric may be deceiving, in part because aging accelerates under certain conditions, such as very high and very low temperatures. 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 (Dinger, et al., 2010). 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. Figure 3-8 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.

Data presented in Figure 3-8 refer only to the degradation of battery life due to the process of charging from the grid and discharging from driving. A question that remains is whether or not participation in V2G will also degrade battery life. Peterson (2009a) 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 (Peterson, Apt, & Whitacre, 2009a).

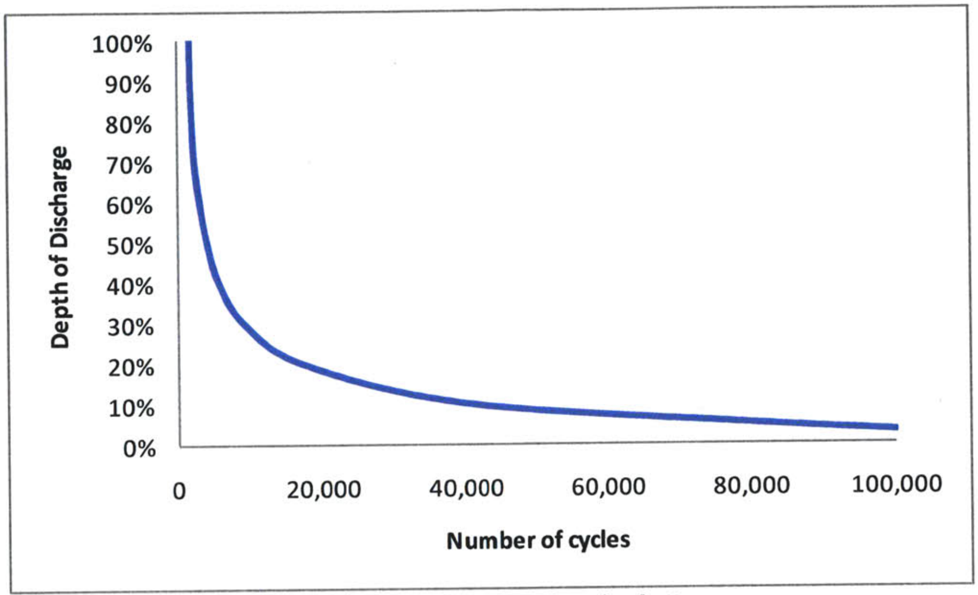


Figure 3-8 Cycle life of a lithium-ion battery (Markel & Simpson, 2006b) and adapted by authors

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 (See Figure 3-8). The model calculates the accumulated number of cycles for the batteries along the evaluation period, and when this number reaches the number of cycles defined for the fleet average SOC, a new battery is purchased at the estimated price for that year (See Figure 3-7 for price of one kWh of battery).

3.1.3.4. 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. For example, it controls the moment in which a PHEV switches over from electric to hybrid mode, assuming a preset state of charge is reached.

During the braking process, the controller directs the electricity produced by the motor into the batteries or capacitors. It ensures that an optimal amount of power is received by the batteries, but also ensures that the inflow of electricity is not more than the batteries can handle. Another important function of the controller is deciding whether the motor is currently capable of handling the force necessary for stopping the car. If it is not, the brake controller turns the job over to the friction brakes. When in hybrid mode, it also determines whether the battery should assist driving or only be charged through regenerative braking (depending on the state of charge). Figure 3-9 depicts an example of the decisions made by the controller, in a PHEV, according to the battery state of charge and the power demand for the car.

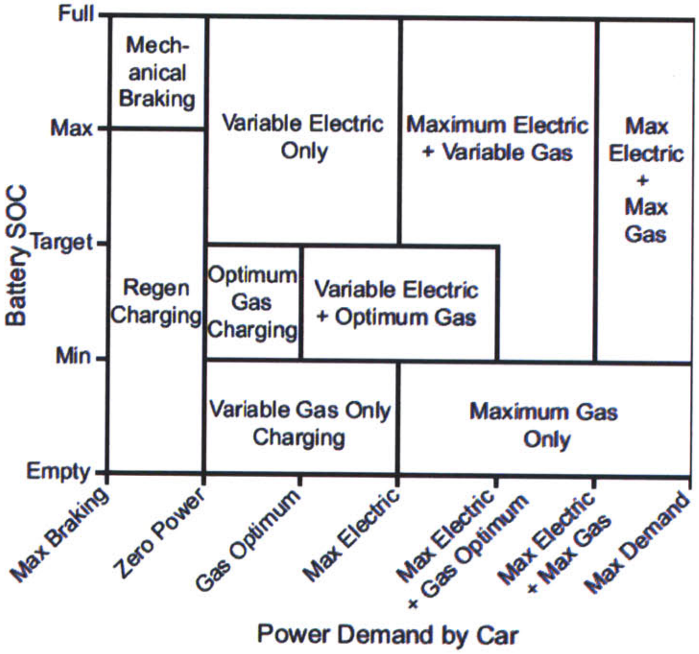


Figure 3-9 Decisions made by a controller in a PHEV (Millner, Judson, Ren, Johnson, & Ross, 2010)

The controller also plays an important role for the provision of V2G services. It allows the vehicle, and its battery, to supply power to the grid in phase with an existing AC signal. According to a preset programming, the controller interfaces with the grid and executes the different activities: ramp up, ramp down, or stop providing services.

The cash flow model calculates the accumulated mileage for the fleet along the evaluation period, and when this number reaches the life of the controller (in miles), a new controller is purchased. Controllers are expected to last the lifetime of the vehicle. However, this trigger is included to make the tool customizable for future use.

3.1.3.5. Charger

Even private, in-garage electric vehicle supply equipment (EVSE) is more complex than it may initially appear. 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. Many home and business garages are currently wired for only 120-volt charging, which could result in long charging times — as long as 15 hours for an EV with a large battery (MIT Energy Initiative, 2010). Currently, discussions revolve around three levels of charging summarized in Table 3-3.

Table 3-3 Charger levels

Charging level	Voltage	Amperage	Power
Level 1	120 V AC	Up to 20 A	Up to 2.4 kW
Level 2	240 V AC	Up to 80 A	Up to 19.2 kW
Level 3	Not yet defined	Not yet defined	20 kW to 250 kW

(MIT Energy Initiative, 2010)

According to Craig Van Batenburg, Level 1 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 (Van Batenburg, 2011). This adds cost and represents an additional hurdle for consumer acceptance (MIT Energy Initiative, 2010). 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. This level of charging requires a different plug and, according Mr. Van Batenburg, is expected to diminish the overall life of the battery. Depending upon its configuration, Level 3 charging could provide an 80% recharge for a 30 kWh battery in less than 10 minutes (Van Batenburg, 2011). 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 (MIT Energy Initiative, 2010).

In order to ensure that all EVs can charge using EVSE produced by different manufacturers, there must be a standard that governs the charging interface. Furthermore, the physical charging interface is important "because it's the thing the consumer touches and handles." (MIT Energy Initiative, 2010). The Society of Automotive Engineers (SAE) has created the J1772 standard to govern the physical power plug to EVs. This five-pin conductive charger will be used for Level 1 and Level 2 charging, and has a variety of safety features to prevent injury during charging (MIT Energy Initiative, 2010).

The charger is also expected to last the lifetime of the vehicle. The rationale behind purchasing a new charger is akin to the controller (based on number of miles driven). Thus, a trigger is built into the cash flow model, customizing it for future use.

3.1.3.6. Brakes

According to Mike Payette, 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. As part of the stopping force is performed by the motor, the brakes do not wear out as fast (Payette, 2011).

The cash flow model calculates the accumulated mileage for the fleet along the evaluation period. When the mileage reaches the lifetime of the brakes (in miles), new brake pads are purchased at the set price for that year.

3.1.3.7. ICE Engine

Both PHEVs and ICEs utilize diesel engines. In the case of the ICE, the engine is the only drive train. For PHEVs, this task is shared with the electric motor. Diesel engines are far more complex than electric motors given the high number of moving parts and fluids that intervene in the combustion process. Van Batenburg (2011) claims that engines should be assumed to last the lifetime of the vehicle. As engines and electric motors are expected to last the vehicle's lifetime, they are not specifically calculated in this cash flow model. However, a trigger based on their lifetime in miles is included for future use.

3.1.3.8. Electric Motor/Generator

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 (Ramsey, 2010). In the case of electric motors, Van Batenburg (2011) also claims that they should be assumed to last the lifetime of the vehicle.

3.1.3.9. Maintenance

Mike Payette explained that annual maintenance costs, in addition to brakes, can be more than four times as high for diesel trucks when compared to an electric truck of the same size and load. The reasoning is that electric vehicles do not require oil changes, expensive diesel filters, belts, or anti-freeze, and they have fewer moving parts (leading to fewer maintenance issues) as compared to the ICE and PHEV (Payette, 2011).

The cost of maintenance is calculated each year. For EVs, this is simply the maintenance cost times the size of the fleet. The ICEs also include the annual diesel filter costs, on top of the maintenance costs. The PHEVs consider the diesel filters as a percentage cost, based on the total mileage they run in hybrid mode, plus the annual maintenance costs.

3.2 Revenue Components

The final, but critical, component of the cash flow model corresponds to the revenue earned through V2G, i.e. the earnings gained through participating in regulation services[4]. As previously explained, regulation service is the use of on-line generation to correct the unintended fluctuations in electricity supply in order to match supply to demand within the balancing area (Kirby, 2007). When the electricity supply exceeds demand, the ISO performs a process known as regulation down (or ramp down), and requests the ancillary service provider, in our case a fleet of batteries, to absorb the appropriate amount of excess energy. In Figure 3-10, ramp down takes place between 12AM and 6AM, when the actual demand is higher than the forecasted demand. Conversely, when demand exceeds supply (between 2PM and 9PM in Figure 3-10), the ISO starts the regulation up (or ramp up) process, through which the fleet provides energy stored in the batteries to the ISO.

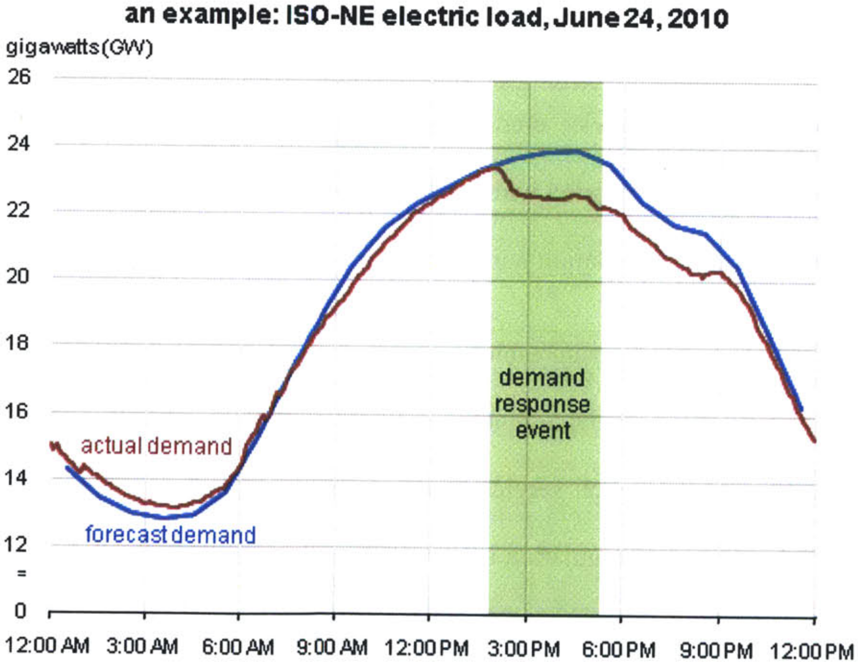


Figure 3-10 New England Electric Load by Hour: June 24, 2010
(U.S. Energy Information Administration, 2011)

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[4] Note that revenue generated by the fleet's primary service for the company is assumed to be the same for each type of vehicle and is thus excluded from the model.

