NATIONAL ENERGY TECHNOLOGY LABORATORY

Assessment of Future Vehicle Transportation Options and Their Impact on the Electric Grid

January 10, 2011

DOE/NETL-2010/1466

U.S. DEPARTMENT OF ENERGY

Assessment of Future Vehicle Transportation Options and Their Impact on the Electric Grid

DOE/NETL-2010/1466

January 10, 2011

NETL Contact:
Justin Adder
Office of Systems, Analyses and Planning

National Energy Technology Laboratory
www.netl.doe.gov

This page intentionally left blank

Table of Contents

List of Tables

List of Figures

Prepared by:
Energy Sector Planning and Analysis (ESPA)

Zephyr Taylor
Booz Allen Hamilton, Inc.

Matthew Merzig
Booz Allen Hamilton, Inc.

Thomas Matta
Booz Allen Hamilton, Inc.

Joe Miller
Horizon Energy Group

Hilal Katmale
Horizon Energy Group

Steven Knudsen
Sextant Technical Services LLC

DOE Contract DE-FE0004001

Acknowledgements

This report was prepared by **Booz Allen Hamilton, Inc. (BAH)** for the United States Department of Energy's National Energy Technology Laboratory. This work was completed under DOE NETL Contract Number DE- FE0004001. This work was performed under BAH Task 430.01.06.

The authors wish to acknowledge the excellent guidance, contributions, and cooperation of the NETL staff, particularly:

Justin Adder, NETL Technical Monitor

Joel Theis, Office of Systems, Analysis and Planning

Steven Bossart, Office of Systems, Analysis and Planning

List of Acronyms and Abbreviations

ARRA	American Recovery and Reinvestment Act
BAH	Booz Allen Hamilton
BAU	Business as usual
BV	Battery vehicle
CAV	Compressed air vehicle
CIDI	Compression ignition, direct injection
CV	Conventional vehicle
DG	Distributed generation
DOE	Department of Energy
DR	Demand response
EIA	Energy Information Agency
EPRI	Electric Power Research Institute
ESPA	Energy Sector Planning and Analysis
EV	Electric vehicle
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse gas
HEV	Hybrid Electric Vehicle
ICE	Internal combustion engine
ISO	Independent system operator
kWh	Kilowatt hours
LDV	Light-duty vehicle
Li-Ion	Lithium Ion
LSE	Load Serving Entity
MSRP	Manufacturer's Suggested Retail Price
NETL	National Energy Technology Laboratory
NERC	North American Electric Reliability Corporation
NGV	Natural gas vehicle
NiMH	Nickel-Metal Hydride
PHEV	Plug-In Hybrid Electric Vehicle
PNNL	Pacific Northwest National Laboratory
RECAP	Regional Capacity Planning Model
RTO	Regional Transmission Organization
SAE	Society of Automotive Engineers
SO_X	Oxides of sulfur, a regulated pollutant
T & D	Transmission and distribution
VMT	Vehicle mile traveled
V2G	Vehicle to grid

Executive Summary

This report examines the impact that electric vehicles (EVs) may have on the electric power grid, and looks at competing transportation technologies in the future. It begins with a discussion of the technology performance characteristics and market potential of key competitors in the vehicle sector, in order to set the stage for the discussion of EVs, which have the highest potential for short-term market penetration. EVs are also the key transportation technology that will have a significant impact on the electric power grid, making their usage and prevalence important to both electric utilities and load-serving entities (LSEs) and consumers.

Although the vehicle technologies covered in this report all have promising features that have the potential to radically reduce the environmental impacts of the automobile industry, it is EVs that seem to have clear advantages in terms of short-term deployment and market penetration. The reasons for this are highlighted in this report, along with a discussion that focuses solely on EVs.

Study results indicate that significant barriers remain to widespread adoption of EVs in the near term (3 to 5 years), but that if critical grid and vehicle issues are resolved, substantial market penetration could occur.

This report identifies the following critical limiting factors:

- An accurate assessment of grid capacity to support EVs without negatively impacting the expected service life of costly grid infrastructure
- Overall costs of the EV technologies
- Charging infrastructure and investment costs
- Demand-response capabilities of the utilities to manage increased load
- Efficacy and viability of vehicle-to-grid (V2G) technology
- Potentially inhibitive environmental and greenhouse gas emission (GHG) regulations that would limit the flexibility of electric utilities to increase load

Significant excess baseload generation capacity on the grid during off-peak hours is reported to exist (Kintner-Meyer, 2007). As further charging data and usage patterns evolve, it is likely that demand models will improve to satisfactorily determine excess capacity. Since excess baseload capacity is a fundamental assumption driving current perspectives on EVs, fully understanding this assumption is integral to accurately predicting the impacts of EVs on the grid.

