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Life-Cycle Cost Modeling to Determine Whether Vehicle-to-Grid (V2G) Integration and Ancillary Service Revenue Can Generate a Viable Case for Plug-In Electric Drive Vehicles

30 June 2013

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ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

ABSTRACT

In an effort to increase U.S. energy security by reducing oil consumption, various federal mandates and executive orders require reduced petroleum use and greenhouse gas emissions by federal non-tactical vehicle fleets. Transitioning federal fleets to plug-in electric drive vehicles (PEDVs) is one option to meet these mandates. This research performs a life-cycle cost analysis using modeling and simulation to determine the parameters under which vehicle-to-grid (V2G) integration and associated revenue streams can create a viable economic case for the transition of federal fleets to PEDVs. Under current market conditions, bidirectional V2G frequency regulation (FR) is not currently viable. Unidirectional FR has potential, but it provides minimal reductions in PEDV life-cycle cost. The cost to meet petroleum reduction mandates by transitioning light-duty fleets to PEDVs is cost prohibitive and impractical, requiring almost a complete one-for-one replacement of the current fleet of traditional light-duty passenger vehicles. Realistically meeting the mandate without fleet downsizing will require implementing a transition toward alternatively fueled vehicles beyond the light-duty passenger vehicle class. However, economic justification will require a reduction in PEDV acquisition costs or improved market conditions for V2G FR (consisting of lower throughput and higher regulation market clearing prices), thereby resulting in considerably greater net revenue.

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ACKNOWLEDGMENTS

There are several people to whom I am indebted for their help with this thesis. I gratefully acknowledge my advisor, Dr. Dan Nussbaum, and second reader, Professor Andy Hernandez, for their knowledge and extraordinary patience, and for providing me the freedom to delve deep into this expansive topic. With your help, this thesis has been a tremendous learning experience which brought together many of the disciplines of this degree.

I would like to acknowledge the several subject-matter experts who provided their time, insight, and technical guidance through interviews, meetings, and e-mails that helped bring the concept and potential of V2G into clarity: Scott Baker—PJM, Jonathon Lowell—ISO New England, Charlie Bostford and Alec Brooks—AeroVironment, Danny Terlip and Cranston Polson—Select Engineering Services, and James Muldoon—USARPAC.

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I would especially like to thank my family for their prayers and encouragement. To my parents, Bill and June, for your love and enduring example of faith, hope, and charity, you have set the bar high. To my lovely bride, Kate, a.k.a "Sally!," for your unwavering support and loyalty; my life and this thesis would not be complete without you. It was with great pleasure and the utmost deservingness to have you type the last two words of this thesis, "The End." You get your husband back …

Finally, and most importantly, I thank the Almighty through which all things are possible.

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ABOUT THE AUTHOR

Capt. Joseph “Southie” Monahan was born and raised in Boston, MA. After graduating from Matignon High School in Cambridge in 1999, he accepted an appointment to Annapolis. There he played on the club hockey team, earned a Bachelor of Science degree in quantitative economics and was commissioned a 2nd Lt., USMC, with the class of 2003.

After completing basics, naval flight officer training, and instruction as an electronic counter measures officer, Capt. Monahan was assigned to Marine Electronic Attack Squadron 2, MAG-14 in Cherry Point, NC. As a member of the VMAQ-2 “Playboys,” Capt. Monahan earned the designation of EA-6B “Prowler” mission commander and served as the department head for Electronic Warfare and Logistics and was an assistant aviation maintenance officer.

Capt. Monahan’s operational experience includes two deployments to Al Asad, Iraq, in support of OIF. During that time, he flew over 600 combat flight hours and served temporary duty as the prowler liaison officer for the Electronic Warfare Coordination Cell (EWCC) at the Multi- National Corps-Iraq (MNCI) Headquarters in Baghdad (September 2007) and at the Combined Air Operations Center (CAOC) located at Al Udeid Air Base, Qatar (December 2008).

Capt. Monahan received a Master of Science degree in operations research from NPS in June 2012. He is currently assigned as an operations research and systems analyst (ORSA) at the Marine Corps’ Operations Analysis Division (OAD) in Quantico, VA.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAA – American Automobile Association
AC – Alternating Current
ACE – Area Control Error
AE – All Electric (range)
AEO – Annual Energy Outlook
AER – All-Electric Range
AEV – All-Electric Vehicle
AFV – Alternatively Fueled Vehicle
AGC – Automatic Generation Control
ARRA –American Recovery and Reinvestment Act
A/S – Ancillary Service
BEV – Battery Electric Vehicle
BMS – Battery Management Service
BP – British Petroleum
BPC – Battery Protection Control
Btu – British Thermal Unit
CAPEX – Capital Expenditure
CASIO – California ISO
CBA – Cost–Benefit Analysis
CRC – Capital Replacement Cost
DC – Direct Current
DOD – Depth of Discharge
DoD – Department of Defense
DoE – Department of Energy
DPB – Discounted Payback
D-SIR – Discounted Savings-to-Investment Ratio
ECRA – Energy Conservation Act
EIA – Energy Information Administration
EVSE – Electric Vehicle Supply Equipment
EOL – End of Life
EDV – Electric Drive Vehicle
EF–LLCM – Energy Flow–Life-Cycle Cost Model

EPA – Environmental Protection Agency
ESP – Energy Service Provider
EV – Electric Vehicle
FAST – Federal Automotive Statistical Tool
FEMP – Federal Energy Management Program
FERC – Federal Energy Regulation Committee
FOB – Forward Operating Base
FR – Frequency Regulation
FY – Fiscal Year
GEV – Grid-Enabled Electric Vehicle
GHG – Greenhouse Gas
GREET – Greenhouse Gasses, Regulated Emissions, and Energy Use in Transportation
GSA – General Service Administration
HECO – Hawaiian Electric Company
HEV – Hybrid Electric Vehicle
Hz – Hertz
ICE – Internal Combustion Engine
IEO – International Energy Outlook
IPC – Ideal Power Converter
ISO – Independent System Operator
ISO-NE – New England Independent System Operator
kWh – Kilowatt Hours
LCC – Life-Cycle Cost
Li-ion – Lithium Ion
LMP – Locational Marginal Pricing
MCBH – Marine Corps Base Hawaii
MPG – Miles per Gallon
MSRP – Manufacturer’s Suggested Retail Price
MTTF – Mean Time to Failure
MW – Megawatt
NEC – National Electric Code
NEV – Neighborhood Electric Vehicle
NG – Natural Gas
NiMH – Nickel-Metal Hydride

NPV – Net Present Value
NREL – National Renewal Energy Lab
OECD – Organization for Economic Co-operation and Development
OEM – Original Equipment Manufacturer
OPEC – Organization of the Petroleum Exporting Countries
OPEX – Operating Expense
OTS – Off the Shelf
PEDV – Plug-In Electric Drive Vehicle
PEV – Plug-In Electric Vehicle
PHEV – Plug-In Hybrid Electric Vehicle
PJM – Pennsylvania New Jersey Maryland Interconnection LLC
POP – Preferred Operating Point
RE – Range Extending
RMCP – Regulation Market Clearing Price ($/MW-h of capacity)
ROI – Return on Investment
R/P – Reserve/Production
RTO – Regional Transmission Organization
SAE – Society of Automotive Engineers
SIR – Savings-to-Investment
SOC – State of Charge
TARDEC – Tank Automotive Research Development Engineer Center
TOR – Time on Regulation
USD(AT&L) – Under Secretary of Defense for Acquisition, Technology, and Logistics
V – Volt
V2B – Vehicle to Building
V2G – Vehicle-to-Grid Energy Transfer
VSM – Vehicle Smart Link
W – Watt
Wh – Watt Hour

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EXECUTIVE SUMMARY

The federal government recognizes its role in leading change for an energy-independent future. In an effort to increase U.S. energy security by reducing oil consumption, various federal mandates and executive orders specifically target the Department of Defense (DoD) and federal non-tactical vehicle fleets. These regulations require fleets of non-exempt vehicles in the 21 covered agencies to reduce petroleum use and greenhouse gas emissions by 30% and 28%, respectively, by 2020 from a fiscal year (FY) 2005 baseline. Additional statutes related to federal vehicle acquisition present a clear momentum toward electric drive vehicles (EDVs) and alternatively fueled vehicles (AFVs) to help meet these regulations. Plug-in electric drive vehicles (PEDVs) are included in the list of potential options, but, due to relatively low gas prices ($4.00) and high initial capital costs, a strong economic case for a government transition to plug-in electric vehicles is not made by reductions in operating and maintenance costs alone.

My research focuses on the potential to offset initial capital costs associated with PEDVs through their integration with the electrical grid by what is known as vehicle-to-grid, or V2G. V2G can offer the participating federal installation many benefits, ranging from energy storage for renewable energy integration to emergency backup power for critical systems or buildings. The benefits of most interest, as they pertain to life-cycle cost (LCC) reduction and the economic justification of PEDVs, are revenue streams from the provision of ancillary services (A/S) to the electrical grid. These services increase grid stabilization and reliability and are paid for by the utility company based on a market clearing price in dollars per megawatt (MW) of capacity per hour of service. Frequency regulation (FR) is a particular A/S that involves balancing load and generation on the grid to maintain a target frequency of 60 hertz (Hz). A fleet of PEDVs is able to provide this service by either unidirectional or bidirectional energy flow, depending on the capability of the grid connected charger. FR is performed by a fleet of PEDVs when their charge profiles are aggregated to respond to a utility company's automatic generation control (AGC) signal. When grid imbalance is the result of over-generation, the AGC would signal a fleet to increase charge rate, while under-generation would result in a signal to reduce charge rate or even transfer energy back to the grid (bidirectional).

In order to construct a thorough economic evaluation of V2G as it pertains to federal non-tactical vehicle fleets, I developed an energy flow–life-cycle cost model (EF–LCCM) that seeks to close the analysis gap linking V2G revenue, energy throughput, battery degradation, salvage value, operating costs, and associated capital investments. This deterministic Excel model enumerates various levels of V2G integration to determine the parameters under which V2G revenue from FR can deliver the necessary financial subsidy for PEDVs to compete with traditional fleet vehicles, and it identifies the level of V2G with the greatest return on investment. The levels of V2G integration range from low-capacity unidirectional chargers with associated lower capital costs (see Table ES1) and lower gross revenue potential to high-capacity bidirectional chargers with higher capital costs and potentially higher gross revenue. Energy flow from FR is modeled in detail to determine net revenue based on regulation market clearing prices (RMCPs), and LCCs are modeled using a constant dollar approach in accordance with the *Life-Cycle Costing Manual for the Federal Energy Management Program* (Fuller & Peterson, 1995).

Table ES1. Charging Infrastructure and Installation Cost Estimates per Vehicle

	High - Current	Low - Current	Best-Case Long-Term
OEM Basic Charging (non-V2G)	$2,355.70	$1,605.70	$1,305.70
OEM Level Unidirectional V2G	$2,482.99	$1,957.43	$1,846.43
Level-2 Hi Capacity Unidirectional	$11,620.21	$7,044.65	$2,985.65
Level-2 Bidirectional	$19,920.21	$12,894.65	$2,985.65
Level-3 Bidirectional	$27,041.63	$13,924.41	$6,615.41

Note. These costs are based on my analysis and represent the per-vehicle costs associated with a fleet installation of 100 vehicles.

My analysis presents a new look at the economic viability of V2G FR by examining actual and recent AGC data from the mid-Atlantic Energy Service Provider, PJM (a regional transportation organization, that coordinates the movement of wholesale electricity). By creating a simulation with the data obtained from PJM, I was able to integrate the dispatch signals over time and quantify actual energy throughput and battery state-of-charge (SOC) swings during FR. The amount of energy throughput sustained by a vehicle's battery, resulting from response to an FR dispatch signal, directly and negatively impacts FR profitability. Because FR payment is based on an hourly rate, revenue is limited by the amount of time a vehicle can provide the service. For unidirectional FR, higher throughput levels result in lower revenue as a battery reaches a full SOC more quickly and, subsequently, can no longer provide the service if it cannot draw power from the grid.

Bidirectional FR can theoretically be performed indefinitely by a storage resource assuming perfect efficiency and an AGC signal that nets to zero over time. However, the data again present evidence contrary to this theory and previous assumptions. By separately integrating the regulation-up and regulation-down signals over the sample set, I was able to determine a statistically significant bias of 3 to 1 in favor of regulation down, meaning the utility consistently over generates, thereby requiring additional load to balance the grid (see Figure ES1). Therefore, even a vehicle performing bidirectional FR without a dynamic base point would absorb more energy than it returned to the grid, and, thus, revenue potential would be limited by time to reach full charge. Additionally, throughput-associated battery degradation must be considered because, by virtue of bidirectional flow, more energy would pass through the battery than it would under a unidirectional charge profile. My model assumes a battery has a limited amount of energy throughput in its useful life, and the model accounts for additional energy throughput from bidirectional FR by adapting a published battery degradation model to quantify the financial impacts associated with degradation.

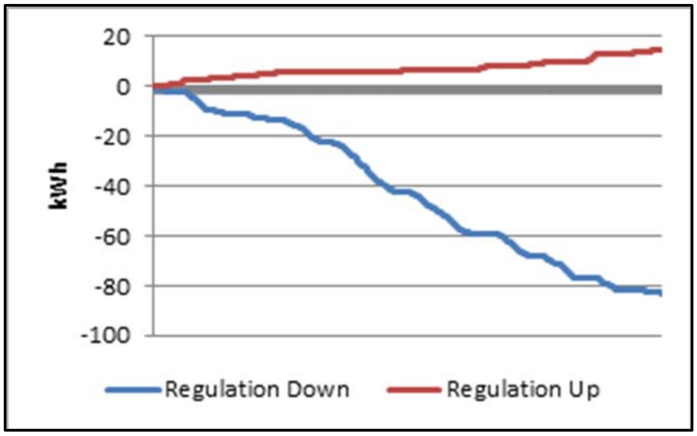

Figure ES1. Integrated Automatic Generation Control Signal Illustrating kWh of Energy Throughput Over 24 Hours of Frequency Regulation Response With a 10-kWh Bidirectional Charger

My analysis compares the LCCs of two base case internal combustion engine (ICE) vehicles with those of a non-plug-in hybrid electric vehicle (HEV) and two PEDVs with and without V2G (see Table ES2). I conclude that, in the presence of high energy throughput (four times greater than previous estimates), and at current RMCPs (< $10/MW; see Figure ES2), there is no economic case for bidirectional FR. The higher capital costs of the bidirectional infrastructure are not justified by net FR revenue and, when accounting for battery degradation, net revenue actually results in a loss. On the other hand, aggregated demand response in the form of controlled unidirectional charging does present a viable option to reduce the initial capital and charging infrastructure expenses associated with PEDVs. However, V2G offers a realistic potential to help PEDVs economically compete with other alternatives only if RMCPs return to levels greater than $24/MW along with a 75% reduction in throughput at best case infrastructure costs. The non-plug-in HEV, with the lowest net LCCs, no initial infrastructure investment, 54% less fuel consumption than the 2005 baseline, and the lowest marginal LCC per gallon reduced, emerges as the dominant alternative to base case 1.[1]

Table ES2. Comparison Vehicles

Category	Vehicle
ICE-Purchase (Base Case 1)	2012 Chevy Cruze
ICE-GSA Lease (Base Case 2)	2012 Ford Focus
HEV	2012 Toyota Hybrid
PEV	2013 Nissan Leaf
PHEV	2012 Chevy Volt

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[1] The Prius' historically high resale value at almost twice a typical ICE helps its position against the base case. Without considering salvage value, average annual mileage must be greater than 15,000 miles at $4.00 gal to compete against the ICE.

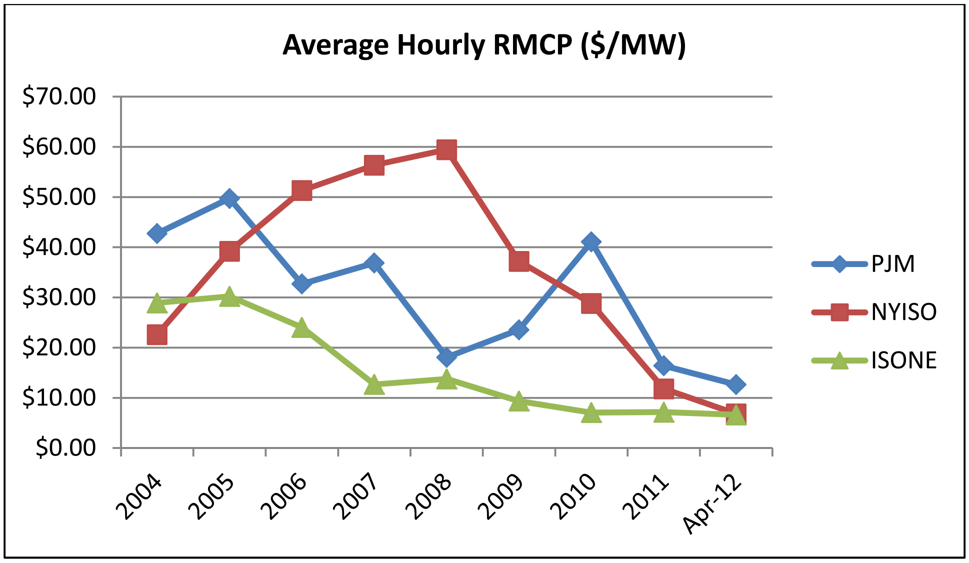
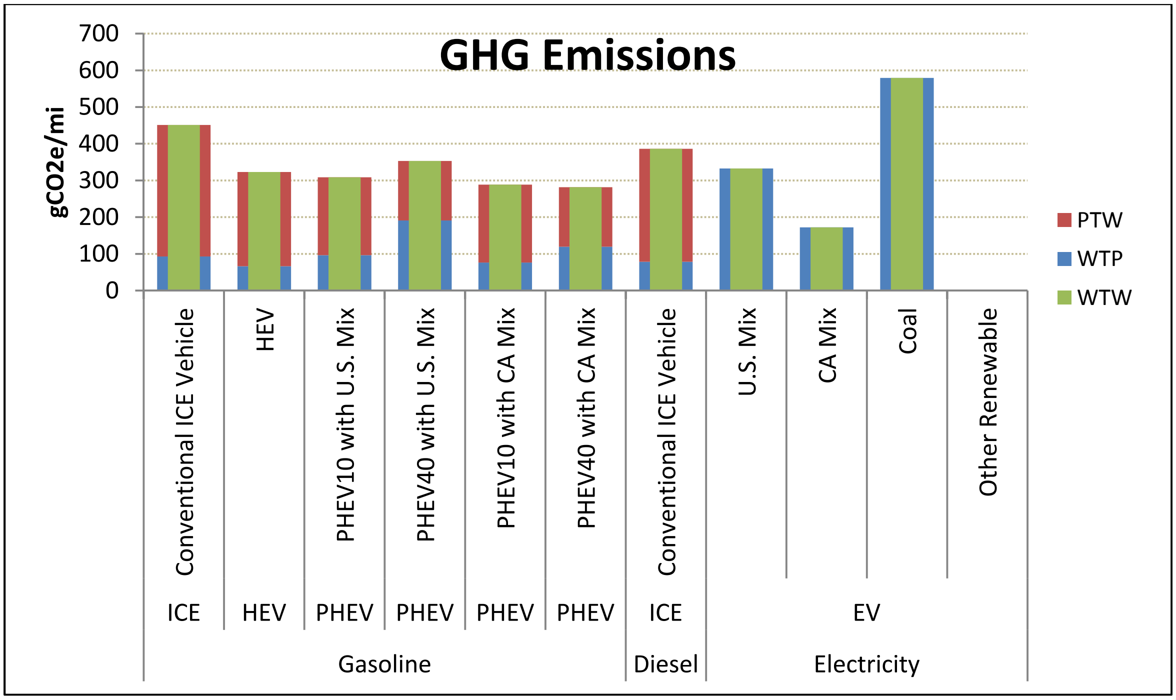


Figure ES2. Regulation Market Clearing Price Trend

In contrast to the ownership comparisons of base case 1, case 2 offers an evaluation of alternatives relative to a GSA (General Services Administration) lease. From this perspective, PEDVs have a much stronger case due to the significantly higher LCCs associated with a lease. Although PEDVs are not the least expensive option, they present agencies operating GSA vehicles the ability to choose PEDV ownership over ICE lease to help meet petroleum reduction mandates while at the same time lowering fleet LCCs.

Conclusion/Recommendation. Advanced levels of bidirectional V2G integration cannot be economically justified under current market conditions from FR revenue alone, but lower levels of unidirectional integration can provide enough revenue to at least offset some, but not all, of the higher initial costs. New federal regulations took effect in late 2012, which created a more attractive environment for fast-responding storage resources such as PEDVs, but greater reimbursement for service and less throughput demand is necessary for a strong economic case. Until capital costs sufficiently decline or the aforementioned market conditions are met, HEVs provide the greatest benefit in terms of LCCs, reduced petroleum consumption, and net emissions reductions. Figure ES3 illustrates the HEVs' ability to create fewer emissions than an electric vehicle (EV) operating off the average U.S. generation mix, while Figure ES4 shows their economic position under current market conditions.



Note. The Department of Energy (DoE) sponsored Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model output: Year 2012 comparison of greenhouse gas (GHG) emissions by technology and fuel based on combined fuel efficiency for an ICE vehicle of 24.8 miles per gallon (MPGmpg). PTW: Pump-to-Wheels; WTP: Well-to-Pump; WTW: Well-to-Wheels

Figure ES3. Emissions Comparison by Vehicle Category and Power Source

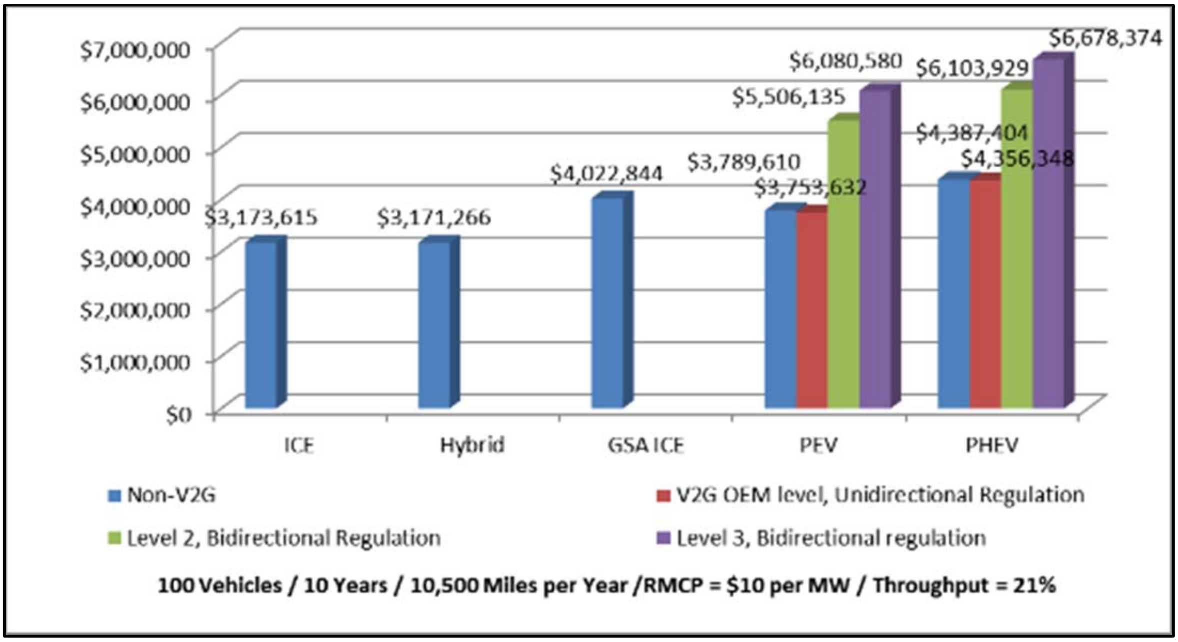


Figure ES4. Government Vehicle Fleet Life-Cycle Cost Comparison Based on Current Market Conditions and High Short-Term Cost Estimate

I. INTRODUCTION

A. SCOPE AND LIMITATIONS

In this thesis, I seek to identify the market and system parameters, as well as capital cost thresholds under which vehicle-to-grid (V2G) systems and plug-in electric drive vehicles (EDVs) present an economically viable case for federal non-tactical light-duty vehicle fleets.

The gallon-for-gallon and pound-for-pound petroleum and tailpipe emissions reduction advantages that electric or hybrid electric vehicles (EVs/HEVs) provide are well documented (Sioshansi & Denholm, 2009). However, it is generally accepted that due to the relatively low cost of fuel (at $4.00 per gallon) and high cost of lithium ion (Li-ion) batteries ($650.00/kilowatt-hour [Ramsey, 2012]),[1] a reversal in the aforementioned trend is necessary to make a strong economic case for the fleet-wide replacement of traditional internal combustion engine (ICE) vehicles (Lave & MacLean, 2002). Otherwise, the vehicles are likely to reach the end of their service life before reaching a break-even point.

This conventional wisdom, however, does not take into account the revenue potential of implementing a V2G system concurrent with an EV transition, nor the various other cost mitigators that could prove to offset initial capital expenditures. My focus in this thesis is to close the analysis gap related to V2G revenue streams, energy throughput, battery degradation, salvage value and associated capital, and operating costs to bring forth a thorough economic evaluation of V2G as it pertains to federal vehicle fleets and the frequency regulation (FR) ancillary service (A/S) market. (Although hydrogen fuel cell vehicles are also capable of grid integration and A/S revenue, they are not a focus of this research.) A systems engineering approach to capital cost estimation, energy flow modeling, and revenue analysis help bring the economics of V2G into focus and provide the comprehensive life-cycle cost (LCC) analysis needed for an informed future investment.

Very few actual V2G systems are in place today, and those that exist are not to the scale of a large federal fleet or military installation, and none currently offer or draw revenue

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[1] Ford’s cost per kWh, $650, was reported by CEO Mulally in April 2012 (Ramsey, 2012) and does not represent installed or replacement costs, which are likely in the $750–$1,000/kWh range.

from A/S. The technology surrounding V2G systems is still new and evolving, which makes data and cost estimates difficult to obtain. Costs acquired from industry experts, utilities, upstart manufacturers, and original equipment manufacturers (OEMs) are highly variable. In the case of upstart manufacturers, costs do not benefit from economies of scale and are difficult to project into the future. In the case of OEMs, costs for this new technology are considered proprietary (at least initially) and must be estimated from available resources, press releases, or appropriate comparisons. Cost estimates utilizing the best obtainable and most recent information are used to derive realistic figures for the various associated LCC components. Ultimately, today's LCCs are compared with those of comparable traditional options to identify thresholds of economic feasibility and determine where we are and where we need to be in order to have a reasonable expectation for a return on investment.

B. PROBLEM STATEMENT

1. U.S. and World Energy

Energy in its many forms is truly the lifeblood of a modern society. Most of the world's energy (87%) is generated from fossil fuels, an abundant resource presently being depleted exponentially faster than it is created, but, fortunately thus far, not faster than it is found[2] (Organization of the Petroleum Exporting Countries [OPEC], 2011). In terms of both total and per capita consumption, the United States is the largest energy consumer in the world, using 20% of world supply (Energy Information Association [EIA], 2011b). While the rest of the modern world expands and developing parts of the world progress, the consumption gap diminishes and greater pressure is placed on limited energy resources. This pressure results in higher energy prices, which in turn generate economic incentives to find, create, conserve, or substitute energy sources in an effort to balance supply and demand. With populations on the rise and more people in less developed countries seeking higher standards of living, the needs of an increasingly modern global community will continue to place greater pressure on current supply levels. Thus, in the short term, the cycle of supply, consume, and discover will continue to meet world demand, but, in the long term, in the

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[2] It takes millions of years for organisms to turn into fossil fuel. Much of the fossil fuel we consume today began as organisms hundreds of millions of years ago (Department of Energy [DoE], 2012).

absence of alternative or renewable energy sources, this cycle may fail to keep pace with rising energy demand.

Figure 1 illustrates world energy consumption since 1990 and projects consumption to more than double by 2035. What is perhaps most interesting is the insight gained from the breakout of the Organization for Economic Co-operation and Development (OECD) and non-OECD countries. OECD membership consists primarily of North America and Western Europe, where non-OECD countries are composed of less developed nations with lower standards of living, such as China and India. It is very clear that non-OECD countries will drive the increased demand on world energy while the energy needs of OECD member nations are expected to increase only moderately. The future energy environment will require a paradigm shift and must be adaptive in terms of source and supply to meet the demands of the future.

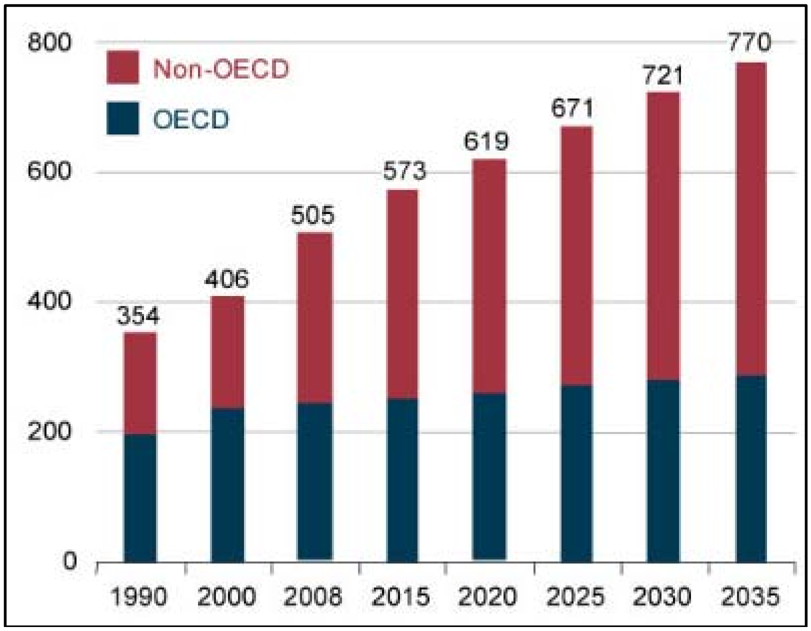

Figure 1. World Energy Consumption, 1990–2035 (Quadrillion British Thermal Units [Btu])
(IEO, 2011)

Oil is the world's primary energy source, accounting for 35% of supplied energy worldwide (OPEC, 2011). As such, it is one of the most sought-after natural resources on the planet, with the health of the modern global economy inseparably linked to its existence. There is a finite amount of oil in the world. In 2009, proven world oil reserves were estimated at 1,376.6 billion barrels. In 2010, 31.9 billion barrels were consumed globally. At this consumption rate, the world's oil supply would last 43 years. Fortunately, new reserves are found every year, allowing 2010 proven reserves to be estimated at 1,383.3 billion barrels, a 0.5% increase year over (British Petroleum [BP], 2011). For this to continue, proven reserves must be discovered at a rate equal to or greater than annual consumption. Figure 2 displays the world reserve/production (R/P) ratio since 1980, which illustrates this fortunate trend. Continued crude oil discoveries, however, are only partly responsible for this historically sustained balance. As Figure 3 indicates, with world crude oil reserves not projected to increase amidst rising demand, unconventional oil sources, made possible through new technologies and greater exploration, are required to meet rising energy demands. With oil being in finite quantity, the trend of increasing demand for a depleting resource is difficult to sustain over the long term. Ultimately, without greater conservation, continued increases in efficiency, and additional suitable alternatives, rising demand will likely outpace new discovery, causing OPEC and other petroleum-producing nations to adjust production in order to maintain satisfactory R/P ratios; their intent is to not run out of oil for as long as possible. This is not to say the world will run out of oil in 50 years or even 100. The truth is, due to the laws of supply and demand, the world will likely never run out of oil because rising prices will clear the market while supply diminishes asymptotically. The real question in a free market becomes not how long until we run out of oil, but rather how long can supply and demand continue to meet at what we consider today to be reasonable prices?

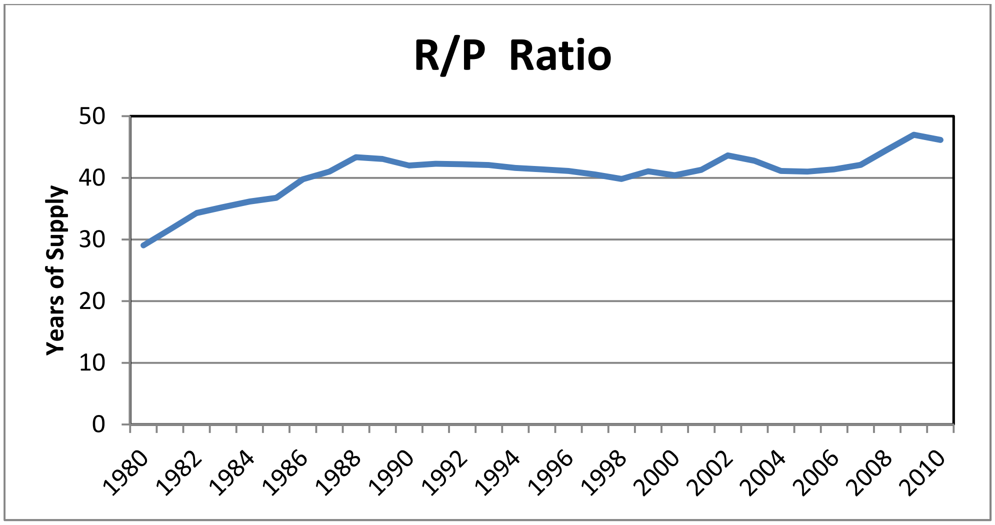

Figure 2. Oil Reserve/Production Ratio
(data from BP, 2011)

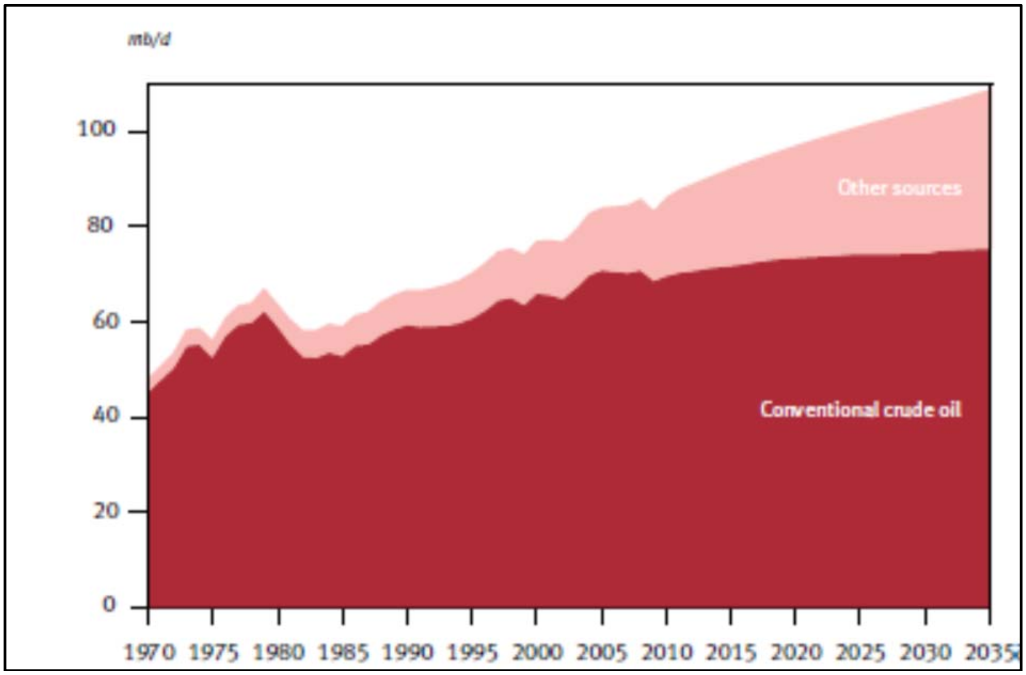

Figure 3. World Oil Supply 1970–2035: Crude and Other Sources
(OPEC, 2011)

The Department of Energy (DoE) classifies U.S. energy consumption into four sectors, with electricity generation and transportation being the largest at 40% and 28% of total consumption, respectively. Figure 4 illustrates the breakdown of U.S. energy consumption by sector and source. It should come as no surprise that liquid petroleum dominates as the power source for the transportation sector, satisfying 94% of the sector's energy demand, while the electricity market is mainly fueled by natural gas, coal, and nuclear power. Oil is not only the single primary source of fuel for the transportation sector, but it is also the dominant element of America's net energy import gap. In 2011, 97% of electricity was generated from domestic sources compared to the transportation sector's 58%[3] (EIA, 2012a). This dichotomy leaves the sector extremely vulnerable to oil supply issues and susceptible to foreign influences. The electricity market, on the other hand, has a more diverse and less restricted spread of alternatives to meet its energy needs. Most important, however, the electricity market has an ability to produce almost all of its energy needs domestically, free from foreign influence.

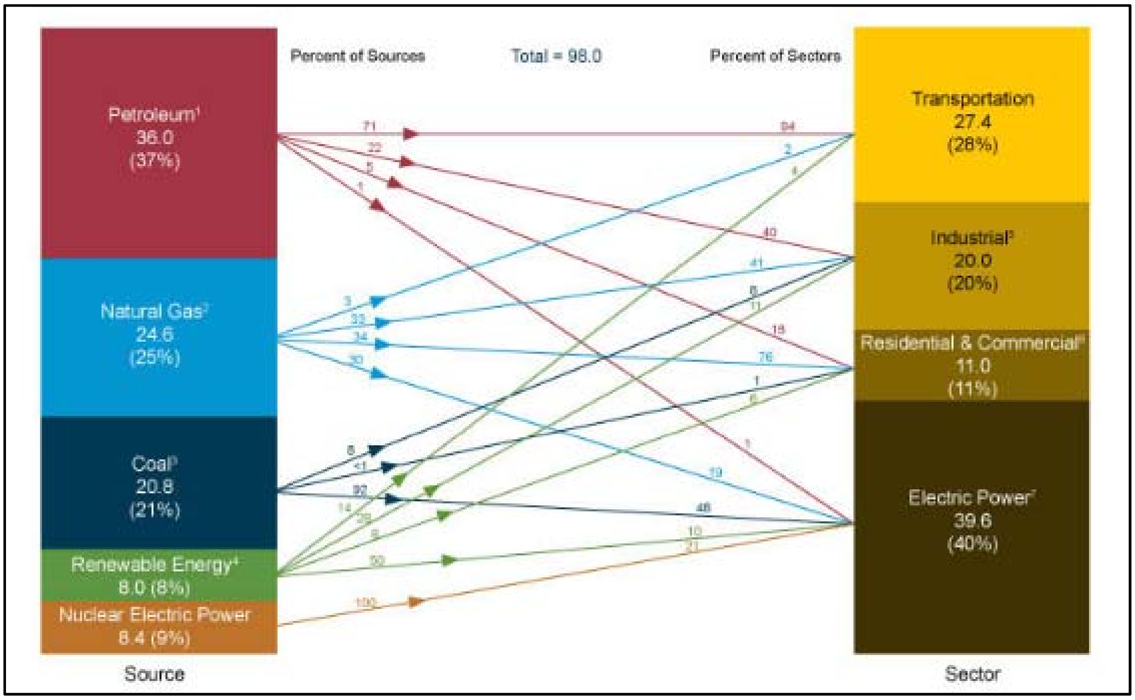

Figure 4. U.S. Primary Energy Consumption by Fuel Source and Sector, 2010 (in Quadrillion BTU)
(EIA, 2010)

The United States is closing the gap on its net energy imports due to reduced energy consumption growth and increased domestic production of natural gas and oil. Higher energy prices have led to new exploration and have inspired the development of new technologies, making the domestic harvesting of natural gas and oil from shale formations

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[3] These figures are based on EIA short-term energy outlook data tables from February 2012 (EIA, 2012), correlating to Natural Gas net imports of 7.5% and liquid petroleum imports of 44.6%.

economically viable while unlocking a new source of domestic petroleum and natural gas. Production from shale oil and gas are credited, in part, with reducing the U.S. oil import gap from a high of 60% in 2005 to a low of 49% in 2010 with the EIA's projection of 36% in 2035. Figures 5 and 6 illustrate the historical trends and future projections of the import gaps for both total energy and liquid fuel, respectively.