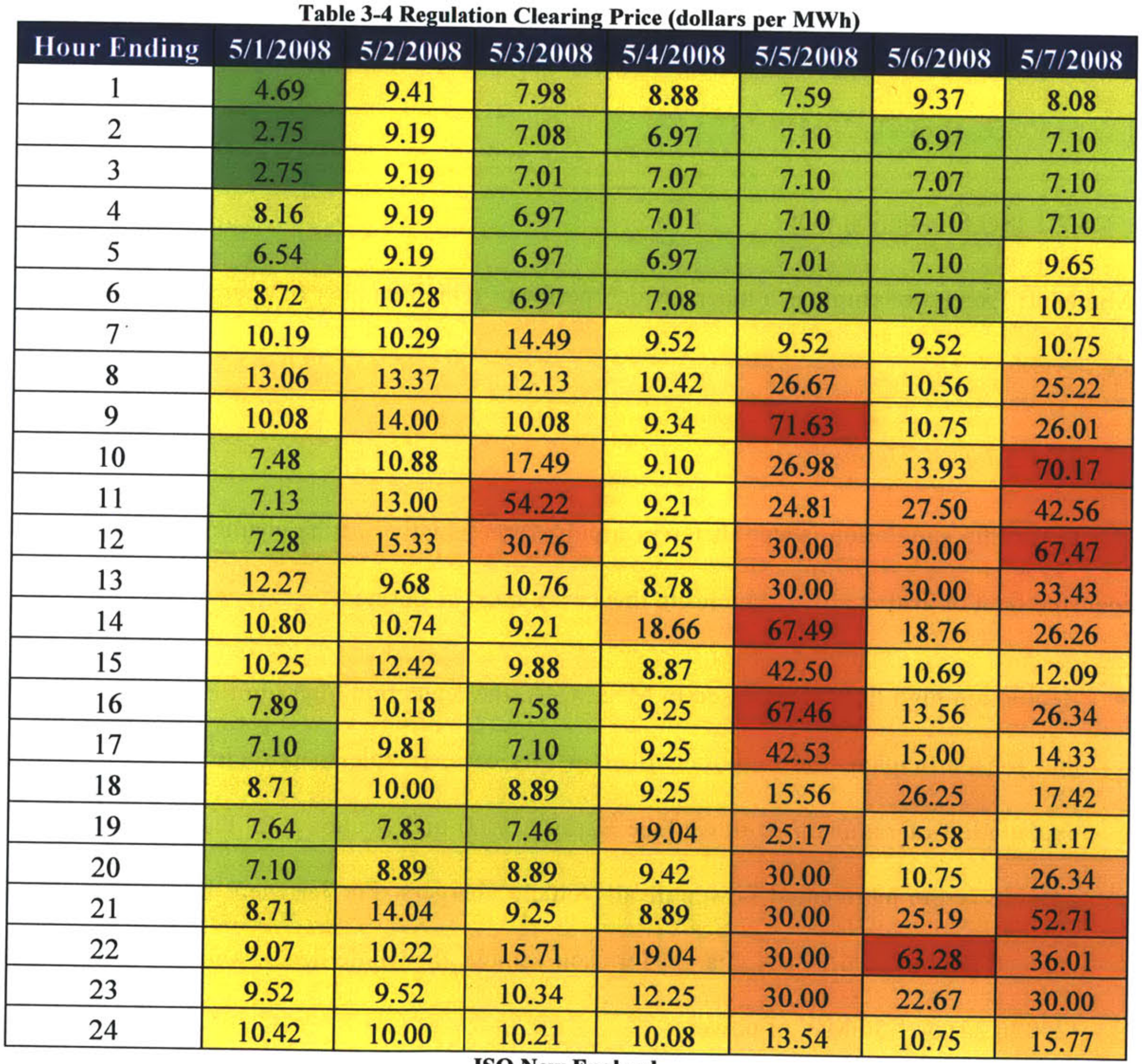
In order to calculate the opportunity for V2G revenue, we simulated fleets of EVs and PHEVs participating in the regulation services market. First, we simulated the ramp down only approach. Under this approach the fleet only responds to the ISO signals which request energy storage. Heidel (2011) and Connors (2011) predict that ramp down only will be the first step for V2G regulation services. 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. Due to the fact that an ICE vehicle does not have the capability to connect to the grid it is not included in this analysis.

The ISO New England provides participants with a market-based system for the purchase and sale of the ancillary 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) (See below). 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). Charges associated with time-on-regulation credits and regulation service credits are allocated to participants based upon their adjusted regulation obligations. Charges associated with regulation opportunity cost compensation are allocated to participants based upon their net regulation purchases.

On an hourly basis, and as needed during each hour of the operating day, the ISO calculates a regulation rank price for each unit eligible to provide regulation based on the sum of each unit's estimated time-on-regulation credits, estimated regulation service credits, estimated regulation opportunity cost and other factors that consider the impact of regulation assignment on the real-time energy market, divided by the unit's regulation capability. Generating units eligible to provide regulation are then arranged in ascending order based on the regulation rank prices. This generating unit rank order list is used by the ISO to assign regulation to the most economically efficient set of units eligible to meet the regulation requirement unless there is a reliability concern that necessitates out-of-merit regulation assignment. Detailed rules for eligibility, obligations, deadlines, and others can be consulted in the ISO New England Manual for Market Operations (ISO New England, 2008).

The Regulation Clearing Price (RCP) is the price per megawatt that the ISO utilizes to compensate participants in the regulation market. It is used for calculating both the time-on-regulation credits (Capacity payment) and regulation service credits (Service payment). Table 3-4 shows the RCP, in dollars per MW, for the week between May 1, 2008 and May 7, 2008 for each hour of the day. Red shading corresponds to high prices and green shading to low prices. As in the case with the LMP matrix, these prices are for the Massachusetts hub.

Table 3-4 Regulation Clearing Price (dollars per MWh)



Hour Ending	5/1/2008	5/2/2008	5/3/2008	5/4/2008	5/5/2008	5/6/2008	5/7/2008
1	4.69	9.41	7.98	8.88	7.59	9.37	8.08
2	2.75	9.19	7.08	6.97	7.10	6.97	7.10
3	2.75	9.19	7.01	7.07	7.10	7.07	7.10
4	8.16	9.19	6.97	7.01	7.10	7.10	7.10
5	6.54	9.19	6.97	6.97	7.01	7.10	9.65
6	8.72	10.28	6.97	7.08	7.08	7.10	10.31
7	10.19	10.29	14.49	9.52	9.52	9.52	10.75
8	13.06	13.37	12.13	10.42	26.67	10.56	25.22
9	10.08	14.00	10.08	9.34	71.63	10.75	26.01
10	7.48	10.88	17.49	9.10	26.98	13.93	70.17
11	7.13	13.00	54.22	9.21	24.81	27.50	42.56
12	7.28	15.33	30.76	9.25	30.00	30.00	67.47
13	12.27	9.68	10.76	8.78	30.00	30.00	33.43
14	10.80	10.74	9.21	18.66	67.49	18.76	26.26
15	10.25	12.42	9.88	8.87	42.50	10.69	12.09
16	7.89	10.18	7.58	9.25	67.46	13.56	26.34
17	7.10	9.81	7.10	9.25	42.53	15.00	14.33
18	8.71	10.00	8.89	9.25	15.56	26.25	17.42
19	7.64	7.83	7.46	19.04	25.17	15.58	11.17
20	7.10	8.89	8.89	9.42	30.00	10.75	26.34
21	8.71	14.04	9.25	8.89	30.00	25.19	52.71
22	9.07	10.22	15.71	19.04	30.00	63.28	36.01
23	9.52	9.52	10.34	12.25	30.00	22.67	30.00
24	10.42	10.00	10.21	10.08	13.54	10.75	15.77

ISO New England

The ISO calculates the hourly real-time regulation clearing price by integrating the interval-based RCPs calculated for the hour. The ISO's regulation clearing price software ranks all generators providing regulation in ascending regulation supply offer price for each interval. The highest regulation supply offer price associated with the regulation capability provided to meet the regulation requirement for that interval becomes the RCP for that interval. The hourly RCP is then calculated and is equal to the time-weighted average of the interval RCPs for that hour. According to the number of participants, the season of the year, the price of coal, natural gas, and oil, and other factors, the RCP can fluctuate dramatically, even during the same day.

Jonathan Lowell, a Principal Analyst at the ISO New England who specializes in market development, provided us with a simulation tool that the ISO utilizes to estimate revenues for the provision of regulation services (Lowell, 2011).

3.2.1 ISO Simulation tool

The Microsoft Excel tool employs a macro which performs a high number of operations in a short period of time.

3.2.1.1. Inputs

In order to run the simulation, seven different inputs, representative of the characteristics of the service provider (the fleet of grid-enabled vehicles in this case), must be defined:

- Regulation high limit: Expressed in Megawatts, the regulation high limit is the amount of power that the participant, the corporate fleet in this case, is able to provide for ramp up. For an explanation of ramp up & down, see Kirby (2007) and Section 3.2. The power the fleet can provide is the aggregated power of all vehicle chargers. For instance, if a 250-vehicle, grid-enabled fleet has a 6.24 kW charger for each vehicle, the whole fleet is able to provide 1,560 kW (250*6.24) or 1.56 MW of power.

- Regulation low limit: The same rationale for the regulation high limit applies here. The difference is that this is the amount of power or capability that the participant is able to provide to the ISO for ramp down. The regulation low limit is denoted with a negative sign. The absolute values of the regulation low and high limits might be equal in real life. However, for the simulation, the midpoint of the high and low limits cannot be set exactly at zero due to an internal configuration of the simulation tool. We calculated the regulation low limit as the negative result of the regulation high limit times 0.99.
- Automatic response rate: In the case of a coal or a gas-powered plant, there is a set-up time and delay between the moment the plant receives the signal and when they reach the desired regulation target, often taking as much as 10 minutes. V2G has a high response rate as energy is stored in the battery and the battery is already connected to the grid. We are assuming a 50 MW per minute response rate, a relatively high number. Assuming the regulation limit of 1.56 MW, the corporate fleet would be able to respond in only 1.87 seconds.
- Storage when fully charged: This is the aggregated amount of energy when the batteries (in all vehicles) are fully charged. Given energy loss in the battery (See Section 4.1.1.9), a 90% efficiency factor is applied. For a 250-vehicle fleet with 250 electric vehicles, each with 80kWh batteries, the total storage would be 18 MWh (250*80*0.9). However, the simulation works with energy in terms of MW-4s (Megawatts – 4 seconds). The transformation is straightforward: MWh * 60 * 15 (an hour has 60 minutes and a minute has 15 4-second periods). In this case, the storage in this example is 16,200 MW-4s.
- Initial value of storage: This variable corresponds to the storage, in MW-4s, when the fleet initially connects to the grid. The initial value of storage is equal to the storage when fully charged, defined above, times the minimum state of charge (SOC) of the fleet. For a 50% SOC, the initial value of storage in this example is 8,100 MW-4s.

- Charging and discharging efficiency: The same value is defined for both inputs and we assumed an efficiency of 90% due to the ohmic losses (See section 4.1.1 on chargers efficiency). When the fleet contracts 1.56 MW of power, the vehicles actually provide 1.40 MW.

3.2.1.2. Modifications

The ISO simulation was originally conceived to simulate revenue for traditional generation plants and alternative resources such as flywheels. We modified a few parameters in order to adapt it to the needs of V2G, while being cognizant to not compromise the structure of the calculations and reliability of the results.

The first modification was the number of days the model could simulate. Originally the tool simulated a seven-day week and if the modeler wanted to run a different week, he or she had to modify the simulation with new data (ACE and RCP, to be explained in the next section) and run it again. We tweaked it to run over four 5-day weeks at the same time. We used five business days per week and four weeks, each week representative of one season (autumn, winter, spring, summer) in New England.

The second modification was related to the independency of the simulated days. The simulation assumes that the provision of the service is continuous. That means that the parameters of the regulation service, such as state of charge and energy service were the same at the end of one day and at the beginning of the next. This is clearly not realistic for a fleet of vehicles since they must unplug from the grid during the day. Our modification allows the simulation to simulate the revenues with new, independent parameters every day.

Another characteristic of the original simulation tool is that it simulates each hour in the day (24 hours total). Certainly, a corporate fleet cannot be connected to the grid for 24 hours. Our version allows the modeler to choose the hours of the day (according to their operations) during which the fleet is parked.

Finally, the fleet needs to fully charge its batteries (i.e. reach a 100% SOC) to operate the next day. However, the simulation did not originally ensure that the batteries were fully charged at the end of the day. We introduced a modification to the simulation where the controller detects the exact moment in which the remaining connection time is just enough to fill up the battery. At that moment, the provision of regulation service stops and the only activity allowed is the charging of the batteries.

3.2.1.3. Data

Besides the simulation tool, the ISO simulation requires additional information such as the Regulation Clearing Price (RCP), Locational Marginal Price (LMP), and Area Control Error (ACE). The ISO New England provided us with these data for four weeks of the year, each one representing a season. RCP and LMP were previously described.

Table 3-5 ACE signals ISO New England

Start Time	8/7/08 0:00:00	8/7/08 1:00:00	8/7/08 2:00:00	8/7/08 3:00:00	8/7/08 4:00:00	8/7/08 5:00:00
End Time	8/7/08 1:00:00	8/7/08 2:00:00	8/7/08 3:00:00	8/7/08 4:00:00	8/7/08 5:00:00	8/7/08 6:00:00
1	-2.5206	67.0599	-7.2603	-0.7166	-18.2148	-27.1982
2	63.9328	46.2432	-1.4934	-5.8566	-21.7475	-84.4982
3	55.7934	81.9356	14.2613	-8.6441	-28.5102	-84.1400
4	41.8607	41.3259	6.2905	-19.6843	6.0845	-89.2946
5	52.1221	41.0455	23.9211	-24.4205	2.7513	-74.0593
6	66.7099	69.1772	0.2577	-18.1002	-13.7054	-80.1086
7	33.8168	66.2831	8.4566	-42.3281	-24.3174	-117.4079
8	61.9456	40.1802	37.8977	0.2234	-25.3748	-117.4079
9	51.7906	18.5628	24.5076	-10.6283	-30.8260	-81.8541
10	66.2724	31.2110	23.4600	-7.6835	-17.4895	-95.4631
11	57.0764	29.3409	17.7455	-13.8073	-26.4848	-118.3392
12	39.7932	35.2329	25.6526	-4.3678	-26.4848	-81.8979
13	65.9038	22.9330	13.3036	5.8635	-14.1263	-112.4036
14	67.4132	29.8666	-3.6262	14.2084	-19.5388	-123.3732
15	28.0468	22.2243	2.0313	11.0456	-5.9518	-121.7736
16	36.5487	-5.9300	-2.8277	10.0456	-12.8265	-140.0794

17	27.0148	-3.2984	13.8540	30.9945	-18.9954	-144.6316
18	37.6193	2.6915	30.9993	8.6101	-4.3085	-142.7667
19	29.5069	3.5818	5.1332	-10.7395	-8.6408	-142.1766
20	5.0796	10.4245	-14.7419	14.8862	-12.4248	-148.4002

ISO New England

On the other hand, ACE is the signal sent by the ISO when the electric grid requires a regulation action from connected participants. The ACE is the power imbalance, in Megawatts, between the supply and demand of electricity. The ISO sends an ACE signal every four seconds (which is why the units of storage for the simulation must be in MW-4). An ACE signal every four seconds is equal to 900 signals in one hour, 21,600 in one day, and 151,200 in seven days. Table 3-5 shows part of the ACE signals for August 7, 2008. The original table for one day has 900 rows and 24 columns. A positive ACE means that the ISO is performing ramp down, that is, providing energy to the fleet. Likewise, a negative ACE is indicative of ramp up, or requesting energy from the fleet.