Much of the current work does not thoroughly evaluate the incremental value of the Smart Grid infrastructure and its role in facilitating the benefits of EVs. The value of Smart Grid technologies is mostly implied, as the management of these mobile, distributed storage and generation devices is likely to be complex and best approached using advanced grid technologies. Focused analyses are scarce, particularly those entering explicitly around particular technology portfolios that could mitigate and/or manage the impact of EVs on the electric grid. The work covered in this report indicates the key impacts that take precedence in an intelligent design of the Smart Grid.

The value of the Smart Grid in managing and effectively utilizing the theoretical potential of EVs comes primarily in the form of demand response and the necessary data exchange to facilitate variable and complex charging and discharging schemes. However, there are a number of valuable topics for research and analysis that should be explored to better understand the role of the Smart Grid in EV fleet and infrastructure development and management. These include looking at the issue from the grid infrastructure, vehicle technology, and consumer perspectives.

1.0 Introduction

This report focuses on the potential impact of electric vehicles (EVs) on the North American electric power grid, market penetration scenarios, and potential Smart Grid mitigation roles. According to Smart Grid Basics (2010), "The Smart Grid is an automated electric power system that monitors and controls grid activities, ensuring the two-way flow of electricity and information between power plants and consumers—and all points in between." It also examines the myriad challenges to EV integration and market adoption, including costs and consumer preferences. This assessment is an attempt to capture the breadth of analytical and conceptual research surrounding the dynamic and interactive role that EVs will play in the electricity infrastructure as they become increasingly significant players in the light-duty vehicle sector.

Before focusing on EVs, this report briefly discusses the performance, costs, and potential market penetration scenarios of key competing transportation technologies, such as compressed air vehicles (CAVs), natural gas vehicles (NGVs), hydrogen vehicles (HVs), and traditional gasoline/diesel vehicles. This helps to put in context the complexity and potential value of EVs as they stand in comparison to other transportation technologies.

The electricity infrastructure includes the entire generation, transmission, and distribution network. As discussed in this report, EVs include all vehicles that have some grid-connected charging and/or vehicle-to-grid (V2G) component, including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Generally, both EV technologies will have similar interactions with the grid in the form of battery charging and potential distributed storage and generation capabilities.

EVs present both tremendous opportunities for and challenges to greenhouse gas (GHG) emissions reductions, energy security and reliability, and electricity generation and distribution infrastructure. The shift from conventional vehicles (CVs) to electric vehicles offers the potential to radically reshape the fuels consumption portfolio of the United States while simultaneously reducing GHGs through the expanded use of renewable electricity-fueled transportation and reduced emissions per vehicle-mile (VMT).

On a VMT basis, EVs can have fewer emissions than CVs because of greater electrical efficiency. However, there is more variability in the emissions of EVs versus CVs, depending on their primary generation technology source (e.g., coal, nuclear, hydroelectric). In the case of EVs, displacing current CV will correspond to tremendous new demands on the electricity generation infrastructure. It is the effective and active management of these demands that will largely determine the ramifications of this new industry. For example, if EVs are exclusively charged during off-peak, nighttime hours, then the current infrastructure could support nearly 50 percent of our current transportation energy needs (PNNL, 2010). However, if actual charging behaviors do not occur on this approximate schedule, then the impact of EVs will be significantly different.

EVs have the potential to utilize idle baseload generation capacity during off-peak hours, eliminating the need for increased capacity and the associated capital investment costs. With V2G technology, which allows these EVs to sell energy back onto the grid, they could act as peak-demand load shavers that can be tapped for energy during the times of high demand instead of ramping up peaking power plants. This rests on the assumption that these vehicles will be connected to the grid during peak hours, will have effective metering and accounting technologies to ensure proper payment and discharging, and will have sufficient capacity to supply the required electricity. V2G also has the capability to enable practical utilization of intermittent renewable energy resources.