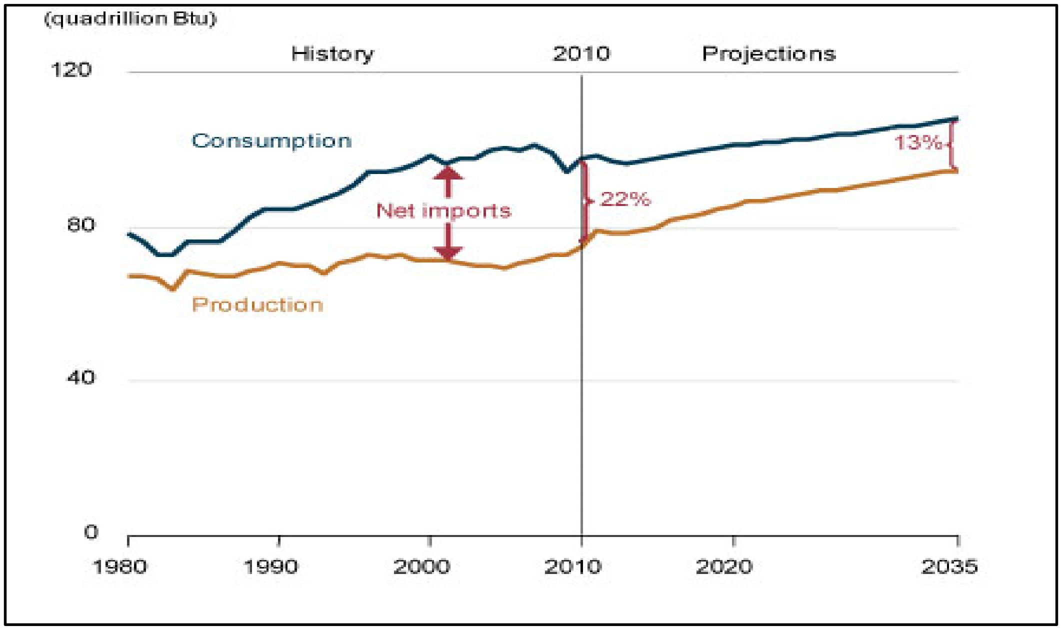


Figure 5. Total U.S. Energy Production and Consumption
(EIA, 2012a)

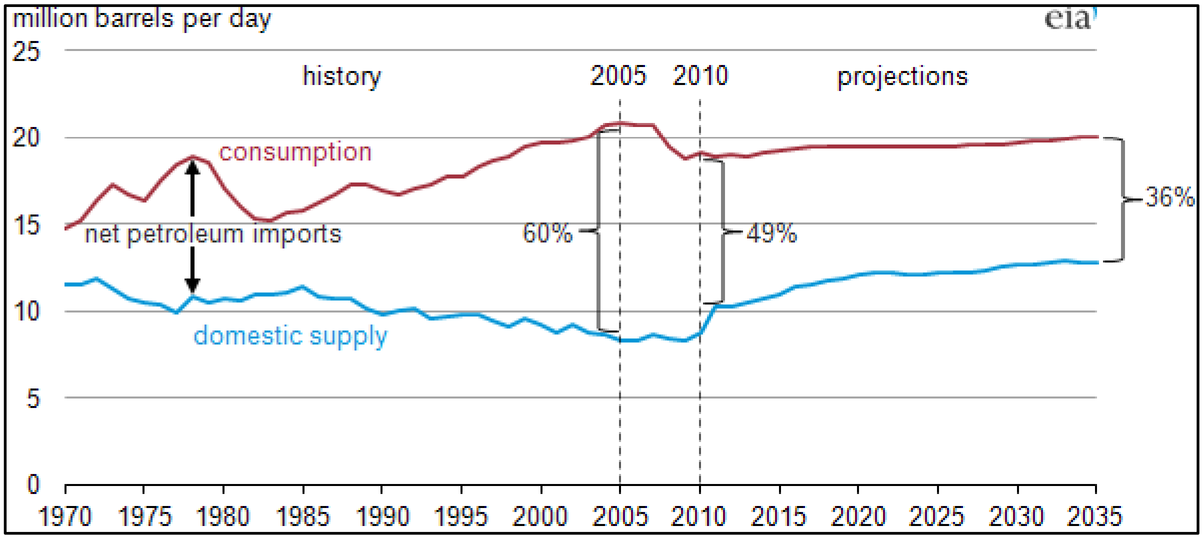


Figure 6. U.S. Liquid Fuel Supply
(EIA, 2012a)

With U.S. consumption expected to slow in growth due to greater energy efficiencies and an “extended economic recovery” (EIA, 2012a), increased use of alternative and renewable energies, along with greater domestic supply and production, will contribute to reductions in future energy import gaps.

2. National Security and Energy Independence

The U.S. energy import gap is the critical vulnerability of U.S. energy security. The United States’ reliance on fossil fuels sourced from potential adversaries or regions rife with violence and political turmoil is unsustainable and threatens the country’s energy security. Just as energy drives the modern world, so does it drive the modern military. As a whole, the United States is the largest energy consumer in the world, and the Department of Defense (DoD) is the largest single consumer of oil in the world at 360,000 barrels a day. That number alone is a higher daily consumption rate than 85% of the world’s nations (BP, 2011). The DoD’s thirst for fossil fuel has reached unprecedented proportions in the wake of the recent conflicts in southwest Asia and truly illustrates just how beholden the DoD is to fossil fuel. With the exception of nuclear warships and ballistic missile capabilities, the absence of petroleum in today’s military would have a crippling effect on its ability to protect national interests and engage global adversaries. To that end, it seems fitting for the DoD to take a leadership role in energy conservation and alternative energy research for the purpose of securing the country’s energy future.

Despite projections of reduced oil imports, there is still reason for concern. Although these trends are encouraging, any import gap threatens U.S. energy security. Reliance on foreign oil for over a third of the U.S. supply during the next two decades is cause for concern. Currently, the most populated countries are using a fraction of oil per capita compared to the average American. Developing countries are continuing to modernize and demand more and more of the world’s oil supply. If China’s per capita oil consumption increased to just one fifth of the United States’ consumption, worldwide daily consumption would increase by seven million barrels per day and outpace today’s production rate by 8%. If that trend were to spread to other developing countries, worldwide demand would quickly outpace peak production. Oil attained from foreign sources would then compete against worldwide demand and directly impact the entire U.S. oil supply. According to OPEC

(2011), developing countries' oil demand is projected to increase 72% by 2035, while developed nations will witness a 9% reduction over the same period (see Table 1).

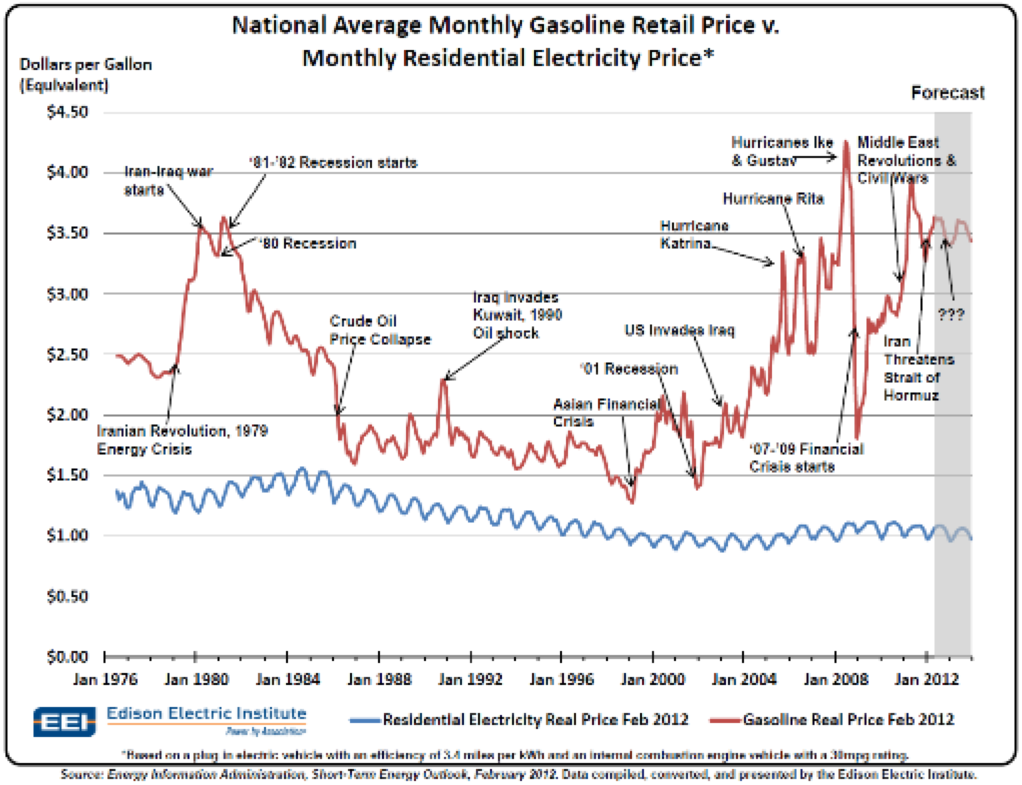
Table 1. World Oil Demand Outlook, Million Barrels per Day (mb/d)
(OPEC, 2011)

	2010	2015	2020	2025	2030	2035
North America	23.9	24.1	23.8	23.4	22.9	22.3
Western Europe	14.5	14.2	14.0	13.7	13.3	12.9
OECD Pacific	7.8	7.7	7.4	7.2	6.9	6.7
OECD	**46.1**	**46.0**	**45.2**	**44.2**	**43.1**	**41.9**
Latin America	5.2	5.7	6.0	6.3	6.6	6.8
Middle East & Africa	3.4	3.7	4.0	4.4	4.7	5.1
South Asia	4.0	4.8	5.8	6.8	8.0	9.2
Southeast Asia	6.2	6.8	7.6	8.4	9.1	9.9
China	8.9	11.6	13.8	15.6	17.1	18.4
OPEC	8.1	9.2	9.9	10.7	11.6	12.5
Developing countries	**35.9**	**41.8**	**47.2**	**52.2**	**57.0**	**61.9**
Russia	3.1	3.3	3.3	3.4	3.4	3.4
Other transition economies	1.7	1.9	2.0	2.2	2.3	2.5
Transition economies	**4.8**	**5.1**	**5.3**	**5.5**	**5.7**	**5.9**
World	**86.8**	**92.9**	**97.8**	**102.0**	**105.8**	**109.7**

Table 2. World Supply of Primary Energy
(OPEC, 2011)

	Levels mboe/d				Growth % p.a.	Fuel shares %			
	2008	2010	2020	2035	2008–35	2008	2010	2020	2035
Oil	80.6	81.2	90.8	101.0	0.8	35.2	34.5	32.3	28.4
Coal	66.6	69.2	83.6	101.5	1.6	29.1	29.4	29.7	28.5
Gas	52.0	53.6	66.6	90.0	2.0	22.7	22.8	23.7	25.3
Nuclear	14.3	14.6	16.6	22.5	1.7	6.2	6.2	5.9	6.3
Hydro	5.5	5.8	7.5	10.3	2.3	2.4	2.5	2.7	2.9
Biomass	8.5	9.2	12.8	20.3	3.3	3.7	3.9	4.6	5.7
Other renewables	1.5	1.7	3.5	10.4	7.5	0.6	0.7	1.2	2.9
Total	**229.0**	**235.4**	**281.3**	**355.9**	**1.6**	**100.0**	**100.0**	**100.0**	**100.0**

Either large discoveries followed by greater production capacity or a reversal in demand trend are necessary to meet future world demand; otherwise, prices will surely reach levels beyond today's comprehension. Eliminating the energy import gap would insulate the United States from a potential short-term energy crisis and deliver the security that comes from energy independence, a posture achievable through increased efficiencies and rebalanced consumption profiles that fall within the indigenous production capabilities of the United States. In the long term, however, due to the global free market, the equilibrium price of oil would still rise to meet global demand. Therefore, the only absolute way to isolate the United States from global energy demand issues is by switching to alternative or renewable energies that do not compete on the global market, such as electricity generated by nuclear, hydro, wind, or solar power. Figure 7 illustrates why this might be beneficial from a price stability standpoint, and Figure 8 demonstrates the current projection for the expansion of alternative fuel sources relative to conventional fuels.



*Based on a plug in electric vehicle with an efficiency of 3.4 miles per kWh and an internal combustion engine vehicle with a 30mpg rating.

Source: *Energy Information Administration, Short-Term Energy Outlook, February 2012.* Data compiled, converted, and presented by the Edison Electric Institute.

Figure 7. U.S. Average Gasoline Price vs. Residential Electricity Price
(EIA, 2012c)

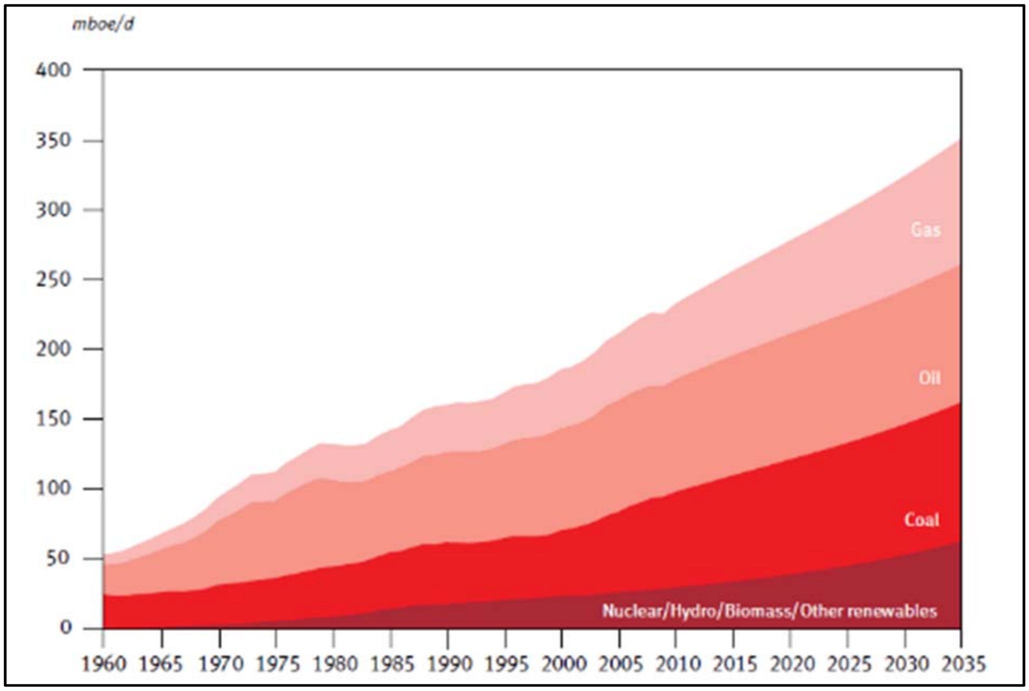


Figure 8. World Supply of Primary Energy by Fuel Type
(OPEC, 2011)

3. Federal Mandates Targeted at Federal Vehicle Fleets

The federal government recognizes its role in leading change for an energy-independent future. In an effort to increase U.S. energy security by reducing oil consumption (on the governmental level), various federal mandates and executive orders have been issued that specifically target DoD and federal non-tactical vehicle fleets, which totaled over 662,000 vehicles worldwide in 2010 (DoE, 2010). The Energy Independence and Security Act of 2007, signed by President Bush, requires federal vehicle fleets to reduce petroleum consumption at least 20% by 2015 from a 2005 baseline.[4] Executive Order 13,514, signed in October of 2009, called for an additional 10% reduction in petroleum use by 2020. The same order also requires federal agencies to set for fiscal year (FY) 2020 targets of at least 28% for greenhouse gas (GHG) reduction applicable to non-tactical vehicle fleets (Under Secretary of Defense for Acquisition, Technology, and Logistics [USD(AT&L)], 2011). The American Recovery and Reinvestment Act (ARRA) of 2009 provided "$300 million in funding for capital expenditures and necessary expenses in the acquisition of motor vehicles with higher fuel economy, including: hybrid vehicles, electric vehicles, and plug-in hybrid vehicles (PHEVs)." Additionally, the Energy Conservation Reauthorization Act (ECRA) of 1998 and the Energy Policy Act of 2005 (EPAct) require that 75% of light-duty vehicle acquisitions in covered fleets be alternatively fueled vehicles (AFVs). The requirements are clear. The momentum toward electric and alternatively fueled vehicles is evident. With the advent of emerging technologies, these vehicles are becoming increasingly more capable and promise to offer potential solutions. This places the DoD in a distinct position to once again advance technology for national and global progress and is in lock step with the president's Executive Order No. 13,542 (2009), *Federal Leadership in Environmental, Energy and Economic Performance*, by pursuing research that explores the potential and capabilities AFVs offer.

C. ELECTRIC VEHICLES: A POTENTIAL SOLUTION

1. Reduced Petroleum Consumption

Electricity generation and transportation are the two largest sectors of energy consumption in the United States, and electric vehicles have the unique ability to impact both sectors and rebalance the energy demand between them. This also demonstrates the

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[4] The historical peak of U.S. oil consumption was in 2005 (EIA, 2012b).

significant impact EVs can have on U.S. energy security. Using the combined efficiency rating of an average mid-size North American car[5] and 15,000 annual miles traveled, we see that as many as 600,000 gallons of fuel can be displaced per 1,000 EVs versus traditional gas-powered vehicles. The widespread use of EVs has the potential to significantly reduce national liquid petroleum consumption and minimize or eliminate the oil import gap by shifting the largest energy-use sector of petroleum toward a domestically fueled energy source. This drastic shift, however, unless integrated "smartly," would greatly increase the demand of today's electricity supply (Hadley, 2007).

2. Greenhouse Gas Emissions

Most evidence suggests that EVs can significantly reduce GHG emissions when a sufficient percentage of U.S. transportation is replaced with such vehicles. Using the previously mentioned scenario, in addition to the fuel savings of 1,000 displaced ICE vehicles, as much as 5,880 tons of gross carbon dioxide emissions would be avoided (Environmental Protection Agency [EPA], 2012). Even though EVs themselves produce zero tailpipe emissions and HEVs produce significantly less compared to a traditional ICE, one cannot overlook the GHGs produced while generating the electricity used to power them. Some research has indicated that even EVs that are powered solely by relatively "dirty" coal-powered electric plants have significantly less net GHG emissions than traditional vehicles (Electrification Coalition, 2010). However, based on my inputs to the latest DoE-sponsored GHGs, regulated emissions, and energy use in transportation (GREET) model, this is not the case. The GREET model considers the well-to-wheels implications for GHG emissions, which in the case of electricity includes emissions produced from the mining and transport of coal. Figure 9 clearly shows that the amount of emissions used for comparison is largely dependent on the energy source and, in the case of electricity, further dependent on the fuel mix by which the electricity was generated (Duvall, Knipping, Alexander, Tonachel, & Clark, 2007). It is also important to note that when renewable energy sources, such as solar or wind, are evaluated as the sole energy source, GHG emissions are little to none.[6] Additionally, the California mix of electricity appears much cleaner than the average U.S. mix. This cleaner

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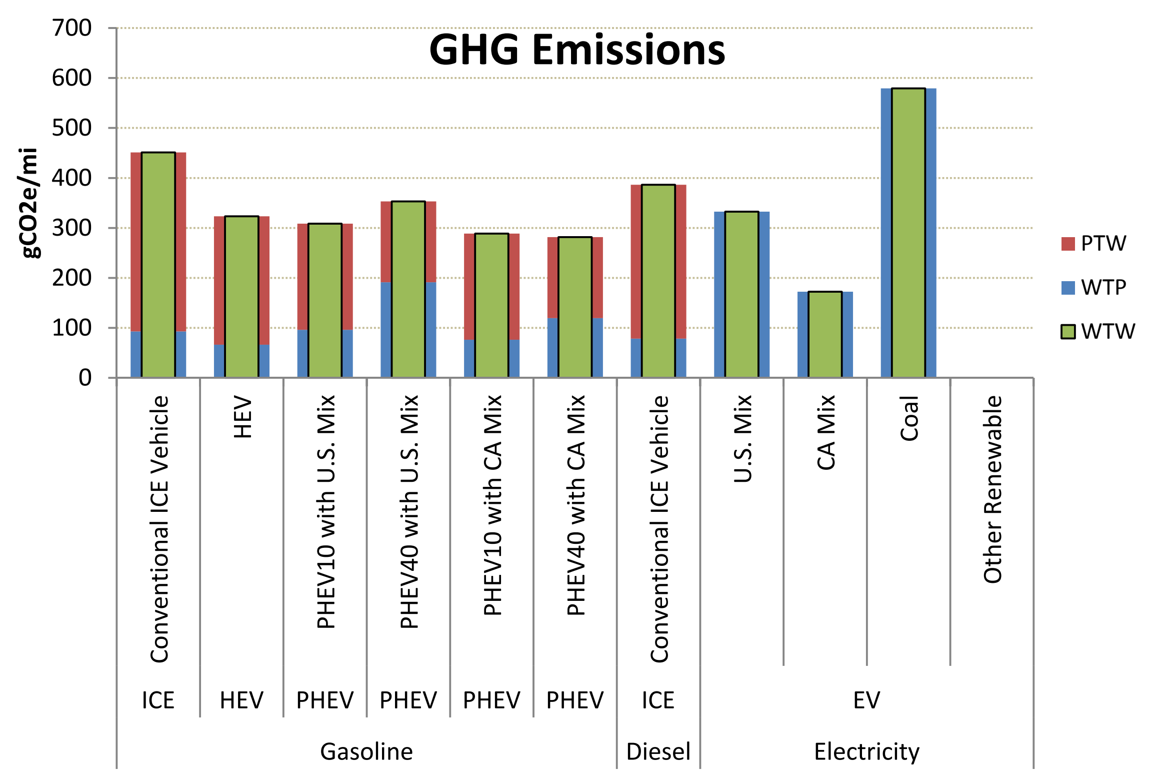
[5] 25 MPG

[6] This does not include GHGs resulting from the production of energy-harnessing devices (e.g., solar panels, wind turbines, etc.).

mix is due to the substantial percentage of renewable power in California's generation portfolio. As renewable power generation increases across the country, there is potential for this trend to spread and reduce the average GHG emissions associated with EVs even further. Currently, only in the case where renewably generated electricity powers an EV is it truly a zero-emissions vehicle; otherwise, the term *zero tailpipe emissions* is more appropriate. The key takeaway here is that a proper assessment of GHG emissions reductions requires an evaluation of net emissions based on generation mix in the region of employment.



Note. This figure shows the DoE-sponsored GREET 2011 model output: Year 2012 comparison of GHG emissions by technology and fuel based on combined fuel efficiency for an ICE vehicle of 24.8 MPG. PTW: Pump-to-Wheels; WTP: Well-to-Pump; WTW: Well-to-Wheels

Figure 9. Greenhouse Gas Emissions by Technology
(GREET Model)

3. Reduced Operations and Maintenance Costs

Reductions in operating and maintenance costs associated with EVs are a significant element in the LCC comparison with traditional ICE vehicles. The fuel cost comparison involves breaking down the cost per mile of travel by multiplying the cost of electricity ($/kWh) by the EVs' relative electric efficiency in kWh/mile. The EV's fuel cost in $/mile is then compared to the ICE's by using the cost per gallon of petroleum divided by the ICE's miles-per-gallon (MPG) rating. Generally, the EV's fuel costs are less than half that of a comparable ICE. Additionally, reports indicate that maintenance costs associated with EVs are expected to be far less than those of a comparable ICE (Werber et al., 2009). Electric motors have fewer moving parts and generally items that receive less wear (belts, hoses, sparkplugs, etc.; Loveday, 2010). Also, oil changes and some of the routine maintenance procedures commonly found with an ICE are not required, resulting in overall lower maintenance costs associated with EVs when compared to their ICE counterparts. This assumes that the EVs' battery pack lasts the life of the vehicle. A premature battery failure not covered under warranty would quickly consume any observed maintenance savings. Because long-term empirical evidence and associated research regarding the durability of the battery and onboard electronics for the newest generation of plug-in EVs do not yet exist, this research accounts for the cost of a replacement battery at a future projected rate in the maintenance calculation, as well as sensitivity analyses involving a published battery degradation model that aims to quantify battery degradation associated with V2G participation. This additional maintenance cost is partially recovered, however, by substantiating a higher salvage value for the vehicle after the 10-year projection period.

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II. LITERATURE REVIEW

The concept of V2G systems and EVs integrating with the electric grid is a relatively new one and may prove more prescient than its original conceivers ever intended. The original concept of V2G systems and EVs arose from the desire to promote the EV as an alternative to petroleum-powered vehicles. But if the displacement of ICE vehicles by EVs progresses by any significant degree, V2G systems may emerge on a large scale out of logistical necessity rather than the potential economic and ancillary reasons I examine in this thesis. Millions of EVs simultaneously charging during peak demand periods would overwhelm the current electrical grid, but properly integrated EVs, with the use of an intelligent charging scheme, would not only reduce grid loads but also serve to balance demand cycles and increase reliability while optimizing the integration of renewable energies (Kromer & Heywood, 2007; Galus & Andersson, 2008). However, before the market and technology reach that level, V2G and its revenue potential must be proven on a large scale.

With the technology still in development, it has been difficult for V2G to emerge from its current pilot stage. This fact, along with its high initial capital cost, continues to be a significant deterrent to wide-scale adoption. Most research has been geared toward private-sector applications and energy service provider (ESP) implications. Because only small-scale V2G systems have been tested, little research exists from a fleet perspective, and what does exist is largely theoretical and quickly outdated by continuous evolvements in cost and technology. In this research, I apply current V2G technology to a light-duty federal vehicle fleet model, break down the various costs and revenue potential, and assess whether EVs and V2G can offer a cost-effective alternative for federal fleets seeking to meet mandated consumption and emission reductions.

The research I conducted or referenced for this thesis ranged from conversations and interviews with industry experts to conference presentations and analyses, and also from various governmental agencies and laboratories to private-sector utility-sponsored and academic research. In this chapter, I include concise synopses of related work with a critical review of their findings and an assessment of value as it pertains to a large-scale valuation of V2G applications for federal vehicle fleets operating on federal installations.

In 2007, Willett Kempton, a founding father of the V2G concept and supporting technologies, led the first successful live demonstration of a V2G system interacting with an ESP. In this demonstration, an appropriately outfitted plug-in electric drive vehicle successfully performed bidirectional energy flow with the electrical grid in response to live signals from PJM (the local Regional Transmission Organization [RTO]). The ability to accurately respond to an actual AGC signal originating from an ESP is the fundamental technology that drives the prospect of V2G's revenue potential. This demonstration validated the technology and the theory behind EVs providing A/S to the grid and serves as a valuable building block for moving into larger scale applications. In a report entitled "A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System," Kempton et al. (2008) pointed out that FR (the service demonstrated) and spinning reserve have the highest profit potential in the A/S market and estimated the U.S. frequency regulation and spinning reserve market share to be about $9.6 billion annually. PJM, one of 10 independent service operators (ISOs) and RTOs servicing North America, spent $250 million in 2010 for frequency regulation services alone (PJM, 2012).

The same report (Kempton et al., 2008) concluded that frequency regulation not only has the greatest earning potential[7] at $35–40 per MW-hour (MW-h) but also has the least degradation effect on a vehicle's battery, making it the most preferred form of A/S for EV owners to participate and thus the only one I consider in my analysis. Spinning reserves, on the other hand, averaged only $10/MW-h and, although only needed four to five times per month, can result in deep battery discharges, possibly affecting battery life, whereas regulation (according to the Kempton et al. [2008]) is used more frequently but results in only small cycles of charge and discharge and causes little battery degradation. A key point made in Kempton et al.'s (2008) report is that both services provide payment primarily for "capacity rather than energy" (p. 3), and this capacity is a function of both battery capacity (kWh) and the flow capability of the bidirectional connection to the grid (kW), with the latter likely being the limiting factor.

Kempton et al. (2008) also highlighted the value that EVs bring to the electrical grid with their inherent storage capacity and asserted the role EVs will play in the integration of

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[7] This assessment assumes an RMCP of $40 per MW-h of capacity, which was not overly optimistic at the time but far greater than the average of $9–10/MW-h today.

emergent renewable energy sources, such as wind and solar. In my thesis, I briefly address this potential as it pertains to military bases and federal installations in light of recent efforts to create “net-zero” energy-consuming facilities. These efforts involve increased efficiency measures and on-site renewable power generation where V2G systems can be key players.

Overall, Kempton et al.’s (2008) report presents a valuable demonstration of the technology’s potential and delivers the necessary proof of concept needed to validate the theory of V2G ancillary support. However, the economic validation on a large scale remains to be done. Kempton et al. (2008) pointed out that the next step in the V2G progression is to develop a business model at the “scale of 100 to 300 vehicles,” which is a goal of my thesis. My research builds on the work of Kempton et al. (2008) and Kempton and Tomic (2004) by considering the recent decreasing trend of RMCPs and including a comprehensive fleet-based infrastructure cost estimate derived from current technology and prices; where my analysis makes a significant departure from this and other related research (see White & Zhang, 2010; Brooks, 2002) is with respect to key assumptions used to model A/S revenue from FR. These assumptions include vehicle A/S availability, regulation dispatch signal, and energy throughput from FR. Based on my findings, I conclude that battery degradation from bidirectional FR is significant and that FR revenue is less a function of vehicle availability or grid connection capacity and more a function of battery capacity and dispatch signal characteristics. See Chapter VII for further detail and dispatch signal analysis.

In 2009, Len Beck (a colleague of Kempton) wrote and self-published *V2G-101*, a book in which he conducted a fairly inclusive discussion of the technology, its applications, and its potential costs and benefits from an MBA’s perspective, offering the reader a rather broad understanding of the topic. Beck (2009) addressed current technologies and future challenges, providing keen insight for the road ahead. I consider many of the calculations he presented for application in the federal fleet business model, but Beck’s book is mostly geared toward the potential EV consumer or casually interested party. Beck (2009) also made many assumptions that do not apply in the case of federal vehicle fleets, such as government rebates and tax incentives that obviously offer no value to this economic assessment, as well as assumptions relating to vehicle utilization that may be consistent with the usage profile of an average consumer but not with a federal fleet. Most related research (see White & Zhang, 2010; Kempton et al., 2008) assumes that the average U.S. light-duty vehicle is used only 1–2 hours per day with availability on average of 22–23 hours per day for A/S participation. Government fleet vehicles generally have higher utilization rates and thus less idle time to allocate to A/S participation. On the other hand, they are more reliable in terms of recurrent availability during weekends and holidays as opposed to personally owned plug-in electric vehicles (PEVs). My research makes A/S availability assumptions that are more consistent with the usage profile of a federal non-tactical vehicle fleet. Overall, Beck's (2009) *V2G-101* is a great resource regarding V2G technology and applications, and I used it as such, but it is not intended as the sole source for complex modeling and LCC estimation of V2G.

In a DoE report, Morrow, Karner, and Francfort (2008) detailed the infrastructure costs associated with a PHEV deployment and laid out the necessary components for the required charging infrastructure, as well as some rather realistic infrastructure cost estimates. Morrow et al. (2008) also investigated the various all-electric range (AER) capabilities among different classes of PHEVs and presented optimal acquisition strategies based on available infrastructure when selecting a PHEV with a specific AER capability. AER has interesting implications for federal vehicle fleets of PEVs because lower AER capabilities would be sufficient for vehicles never intended to leave the base or installation, whereas higher AER capabilities would be required for vehicles that do. The lower the AER, the lower the battery capacity and, subsequently, the lower the initial acquisition cost. The downside, from an A/S revenue perspective, is a likely smaller aggregate fleet regulation service capacity and, therefore, lower revenue potential.[8] In my report, I consider the laundry list of costs Morrow et al. (2008) presented for development of the capital expense element of my model, and I also consider both a PEV and PHEV with different AERs that serve to illustrate the LCC differences associated with limited (PEV) versus indefinite (PHEV) range capabilities.

Simpson (2006), in association with the National Renewable Energy Lab (NREL), conducted a cost–benefit analysis (CBA) on PHEV technology and focused on the cost savings from lower operating costs driven by reduced petroleum consumption versus higher associated vehicle acquisition costs. Simpson (2006) eventually concluded that "higher fuel

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[8] Regulation service capacity is primarily limited by charger/inverter capability, but battery size is a second-order limitation.

prices and lower battery costs are needed to make a compelling business case of the PHEVs in the absence of other incentives." This finding is generally an industry consensus, but the "other incentives" are the premier focus of my research. To date, few researchers have attempted to incorporate A/S revenue into a business case for electric drive fleets, but these are the "other incentives" V2G systems can offer this type of transition and are worthy of investigation. A surface investigation will reveal that the two LCC drivers for traditional ICE vehicles and PHEVs are petroleum and battery costs, respectively. What is less obvious, as Simpson (2006) pointed out, is that "vehicle performance and driving habits have a strong influence on the relative value of PHEVs." The latter observation is noteworthy and should be incorporated into the acquisition decision process through a comparative assessment of how LCC and performance capability align with a vehicle's (or fleet of vehicle's) intended use. My research picks up where Simpson's CBA leaves off by determining whether the "other incentives" provided by V2G can close the LCC gap separating traditional and electric drive vehicles.

Very little research accounts for battery salvage value in a V2G cost assessment, and none as it pertains specifically to a federal vehicle fleet. With batteries comprising upwards of 50% of the total vehicle cost, battery salvage value must be considered for an accurate assessment of V2G LCCs because, according to Neubauer and Pesaran (2011), various uses for Li-ion batteries exist after they cease to meet the requirements for vehicle propulsion. Generally, once a Li-ion battery pack onboard an electric drive vehicle reaches 70–80% of its original capacity, replacement is required. The NREL report (Pesaran, 2011) suggested that the second-use market could provide a significant economic offset for the high initial battery cost, the primary cost driver for EVs. Some proposed second-use markets include utility and recreational vehicles, on- or off-grid backup power, and renewable energy storage. These second-use markets have potentially significant impacts on the viability of EVs now and in the future. The used battery's value comes from either a sale on the second-use market or the benefit obtained from being reintegrated into the installation's energy storage capacity by using an auxiliary battery bank. This would further expand A/S capacity and increase revenue potential, causing further reductions in LCCs. Using my model, I account for vehicle battery salvage value, as well as the higher vehicle residual value resulting from a replacement battery.

The concept of energy throughput became a major aspect of my research and, from actual data obtained from ESP's PJM and ISO-NE, I've determined the amount of throughput from the provision of FR to be far greater than most industry assumptions and previous related research (see Brooks, 2002; Tomic & Kempton, 2007). This discovery is significant because it redefines the profit potential of V2G FR in the presence of battery degradation and throughput levels derived from actual AGC signals. V2G FR can provide a revenue stream, but neglecting the associated costs yields an incomplete economic assessment and misrepresents the viability of V2G FR. As the primary cost driver, the battery holds a key position in the economics of V2G, and thus the costs associated from premature degradation resulting from participation in V2G must be considered. In a report entitled "Lithium-Ion Battery Cell Degradation Resulting From Realistic Vehicle and Vehicle-to-Grid Utilization," Peterson, Apt, and Whitacre (2010) quantified battery degradation for both normal vehicle usage and V2G energy arbitrage. Peterson et al. (2010) concluded that energy throughput is a better metric of battery degradation for the newest generation of lithium batteries rather than cycle life relative to depth of discharge (DOD). From lab testing, Peterson et al. (2010) determined "the strongest indicator of capacity fade for the type of cell tested (A123 systems M1 Cell) was the integrated capacity or energy processed, regardless of DOD experienced." Peterson et al. (2010) also concluded that "V2G energy incurs approximately half the capacity loss per unit energy processed compared to that associated with more rapid cycling encountered while driving." Peterson et al. (2010) correlated capacity fade relative to original capacity with energy processed and, from regression analysis, assigned a degradation coefficient that varies based on the "mode" under which the energy was discharged. For example, testing showed greater degradation from driving than V2G and thus the degradation coefficient derived for driving was greater. A distinguishing detail of Peterson et al.'s (2010) comparative assessment regarding driving degradation versus V2G degradation is that their analysis focused on V2G energy arbitrage rather than V2G FR, and their lab testing was reliant on a synthetic signal consistent with assumptions from previous related research. The regime they used to simulate V2G consisted of a C/2 galvanostatic discharge rate for a specified time.[9] Although a C/2 rate is a reasonable assumption for both energy arbitrage and

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[9] A "C" rate describes the charge or discharge rate a battery is subjected to and is relative to the capacity rating of the battery. For example, a C/2 discharge rate for the Nissan Leaf's 24 kWh battery would equate to a 12-

FR, a timed galvanostatic discharge does not represent the cycling observed from a resource responding to an actual FR dispatch signal. Although the V2G discharge rate is lower than the driving rate (which varies but can be as high as 3C), the cycle rate for FR is actually closer to that of driving. Therefore, although I incorporate the Peterson battery degradation model (Shiau et al., 2010) within my EF-LCC model, I adjust the V2G degradation coefficient to more accurately represent the cycle rate associated with a storage device following an FR dispatch signal.

Other research (see Kempton et al., 2008) has recognized that the signal relayed to traditional FR generators may not be ideal for a storage-based resource, such as EVs and flywheels, and suggests that a separate signal may be more appropriate. This has turned out to be fairly prescient because a recent Federal Energy Regulatory Commission (FERC) order (755) may lead to such a development when it takes effect later this year (2012). In an effort to comply with the order, which seeks to create a more equitable compensation environment for storage-based FR market participants, some ESPs have proposed plans that include separate signals for traditional gas-powered generators and storage-based resources. My research quantifies the parameters of such a signal, as well as the market conditions necessary to make a strong case for V2G FR.

In summary, my analysis builds on some of the fundamental research surrounding V2G technology and applies it to a government fleet-specific scenario. My conclusions on V2G profitability, however, differ from some previous research due to dramatically lower RMCPs (which have suffered from a significant decreasing trend in recent years), less optimistic A/S availability assumptions consistent with a federal fleet usage profile, and recent data that indicates far greater throughput from regulation dispatch resulting in higher battery degradation costs.

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kW load whereas a 2C rate would equate to a 48-kW load. Therefore a C/2 rate assumes a grid connection of ½ the battery's capacity rating and a reasonable assumption based on my simulations discussed in Chapter VII.

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III. BACKGROUND

A. VEHICLE TO GRID

1. Smart Grid Technology and Infrastructure Components

a. The Smart Grid

The discussion of V2G systems must begin with an understanding of the concept of the smart grid, the avenue through which PEVs fully integrate with the modern utility grid as a means of storage, power, and demand response. The term *smart grid* refers to an improved form of the current electrical grid that incorporates command and control with the ability to respond to real-time information while integrating alternative energies and storage for enhanced grid stability, reliability, and efficiency. It moves away from the current paradigm of centralized generation to decentralized generation and demand response where alternative energies and even traditional consumers can supply power to the grid or intelligently regulate demand. The ability to control and monitor delivery and consumption of power through interactive communication with the electrical grid is the cornerstone of the V2G concept.