3.2.2 Regulation Service Compensation

According to ISO terminology, compensation is known as settlement. Regulation settlement is a zero-sum calculation based on the regulation provided to the market for regulation by generation owners and purchased from the market for regulation by market participants with regulation obligations. Regulation credits (payments) are defined by three different compensations: capacity, service, and opportunity cost. Table 3-1 shows the revenue components evaluated in the cash flow model.

Table 3-6 Cash flow model revenue components

Revenue	EV	PHEV	ICE
Capacity payment	X	X	
Service payment	X	X	
Opportunity cost payment	X	X	
Percentage of revenue for aggregator	X	X	

3.2.2.1. *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 to

$$Cap = RCP \times TRM\,, \tag{3-1}$$

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

$$TRM = Regulation\ Capability \times \frac{minutes\ of\ regulation}{60}\,, \tag{3-2}$$

where the regulation capability is the amount of power that the participant, the corporate fleet in this case, is able to provide to the ISO for regulation (the regulation high limit) and minutes of regulation is the total time during the hour that the participant is able to provide the service. Note that if the participant provides the service for fewer than 60 minutes, TRM is proportional to the actual time of service. As an example, let regulation capability or regulation limit be 1.40 MW provided from 13:00 to 14:00 on May 4, 2008. According to Table 3-4, RCP is equal to $18.66 per MW. In this case, the TRM for that hour is equal to 1.4 [1.4*(60/60)] and the capacity payment is equal to $26.12 (1.4*18.66). This calculation is performed every hour the fleet is connected to the grid and providing the service.

3.2.2.2. *Service payment*

Regulation service megawatts in an hour are calculated as the sum of the absolute value of positive and negative movement requested by the ISO while providing regulation within the hour. The computation of regulation service megawatts assumes that generators providing regulation will track their AGC set point signals at their claimed automatic response rate without delay or overshoot. This tracking computation is known as perfect AGC response (PERFAGC). The regulation service megawatts are computed as the sum of absolute values of the differences in PERFAGC between successive four second samples during an hour while providing regulation. Service is then calculated according to

$$Svc = RCP \times CSR \times RSM \ , \tag{3-3}$$

where RCP is the regulation clearing price in dollars per megawatt, CSR is a dimensionless capacity-to-service ratio, and RSM is the regulation service megawatts. RCP and RSM were already explained in previous lines. CSR is a value calculated by the ISO such that the total revenues received for time-on-regulation megawatts and regulation service megawatts is split equally between the two services. First, the ISO calculates the historical relationship between time-on-regulation megawatts and regulation service megawatts. The capacity-to-service ratio is then calculated based on this historical relationship and the objective 50/50 split of revenues between time-on-regulation megawatts and regulation service megawatts. Based on empirical study results, a megawatt of 5-minute regulation capability being provided for a full hour produces a value of regulation service megawatts that is equal to ten, on average. Thus, the capacity-to-service ratio is set equal to 0.1 to produce the desired 50/50 mix of revenues paid for time-on-regulation megawatts and regulation service megawatts. The actual relationship between time-on-regulation megawatts and regulation service megawatts will vary across individual generators and hours, with the capacity-to-service ratio representing a median value to achieve the desired revenue ratio.

Before starting providing the service, the provider sets a regulation low limit (RLL) and a regulation high limit (RHL). At the first moment, when the fleet is connected, the regulation power (target) is set to the midpoint between RLL and RHL. If five consecutive 4-second ACE[5] cycles exceed the 25MW, the target is changed to the RLL. This target does not change until five consecutive 4-second ACE cycles are less than 25 MW, case in which the target is changed back to the midpoint. Now, if the target is at the midpoint and five consecutive 4-second ACE cycles are less than -25 MW, the target is changed to the

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[5] A positive ACE means that the ISO is performing ramp down, that is, is providing energy to the fleet. Likewise, a negative ACE is indicative of ramp up, requesting energy from the fleet.

RLL. This target does not change until five consecutive 4-second ACE cycles are greater than -25 MW, the case in which the target is changed back to the midpoint. The sum of the absolute value of the difference between consecutive targets is the regulation service megawatts (RSM). Service is based on moving from one target point to another.

Jonathan Lowell from the ISO New England utilized the following example for the calculation of RSM (Lowell, 2011). The example leaves out the condition of having five consecutive 4-second ACE cycles below -25 MW or above 25 MW. It is assumed that the target changes are complying with these requirements.

Let us suppose there is a battery that can hold 2 MWh of energy when fully charged. It can charge continuously at a rate of 1 MW (RHL), discharge at a rate of -1 MW (RLL), or sit idle (not charging or discharging). Let us assume the battery begins the hour half full, i.e. with 1 MWh of energy, and the ACE is initially zero. After one minute the ACE goes positive, and the ISO sends a target point of -1 MW (i.e. charge at a rate of 1 MW), and the fleet gets 1 MW of service. After a minute, ACE goes back to zero and the ISO sends a target of 0 MW, crediting the provider with another 1 MW of service, for a total of 2 MW-miles. The resource is now a little more than half full (1/60th of a MWh was added to the battery during the minute it was charging). At time equal to three minutes ACE goes positive again, and the target is set at -1 MW again, providing the resource with another mile (3 MW so far). ACE stays positive for the next 70 minutes. At time equal to 62 the resource is full and cannot continue to charge. The charge rate drops to 0 MW and the resource is not able to follow the 1 MW AGC dispatch signal. The fleet does not receive a service credit for moving from -1 MW to 0 MW because it was not "instructed" movement – it was "failure to follow" movement, so the final service or RSM was 3 MW. Assuming an RCP of 18.66 dollars per MW and a CSR of 0.1, the service payment for that hour would be $5.60 (18.66*0.1*3).

The service the fleet is able to provide and receive compensation for is related to instructed movement. The more frequently ACE crosses zero, the more the resource is dispatched up & down, and the more service payment the resource receives. However, if ACE is highly variable, but never crosses zero, a storage resource will eventually become either empty or full. Once full, the resource would be forced back to 0 MW, and would only be able to follow the dispatch in the discharging direction (until it emptied a bit). When a resource is able to follow the dispatch signal, it receives compensation for the movement (service payment) and the availability (capacity payment). Movement that is not following the dispatch is not eligible for compensation and diminishes the minutes of regulation variable in Equation 3-2.

3.2.2.3. Opportunity cost payment

Regulation opportunity cost payment is only provided to those participants known as pool-scheduled resources. Pool-scheduled resources are those resources for which market participants submitted supply offers to sell energy in the day-ahead energy market, and which the ISO scheduled in the day-ahead energy market, as well as generators committed by the ISO subsequent to the day-ahead energy market. The day-ahead energy market is the wholesale electricity market where generators and loads make commitments to the market to sell and buy electricity the following day, thus creating a financially binding schedule of commitments the day before the operating day for the production and consumption of electricity (Saran & Siegert, 2009). The opportunity cost payment is intended to compensate these resources for the revenues they are losing by participating in the regulation market in lieu of the wholesale generation market. On the other hand, self-schedule is the action of a market participant in committing and/or scheduling its resource, in accordance with applicable ISO New England manuals, to provide service in an hour, whether or not in the absence of that action the resource would have been scheduled or dispatched by the ISO to provide the service. A corporate fleet providing regulation services is considered a self-scheduled Resource, so that no opportunity cost payment is calculated. For further details on regulation opportunity cost, please see ISO New England Manual for Market Operations, published in 2008.

3.2.2.4. 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, it is necessary to extrapolate the results of those four weeks 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 are also assuming 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. For instance, if a given scenario shows capacity and service revenues of $15,000 and $25,000 respectively, for the four simulated weeks, the assumption is that the capacity and service revenues for the whole year are $189,750 and $316,250, and those are the values presented in the cash flow model. The total payment is the sum of these two figures.

3.2.2.5. Percentage of revenue for aggregator

An aggregator could play the role of managing multiple fleets and present the combination as a larger distributed energy resource (DER) to the ISO. It is considered to be a critical entity to make the V2G concept implementable (Guille & Gross, 2009). The aggregator would have no direct control over operating schedules of individual vehicles, but would provide financial incentives to stay plugged in when possible (Kempton & Tomic, 2004b). The ISO deals directly with the aggregator, who sells the aggregated capacity and energy services that the collection of vehicles can provide. The aggregator's role is to effectively collect the DERs into a single entity that can act either as a generation/storage device capable of supplying capacity and energy services needed by the grid or as a controllable load to be charged in a way so as to be the most beneficial to the grid. It is the role of the aggregator to determine which vehicles to select to join the aggregation and to determine the optimal deployment of the aggregation (Guille & Gross, 2009). For more information related to the role of the aggregator, see Guille & Gross, 2009 and Beck, 2009.

Due to the fact that the role of the aggregator is not yet fully defined and V2G is not operating at great scale we did not include this value in our assessment. However, it can easily be added to the cash flow model in the future.

4 Model Configuration

To assess the economic viability for a corporate fleet to participate in the V2G market, we built a cash flow and simulation model, as described in Chapter 3. We ran the cash flow model with a variety of different parameters to observe how their variation affects the overall business case. In the following chapter we describe how we varied the input parameters to create a variety of operational scenarios. Specifically, we define the configuration for each component explained in Chapter 3, their possible values, drivers, and interrelations. We also describe the control panel for the cash flow model.

4.1 Model Control Panel

The control panel is a dynamic tool which allows the user to quickly update each scenario by changing one or more inputs. The control panel for the base case (all vehicle types) is depicted in Table 4-1.

It is important to mention one more parameter that is not defined in the control panel but in the ISO simulation tool: it is assumed that the fleet is connected to the grid twelve hours per day, five days per week, between 6:00 PM and 6:00 AM. The numerical values above are representative of one simulation run. The blue values with yellow backgrounds are hard-coded and never manipulated in the runs. The black values are dynamic, meaning they are formulas which depend on other parameters. The values highlighted in green (the PHEV battery size, the minimum SOC at the end of day, and charger capacity) are the values which can be manipulated in the simulations to create different scenarios. Finally, those cells without values represent parameters not applicable to that specific type of vehicle. For example, ICEs do not receive government incentives, and no valued is defined in that cell. A variety of sensitivity analyses were run in order to determine how changes to the green parameters affect the overall business case (See Chapter 5).

Table 4-1 Base Case – Control Panel

Parameter	EV	PHEV	ICE
Fleet size	250		
Average miles per vehicle per day (miles)	70		
Workdays per year	253		
Cost per vehicle ($)	130,500	59,400	50,000
Subsidy	21,300	0	
Electric mode efficiency (kWh/mile)	0.8		
ICE mode efficiency (mile/gallon)		11.56	10.14
Fuel cost ($/gallon)		4	
Battery efficiency	90%		
Charger Efficiency	90%		
Percent of electricity added by regenerative braking	14%		
Battery size (kWh)	85	3.9	
Minimum battery state of charge end of day	20%	30%	
Battery life (cycles)	2,455	2,300	
Cost battery year 0 ($/kWh)	1,000		
Cost controller ($)	1,500		
Life of Controller (miles)	500,000		
Cost charger, wiring, switches, adapter ($)	2,000		
Life of Cost charger, wiring, switches, adapter (miles)	500,000		
Cost brakes ($)	1,200		1,200
Life of brakes (miles)	90,000		30,000
Cost Electric Motor/Generator - ICE Engine and transmission ($)	2,000		10,000
Life of Electric Motor/Generator - ICE Engine (miles)	500,000		500,000
Cost Maintenance/vehicle ($/year)	250	3,250	3,400
Diesel filters ($/year/vehicle)		2,500	
Discount rate	10%		
Charger capacity (kW/veh)	30.00	1.92	
Infrastructure costs for Charge Level 2 and higher ($/veh)	20,000	0	
Percent average fleet connected every day	100%		
Percent of revenue for aggregator	0%		

Note that the number of parameters on the control panel is much larger than the number of cost and revenue components explained in Chapter 3. This difference is due to the fact that cost components can be driven by multiple parameters. For example, the capital costs are the result of the cost per vehicle and the fleet size. In the next section, we explain the rationale behind each parameter on the control panel and the values we utilized in the simulation. Table 4-2 presents the cash flow components (as defined in Chapter 3), and the parameters that drive their values.

Table 4-2 Cash flow components and their drivers

Cost component	Drivers from the control panel
Capital costs	Fleet size
	Cost per vehicle
	Government incentive
Infrastructure costs	Fleet size
	Charger capacity
	Infrastructure
Operating costs	
Electricity	Fleet size
	Workdays per year
	Charger efficiency
	Regenerative braking efficiency
	Battery size
	Battery state of charge end of day
Diesel	Fleet size
	Average miles per vehicle per day
	Workdays per year
	ICE mode efficiency
	Fuel cost
Battery	Fleet size
	Battery size
	Battery life
	Cost battery year 0
Controller	Fleet size
	Cost controller
	Life of Controller
Charger and wiring	Fleet size
	Cost charger, wiring, switches, adapter
	Life of charger, wiring, switches, adapter
Brakes	Fleet size
	Cost brakes
	Life of brakes
ICE Engine Electric Motor/Generator	Fleet size
	Cost electric motor/generator - ICE engine
	Life of electric motor/generator - ICE engine
Maintenance	Fleet size
	Cost maintenance

	Diesel filters
V2G revenues	Fleet size
	Workdays per year
	Battery efficiency
	Charger efficiency
	Battery size
	Battery state of charge end of day
	Charger capacity
	Percent average fleet connected every day
	Percent of revenue for aggregator

4.1.1 Control panel parameters

We consulted the literature, as well as our discussions with industry insiders, to determine the values of each parameter.