Beyond these straightforward technological and grid-interconnection aspects, there remain myriad uncertainties and obstacles to overcome before EVs can realize a significant market share and environmental impact. These include the levels of consumer adoption and market penetration, based on, for example, consumer preferences, technological efficacy and comparability to current transportation technologies, availability of substitutes, and fuel costs; the availability of rare earth metals needed for battery manufacturing; and the economic costs of infrastructure investments needed to support the additional benefits of EV fleets utilizing the V2G concept. Further, the existence and prevalence of EVs will change the load management requirements of the electric grid, creating potential issues with reliability, expected service life of grid infrastructure, and power quality. Given the significant uncertainty around these issues, this assessment attempts to summarize the current findings and discussion on these topics.

This work also examines the operational and technological impacts of EVs on the grid, consumer adoption and economic considerations, and competing vehicle technologies and their relative prospects for posing a serious competitive threat to EVs in the marketplace.

Some of the key topics addressed in this report are:

- Key transportation vehicles and their relative costs, performance, and market potential
- The feasibility of EVs from a consumer perspective
- Utility perspectives on EVs.
- How the emergence of EVs impact load profile, particularly peak demand. How will this overlap with existing peak demands?
- The net environmental impacts of EVs.
- What the EV charging infrastructure will look like, particularly in reference to the composition of residential, commercial, or industrial charging stations
- The costs and benefits to end users and society from the use of vehicles
- The potential of EVs to facilitate increased renewable energy generation

The automobile industry could play a major role in safeguarding the environment and creating more sustainable ways of utilizing the earth’s resources. Following its initial failed launch in the early 1900s and unsuccessful revival in the 1990s, the potential for an EV comeback will be dependent upon the alignment of a number of different market, technological, consumer demand and regulatory factors.

Increasing gasoline prices make vehicle electrification an attractive option, with recent market trends spawning a range of hybrid drive vehicles, such as General Motor’s EV1 and Toyota’s Rav4. Hybrid vehicles supplement existing gasoline engines with an electric battery, allowing for increased gas mileage and fewer CO_2 emissions. PHEVs are an extension of hybrid vehicles that allow users to charge their batteries at home. Improvements in battery technology, such as lithium ion batteries, have improved the range and lifetime of plug-in hybrids.

Table 1 provides the classification for various vehicle types.

Table 1: Vehicle Classification Table

Vehicle Type	Acronym	Description
Internal Combustion Engine Vehicle / Conventional Vehicle	ICE / CV	A vehicle that uses a standard internal combustion motor running off of gasoline or diesel fuel
Compressed Air Vehicle	CAV	A vehicle running off of compressed air, with the air compressor being powered by the electric power grid
Natural Gas Vehicle	NGV	An internal combustion vehicle that uses Natural Gas as opposed to traditional gasoline or diesel fuel
Hydrogen Vehicle	HV	A vehicle that uses Hydrogen fuel cell technology to power the drivetrain.
Electric Vehicle	EV	Vehicles that use an electric motor instead of a traditional internal combustion engine (ICE)
Battery Electric Vehicle	BEV	Electric Vehicles that run purely on electrical power from battery packs
Hybrid Electric Vehicle	HEV	Electric vehicles that use a gasoline-powered motor in addition to the electric motor
Plug-in Hybrid Electric Vehicle	PHEV	A type of Hybrid Electric Vehicle with powerful batteries that can be charged with a plug through a wall socket
Extended-Range Electric Vehicles	EREV	A plug-in hybrid electric vehicle (PHEV) with an IC engine or other secondary source connected to a generator to resupply the batteries
Full Performance Battery Electric Vehicle	FCEV	An electric vehicle that uses a fuel cell rather than a more traditional battery to provide electricity that powers the car
Hydrogen Internal Combustion Vehicle	H2ICV	An altered version of the traditional gasoline internal combustion engine car. The hydrogen engine burns fuel in the same way as gasoline engines.
City Electric Vehicle	CEV	Battery Electric Vehicles with limited acceleration and a top speed
Neighborhood Electric Vehicle	NEV	Battery Electric Vehicles with limited acceleration and a top speed
Fuel Cell Auxiliary Power Unit Vehicle	FCAPUV	Fuel Cell Vehicles using a solid oxide fuel cell utilizing a solid ceramic material as the electrolyte
Neighborhood Zero Emission Vehicle	NZEV	Battery Electric Vehicles with limited acceleration and a top speed
Low Speed Vehicles	LSV	Battery Electric Vehicles with limited acceleration and a top speed

2.0 Study/Research Methodology and Findings

This review highlights and summarizes the interaction of EVs with the electric grid and various market adoption and environmental impact scenarios. The relative value of the Smart Grid is then discussed to describe its potential for added value to the positive impacts of EVs. The report also discusses some of the key competing vehicle technologies currently available in the market or being proposed for commercial production. In doing this, the report sets the stage for the discussion of EVs by performing a comparative analysis highlighting the relative market penetration significance of EVs over the other vehicles.