Every V2G system requires the same essential components: an electric-powered vehicle with a suitable battery capacity; a unidirectional or bidirectional charger with grid connection; a vehicle smart-link; an aggregator; the utility or renewable power source; and finally, the necessary software and communication links required to remotely control, monitor, and integrate it all together. Millions of PEVs charging together at periods of peak demand could overwhelm current grid capacity (Lyon, Michelin, Jongejan, & Leahy, 2010); however, the surplus grid capacity during periods of low demand "could generate and deliver the necessary energy to fuel the majority of the U.S. light duty vehicle fleet" (Kintner-Meyer, Schneider, & Pratt, 2007). Therefore, smart grids and intelligent charging schemes are an integral component of EV market expansion. When integrated properly, PEVs have the potential not only to help balance demand curves, but also to optimize grid efficiency and reliability. Figure 10 depicts a visual representation of a smart grid.

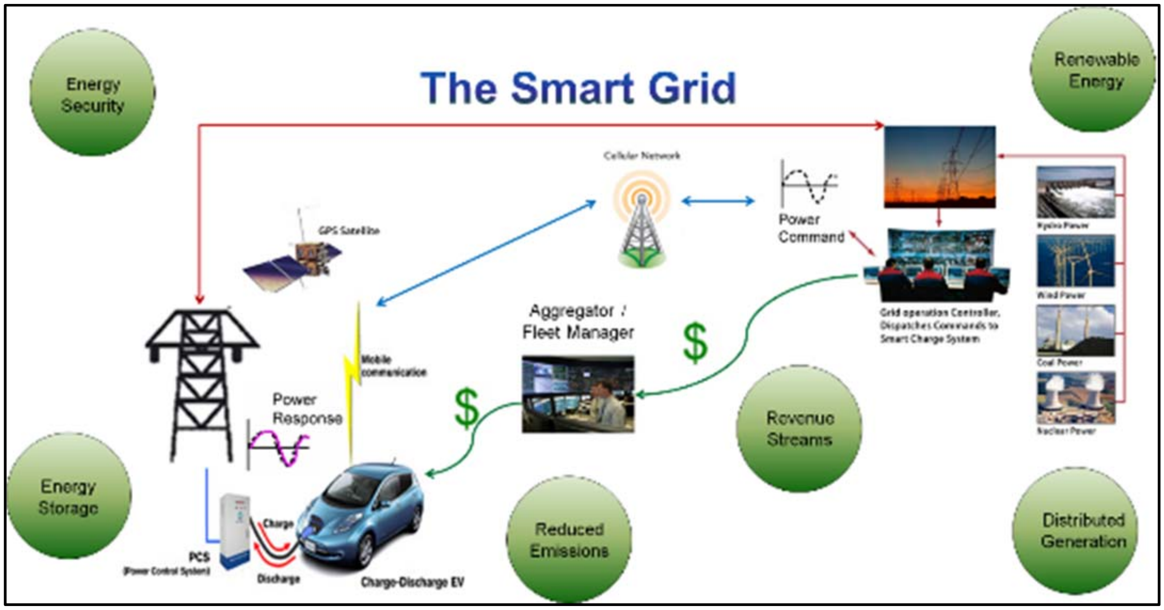

Figure 10. The Smart Grid

b. Types of Electric Vehicles

There are numerous classifications of EVs with even more acronyms used to describe them. Battery electric vehicles (BEVs) or more commonly PEVs are the most pure form of EV because they rely solely on battery power as the energy source for propulsion. For the purposes of this thesis, PEVs are defined as a 100% electric-powered replacement to the traditional ICE-powered motor vehicle and should not be confused with neighborhood electric vehicles (NEVs), which are essentially oversized golf carts with non-lithium-based cell chemistries and very limited speed and range, but which carry the potential to be well suited for certain applications on federal installations. EVs are used to refer generally to vehicles that have some degree of electric drive. Hybrid electric vehicles (HEVs) are, as the name implies, a hybrid form of EV using both a traditional ICE to power the vehicle during periods of normal to high energy demand, as well as an electric motor powered by a storage battery capable of meeting requirements during low energy demand. A key distinguishing factor for HEVs is that they do not plug in or draw power from the grid; instead, the HEV's battery draws power generated from an energy recovery mechanism known as regenerative braking. Regenerative braking is a process by which the kinetic energy of the vehicle is converted into electricity when the motor transitions to a resistive generator and transfers power back to the battery (Brandenburg & King, 1994). This method not only stores potential energy but also effectively slows the vehicle, reducing wear on the brake pads and vastly increasing the service interval of the brakes, which contributes to lower maintenance costs.

A plug-in hybrid electric vehicle (PHEV) is similar to an HEV, but it benefits from a larger battery with greater storage capacity, allowing it more all-electric driven miles. The small onboard internal combustion engine is most often not connected to the drivetrain, as with an HEV, and is used only when the battery drops below a specified charge level to extend vehicle range. At that point, the onboard engine acts as a generator recharging the battery and providing continued propulsion using the electric motor, but now limited by the potential energy in the fuel tank rather than the battery. The final major factor distinguishing the PHEV from an HEV is that which was previously mentioned: its ability to plug in and draw power from the electrical grid while not in use to recharge the battery. With this functionality, it is possible not to require the onboard ICE if driving profiles are kept within the range limitation of the battery. To establish classifications among the different PHEVs, a common industry convention is to list the number of miles that can be driven solely on battery power after the acronym PHEV. For example, a PHEV-40 is a PHEV capable of traveling 40 miles solely on electric power before needing a recharge by either a charging station or its onboard ICE. Figure 11 depicts a typical charge-depleting profile for a PHEV-40.

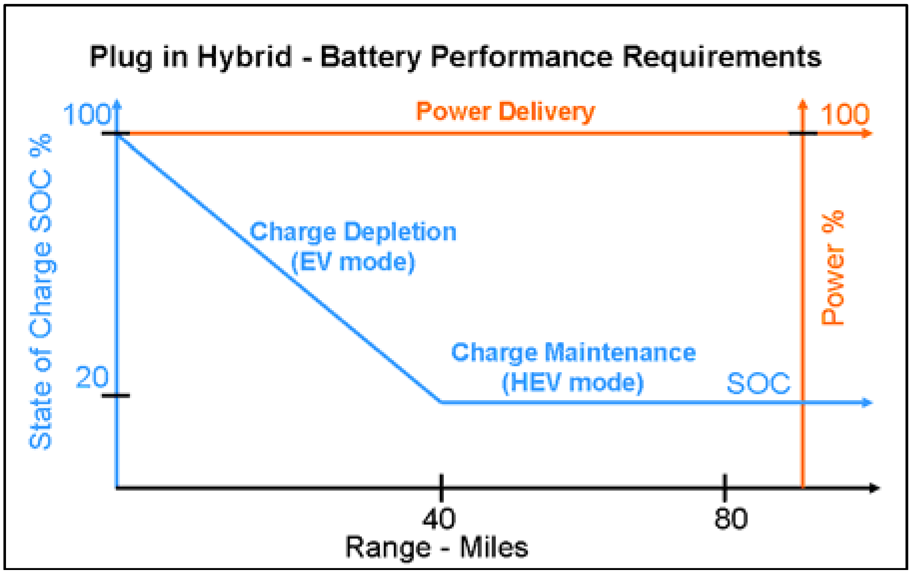

Figure 11. Plug-In Hybrid Electric Vehicle State of Charge Profile
(Woodbank, 2012)

Finally, the classification of EV that is most relevant to this thesis is the grid-enabled electric vehicle (GEV). The GEV is important to this study because it involves a PEV or a PHEV with the capability not only to connect to the electrical grid but also to intelligently draw and/or exchange power with it. I often refer to PEVs and PHEVs together; as such, I refer to them as plug-in electric drive vehicles (PEDVs) as a distinction from non-plug-in HEVs.

c. The Battery

The current fleet of 2012 PHEVs and PEVs demonstrates that Li-ion batteries are today's technology of choice for EV energy storage, a distinct shift from the previous generation of PEVs, which primarily use nickel-metal hydride (NiMH). This new technology offers much promise to the future of electric propulsion with increased cycle life, extended range, and lighter weight over the technology's predecessor, and it is projected to remain the technology of choice in the future (Kromer & Heywood, 2007). The prevailing challenge for Li-ion batteries, however, remains their expense. This is a challenge that some predict to lessen in coming years (Massachusetts Institute of Technology [MIT], 2010) as the technology develops and the economies of scale act to reduce prices, but these forecasts are based on rather optimistic assumptions that rely heavily on market expansion and consumer acceptance.

High-priced Li-ion battery packs contribute to the single largest cost component of an electric drive vehicle and as such are the principal specification used to assess an EV's capabilities. The generally accepted specification is a kWh rating, and the higher the better, at least in terms of utility, but not in terms of weight or price. These three competing factors must be balanced when choosing a battery and a vehicle for its intended purpose. Actual OEM costs for powertrain Li-ion batteries are largely speculative and considered proprietary because the market and technology are still relatively new. Estimates range from $800–$1,200 per kWh (Pesaran & Markel, 2009). Using the 2012 Nissan Leaf (PEV) as an example and a price point of $1,000/kWh, the battery accounts for 68% of its $35,000 manufacturer's suggested retail price (MSRP). For federal vehicle fleets where high utilization is likely and A/S revenue an objective, a capacity in the 15–40 kWh range is desirable. Most ESPs have a minimum capacity requirement to participate in the A/S market. PJM (the mid-Atlantic RTO) previously required a minimum of one megawatt (MW) of capacity. Considering a PEDV with 20 kWh of usable battery capacity and a maximum uplink connection of 10 kW, the minimum fleet size to participate in the A/S market would have been about 100 vehicles. However, recent regulations and initiatives have reduced this minimum to .1 MW (or 100 kW), consequently reducing the minimum fleet size under the same V2G scenario to only 10 vehicles. This is a significant development in the practicality of light-duty vehicle fleets participating in the A/S market. In summary, battery size (in kWh) directly determines not only the vehicle price, but also the electric range, the minimum size of the fleet (for A/S participation), and the A/S revenue potential.

A final yet important consideration in understanding the role batteries play in the economics of V2G systems is battery service life. Because batteries are the major cost driver for V2G systems, they are the biggest variable for future LCC calculations. The two main metrics to assess battery durability and longevity are cycle life and calendar life. These vary widely based on cell chemistry and technology but are a factor for all Li-ion batteries (they do not last indefinitely). *Cycle life* refers to the number of charge and discharge cycles a battery can experience in its usable service life and is dependent on numerous variables. The set of variables that *do not* lead to increased cycle life can generally be agreed upon. The topic of debate becomes which of these variables contributes the most to battery degradation. Currently, the leading contenders are depth of discharge (DOD) and energy throughput.[10] *Calendar life* refers to the actual lifetime of a battery and can be affected by factors that, in addition to DOD and SOC, include storage and operating temperature (Bloom et al., 2001). The battery parameter that fades whether due to cycles, time, or throughput is capacity. It is generally accepted that when a battery loses 20% of its original capacity, it can no longer meet its requirements as a drivetrain power source.

Optimal SOC and DOD profiles vary based on cell chemistry, and each OEM incorporates battery protection controls (BPCs) on these parameters to maximize battery life, minimize warranty claims, and ensure minimum performance requirements. For example, the Ford Escape Hybrid's 1.8 kWh battery has a cell design allowing for an SOC range between 40% and 60%, whereas the Chevy Volt's 16 kWh battery allows an SOC range between 30% and 80% ("Chevy Volt," 2007), and the alternating current (AC) prolusion E-box with a 36.6 kWh battery operates with an SOC range between approximately 10% and 95% (Beck, 2009). By limiting SOC, OEMs can limit DOD and theoretically reduce battery degradation. The significance, as it pertains to my model, is that increased cycle life results in lower total cost of ownership over time, whereas greater SOC ranges result in higher utility value and a greater A/S revenue potential. The SOC to which a vehicle is limited is called its usable battery capacity, which differs among manufacturers. The aforementioned properties and implications to battery life and cost are well delineated in a report by A123 Systems (2009), which asserted that A123 Systems' patented MIT-developed Li-ion chemistry meets the desired characteristics of an optimal battery for transportation and storage application. Figure 12 indicates the cycle life and useable power curves of their battery compared to a leading competitor.

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[10] Recent research and improved cell chemistries among Li-ion–based batteries are changing the previously accepted paradigm that shallower DODs resulted in greater cycle life. Newer cell chemistries are more robust to deep DOD and suggest that amount of energy processed or throughput is a better metric (Peterson et al., 2010).

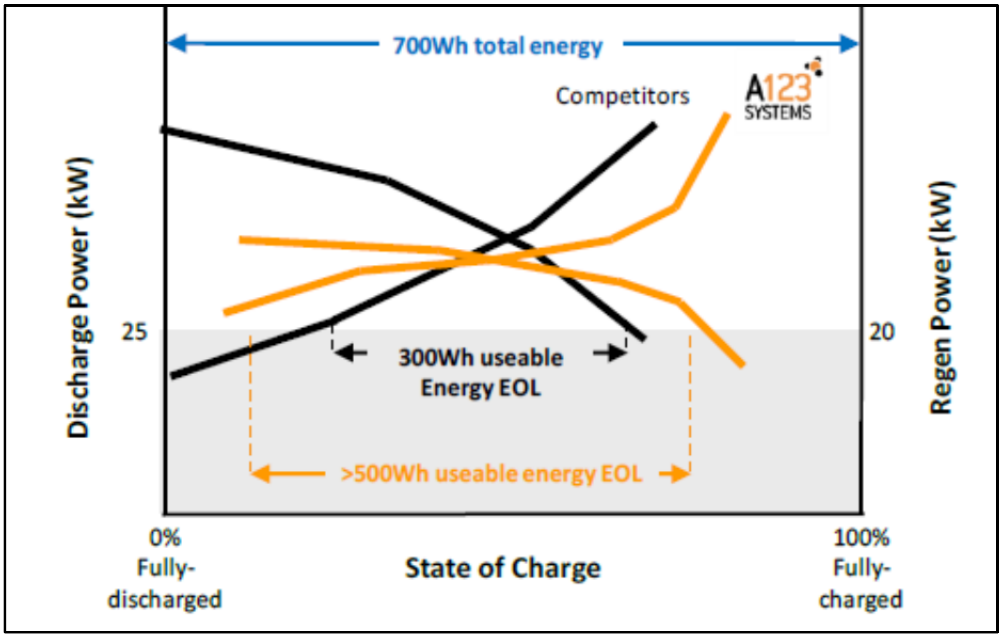


Figure 12. Useable Battery State of Charge
(A123 Systems, 2009)

d. *Charging Stations: Level 1, Level 2, and Level 3 (Direct Current Fast Charging)*

Charging stations, or the industry term *electric vehicle supply equipment* (EVSE), are the instrument through which PEDVs draw power from and connect to the utility grid. There are various makes, models, and types, but the significant differences among charging stations are the rates at which they transfer charge to a vehicle (semi-standardized by Levels 1, 2 and 3), their respective infrastructure and installation requirements, as well as the vehicle connection port. Level 1 and Level 2 EVSEs are simply a safe conduit for electrical current to flow from the grid to the vehicle's onboard battery charger. The onboard charger then converts the grid-supplied AC input voltage to direct current (DC) output voltage necessary for battery charging. Level 3 EVSEs, on the other hand, actually charge the battery by bypassing the onboard charger (if equipped) and delivering high voltage DC directly to the battery. A kW rating is the standard metric used to quantify an EVSE's rate of charge capability and varies widely across manufacturers and charging levels. Both Level 1 and 2 EVSEs use the same SAE J1772 charging port, standardized by the Society of Automotive Engineers, while Level 3 EVSEs require a dedicated charging port that has yet to be globally standardized. Figure 13 shows both charging ports installed (optional) on a Nissan Leaf.

Note. (Left) Level 3 CHAdeMO charge port; (Right) Levels 1 and 2 SAE J1772 charge port

Figure 13. PEDV Charging Ports
(plugincars.com)

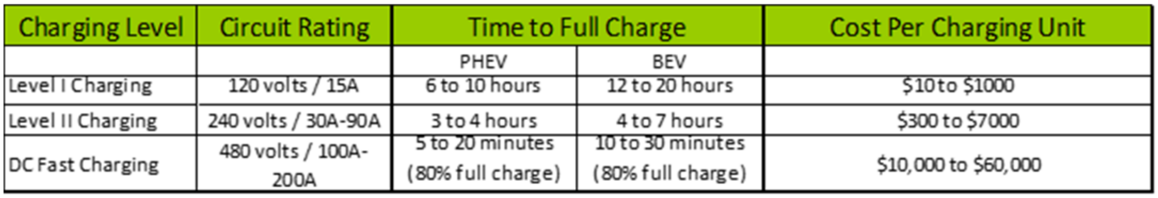
Level 1 is a low-power EVSE that is fed by a standard U.S. household 120 volt AC (VAC) utility connection and typically requires no infrastructure upgrades. This type of EVSE meets the requirements for most civilian commuters whose usage profiles do not conflict with an overnight charge duration requirement. Level 2 charging is for both home and commercial use and requires a 240-VAC utility connection. Unless a dedicated 240-VAC circuit is readily available, additional installation requirements are usually associated with this level of charging, and costs are estimated to be about $1,852 per unit (Morrow et al., 2008) plus the cost of the EVSE. My research indicates current infrastructure costs, at the fleet level and including the EVSE, should range from $1,600–$2,400 per vehicle for non-V2G Level 2 charging.

Level 3 fast charging, which is still in the early stages of wide-scale market release, has the most extensive installation and infrastructure requirements and uses a three-phase, 480-VAC utility connection that allows for extremely fast charges. Some applications can experience a 50% charge in three minutes or, in the case of the Nissan Leaf's relatively large battery, 80% in 30 minutes. At the fleet level, I estimate the installed costs of Level 3 chargers to range from $14,000 to over $27,000 per vehicle. At the higher end, Level 3 chargers can cost over $60,000 per unit but are capable of multiple ports and, thus, can charge more than one vehicle at the same time.

It is worth noting the industry concern that Level 3 rapid charging could result in greater than normal battery degradation relative to Levels 1 and 2. For this reason, SOC gained from Level 3 charging is usually limited to 80%. Without much published research on the topic, the potential degradative effect is not well understood. However, because Nissan recently released the first mass-produced Level 3 chargers in Japan for use with its Leaf with no reductions to its 8-year/100,000-mile warranty, I assume normal cell life for unidirectional charging across all three charging levels.

Table 3 depicts information from various sources regarding charge times, costs, and circuit requirements for the three charging levels. The time it takes a Level 1 charger to bring a vehicle to full charge is not practical in a scenario where a vehicle fleet participates in the A/S market. For this reason, I consider only Level 2 or higher chargers in this analysis.

Table 3. Charging Level Comparison Chart
(data from Pacific Gas and Electric Company, 2012; Southern Cal Edison, 2011)



Charging Level	Circuit Rating	Time to Full Charge		Cost Per Charging Unit
		PHEV	BEV	
Level I Charging	120 volts / 15A	6 to 10 hours	12 to 20 hours	$10 to $1000
Level II Charging	240 volts / 30A-90A	3 to 4 hours	4 to 7 hours	$300 to $7000
DC Fast Charging	480 volts / 100A-200A	5 to 20 minutes (80% full charge)	10 to 30 minutes (80% full charge)	$10,000 to $60,000

Note.
-Not all charging levels are compatible with all makes and models.
-Charging time will vary based on SOC, cell chemistry, and manufacture specifications.
-Costs per unit do not reflect installation costs and include recent and near-term market participants.

e. Bidirectional Capability

Bidirectional capability is the ability of a GEV to return grid synchronous quality AC power back to the power grid and is authorized under the National Electrical Code (NEC) per NEC Article 625 Section 26. This capability is a fundamental functionality that provides the full range of benefits associated with a V2G system. There are two basic ways to implement this interface: onboard or off-board the vehicle. Today, options are still very limited when it comes to the mechanisms (bidirectional chargers) that provide this capability, and this limitation is one of the major barriers to establishing a large-scale V2G network. Current options include retrofitting and integrating a grid-tie inverter into the vehicle's onboard system or using a Level 3 EVSE with an inherent bidirectional capability. The inverter option gives a vehicle the added functionality of true distributed generation, whereas a bidirectional EVSE requires the vehicle to be plugged into a particular grid connection but requires far less vehicle modification and greater nominal power potential. From a functionality and cost perspective, the optimal solution is to integrate the bidirectional capability into a PEDV's onboard system at the OEM level, providing the vehicle a mobile grid-enabled power source without the additional hardware and greater marginal expense of a retrofit or off-board system.

2. Benefits Beyond Economics

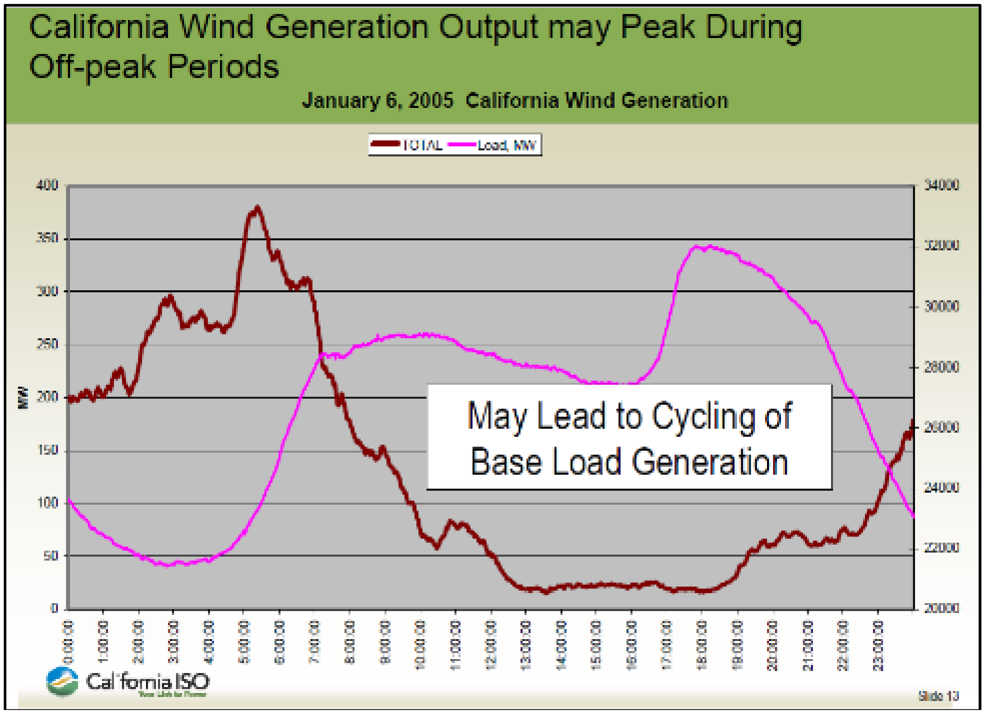
a. Emergency Backup

Beyond the economic incentives of V2G applications are some very useful fringe benefits that have a wide-ranging potential for federal installations. Among them is the capability of providing emergency backup power. Military bases and some federal installations are unique in that they are often mostly self-sufficient mini cities, with all the necessary security, logistics, and amenities of a small town. Despite their relative independence, in most cases they are still dependent on the local utility to provide their electrical needs. This means that when the inevitable power loss happens, the installation must either wait for the local utility for recovery or maintain its own costly emergency generation system. A fleet of grid-enabled PEDVs has the potential to meet an installation's mobility needs while delivering local, responsive, mobile backup power when necessary.

With the often high density of mission-critical capabilities reliant on electrical power onboard military and federal installations, backup power is not just a desirable capability but a security requirement. Additionally, the national electric grid is highly susceptible to terrorist attacks or natural disasters (Salmeron, Wood, & Baldick, 2004). With some state-side installations providing real-time warfare support, operating centers cannot afford an untimely power outage. Once again, a properly integrated V2G fleet can provide seamless emergency backup power. A fully charged and properly integrated Nissan Leaf can provide over a day's worth of electricity to a single home, while a fleet could temporarily power an entire installation or at least critical systems and command centers. Furthermore, bidirectional PEDVs, by virtue of their onboard internal combustion engine, could provide an indefinite power supply in the event of a prolonged outage, thereby effectively eliminating the need for large, single-use backup generators.

b. Net-Zero Energy Installations and Renewable Power Integration

Across the federal government, recent energy initiatives to create sustainable net-zero energy installations will yield new and increased measures for on-base renewable power generation. An important component of renewable power is storage. Due to its highly intermittent power generation characteristics, energy storage is needed to optimally integrate renewable power into the electrical grid. Photovoltaic generation (or solar power) is largely dependent on the time of day and the time of year, while wind power generation is less predictable and highly variable. The storage capacity of a V2G fleet can serve to harness the power of renewable generation during periods where its supply is greater than demand, thereby limiting wasted energy and balancing the grid power supply (Kempton & Tomic, 2005). This stored energy can then be either used to fuel the fleet for free or returned to the grid during periods of peak demand and low renewable supply. Figure 14 is a graph from the California ISO illustrating a typical demand cycle where wind generation is greatest during periods of low demand and lowest during periods of high demand. This dichotomy makes V2G systems an ideal candidate for wind power integration. However, it is important to note that at the installation level it is unlikely demand would fall below renewable power generation until significant increases in the DoD and federal government's renewable power portfolio take place.


California Wind Generation Output may Peak During Off-peak Periods

January 6, 2005 California Wind Generation

May Lead to Cycling of Base Load Generation

Figure 14. Wind Generation Versus Peak Demand
(Helman, 2009)

B. ELECTRICAL GRID OPERATIONS, REQUIREMENTS, AND MARKETS

1. Independent Service Operators and Regional Transmission Organizations

ISOs and RTOs are independent entities subject to federal oversight and the rules and regulations that manage much of our nation’s electrical grids. The ISOs and RTOs operate in a similar manner, with RTOs having the distinction of greater authority and responsibility over their regions’ transmission lines. An important distinction to note is that ISOs and RTOs do not generate power; that function belongs to over 3,200 electrical utilities across the nation (Schnapp, 2007). Additionally, not all electrical utilities operate under the jurisdiction of an RTO or ISO. This is typically true of smaller markets, which still fall under federal guidelines set forth by the Federal Energy Regulatory Committee (FERC, 2012).

According to the Energy Information Administration, “these organizations have broad operational control of participating utilities’ transmission systems, ensuring non-discriminatory access to market participants. Additionally, they operate competitive wholesale markets for energy services and demand response, and have authority over transmission system planning” (Schnapp, 2007). The key point here, as it pertains to this thesis, is that ISOs and RTOs control the wholesale electricity market in their region, along with ensuring reliability, maintaining grid performance, and conducting long-term planning for future supply and demand. In that function, they operate with little difference. Therefore, for the remainder of this thesis I will use these terms interchangeably (or refer to them together as ESPs) with the assumption that a prospective V2G system will operate within a region having a wholesale energy market. A final point on the relevance and importance of ESPs is their role in ensuring grid reliability. This role implies ensuring adequate sourcing and availability of A/S, which makes ESPs a key player in the proposed V2G business model.

2. Ancillary Services

The FERC defines A/S as “those services necessary to support the transmission of electric power 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” (Kirby & Hirst, 1996). The types of A/S are varied and include frequency regulation, peak shaving, load balancing, spinning reserves, and non-spinning reserves. FR is the A/S that serves as the focus for the proposed business model to follow, which I cover in-depth in the following section, along with brief descriptions of the others.

Due to variations in load, generation, and system failures, A/S are vital to ensuring the continued reliable operation of the electrical grid. With the high energy demand that today’s technologically driven society places on an aging infrastructure, utilities often operate with little reserve capacity beyond forecasted peak demand. On the other hand, there are large gaps between demand troughs and generation capacity, making A/S an attractive alternative to large-scale capacity upgrades that require huge sums of capital to service a relatively small portion of the day. This leaves ESPs reliant on the wholesale energy market and open to third-party generators and service providers, who play a substantial role in today’s grid operations. Figure 14 depicts a typical 24-hour demand cycle by charting grid load (pink line) in MWs throughout the day. The variances in daily load provide both the need and opportunity for the A/S market.

a. Frequency Regulation: Power Quality and Reliability

FR is an essential service that requires fast response and, in the case of V2G systems, is *believed* to have the most profit potential with the least degradation to an EV's battery (Kempton et al., 2008). In the United States, the target grid frequency to maintain is 60 Hz (50 Hz in Europe). The stability of the grid frequency can be viewed as a metric for power quality, with well-conditioned, high-quality electricity having stable frequency characteristics. Energy demand on the grid is dynamic, and generally the grid has little to no storage capacity; thus, supply and demand must be matched incrementally throughout the day, or frequency will drift. This drift is called the area control error (ACE) in MW, and ideally the ACE is zero, meaning generation and consumption are exactly in sync. Smaller deviations from zero can damage highly sensitive electronics (this is why we use surge protectors for our home computers and plasma TVs), while larger deviations can result in transformer malfunction and power outages (Frequency Regulation Compensation in the Organized Wholesale Power Markets, 2011). Figure 15 shows the real-time grid frequency for the PJM RTO on October 1, 2011, for an eight-hour period. The blue line indicates the instantaneous grid frequency, and the red line shows the average frequency that nets to the target frequency of 60 Hz over time.

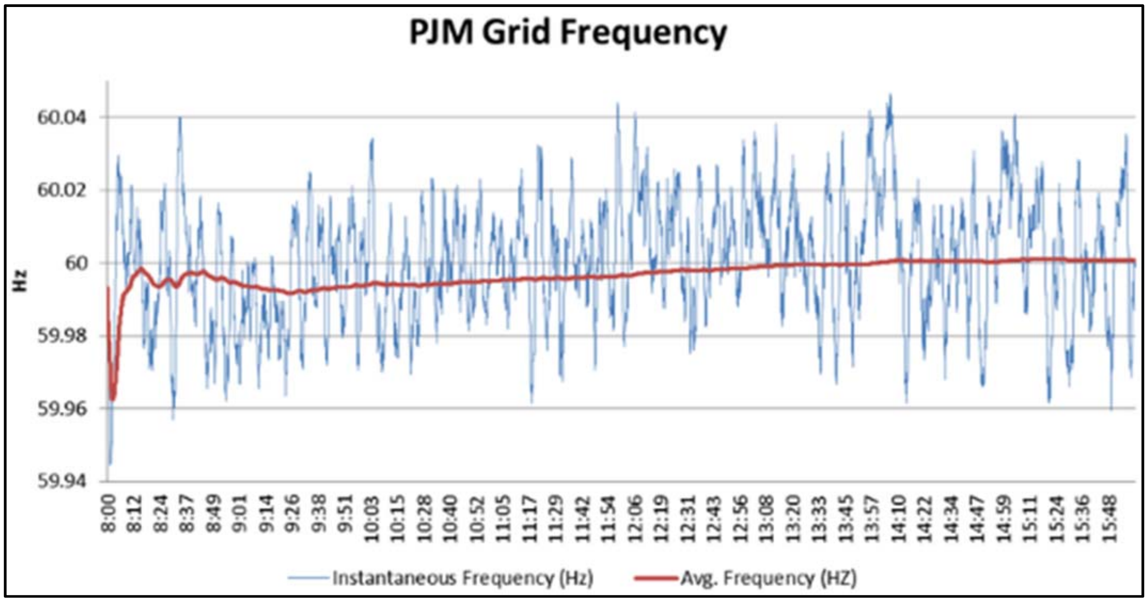


Figure 15. PJM Real-Time Grid Frequency

Maintaining the proper grid frequency requires either frequency response or FR (Frequency Regulation Compensation in the Organized Wholesale Power Markets, 2011). The difference is not trivial. Frequency response is done automatically via AGC and involves throttling individual generators to increase or decrease output as demand dictates. FR, on the other hand, is the A/S that is requested from an ESP and involves the direct "injection or withdrawal of real power." It could also, however, involve throttling consumption, as in the case of integrated storage systems such as flywheels, compressed air, and reverse hydro. ESPs communicate a power imbalance via an AGC signal, which is sent as a request for regulation and monitored by contracted regulation providers, called resources.

When load exceeds supply, a lower-than-target frequency is observed and, consequently, a negative ACE value. This generally results in a positive AGC signal to increase generation and balance the load. The contrary is true when demand falls below generation: a positive ACE value resulting in a negative AGC. Figure 16 shows actual ACE values from ISO New England (ISO-NE), and Figure 17 shows ACE values from PJM. The *y*-axis indicates the generation error in MW with time of day on the *x*-axis. Both are shown here to demonstrate similarities and differences between the two ESPs. ISO-NE has a much smaller market and service requirement than PJM. This is inferred by the maximum and minimum ACE values displayed on the *y*-axis. A larger market such as PJM may have greater variances in magnitude but similar ACE/load ratios. Despite differences in market size, key similarities exist in the ACE characteristics of the two ESPs. Both tend to over generate, as evidenced by an ACE that nets to a positive value, and both have an average hourly ACE that is relatively small compared to its generation capacity, less than 10%. The similarity between these different markets merely supports the proposition that statistical inference from the data of one market may be applicable to the energy market as a whole. This research focuses primarily on the data from the PJM market, which is assumed to be representative of others (see Chapter VII).

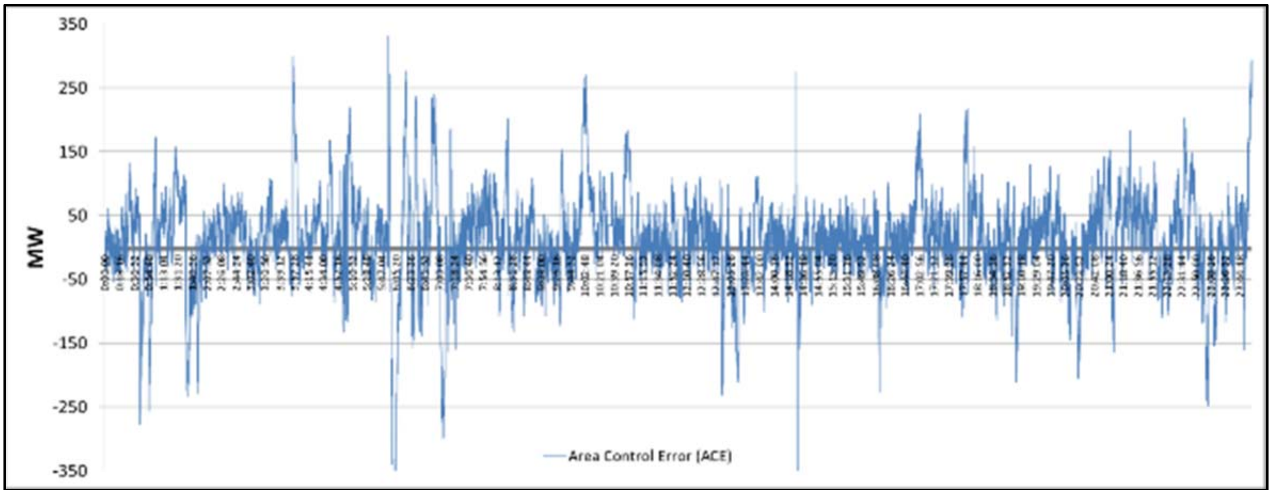


Figure 16. ISO-NE 24-Hour Area Control Error

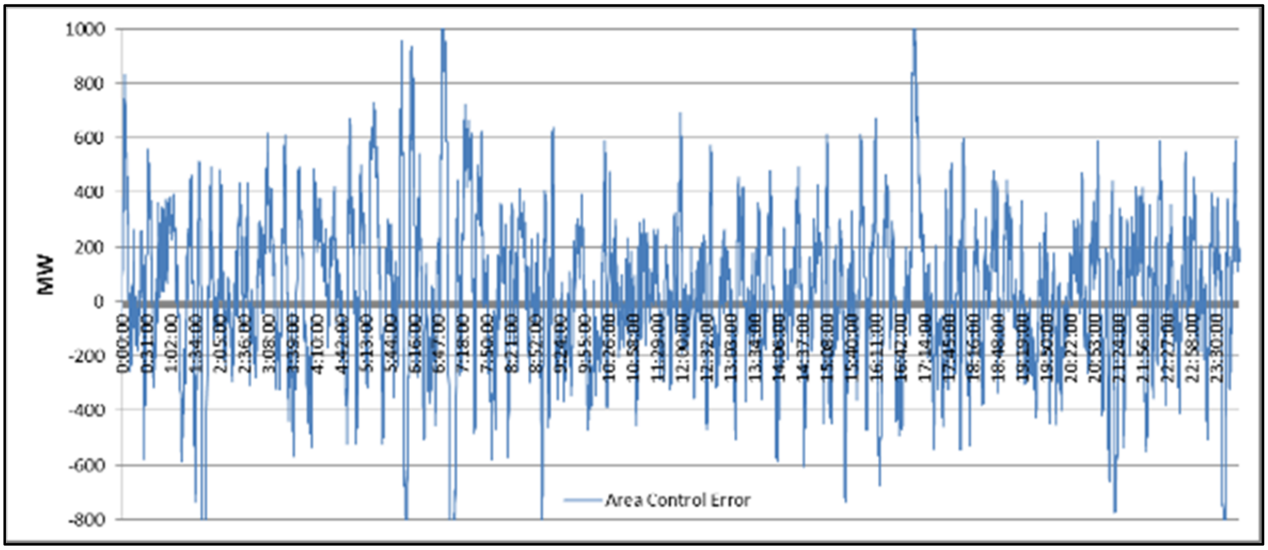


Figure 17. PJM 24-Hour Area Control Error

b. Other Services

(1) Demand-Side Management. Additional ways PEDVs benefit the electric grid are through load balancing and peak shaving. Both are forms of demand-side management and have the potential to assist utilities or even island micro-grids with balancing power consumption (Galus & Andersson, 2008). *Load balancing* is simply shifting demand to times of day where load is generally low and the ESP has a surplus generation capacity, typically after midnight and before 0600 hours (see Figure 14). The demand cycle can also benefit a fleet manager because electricity costs in markets that offer

dynamic pricing are less expensive during times of low demand and could reduce vehicle operating costs.

Peak shaving involves reducing the peak demand of large electricity consumers such as commercial or federal installations. These large consumers pay high-demand fees in addition to usage charges that often make up a significant portion of the monthly electrical bill (Millner, Judson, Ren, Johnson, & Ross, 2010). In an MIT report, Millner et al. (2010) investigated the economic viability of using a V2G system for this service. Their findings are somewhat encouraging and worthy of further research and seem to be well suited for a large fleet with Level 3 bidirectional EVSEs. Applicability for government installations, however, is questionable because fleet availability and installation demand peaks would likely be non-synchronous. A more suitable scenario, from a utility perspective, involves compensating and using commuter vehicles owned by installation personnel because commuter vehicles are predominately idle during business hours. However, the service would need to be employed in such a way as not to leave commuters stranded at work with empty batteries.

For a final consideration of demand-side management, Marine Corps Base Hawaii is involved in a program managed by HECO (Hawaiian Electric Company), the island's ESP, where on request from HECO the base reduces demand and powers specific buildings with standby generators. Depending on the frequency, duration, and compensation for such a service, this may also be a potential application for a V2G system.

(2) Spinning Reserves and Non-Spinning Reserves. The use of a federal fleet of PEVs for capacity reserves for an ESP is not sustainable in the long term and is generally not practical or profitable. *Spinning reserves* are online supplemental generation, while *non-spinning reserves* are off-line supplemental generation, both intended as backup power in the event of a major system failure. Although a properly integrated V2G system could provide the rapid response necessary for such a service, the capacity would likely not be great enough to provide the necessary supply for very long. In the case of a prolonged failure, a fleet could possibly discharge all of its power before the failure is corrected, leaving the fleet unusable prior to recharging. On the other hand, capacity reserves for a smaller demand market, such as a federal installation or perhaps even a forward operating base

(FOB) in a deployed environment, would be applicable. At any rate, these are potential applications, but they are not considered in this analysis.