4.1.1.1. Fleet size

The fleet size of 250 is assumed to be a general figure for a retail fleet. For instance, Staples, Inc., a large retailer, has over 2,000 vehicles and about 50 electric trucks (Payette, 2011). It is assumed that the fleet size under consideration is the same for each vehicle type: EV, PHEV, and ICE.

4.1.1.2. Average miles per vehicle per day

The average miles are hard-coded. Mike Payette informed us that, due to the restriction in mileage for the electric vehicles, EVs run about 70 miles per day while the ICEs run an average of 120 miles per day (Payette, 2011). To simplify the model, we assumed an overall average of 70 miles per day (most likely for a shorter, urban route).

4.1.1.3. Workdays per year

The number of workdays is assumed to be 253, as per Staples' annual operations (Payette, 2011), and a representative figure for delivery trucks.

4.1.1.4. Cost per vehicle

The Cost per Vehicle is a bit more complicated. In this analysis, we assume the fleet purchases new vehicles in year 0. Staples, Inc. employs Isuzu trucks as their diesel models (from 14K lb. to 24K lb.) (Payette, 2011). Thus, for the ICE vehicle we quoted an approximate value of $50,000. For the PHEV, we assumed the cost of the ICE vehicle plus an additional cost for the battery, controller, charger, wiring, switches, and adapter, as well as the electric motor. Finally, for the EV we included the same parameters as the PHEV minus the cost of the engine. To note, the EV price is significantly higher than the PHEV due to the larger battery size on the EV. As previously stated, the vehicle cost corresponds to a new vehicle and we did not take into account retrofit or conversion costs.

4.1.1.5. Government incentives

To determine the overall investment value for the vehicles, we also needed to include any government subsidies. According to Berman (2011), buyers of plug-in hybrid and electric vehicles benefit from a tax credit of $2,500 to $7,500, depending on the size of the battery in the vehicle. On the low end of the spectrum, vehicles with 4 kWh battery packs will qualify for a $2,500 tax credit. The credit maxes out at $7,500 for vehicles with a 16 kWh battery pack. These incentives are provided as part of the American Recovery and Reinvestment Act, otherwise known as the “stimulus bill.” (Berman, 2011). An additional $200 of tax credit is added for every Kilowatt-hour (Center for Sustainable Energy California, 2010). Some states such as California, Delaware, and Georgia, offer additional incentives.

4.1.1.6. Electric mode efficiency

The electric mode efficiency for a medium-sized delivery truck oscillates around 0.8 kWh per mile (EVsRoll, 2010). Actual cost data from manufacturers are not publicly available, however, largely because of proprietary restrictions. This value is an estimate for a Smith Newton truck, similar to those employed by Staples, Inc.

4.1.1.7. ICE mode efficiency

We assume 10.14 miles per gallon for the ICE mode efficiency (as per Staples data) (Payette, 2011). Due to the regenerative braking, PHEVs in hybrid mode can use part of the electricity in the battery to assist in driving and thus consume less fuel. This method can produce up to 14% greater fuel efficiency (MakeMineElectric, LLC, 2011), or 11.56 miles per gallon.

4.1.1.8. Fuel cost

For the fuel cost, we assumed the current average diesel price (as of April 26, 2011) of approximately \$4.00. Fuel prices are volatile and difficult to forecast and, as a result, we used the \$4.00 as a real price for all ten years.

4.1.1.9. Battery efficiency

As per Section 3.1.3.3, and according to Peterson et al, several thousand driving/V2G driving days incur substantially less than 10% battery capacity loss. As a conservative measure, we use a 10% capacity loss, or 90% efficiency for the battery (Peterson, Apt, & Whitacre, 2009a).

4.1.1.10. Charger efficiency

When electric current passes through a conductor, it releases heat. This phenomenon is knows as Joule or Ohmic heating. Level 1 and 2 chargers utilize relatively low currents (below 100 Amperes), and energy loss is small. Level 3 chargers, while still in the developmental stages, are expected to use very high currents (hundreds of Amperes), and energy loss can be significant. For our simulation, we are assuming a standard 90% efficiency, expecting that Level 3 chargers will be technologically advanced enough to mitigate such energy losses.

4.1.1.11. Regenerative braking efficiency

Due to regenerative braking, PHEVs and EVs can generate electricity for their own use. This process allows the company to buy less electricity from the grid; contributing up to 14% of the electricity utilized for vehicle operations (MakeMineElectric, LLC, 2011).

4.1.1.12. Battery size

Battery size is a very important factor for the EV since the amount of energy stored in the battery determines the vehicle range. 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. The battery size is calculated to be.

$$BS = \frac{(AVMMILE + (0.2 \times AVMILE)) \times KWHM}{(1 - STCH - (1 - BEFF)) \times (1 + REGEN)}, \qquad \textbf{(4-1)}$$

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 (scenario parameter), 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 Equation 4-1 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.

4.1.1.13. Battery state of charge end of day

The minimum battery SOC corresponds to the expected SOC of the battery at the end of the day when the vehicle connects to the grid. A higher SOC means less electricity is needed to fully charge the battery. However, it also means that some of the capacity, or possible storage, for regulation services is compromised. In contrast, running the battery down to a 0% SOC may degrade the battery, leading to a shorter lifespan (See Section 3.1.3). For the simulation, the SOC for PHEVs can take on three different values: 30%, 50%, and 70%. The SOC for EVs can be 20%, 30%, and 40%.

4.1.1.14. Battery life

The battery life (in cycles) is based on the depth of discharge (*DOD = 1 - SOC*), which is the percentage of battery life consumed in one cycle. As the DOD of the battery increases, the number of possible cycles decreases. Using data from an article by Markel and Simpson (2006b), we extrapolated a formula for the battery cycles and constructed the curve shown in Chapter 3, Figure 3-8.

4.1.1.15. Cost of battery

The cost of the battery is assumed to be $1,000 per kWh in year zero and drop to $500 per kWh by year 10 according to Chapter 3, Figure 3-7.

4.1.1.16. Cost of controller

According to industry insiders, the cost of the controller can be around $1,500 (CarsDirect, 2011).

4.1.1.17. Life of controller

According to Van Batenburg (2011), CEO of ACDC, the vehicles' components should be assumed to last the lifetime of the vehicle. In reality, components such as the controller can be damaged in accidents or through poor climate conditions. For the purpose of this analysis, however, we set their lifetime at 10+ years, or 500,000 miles.

4.1.1.18. Cost of charger, wiring, switches, adapter

According to industry insiders, the cost of these items can be around $2,000 (CarsDirect, 2011).

4.1.1.19. Life of charger, wiring, switches, adapter

For the purpose of this analysis we set their lifetime at 10+ years, or 500,000 miles. See explanation on controller life (Section 4.1.1.17).

4.1.1.20. Cost of brakes

According to Mike Payette from Staples, Inc., a brake replacement can reach $1,200 per vehicle (Payette, 2011).

4.1.1.21. Life of brakes

Mike Payette explained that, due to the regenerative braking process, the brakes last five times as long on an EV than an ICE. ICE trucks require annual brake replacements, whereas EVs can go five years before requiring new brakes. Mr. Payette provided us with this data assuming that EVs drove an average of 70 miles while the ICEs drove an average of 120 miles. Taking into account these differences we calculated the typical brake life in terms of miles. We determined that the ICE would require new brakes at 30,000 miles while the EV would require new brakes at 90,000 miles (Payette, 2011).

4.1.1.22. Cost of electric motor/generator – ICE engine

According to industry insiders, the cost of an electric motor can be around $2,000. The cost of ICE engines, although very variable, can be around $5,000 (CarsDirect, 2011).

4.1.1.23. Life of electric motor/generator - ICE engine

For the purpose of this analysis we set their life time at 10+ years, or 500,000 miles. See explanation on controller life (Section 4.1.1.17).

4.1.1.24. Cost of maintenance

The average maintenance costs for the EVs at Staples, Inc., are $250 per year per vehicle, and the ICE maintenance costs are approximately $3,400 (Payette, 2011). 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. This value is variable as these percentages depend on the battery SOC.

4.1.1.25. Diesel filters

According to Staples, Inc., the diesel filters on the ICE vehicles require annual replacements. As PHEVs also have an ICE component, this value is included in their operational costs as well, based on the number of miles driven in hybrid mode per year. Diesel filters are priced at $2,500 per year per vehicle (Payette, 2011).

4.1.1.26. Discount rate

The chosen discount rate for the cash flow model is 10%. For background on the discount rate rationale, see Chapter 3.

4.1.1.27. Charger capacity

The charger capacities (for the EV and PHEV) are manipulated throughout the simulation runs. PHEVs are evaluated using Level 1 chargers with a 1.92 kW capacity and Level 2 chargers with a 6.24 kW and 19.2 kW capacity. EVs were evaluated using Level 2 chargers with a 6.24 kW and 19.2kW capacity, and Level 3 chargers with a 30 kW capacity. See Section 3.1.3 for further detail on chargers.

4.1.1.28. Infrastructure costs

A Level 1 charger requires no change to infrastructure and can be used in regular household outlets. Level 2 and 3 chargers, however, require specific wiring with higher voltage and amperage capacity. For the basis of the project we assume charger sizes and prices per vehicle presented in Table 4-3. The infrastructure investment value is automatically updated in the control panel according to the capacity of the charger.

Table 4-3 Infrastructure changes costs according to the type of charger

Charging level	Voltage	Amperage	Power	Infrastructure cost
Level 1	120 V AC	Up to 20 A	Up to 2.4 kW	$0
Level 2	240 V AC	Up to 80 A	Up to 19.2 kW	$2,000
Level 3	Not yet defined	Not yet defined	20 kW to 250 kW	$20,000

(MIT Energy Initiative, 2010). Price based on interviews with Van Batenburg, 2011

4.1.1.29. Percentage of average fleet connected every day

It is possible that all fleet vehicles are not available every day to participate in V2G due to a variety of reasons. For the purpose of this thesis we assume that 100% of the fleet is plugged into the grid every workday. This may not be the case for all fleet managers and can be customized to meet individual needs.

4.1.1.30. Percentage of revenue for aggregator

As stated before, we did not include this value in our assessment. However, it can be updated accordingly in the future. (See Section 3.2.2 for details on the aggregator functions).

5 Results and Sensitivity Analysis

To begin our analysis, we ran the cash flow and simulation model using our base case scenario (as highlighted in Chapter 4). We ran the model using two different approaches: ramp down V2G and ramp up & down V2G. We then compared the ten year NPV, including the capital investment, infrastructure, and operating costs for the fleet. Following this analysis, we compared just the operating costs and revenue, representing the cost to run the vehicles over the ten year period. In addition, we ran several sensitivity analyses to determine how different parameters affect these revenue and cost factors.

5.1 Base case

The base case scenarios for the EV and PHEV are defined in Table 4-1 Base Case – Control Panel in Chapter 4.

5.1.1 Ramp down V2G

When following the ramp down approach, the vehicle only responds to positive performance signals, i.e. when electricity generation exceeds demand. This differs from ramp up & down V2G where the vehicle responds to positive and negative signals. Dr. Heidel and Steven Connors believe ramp down, or grid-to-vehicle, is the most viable scenario in the near future (Heidel, 2011; Connors, 2011). Since the vehicle will only respond to one of the signals being dispatched from the grid, we expect the revenue opportunities for the ramp down approach to be less than the ramp up & down V2G approach.

5.1.1.1. Total overall costs

The most relevant term for a fleet manager is likely the cost per mile. It is important to take into account that even though our model was run on a fleet of 250 vehicles, the results per mile and day are applicable for any fleet size. We ran several control simulations with different fleet sizes to make sure the results are scalable to any number of vehicles. This is possible since we are not assuming any economies of scale, such as volume discounts in batteries, maintenance, or components, from the addition of trucks,

Table 5-1 Total Overall Costs – Ramp down – V2G Base Case

Results from 10 year projected cash flow	EV	PHEV	ICE
Total Cost ($)	$33,796,275	$32,890,870	$33,198,377
Total V2G Revenue ($)	$2,127,789	$182,612	$0
Total Cost with V2G Revenue($)	$31,668,486	$32,708,259	$33,198,377
Cost per mile($)	$0.763	$0.743	$0.750
Revenue per mile ($)	$0.048	$0.004	$0.000
Total Cost per mile with V2G Revenue ($)	$0.715	$0.739	$0.750
% change in costs due to V2G Revenue	6.30%	0.56%	0.00%
Average Cost per day per veh ($)	$53.43	$52.00	$52.49
Average V2G Revenue per day per veh ($)	$3.36	$0.29	$0.00
Average Cost per day per veh with V2G Revenue ($)	$50.07	$51.71	$52.49
Average Cost per veh ($)	$135,185	$131,563	$132,794
Average V2G Revenue per veh ($)	$8,511	$730	$0
Average Cost per veh with V2G Revenue ($)	$126,674	$130,833	$132,794

As evidenced in Table 5-1, the EV has the largest overall cost without V2G revenue: $0.763 per mile. However, with V2G revenue the EV has the lowest overall cost: $0.715 per mile. The operating cost for the PHEV is slightly better,$0.743 per mile, but does not benefit as much from the V2G revenue, netting $0.739 per mile. Finally, the overall costs for the ICE are the greatest when including V2G revenue: $0.750 per mile. The difference in total costs between the vehicles is due to differences in capital expense (the vehicle cost is highest for the EV and lowest for the PHEV), infrastructure investment (the cost to install new charging equipment), maintenance, fuel vs. electricity prices, and the cost of replacement components. The EV has the greatest overall cost without V2G revenue because of the high capital and infrastructure expense. However, when V2G revenue is included the EV and PHEV become favorable alternatives to the ICE.