Three major impact focus areas emerged based upon the study: the feasibility of EVs and their comparative standing among other vehicle technologies, the utility perspective on EVs, and the complex environmental impacts of EVs.

3.0 Comparison of Transportation Vehicles

To appropriately frame the issue of EVs and their impact on the grid, their place first has to be put in context among a suite of transportation technologies and fuels. The purpose here is to appropriately frame why EVs are worth discussing, and to illustrate their relative connection with the electric power grid in comparison with other potential transportation vehicles. The following sections, therefore, briefly summarize and discuss the market potential and performance characteristics of various transportation technologies. These are technologies that are currently being produced or are expected to see future production based on prototype development or expansive R&D programs.

3.1 Compressed Air Vehicles

Like EVs, compressed air vehicles are another form of transportation that would directly interact with the electric utility grid. Unlike EVs, however, CAVs do not store their charged electricity in batteries. Rather, electricity is used to pump air into a compressed storage tank, which is discharged to drive the vehicle at a later point. There are currently no CAVs in commercial production, and they are widely seen by analysts to have limited future market potential due to their overall poor performance and relative efficiency.[1] CAVs are the only other transportation technology besides EVs that would have direct and potentially significant impacts on the electric power grid. From the standpoint of understanding these vehicles interaction with the grid, CAVs and EVs will be the only technologies that have the potential to shift the electric power generation portfolio, impact the use of fossil energy, and change the overall economics of electricity delivery and usage. One major auto manufacturer, Tata Motors, had planned to commercially manufacture a CAV, but later delayed the introduction due to continued research on the technology.[2] This lack of commercial development and investment further adds to the bleak market penetration outlook of this niche technology.

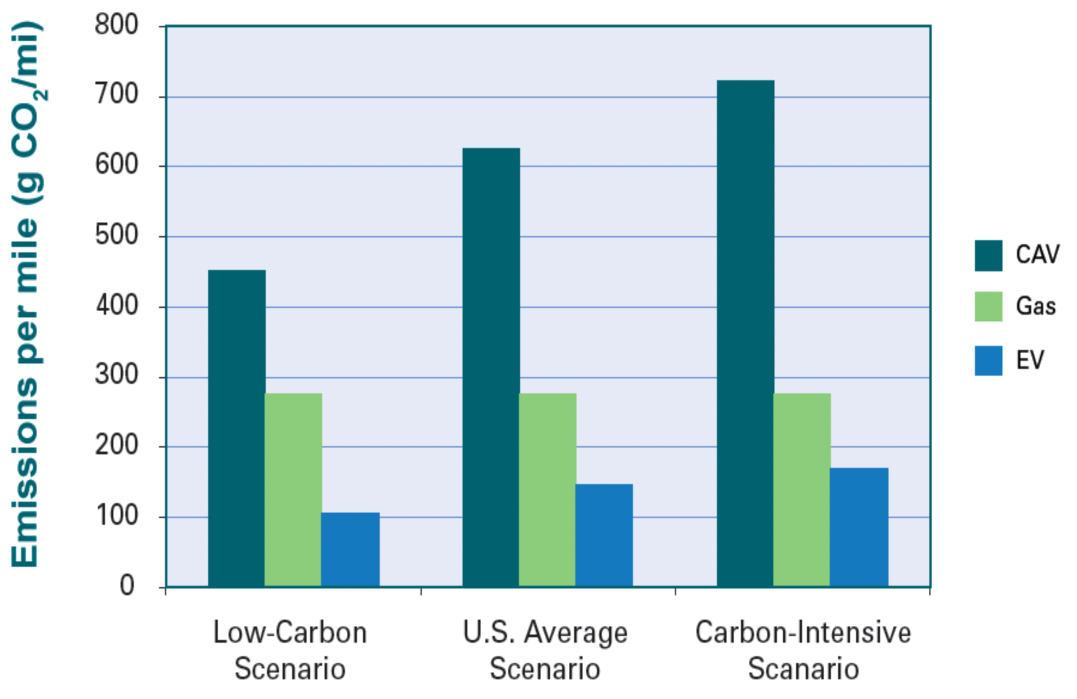
An ICF International (ICF, 2010) report indicates that CAVs perform worse than EVs in nearly every performance metric, and emit higher levels of GHGs per VMT. This is based primarily on their relatively inefficient drivetrains and energy storage resulting from the conversion from mechanical to air power. Figure 1 and Table 2 below illustrate the comparison in GHGs between CVs, CAVs, and EVs.