3. Aggregator and Energy Market

The aggregator is the person, system, and/or software necessary to manage the fleet of grid-enabled vehicles. To take full advantage of the V2G system in a fleet setting, software is required to remotely communicate with the vehicle via a vehicle smart link (VSL) in order to manage fleet and individual vehicle usage profiles. Some of the major duties of the aggregator are to manage these profiles and bid on the open electrical grid A/S market for A/S contracts. The aggregator must balance the needs of the vehicle fleet to accomplish its primary mission, transportation support, while maximizing profit potential from A/S contracts. As in any modern market, the energy market is highly organized and consists of buyers and sellers; prices are set and sales are made. The commodity bought and sold is A/S. The buyers are the ESPs; the sellers are the resource providers authorized to participate in a specified service market.

FR contracts are usually on an hourly basis and based on a resource’s stated energy capacity in MWs (PJM, 2011). Some ESPs require a symmetric regulation up and down capability for FR, meaning that a bid for 1 MW capacity would mean the ability to provide 1 MW of regulation up and 1 MW of regulation down from a set operating point. Other ESPs, such as CASIO (California ISO), split the regulation market into two segments and allow resources to participate in either regulation up or down or in both. Each A/S has two sub-markets: day-ahead and hour-ahead. The contracts bought and sold in the day-ahead market are executed the following day and based on projected demand, while the hour-ahead market is far more dynamic and adjusts relative to near real-time information regarding system demands and market trends. In both cases, the aggregator acts as a middle man between the ESP and the resources, or in this case the fleet of PEDVs. As one may imagine, the aggregator could bid into both markets based on the availability and capability of the fleet in order to maximize profit while meeting the needs of the fleet’s primary purpose: transportation.

IV. METHODOLOGY, ASSUMPTIONS AND CONSIDERATIONS

This chapter provides a broad overview of the research methodology employed as well as the assumptions and considerations relating to key elements of this analysis. These elements include justification and reasoning behind comparison fleet selection, data collection, cost estimation, and model development.

A. OVERVIEW

With V2G still in the pilot stage, most associated research operates under generalities and optimistic assumptions regarding costs, A/S revenue, battery degradation, infrastructure requirements, and throughput. In an effort to present a relevant, realistic, and inclusive evaluation of V2G and its ability to lower LCCs for government non-tactical vehicle fleets transitioning to PEDVs, I began my research by examining the most current and commercially (or semi-commercially) available technologies, from vehicles to infrastructure, and selected the most appropriate for consideration. Data were collected on the various elements of a V2G system to include PEDVs, system performance metrics, cost components, and required infrastructure. Individual cost components that could not be readily determined were derived or estimated. Data analysis was performed on actual AGC dispatch signal data to determine its properties and characteristics. This data analysis led to an effort to quantify V2G FR-associated battery degradation, which I then integrate into the V2G FR revenue assessment via the Energy Flow–Life-Cycle-Cost Model (EF–LCCM).

I develop the EF–LCCM to enumerate through the various levels of V2G FR and provide a determination on whether V2G can deliver the necessary financial subsidy for PEDVs to compete with traditional fleet vehicles over their life cycle and to identify the level of V2G with the greatest return on investment. Finally, I create a simulation using actual AGC signal data that present a realistic picture of battery SOC swings and quantify expected energy throughput from a vehicle providing FR. This simulation is used to cross-validate the results of the EF–LCCM and forms the basis for key assumptions regarding energy throughput, battery degradation, and overall system limitations. The EF–LCCM is then run with validated throughput and energy flow parameters. Finally, several sensitivities are performed on various cost components, parameters, and variables in detail to present a thorough assessment of the economic viability of V2G in order to inform potential near-term investments for government applications. Figure 18 illustrates a graphical overview of the methodology. Detailed descriptions of methodology, model inputs, parameters, and key assumption are provided in following sections.

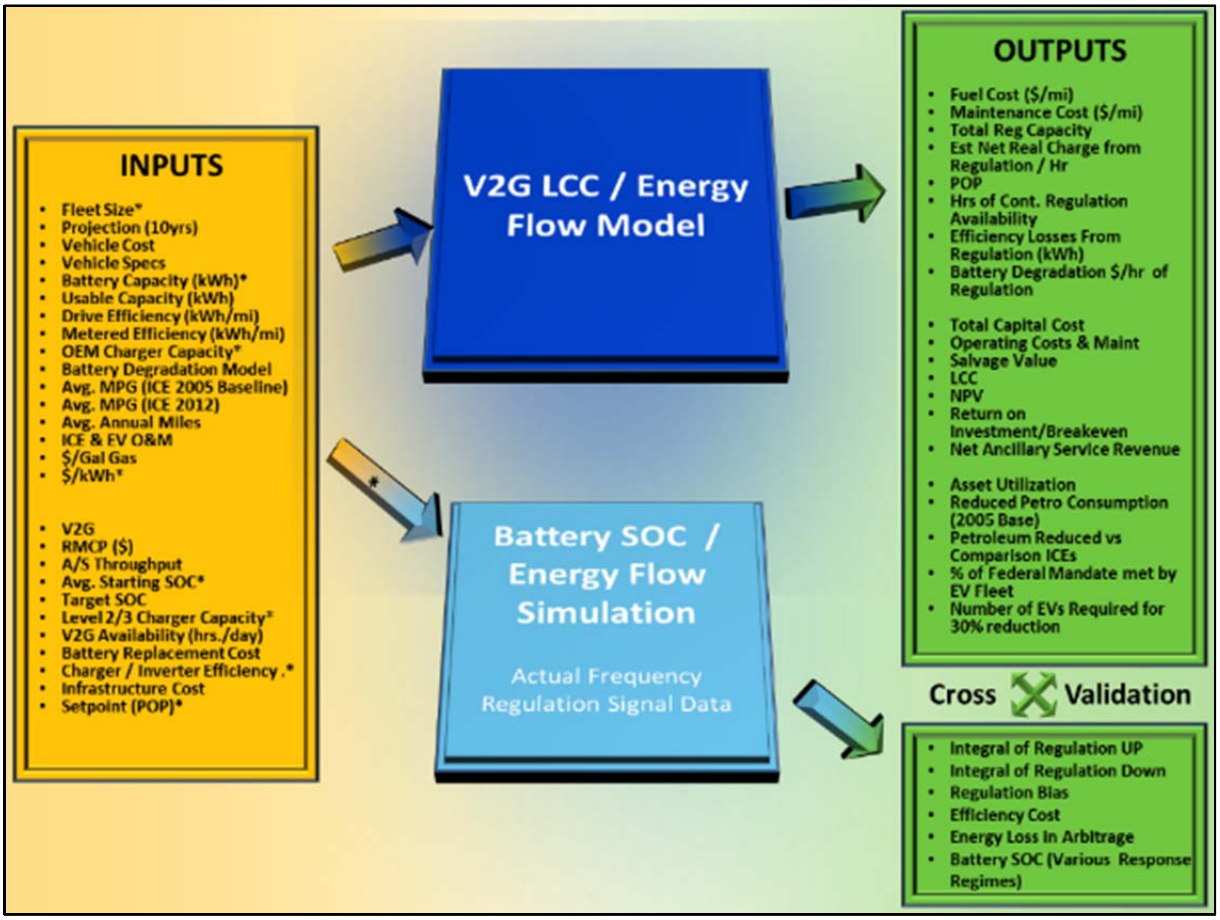


Figure 18. Methodology Overview

B. VEHICLES

1. Selection and Rational

The EDVs used in past and present V2G pilot programs, both government and private, are typically OEM gliders, provided by entrepreneurial conversion shops, that are stripped of their factory drive trains, retrofitted with large-capacity traction batteries, and equipped with an integrated power electronics system, purpose built for bidirectional grid services. These options range in price from $80,000 to $150,000[11] and, in some cases, are woefully ineffectual due to reliability issues.[12] The emergence of the newest generation of PEVs will make these options obsolete by providing the same functionality at a fraction of the cost. With PEVs from major automotive producers ranging in price from $35,000 to $45,000, the additional marginal costs to obtain V2G capability can be achieved for far less than the glider conversion method.[13] For example, basic unidirectional V2G can be obtained with the Siemens' VersiCharge™, a Level 2 EVSE designed with smart grid interoperability standards, onboard communications, and variable amperage demand response (Siemens, 2012) and was available in late 2012 for under $2,000. For basic V2G capability, factory PEVs reduce the retrofit process from a drive train swap to software modifications, supplemental communication electronics, and the possible addition of an inverter for bidirectional capabilities. If retrofits are required to obtain V2G capability, the most cost-effective way will be to start with an OEM EDV rather than an OEM ICE. For this reason, my analysis considers only EDVs currently available by OEMs as realistic alternatives for current government non-tactical fleet vehicles.

2. Categories and Classes

Altogether, this analysis considers five vehicles in five categories:

Table 4. Vehicle Categories

Category	Vehicle
ICE-Purchase (Base Case 1)	2012 Chevy Cruze
ICE-GSA Lease (Base Case 2)	2012 Ford Focus
HEV	2012 Toyota Hybrid
PEV	2013 Nissan Leaf
PHEV	2012 Chevy Volt

These vehicles represent the latest OEM production models in the small to mid-size four-door passenger class. The categories ICE-Purchase and ICE-GSA Lease are used as

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[11] AC Propulsion's eBox: $70,000 (retrofit cost) + ~ $10,000 = $80,000; Rapid Electric Vehicles' Ford Escape (retrofit): $150,000

[12] Based on site visit to the U.S. Army Tank Automotive Research Development Engineering Center's (TARDEC's) demonstration Micro-Grid at Wheeler Air Base, Hawaii, March 2012.

[13] This assessment applies to passenger vehicle fleets only and does not apply to electric drive SUVs or DoD specialty-use vehicles that may be under consideration because those options currently do not exist at the OEM level.

base cases from which to compare the three other categories and the presence of a non-plug-in HEV in the comparison matrix aims to address Executive Order No. 13,423 (2007), which requires federal agencies to acquire plug-in HEVs when available and when LCCs are comparable to non-plug-in HEVs. LCCs and NPVs of all vehicles are then analyzed under various parameters to determine the value of base-case alternatives (with and without V2G where applicable).

3. Purchase vs. Lease

Sixty-nine percent of federal fleet vehicles are owned by their respective agencies with the remaining classified as GSA or commercial leases (DoE, 2010). The lease option for plug-in vehicles participating in V2G is not addressed in this research for the same reason OEMs have thus far been unwilling to participate in the V2G discussion. Due to unproven technology and undocumented long-term effects on the vehicle's most expensive component (the battery), OEMs are rightfully concerned about vehicle reliability and premature component failure creating a substantial financial risk from potentially higher warranty claim rates. In a similar manner, it is unlikely that the GSA or commercial leasing agent would assume such a risk and provide lease agreements with prescribed mileage rates for vehicles participating in V2G without documented evidence on maintenance and degradation costs associated with V2G participation (particularly bidirectional V2G) to assess risk. Therefore, it is assumed that the initial stages of such an acquisition would be financed through federal grants or agency funding and owned outright by the agency until empirical evidence or further research can adequately assess the degree of associated risk imposed by V2G and V2G FR. The GSA lease vehicle, on the other hand, is presented as a base case for additional ICE alternatives. Because leases represent a significant portion of the federal fleet, this analysis will determine whether agency-owned, V2G-integrated PEVs can compete with current lease options on an LCC basis.

C. DATA COLLECTION AND COST ESTIMATES

Initially, the data for this research consisted primarily of technical specifications and cost estimates. These came from a variety of sources, including published and non-published interviews from industry experts or self-derivations. Later in the research process, I acquired data from the mid-Atlantic ISO PJM, which significantly impacted the overall results of this thesis by completely redefining the key assumptions regarding energy throughput during frequency regulation (see Section VIII.B). These data formulate the basis for the EF–LCCM that enumerates through the various degrees of V2G integration and calculates net energy flows, efficiency losses, and battery degradation to determine net revenue as a function of battery pack and charger/inverter limitations.

1. Vehicle Costs and Specifications

Purchase cost, efficiency, and technical data for the vehicles were readily available and obtained primarily from manufacturers' websites. Figures for purchase costs consist of manufacturer-suggested retail prices (MSRPs) with no consideration given for possible government bulk purchase discounts. ICE and HEV efficiency data came from published EPA combined MPG ratings. For the PEV and PHEV, two different types of efficiencies are used: consumption-based efficiency and drive efficiency. *Consumption efficiency* relates miles driven to real power consumed from the grid by accounting for charger efficiency losses. This metric is derived from the observed energy flow from the utility meter to the charger and converted into a consumption or meter-based efficiency rating by using the vehicle's published combined highway/city range in miles. In other words, it is the amount of "metered energy" required to bring the battery to a full charge from a complete DOD, divided by the maximum distance an EV can travel on a fully charged battery on a combined highway/city basis. My independent calculations, based on published combined vehicle range and charger efficiency, were nearly identical to the EPA's published efficiency ratings (see Figure 19); therefore, the EPA estimates are used for consistency. *Drive efficiency* describes the vehicle's ability to convert kWh of energy stored into miles driven, also on a combined city/highway basis and is calculated by dividing the usable battery capacity (limited by the onboard battery management system [BMS]) by the vehicle's published combined maximum electric range. The additional miles traveled as a result of regenerative breaking are accounted for in both consumption and drive efficiency.

EPA Fuel Economy and Environmental Comparisons

Electric Vehicle

99 MPGequivalent

106 city

92 highway

combined city/hwy

34 kW-hrs per 100 miles

Charge & Range

Annual Electric Cost

$561

73 miles

How This Vehicle Compares

Environment

See the FREE Fuel Economy Guide at dealers or www.fueleconomy.gov

EPA Fuel Economy and Environmental Comparisons

Dual Fuel Vehicle: Electricity-Gasoline

Charge Time

4 hours @240V

All Electric

When battery is fully charged, first 35 miles only.

93 MPG equivalent

36 kW-hrs per 100 miles

combined city/hwy

$601 cost per year if always run in All Electric

Gas Only

When electricity is used up, runs on gas for another 344 miles.

37 MPG

2.7 gallons per 100 miles

combined city/hwy

$1,302 cost per year if always run in Gas Only mode

Range (Miles)

All Electric Range (battery) 35

Extended Range (gas)

379 TOTAL

How This Vehicle Compares (combined composite)

Among all vehicles and within compact cars

Worst 14MPG — 60 — 60MPGe Best

Compact Cars

Greenhouse Gases (CO_2 g/mile, tailpipe only)

Worst 987 — 84 — 0 Best

Other Air Pollutants

Worst 1 — 6 — 10 Best

Examples: Charging Routines

Miles driven between full charge	Fuel Economy MPG	Electricity Consumed	Electricity + Fuel Energy Cost
30	NA	10.9 kWh	4¢/mi
45	168	12.9 kWh	5¢/mi
60	89	12.9 kWh	6¢/mi
75	69	12.9 kWh	7¢/mi
Never Charge	37 35 city / 40 hwy	N/A	9¢/mi

Your actual mileage and costs will vary with fuel cost, temperature, driving conditions, and how you drive and maintain your vehicle. Cost estimates are based on 15,000 miles per year at $3.20 per gallon and 11 cents per kW-hr. MPG equivalent: 33.7 kW-hrs = 1 gallon gasoline energy.

Visit www.fueleconomy.gov to download the Fuel Economy Guide (also available at dealers).

Figure 19. Monroney Sticker: Environmental Protection Agency

Table 5. Vehicle Costs and Specifications

Category	ICE-Purchase	PEV	PHEV	Hybrid	ICE-GSA Lease
Model	2012 Chevy Cruze	2013 Nissan Leaf	2012 Chevy Volt	2012 Prius (3rd Gen)	2012 Ford Fusion
MSRP	$16,800	$35,200	$39,145	$24,000	NA
10-year Lease Cost	NA	NA	NA	NA	$30,360
Battery Capacity (kWh)	NA	24	16	1.8	NA
Usable Capacity (kWh)	NA	21.6	10.3	0.9	NA
OEM Charger (kW)	NA	6.6	3.3	NA	NA
Charger Efficiency	NA	85.00%	80.00%	NA	NA
Full Recharge Consumption (kWh)	NA	25.41	12.88	NA	NA
Battery Warranty	NA	8yr/100k mi	8yr/100k mi	NA	NA
MPGe (City/Hwy)	NA	106/92	95/93	NA	NA
EPA Combined MPGe	NA	99	94	NA	NA
MPG-G (City/Hwy)	25/36	N/A	35/40	51/48	23/33
EPA Combined MPG gas	30	N/A	37	50	26
EPA Combinded Hybrid	N/A	N/A	60	N/A	N/A
Range -Electric only	N/A	99	35	N/A	100
Range -Total (City/Hwy)	390/561	N/A	407	606/571	402/577
Range EPA combined	468	73	379	595	76
Drive Efficiency	N/A	0.296	0.294	N/A	N/A
Meter Based Eff. (kWh/mi-EPA)	N/A	0.340	0.359	N/A	N/A
$/mi Electric ($0.10/kWh)	N/A	0.035	0.036	N/A	N/A
$/mi Gas ($4.25/gal)	$0.142	N/A	$0.115	$0.085	$0.08 (1)
$/mi Combined (Gas-Elec)	N/A	N/A	$0.0454 (2)	N/A	N/A
Maintenance $/mi	$0.0487	$0.0797 (3)	$0.0691 (3)	$0.0487	$0.08 (1)
Total O&M/mi	$0.190	$0.115	$0.115	$0.134	$0.160

*Note*s.

(1) GSA mileage rate covers both gas and maintenance for the Ford Fusion at $.16/mi.

(2) Combined efficiency for the Volt is computed by EF–LCCM based on average miles per day. Fewer miles per day means more all-electric miles and thus lower fuel cost per mile.

(3) Maintenance for PEV and PHEV includes the cost to replace the battery at 100,000 miles and a projected cost of $350/kWh versus current costs of $750–$1,000/kWh.

2. Cost Estimates

The cost estimates required for this research consist of two main categories:

- charging equipment and vehicle modification cost, and
- infrastructure installation cost.

a. *Equipment Market Overview*

V2G has never been deployed on a large scale. The technology to do so exists but has yet to reach economies of scale in some aspects, particularly where bidirectional capabilities are concerned. Prices for most elements of the charging infrastructure are under major downward pressure as demand increases, technology advances, and new participants enter the market. The market for Level 2 chargers is a good example of this, with prices over $2,000 for basic Level 2 chargers just a couple years ago; now the Home Depot sells basic Level 2 chargers on its website for under $800 (Home Depot, 2012). Perhaps the best example, however, is the market for Level 3 DC fast chargers. In late 2011, Nissan announced the release of a Level 3 fast charger for under $10,000, where previous costs for such chargers were in the $50,000 range (Motavalli, 2011a). Nonetheless, the industry remains in rapid development and is reluctant to share price information for developing or soon-to-be-released technologies in fear of losing a competitive advantage or out of concern that pre-full-scale production costs will discourage the market. Thus, cost estimates for the more advanced levels of V2G infrastructure represent thorough investigative research and come from unpublished sources or interviews with company employees and industry experts. The variability in these estimates is believed to be heteroscedastic in nature, with variability increasing as the level of V2G increases. From the sensitivity analyses performed, the reader will gain an understanding of where cost could be and where they are going with “current low,” “current high,” and “long-term projected” infrastructure cost estimates.

b. *Charging Equipment and Vehicle Modification Costs*

The charging equipment consists of the EVSE and ranges from basic unidirectional Level 1 to smart grid integrated bidirectional Level 3. It is important to remember that Level 1 and 2 EVSEs, in their basic form, are simply a vestibule for electricity to pass to the vehicle and do not actually charge the vehicle. The charger for Level 1 and 2 charging is located onboard the vehicle itself. Costs associated with Level 1 and 2 EVSEs are fairly straightforward. Numerous commercial manufacturers and even entrepreneurial third-tier manufacturers supply Level 1 and Level 2 chargers for thousands of PEV owners across the United States. The Level 1 charging infrastructure is not considered in this analysis due to its associated extended charge durations (10–20 hours) and its lack of interoperability with the smart grid. Therefore, only Level 2 and Level 3 charging infrastructures are considered.

Level 2 charging equipment costs range in price from $300 for basic Level 2 charging (EVSE Upgrade, 2012), 1,000–2,000 for Level 2 V2G smart charging (Siemens, 2012),[14] and as much as $10,000–15,000 for Level 2 high-capacity bidirectional charging (Eetrex, 2012).[15] The $300 option is provided by a small upstart and probably not the preferred method for a government fleet but demonstrates where prices are heading. The $15,000 option is a good example of emerging technology from expanded market participation and includes a cutting edge “inverger.” An inverger involves replacement of the OEM charger with a combined charger/inverter and provides onboard bidirectional capability with true distributed generation. Onboard power generation via an inverger will likely be the option of choice for retrofits where distributed vehicle to building (V2B) is desired. The intermediate option from Siemens is the most realistic near-term option for a government fleet and includes smart grid interoperability, network communication, and upgradability at an attractive price.

Bidirectional Level 3 options range from the aforementioned Nissan Leaf fast charger at $10,000 to other alternatives costing between $1.00–1.50/kW (C. Botsford, Personal Communication, April 10, 2012), which for a 50-kW charger would amount to $50,000-75,000. While these particular options are not purpose built for bidirectional flow, when equipped with an active switching full bridge rectifier, they can be modified to provide bidirectional functionality (C. Botsford, personal communication, April 10, 2012). Once again, however, the market is rife with technological progression, and already a market participant, Ideal Power Converters (IPC), is marketing and set to release a purpose-built, bidirectional vehicle charger that is 90% lighter than current Level 3 chargers, easier to install, built for indoor/outdoor use, and that has a reduced transformer requirement and is cost competitive at a first unit price of $12,000 with a 25–30-kW capacity (P. Bundschuh, personal communication, May 22, 2012). IPC bases this product off the relatively mature technology existent in the photovoltaic industry that has been converting DC energy to grid-

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[14] Based on the Siemens VersiCharge (30A) and VersiCharge SG (70A)

[15] This price is based on pre-production levels of the Eetrex Inc. Gen III, 10-kW Inverger, currently in development.

quality power for years. The key feature bidirectional Level 3 chargers bring to the V2G equation is the fact that vehicle modification is reduced to software adjustments and changes to the vehicle charge port (if not already equipped with a Level 3 port from the factory). Although this option does not result in true distributed power generation, as an onboard inverter does, it does provide bidirectional capability with the potential for reduced modification and installation costs. From cost to performance, these currently represent the best Level 3 option on the market.

The price point offered by IPC (~$.50/watt) is a very encouraging market development for Level 3 bidirectional chargers, considering it represents a pre-full-scale production price and is represented in the following estimates. The figures I use in the EF–LCCM for Level 3 DC fast chargers are $13,000 as the "low-current" estimate and a "high-current" estimate, which assumes a 125-kW AeroVironment multi-port charger costing $1.25/kW, providing 20 kW of bidirectional charging capability for six vehicles, at $26,000 per vehicle. In both cases, bidirectional functionality, necessary vehicle connection hardware, and smart grid interoperability are assumed to be included in the price by the time of full-scale market release. The total initial capital costs for a fleet of PEDVs, including infrastructure estimates for the various levels of V2G used in the EF–LCCM, are presented in Table 6.

My analysis assumes vehicle modification costs are limited to Level 2 bidirectional V2G only. Lower levels of unidirectional V2G can be achieved with simply a smart charger capable of network communication, and bidirectional Level 3 V2G is obtainable off board the vehicle with a DC fast charger. Therefore, only in the case of bidirectional Level 2 where the additional component of an inverter is required are modifications necessary beyond software alterations, such as an upgraded onboard charger. In the case of the REV vehicles, currently in use by government V2G pilot programs, an off-the-shelf (OTS) $3,000, 3.8kW, grid tied Fronius (brand name) inverter, outfitted with a fairly elaborate but not completely necessary communications suite, is bolted in the trunk and provides the vehicle's bidirectional capability. A more integrated approach would use a product like the Eetrex inverger. Although neither option is currently financially feasible, in the absence of OEM participation, they provide near-term solutions for demonstration purposes. Cost breakdowns of each option are included in the equipment cost estimate within the EF–LCCM for respective levels of V2G. The “low-current” estimate accounts for an 11-kW Fronius inverter at $4,500 and the “high-current” estimate includes a 10-kW charger at $15,000.

c. Installation Costs

Charging infrastructure cost estimates reference a Pacific Gas and Electric Company (PG&E) EV infrastructure installation guide (PG&E, 1999) and are adjusted for inflation. Results are based on specific assumptions and reflect an existent and fairly robust electrical infrastructure, representative of most military installations. Specifically, existing infrastructure assumptions are modeled after the electrical grid specifications of Marine Corps Base Hawaii (MCBH), including transformer capacity and load profile. The surplus capacity of MCBH’s electrical grid during the non-working hours representative of the V2G availability regime associated with a typical government fleet (only operating during business hours and non-federal holidays) was deemed adequate for a fleet with greater than 2 MW of regulation capacity; MCBH’s normal load differential between peak and off peak usage is about 6 MW. Therefore, it is assumed that a fleet of EVs participating in V2G with a capacity between 1 and 3 MWs would not overload the existing local infrastructure of a federal or military installation, and no additional requirements for dedicated transformers are necessary.

Dimensional and proximity assumptions regarding a parking lot layout and power source location are based on measurements taken on board the Naval Postgraduate School. These measurements help develop an energy distribution diagram that forms the inputs for the EF–LCCM, which calculates installation cost for a fleet of 100 vehicle as well as the marginal cost of additional vehicles using a tree-and-branch methodology. Marginal costs are calculated relative to the proportional cost of adding an additional branch to the distribution system. Therefore, the model can accommodate sensitivity analyses regarding fleet size by dynamically recalculating total capital cost as fleet size is altered. The infrastructure estimates include costs associated with cabling, trenching, demolition, paving, and distribution panels. These requirements vary with respect to the level of V2G, particularly with regard to cable thickness and distribution panels, and were modeled appropriately. The parameters modeled in this estimate reflect a centralized parking scheme and a transformer or substation within 100 feet of the first parking space. It is important to note that these estimates are highly specific, and actual costs will vary widely depending on the particular installation, the degree to which parking is centralized, the parking lot's proximity to the substation, and transformer availability.

D. MODELING AND ANALYSIS

In this chapter, I highlighted just some of the considerations and inputs that go into modeling the LCCs of a V2G system. The deterministic EF–LCCM is designed to perform comparative analysis between different government fleet options while incorporating V2G FR revenue into the assessment. I provide further detail in formulaic form in subsequent chapters. Every effort was made to ensure that the inputs used were as accurate and realistic as possible. To account for uncertainty related to some of the cost estimates, a high and low estimate is used for each level of V2G's capital cost in an attempt to frame today's cost for the technology. A third estimate for each level of V2G is based on industry projections or related research and intended to demonstrate potential future capital costs if downward pressure on prices of related technology continues and OEMs decide to produce a V2G-capable PEV direct from the factory. Additional sensitivity analyses to follow will focus on other areas of variability or uncertainty from the input data to illustrate important ideas, break-even points, cost and revenue drivers, or to identify bounds of estimation.

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V. VEHICLE-TO-GRID ECONOMICS

In this chapter, I present the fundamental elements that drive the economics of V2G. I detail the various cost and revenue components that exist in the life cycle of a V2G project and that are necessary to perform an LCC analysis in accordance with procedures and considerations published in the *Life-Cycle Costing Manual for the Federal Energy Management Program* (Fuller & Peterson, 1995), because this type of investment could be categorized as an energy conservation investment. This LCC analysis uses the DoD and federal government's preferred constant dollar approach with a base year of FY2012 (versus the private sector's preferred approach of current dollar). In keeping with the procedures of a constant dollar analysis, a "real" discount rate of 3%, as published annually by the DoE for federal energy-related projects, is used to discount all future cash flows to their present value. A constant dollar analysis is opposed to performing a current dollar analysis with a nominal discount rate (accounts for inflation), which is more applicable to the private sector with the added implication of tax considerations.

It has already been determined that the operating cost savings alone are not enough to economically justify a transition to PEDVs from traditional ICEs. What remains is to determine whether net revenue from V2G FR can make up the difference and drive PEDVs into economic competition with traditional vehicles. In earlier chapters, I address the benefits of petroleum reduction pertaining to the environment and energy security, but with this analysis I focus on V2G's justification purely on the grounds of its economic viability and, thus, no further economic benefit is assigned to petroleum reduction other than its associated cost savings. I assess economic competiveness by comparing Net Discounted LCCs of a traditional ICE and a GSA lease vehicle with PEDV alternatives and varying degrees of V2G. In the following sections of this chapter, I present the economic fundamentals necessary to derive the LCCs of V2G.

A. LIFE-CYCLE COSTS

LCCs are calculated using the present cost of the initial capital expense and the sum of all future cash flows discounted back to present value in FY2012 dollars. This present value analysis aims to determine whether the net savings from reduced operating costs and

A/S revenue can provide the economic justification for a V2G infrastructure and at what level. LLCs are calculated using Equation 1.

$$LCC = \sum_{t=0}^{n} \frac{s(O_t)}{(1+d)^t} + CAPEX; \quad s(O_t) = \begin{cases} O_8 + CRC & ,t = 8) \\ O_{10} - SV & ,t = 10 \\ O_t & ,otherwise \end{cases} \tag{1}$$

O_t – annual operating costs in year - t

d – discount rate

CRC – capital replacement cost

SV – salvage value

In some cases, the discounted savings-to-investment ratio (D-SIR) with a base year of FY2012 is presented to determine the economic strength of an alternative relative to a base case using Equation 2. D-SIR is calculated by discounting future cash flows from annual operating expenses after the initial investment by using Equation 3. Annual savings are bundled and discounted as end-of-year cash flows.

$$D - SIR = \frac{NPV_{Savings}}{Investment} \tag{2}$$

$$NPV_{Savings} = \sum_{t=0}^{n} \frac{S_t}{(1+d)^t} \tag{3}$$

An SIR value of 100% indicates that all of the additional investment was recovered by operational cost savings and that the alternative’s LCC is lower than the base case. The investment is considered the initial capital amount over the base case consisting of vehicle purchase price, charging infrastructure, and installation costs relative to the respective degree of V2G. The savings compared to the base case are the reduced annual operating costs associated with lower \$/mi operating expenditures and V2G net revenue. The investment and associated savings form the basis of an NPV of savings assessment for each degree of V2G at given model parameters. In the case of V2G, if FR revenue is large enough, annual operating costs will be negative.

B. CAPITAL EXPENDITURES

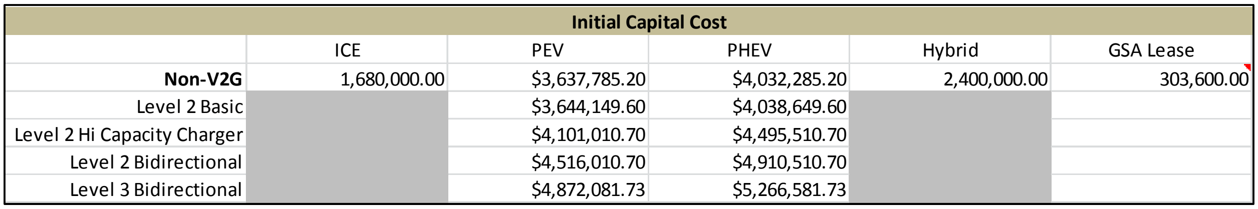
Capital expenditures (CAPEXs) are cash flows that consist of initial capital expenses, CRCs, and salvage value. These cash flows are separated in the LCC calculation to properly discount their value in the year they take place: CRCs in Year 8 and salvage value in Year 10, all others in Year 1.

1. Initial Capital Expense

Initial capital costs include vehicle purchase price, charging infrastructure, and installation costs. Planning and design costs are not accounted for in this analysis. The projection period for expected government vehicle life cycle prior to salvage is 10 years, but infrastructure is assumed to have at least a 20-year service life. Therefore, only 50% of the infrastructure cost is computed for the PEDVs in the base case. Accounting for only half the infrastructure cost reduces the return-on-investment (ROI) burden of PEDVs from justifying a 20-year infrastructure with only 10 years of savings and V2G revenue.

Table 6 indicates the initial capital costs associated with the six vehicle categories and the varying levels of V2G.

Table 6. Initial Capital Costs



Initial Capital Cost					
	ICE	PEV	PHEV	Hybrid	GSA Lease
Non-V2G	1,680,000.00	$3,637,785.20	$4,032,285.20	2,400,000.00	303,600.00
Level 2 Basic		$3,644,149.60	$4,038,649.60		
Level 2 Hi Capacity Charger		$4,101,010.70	$4,495,510.70		
Level 2 Bidirectional		$4,516,010.70	$4,910,510.70		
Level 3 Bidirectional		$4,872,081.73	$5,266,581.73		

2. Capital Replacement Costs

According to the Federal Energy Management Program, the cost for battery replacement is considered a capital replacement cost. A battery may not completely fail prior to the end a vehicle’s life cycle, but including it as a CRC represents the degree of uncertainty associated with battery cell maintenance and reliability, especially in the presence of V2G. So while a vehicle may not need a battery replacement, it may require maintenance or individual cell replacement. Therefore, sensitivity analyses on CRCs can be viewed not just as a function of cell replacement cost but also as the relative cost of incurred battery maintenance. Lower battery costs can represent either a low future cost of traction batteries in the event of replacement or low battery-associated maintenance cost. For this reason, the sensitivity analysis includes a battery replacement cost of zero.

It should be noted that in the presence of CRCs, LCCs become slightly lower. Instead of having just a PEDV to salvage with a battery that presumably is close to its end of life (EOL) for electric drive propulsion, one also has a PEDV with a fresh battery and the benefit of salvaging the old battery on the second-use marketplace. Assumptions are that 75% of the CRCs will be recovered through a higher residual value and that 30% of the CRCs are recovered from the salvage of the old battery. The result is a marginally better economic result rather than ignoring CRCs because CRCs occurring near the end of the vehicle's government service life are partially recouped during vehicle resale. Essentially, a PEDV would likely fetch a higher price on the used government vehicle auction block with a recently replaced battery. CRCs provide more variable results in the presence of battery degradation from V2G where degradation costs increase as CRCs increase. CRCs are computed from a projected battery replacement cost per kWh using Equation 4.

$$\text{CRC} = \text{Batt}_{\text{Cost}} \text{ (\$/kWh) x Battery Capacity (kWh)} \tag{4}$$

3. Salvage

Net salvage value is based on the vehicle's residual or resale value, including the added value of having a recently replaced battery, plus the salvage value of the old battery less the cost of the new battery (CRC). The PEDV's base residual value is linked to that of the ICE (9%), which is historically lower than the HEV (20%). Net salvage value is computed using Equation 5 or a simplified version, Equation 6.

$$S_{Net} = R_{Veh} + .75\, Batt_{New} + .3\, Batt_{Old} - CRC \tag{5}$$

$$S_{Net} = R_{Veh} + .05\, CRC \tag{6}$$

R_{Veh} – PEDV's base residual value.

$Batt$ – projected battery replacement cost (battery capacity (kWh) x replacement cost ($/kWh))

a. Battery

The salvage value of the battery is the value a Li-ion battery might fetch on the second-use market when it no longer meets the requirements necessary for mobility purposes after its capacity falls below 70–80% of initial capacity. Salvage value could also demonstrate savings of a foregone energy storage expense if the batteries were re-integrated into a federal facilities energy sustainment plan. My analysis uses an estimated future value based on the projections in Figure 20 and validated by research from the NREL (Neubauer & Pesaran, 2011). Many analysts believe that $100–200/kWh is the necessary price point to reach parity with ICE vehicles (not including potential A/S revenue). For my analysis, I’ve chosen a future price point of $350/kWh as an installed battery replacement cost. I use this same figure to estimate what a battery’s worth might be on the second-use market. This is a difficult proposition with no historical data, but it is reasonable to conclude that the residual value would not be the product of its remaining capacity (70–80%) and current new battery market price, and, thus, must fall somewhere between that percentage and zero. I have chosen to use 30% of the projected future price for an amount of $105/kWh for the valuation of a used traction battery on the second-use market. This estimate contrasts with NREL research that places the potential value as high as $170/kWh with the capability to discount initial battery costs as much as 12% (Pesaran & Neubauer, 2011). I include both projected battery cost and salvage in Year 10’s cash flow and discount to present value for the LCC analysis.

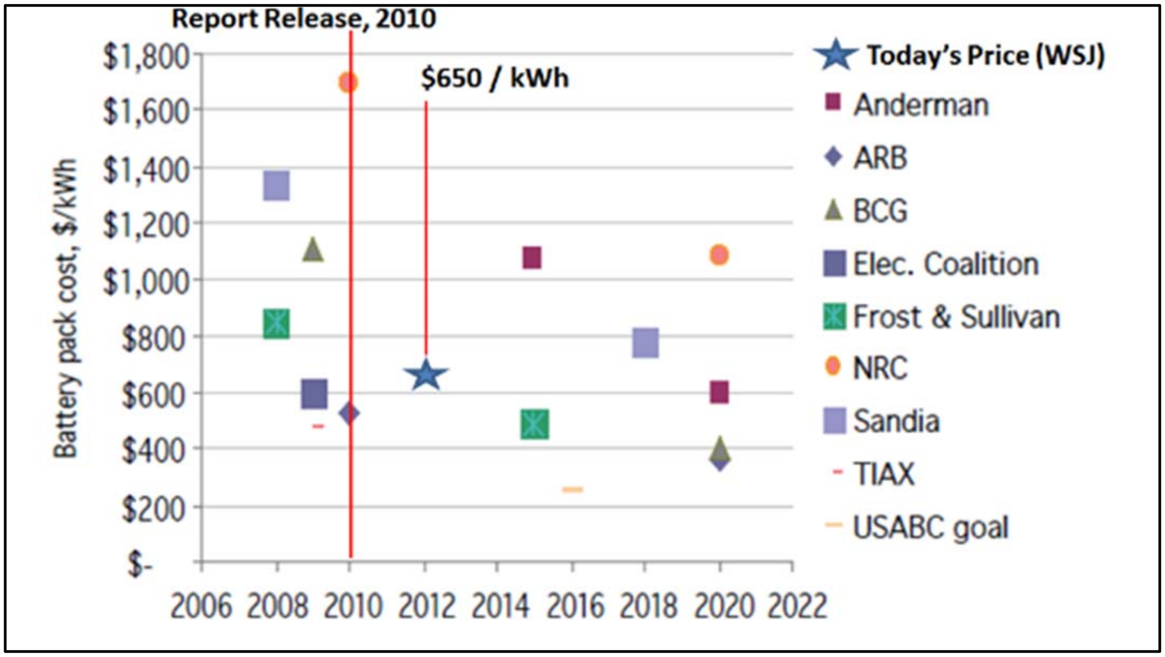


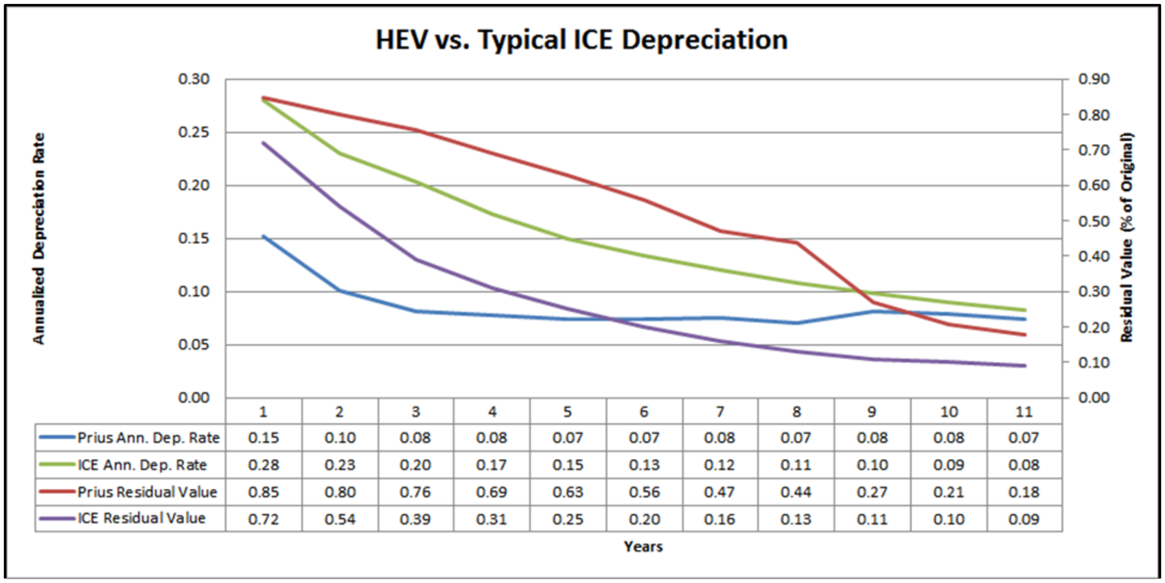
Figure 20. Cost Estimates of Electric Vehicle Battery Packs
(MIT, 2010)

b. Vehicle

Depreciation data from which to develop an estimate for the residual value of a PEDV is non-existent because the technology is still in its nascency, with only recent wide-scale release on the OEM level. A close comparable, however, is the HEV Toyota Prius. Although not an all-electric drive vehicle like the Volt and the Leaf, it is a partial electric drive vehicle with over 10 years of depreciation data to offer.