We conducted some sensitivity analyses on the price of fuel. If the price of diesel decreases to $2 per gallon, from $4 per gallon, the most inexpensive option is the ICE with total costs of $0.63 per mile, followed by the PHEV with $0.64 per mile, and the EV with the same $0.72 per mile, since it does not consume diesel. Clearly, a 50% reduction in the price of diesel has a significant impact on overall costs since fuel costs are 50% and 52% of total costs at $4 per gallon, and 33% and 35% at $2 per gallon, for the PHEV and ICE, respectively. On the other hand, if the price of fuel reaches $6 per gallon, the most attractive option is the EV with total costs of $0.72 per mile, followed by the PHEV and ICE with $0.84 and $0.87 per mile. Table 5-2 summarizes the costs per mile according to the fuel price.

Table 5-2 Total cost per mile according to diesel price - Ramp down – V2G Base Case

Fuel price ($/gallon)	$2			$4			$6		
Vehicle	EV	PHEV	ICE	EV	PHEV	ICE	EV	PHEV	ICE
Total cost per mile with V2G Revenue ($/mile)	$0.72	$0.64	$0.63	$0.72	$0.74	$0.75	$0.72	$0.84	$0.87

While exhibiting higher initial costs, the EV has higher V2G revenue services revenue than the PHEV: $0.048 per mile vs. $0.004 per mile. This discrepancy is most likely due to differences in battery size, state of charge, and charger capacity required for an all electric vehicle.

Table 5-3 Percent Change Overall Costs –Ramp down – V2G Base Case

Results from 10 year projected cash flow	EV vs. ICE	% Change in Costs	PHEV vs. ICE	% Change in Costs
Total Cost ($)	$597,898	2%	($307,506)	-1%
Total V2G Revenue ($)	$2,127,789	n/a	$182,612	n/a
Total Cost with V2G Revenue($)	($1,529,891)	-5%	($490,118)	-1%
Cost per mile($)	$0.013	2%	($0.007)	-1%
Revenue per mile ($)	$0.048	n/a	$0.004	n/a
Total Cost per mile with V2G Revenue ($)	($0.035)	-5%	($0.011)	-1%
% change in costs due to V2G Revenue	$0.063	n/a	$0.006	n/a
Average Cost per day per veh ($)	$0.94	2%	($0.49)	-1%
Average V2G Revenue per day per veh ($)	$3.36	n/a	$0.29	n/a
Average Cost per day per veh with V2G Revenue ($)	($2.42)	-5%	($0.77)	-1%
Average Cost per veh ($)	$2,392	2%	($1,230.03)	-1%
Average V2G Revenue per veh ($)	$8,511	n/a	$730.45	n/a
Average Cost per veh with V2G Revenue ($)	($6,120)	-5%	($1,960.47)	-1%

Table 5-3 is a breakdown of the percentage change in overall costs (for the EV and PHEV) versus the ICE. The EV has 5% lower total costs while the PHEV has 1% lower total costs.

5.1.1.2. Operating costs

In order to run the cash flow model and simulation tool to depict only operating costs and grid revenue, we eliminated the capital investment and infrastructure costs from each model. When the capital investment and infrastructure costs are taken out of the equation, we can clearly see the tradeoff between up-front capital investment and ongoing operating expenses, especially for the EVs.

Table 5-4 Operating Costs –Ramp down – V2G Base Case

Results from 10 year projected cash flow	EV	PHEV	ICE
Total Cost ($)	$33,796,275	$32,890,870	$33,198,377
Total Capital & Infrastructure Investment	$27,770,000	$14,850,000	$12,500,000
Total Operating Cost ($)	$6,026,275	$18,040,870	$20,698,377
Total V2G Revenue ($)	$2,127,789	$182,612	$0
Total Operating Cost with V2G Revenue($)	$3,898,486	$17,858,259	$20,698,377
Total Operating Cost per mile ($)	$0.136	$0.407	$0.470
Revenue per mile ($)	$0.048	$0.004	$0.000
Total Operating Cost per mile with V2G Revenue ($)	$0.088	$0.403	$0.470
% change in costs due to V2G Revenue	35.31%	1.01%	0.00%
Average Operating Cost per day per veh ($)	$9.53	$28.52	$32.72
Average V2G Revenue per day per veh ($)	$3.36	$0.29	$0.00
Average Operating Cost per veh with V2G Revenue ($)	$6.16	$28.23	$32.72
Average Operating Cost per veh ($)	$24,105	$72,163	$82,794
Average V2G Revenue per veh ($)	$8,511	$730	$0
Average Cost per veh with V2G Revenue ($)	$15,594	$71,433	$82,794

According to Table 5-4, the total cost with V2G revenue for the EV, PHEV, and ICE are $0.09, $0.40, and $0.47 per mile respectively. This shows a dramatic difference between the EV and ICE, mostly due to differences in electricity vs. fuel prices, maintenance, and component costs (e.g. an EV has an extended brake life). The PHEV difference is not as great as the EV due to the fact that the PHEV relies on electricity as well as fuel and has higher maintenance costs than the EV.

Table 5-5 Percent Change Operating Costs –Ramp down – V2G Base Case

Results from 10 year projected cash flow	EV vs. ICE	% Change in Costs	PHEV vs. ICE	% Change in Costs
Total Cost ($)	$597,898	2%	($307,506)	-1%
Total Capital & Infrastructure Investment	$15,270,000	122%	$2,350,000	19%
Total Operating Cost ($)	($14,672,102)	-71%	($2,657,506)	-13%
Total V2G Revenue ($)	$2,127,789	n/a	$182,612	n/a
Total Operating Cost with V2G Revenue($)	($16,799,891)	-81%	($2,840,118)	-14%
Total Operating Cost per mile ($)	($0.334)	-71%	($0.063)	-13%
Revenue per mile ($)	$0.048	n/a	$0.004	n/a
Total Operating Cost per mile with V2G Revenue ($)	($0.382)	-81%	($0.067)	-14%
% change in costs due to V2G Revenue	$0.353	n/a	$0.010	n/a
Average Operating Cost per day per veh ($)	($23.19)	-71%	($4.20)	-13%
Average V2G Revenue per day per veh ($)	$3.36	n/a	$0.29	n/a
Average Operating Cost per veh with V2G Revenue ($)	($26.56)	-81%	($4.49)	-14%
Average Operating Cost per veh ($)	($58,688)	-71%	($10,630)	-13%
Average V2G Revenue per veh ($)	$8,511	n/a	$730	n/a
Average Cost per veh with V2G Revenue ($)	($67,200)	-81%	($11,360)	-14%

Table 5-5 highlights the large difference in operating costs between the three vehicle types. The EV ongoing operating expenses are 81% less than the ICE while the PHEV expenses are 14% less.

5.1.2 Ramp up & down V2G

Following the ramp down approach, we ran the base case scenarios using the ramp up & down V2G approach. We expect to see differences in total V2G revenue (the vehicles will now provide both ramp down and ramp up service) and total costs (electricity costs will differ according to time of day and price when purchased).

5.1.2.1. Total overall costs

According to Table 5-6, the overall results are similar for the ramp up & down approach: the EV has the lowest total cost per mile with V2G revenue and the ICE is the most expensive. The reasons behind these cost differentials include differences in electricity and fuel prices, maintenance, component costs, and revenue earned by participating in V2G services. However, the ramp up & down V2G approach shows greater V2G revenues: approximately $1.1M greater for the EV and $122K for the PHEV. In addition, the overall costs are slightly higher for the ramp down V2G approach: $276K for the EV and $19K for the PHEV. This is most likely due to variances in the price of purchased electricity.

Table 5-6 Total Overall Costs – Ramp up & down - V2G Base Case

Results from 10 year projected cash flow	EV	PHEV	ICE
Total Cost ($)	$34,072,709	$32,909,959	$33,198,377
Total V2G Revenue ($)	$3,257,213	$304,820	$0
Total Cost with V2G Revenue($)	$30,815,496	$32,605,139	$33,198,377
Cost per mile($)	$0.770	$0.743	$0.750
Revenue per mile ($)	$0.074	$0.007	$0.000
Total Cost per mile with V2G Revenue ($)	$0.696	$0.736	$0.750
% change in costs due to V2G Revenue	9.56%	0.93%	0.00%
Average Cost per day per veh ($)	$53.87	$52.03	$52.49
Average V2G Revenue per day per veh ($)	$5.15	$0.48	$0.00
Average Cost per day per veh with V2G Revenue ($)	$48.72	$51.55	$52.49
Average Cost per veh ($)	$136,291	$131,640	$132,794
Average V2G Revenue per veh ($)	$13,029	$1,219	$0
Average Cost per veh with V2G Revenue ($)	$123,262	$130,421	$132,794

We conducted some sensitivity analyses on the price of fuel for the ramp up & down V2G approach as well. If the price of diesel decreases to $2 per gallon, from a price of $4 per gallon, the most inexpensive options are the ICE and PHEV with total costs of $0.63 per mile, followed by the EV with $0.70 per mile. On the other hand, if the price of diesel increases to $6 per gallon, the most attractive option is the EV with a total cost of $0.70 per mile, followed by the PHEV and ICE with $0.84 and $0.87 per mile. Table 5-7 summarizes the costs per mile for the ramp up & down approach, according to the fuel price.

Table 5-7 Total cost per mile according to diesel price - Ramp up & down – V2G Base Case

Fuel price ($/gallon)	$2			$4			$6		
Vehicle	EV	PHEV	ICE	EV	PHEV	ICE	EV	PHEV	ICE
Total cost per mile ($/mile)	$0.70	$0.63	$0.63	$0.70	$0.74	$0.75	$0.70	$0.84	$0.87

Table 5-8 displays the percent change in costs between the EV and ICE and the PHEV and ICE.

Table 5-8 Percent Change Overall Costs – Ramp up & down - V2G Base Case

Results from 10 year projected cash flow	EV vs. ICE	% Change in Costs	PHEV vs. ICE	% Change in Costs
Total Cost ($)	$874,333	3%	($288,418)	-1%
Total V2G Revenue ($)	$3,257,213	n/a	$304,820	n/a
Total Cost with V2G Revenue($)	($2,382,880)	-7%	($593,238)	-2%
Cost per mile($)	$0.020	3%	($0.007)	-1%
Revenue per mile ($)	$0.074	n/a	$0.007	n/a
Total Cost per mile with V2G Revenue ($)	($0.054)	-7%	($0.014)	-2%
% change in costs due to V2G Revenue	$0.096	n/a	$0.009	n/a
Average Cost per day per veh ($)	$1.38	3%	($0.46)	-1%
Average V2G Revenue per day per veh ($)	$5.15	n/a	$0.48	n/a
Average Cost per day per veh with V2G Revenue ($)	($3.77)	-7%	($0.94)	-2%
Average Cost per veh ($)	$3,497	3%	($1,153.67)	-1%
Average V2G Revenue per veh ($)	$13,029	n/a	$1,219.28	n/a
Average Cost per veh with V2G Revenue ($)	($9,532)	-7%	($2,372.95)	-2%

5.1.2.2. Operating costs

As seen in Table 5-9, the operating costs for the ramp up & down V2G approach yield similar results to the ramp down only approach. The EV scenario costs significantly less than the ICE and the ICE remains the most costly of the three vehicle types.

Table 5-9 Operating Costs – Ramp up & down - V2G Base Case

Results from 10 year projected cash flow	EV	PHEV	ICE
Total Cost ($)	$34,072,709	$32,909,959	$33,198,377
Total Capital & Infrastructure Investment	$27,770,000	$14,850,000	$12,500,000
Total Operating Cost ($)	$6,302,709	$18,059,959	$20,698,377
Total V2G Revenue ($)	$3,257,213	$304,820	$0
Total Operating Cost with V2G Revenue($)	$3,045,496	$17,755,139	$20,698,377
Total Operating Cost per mile ($)	$0.142	$0.408	$0.470
Revenue per mile ($)	$0.074	$0.007	$0.000
Total Operating Cost per mile with V2G Revenue ($)	$0.069	$0.401	$0.470
% change in costs due to V2G Revenue	51.68%	1.69%	0.00%
Average Operating Cost per day per veh ($)	$9.96	$28.55	$32.72
Average V2G Revenue per day per veh ($)	$5.15	$0.48	$0.00
Average Operating Cost per veh with V2G Revenue ($)	$4.82	$28.07	$32.72
Average Operating Cost per veh ($)	$25,211	$72,240	$82,794
Average V2G Revenue per veh ($)	$13,029	$1,219	$0
Average Cost per veh with V2G Revenue ($)	$12,182	$71,021	$82,794

Finally, Table 5-10 highlights the large difference in operating costs between the vehicles. The EV costs are 85% less than the ICE while the PHEV costs are 14% less. The operating cost analyses are intended to illustrate the fact that the high infrastructure cost and capital expense are the biggest barriers of entry for the adoption of EVs and PHEVs. As previously discussed, several insiders agree that both infrastructure and capital expenses will decrease in the future, as technology advances and the rate of adoption increases. As these analyses show, the EV and PHEV will become even more cost-effective as these costs decrease. Hereafter, all costs presented in this thesis are overall costs, including infrastructure, capital, and operating expenses.