---

[1] http://iopscience.iop.org/1748-9326/4/4/044011/fulltext

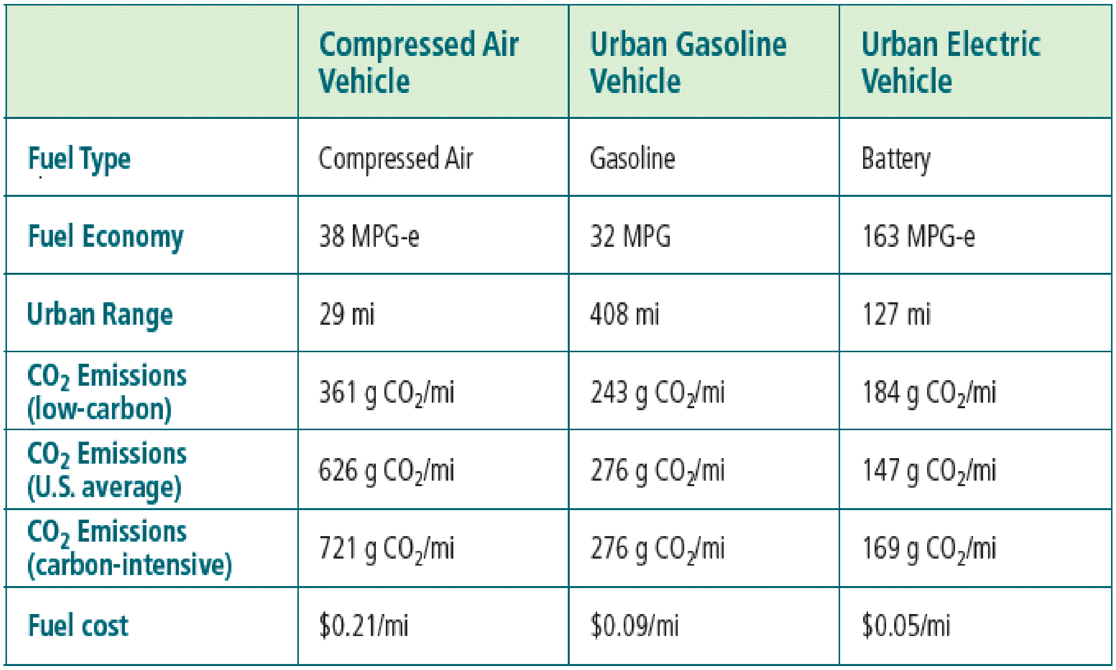
[2] http://www.dnaindia.com/money/report_tamo-s-ambitious-air-car-faces-starting-trouble_1316093

Figure 1: Carbon Footprint of Selected Vehicle Types



Source: (ICF, 2010)

Table 2: Summary Performance and Cost Metrics



	Compressed Air Vehicle	Urban Gasoline Vehicle	Urban Electric Vehicle
Fuel Type	Compressed Air	Gasoline	Battery
Fuel Economy	38 MPG-e	32 MPG	163 MPG-e
Urban Range	29 mi	408 mi	127 mi
CO_2 Emissions (low-carbon)	361 g CO_2/mi	243 g CO_2/mi	184 g CO_2/mi
CO_2 Emissions (U.S. average)	626 g CO_2/mi	276 g CO_2/mi	147 g CO_2/mi
CO_2 Emissions (carbon-intensive)	721 g CO_2/mi	276 g CO_2/mi	169 g CO_2/mi
Fuel cost	$0.21/mi	$0.09/mi	$0.05/mi

Source: (ICF, 2010)

3.2 Natural Gas Vehicles

Natural gas vehicles have relatively few emissions compared to gasoline-powered CVs. Although the extraction of natural gas is complex and has significant environmental impacts, the reduced GHGs coming from natural gas as a vehicle fuel is the key value added. The fuel efficiency gains from NGVs are considered negligible, making their appeal almost entirely based on reduced emissions and price. Natural gas costs, on average, approximately 75 percent of the cost of standard gasoline. For purposes of this analysis, however, NGVs are not particularly relevant due to their limited direct impact on the electric power grid. Rather, their impact would come from competing demand for the fuel itself, which is widely used for peaking plant power generation.