It is well understood that once a typical vehicle is driven off the dealer lot, it experiences a significant depreciation in its original value. This trend continues for another year or two before the depreciation rate becomes less severe. Some vehicles hold their value better than others, but it should be noted that vehicle depreciation rate is quite variable and highly dependent on the vehicle model, class, and manufacturer. It is uncertain how this first generation of high-volume production EDVs will hold their value, but if the Toyota Prius is any indication, it could be quite well.

I examined data collected from KelleyBlueBook.com and Edmunds.com, two vehicle price information websites. My analysis, depicted in Figure 21, revealed that the Prius did not experience a drastic initial depreciation rate and after the first two years reached a fairly consistent annualized depreciation rate between 7% and 8%, with a 10-year “real” residual value of 20% of its inflation-adjusted MSRP, while a comparison ICE was reduced to a “real” 9% of its original value. To further illustrate this point, a 2002 Toyota Prius had an inflation-adjusted FY2012 MSRP of $24,129 and today has an “average used retail” price with 100,000 miles of $4,992. For analysis purposes, because the salvage value in Year 10 is discounted back to a present value, the residual values used in the model to estimate vehicle salvage are a nominal 9% and 20% for the ICE and HEV, respectively. After accounting for the replacement battery costs represented in the mileage rate, the net real residual values for the PEV and PHEV are 10.2% and 9.7%, respectively (also see Table 18).



	1	2	3	4	5	6	7	8	9	10	11
Prius Ann. Dep. Rate	0.15	0.10	0.08	0.08	0.07	0.07	0.08	0.07	0.08	0.08	0.07
ICE Ann. Dep. Rate	0.28	0.23	0.20	0.17	0.15	0.13	0.12	0.11	0.10	0.09	0.08
Prius Residual Value	0.85	0.80	0.76	0.69	0.63	0.56	0.47	0.44	0.27	0.21	0.18
ICE Residual Value	0.72	0.54	0.39	0.31	0.25	0.20	0.16	0.13	0.11	0.10	0.09

Note. Data were derived from KBB.com and Edmunds.com using average annual mileage of 10,000 mi/yr.

Figure 21. Vehicle Depreciation Chart

C. OPERATING EXPENITURES

Operating expenses (OPEXs) consist of annual fuel and maintenance costs. The service date for operating expenditures is assumed to be concurrent with investment date. Vehicles are operational upon delivery, and charging infrastructure is in place. Using the Nissan Leaf’s service manual as a reference (Nissan, 2011), routine maintenance and subsequently maintenance costs are minimal for EVs. Maintenance costs for ICE vehicles are based on the American Automobile Association’s (AAA’s) most current published U.S. average maintenance cost per mile; and the PHEV costs, similar to its fuel rate, are based on the ratio of all-electric (AE) miles to range-extending (RE) miles from the average daily miles driven.

The vehicles will be covered under the manufacturer’s warranty for the vast majority of their service life; therefore, only basic maintenance is accounted for. For PEVs, maintenance is limited to brake fluid changes, tire rotation, and inspections. However, it should be assumed, based on the current OEM apprehension toward V2G, that participation in A/S would void the warranty on the battery. It is unknown what actual maintenance costs will be. Although it is true that there are fewer moving parts to fail, failures could be realized in software malfunctions and battery management system issues leading to individual cell replacement, if not the whole battery, during its service life.

D. ANCILLARY SERVICE REVENUE

Net revenue associated with this LCC element is subtracted from annual operating costs and, when positive, contributes to a stronger case for PEDV employment. Payment for A/S is made by the ESP to the servicing resource. In the case of V2G FR, revenue is generally a function of the RMCP per MWh of capacity, aggregate capacity of the fleet, and the time contracted and able to perform FR or time-on-regulation (TOR). For net revenue from V2G to be positive, gross revenue driven by the RMCP must be large enough to offset the costs of degradation, net power transferred (bidirectional V2G), and efficiency losses (see Equation 7). Maximum fleet capacity is limited by the smaller of the uplink (kW) and charger/inverter capacity (kW). Equation 7 is the general equation for net revenue calculations. Gross revenue is described in detail in the following section, battery degradation and efficiency loss are addressed in Section VII.B, and the aggregator fee is assumed to be a fixed 10% of gross revenue.

$$\text{Net Revenue} = \text{Gross Revenue} - \text{Battery Degradation Cost} - \text{Efficiency loss Cost} - \text{Aggregator Fee} \tag{7}$$

1. Frequency Regulation Compensation

Previously, compensation for the provision of FR was calculated using a price per unit of capacity per hour. Gross revenue from FR could generally be computed using Equation 8. However, according to the recent FERC Order 745 (Demand Response Compensation in Organized Wholesale Energy Markets, 2011), RTOs and ISOs are required to compensate FR resources based not only on a resource's capacity to perform regulation, but also for its accuracy in responding to an AGC dispatch signal. Order 745 allows fast-responding resources, such as PEDVs, to potentially generate as much or more revenue with less capacity and subsequently less cost. In theory, PEDVs would earn more revenue per unit of capacity serviced than traditional, slower responding FR resources. However, it is not yet clear how this will play out in terms of realized revenue per unit of capacity or, if so, by how much the revenue for fast-responding resource will increase. Therefore, this analysis does not predict RMCP based on the two-part pricing scheme of capacity and performance but a single price (for regulation up and down) based on historical RMCP performance using Equations 9 and 10. Far more detailed calculations are used to determine net revenue relative to the level of V2G and a multitude of system parameters.

$$\text{Gross Revenue} = \text{RMCP x Regulation Capacity x TOR} \tag{8}$$

$$\$Reg_{Dn} = \prod_{k=1}^{TOR} (RMCPd_k * CapRD_k) \tag{9}$$

$$\$Reg_{Up} = \prod_{k=1}^{TOR} (RMCPu_k * CapRU_k) \tag{10}$$

$\$Reg_{Dn}$ – annual operating costs in year - t

$\$Reg_{Up}$ – discount rate

TOR – duration FR is performed

$CapRD_k$ – aggregate fleet capacity for regulation down in hour k

$CapRU_k$ – aggregate fleet capacity for regulation up in hour k

$RMCPd_k$ – regulation market clearing price for regulation down in hour k

$RMCPu_k$ – regulation market clearing price for regulation up in hour k

Figure 22 plots average RMCPs since 2003 from three different ESPs and gives an indication of where RMCPs might be heading.

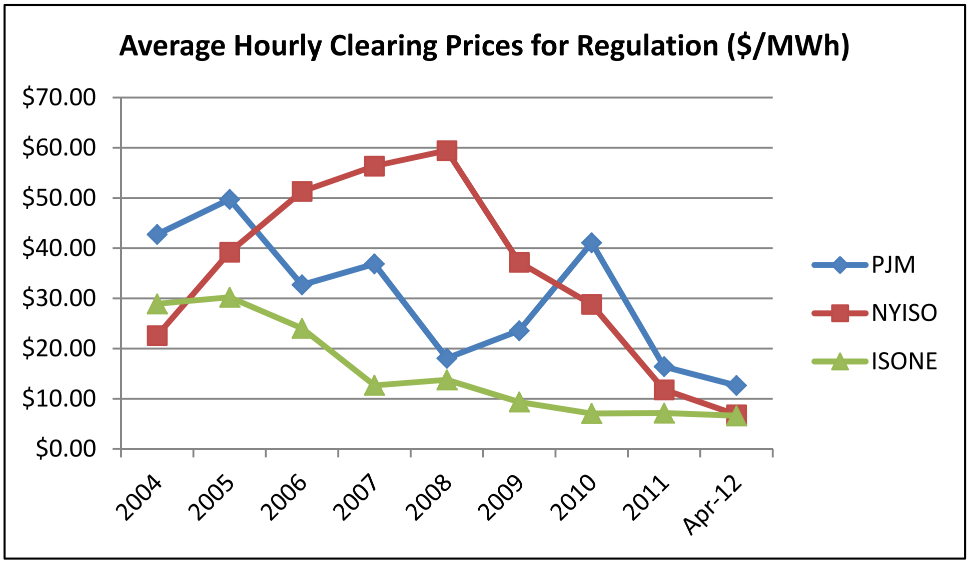
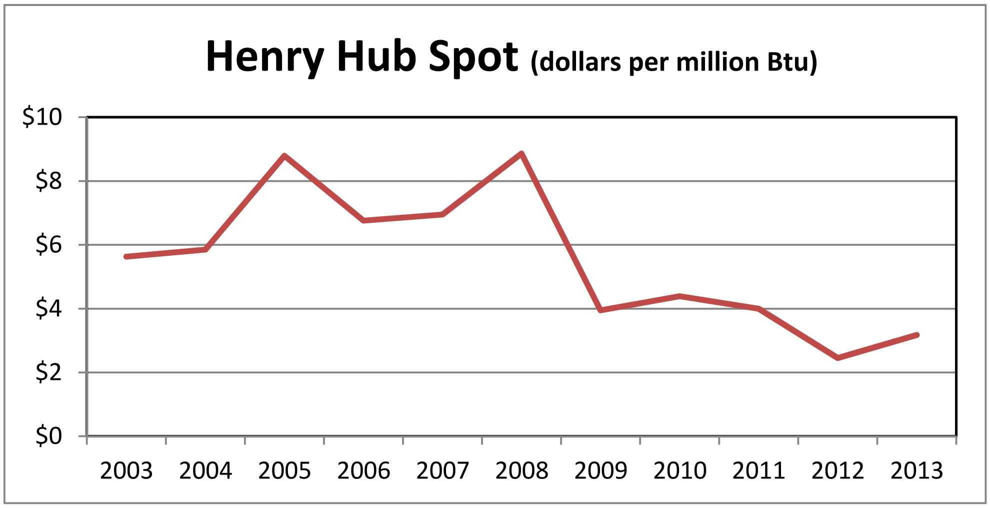


Figure 22. Historical Regulation Market Clearing Prices (Nominal)

Because the primary resources providing frequency regulation today are natural gas-powered turbine-fired generators, the price of natural gas might be a further indication of future RMCPs. Comparing natural gas prices (Figure 23) with RMCPs over the same period indicates that correlation is likely to exist. The EIA's Short-Term Energy Outlook (EIA,

2013) predicts NG prices to remain stable, which does not suggest that RMCPs under the previously established pricing model will improve.



Note. Prices reflect historical nominal price data up to April 2012. Beyond April 2012, data reflect EIA Short-Term Energy Outlook projections (EIA, 2012c).

Figure 23. Natural Gas Spot Prices

2. Frequency Regulation Costs

Battery degradation is the major cost associated with the provision of V2G FR, followed by costs incurred by energy losses resulting from energy exchange and aggregator service fees. It is currently unknown what a reasonable aggregator service fee will be, but likely it will be a percent of revenue. I estimate the service fee to range from 10% to 60% of revenue. Any energy processed beyond that which would be used to normally power and recharge the vehicle for mobility use is considered additional energy throughput and subject to premature battery degradation costs. It is not necessary to account for net energy supplied or consumed because it is assumed that the locational marginal pricing (LMP) of energy supplied and purchased is the same, and, therefore, the gross cost of net energy flow would net to zero when the transaction was reconciled. There is no “free charging,” as other research suggests (see Tomic & Kempton, 2007). Vehicles that gain a net charge while participating in FR pay for any net electricity drawn from the grid at the LMP, just as they would for normal charging (A. Brooks, personal communication, May 12, 2012). This leaves energy losses due to efficiency unaccounted for because these are sunk costs when participating in A/S and are not reimbursed by the utility. Therefore, the only energy exchange costs accounted for, aside from degradation, are those arising from energy lost in the transfer of energy due to system inefficiencies. Costs for both efficiency losses and degradation vary by level of V2G and are discussed in further detail in Section VII.B.

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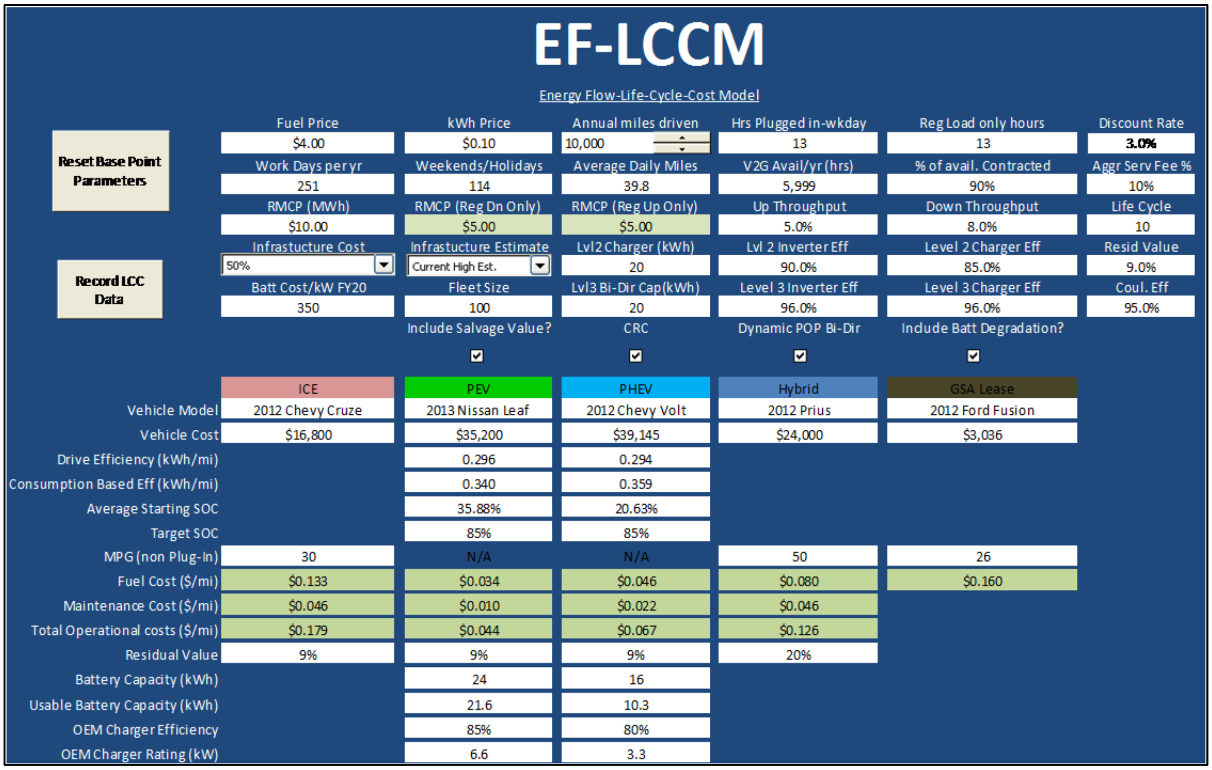
VI. MODEL

The EF–LCCM used in this research is a deterministic spreadsheet model that quantifies LCCs for federal vehicle fleets across a range of traditional and alternative vehicles options. The unique aspect of this model is its ability to incorporate a comprehensive assessment of PEDV LCCs in the presence of V2G FR revenue streams through detailed energy flow and revenue modeling.

The model enumerates through various levels of V2G integration and their related LCC components to evaluate and compare the economic strength of each level under various parameters. Ultimately, I compare each level of V2G using a discounted D-SIR to determine whether the savings generated by FR revenue and lower operating costs can justify the greater vehicle cost of a PEDV and the additional investment of a V2G infrastructure compared to other fleet vehicle options.

A. CONTROL PANEL INPUTS

Figure 24 is a depiction of the EF–LCCM control panel, followed by a brief description of relevant inputs.



EF-LCCM

Energy Flow-Life-Cycle-Cost Model

Fuel Price	kWh Price	Annual miles driven	Hrs Plugged in-wkday	Reg Load only hours	Discount Rate
$4.00	$0.10	10,000	13	13	3.0%
Work Days per yr	Weekends/Holidays	Average Daily Miles	V2G Avail/yr (hrs)	% of avail. Contracted	Aggr Serv Fee %
251	114	39.8	5,999	90%	10%
RMCP (MWh)	RMCP (Reg Dn Only)	RMCP (Reg Up Only)	Up Throughput	Down Throughput	Life Cycle
$10.00	$5.00	$5.00	5.0%	8.0%	10
Infrastucture Cost	Infrastucture Estimate	Lvl2 Charger (kWh)	Lvl 2 Inverter Eff	Level 2 Charger Eff	Resid Value
50%	Current High Est.	20	90.0%	85.0%	9.0%
Batt Cost/kW FY20	Fleet Size	Lvl3 Bi-Dir Cap(kWh)	Level 3 Inverter Eff	Level 3 Charger Eff	Coul. Eff
350	100	20	96.0%	96.0%	95.0%
	Include Salvage Value?	CRC	Dynamic POP Bi-Dir	Include Batt Degradation?	
	☑	☑	☑	☑	

	ICE	PEV	PHEV	Hybrid	GSA Lease
Vehicle Model	2012 Chevy Cruze	2013 Nissan Leaf	2012 Chevy Volt	2012 Prius	2012 Ford Fusion
Vehicle Cost	$16,800	$35,200	$39,145	$24,000	$3,036
Drive Efficiency (kWh/mi)		0.296	0.294		
Consumption Based Eff (kWh/mi)		0.340	0.359		
Average Starting SOC		35.88%	20.63%		
Target SOC		85%	85%		
MPG (non Plug-In)	30	N/A	N/A	50	26
Fuel Cost ($/mi)	$0.133	$0.034	$0.046	$0.080	$0.160
Maintenance Cost ($/mi)	$0.046	$0.010	$0.022	$0.046	
Total Operational costs ($/mi)	$0.179	$0.044	$0.067	$0.126	
Residual Value	9%	9%	9%	20%	
Battery Capacity (kWh)		24	16		
Usable Battery Capacity (kWh)		21.6	10.3		
OEM Charger Efficiency		85%	80%		
OEM Charger Rating (kW)		6.6	3.3		

Figure 24. Energy Flow–Life-Cycle Cost Model Control Panel

- Fuel Price

  Fuel cost is set at $4.00/gallon in the base case and applies to the ICE and the HEV. The GSA lease vehicle has a set mileage rate, which includes the cost of fuel and is not dynamically linked to the model's fuel cost. For this reason, fuel cost sensitivities for the GSA lease are limited.

- Electricity Cost

  Electricity cost is the price per kWh billed to a federal installation. The cost of $0.10 is assumed to be representative of current prices, which reflects a bulk discount.

- Annual Miles

  Annual miles are the average miles driven by each vehicle in the fleet. Annual miles multiplied by the expected LCC of 10 years yields the total expected government use miles of 100,000.

- Average Daily Miles

  Average daily miles are the annual miles divided by the number of government use days.

- Work Days per Year

Work days per year are the total number of government use days, and this term refers to the number of days in the year less weekends and federal holidays.

- Weekends and Holidays

  This term refers to the number of non-government use days and consists of weekends and federal holidays. During these days it is assumed V2G FR availability is 24 hours per day.

- Daily V2G Availability

  Daily V2G availability includes the hours plugged-in each week day, the regulation-load-only hours, and V2G availability per year. The availability profile is based on assumed government usage: typically eight hours a day, Monday through Friday, and no federal holidays. “Regulation-load-only hours” represent the hours in a day that a PEDV is available to engage in the A/S of FR for unidirectional levels of V2G. “Hours plugged-in weekday” refers to bidirectional resources and determines the TOR during the week. Theoretically, TOR could be much longer over the course of a weekend for a bidirectional resource than on a week night. “V2G availability per year” is the theoretical maximum number of hours per year a government PEDV can perform FR.

- Percent of Availability Contracted for Frequency Regulation

  This is the ratio of hours the government fleet is contracted and paid to perform frequency by the ESP to the number of hours the government fleet is available.

- Projected Battery Replacement Cost

  The projected cost per kWh of capacity to replace a PEDV’s battery upon reaching 80% capacity fade.

- Fleet Size

  The quantity of PEDVs in the fleet to be modeled.

- Discount Rate

  The discount rate is used for discounted cash flows and net present value (NPV) calculations.

- Regulation Up

  This is the ratio of hourly energy processed from regulation up to capacity bid for regulation up.

- Regulation Down

  This is the ratio of hourly energy processed from regulation down to capacity bid for regulation down.

- Life-Cycle Infrastructure Cost

This pull-down list allows either 50% or 100% of the infrastructure cost to be included in the LCC calculations.

- Aggregate Service Fee

  This is the percentage of FR revenue that is deducted for the cost of an aggregator service.

- Charger Efficiency: OEM, Level 2, Level 3

  These are the charger efficiencies for the various levels over V2G used in the energy flow calculations.

- Inverter Efficiency: OEM, Level 2, Level 3

  This is similar to charger efficiency.

- Residual Value

  This refers to the PEDV’s resale value at the end of the government life cycle.

- Coulombic Efficiency

  This refers to the internal battery efficiency.

- RMCP

  This is the regulation market clearing price per MW of capacity.

- Dynamic Preferred Operating Point

  This is a selectable option and applies to bidirectional FR. The concept of preferred operating point (POP) is discussed in the literature (see Brooks, Lu, Reicher, Spirakis, & Weihl, 2010) and involves responding to a dispatch signal from a baseline output other than zero. This can be useful when the dispatch signal characteristics result in a net bias toward either regulation up or down. Selecting this option produces revenue calculations based on the assumption that the aggregator uses an advanced algorithm to adjust POP dynamically throughout the FR contract period to maintain SOC within acceptable limits and subsequently extends TOR for the entire vehicle availability.

- Battery Degradation

  This is a selectable option and applies to all levels of V2G FR. When selected, this option subtracts the cost of battery degradation from the gross revenue generated from FR.

- Capital Replacement Costs

  This is a selectable option. When selected, CRC costs are included in PEDV cash flows in Year 8.

- Vehicle MSRP

This is the manufacturer's suggested retail price for the commercially available vehicle used to represent the respective vehicle category. No government discount is assumed.

- Consumption or Meter-Based Efficiency (kWh/mile)

  This is the electricity consumed (kWh) at the meter to recharge a PEDV for a given number of miles traveled.

- Drive Efficiency (kWh/mile)

  This is the amount of energy consumed during constant discharge for vehicle propulsion.

- Starting SOC

  This is the expected SOC that a PEDV would begin V2G FR at the completion of the work day and derived from the average daily miles driven.

- Target SOC

  This is the desired SOC for a PEDV at the completion of unidirectional V2G FR or prior to the next work day for bidirectional V2G FR.

B. TYPES OF FREQUENCY REGULATION

My analysis does not make the assumption that V2G implicitly implies a bidirectional capability. Removing or reducing a load from the grid can have the same effect as the injection of real power into the grid (Brooks et al., 2010). When this is done in response to a signal from an ESP, the result can achieve the ancillary benefit of grid stabilization through frequency regulation. Vehicles equipped with a network integrated smart charger can offer both demand response and frequency regulation with unidirectional charging and no additional energy throughput by simply cycling charge on and off or modulating the rate of charge in response to a signal from a controlling authority. Thus, there is a scalability factor related to V2G integration from low-cost, basic charging infrastructure, virtually no vehicle modification, and unidirectional response capability to high-cost, Level 3 charging infrastructure, moderate vehicle modifications, and bidirectional response capability. The reminder of this chapter provides a description of the various types and levels of V2G FR that the EF–LCCM is capable of modeling to determine the level with the greatest revenue return for the investment under varying conditions.

1. Unidirectional Frequency Regulation—Load Response

Unidirectional FR is provided by cycling the charge rate in response to an FR dispatch signal. It can also be referred to as *load response* because it involves varying the electrical load on the grid based on grid demand. The benefit of unidirectional FR is that no additional throughput is experienced by the battery because the battery would need to be charged anyway after a drive cycle and only the delta of additional degradation from a higher cycle rate compared to normal charging needs to be accounted for. Unlike bidirectional FR, however, unidirectional FR relies on a partial discharged battery, meaning the vehicle must be used earlier in the day to be available for unidirectional FR later. Also, unidirectional FR revenue is directly related to TOR, which is limited by an hourly AGC throughput rate. A higher throughput rate causes the battery to reach full charge faster and reduce TOR, which reduces revenue.

Depending on the throughput parameters of the dispatch signal, a POP can also be used when performing unidirectional FR. Implementation of a POP is particularly useful when the throughput level is too low to ensure that the vehicle reaches the target SOC before the FR contract period or prior to the next transportation use. The EF–LCCM auto calculates a static POP based on expected hourly throughput and the FR capacity relative to the level of V2G integration to bring the PEDV to the target SOC by the end of the contract period. If throughput is high enough that the vehicle reaches the desired SOC at or prior to the end of the contract period, the POP is zero.

a. OEM Level 2: Regulation Down

OEM Level 2 uses the OEM-equipped charger capacity for both PEDVs (PHEV = 3.3 kW, PEV = 6.6 kW) and the associated infrastructure costs to model FR revenue and net LCC.

b. High-Capacity Level 2: Regulation Down

High-capacity Level 2 uses a higher capacity Level 2 charger (9 kW in the base case) and the associated infrastructure costs to model FR revenue and net LCC.

c. Symmetric Regulation Up and Down—Load Only

POP can also be used during unidirectional FR to perform bidirectional response because removing a load can be perceived by the grid in a way similar to injecting additional power. A POP set below the nominal set point of zero can provide regulation up by reducing charge as much as zero. For example, a vehicle equipped with a 10-kW charger performing FR with a POP set to 5 kW could theoretically bid into the FR market for bidirectional response with a 5-kW capacity for regulation up and 5-kW capacity for regulation down. A negative POP usually results in a vehicle reaching a full SOC charge relatively quickly, thus having a lower TOR despite earning a higher payment per hour (RMCP for both regulation up and down versus just regulation down) and, subsequently, a lower net revenue. Therefore, the following analysis focuses on the other levels of unidirectional V2G.

2. Bidirectional Frequency Regulation

Bidirectional V2G FR involves both injecting and withdrawing power from the grid in response to an AGC dispatch signal and earns typically twice the gross revenue per hour as unidirectional V2G for a given capacity (except in the case of symmetric unidirectional as described in Section V.B.1.c). For bidirectional V2G, POP is considered slightly differently. In this case, POP is assumed to adjust throughout the contract period via an advanced algorithm, which dynamically shifts the nominal set point, thereby maintaining an SOC within an acceptable range in order to extend TOR indefinitely. Implementing a dynamic POP also assumes that gross capacity remains stable while regulation up and down capacities are shifted in the interim change periods, which maximizes TOR and consequently gross revenue. Without using dynamic POP for bidirectional V2G, the battery will eventually either be depleted or reach a full charge, depending on the dispatch signal bias. It is highly unlikely for the regulation up and down signals to exactly offset the battery’s SOC swing resulting in no net charge.

Because bidirectional FR response may result in the battery’s SOC at the end of the contract period being less than necessary to complete its daily transportation requirement, weekday availability for bidirectional V2G is reduced by one hour. This hour allows for time to bring the PEDV to its target SOC prior to the start of the use day and is considered reasonable due to Level 3’s high rate of charge capability; however, this final charge hour also reduces revenue by reducing TOR by one hour.

a. Level 2

Bidirectional FR and its associated costs and revenue are modeled using a 9-kW, Level 2 bidirectional capacity, along with associated capital and infrastructure costs.

b. Level 3

This is similar to Level 2 but considers a 12-kW bidirectional capacity and higher associated charger/inverter efficiency levels.

VII. ANALYSIS

Because a fleet of PEDVs are required to achieve the necessary capacity to bid into the A/S market, I construct this analysis and the comparisons to follow using LCCs associated with a fleet of 100 vehicles from each category.[16] LCCs are derived from a 10-year life-cycle projection with an average annual mileage of 10,000 miles per vehicle. This mileage is consistent with the average annual mileage of a passenger vehicle across all government agencies, which was 10,077 in 2010 (DoE, 2010). Because the vehicle life cycle for government fleet use is projected to be 10 years and the life cycle of the charging infrastructure is assumed to be 20 years, only 50% of the "high-current" infrastructure costs are included in the base point parameters. Table 7 summarizes some of the base point parameters used for all initial comparisons. See Figure 24 for a more complete list of parameters.

Table 7. Life-Cycle Cost Base Point Parameters

Fuel Price ($/gal)	Electricity Price ($/kWh)	Annual miles driven/vehicle	Fleet Size	Discount Rate	Batt Cost/kW FY20	Infrastucture Cost
$4.00	$0.10	10,000	100	3.00%	$350.00	50%

Per the FEMP LCC handbook (Fuller & Peterson, 1995), when comparing mutually exclusive alternatives, net savings (Equation 11) should be used to determine whether an alternative is cost effective.

$$Net\ Savings = LCC_{Base\ Case} - LCC_{Alternative} \tag{11}$$

Therefore, net savings will be the primary metric of determination. However, because fleets could choose a composition of the vehicles considered in this analysis, the metrics of SIR ratio and discounted payback (DPB) are given for added consideration where appropriate. Figures referring to LCCs represent the fleet as a whole unless otherwise noted. However, because the quantity and time parameters used are primarily factors of 10, individual LCCs and LCCs/mile can be computed at a glance. For example, referencing

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[16] New regulations and changes to ESP business practices that occurred in 2012 reduced the minimum aggregate capacity requirement, which could result in ancillary market participation by PEV fleets as small as 10 vehicles.

Table 9, one can quickly see that the LCC per mile for a Chevy Cruze (ICE) using the base point parameters is \$0.31/mile compared to that of the Volt (PHEV) at \$0.43/mile.

A. BASE CASE: ALTERNATIVE VEHICLE ANALYSIS WITHOUT V2G INTEGRATION

The analysis begins with an economic assessment of how EDVs compare to the two ICE base cases ("ICE purchase" and "GSA lease") without the capital expenses or revenue associated with V2G. For illustrative purposes, Figure 25 shows the undiscounted constant dollar cash flows for the five vehicle categories without V2G revenue; however, discounted LCCs will be used for comparative analysis between alternatives. Year 1 includes all associated initial capital and first-year operating expenses, while Year 10 includes Year 10's operating expenses less the vehicle and used battery's projected salvage value (if applicable). Year 8 includes a one-time CRC for the PEV and PHEV that consists of a projected future cost (per kWh) of a replacement battery multiplied by the vehicle's battery capacity.

CRCs apply only to plug-in alternatives (PEVs and PHEVs) and in the base case, without V2G-associated battery degradation, these costs are generally offset by salvage value and have little impact on a PEDV's standing with respect to alternatives. Essentially, the CRCs are recovered from the combined salvage value of the old battery and the PEDV (now with a relatively fresh replacement battery). CRCs as a function of battery capacity in \$/kWh will have a greater impact on the comparative results when battery degradation from V2G participation is considered later in the analysis (see Subsections B and C). The HEV, on the other hand, represents a reliable and proven technology with a decade's worth of historical data contributing to high reliability ratings (J.D. Power, 2012). Therefore, no CRCs are a benefit to the HEV because it is assumed unlikely for an HEV to require a battery replacement during its government service life and because of the HEV's historically high salvage value (around 20% versus an ICE salvage value of about 9%).

There is no upfront capital cost associated with a GSA lease; as such, cash flows consist of a fixed lease payment and mileage rate (which covers fuel and maintenance); thus, the line representing these costs is linear. Again, because Figure 25 includes undiscounted cash flows, it is not to be used for comparative analysis but rather to gain insight into how variables such as battery replacement cost and salvage value can affect the slope of the cost curve before considering the comparative metric of discounted net savings.

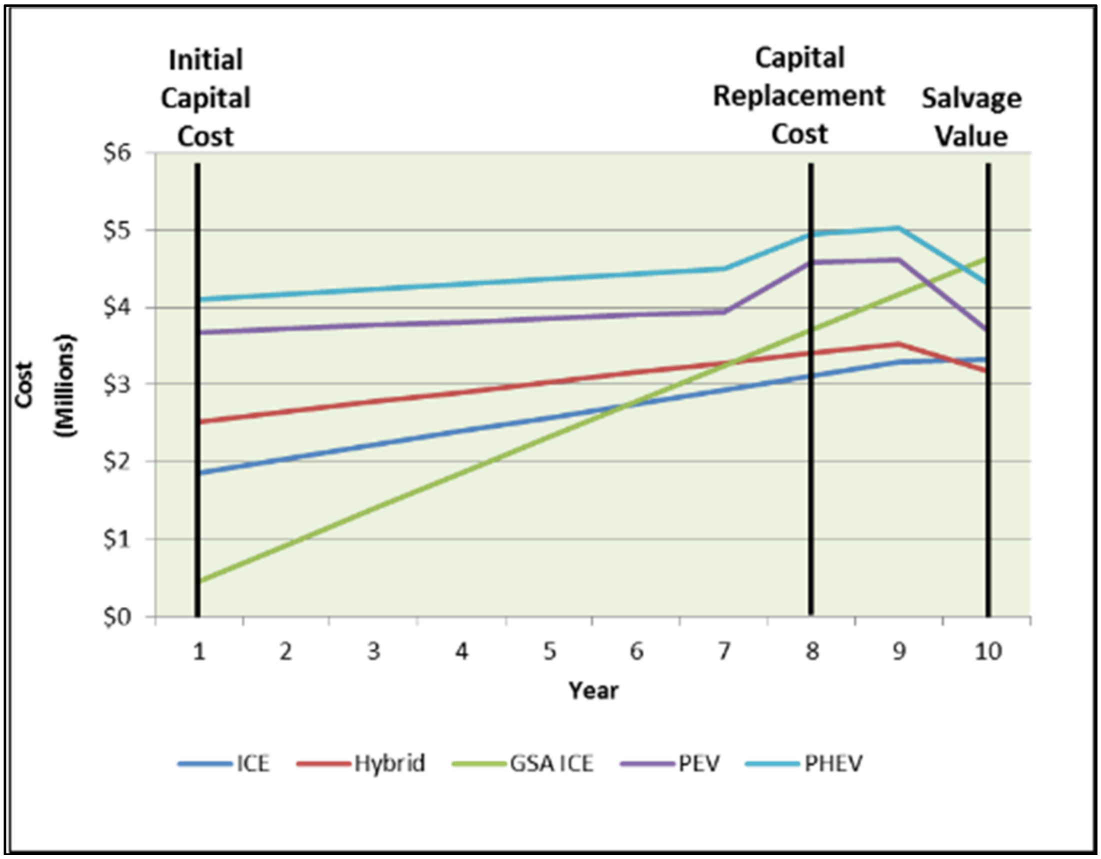


Figure 25. Undiscounted Cash Flow Diagram (No V2G)

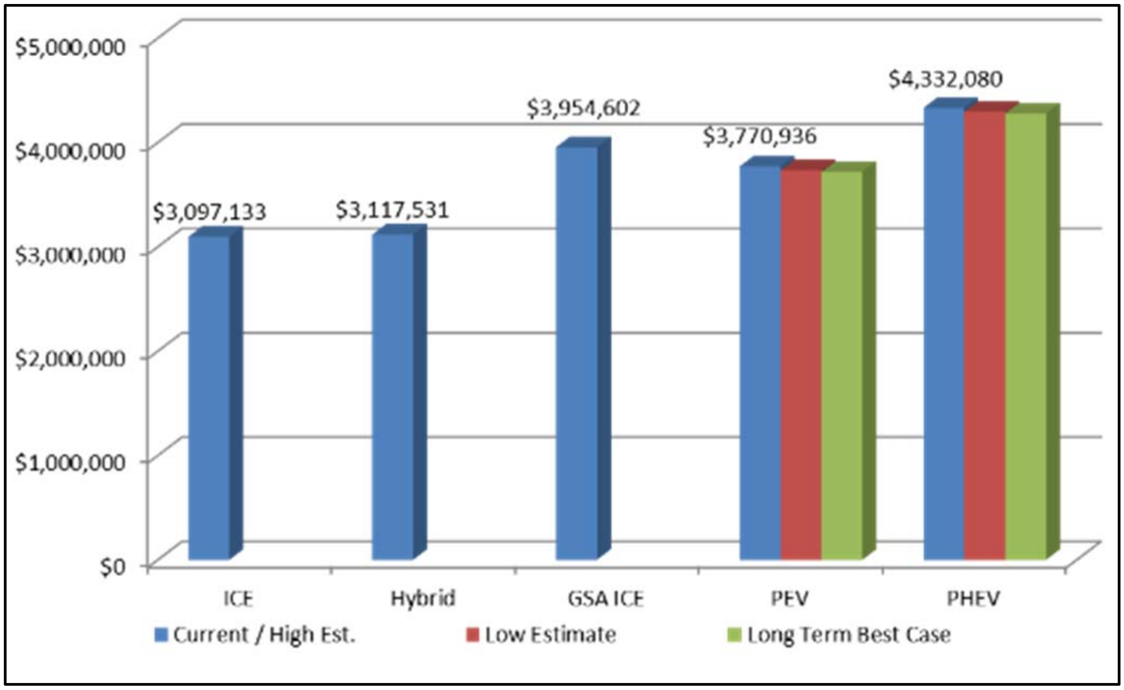
With a constant-dollar analysis, cash flows are generally stable year to year in the base case, consisting of mostly maintenance and fuel costs with the exception of Years 8 and 10 as described earlier in this section. For an alternative with higher upfront costs, economic justification must be made through sufficiently lower operational costs over the alternative's life cycle (Fuller & Peterson, 1995). Smaller slopes indicate lower annual operating and maintenance costs. A breakdown of these costs is shown for the respective vehicle categories in Table 8 using the base point parameters.

Table 8. Base Case Operating Costs

	ICE	PEV	PHEV	Hybrid	GSA Lease
Annual Maintenance per Vehicle	459.87	97.44	216.07	459.87	1,600.00
Annual Fuel per Vehicle	1,333.33	340.40	446.30	800.00	
Annual Lease per Vehicle					3,036.00
Total Operating Costs per Vehicle	**$1,793.21**	**$437.84**	**$662.37**	**$1,259.87**	**$4,636.00**
Annual Fleet Maintenance	45,987.18	9,743.59	21,606.54	45,987.18	160,000.00
Annual Fleet Fuel	133,333.33	34,040.40	44,630.29	80,000.00	
Annual Fleet Lease					303,600.00
Total Annual Fleet Operating Costs	**$179,320.51**	**$43,783.99**	**$66,236.83**	**$125,987.18**	**$463,600.00**

Note. The total annual operating costs associated with the GSA lease include the mileage rate as well as the lease payment (a recurring capital expense).

Figure 26 shows the discounted net LCCs with no V2G under the base point parameters. Three separate LCCs are given for the two PEDVs based on the high-current, low-current, and long-term, best-case infrastructure estimates. In the base case, the estimates for the PEDVs are noticeably less variable due to fewer ambiguities surrounding the costs associated with a basic charging infrastructure.