Table 5-10 Percent Change Operating Costs – Ramp up & down - V2G Base Case

Results from 10 year projected cash flow	EV vs. ICE	% Change in Costs	PHEV vs. ICE	% Change in Costs
Total Cost ($)	$874,333	3%	($288,418)	-1%
Total Capital & Infrastructure Investment	$15,270,000	122%	$2,350,000	19%
Total Operating Cost ($)	($14,395,667)	-70%	($2,638,418)	-13%
Total V2G Revenue ($)	$3,257,213	n/a	$304,820	n/a
Total Operating Cost with V2G Revenue($)	($17,652,880)	-85%	($2,943,238)	-14%
Total Operating Cost per mile ($)	($0.328)	-70%	($0.062)	-13%
Revenue per mile ($)	$0.074	n/a	$0.007	n/a
Total Operating Cost per mile with V2G Revenue ($)	($0.401)	-85%	($0.069)	-14%
% change in costs due to V2G Revenue	$0.517	n/a	$0.017	n/a
Average Operating Cost per day per veh ($)	($22.76)	-70%	($4.17)	-13%
Average V2G Revenue per day per veh ($)	$5.15	n/a	$0.48	n/a
Average Operating Cost per veh with V2G Revenue ($)	($27.90)	-85%	($4.65)	-14%
Average Operating Cost per veh ($)	($57,583)	-70%	($10,554)	-13%
Average V2G Revenue per veh ($)	$13,029	n/a	$1,219	n/a
Average Cost per veh with V2G Revenue ($)	($70,612)	-85%	($11,773)	-14%

5.2 Sensitivity Analysis Scenarios

Following the base case simulations, we ran several sensitivity analyses to examine how different factors, such as the battery size, charger capacity, battery state of charge, and time of day connected to the grid, affect the total overall costs, in both the ramp down V2G and ramp up & down V2G approaches. Since the cost per mile is a common metric for the fleet manager, we report the results of these analyses in terms of this value. We constructed a matrix for each scenario. The rows and columns of the matrix are the parameters evaluated, and the values inside the boxes are the overall cost per mile. These factors are highlighted according to their value; ranging from dark to light, or high to low. The highest cost is deep gray while the lowest cost is pure white. Table 5-11 shows the scenarios and parameters we analyzed.

Table 5-11 Sensitivity analysis scenarios - Electric Vehicle

Scenario	Parameters analyzed
1	Battery size - Charger size
2	Battery size - SOC
3	Battery size - Regulation duration
4	Battery size - Regulation period
5	SOC - Charger size

5.3 Ramp down V2G

5.3.1 Electric Vehicle

Table 5-12 shows the parameters for the electric vehicle configurations, their possible values, and their base case values. This section conducts sensitivity analysis for the Electric Vehicle only, and the next section considers the PHEV.

Table 5-12 Possible values for sensitivity scenarios – EV –Ramp down – V2G

Parameter	Possible Values	Base case value
Battery size (kWh)	Dynamic	Dynamic
Charger size (kW)	6.24 / 19.2 / 30	19.2
SOC (%)	20 / 30 / 40	20
Regulation duration (h)	12 / 14 / 16	12
Regulation period (h)	20-8 / 18-6 / 16-4	18:00 - 6:00

In the case of electric vehicles, the battery size is a parameter that depends on other parameters such as the mileage driven, battery efficiency, and battery state of charge. For these reasons, this parameter is dynamic.

1. Scenario 1. Battery size - Charger size

In the first scenario we altered the charger capacity. The battery size stayed constant at 85 kWh.

Table 5-13 Scenario 1 - EV - Ramp down – V2G

		Charger size (kW)		
		6.24	19.2	30
Battery size (kWh)	85	$0.75	$0.72	$0.80

The charger capacity of 19.2 kW had the lowest total cost per mile. However, a 30 kW charger had the largest average revenue, $1,184 per vehicle per year. While a 30 kW charger may generate the most revenue it also requires the greatest infrastructure investment (a Level 3 charging station). The results in Table 5-13 show that the increase in V2G revenue achieved with a greater capacity charger is not enough to offset the greater infrastructure costs.

2. Scenario 2. Battery size – SOC

In the second scenario we altered the battery SOC and battery size.

Table 5-14 Scenario 2 - EV - Ramp down – V2G

		SOC (% charge)		
		20%	30%	40%
Battery size (kWh)	85	$0.72		
	99		$0.69	
	118			$0.77

A 99 kWh battery at a 30% SOC has the lowest total cost per mile. In the above scenario, a battery at 40% SOC is sized at 118 kWh while a battery at 20% SOC is sized at 85 kWh. Since the EV can only drive in electric mode, and the mileage range was not altered throughout these scenarios, the battery size must increase as the SOC increases. The change in battery size due to the change in the SOC is the driving force behind the change in total costs. However, these changes did not have a significant impact on the amount of generated V2G revenue since the capacity for storage at each SOC is similar. Due to its higher size, a 118 kWh battery has the highest cost. On the other hand, even though an 85 kWh generates the lowest up-front cost, its low SOC produces a more frequent battery change given that a high depth of discharge reduces the life of the battery, which eventually increases costs. As each option produced a similar amount of revenue, hovering around \$0.05 per mile, the scenario with a 30% SOC and 99 kWh battery still had the largest decrease in costs due to V2G revenue.

3. Scenario 3. Battery size - Regulation duration

In the third scenario we adjusted the number of hours plugged into the grid.

Table 5-15 Scenario 3 - EV - Ramp down – V2G

		Regulation duration (hours)		
		12 Hours	14 Hours	16 Hours
		18:00 – 6:00	17:00 – 7:00	16:00 – 8:00
Battery size (kWh)	85	\$0.72	\$0.71	\$0.70

The scenario where the battery is plugged in for 16 hours, instead of the 12 hours of V2G time with the base case, has the lowest total cost since it has the highest average V2G revenue per vehicle per year. The driving force behind the differentials is the number of hours the battery is plugged in and providing V2G services. It is clear that being plugged in longer has positive ramifications for the amount of revenue earned through V2G.

4. Scenario 4. Battery size - Regulation period

In the fourth scenario we modified the 12 hour period in which the vehicle was plugged into the grid.

Table 5-16 Scenario 4 - EV - Ramp down – V2G

		Regulation period (hours)		
		20:00 - 8:00	18:00 - 6:00	16:00 - 4:00
Battery size (kWh)	85	\$0.71	\$0.72	\$0.72

The scenario where the vehicle is plugged in from 8PM – 8AM produced the lowest total cost per mile as well as the greatest percent decrease in costs due to V2G revenue (6.64%) and greatest average revenue, \$897 per vehicle per year. These results show us that the period from 8PM – 8AM must have a lower overall cost of electricity. In addition, the grid must dispatch more ramp-down signals during this period.

5. Scenario 5. SOC - Charger size

In the fifth scenario, we altered the charger size and the SOC.

Table 5-17 Scenario 5 - EV - Ramp down – V2G Total Cost per Mile

		SOC (% charge)		
		20%	30%	40%
Charger size (kW)	6.24	$0.75	$0.73	$0.81
	19.2	$0.72	$0.69	$0.77
	30	$0.80	$0.77	$0.86

The scenario with a 30% SOC and a 19.2 kW capacity charger has the lowest total cost per mile. However, the scenario with the greatest percent decrease in costs due to V2G revenue (8.01%) is a 30% SOC with a 30 kW capacity charger and the scenario with the greatest average revenue ($1,193 per vehicle per year) is a 40% SOC with a 30 kW capacity charger. Due to the fact that the SOC directly affects the size of the EV battery, a higher SOC implies a larger, more expensive battery. Thus a 20% SOC battery will have lower investment costs, but it also reduces the battery life. In addition, a battery with a lower SOC will be able to provide more storage capabilities to the grid. It appears that the charger capacity is more beneficial for providing V2G services and earning revenue as the battery size and SOC increases. At 6.24 kW, the 20% SOC battery had the highest revenues ($259 per vehicle per year), at 19.2 kW the 40% SOC battery had the highest revenues ($867 per vehicle per year), and at 30 kW the 40% SOC battery had the highest revenues ($1,193 per vehicle per year).

5.3.2 Plug-in Hybrid Electric Vehicle

In this section, we repeat similar sensitivity analysis as above but with the PHEV. Table 5-18 shows the parameters for electric vehicles we altered, their possible values, and their base case values.

Table 5-18 Possible values for sensitivity scenarios – PHEV –Ramp down – V2G

Parameter	Possible Values	Base case value
Battery size (kWh)	3.9 / 10 / 20	3.9
Charger size (kW)	1.92 / 6.24 / 19.2	1.92
SOC (%)	30 / 50 / 70	30
Regulation duration (h)	12 / 14 / 16	12
Regulation period (h)	20-8 / 18-6 / 16-4	18:00 - 6:00

1. Scenario 1. Battery size - Charger size

In the first scenario, we manipulated the battery size and charger capacity.

Table 5-19 Scenario 1 - PHEV - Ramp down – V2G

		Charger size (kW)		
		1.92	6.24	19.2
Battery size (kWh)	3.9	$0.74	$0.74	$0.72
	10	$0.72	$0.73	$0.70
	20	$0.73	$0.73	$0.70

The lowest cost per mile is for a 10 kWh battery with a 19.2 kW charger and, overall, a 19.2 kW charger generates the lowest cost per mile for each battery size. When we looked closely at the percent decrease in costs and the average revenue per vehicle per year results, however, the scenario with a 20 kWh battery and a 19.2 kW charger was greater. These results show that a 20 kWh battery can generate more revenue, due to its greater capacity and energy storage capability, but the extra cost for the larger battery offset this advantage. However, the extra costs for a 19.2 kW charger (a Level 2 charger) do not appear to have the same effect.

2. Scenario 1. Battery size – SOC

In the second scenario we manipulated the SOC and battery size.

Table 5-20 Scenario 2 - PHEV - Ramp down – V2G

		SOC (% charge)		
		30%	50%	70%
Battery size (kWh)	3.9	$0.74	$0.74	$0.75
	10	$0.72	$0.73	$0.74
	20	$0.73	$0.73	$0.77

The lowest cost per mile is a 10 kWh battery with a 30% SOC. When we examined the largest percent decrease in costs due to V2G revenue (0.77%) and the average revenue ($101 per vehicle per year), both values were greatest for a 20 kWh battery with a 50% SOC. This result is similar to the previous scenario: the larger battery can provide more V2G services due to its greater capacity. In addition, a larger battery enables the PHEV to drive more miles in all-electric mode. The extra cost of a larger battery, however, outweighs these benefits overall. In addition, we assume the same charger for all scenarios (1.92 kW). This charger has a low capacity, leading to a small possible power transfer. Thus, a larger battery will not necessarily be able to utilize all of its available capacity due to the charger capacity.

3. Scenario 1. Battery size - Regulation duration

In the third scenario we manipulated the number of hours the vehicles are plugged into the grid.

Table 5-21 Scenario 3 - PHEV - Ramp down – V2G

		Regulation duration (hours)		
		12 Hours	14 Hours	16 Hours
		18:00 – 6:00	17:00 – 7:00	16:00 – 8:00
Battery size (kWh)	3.9	$0.74	$0.74	$0.74
	10	$0.72	$0.72	$0.72
	20	$0.73	$0.72	$0.72

A 10 kWh battery, plugged in for 16 hours, has the lowest overall cost. However, a 20 kWh battery plugged in for 16 hours has the largest percent decrease in costs due to V2G revenue (1.14%) and the largest average revenue, $148 per vehicle per year. It is clear, through the previous scenarios as well, that a 20 kWh battery can generate the largest amount of V2G revenue. However, this benefit may not be enough to offset the high investment associated with the larger battery.

4. Scenario 4. Battery size - Regulation period

In the fourth scenario we altered the 12 hour period in which the vehicles were plugged into the grid as well as the battery size.

Table 5-22 Scenario 4 - PHEV - Ramp down – V2G

		Regulation period (hours)		
		20:00 - 8:00	18:00 - 6:00	16:00 - 4:00
Battery size (kWh)	3.9	$0.74	$0.74	$0.74
	10	$0.72	$0.72	$0.72
	20	$0.72	$0.73	$0.73

The scenario with a 10 kWh battery, plugged into the grid from 8PM – 8AM has the lowest overall costs. However, a 20 kWh battery plugged in from 8PM – 8AM has the greatest percent decrease in costs due to V2G (0.84%) as well as average revenue, $109 per vehicle per year. Again a 20 kWh battery clearly generates more V2G revenue due to its capacity. Additionally, being plugged into the grid form 8PM-8AM appears to benefit the bottom line, possibly providing the vehicle with more ramp down opportunities and a lower overall cost of electricity.

5. Scenario 5. SOC - Charger size

In the fifth and final scenario for the PHEV we manipulated the battery SOC and the charger capacity.

Table 5-23 Scenario 5 - PHEV - Ramp down – V2G

		SOC (% charge)		
		30%	50%	70%
Charger size (kW)	1.92	$0.74	$0.74	$0.75
	6.24	$0.74	$0.74	$0.75
	19.2	$0.72	$0.72	$0.73

The scenario with a 19.2 kW capacity charger and a 30% SOC had the lowest total cost per mile as well as the largest percent decrease in costs due to V2G (4.73%) and largest average revenue, $632 per vehicle per year. In this scenario, and prior scenarios, the increase in costs for the greater charger capacity does not have a negative effect on the bottom line. Having a battery with a 30% SOC appears to have positive ramifications for the V2G revenue; enabling the vehicle to store the most requested energy. In addition, the PHEV is able to drive the most all-electric miles with a 30% SOC.