NGVs have yet to catch on in large numbers. They are primarily concentrated in the heavy-duty fleet (e.g., buses, garbage trucks, large trucks). Many of the major automobile manufacturers have produced a consumer version of the NGV during the last decade, but these are now almost entirely discontinued in the U.S. market. The Honda Civic GX is the only commercially available vehicle in the United States that runs on natural gas.[3] There are approximately 110,000 NGVs and 1,100 fueling stations in the United States, and over 11 million worldwide.[4] A majority of these, however, are fleet vehicles, belonging to municipalities or other organizations. Further, nearly half of all NG fueling stations in the United States are for private or municipality use only, making access limited for the average citizen. NGVs have realized significant market growth over the past several years, but again this growth has primarily been focused on the heavy duty (particularly buses) fleet. The absence of significant consumer choices and announcements of forthcoming light-duty vehicles (LDVs) from the major auto manufacturers sheds some light on their near-term market penetration into the LDV sector.

3.3 Hydrogen Vehicles

Although hydrogen fuel has received a considerable amount of media attention for its potential to radically change the energy economy and infrastructure, it is still very much in the experimental stages. Commercially available hydrogen vehicles have just begun entering production, with Honda producing the FCX Clarity, a model only initially available in southern California. This is one of the only commercially available HVs on the market, with most of the other manufacturers producing only experimental prototypes at this point. Some manufacturers, such as Ford, have canceled all hydrogen fuel cell development efforts.

3.4 Summary

Table 3 provides a general performance and cost metric comparison table between a typical “best in class example” of various vehicular technologies and fuels from multiple sources. Figure 2 provides market penetration scenarios for CVs and select alternative transportation technologies.

---

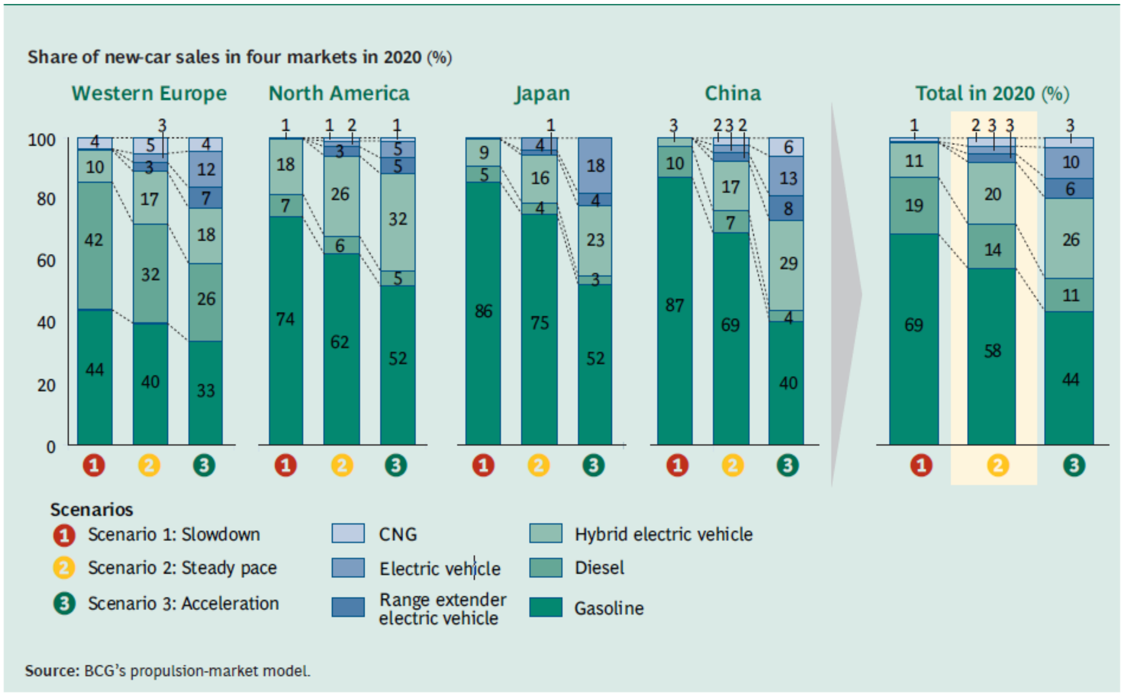
[3] http://alternativefuels.about.com/od/2008ngvavailable/a/2008CNGvehicles.htm