Note. The figures in the chart represent respective fleet LCCs under the base point parameters. PEDV alternatives are presented with high and low current estimates, as well as long-term, best-case estimates.

Figure 26. Base Case Discounted Life-Cycle Costs Comparison

1. Base Case 1: Internal Combustion Engine vs. Alternatives

Comparing the LCCs of the ICE (2012 Chevy Cruze) with those of the alternatives (see Table 9), one can see that although the HEV is very close, none of the alternatives have a lower LCC when using the base point parameters. I show, however, that this result is sensitive to many variables, including annual mileage, fuel price, and salvage value. Figure 27 displays the payback period for the alternatives by plotting the cumulative discounted annual savings in operating costs over the respective additional investment. A positive slope indicates net annual savings compared to the ICE, while a negative slope indicates higher comparative annual costs. It is rather easy to identify the trend and relative impact that CRCs (Year 8) and salvage value (Year 10) have on an alternatives' economic competitiveness. The HEV is able to regain 97% of its additional initial capital expense through lower operating costs and a higher salvage value, while the initial savings from the GSA ICE are continuously diminished until they fall below zero in Year 7. This result illustrates how the initial savings from leasing rather than purchasing are quickly reduced to zero and by the end of the 10-year life cycle, the GSA lease results in a 45% loss from what was initially saved. As for the plug-in alternatives, the savings from reduced O&M alone recoup only 65.6% and 47.5% for PEV and PHEV, respectively, and are therefore unable to achieve economic competitiveness with the ICE. See Subsection 3 for further sensitivities.

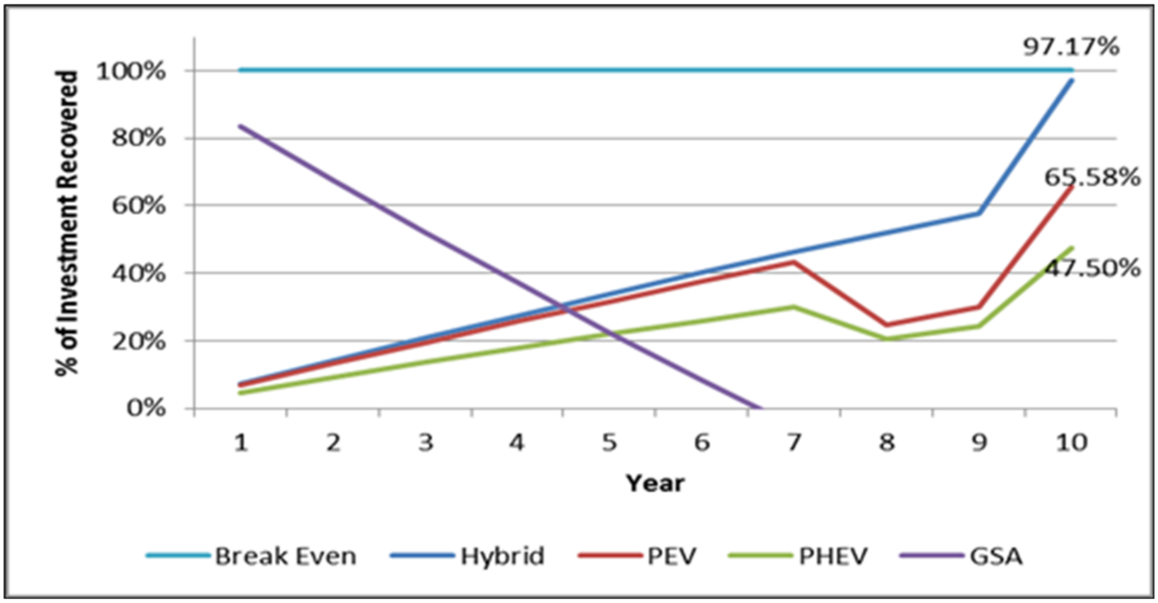


Figure 27. Break-Even Analysis (ICE)

2. Base Case 2: GSA Lease Internal Combustion Engine vs. Alternatives

The case for economic feasibility is met far more easily when alternatives are compared to the GSA lease base case. In this comparison, all alternatives except for the PHEV reach a break-even point within the payback period. Figure 28 shows the break-even point of the alternatives compared to the GSA lease and offers further evidence that a lower yet recurring capital expense (in the form of a lease payment) is more expensive over the life cycle in most cases than the higher one-time capital expense of ownership. The ICE reaches a break-even point in Year 6, followed by the HEV in Year 8 and the PEV in Year 10. In this comparison, the economic case for the ICE and HEV is strong because they are able to reach a break-even point well prior to the end of the payback period and without accounting for salvage value, whereas the PEV still depends on salvage value and the entire payback period. The PHEV comes close but by year 10 recoups only about 90% of its additional upfront cost.

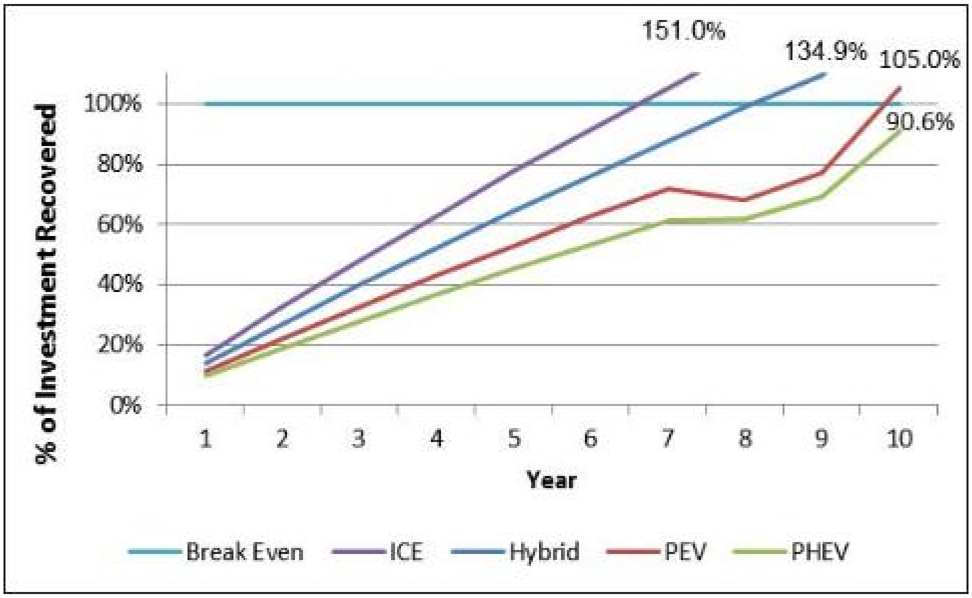


Figure 28. Break-Even Analysis (GSA Lease)

3. Sensitivity Analysis

My analysis of the two base cases indicates that the ICE is the most cost-effective option for a federal fleet of non-tactical passenger vehicles under the base point parameters. In this section, I examine this result further and show how economic competitiveness is sensitive to fuel price, annual mileage, salvage value, MSRP, and other variables.

Table 9 contains the LCCs of the various fleet options and illustrates how LCCs change relative to several parameters. Blue cells indicate when a PEDV fleet offers a lower LCC than the GSA base case, and green cells indicate the vehicle fleet with the lowest *overall* LCC. Fuel-cost comparisons between the GSA lease and alternatives do not continue past $4.00/gallon because GSA mileage rates at those fuel prices are currently unknown. However, because GSA mileage rates are certain to increase with rising fuel costs, the economic competiveness of alternatives would be expected only to improve.

Table 9. Base Case Sensitivities—Fleet Life-Cycle Costs

		Base Case - Gas Price Sensitivity				
		With Salvage Value				
	$3	$4	$5	$6	$7	$8
ICE	$2,812,793	$3,097,133	$3,381,473	$3,665,814	$3,950,154	$4,234,494
Hybrid	$2,946,927	$3,117,531	$3,288,135	$3,458,739	$3,629,343	$3,799,947
GSA	$3,954,602	$3,954,602				
PEV (High - Current)	$3,770,936	$3,770,936	$3,770,936	$3,770,936	$3,770,936	$3,770,936
PHEV (High - Current)	$4,304,068	$4,332,080	$4,360,091	$4,388,102	$4,416,114	$4,444,125

		Base Case - Gas Price Sensitivity				
		Without Salvage Value				
	$3	$4	$5	$6	$7	$8
ICE	$2,925,300	$3,209,640	$3,493,980	$3,778,321	$4,062,661	$4,347,001
Hybrid	$3,304,092	$3,474,696	$3,645,300	$3,815,904	$3,986,508	$4,157,112
GSA	$3,954,602	$3,954,602				
PEV (High - Current)	$4,674,375	$4,674,375	$4,674,375	$4,674,375	$4,674,375	$4,674,375
PHEV (High - Current)	$5,011,357	$5,039,368	$5,067,379	$5,095,391	$5,123,402	$5,151,413

		Base Case - Annual Mileage Sensitivity				
		With Salvage Value				
	7,500	10,000	12,500	15,000	17,500	20,000
ICE	$2,714,723	$3,097,133	$3,479,543	$3,861,954	$4,244,364	$4,626,774
Hybrid	$2,848,857	$3,117,531	$3,386,205	$3,654,879	$3,923,553	$4,192,227
GSA	$3,613,394	$3,954,602	$4,295,810	$4,637,018	$4,978,226	$5,319,434
PEV (High - Current)	$3,677,564	$3,770,936	$3,864,308	$3,957,679	$4,051,051	$4,144,422
PHEV (High - Current)	$4,134,660	$4,332,080	$4,608,703	$4,885,326	$5,161,949	$5,438,572

		Base Case - Annual Mileage Sensitivity				
		Without Salvage Value				
	7,500	10,000	12,500	15,000	17,500	20,000
ICE	$2,827,230	$3,209,640	$3,592,050	$3,974,461	$4,356,871	$4,739,281
Hybrid	$3,206,022	$3,474,696	$3,743,370	$4,012,044	$4,280,718	$4,549,392
GSA	$3,613,394	$3,954,602	$4,295,810	$4,637,018	$4,978,226	$5,319,434
PEV (High - Current)	$4,581,004	$4,674,375	$4,767,747	$4,861,118	$4,954,490	$5,047,862
PHEV (High - Current)	$4,841,948	$5,039,368	$5,315,991	$5,592,614	$5,869,237	$6,145,860

a. Fuel Price

In the base case, the ICE maintains the lowest LCCs at fuel prices below $4.18. At prices higher than $4.18, the HEV becomes the preferred choice and remains so until fuel prices rise 96% to $7.83/gallon. At that point, a PEDV achieves the lowest LCC. These results illustrate how closely competitive the Hybrid is as an alternative and just how far away the current plug-in options are, absent other incentives. For the Hybrid, marginally higher fuel prices (~5%) allow its lower operating costs to overcome its greater initial cost, while the infrastructure and capital costs associated with plug-ins require substantially higher fuel prices for economic viability. It should be noted that the PHEV never attains the lowest LCC and does not compete with the ICE until fuel prices rise above $8.90/gallon.[17] This is, in part, due to the fact that LCCs of the PHEV are still correlated with petroleum prices but have no impact on the LCCs of the PEV. Hence, the PEV is able to achieve a net savings at a fuel price well below that of the PEDV.

Table 10 indicates the $/gallon that current fuel prices must rise to for cost competiveness of the respective alternative. Cells highlighted in green are highly competitive. The GSA mileage rate is held constant under the base point parameters, and thus, a break-even analysis is not performed here for the GSA lease because normally the mileage rate would rise with a rise in fuel prices. Even with the mileage rate held constant, alternatives remain competitive beyond $7/gallon; for the PHEV, however, the GSA mileage rate would need to rise from $0.16/mile to $0.21/mile for the PHEV to be a lower cost alternative to the GSA lease.

Table 10. Internal Combustion Engine—Break-Even Fuel Price

$/Gal	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE		$6.37	$8.91	$4.18	N/A

Unlike the PHEV, the price of petroleum has no direct effect on the LCC of the PEV because it is an all-electric vehicle (AEV). Nonetheless, the electricity costs for

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[17] All fuel prices cited reference the price of regular unleaded fuel; however, the Chevy Volt (PHEV) requires premium unleaded fuel. To account for the price of premium fuel, a 9% increase per gallon is included in all cost calculations pertaining to the PHEV.

both PEDVs are so small at $0.10/kW that sensitivities on electric rates are not significant enough to improve their economic case. All else held equal, even if the cost of electricity were reduced to zero, neither PEDV would be competitive with the ICE or HEV. The interesting price point for electricity occurs just over $0.30/kWh. At this point, it is more cost effective for the Volt to make its own electricity from its onboard petroleum-powered generator (at $4/gallon) than to recharge its battery with grid power. This scenario is possible in places like Hawaii where residential electricity rates can average as high as .44/kWh (State of Hawaii, Public Utilities Commission, 2012).[18] The PEV reaches fuel cost parity with the HEV when rates rise to $0.24/kWh and with the ICE to $0.39/kWh. These electricity cost thresholds are derived from the ICE's fuel cost of $0.13 per mile. Fuel costs per mile for all vehicles, under the base point parameters, are presented in Table 11.

Table 11. Fuel Cost per Mile in the Base Case

	ICE	PEV	PHEV	Hybrid	GSA Lease
($/mi)	$0.133	$0.034	$0.045	$0.080	$0.160

Note. Fuel costs for all vehicle categories are constant regardless of annual miles, except for the PHEV. Fuel costs for the PHEV are calculated by using the cost per electric mile for the first 35 miles of average daily miles and the cost per petroleum mile for every mile thereafter. Thirty-five miles is the all-electric range for the Volt with a fully charged battery. The PHEV's average fuel cost per mile will increase as annual mileage increases. Cost shown represents fuel cost per mile at 10,000 miles per year (~40 miles per government use day).

b. Annual Mileage

LCCs increase for all vehicle categories as annual mileage increases; however, the rate at which these costs increase as a function of mileage differs. The comparative metric of operational cost per mile (composed of fuel and maintenance) is used to determine the impact of annual mileage on LCCs across the various vehicle categories. Vehicles with lower operating costs gain a comparative advantage as annual mileage increases. Thus, when comparing any two alternatives, the economic case is made stronger as annual mileage increases for the vehicle with the lower operational cost per mile. Petroleum-based vehicles have both higher fuel and higher maintenance costs per mile. Table 12 shows the breakdown of operational costs per mile for each category in the base case. The costs shown in Table 12

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[18] This high electricity cost also highlights the inefficiencies associated with a liquid petroleum-based electric utility because Hawaii generates the majority of its electricity by burning liquid petroleum.

remain stable for all vehicles (given that fuel costs remain stable) except the PHEV for which costs per mile generally increase as annual mileage increases.[19]

Table 12. Combined Fuel and Maintenance Cost per Mile

	ICE	PEV	PHEV	Hybrid	GSA Lease
($/mi)	$0.179	$0.044	$0.067	$0.126	$0.160

For demonstrational purposes, Figure 29 shows the undiscounted constant dollar impact of annual mileage on LCCs. Salvage value and CRCs are omitted in the annualized LCC calculations here to illustrate the comparative impact of changing annual operating costs on LCCs relative to annual mileage. The comparison begins at 5,000 miles per year and initially displays an unambiguous hierarchy for LCC comparisons, with the ICE and PHEV the clear winner and loser, respectively. The PEV has the greatest comparative advantage because it has the smallest slope, and despite being one of the most expensive vehicles, it becomes the least expensive as annual mileage increases. The ICE has the lowest competitive advantage in terms of operational cost per mile, but due to its low initial capital cost, it maintains the strongest economic position over a wide mileage range.

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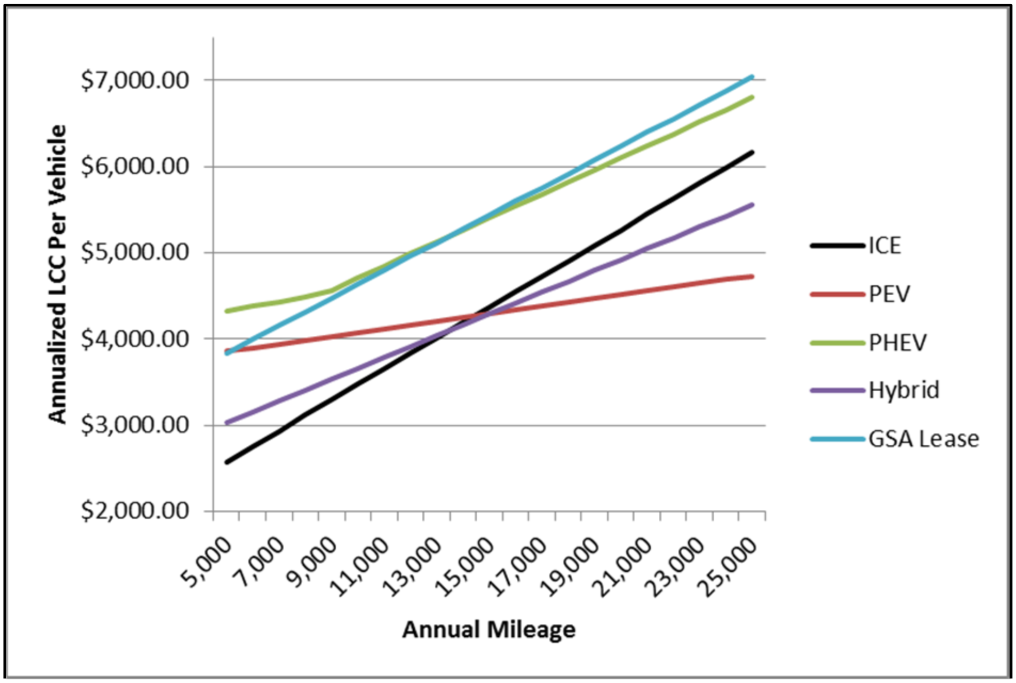
[19] This assumes that average daily miles driven occur from a single charge and that all miles beyond the Volt's rated AER of 35 miles are gas powered. Multiple recharges throughout the daily use period could offset this result and cause actual cost to be less. However, this is more likely in a personal commuter-use scenario, rather than a government use scenario.



Note. The annualized LCC calculations in this chart omit CRCs and salvage value to isolate the impact of operating costs of each vehicle category on overall LCCs.

Figure 29. Non-Discounted Annualized Life-Cycle Costs per Vehicle

Figure 29 also identifies two significant mileage points at 8,800 and 16,000 annual miles.

For the PHEV, economic competiveness decreases as annual mileage increases. The point at which the slope of the PHEV annualized LCC curve becomes nonlinear and begins to lose its comparative advantage is 8,800 annual miles. When annual mileage is greater than 8,800, the average daily mileage per government use day becomes greater than the PHEV's AER of 35 miles. Consequently, the operational cost per mile continually increases from a low of $0.057 per mile at 8,800 miles to a high of $0.111 per mile at 25,000 annual miles and asymptotically approaches $0.14 per mile thereafter as more petroleum-powered miles per day are required. As a result, the break-even point where the PHEV reaches LCC parity with the ICE occurs beyond 45,000 annual miles (see Table 13). This inconvenient connection of increasing operating costs per mile as annual mileage increases is compounded by the fact that the PHEV requires premium unleaded fuel and prevents the PHEV from realistically obtaining a lower LCC than any other category except the GSA ICE.

At approximately 16,000 annual miles, three LCC curves intersect, indicating LCC parity among the ICE, HEV, and PEV. The break-even point for comparison with the ICE can be considered as 16,000 annual miles. As annual mileage continues to increase, the economic case for the HEV and PEV becomes even stronger. Again, the principles in Figure 29 hold for this analysis and serve to demonstrate the relationship between annual mileage and LCC, but the specific LCCs depicted in Figure 28 are non-discounted and do not include salvage value or CRC. Discounted LCCs are used henceforth (unless otherwise noted) for comparative analysis in order to establish annual mileage break-even points under various circumstances.

Table 13 indicates the required annual mileage per vehicle necessary to reach LCC parity with the two ICE base cases. Cells highlighted in green indicate a strongly competitive alternative to the respective base case and N/A indicates that net savings are obtained even at zero miles per year. Annual mileage specified indicates a break-even point, beyond which lower LCCs, and consequently net savings, are achieved for the respective vehicle category.

Table 13. Annual Mileage Break-Even Analysis—Base Point Parameters

Annual Miles	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE		15,825	> 45,000	10,450	>60,000
GSA	N/A	8,150	32,150	N/A	

Because fuel cost per mile has a majority share in total operational cost per mile, fuel price and annual mileage are closely correlated and impact the LCCs of the ICE and HEV in a similar manner.[20] As such, annual mileage follows a similar pattern to the fuel price sensitivity analysis in the base case where a marginal increase of just over 450 additional miles per vehicle per year (~5%) is necessary to make the Hybrid the lowest LCC option. The PEV, on the other hand, requires almost double the annual mileage to become the preferred option overall at 19,400 miles (see Table 9). However, significantly fewer

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[20] The GSA lease, although an ICE, is omitted here because it has a fixed operational cost per mile.

annual miles, at 15,825, are needed for the PEV to obtain a net savings from the ICE base case (Table 13).

Table 14. Annual Mileage Break-Even Analysis—Without Salvage Value or Capital Replacement Costs

Annual Miles	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE		16,925	> 50,000	15,850	>55,000
GSA	N/A	10,575	> 45,000	N/A	

Table 14 presents the same scenario used in Figure 29 but uses discounted LCC figures for the break-even calculation and is thus usable for comparative analysis. Assuming no battery replacement costs for the PEDVs and no residual value across all categories makes for a difficult case against the ICE. An increase of annual mileage greater than 50% is necessary for the closest alternatives to achieve economic competitiveness with the ICE. Despite a less optimistic scenario for GSA alternatives, the economic case against the GSA lease remains fairly convincing for all except the PHEV.

Table 15. Annual Mileage Break-Even Analysis—Without Salvage Value but With Capital Replacement Costs

Annual Miles	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE		22,675	> 60,000	15,850	>60,000
GSA	N/A	17,275	>60,000	N/A	

Table 15 shows the results of including battery replacement costs while omitting salvage value. This results in the least favorable scenario for all alternatives to the base cases. Even so, the ICE and Hybrid remain solid alternatives to the GSA lease base case. Because CRCs are not considered for the Hybrid, its break-even mileage against the ICE remains unchanged from Table 14. Table 15 indicates an approximate break-even mileage for the PEV of 22,675. It should be noted that ideal conditions are required for the PEV to achieve annual mileage much greater than this on a single charge per government use day.[21] Beyond 25,000 miles, the PEV would require multiple charges within a government use day, which may be less practical or realistic under such high-use scenarios for most government purposes.

The scenario presented in Table 16 surprisingly does not present the most optimistic case for the PEDVs and actually results in a slightly higher break-even mileage for the two plug-in options. This is consistent with why LCCs are actually lower when both salvage value and CRCs are included in the analysis. Despite the additional outlay of CRCs, CRCs lead to a higher salvage value, in part by offering an additional resource to be salvaged (the old battery) and result in a higher net residual value. See Chapter V for further explanation. Results remain unchanged for non-plug-ins from those of Table 13 for reasons previously mentioned.

Table 16. Annual Mileage Break-Even Analysis—With Salvage Value but Without Capital Replacement Costs

Annual Miles	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE		15,875	> 45,000	10,450	>60,000
GSA	N/A	8,200	32,300	N/A	

Table 17 indicates the number of annual miles necessary to reach a break-even point with the LCCs of the ICE in Base Case 1 relative to fuel price. Mileage in excess of that indicated in Table 17 results in a net savings compared to the base case. As one might expect, alternatives become more attractive as fuel prices rise, and subsequently fewer annual miles traveled are required for economic competiveness.

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[21] These conditions include a 99-mile all-electric range and 251 government use days per year.

Table 17. Annual Mileage—Internal Combustion Engine Break-Even Point vs. Fuel Price

ICE $/gal	$3.00	$3.50	$4.00	$4.50	$5.00	$5.50
Hybrid	13,930	11,950	10,450	9,275	8,360	7,600
GSA		N/A	62,000	33,300		
PEV	21,000	18,050	15,825	14,150	12,700	11,565
PHEV	59,000	52,400	46,600	41,350	36,550	32,175

c. Salvage Value

Referencing Table 9 again, one can see how the presence of salvage value impacts the LCCs of the comparison fleet relative to annual mileage and fuel cost. Interestingly, the economic case for the ICE is actually strengthened when salvage value is ignored, whereas alternatives to the ICE base case are heavily reliant, particularly the HEV, which benefits from approximately twice the net residual value of any other option (in terms of percentage relative to MSRP). The HEV is 33% more expensive than the ICE, yet, due in part to salvage value, recovers 97% of its additional cost in 10 years (using a D-SIR). Omitting salvage value from the LCC analysis, the Hybrid is only able to recoup 63% of its additional investment under BPPs, and 59% higher fuel prices or annual mileage use per vehicle is required to achieve lower LCCs. Salvage value also affects the viability of PEDVs; however, it is more impactful in terms of net savings when compared to the GSA lease as opposed to the ICE. For the presence of salvage value to create net savings for PEDVs compared to the ICE, substantially higher fuel prices and/or annual mileage over the base point parameters are required. Salvage value for each vehicle category is quantified in Table 18.

Table 18. Salvage Value

Salvage Value					
	ICE	PEV	PHEV	Hybrid	GSA Lease
Vehicle	$1,512.00	$9,468.00	$7,723.05	$4,800.00	$0.00
Battery	$0.00	$2,520.00	$1,680.00	$0.00	$0.00
Total Salvage	$1,512.00	$11,988.00	$9,403.05	$4,800.00	$0.00
CRCs	$0.00	($8,400.00)	($5,600.00)	$0.00	$0.00
Net Residual Value ($)	$1,512.00	$3,588.00	$3,803.05	$4,800.00	$0.00
Net Residual Value (%)	9.0%	10.2%	9.7%	20.0%	0.0%

d. Capital Replacement Costs

An interesting result from this analysis is that a battery replacement before the end of a PEDV's government service life resulting in the aforementioned CRCs may actually reduce the LCCs of the PEDVs. This at first may seem counterintuitive and overly optimistic, but when battery replacement is not accounted for, there remains only a PEDV to salvage: more specifically, a PEDV with a 10-year-old battery that is presumably near its EOL for electric drive propulsion. On the other hand, with CRCs, now the prospect includes both a PEDV (with a relatively fresh battery), along with the additional economic benefit obtained from salvaging the old battery on the second-use market. Three assumptions take place here: (1) CRC results from a complete battery replacement in Year 8; (2) 75% of the battery replacement cost is recovered from obtaining a higher vehicle salvage value; and (3) the old battery sells for 30% of the projected future battery replacement cost. These assumptions may again seem specific and optimistic, but in the end, what is important is the net salvage value compared to the alternatives. In this case, even with CRCs and the aforementioned assumptions, net salvage values for the PEDVs are around 10%. Considering historic salvage values for the ICE and HEV at 9% and 20%, respectively, 10% is rather reasonable.

e. Battery Cost

CRCs exist only for the PEDVs and rely primarily on the projected cost of the vehicle's traction battery. There is a significant element of uncertainly related to future battery costs, and even if the price per kilowatt were reduced to zero, the case for PEDVs does not improve enough to change their position relative to other alternatives. Thus, no further sensitivity analysis is conducted in the base case, and future battery costs are held at the projected rate of $350 per kilowatt. The variability of future battery costs becomes more relevant as it pertains to battery degradation from V2G FR and, thus, further sensitivities are not explored here.

f. Internal Combustion Engine Fuel Economy

To understand the impact of fuel economy on the ICE's economic competitiveness compared to the other vehicle categories, I first conduct a break-even analysis to identify the minimum MPG rating for an ICE to remain LCC competitive with an alternative. I then conduct a sensitivity analysis by varying the MPG rating of the ICE to determine how the ROI of an alternative's greater initial cost changes.

Under base point parameters, the ICE has a fuel economy rating of 30 MPG, which helps earn it the lowest LCCs of any category. Table 19 illustrates the strength of this position, relative to fuel economy, by indicating the minimum MPG rating of the ICE to maintain LCC competitiveness with the respective alternative. As shown in Table 19, the ICE can afford only a minimal decrease in MPG to maintain LCC parity with the HEV, but it could suffer as much as a 52% decrease in MPG rating and not lose its LCC advantage to the most expensive alternative, the PHEV.

Table 19. Internal Combustion Engine Miles-per-Gallon Break-Even Analysis

Alternative	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE MPG	30	18.8	14.3	29.5	17
Change in MPG	(0)	(11.2)	(15.7)	(.5)	(13)
% Change in MPG	(0%)	(37%)	(52%)	(1.6%)	(43%)

Advancements in technology have led to increased efficiency ratings over the years, and it is likely that Detroit has not squeezed the last mile out of a gallon of gas for passenger vehicles. Continued improvements in efficiency will keep the ICE competitive (given that fuel prices remain relatively stable) even as improved technology helps the cost of alternative vehicles decline. Table 20 shows the ROI of additional capital costs recovered over a fleet's life cycle relative to an ICE with the respective fuel economy rating. For example, all else being equal, the PHEV, the least competitive option, would recover 95% of its additional capital expense if the ICE were to yield only 15 MPG. On the other hand, the most competitive alternative, the HEV, would fail to recover even half of its additional capital expense if the ICE were to yield as much as 45 MPG. The base case uses the Chevy Cruze's fuel economy rating of 30 MPG. With all else held equal, an ICE fuel economy increase of just five MPG causes the most competitive alternative (HEV) to become significantly less attractive. All the alternatives follow the same trend where the difference in annual operating costs diminishes as ICE MPG increases. The spectrum of 15–45 MPG represents where fuel economy for a small to mid-size passenger car has come from and where it might be heading. The free market will naturally continue to put pressure on both competing technologies: the ICE for better efficiency and PEDVs for more competitive pricing. The latter must occur at a faster rate in order for net savings to appear.

Table 20. Internal Combustion Engine Miles-per-Gallon Sensitivity Analysis

ICE MPG	15	20	25	30	35	40	45
ROI							
HEV	255.13%	176.15%	128.76%	97.17%	74.60%	57.68%	44.51%
PEV	123.68%	94.63%	77.20%	65.58%	57.28%	51.06%	46.22%
PHEV	95.42%	71.25%	56.74%	47.07%	40.16%	34.98%	30.95%
GSA	23.36%	-10.49%	-30.80%	-44.34%	-54.01%	-61.27%	-66.91%

Note. The MPG for the Hybrid and GSA ICE are held constant at 50 and 26 MPG, respectively.

g. Manufacturer's Suggested Retail Price

The final variable I examine in the economic case for alternative government passenger vehicle fleets is perhaps the most conspicuous, as well as the single largest contributor driving disparity between LCCs. Table 21 indicates, in order, the break-even MSRP for alternatives when compared to the respective base case, the difference from current MSRP, and the difference as a percentage. In the case of the GSA lease, the recurring capital expense of the annual lease is considered, rather than MSRP. All other costs under the base point parameters remain unchanged, including infrastructure costs for the PEDVs. Here the overall trend continues with the HEV remaining strongly competitive with the ICE and all categories, except the PHEV, competitive against the GSA lease. Figures with a parenthesis indicate that a reduction in MSRP is required, while figures proceeded by + represent alternatives that could withstand a price increase and still remain competitive.

Table 21. Manufacturer's Suggested Retail Price Break-Even Point

	ICE	PEV	PHEV	Hybrid	GSA Lease
ICE	MSRP delta % delta	$27,980 ($7,220) (21%)	$25,800 ($13,345) (34%)	$23,760 ($240) (1%)	$2,030 ($1,006) (33%)
GSA	$25,990 + $9,190 55%	$37,170 + $1,970 5.6%	$34,990 ($4,155) (11%)	$33,835 + $9,835 41%	MSRP delta %delta

Table 22 shows how the MSRP break-even point changes with respect to fuel price.

Table 22. Alternative Manufacturer's Suggested Retail Price Break-Even Point vs. Fuel Price

ICE $/gal	$3.00	$3.50	$4.00	$4.50	$5.00	$5.50
Hybrid	$22,420	$23,090	$23,760	$24,430	$25,100	$25,765
GSA		$1,864	$2,030	$2,198		
PEV	$24,930	$26,455	$27,980	$29,500	$31,025	$32,550
PHEV	$23,080	$24,440	$25,800	$27,160	$28,520	$29,880

h. Infrastructure

For certain government projects, it is not uncommon to neglect infrastructure costs in the cost analysis. Table 23 shows the impact of not including charging infrastructure in the LCCs of PEDV relative to fuel price. A higher break-even MSRP indicates a stronger economic case. Break-even MSRPs compare to the 2013 Nissan Leaf (PEV) and 2012 Chevy Volt (PHEV) MSRPs of $35,200 and $39,145 respectively.

Table 23. Manufacturer's Suggested Retail Price Break-Even Point With No Infrastructure Cost

ICE $/gal	$3.00	$3.50	$4.00	$4.50	$5.00	$5.50
PEV	$26,200	$27,710	$29,245	$30,780	$32,285	$33,810
PHEV	$24,345	$25,700	$27,065	$28,425	$29,780	$31,145

Table 24 shows the break-even MSRP with varying infrastructure costs, all else held constant under BPPs.

Table 24. Manufacturer's Suggested Retail Price Break-Even Point vs. Infrastructure Cost

Infrastructure Cost	None	Long Term	Current-Low	Current-High
PEV	$29,245	$27,840	$27,520	$26,720
PHEV	$27,065	$25,670	$25,350	$24,540

B. THROUGHPUT

Battery throughput has major implications to the viability of V2G. Batteries degrade over time, and degradation is a multivariate function, but one metric to quantify battery wear or degradation is throughput. Throughput is the amount of energy processed by a battery in a charge/discharge cycle. It is rather incontrovertible that a battery has a finite amount of throughput in its lifetime. In an experiment designed to quantify battery degradation defined by capacity fade, Peterson et al. (2010) demonstrated that "the strongest indicator of capacity fade . . . was the integrated capacity or energy processed regardless of depth of discharge," the DOD having formerly been considered the leading contributor used to quantify battery degradation. Capacity fade is the most relevant metric of battery degradation for PEDVs because, as previously stated, a battery typically needs at least 80% of its initial energy capacity to remain suitable for electric drive propulsion. If a substantial amount of additional throughput is incurred from V2G FR, it reduces a battery's overall lifespan faster than driving alone. For V2G to be economically viable, the economic benefit must be greater than the additional battery degradation incurred. In this thesis, I attempt to quantify throughput and associated battery degradation from V2G FR while incorporating the two into the economic evaluation of PEDVs and V2G.

1. Quantifying Throughput

Throughput, or more specifically, battery throughput, generally refers to round-trip energy processed. For example, assuming perfect efficiency and no regenerative breaking, if a PEV with a fully charged 24-kWh battery leaves its charging point, drives a specified distance discharging 20 kWh, and returns requiring 20 kWh of metered energy to fully recharge the battery, 20 kWh is both the throughput and the amount of energy or grid-supplied electricity consumed in kWh for the distance traveled. The actual energy processed during this cycle, however, is 40 kWh, the sum of the energy discharged from driving and returned to the battery in the charging process. Because of regenerative breaking, the amount of energy processed while driving is actually greater than the amount required to recharge the battery, and due to efficiency losses, the metered energy to recharge the battery is greater than the energy processed by the battery during recharging. Coulombic efficiency, which is the internal efficiency of the battery, must also be considered and is assumed to be 95%.

Similar differences in energy flow and energy processed occur from the energy exchange associated with bidirectional FR. A bidirectional FR resource following an AGC signal can provide either regulation up or regulation down by injecting or withdrawing power from the grid, depending on the polarity of the dispatch signal. In theory, with a fast-responding resource, such as a PEDV equipped with a bidirectional charger, the grid would perceive the exact amount of energy flow prescribed by the AGC signal relative to the contracted regulation capacity for a given period. Due to inefficiencies, the battery, on the other hand, would experience more energy processed during regulation up and less energy processed during regulation down. Even if the AGC signal netted to zero, there would be a net energy exchange differential observed by the battery. For example, an AGC signal over a two-hour period that consists of one hour of 100% regulation up and one hour of 100% regulation down would result in a net grid metered energy flow of zero. If a 10-kW bidirectional charger with perfect two-way efficiency was responding to the aforementioned signal, the battery would experience 20 kWh of energy processed, a net charge of zero, and

10 kWh of throughput. However, accounting for efficiency losses, the same battery would discharge 11.1 kWh and receive only 8.5 kWh, for a total of 19.6 kWh of energy processed directly from V2G, and 22.2 kWh as a result of V2G.[22] The economic implications of the above scenario to V2G are 2.6 kWh of electricity lost to efficiency and billed at the cost of electricity ($0.10/kWh) and 11.1 kWh of additional throughput expended.

Therefore, to accurately assess throughput and assign the appropriate degradation coefficient based on the "mode" of throughput, throughput is quantified in total energy processed and separated into five categories: driving, charging, regulation up, regulation down, and net regulation down. As in the case previously mentioned, the sum of energy processed during regulation up and down is not necessarily the cumulative throughput attributable to V2G. In the event of net regulation up, the energy processed necessary to bring the battery back to its starting SOC must also be accounted for and attributed to additional V2G throughput. Net regulation down has its own category because it results in a net charge. Presumably, the battery must be recharged eventually anyway; therefore, only the difference in degradation between normal charging and V2G FR is assigned via the appropriate degradation coefficient to the quantity of energy resulting in a net charge from FR. Section VII.B.3 will explore quantifying degradation in further detail.

To gain perspective on the quantitative assessment of throughput as it pertains to the additional burden V2G FR places on a battery, it is necessary to quantify expected lifetime throughput for a PEDV under normal driving conditions. This LCC analysis considers a 10-year vehicle life cycle and a usage rate equal to the GSA average of 10,000 mi/year for government passenger cars. This is close to the manufacturer's battery warranty period for the PEDVs modeled, eight years/100,000 miles. Calculating the normal throughput expected over the course of the OEM warranty period of 100,000 miles with an average drive efficiency of 0.29 kWh/mi, a PEDV would process a minimum of 63,586 kWh or approximately 31,793 kWh of throughput.[23] Ten thousand mi/year equates to 39.84 mi/government use day and results in 2,510 cycles over a 10-year life cycle at an

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[22] Figures assume charger efficiency of 85%, inverter efficiency of 90%, and throughput relative to a net zero energy flow cycle.

[23] This figure accounts for additional throughput while driving from regenerative breaking and internal battery inefficiency but does not account for charger inefficiency and, therefore, should not be considered the metered energy consumption over the warranty period.

approximate average DOD of 48% or average SOC swing of 52%. Assuming that the battery is the primary wear point for a PEDV (or at least the one with the greatest financial implications), the manufacturer's warranty gives us some indication of the battery's expected lifespan and is based on a mean time to failure (MTTF) or in this case an expected MTTF.[24] Presumably, the manufacturer's expected MTTF would be somewhat greater than the warranty period, which would put 2,500 cycles at the approximate low end of the possibility spectrum.

Peterson et al.'s (2010) analysis of empirical evidence suggests that newer Li-ion batteries might be capable of twice the expected throughput of a PEDV's warranty period. They predicted that newer Li-ion cells could be capable of 5,300 cycles at 95% DOD, which for the Nissan Leaf would equate to approximately 387,000 miles of repeated max-range trips before reaching 20% capacity fade. This prediction, however, is based on lab experiments absent the presence of time, temperature variations, and highly variable DOD cycles that would occur in reality, but it at least suggests that there is room for some quantity of additional throughput from FR participation over and above the throughput necessary to drive to the extent of the manufacturer's warranty period and government use life cycle.