5.4 Regulation up & down V2G

The main differences we expect to see between the V2G scenarios (ramp down vs. ramp up & down) are that V2G revenue should be higher when including ramp up and total costs may be impacted by discrepancies in price and time of day when purchasing the electricity.

5.4.1 Electric Vehicle

Table 5-24 shows the parameters for electric vehicles we altered, their possible values, and their base case values. This section conducts sensitivity analysis for the Electric Vehicle only, and the next section considers the PHEV.

Table 5-24 Possible values for sensitivity scenarios – EV – Ramp up & down - V2G

Parameter	Possible Values	Base case value
Battery size (kWh)	Dynamic	Dynamic
Charger size (kW)	6.24 / 19.2 / 30	19.2
SOC (%)	20 / 30 / 40	20
Regulation duration (h)	12 / 14 / 16	12
Regulation period (h)	20-8 / 18-6 / 16-4	18:00 - 6:00

In the case of electric vehicles, the battery size is dynamic, i.e. its value depends on other parameters such as mileage, battery efficiency, and state of charge.

1. Scenario 1. Battery size - Charger size

Altering the charger size yielded similar results for the ramp up & down V2G scenario as for the ramp down alone. According to Table 5-25, a 19.2 kW charger contributed the lowest total cost per mile. In addition, a 30 kWh charger has the greatest revenue potential ($1,944 per vehicle per year), but the additional costs to install the infrastructure outweigh the benefit. It is important to note that the cost per mile at a 19.2 kW charger in the ramp up & down V2G scenario is two cents cheaper per mile than the ramp down only.

Table 5-25 Scenario 1 - EV – Ramp up & down - V2G

		Charger size (kW)		
		6.24	19.2	30
Battery size (kWh)	85	$0.75	$0.70	$0.76

2. Scenario 2. Battery size – SOC

Again, the ramp up & down V2G scenario yields similar results to the ramp down only approach when altering the battery size and SOC. A 99 kWh battery at 30% SOC has the lowest overall cost per mile (two cents cheaper per mile for ramp up & down V2G vs. ramp down only). The larger battery yields greater revenue potential ($1,301 per vehicle per year), but higher battery costs make the 99 kWh battery the cheapest per mile overall.

Table 5-26 Scenario 2 - EV – Ramp up & down -V2G

		SOC (% charge)		
		20%	30%	40%
Battery size (kWh)	85	$0.70		
	99		$0.67	
	118			$0.75

3. Scenario 3. Battery size - Regulation duration

Plugging into the grid for 16 hours also yields the lowest cost per mile. The ramp up & down V2G approach contributes more revenue than the ramp down alone: 10 cents per mile vs. 6 cents per mile.

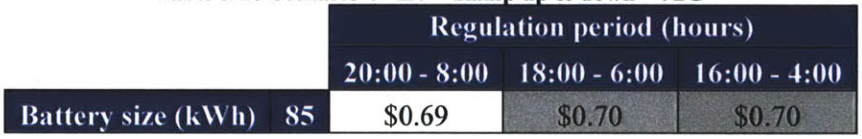
Table 5-27 Scenario 3 - EV – Ramp up & down - V2G

		Regulation duration (hours)		
		12 Hours	14 Hours	16 Hours
		18:00 – 6:00	17:00 – 7:00	16:00 – 8:00
Battery size (kWh)	85	$0.70	$0.68	$0.67

4. Scenario 4. Battery size - Regulation period

Plugging in from 8PM – 8AM yields cheaper costs per mile for the ramp up & down V2G case as well. While the ramp down only is 71 cents per mile the ramp up & down V2G is 69 cents per mile. It appears this is the best time to provide services to the grid, most likely due to the peak period between 6AM and 8AM.

Table 5-28 Scenario 4 - EV – Ramp up & down - V2G



		Regulation period (hours)		
		20:00 - 8:00	18:00 - 6:00	16:00 - 4:00
Battery size (kWh)	85	$0.69	$0.70	$0.70

5. Scenario 5. SOC - Charger size

Finally, we considered the scenario where the battery SOC and charger capacity are altered. As in the ramp down only case, a 30% SOC battery and 19.2 kWh charger contribute to the lowest cost per mile (67 cents per mile for ramp up & down V2G vs. 69 cents per mile for ramp down only). A 30 kW charger yields the most revenue in both cases: 11 cents per mile for ramp up & down V2G and 7 cents per mile for ramp down only.

Table 5-29 Scenario 5 - EV – Ramp up & down - V2G

		SOC (% charge)		
		20%	30%	40%
Charger size (kW)	6.24	$0.75	$0.73	$0.81
	19.2	$0.70	$0.67	$0.75
	30	$0.76	$0.73	$0.82

5.4.2 Plug-in Hybrid Electric Vehicle

In this section, we repeat similar sensitivity analysis as above but with the PHEV. Table 5-30 shows the parameters we altered, their possible values, and their base case values.

Table 5-30 Possible values for sensitivity scenarios – PHEV – Ramp up & down - V2G

Parameter	Possible Values	Base case value
Battery size (kWh)	3.9 / 10 / 20	3.9
Charger size (kW)	1.92 / 6.24 / 19.2	1.92
SOC (%)	30 / 50 / 70	30
Regulation duration (h)	12 / 14 / 16	12
Regulation period (h)	20-8 / 18-6 / 16-4	18:00 - 6:00

1. Scenario 1. Battery size - Charger size

In the ramp up & down V2G scenario, a 20 kWh battery with a 19.2 kW capacity charger yields the lowest overall cost per mile. This contrasts with the ramp down only case in which a 10 kWh battery and 19.2 kW capacity charger yielded the lowest overall cost per mile. The revenue potential for a 20 kWh battery is clearly greater in the ramp up & down V2G case compared with ramp down alone: 7 cents per mile vs. 4 cents per mile in ramp down. The benefit of extra revenue is able to offset the increase in battery costs for the ramp up & down case, but fails to counterbalance the extra costs in the ramp down only scenario.

Table 5-31 Scenario 1 - PHEV – Ramp up & down - V2G

		Charger size (kW)		
		1.92	6.24	19.2
Battery size (kWh)	3.9	$0.74	$0.73	$0.70
	10	$0.72	$0.72	$0.68
	20	$0.73	$0.72	$0.68

2. Scenario 1. Battery size – SOC

A 10 kWh battery at a 30% SOC contributes to the lowest overall cost per mile in Table 5-32. We achieved the same results in the ramp down only case. However, in the ramp down case the largest revenue potential was for a 20 kWh battery with a 30% SOC. For ramp up & down V2G, the largest revenue potential was for a 20 kWh battery with a 70% SOC. This is due to the fact that the ramp down is biased towards a battery with a large storage capacity; and adding ramp up requires a higher amount of energy in order to take advantage of the grid requests. However, requiring a higher amount of residual energy at the end of the vehicle's service day may not be practical.

Table 5-32 Scenario 2 - PHEV – Ramp up & down – V2G

		SOC (% charge)		
		30%	50%	70%
Battery size (kWh)	3.9	$0.74	$0.74	$0.74
	10	$0.72	$0.73	$0.74
	20	$0.73	$0.73	$0.76

3. Scenario 1. Battery size - Regulation duration

A 10 kWh battery plugged in for 16 hours contributes the lowest total cost per mile for ramp up & down V2G and ramp down only. In the ramp down only scenario, however, a 20 kWh battery was able to provide the most revenue whereas a 10 kWh battery in the ramp up & down V2G scenario provided the most revenue. Again, this is due to capacity: a 20 kWh battery provides more storage than a 10 kWh battery.

Table 5-33 Scenario 3 - PHEV – Ramp up & down - V2G

		Regulation duration (hours)		
		12 Hours	14 Hours	16 Hours
		18:00 – 6:00	17:00 – 7:00	16:00 – 8:00
Battery size (kWh)	3.9	$0.74	$0.74	$0.73
	10	$0.72	$0.72	$0.72
	20	$0.73	$0.72	$0.72

4. Scenario 4. Battery size - Regulation period

As in the ramp down only case, a 10 kWh battery plugged in from 8PM – 8AM yields the lowest cost per mile. As in prior scenarios, a 20 kW battery provides the highest V2G revenue for ramp down only while a 10 kW battery provides the highest V2G revenue for ramp up & down V2G.

Table 5-34 Scenario 4 - PHEV – Ramp up & down - V2G

		Regulation period (hours)		
		20:00 - 8:00	18:00 - 6:00	16:00 - 4:00
Battery size (kWh)	3.9	$0.74	$0.74	$0.74
	10	$0.72	$0.72	$0.72
	20	$0.73	$0.73	$0.73

5. Scenario 5. SOC - Charger size

In both cases, the 30% SOC battery with a 19.2 kW charger contribute to the lowest overall cost per mile (70 cents for ramp up & down V2G vs. 72 cents for ramp down only), greatest percent decrease per mile, and greatest revenue per mile (6 cents for ramp up & down V2G vs. 4 cents for ramp down only).

Table 5-35 Scenario 5 - PHEV – Ramp up & down V2G

		SOC (% charge)		
		30%	50%	70%
Charger size (kW)	1.92	$0.74	$0.74	$0.74
	6.24	$0.73	$0.74	$0.74
	19.2	$0.70	$0.70	$0.71

5.5 Best case scenario

The sensitivity analysis allowed us to determine the best values and combinations of parameters to reach the lowest overall cost per mile for each vehicle type and each V2G approach. Table 5-36 shows the control panel for the ramp down best case scenario. The control panel for the ramp up & down scenario is exactly the same, except for the PHEV battery size, which is 20kWh.

Table 5-36 Control Panel - Best Case Scenario

Parameter	EV	PHEV	ICE
Fleet size	250		
Average miles per vehicle per day (miles)	70		
Workdays per year	253		
Cost per vehicle ($)	144,500	65,500	50,000
Subsidy	24,100	5,000	
Electric mode efficiency (kWh/mile)	0.8		
ICE mode efficiency (mile/gallon)		11.56	10.14
Fuel cost ($/gallon)		4	
Battery efficiency	90%		
Charger Efficiency	90%		
Percent of electricity added by regenerative braking	14%		
Battery size (kWh)	99	10	
Minimum battery state of charge end of day	30%	30%	
Battery life (cycles)	3,039	2,300	
Cost battery year 0 ($/kWh)	1,000		
Cost controller ($)	1,500		
Life of Controller (miles)	500,000		
Cost charger, wiring, switches, adapter ($)	2,000		
Life of Cost charger, wiring, switches, adapter (miles)	500,000		
Cost brakes ($)	1,200		1,200
Life of brakes (miles)	90,000		30,000
Cost Electric Motor/Generator - ICE Engine and transmission ($)	2,000		10,000
Life of Electric Motor/Generator - ICE Engine (miles)	500,000		500,000
Cost Maintenance/vehicle ($/year)	250	3,015	3,400
Diesel filters ($/year/vehicle)		2,500	
Discount rate	10%		
Charger capacity (kW/veh)	19.20	19.20	
Infrastructure costs for Charge Level 2 and higher ($/veh)	2,000	2,000	
Percent average fleet connected every day	100%		
Percent of revenue for aggregator	0%		

These scenarios do not necessarily produce the lowest operating cost or the highest V2G revenue, but they do generate the best overall blend of operating cost and V2G revenue, which yields the lowest total cost of ownership. In all cases, the total cost per mile is lower than the total cost per mile for the ICEs ($0.75). Table 5-37 shows the best case scenario configurations.

Table 5-37 Results Best Case Configuration

Results from 10 year projected cash flow	Ramp down – V2G		Ramp up & down - V2G	
	EV	PHEV	EV	PHEV
Total Cost Without V2G ($)	32,529,037	32,723,614	32,747,383	33,032,631
Total V2G Revenue ($)	2,268,780	1,758,834	3,499,284	3,124,115
Total Cost Including V2G Revenue ($)	30,260,257	30,964,780	29,248,099	29,908,516
Cost per mile Without V2G($)	0.73	0.74	0.74	0.75
V2G Revenue per mile ($)	0.05	0.04	0.08	0.07
Total Cost per mile Including V2G Revenue ($)	0.68	0.70	0.66	0.68
Percent decrease in costs due to V2G revenue	6.97%	5.37%	10.69%	9.46%
Average Cost per day per veh without V2G($)	51.43	51.74	51.77	52.23
Average V2G revenue per day per veh ($)	3.59	2.78	5.53	4.94
Average Cost per day per veh Including V2G Revenue($)	47.84	48.96	46.24	47.29

As per our detailed analyses, we discovered that charger capacity, rather than battery size, is the main driver of V2G revenue. Higher charger capacity results in greater V2G revenue up to a point. In our results, the 30 kW (Level 3) is not as attractive due to its higher investment. A 19.2 kW charger offers the best return on investment.

Batteries exhibit similar behavior. A larger battery can generate more revenue, but the current high cost associated with batteries limits the battery size to a certain level. This is more noticeable in the PHEV ramp down. Revenues for a PHEV providing ramp down only can be as much as 50% less than a PHEV that participates in ramp up & down V2G, so that vehicles providing ramp down only require a smaller battery in order to reduce the overall costs. Note that the battery sizes presented in Table 5-37 correspond to the best cases among the options evaluated in our analysis, which is not necessarily the optimal battery size. In order to determine a size that is closer to optimal, we ran simulations for 1 kWh incremental changes in battery size, between 3.9 and 20 kWh. We found that the best size for both ramp down and ramp up & down is 16 kWh. However, the decrease in overall costs with respect to the best case presented in Table 5-37 were just 0.37% for ramp down and 0.43% for ramp up & down.