[4] http://www.ngvc.org/about_ngv/index.html

Table 3: Performance and Costs Metrics for Best In-Class Alternative Vehicle Examples

Vehicle Type	Compressed Air Vehicle	Urban Gasoline Vehicle	Chevy Cruze	Urban Electric Vehicle	Chevy Volt	Honda Civic GX
Fuel	Compressed Air	Gasoline	Gasoline	Battery	Battery	Natural Gas
Fuel Economy	38 MGP-e	32 MPG	40 MPG	163 MPG-e	168 MPG-e electric 50 MPG gas	36 MPG-e
Urban Range	29 mi	408 mi	450 mi	127 mi	450 mi	250 mi
Fuel cost per mile	$0.21/mi	$0.09/mi	$0.07/mi	$0.05/mi	$0.019/mi	$0.026/mi
Source	ICF International	ICF International	EV Lit Review Table	ICF International	EV Lit Review Table	EV Lit Review Table

Figure 2: Market Penetration Scenarios for Alternative Vehicles and CVs



Source: BCG's propulsion-market model.

Source: (BCG, 2010)

Technologies that may be implemented as an alternative to battery power include compressed air technology, natural gas, and hydrogen. Hydrogen technology is far from commercially viable. . Compressed air vehicles can have a short range (<50 miles), and while the fuel economy is comparable to ICEs with a potential efficiency of 38 MPGe, the fuel cost at $0.21/mile is higher than electric vehicles. Natural gas engines typically gain 36 MPGe, and the commercially available Honda Civic GX has an urban range of 250 miles. The operating expense of $0.026/mile is better than ICEs, but still not as strong as the $/mile for an EV such as the Chevy Volt ($0.019/mile).

This brief overview and analysis of the competing alternative vehicle technologies shows notable market adoption and performance advantages for EVs. The rest of this review will, therefore, focus solely on EV technologies. Key performance advantages for EVs include relative fuel cost advantages, performance and efficiency, commercial efficacy, and policy support. This results in what is shown as relatively high near-term market penetration. However, it should be noted that these alternative transportation technologies (including EVs) are all part of a very nascent industry, making predictions about technology evolution and market penetration difficult and without precedent. Further, as will be discussed throughout this report, there are significant assumptions about trends and future scenarios that must be made in order to develop estimates of short- and long-term proliferation of these new technologies, and their impacts on the electric power grid.

4.0 Electric Vehicles

4.1 Feasibility of EVs

The feasibility of EVs is the most critical driver of widespread adoption of the technology in the United States. The feasibility aspect includes consumer preferences, technological and economic efficacy, electric utility grid infrastructure integration capabilities, and petroleum supply. As with any major industry requiring widespread consumer adoption and infrastructure investments, the challenges can be great and the transition away from the alternatives often requires a combination of market-driven growth and policy-level investment frameworks to catalyze the successful industry's launch.

4.1.1 Range and Charging Expectations for EVs

In a recent survey (Deloitte Automotive, 2010) of 2,000 current vehicle owners and automotive industry executives in the United States, key factors were identified about the feasibility of EVs from a consumer perspective. One of the most significant findings was that 70 percent of those surveyed indicated they would not purchase an EV until it had a 300-mile range. Also, it is important to note that a 300-mile range assumes some use of air conditioning or heat in the car, which can reduce the driving range of EVs up to 15 to 20 percent. This desire for an EV range equivalent to existing light-duty consumer vehicles is not surprising, but it is nevertheless extremely challenging for automakers to achieve at equivalent cost and packaging efficiency, because current batteries require more space per VMT than do gasoline tanks.

Another significant feasibility issue for EVs is where to "refuel." A charging infrastructure is proposed, but a notable conclusion of this survey was that most would prefer to charge their EVs at home, rather than at work. This implies that commercial charging infrastructure to compensate for limited range (<300 mi) is unlikely to be adopted by average consumers unless the charging facilities provide sufficient ease of use, including both physical connectivity and electricity accounting.

If it can be assumed that EVs will be charged at home, there arises an important question of when the recharging occurs. It could be late at night (which is beneficial to the utilities because it is off-peak time) or at other times throughout the day that are convenient for the drivers (e.g., in the evening, after the commute back home). Assessing the impacts of this critical question requires quantification of the effects of drivers' charging behavior on the grid from a technical and economic perspective. Further, the ability of consumers to decide based on their personal preference profile when to charge their vehicles will likely play a central role in their acceptance of EV technology, unless the utilities provide economic incentives that are high enough to change their behavior (e.g., reduced electricity costs during off-peak hours).