2. Quantifying Throughput From Frequency Regulation

In order to quantify the cost of battery degradation from the performance of V2G FR, one must first quantify the expected additional throughput FR would demand. My research is unique in that I do not make the assumption that energy processed from FR nets to zero or that the dispatch signal would resemble the ACE, but I do assume a fleet of vehicles would respond to the same dispatch signal as traditional market participants and be reimbursed at the same rate. Therefore, I rely on data from actual AGC signals to determine the dispatch signal parameters and characteristics used to model V2G FR and its economic viability.

The sample set of AGC dispatch signal data I obtained from PJM consisted of 35 days spanning five different months and all four seasons. Figure 30 graphically depicts the AGC signal from one of these days.

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[24] MTTF is expected because empirical data do not exist yet with any significant sample size because production levels of the latest generation of Li-ion PEDV are relatively low and recent.

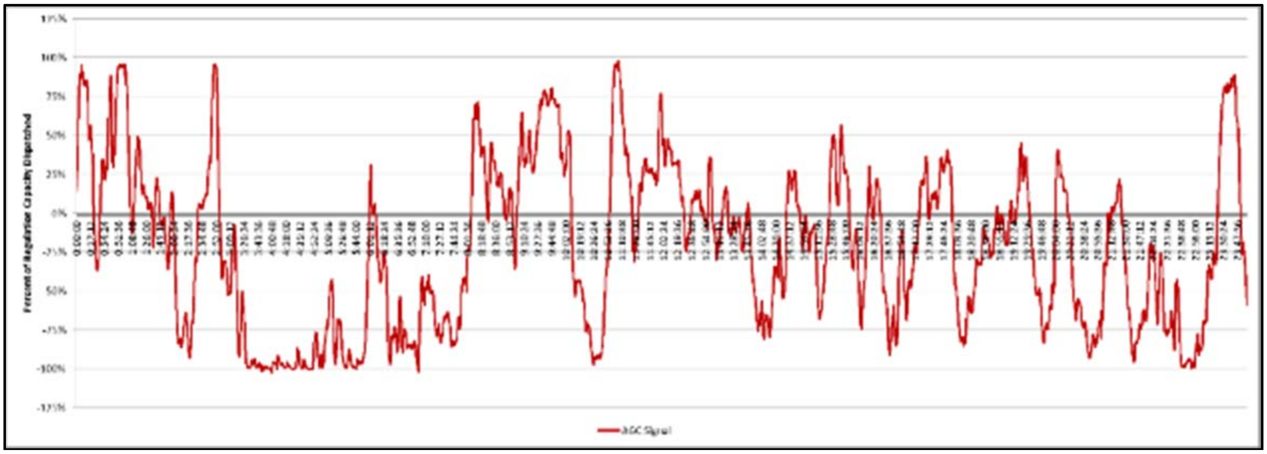


Figure 30. Example Automatic Generation Control Dispatch Signal

This particular day was chosen from the sample set because the cumulative statistics closely resemble the sample's mean parameters. The primary parameter of interest is the resulting integral of energy processed (or throughput) dependent on the capacity bid. In this case, the integral is based off a 20-kW bidirectional capacity bid and is computed separately for regulation up and down using Equations 12 and 13.

Regulation Up =

$$\sum_{i=0}^{t=900*TOR}\left(\frac{f(x_t)*Cap}{900}\right);f(x_i)=\begin{cases} s(x_i),\ s(x_i)>0 \\ 0,\ otherwise \end{cases} \tag{12}$$

Regulation Down =

$$\sum_{i=0}^{t=900*TOR}\left(\frac{f(x_i)*Cap}{900}\right);f(x_i)=\begin{cases} s(x_i),\ s(x_i)<0 \\ 0,\ otherwise \end{cases} \tag{13}$$

TOR – hours performing frequency regulation

Cap – frequency regulation capacity bid in kilowatts

s(x) – AGC dispatch (percent of capacity bid requested)

An AGC dispatch signal is sent every four seconds (900 per hour), and the polarity of the signal determines whether regulation up or down is requested. Figure 31 shows the integrals computed for a resource with a 20-kW capacity following the AGC signal in Figure 30.

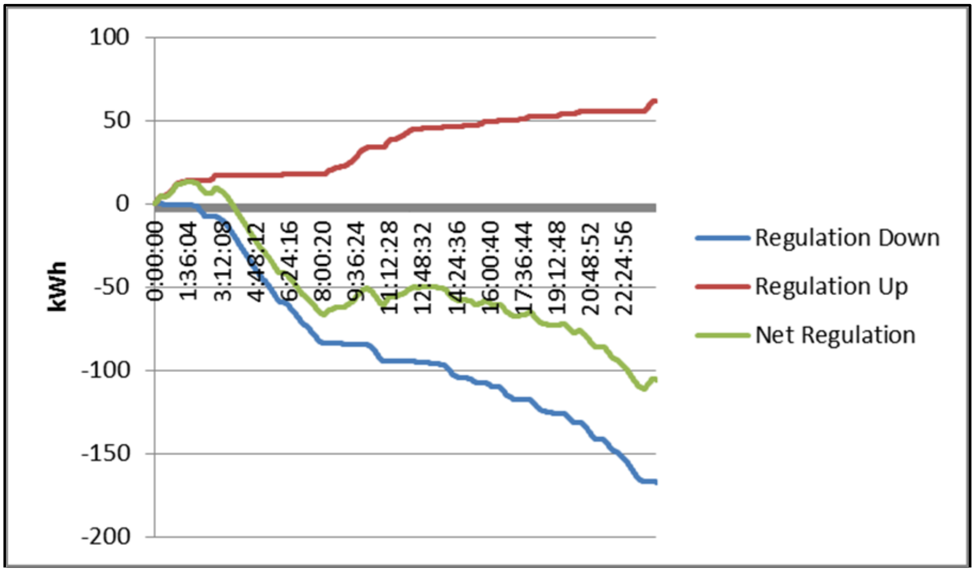


Figure 31. 24-Hour Cumulative Throughput From Automatic Generation Control Dispatch Signal

Net regulation is also shown here to display the signal's bias as it develops over time. In this case, the signal developed a significant bias toward regulation down throughout the day, which indicates a trend of over-generation by the ESP that would result in a net charge for a responding bidirectional resource without an offsetting POP.

The parameters from this sample day consist of an average hourly demand of 35% and 13% of capacity for regulation down and up, respectively. It becomes apparent under these conditions that a significant amount of additional throughput is demanded. In this example, a PEDV with a 20-kW bidirectional capacity following the dispatch signal for the 24-hour period would experience 234 kWh of additional throughput (accounting for charger/inverter/Coulombic inefficiencies). This kWh amount is approximately equal to the amount of energy processed by the Nissan leaf's battery during 361 miles of normal driving (including both charging and discharging) or in terms of time, 6.5 hours of driving at 55 mph. The hourly rate of throughput from this AGC signal is less than for driving, but over a 24-hour period, it amounts to more than 3.5 times the energy processed on a single drive cycle.

Although the intraday distribution of the AGC signal did not follow a published distribution, the average hourly integrated regulation up, regulation down, and signal bias were found to be normally distributed across the 35-day sample set. Thus, the average values for regulation up and down from the sample set serve as the input values for the EF–LCCM in the base case. Given a charger and inverter capacity or contracted FR capacity, these values can be used to predict expected throughput from FR and modeled to determine profitability in the presence of battery degradation. Figure 32 shows the histogram of bias from the sample set, which appears normally distributed, and Table 25 shows the descriptive statistics of the sample set. An average bias of zero would support the notion that the AGC signal would usually net to zero. Applying the One-Sample *t*-Test to the PJM AGC signal data with a significance level of .05 and 34 degrees of freedom, we reject the null hypothesis of $\mu = 0$. The data exhibit a bias of almost 3-1 in favor of regulation down and the 95% confidence interval for the signal bias is (-20.2,-12.9), which seems to invalidate the assumption that the dispatch signal nets to zero over time.

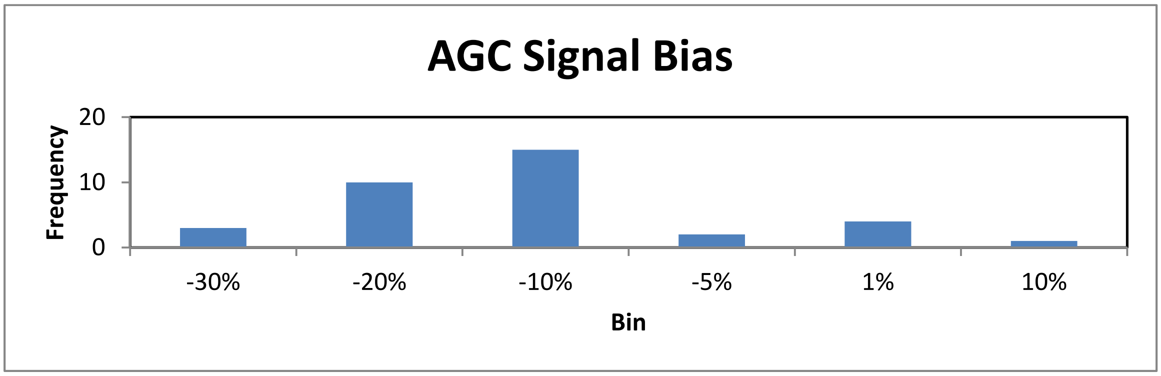


Figure 32. Histogram of Automatic Generation Control Signal Bias

Table 25. Automatic Generation Control Signal Sample Set Statistics

Regulation	Average	95% Confidence Interval	
UP	13.5%	11.7%	15.4%
Down	-30.1%	-27.8%	-32.3%
Bias	-16.6%	-20.2%	-12.9%
Total	43.6%	41.6%	45.6%

Figure 33 plots the daily ACE value with the corresponding AGC signal (displayed over a 12-hour period for greater fidelity). It is shown that the AGC does indeed generally flow opposite the ACE, but there are periods of lag where ACE and AGC share polarity. Additionally, the frequency with which the AGC changes polarity is far less than the ACE. This results in larger integrals of energy processed for a resource responding to an actual

AGC signal than one theoretically responding to the ACE, which makes the assumption of V2G throughput levels based on the ACE overly optimistic. However, as I will show in the sections to follow, throughput levels would need to be closer to that of the ACE for the economic feasibility of V2G FR.

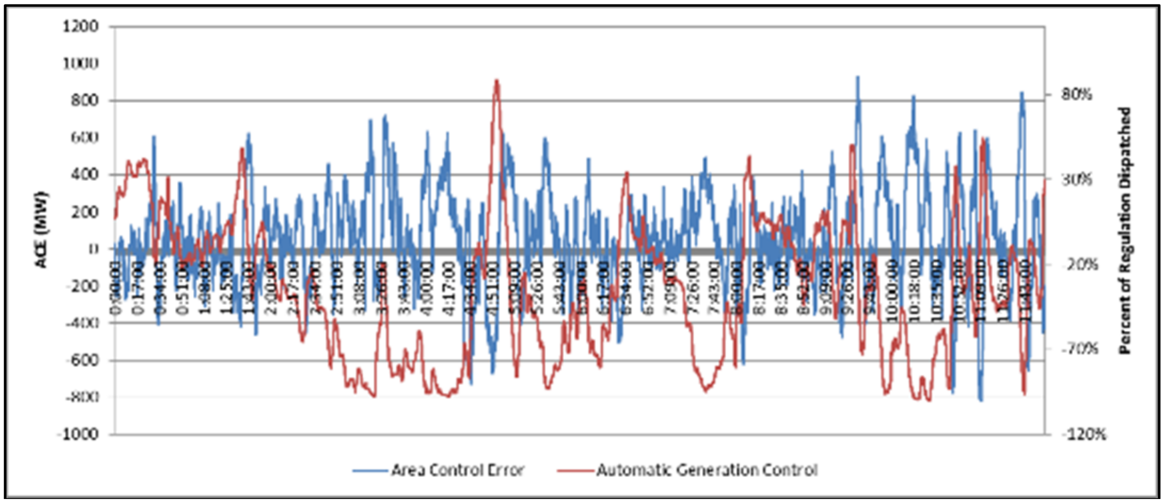


Figure 33. Area Control Error vs. Automatic Generation Control Signal

3. Quantifying Battery Degradation

The V2G concept far too optimistically overlooks battery degradation as a consequence of participation. Without considering realistic battery degradation, the true economic assessment of V2G FR cannot be evaluated. The EF–LCCM quantifies battery degradation using a modified version of the Peterson degradation model (Shiau et al., 2010) to predict lifetime V2G throughput in kWh of energy processed. The cost per kWh processed is then computed from a projected battery replacement cost of $350/kWh. Peterson et al. (2010) determined that battery degradation varies based on the “mode” of throughput; therefore, degradation is not computed as a constant per unit of energy processed. Rather, in order to properly assign degradation coefficients, degradation is calculated separately for driving, charging, regulation, and net regulation down.

Equation 14 is the Peterson degradation model from the literature (Shiau et al., 2010), which is formulated to quantify battery degradation from an average daily driving cycle. This model can be used to predict the expected lifetime mileage of a PEDV before the battery’s capacity degrades below 80% of original.

a. Peterson Degradation Model

$$\beta_{DRV} = \left(\frac{r_{EOL}}{r_D}\right) \tag{14}$$

$$r_D = \frac{[(\alpha_{DRV} * w_{DRV} + \alpha_{CHG} * w_{CHG})]}{\beta_{Cap}}$$

r_D – relative energy capacity decrease

r_{EOL} – relative energy capacity drop resulting in battery EOL = 20%

w_{DRV} – energy processed while driving (kWh)

w_{CHG} – energy processed while charging (kWh)

β_{Cap} – battery capacity (kWh)

β_{DRV}– battery lifetime (average driving cycles)

Degradation coefficients:

α_{DRV} – driving = 3.46 x 10-5

α_{CHG} – constant rate 1C charging = 1.72 x 10-5

Equation 15 is a generalized version of the Peterson degradation model that I modified and formulated to quantify battery degradation from V2G FR.

b. Battery Degradation From V2G Frequency Regulation Model

$$\mathrm{\beta_{V2G}} = \left(\frac{\mathrm{r_{EOL}}}{\mathrm{r_D}}\right) \tag{15}$$

$$r_D = \frac{\left[\left(e(w_i) * \alpha_{Reg} + \Delta w * d(\alpha_i)\right)\right]}{\beta_{Cap}};$$

$$e(w_i) = \begin{cases} w_{RegUp} + w_{RegDn}\,, & w_{RegUp} > w_{RegDn} \\ 2(w_{RegUp})\,, & otherwise \end{cases}$$

$$d(\alpha_i) = \begin{cases} \alpha_{CHG}\,, & w_{RegUp} > w_{RegDn} \\ \alpha_{NetRegDn}\,, & otherwise \end{cases}$$

r_D – relative energy capacity decrease

r_{EOL} – relative energy capacity drop resulting in battery EOL

w_{CHG} – energy processed while charging (kWh)

w_{RegUp} – energy processed per hour while performing regulation up (kWh)

w_{RegDn} – energy processed per hour while performing regulation down (kWh)

Δw – net energy processed from regulation—abs $(w_{RegUp} - w_{RegDn})$

β_{Cap} – battery capacity (kWh)

β_{V2G}– battery lifetime—hours of V2G

Degradation Coefficients:

α_{CHG} – constant rate 1C charging = 1.72 x 10^{-5}

α_{Reg} – V2G FR = 2.59 x 10^{-5}

$\alpha_{NetRegDn}$ – net regulation down = 8.75 x 10^{-6}

α_{ORegDn} – OEM capacity regulation down (unidirectional) = 4.375 x 10^{-6}

Some degradation coefficients are adjusted from those in the literature (see Peterson et al., 2010; Shiau et al., 2010) to more accurately reflect characteristics of charge and cycle rate per the mode in which energy is processed. From their analysis, Peterson et al. (2010) determined that “low rate constant discharge [was] associated with roughly half the degradation of the dynamic discharge” and concluded a “correction factor attributed to the kind of cycling encountered is [necessary]” (Peterson et al., 2010). Therefore, the throughput degradation coefficients I use are relative to the expected degree of cycling intensity.

From the modified model (Equation 15), the cost of degradation ranges depending on the level of FR response. For bidirectional FR, degradation is about $0.045 cents per kWh serviced or 0.09/kWh of roundtrip throughput. For OEM-level unidirectional FR, degradation is about $0.008 per kWh serviced. The cost of degradation per hour of FR serviced is perhaps the best metric and varies dependent upon throughput and bias. Figure 34 shows degradation cost as a ratio of gross V2G revenue. Less than 100% indicates profitability; therefore, lower ratios are preferred. There are two throughput levels given for presentation purposes: One was determined to be favorable for V2G, and the other represents the mean parameters from the sample set. Higher throughput results in higher cost-to-revenue ratios and, in the case of bidirectional FR, results in negative revenue. Level 3 FR achieves better results than Level 2 under these parameters because of higher equipment efficiency. Unidirectional V2G is always profitable here but yields a greater return with lower throughput and consequently longer durations of TOR.

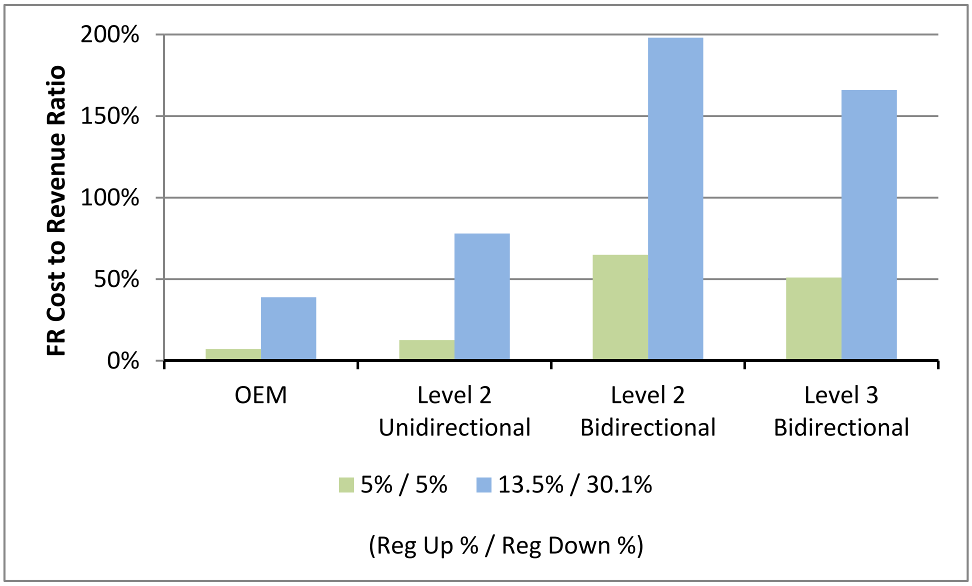
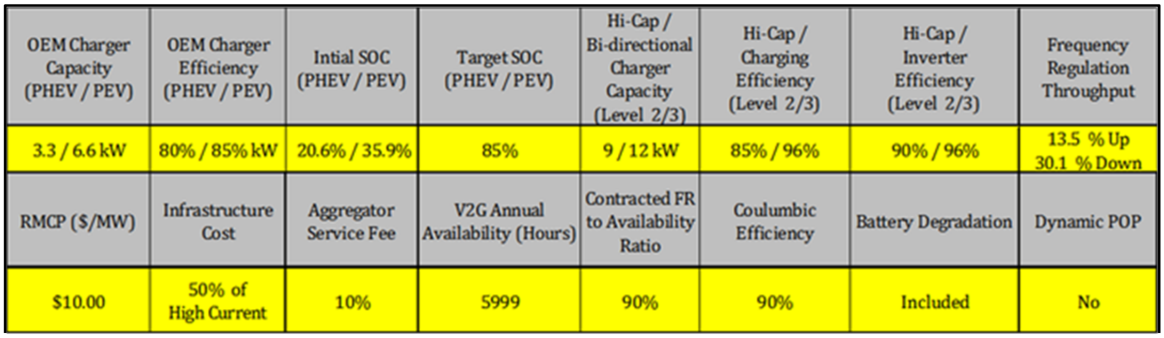


Figure 34. Throughput Effects on V2G's Cost-to-Revenue Ratio

C. V2G: FREQUENCY REGULATION

It is important to note that the performance of bidirectional FR relies on the existence of an appropriately discharged battery. Vehicles that go unused during the day and have a fully charged battery cannot conduct regulation down and can only conduct bidirectional regulation once they have supplied a sufficient amount of regulation up, resulting in a reduced SOC. Therefore, the underlying assumption accompanying this analysis is that vehicles are used daily and are available for FR after they are complete with transportation service for the government use day. Table 26 depicts the base point parameters for the V2G FR analysis. The initial SOC shown therein represents the estimated charge remaining after traveling the average daily miles.

Table 26. V2G Base Point Parameters



OEM Charger Capacity (PHEV / PEV)	OEM Charger Efficiency (PHEV / PEV)	Intial SOC (PHEV / PEV)	Target SOC (PHEV / PEV)	Hi-Cap / Bi-directional Charger Capacity (Level 2/3)	Hi-Cap / Charging Efficiency (Level 2/3)	Hi-Cap / Inverter Efficiency (Level 2/3)	Frequency Regulation Throughput
3.3 / 6.6 kW	80% / 85% kW	20.6% / 35.9%	85%	9 / 12 kW	85% / 96%	90% / 96%	13.5 % Up 30.1 % Down
RMCP ($/MW)	Infrastructure Cost	Aggregator Service Fee	V2G Annual Availability (Hours)	Contracted FR to Availability Ratio	Coulumbic Efficiency	Battery Degradation	Dynamic POP
$10.00	50% of High Current	10%	5999	90%	90%	Included	No

To gain a better understanding of the SOC swings that a PEDV would encounter while responding to an actual FR dispatch signal relative to battery size, regulation capacity, and throughput levels, I developed a simulation to model the battery's SOC while following an AGC dispatch signal. Figure 35 illustrates how a PEDV with an adequate battery-to-FR capacity ratio can respond to an AGC dispatch signal and maintain an SOC within an acceptable operating window. The primary vertical axis (left) indicates the battery SOC, as well as the percentage of contracted regulation capacity requested via the AGC signal incrementally throughout the day. The feasible range for a battery SOC is 0–100%. (Acceptable battery SOC range will vary based on manufacturer recommendations; I assume a feasible SOC between 5% and 95%.) The secondary vertical axis (right) indicates the efficiency losses resulting from bidirectional energy exchange. The red line indicates the battery's SOC resulting from bidirectional FR with a nominal operating point or POP of zero. Based on this sample signal, and a beginning SOC of 30%, a PEDV could provide approximately 21 hours of regulation before reaching its maximum SOC threshold of 95%. Using a small non-dynamic POP of + 0.75 kW (regulation up), TOR potential is extended into the next 24-hour period. On the other hand, providing unidirectional response would result in approximately seven hours of TOR. (A positive POP value does not apply to unidirectional FR; thus, the SOC plots for unidirectional SOC overlay and the green line is hidden under the light blue.)

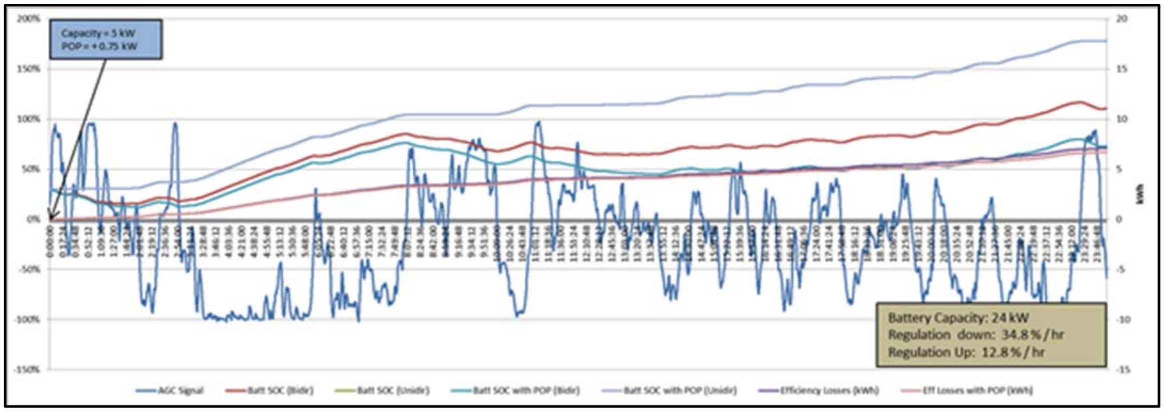


Figure 35. State of Charge Simulation—Low Capacity

Figure 36 shows the same signal with a much higher battery-to-FR capacity ratio. Here, SOC swings are far more erratic and rather unmanageable. Bidirectional FR without a POP falls below the SOC threshold within the first hour, and even a significant negative POP is unable to significantly increase TOR. At this FR capacity, unidirectional V2G without a POP has the longest TOR, at approximately 3 hours 45 minutes, and would yield the greatest revenue.

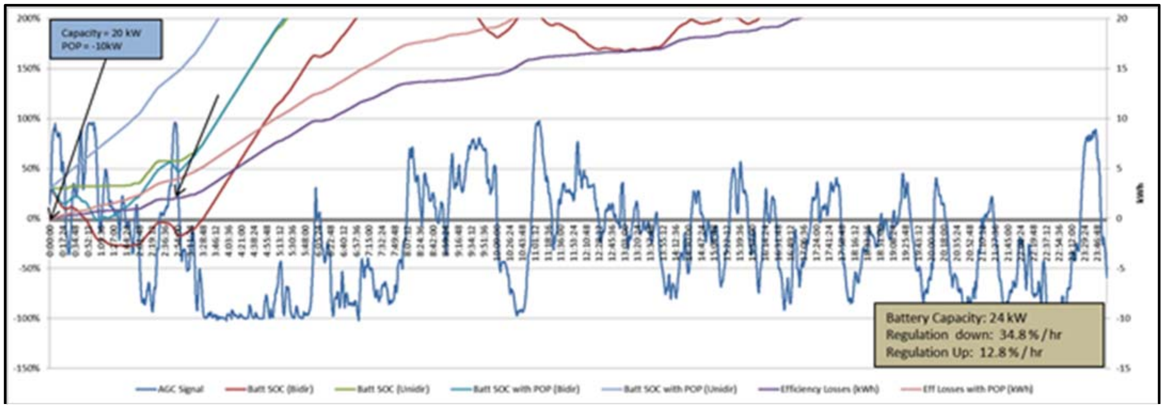


Figure 36. State of Charge Simulation—High Capacity

Figure 37 shows yet another SOC simulation, but in this case, the POP and capacity are dynamically adjusted for bidirectional FR. The blue box and arrow indicate the POP, the bidirectional capacity, and the time it is changed. Without a dynamic POP, the battery SOC rises beyond the threshold, at approximately 6 hours 45 minutes, but with a dynamic POP, SOC could potentially be maintained within acceptable limits indefinitely.

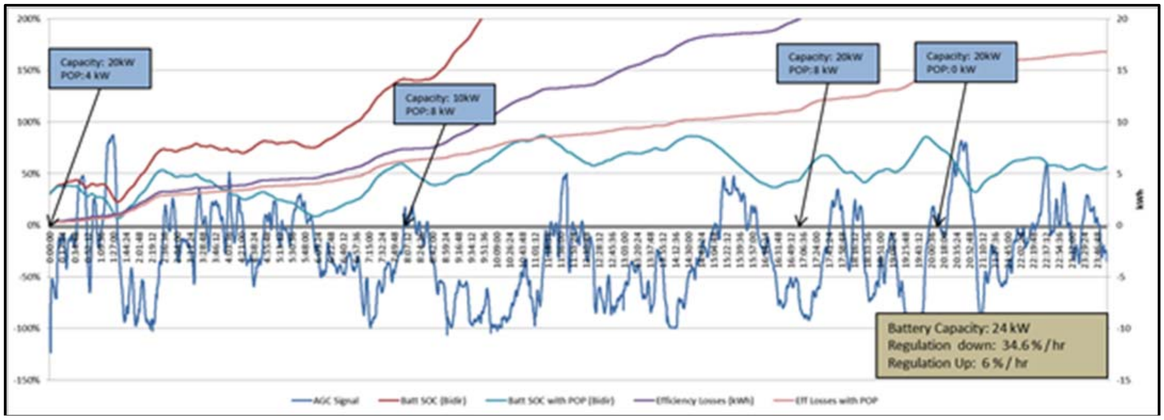


Figure 37. State of Charge Simulation—High Capacity With a Dynamic POP

From battery simulations of the sample AGC signal data, I found that by varying the capacity of the bidirectional charger, contracted capacity larger than 50–60% of the battery capacity is infeasible. Even with perfect information and a dynamic POP, the throughput levels in the sample AGC signal data make it difficult to maintain an SOC window within the feasible region for a 24-kWh battery paired with a 20-kW inverger. Figure 37 illustrates this challenge. Therefore, the LCC modeling and revenue estimates are derived using bidirectional charger capacities of 9 kW for Level 2 and 12 kW for Level 3. In some cases, because the Chevy Volt’s battery capacity is only 16 kWh, the FR revenue generated by the PHEV is considered optimistic.

Figure 38 indicates the percentage of additional investment recovered as a result of V2G FR under the V2G base point parameters. The additional investment is relative to the LCC of the ICE in the base case. Implementation of a low-capacity unidirectional V2G system using OEM equipment and a smart charger is the investment with the greatest return and results in slightly lower LCCs when compared to no V2G integration. This indicates that V2G, at the lowest level, at least pays for its own cost but has minimal economic impact on the case for PEDVs. Higher levels of V2G prove cost prohibitive due to greater initial capital costs, greater battery degradation from more throughput, and RMCPs that are unable to offset these costs. Under these conditions, the use of a dynamic POP only exacerbates the situation by resulting in even more throughput and associated degradation costs.

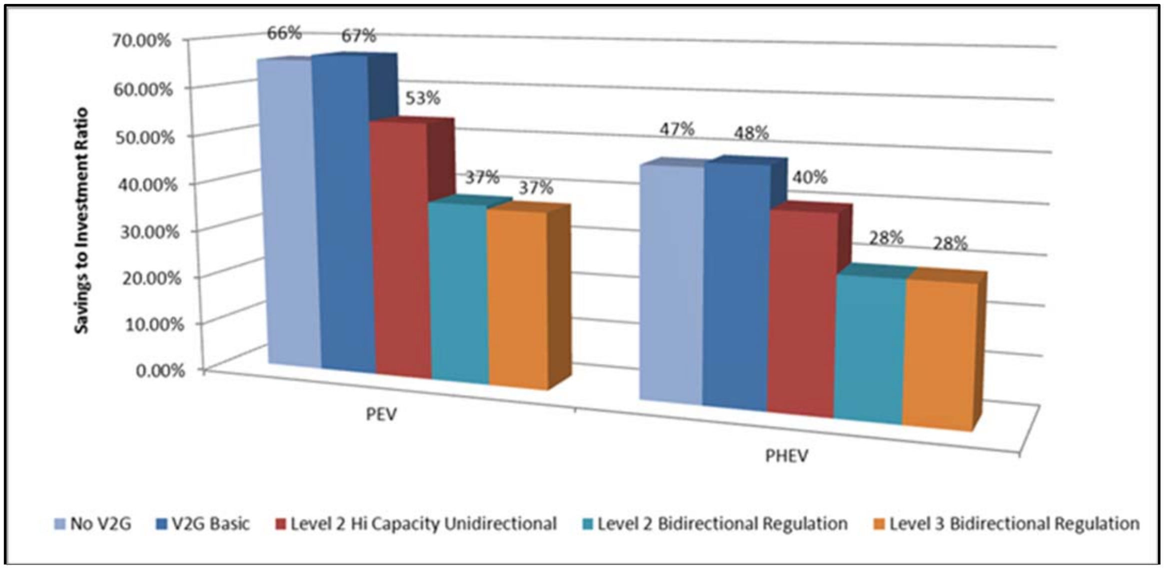


Figure 38. Vehicle-to-Grid Viability—Base Case

Figure 39 shows a highly optimistic scenario for V2G. Here, the long-term mature technology infrastructure cost estimate is used along with lower throughput (5% up/5% down), a dynamically adjusted POP, and an RMCP of $24.50. Under these parameters, the PEV is able to recover all of its additional investment from Level 3 bidirectional V2G FR revenue. The PHEV, on the other hand, is able to better its case by only 30% with V2G FR revenue and is still far from competitive with the ICE.

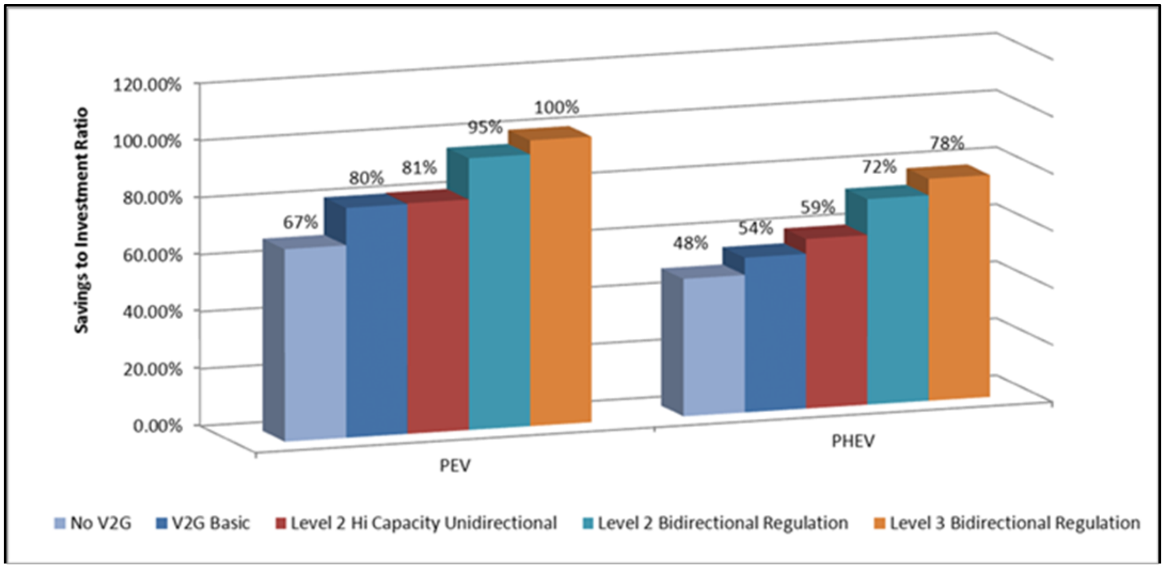
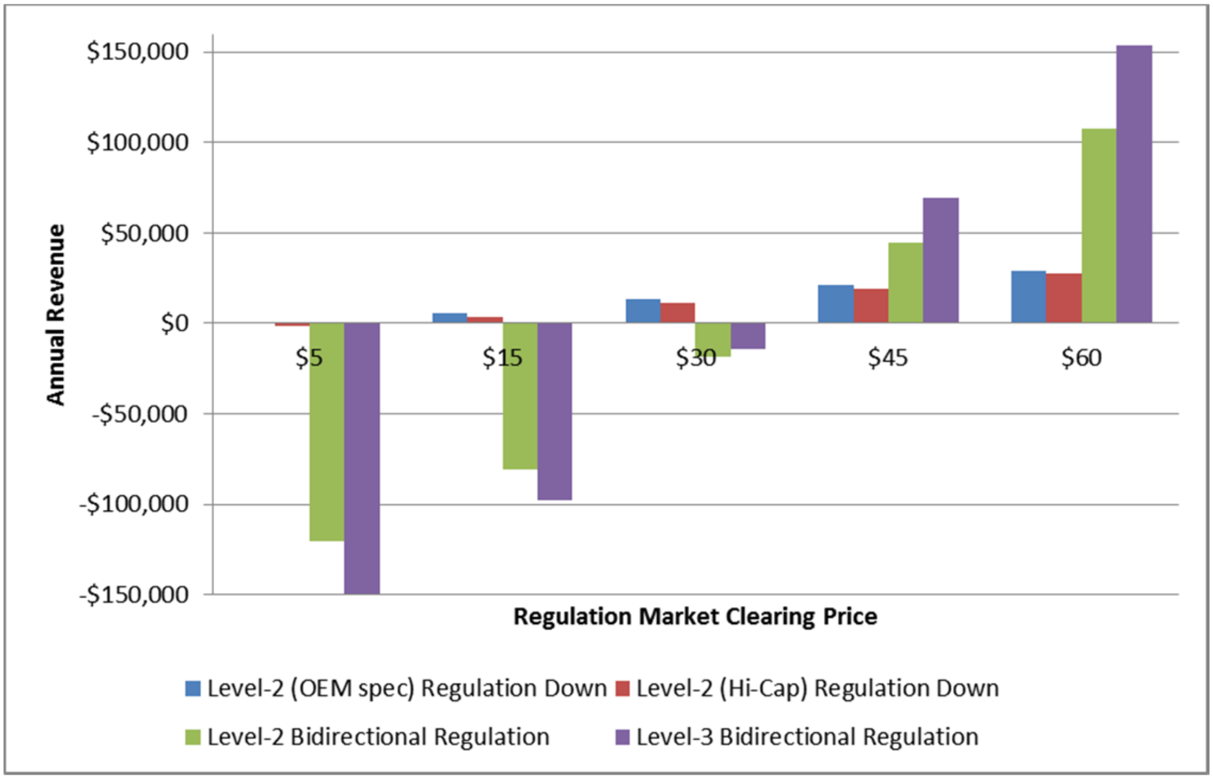


Figure 39. Vehicle-to-Grid Viability—Ideal Case

1. Sensitivities

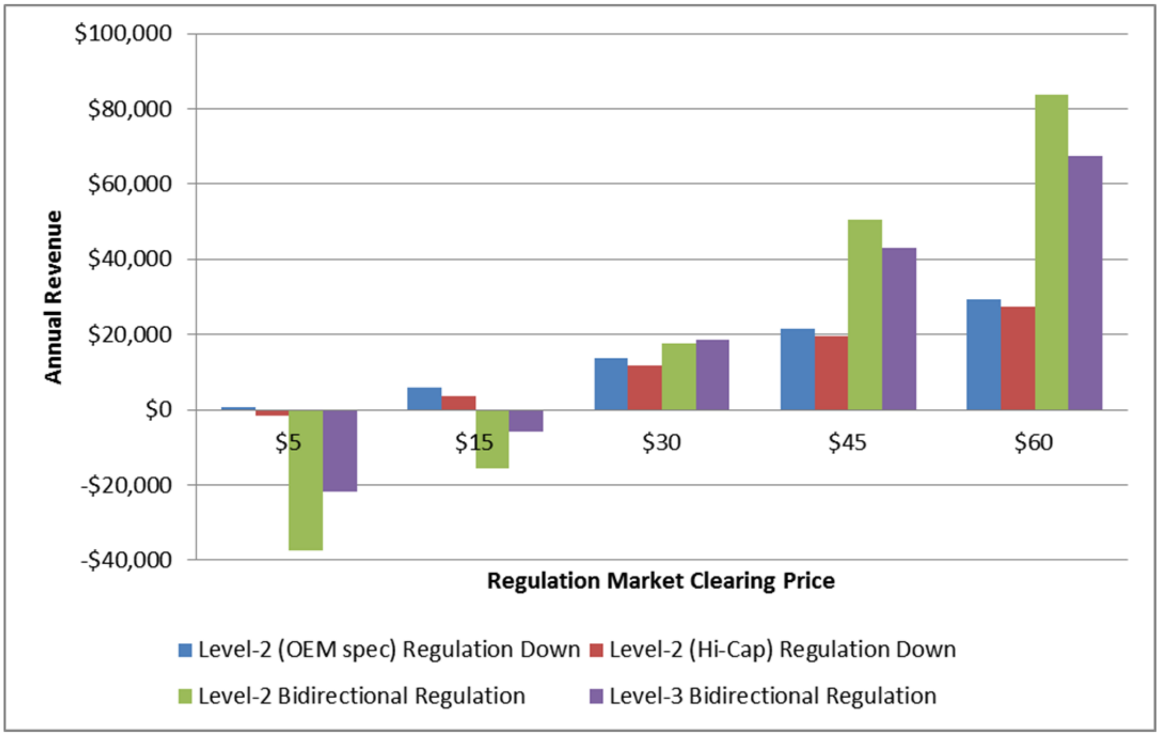
The following sensitivity analysis is limited to the most relevant variables for V2G viability: RMCP, infrastructure cost, throughput, and battery degradation.