The state of charge also plays a role in the balance between revenue and cost. Analysis conducted on the 216,000 different ACE signals[6] provided from the ISO NE show that the grid is biased toward providing energy: 66% of ACE signals are positive (ramping down or providing energy) and 34% are negative (ramping up or requesting energy). Thus, a battery with a low state of charge would generate the highest revenues as it can respond to the higher number of positive signals. However, a low state of charge, or a high depth of discharge, diminishes the life of the battery, forcing the fleet manager to invest in new batteries earlier. As a result, we found that the best battery SOC is 30%, a point where revenues are high enough to compensate the costs of battery replacement.

Our base case simulated the economics of the fleet providing V2G service between 6PM and 6AM. However, the results of our analyses show that higher revenues and lower costs are obtained if this period is shifted forward by 2 hours, that is, between 8PM and 8AM. We found the average RCP (regulation clearing price) to be $16.94 between 6AM and 8AM versus $11.96 between 6PM and 8PM. Thus, the revenues earned for providing the service between 6AM and 8AM are higher than the revenues lost for not providing the service between these hours. Additionally, electricity costs are lower during this period: the LMP (locational marginal price) between 6AM and 8AM is $92.93 versus $97.42 for the period between 6PM and 8PM. However, this may impact the fleet service requirements. Fleet managers should consider this V2G revenue opportunity when it is possible to commence fleet service operations after the morning rush hour.

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[6] Assuming twelve hours of regulation per day (8PM – 8AM), 900 ACE signals per hour (one ACE signal every 4 seconds), and 20 days per simulation. 12*900*20 = 216,000.

Finally, the V2G revenue is directly proportional to the regulation duration. We found that a fleet providing V2G service to the grid can increase its revenue by between 14% and 30%, depending on the battery size and charger capacity, for every additional hour connected to the grid. The increment in costs due to this additional hour is negligible, no more than 0.2%. The value of this marginal increase in grid connection time can be useful in determining the appropriate mix of fleet service time and grid service time.

6 Conclusions

This thesis contributes not only to a better understanding of V2G potential benefits for corporate fleets, but also creates an analytical methodology for further investigation on the topic. We identified three key contributions from our research: (1) a detailed cost structure for corporate fleets that can be easily 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 for both ramp down only and ramp up & down approaches.

It is well known that electric and plug-in hybrid electric vehicles have a few fundamental differences. EVs run solely on electricity and are less expensive to operate. However, they have larger, more expensive batteries and their driving range is restricted. PHEVs run on both electricity and fuel. They are more expensive to operate, but have smaller, less expensive batteries and their driving range is not restricted. The differences between these vehicles drove the results of our analysis. As we have shown throughout our research, both EVs and PHEVs are well-suited to serve the regulation services market. These vehicles can process performance signals from the grid and use their batteries as both energy and storage sources. In order to calculate the monetary benefits from participating in V2G, we analyzed an urban delivery fleet.

In each scenario the average miles per day were given. Thus, in the EV case, the state of charge (SOC) at the end of the day must accommodate the given number of miles driven; and a higher SOC parameter meant a larger, more expensive battery was required. In the PHEV case, the battery size did not restrict the number of miles driven, but a smaller battery or a higher SOC at the end of the day meant the vehicle was driving more miles in hybrid mode; increasing its fuel consumption. A larger battery, however, also led to higher overall costs.

Throughout the EV scenarios, the charger capacity was shown to play a large role. Level 3 charging (a 30 kW capacity charger) is still in its developmental stages and is expected to require a large infrastructure investment. While the high cost of implementing the Level 3 charging infrastructure currently prices it out of the market, it was shown to provide the largest V2G revenue stream in multiple scenarios. However, the charger's ability to earn the highest level of income is directly related to the size of the battery. If the capacity is too large, it will charge or deplete a small battery too quickly, hindering its ability to provide regulation services. It is important to match the charger capacity to the appropriate battery size and SOC.

In addition, if the vehicles can be parked for a greater number of hours, especially during the peak morning hours from 6 AM – 8 AM, revenues can increase up to 30% per additional hour. There is clearly an incentive to connect the fleet to the grid as long as possible. Our results show that a 19.2 kW capacity charger and a 99 kWh battery at 30% SOC provides the lowest cost scenario for the EV (in both the ramp down and ramp up & down V2G cases) and greater revenue can be earned by participating in regulation during peak periods, e.g. from 6AM – 8AM given the favorable differences in RCP and LMP values.

The charger capacity also played a large role in the PHEV scenarios. The Level 2 charger at a 19.2 kW capacity provided the lowest costs with a 10 kWh battery at 30% SOC for the ramp down only approach. However, for ramp up & down V2G, a 20 kWh battery provided the lowest overall costs. There is a tradeoff for the PHEV in terms of battery size. A larger battery, such as a 20 kWh battery, will generate more money from regulation services and enable the vehicle to drive longer distances in all-electric mode, but the high cost of the battery may prevent it from being cost effective. Since ramp up & down V2G generates more revenue, a 20 kWh battery is cost effective, whereas it is not the case for the ramp down only due to its smaller revenue opportunity. Like the EV, the PHEV benefits from being plugged into the grid for longer periods, enabling it to provide regulation services during the peak morning and evening hours. The PHEV clearly has more flexibility than the EV in terms of mileage. It might make sense for a fleet of vehicle to operate EVs on shorter routes and save the PHEVs for the longer routes.

Though there are benefits from participating in ramp down only, the gains are greatest when vehicles are aggregated in a large number and can provide both energy and storage, i.e. ramp up & down V2G. Our calculations showed that a PHEV can earn an average of up to $703 per vehicle per year performing ramp down only and $1,250 per vehicle per year with ramp up & down V2G capabilities. Alternatively, an EV can earn of average of $908 per vehicle per year performing ramp down only and $1400 per vehicle per year with ramp up & down V2G capabilities. Though the economics of V2G are still being explored and the future of the market rests heavily on technological innovation, fleet managers, willing to participate in this future market, have the potential for great benefit.

6.1 Future research

While our analysis provides solid groundwork for this technology and its application for delivery fleets, we acknowledge that further research could enhance our business assessment. Currently, our model for regulation services considers both ramp down only and ramp up & down regulation services. Discussions with industry insiders also referenced the idea of energy arbitrage, or charging when the prices are low and discharging when the prices are high. A next step would be to build the model out to consider these scenarios and evaluate any additional benefits.

As the market for V2G becomes a reality, there is always the possibility that it could become saturated and regulation prices could fall. As the market for regulation services decreased from $50 million in 2008 to $15 million in 2010, this threat is real. The 2008 prices that we are using as representative of the future regulation market might not provide an accurate picture. Likewise, we acknowledge that the locational marginal prices (LMP) utilized are representative of only one node, but some nodes may have higher/more volatile price swings than others. It is likely that regulation revenue opportunities and costs can change depending on which node a corporate fleet is plugging into the grid. If prices fall significantly in the future, the basis of our business case would not be as strong. However, as wind and solar power become more prevalent, the market for regulation could also increase in the future, driving up prices and enhancing our case as well.

The values we quoted for component parts and overall costs constitute another gray area. Our model assumes the same charging rate throughout the cycle. In reality, a charger starts off the cycle strong and the rate tapers off towards the end. In addition, the battery efficiency is held steady over ten years. Our model does not take into account temperature or cycle degradation which could deplete the efficiency even further. As technology advances, the prices of batteries and Level 3 chargers, key drivers in our overall cost scenarios, could fall significantly. A reduction in the price of batteries would equate to lower capital investments for EVs and PHEVs and a decline in Level 3 charging equipment could equate to much larger revenue opportunities.

Our model also assumes discrete choices for the parameters' possible values. Thus, the best cases presented in this thesis are the best combinations of the defined parameters' values and not necessarily the optimum cases. We did add some more detailed analysis for the battery size of the PHEV by considering 1 kWh increments. However, we found that the overall cost of ownership for the best battery size at the 1 kWh resolution is less than 0.5% different than the best overall case among our three primary options. However, the combination of the optimal battery size with other optimal parameters may produce even greater savings. In order to find the optimum cases for the vehicles, a more powerful simulation and optimization tool, which allows continuous values and employs faster simulation times, would be necessary.

The future of V2G includes many uncertainties. However, as technology continues to develop, battery prices fall, and more and more EVs and PHEVs enter the market, this technology could become a reality. V2G has the potential to change the way consumers, businesses, and the electric grid operates, providing benefits to all players involved. The first-movers to realize the promise behind this technology have the potential for great benefit.

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Appendix 1: Cash flow models

Electric Vehicle

Component	Year										
	0	1	2	3	4	5	6	7	8	9	10
Capital investment	30,100,000										
Infrastructure Cost	470,000										
Electricty cost		264,299	264,299	264,299	264,299	264,299	264,299	264,299	264,299	264,299	264,299
Fuel cost											
Battery replacement costs		0	0	0	0	0	0	0	0	0	0
Controller Costs		0	0	0	0	0	0	0	0	0	0
Charger, wiring, switches, adapter Costs		0	0	0	0	0	0	0	0	0	0
Brake Costs		0	0	0	0	0	300,000	0	0	0	0
Engine Costs											
Electric Motor/Generator Costs		0	0	0	0	0	0	0	0	0	0
Maintenance Costs		62,500	62,500	62,500	62,500	62,500	62,500	62,500	62,500	62,500	62,500
Total Costs	30,570,000	326,799	326,799	326,799	326,799	326,799	626,799	326,799	326,799	326,799	326,799
Capacity payment		199,033	199,033	199,033	199,033	199,033	199,033	199,033	199,033	199,033	199,033
Service payment		370,460	370,460	370,460	370,460	370,460	370,460	370,460	370,460	370,460	370,460
Total payment		569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492
Regulation revenue after deducting aggregator fee		569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492	569,492
Net cashflow	-30,570,000	242,693	242,693	242,693	242,693	242,693	-57,307	242,693	242,693	242,693	242,693

Net Present Value	-29,248,099

Component	Year										
	0	1	2	3	4	5	6	7	8	9	10
Capital investment	16,800,000										
Infrastructure Cost	470,000										
Electricty cost		93,126	93,126	93,126	93,126	93,126	93,126	93,126	93,126	93,126	93,126
Fuel cost		1,157,800	1,157,800	1,157,800	1,157,800	1,157,800	1,157,800	1,157,800	1,157,800	1,157,800	1,157,800
Battery replacement costs		0	0	0	0	0	0	0	0	0	2,500,000
Controller Costs		0	0	0	0	0	0	0	0	0	0
Charger, wiring, switches, adapter Costs		0	0	0	0	0	0	0	0	0	0
Brake Costs		0	0	0	0	0	300,000	0	0	0	0
Engine Costs		0	0	0	0	0	0	0	0	0	0
Electric Motor/Generator Costs		0	0	0	0	0	0	0	0	0	0
Maintenance Costs		1,129,946	1,129,946	1,129,946	1,129,946	1,129,946	1,129,946	1,129,946	1,129,946	1,129,946	1,129,946
Total Costs	17,270,000	2,380,872	2,380,872	2,380,872	2,380,872	2,380,872	2,680,872	2,380,872	2,380,872	2,380,872	4,880,872
Capacity payment		169,988	169,988	169,988	169,988	169,988	169,988	169,988	169,988	169,988	169,988
Service payment		338,448	338,448	338,448	338,448	338,448	338,448	338,448	338,448	338,448	338,448
Total payment		508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435
Regulation revenue after deducting aggregator fee		508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435	508,435
Net cashflow	-17,270,000	-1,872,437	-1,872,437	-1,872,437	-1,872,437	-1,872,437	-2,172,437	-1,872,437	-1,872,437	-1,872,437	-4,372,437
Net Present Value	-29,908,516										

Internal Combustion Engine Vehicle

Component	Year										
	0	1	2	3	4	5	6	7	8	9	10
Capital investment	12,500,000										
Infrastructure Cost											
Electricty cost											
Fuel cost		1,746,548	1,746,548	1,746,548	1,746,548	1,746,548	1,746,548	1,746,548	1,746,548	1,746,548	1,746,548
Battery replacement costs											
Controller Costs											
Charger, wiring, switches, adapter Costs											
Brake Costs		0	300,000	0	300,000	0	300,000	300,000	0	300,000	0
Engine Costs		0	0	0	0	0	0	0	0	0	0
Electric Motor/Generator Costs											
Maintenance Costs		1,475,000	1,475,000	1,475,000	1,475,000	1,475,000	1,475,000	1,475,000	1,475,000	1,475,000	1,475,000
Total Costs	12,500,000	3,221,548	3,521,548	3,221,548	3,521,548	3,221,548	3,521,548	3,521,548	3,221,548	3,521,548	3,221,548
Capacity payment		0	0	0	0	0	0	0	0	0	0
Service payment		0	0	0	0	0	0	0	0	0	0
Total payment		0	0	0	0	0	0	0	0	0	0
Regulation revenue after deducting aggregator fee		0	0	0	0	0	0	0	0	0	0
Net cashflow	-12,500,000	-3,221,548	-3,521,548	-3,221,548	-3,521,548	-3,221,548	-3,521,548	-3,521,548	-3,221,548	-3,521,548	-3,221,548
Net Present Value	-33,198,377										