Figures 40 and 41 illustrate V2G FR revenue potential at varying RMCPs with and without using an advanced algorithm to dynamically adjust a POP. If there is a regulation bias, a dynamic POP will increase throughput in an effort to maintain net zero energy flow. This increased throughput increases battery degradation, and subsequently, a higher RMCP is necessary for positive revenue. However, the use of a dynamic POP also allows for increased TOR. Thus, even though a dynamic POP requires a higher RMCP to achieve positive revenue, once this happens, greater revenue is obtained by using a dynamic POP rather than not using one. Under the base point parameters, positive revenue while using a dynamic POP occurs once RMCPs rise above $33/MW, whereas only $18.50 is necessary for positive revenue without a dynamic POP. In summary, using a dynamic POP, in theory, reduces the TOR limitations of V2G FR imposed by a battery's capacity and increases revenue potential, which results in greater net revenue (provided that net revenue is positive).



Note. Revenue based on a 100-car fleet.

Figure 40. Vehicle-to-Grid Frequency Regulation Revenue—PEV With a POP



Note. Revenue based on a 100-car fleet.

Figure 41. Vehicle-to-Grid Frequency Regulation Revenue—PEV Without a POP

Table 27 shows how RMCP and ROI are impacted by the range of infrastructure estimates for the respective level of V2G FR for both PEDVs. The columns in green indicate the RMCP at which 100% of the additional investment is recovered from FR revenue. The percentages in the respective row show the ROI for the various other levels of V2G at the indicated RMCP. Without the use of a POP, Level 2 bidirectional FR recovers its additional investment at a lower cost than other levels of V2G; however, when using a dynamic POP, Level 3 V2G has the strongest financial potential. Under the V2G base point parameters, RMCPs greater than $105/MW and $148/MW, which are 10 to 20 times current levels, are required for the PEV and the PHEV, respectively, to compete with the ICE. Using a real-time, dynamically adjusted POP, the break-even RMCPs reduce to $72/MW and $85/MW, respectively, which is still currently infeasible and makes the economic prospect of V2G FR in the presence of high throughput unviable. Additionally, base point parameters include only 50% of estimated infrastructure costs. Even if infrastructure costs are ignored altogether, break-even RMCPs remain well above current levels.

Table 27. Return on Investment and Regulation Market Clearing Price vs. Infrastructure Cost for Various Levels of Vehicle-to-Grid Frequency Regulation

Infrastructure Cost	PEV					PHEV				
No POP	No V2G	Level -2 (OEM)	Level - 2 (High Cap)	Level -2 (Bidir)	Level -3 (Bidir)	No V2G	Level -2 (OEM)	Level - 2 (High Cap)	Level -2 (Bidir)	Level -3 (Bidir)
High Current Est.	66%	88%	74%	$105.00	77.80%	47%	65%	55%	78%	60%
Low Current Est.	67%	85%	74%	$86.00	87.53%	48%	62%	55%	76%	66%
Mature Tech	67%	79%	76%	$60.00	85.66%	48%	58%	55%	73%	63%
None	70%	81%	81%	$52.00	95.03%	50%	59%	57%	72%	68%
With POP										
High Current Est.	66%	81%	65%	93%	$72.00	47%	59%	48%	76%	83%
Low Current Est.	67%	79%	69%	87%	$59.00	48%	57%	51%	69%	81%
Mature Tech	67%	77%	74%	94%	$51.00	48%	56%	54%	71%	77%
None	70%	80%	79%	89%	$44.50	50%	57%	56%	66%	75%

Note. ROI figures for the "No V2G" column are dependent only upon infrastructure cost and are independent of RMCP.

Figure 42 shows the impact of various throughput levels. Even under low throughput conditions, RMCPs must be substantially higher than current levels to reach a break-even point with traditional vehicles. Only when infrastructure is completely ignored and V2G charger/inverter capacity is increased from 12 kW to 20 kW with low levels of throughput does the RMCP breakeven enter the feasible region, at about $17.00. This cost, however, still remains greater than twice what current market conditions will bear.

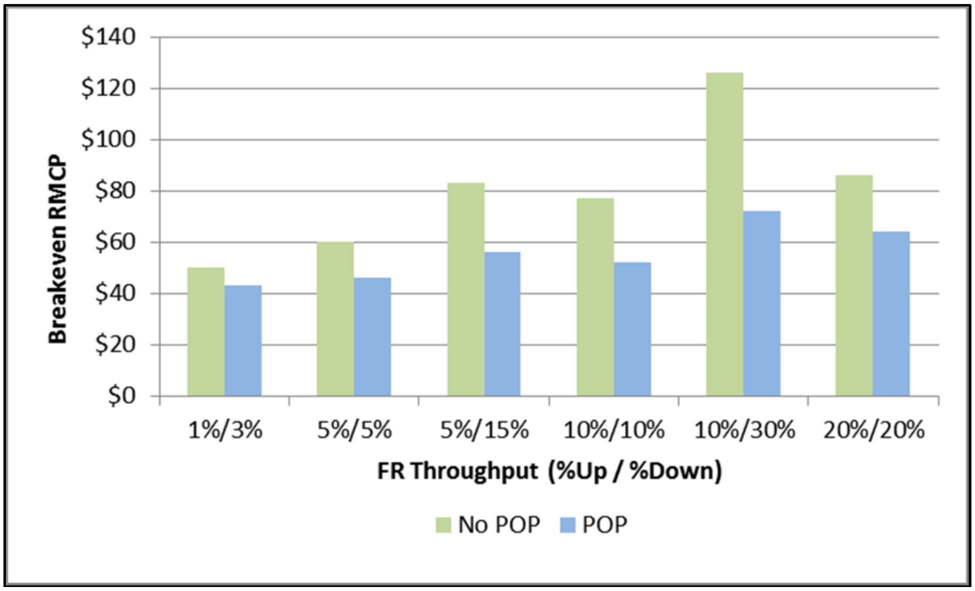


Figure 42. Break-Even Regulation Market Clearing Price Relative to Throughput

Figure 43 shows the impact of projected battery replacement costs under two throughput scenarios: a low of 5% symmetric and a high representative of the sample data of 13.5% regulation up and 30.1% regulation down. Because CRCs correlate directly with the cost of battery degradation, the impact of battery degradation can be explored by varying CRCs. Once again, however, even under the most optimistic scenarios, break-even RMCPs remain unrealistically high.

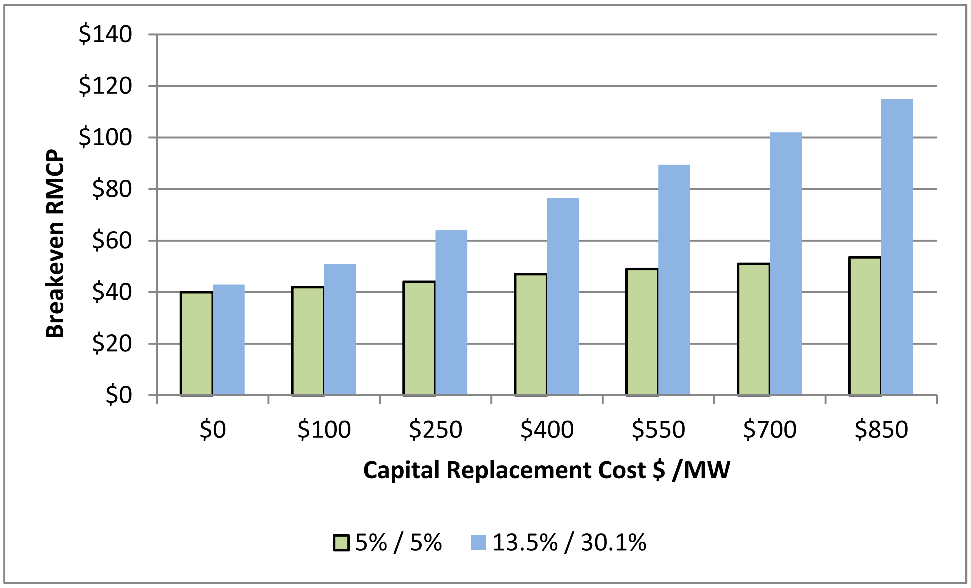


Figure 43. Battery Replacement Costs vs. Regulation Market Clearing Price Breakeven

2. Conditions for Vehicle-to-Grid Viability

a. Economic Viability

PEDVs are considered economically viable when the sum of their discounted net savings from lower operating costs and net V2G revenue recoup 100% of their higher initial capital cost over the base case. Current FR throughput levels require RMCPs to be unrealistically high for V2G FR revenue to provide the necessary economic incentive to propel PEDVs into competition with traditional ICEs. Under the base point parameters, an RMCP of over $100/MW is necessary for either PEDV to compete with the ICE. However, by adjusting the following parameters with all else under the base point parameters held constant, the break-even RMCP for the PEV is reduced to $24.50:

- infrastructure costs are reduced from high-current estimates to long-term, best-case estimates,
- throughput is reduced from 13.5% regulation up/30.1% regulation down to a symmetric 5%, and
- a dynamically adjusted POP is utilized for bidirectional FR.

These adjusted parameters are considered highly optimistic and result in a more reasonable RMCP; yet, the RMCP remains over twice that of current market prices. The PHEV, on the other hand, is unable to reach a competitive position under the aforementioned adjusted parameters and requires an even higher break-even RMCP of $36.50. The PEV has the advantage of a larger battery capacity and lower MSRP, which results in the lower break-even RMCP.

b. Meeting Expected Service Life While Engaging in Vehicle-to-Grid Frequency Regulation

In addition to the economic viability of V2G, it is also important to address viability as it pertains to expected vehicle service life. Total lifetime battery throughput is not indefinite; both driving and FR compete for the same limited resource. Given that the primary purpose of a PEDV is transportation and the expected life cycle is 10 years, an appropriate amount of throughput must be reserved for driving unless the economic benefit from FR can offset the lifetime mileage reduction of the vehicle.

For example, according to the Peterson model (Peterson et al., 2010), the Chevy Volt (PHEV) uses approximately 5.6% of its lifetime throughput annually when driving 10,000 miles per year. With a dispatch signal averaging a symmetric 5% of capacity per hour and V2G availability consistent with the base point parameters, V2G would claim just under 4.3% of the vehicle's lifetime throughput. This particular scenario suggests that with low average FR throughput, a PEDV would be able to fully participate in V2G FR while fulfilling its primary transportation function for the duration of its life cycle. It is important to note, once again, that the Peterson model (Peterson et al., 2010) predicts battery life in the absence of time and temperature variations and should be considered optimistic.

The maximum threshold values for average FR throughput, according to the Peterson model (Peterson et al., 2010), are specified in Table 28. These thresholds indicate the amount of average FR throughput that a PEDV could sustain and still achieve its projected life-cycle mileage of 100,000 miles. Fewer annual hours of V2G availability could sustain higher throughput levels, but when considering the cost of battery degradation, all of these values are capped at 6.9% and 8.6% for Level 2 and Level 3 FR, respectively, for both

PEDVs. These throughput caps indicate the break-even throughput level beyond which the cost of battery degradation is greater than the FR revenue.

Table 28. Maximum Roundtrip Average Throughput Thresholds

	PHEV	PEV
Level 2 Bidirectional V2G	5.5%	11.2%
Level 3 Bidirectional V2G	4.2%	8.7%

c. Modeling V2G With the Area Control Error as the Dispatch Signal

Thus far, I have demonstrated that the sample set of AGC data did not exhibit optimal characteristics for V2G FR viability. A sample set of actual ACE data did, however, demonstrate favorable characteristics if converted to a mock AGC signal by reversing polarity. This is consistent with and supports previous assumptions (see Brooks, 2002; Tomic & Kempton, 2007) about V2G FR viability that were primarily based on analysis of the ACE. Figures 44 and 45 depict the SOC simulations for a PEV and PHEV performing FR by responding to a mock AGC signal derived from real ACE data.

These simulations demonstrate the potential of V2G FR if PEDVs could respond to a signal with characteristics more similar to those of the grid's ACE and illustrate the key advantages of a dispatch signal with lower throughput. These advantages include the ability to use a larger capacity charger/inverter (20 kW) while vastly reducing the SOC swings, which eliminates the need for an advanced algorithm to dynamically shift a POP. The end product is a dispatch signal with characteristics far more suitable for a fast-responding storage resource with limited energy capacity (e.g., PEDVs). The net result is increased revenue through reduced battery degradation, a larger FR capacity, and greater TOR duration. Using the inputs from the simulations in Figures 44 and 45, break-even RMCP falls from $24.50 for the PEV and $36.00 for the PHEV to $18 and $27, respectively.

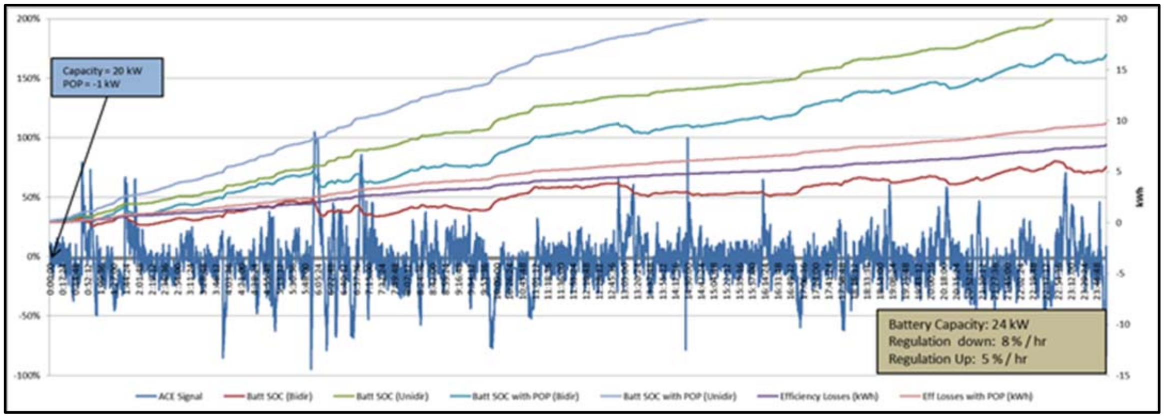
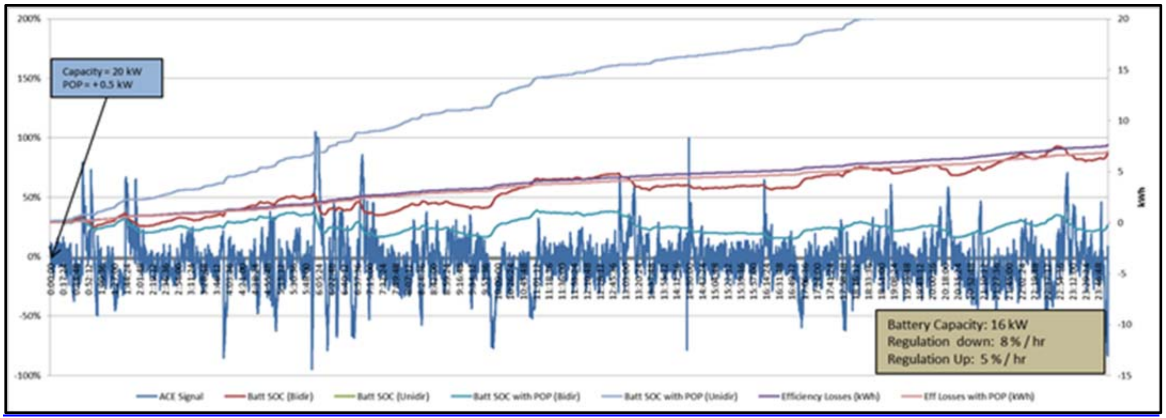


Figure 44. PEV State of Charge Simulation Using ACE as Frequency Regulation Dispatch Signal



Note. The PHEV with a smaller battery capacity (16 kW) can maintain SOC within the feasible region for a 24-hour period with a bidirectional FR capacity of 20 kW.

Figure 45. PHEV State of Charge Simulation Using ACE as Frequency Regulation Dispatch Signal

D. THE COST TO MEET FEDERAL MANDATES

The federal mandates presented in Section I.B.3 and addressed in the following analysis consist of a 30% reduction in petroleum use and a 28% reduction in GHG emissions by non-tactical government vehicles applicable to non-exempt agencies using a 2005 baseline. The following is a list of non-exempt agencies (DoE, 2007):

- Court Services and Offender Supervision Agency
- Department of Agriculture
- Department of Commerce
- Department of Energy
- Department of Health and Human Services

- Department of Homeland Security
- Department of Housing and Urban Development
- Department of Justice
- Department of Labor
- Department of State
- Department of the Interior
- Department of Transportation
- Department of Treasury
- Department of Veterans Affairs
- General Services Administration
- National Aeronautics and Space Administration
- Smithsonian Institution
- Social Security Administration
- Tennessee Valley Authority
- Department of Defense (All Agencies)
- U.S. Postal Service

Ideally, meeting federal mandates of reduced fuel consumption would be offset by the realized savings of forgone fuel purchases. In this case, savings are in the form of reductions in light-duty vehicle fleet operating costs or the sum of those savings and the potential financial gain from using PEDVs to perform V2G FR. However, as the analysis in this chapter concludes, V2G FR revenue and operating cost savings are not enough to compete with traditional vehicles under current market conditions. At most levels, V2G currently increases the LCC of PEDVs and at the basic level has a minimal impact on LCC reduction (see Figure 46). Therefore, the costs to meet federal mandates are presented using the base point parameters without V2G integration.

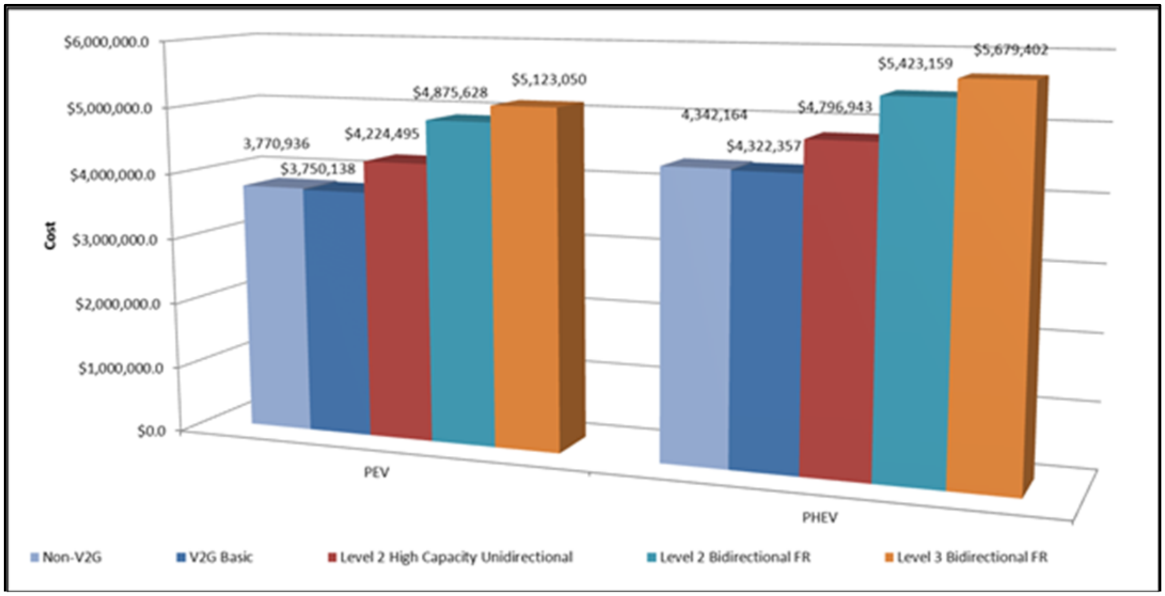


Figure 46. Life-Cycle Cost of Plug-In Electric Drive Vehicles

The higher LCCs of PEDVs makes the goal of reducing fuel consumption and GHGs by transitioning away from traditional government fleet vehicles come at a cost, a cost which can be quantified in cost per gallon of fuel or metric ton of CO_2 reduced. Because federal reduction mandates are on an annual basis, LCCs are annualized to properly quantify the costs of these mandates. Thus, the analysis in the final two sections of this chapter explores the costs to meet annual reduction targets as a function of annualized LCCs for the five vehicle fleet options considered. Reductions are compared to the annual fuel consumption of an average 2005 passenger vehicle with a fuel efficiency of 23 MPG.

1. Petroleum Reduction

Table 29 shows the cost to meet federal petroleum reduction mandates by displacing current federal fleet vehicles (operating at 2005 efficiency levels) with one of the vehicle categories considered in this thesis. Cost to meet the mandate is driven by the per-vehicle LCC, under base point parameters, and the number of vehicles necessary to meet the annual petroleum reduction target of 85,523,099 gallons of gas equivalent (GGE; DoE, 2007; DoE, 2012). PEDVs offer the greatest fuel savings per vehicle, and consequently require the fewest replacement vehicles and thus the lowest cost to meet the federal mandate. However, the initial expense to displace current fleet vehicles with a PEDV versus a more efficient, modern ICE or HEV is cost prohibitive and impractical because the vast majority of the fleet would require replacement. On the other hand, meeting the standard by replacing passenger vehicles with either a more efficient ICE or HEV is not possible because more vehicles would need to be displaced than currently exist in the inventory (as of 2010).

Assuming replacement of current fleet vehicles at the end of their government use life cycle is inevitable; a better metric is the additional LCC required per additional gallon reduced over the base case ICE. Here the HEV is the clear winner, with an additional LCC investment of just $0.15 per additional gallon reduced compared to the PEV and PHEV at $2.02 and $4.14 per gallon, respectively. As presented earlier in this chapter, only a marginal increase in annual mileage or fuel price results in the HEV achieving the lowest fleet LCC while providing greater than twice the petroleum reduction of the base case ICE. Overall, meeting the mandate by solely displacing light-duty passenger vehicles is either impractical or impossible with the vehicles considered in this analysis. Therefore, the mandate is most likely to be met by extending the concept of PEDV displacement beyond light-duty passenger vehicles and incorporating an optimal mix of other AFVs capable of displacing petroleum (hydrogen, compressed natural gas, or E85) along with a combination of increased conservation methods (reduced idle time, increased vehicle utility, reduced fleet size, etc.).

Table 29. Cost to Meet Federal Mandate for Reduced Petroleum Consumption

	ICE	PEV	PHEV	Hybrid	GSA Lease
LCC for 30% Reduction in Federal Fleet Fuel Use	$2,610,924,939	$741,754,921	$923,896,365	$1,135,607,637	$6,741,649,137
LCC for 1% Reduction in Federal Fleet Fuel Use	$87,030,831	$24,725,164	$30,796,545	$37,853,588	$224,721,638
Displacement of Federal Fleet Required to Meet Mandate[1]	374%	87%	95%	162%	756%
LCC per Gallon of Petroleum Reduced	$30.53	$8.67	$10.80	$13.28	$78.83
ΔLCC per Gallon of Petroleum ΔReduction[2]	▨	$2.02	$4.14	$0.15	N/A

Note. (1) Percentages relative to total domestic passenger vehicle fleet of 225,217 in FY2010 (covered agencies). (2) Additional LCC and petroleum reduction differential relative to the base case ICE.

2. Greenhouse Gas Reduction

The cost to meet federal GHG emission reduction mandates can be computed for the ICE and HEV rather easily using the analysis in section VII.D.1. above because reduced GHG emissions generally follow reduced fuel consumption. There are approximately 8.92 x

10^{-3} metric tons of CO_2 emitted per gallon of gas combusted (EPA, 2012). The cost to reduce GHGs by transitioning to a more efficient vehicle is therefore directly correlated with the cost to reduce a gallon of fuel in the same manner. The federal annual GHG emission reduction target is approximately 712,008 metric tons of GHGs. As discussed in Chapter I, when determining PEDV GHG emission reductions, the generation mix of electricity must be considered for an accurate assessment. Basing an assessment of GHG reduction on forgone fuel consumption per traditional vehicle displaced alone is inaccurate and misleading. Therefore, the cost to meet the GHG mandate by replacing traditional vehicles with PEDVs is not explored further, and determining the cost of reducing *net* GHG emissions with PEDVs is left for further research.

Table 30 shows the LCC to achieve the required annual GHG reductions by transitioning to more efficient ICE, HEV, and GSA lease vehicles relative to a 2005 average federal vehicle baseline. The HEV has a slightly higher LCC under base point parameters than the ICE but is able to reduce over twice as much GHGs than the ICE and achieves the standard with the fewest replacement vehicles and the lowest LCC. However, because the HEV is more expensive than the ICE, the metric of additional cost per additional metric ton of CO_2 is presented and equals $17.15. Despite providing GHG reductions from the FY2005 base line, this metric is not applicable to the GSA lease because it does not provide any GHG reductions over the base case ICE.

Table 30. Cost to Meet Federal Mandate for Reduced Greenhouse Gas Emission

	ICE	Hybrid	GSA Lease
LCC for 28% Reduction in Federal Fleet GHGs	$2,436,863,277	$1,059,900,462	$6,292,205,861
LCC per Metric ton of CO2 reduced	$3,423	$1,489	$8,837
ΔLCC per Metric Ton of ΔCO2 Reduction		$17.15	N/A

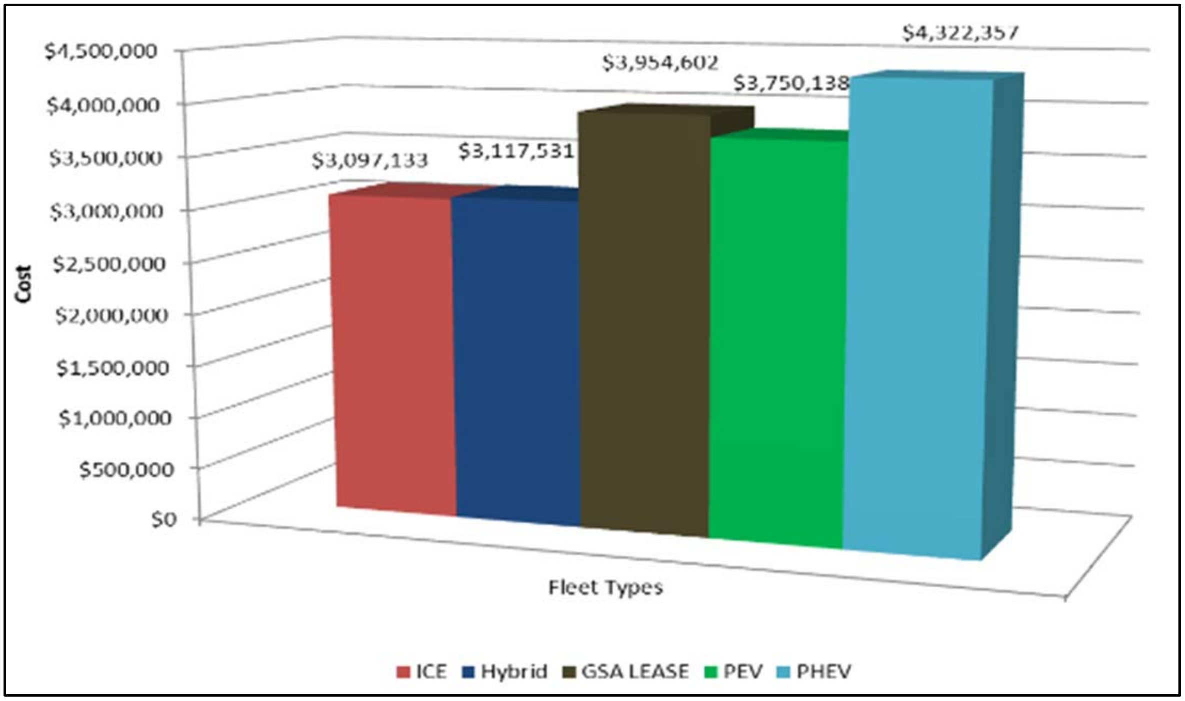
VIII. CONCLUSION

A. SUMMARY AND RECOMMENDATIONS

The goal of this thesis is to objectively and quantitatively assess the economic viability of integrating PEDVs into government light-duty passenger fleets with the proposed economic benefit of supplying A/S to the grid via a V2G infrastructure that would in theory offset the higher capital costs of PEDVs.

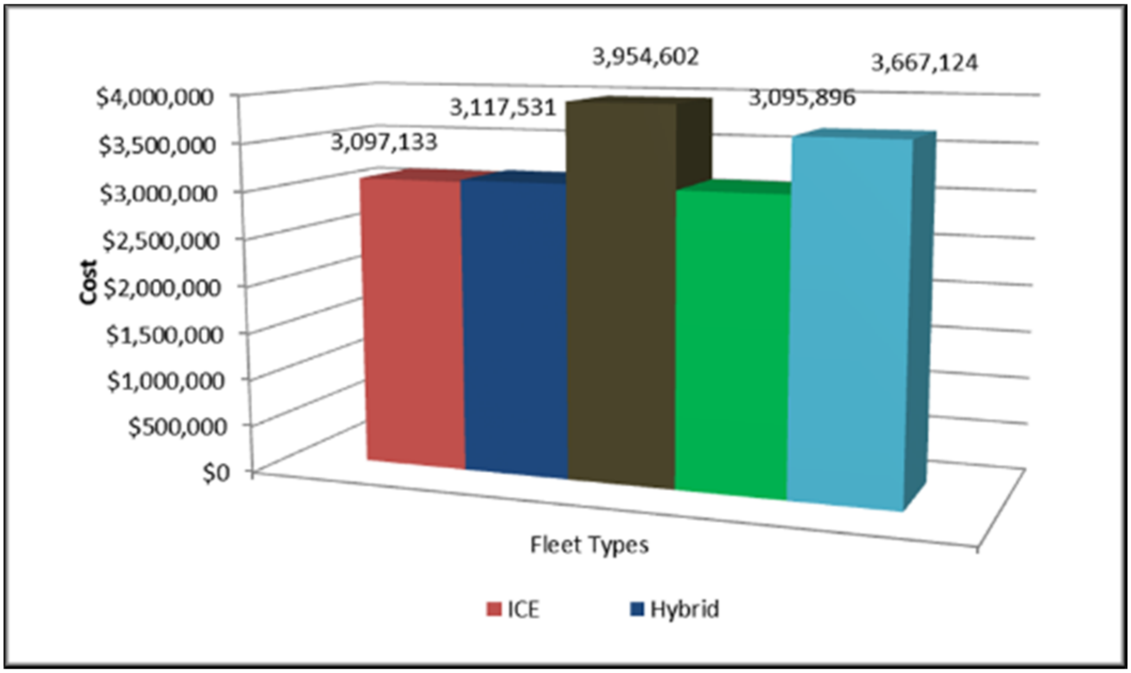
Higher cost alternatives must recoup their additional expenses in lower operating costs within their lifespan to achieve net savings and, subsequently, viability. Under current market conditions, all else held constant, even if electricity cost were reduced to zero, thereby creating the largest possible differential in operating costs, PEDVs would still not achieve economic competiveness with reasonably efficient traditional ICEs. The inability for PEDVs to make up their higher initial costs through lower operating costs places the burden of viability on other incentives. Other incentives may consist of the intangible benefits PEDVs offer, such as reduced oil consumption and CO_2 emissions, but these are difficult to quantify. The primary incentive this thesis investigates is the potential financial incentive of government fleets participating in the FR A/S market.

Figure 47 shows the LCC hierarchy for the various fleet options under the base point parameters. The economic benefit of ownership over lease is readily apparent and allows the PEV to achieve a net savings over the GSA lease option. Ownership of an ICE or HEV, however, results in far lower LCCs than any other alternative. Figure 48 shows the hierarchy under the best-case parameters for PEDVs and V2G FR. Only under very favorable conditions does the revenue generated from Level 3 bidirectional V2G FR allow the PEV to best the ICE as a fleet replacement alternative.



Note. Under base point parameters, OEM level unidirectional V2G FR generates the greatest net revenue.

Figure 47. Life-Cycle Cost Comparison With Vehicle-to-Grid Under Base Point Parameters



Note. Best-case parameters include throughput from FR of 5% up/down, RMCP of $24.50, Level 3 bidirectional V2G FR with use of a dynamic POP.

Figure 48. Life-Cycle Cost Comparison With Vehicle-to-Grid Under Best-Case Parameters

Advanced levels of bidirectional V2G integration cannot be economically justified under current market conditions from FR revenue alone, but lower levels of unidirectional integration can provide enough revenue to offset some, but not all, of the higher initial costs. New FERC regulations, which take effect late 2012, may create a more attractive environment for fast-responding storage resources such as PEVDs, but this will require greater reimbursement for service and less throughput demand to make a strong economic case. Viability of V2G FR is reliant on throughput for two reasons: (1) lower throughput means less battery degradation and higher net revenue; and (2) lower throughput means more manageable battery SOC swings (with or without a POP), which means longer TOR with higher regulation capacity and thus greater revenue. Until capital costs sufficiently decline or the aforementioned market conditions are met, HEVs provide the greatest additional benefit in terms of reduced petroleum consumption and net emissions reductions for the additional LCC over traditional ICEs.

Meeting the federal mandate of reduced petroleum consumption presently comes at a cost. Theoretically, the benefit is increased energy security. If energy security is increased by reducing the need for foreign oil with electric vehicles, then the source from which we power our electric vehicles must not replace one security concern with another. We must ensure that batteries, the countries that make them, and the origin of the materials used to create them are not building a new dependence under an old paradigm. Is it in our best national security interest to trade getting a relatively small amount of oil from the Middle East for getting a large percentage of our batteries from China? To whom do we want our transportation sector and our economy beholden? The truth is, in a global economy, we can never completely isolate ourselves. Accepting oil as our primary fuel and pushing for greater efficiencies and lower consumption through hybrid technology while pursuing research and alternatives for energy storage and alternative fuels seems to be the most viable option for now and the near future. PEDVs are simply not a cost effective option at current market prices, and revenue generated from V2G does not provide enough economic incentive to transition completely away from efficient ICEs and HEVs.

B. RISKS

The following are various risks to V2G and the assumptions made in this analysis:

- **Maintenance Costs**

  Lower maintenance costs are a critical assumption, but with very few fleets of operational PEDVs, the empirical data from which to derive accurate maintenance cost projections remains to be gathered. The PEDVs in use in TARDEC's pilot V2G program in Hawaii have much to be desired in terms of maintenance and reliability of the vehicles power electronics.

- **Battery Durability**

  Battery durability can greatly influence the viability of V2G. If participation in FR voids a manufacturer's warranty and subsequent failures due to cell degradation lead to higher maintenance and capital replacement costs, then the already tenuous proposition of a V2G system becomes an expensive failure.

- **Time and Temperature**

  The research on which my assumptions of battery degradation are based was conducted on battery cells that underwent accelerated usage equivalent to "at least 5 driving years" (Peterson et al., 2010) but were not exposed to highly variable ambient temperatures nor the time that cells in actual vehicles would experience. Also, it does not account for heat cycling or additional energy required for battery cooling during cycling. These factors in actual operation over the life span of a PEDV could lead to less observed battery throughput than predicted.

- **Aggregator Service Fees**

  The economic viability of V2G is tight even under the most optimistic and favorable conditions. Therefore, service fees much greater than the 10% used in the base point parameters are a considerable risk.

- **Ancillary Service Market Rules**

  Much of the prospect of PEDV providing grid services assumes ESP market rules are favorable to storage devices. Unidirectional FR assumes ESPs allow resources to provide regulation up and down separately, concurrently, or singularly. Some ESPs currently require a single capacity bid for which regulation up and down is equal while others allow participation in the regulation up or down separately without the requirement to perform both.

- **Market Saturation for Frequency Regulation**

  According to research (Kempton & Tomic, 2005), fleet market saturation for V2G occurs at approximately 3% of the light-duty fleet. The government is in a good position to have first mover's advantage on this market. This advantage would help cover V2G infrastructure costs (if initial market conditions permit; e.g., higher RMCPs) before wide-scale participation dilutes revenue.

- **Infrastructure**

Assumption of a preexisting robust electrical infrastructure eliminating the need to purchase additional transformers is a significant cost assumption and may not be realistic for every government application or facility.

With greater data available in the years to come, a better understanding of Li-ion cell degradation and PEDV reliability will be available and help inform better assumptions.

C. FUTURE RESEARCH

Possibilities for further research are as follows:

- Further research that accounts for the financial benefit of displacing costly standby generators for emergency backup power and the ability to act as storage for installation renewable energy sources, could strengthen the case for the bidirectional capital investment. Another next step will be to adapt this model for further examination of additional A/S revenue. Although current RMCPs, high throughput, and technology levels create a difficult economic case for V2G, greater economic justification could be provided by conducting more research about installation energy cost savings from peak shaving.
- Investment costs are assumed to occur upfront in Year 1 with no financing schemes and alternative vehicles are a one-for-one replacement for traditional vehicles. Examining potential creative financing methods and the implementation of alternative acquisition strategies or conservation practices that could lead to greater individual vehicle utility (accomplishing the same task with fewer vehicles) is a topic for future research.
- Using the threshold for throughput and price outlined in this thesis, further research could investigate the new RMCP performance-based pricing model and fast-responding resource signal to determine whether it meets identified requirements for viability as data become available.
- Further research might include obtaining AGC data from other markets to determine whether inferences from the PJM sample set are indeed applicable to other service markets.
- This thesis examines the prospect of using small to mid-sized PEDVs as a one-for-one replacement for traditional vehicles in a single vehicle class; light-duty passenger vehicles are held at 2005 average efficiency levels. In 2010, the passenger vehicle category consisted of only 36% of the non-exempt agency worldwide inventory (DoE, 2010). Expanding the analysis to include trucks and buses would provide better clarity on the feasibility of meeting the mandate with a PEDV transition across multiple vehicle classes.
- This thesis determines that displacing traditional ICEs to meet federal petroleum reductions with PEDVs alone is impractical. Further research to determine the optimal mix of AFVs (E85, CNG, hydrogen, electricity, etc.) across vehicle classes and quantifying the cost is necessary.

- FERC (2012) order 755 endeavors to create a more equitable environment for fast-responding resources with limited capacity, such as flywheels and storage batteries. PEDVs responding to FR will benefit from this order if a separate dispatch signal results in lower throughput and higher net revenue. Further research incorporating the new empirical data resulting from this order could re-examine V2G FR profit potential under revised market conditions.

The End[25]

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[25] Mrs. Kathryn Monahan (2013)

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- Managing the Services Supply Chain
- MOSA Contracting Implications
- Portfolio Optimization via KVA + RO
- Private Military Sector
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- Spiral Development
- Strategy for Defense Acquisition Research
- The Software, Hardware Asset Reuse Enterprise (SHARE) Repository

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- Contracting Government Procurement Functions
- Contractors in a 21st-Century Combat Zone
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- Model for Optimizing Contingency Contracting, Planning, and Execution
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- Retention
- The Navy’s Selective Reenlistment Bonus (SRB) Management System
- Tuition Assistance

Logistics Management

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- Army LOG MOD
- ASDS Product Support Analysis
- Cold-Chain Logistics
- Contractors Supporting Military Operations
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- Evolutionary Acquisition
- Lean Six Sigma to Reduce Costs and Improve Readiness

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- Optimizing CIWS Lifecycle Support (LCS)
- Outsourcing the Pearl Harbor MK-48 Intermediate Maintenance Activity
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- Privatization-NOSL/NAWCI
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- Risk Analysis for Performance-Based Logistics
- R-TOC AEGIS Microwave Power Tubes
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