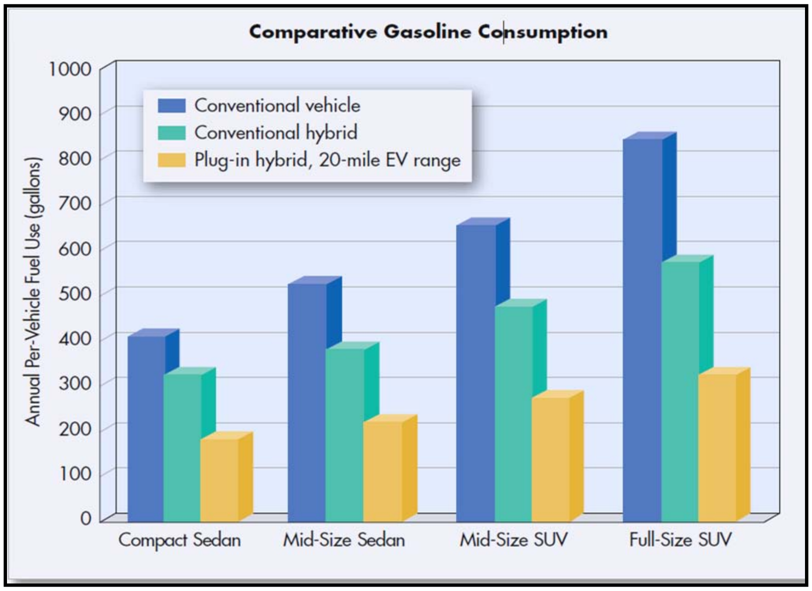
The primary conclusion of the Deloitte study is that all-electric vehicles will likely remain a niche transportation option in the marketplace, with limited adoption or impact on the electricity grid, until their driving range is equivalent to conventional light-duty passenger vehicles. In the interim, PHEVs with petroleum fuel may begin to achieve wider market adoption, with only minimal degradation of the power grid (because of the reduced battery capacity).

4.1.2 Cost Expectations for EVs

EV technologies currently have a cost premium attached to them that may discourage many consumers from purchasing. The batteries in particular are a primary cost driver for these EVs. However, as cited in Sanna (2005), battery costs are expected to decline significantly as economies of scale are realized from increased production. If this downward trend is realized, it will be more realistic to expect consumers to substitute EVs for their current vehicles.

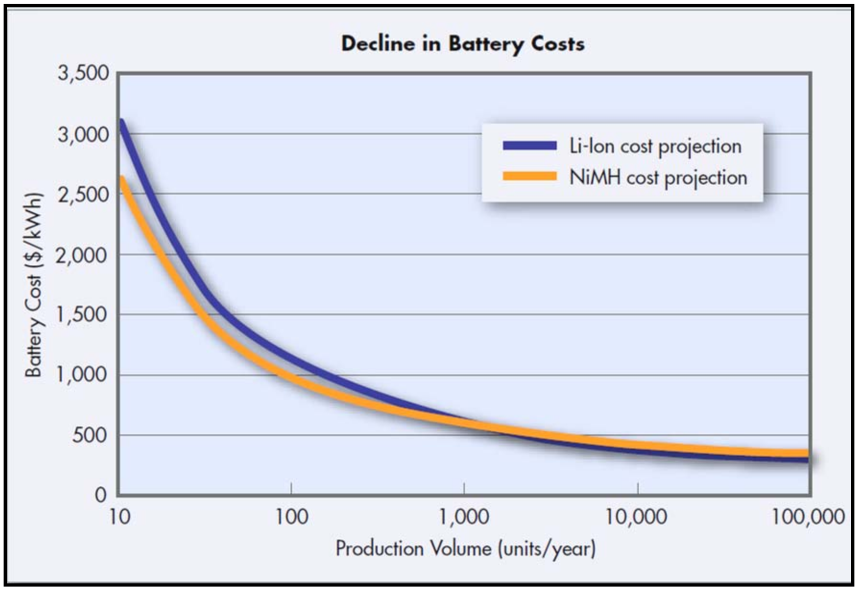
Figure 3 and Figure 4 below illustrate gasoline consumption and EV battery production costs. The battery production chart provides data for both lithium-ion (Li-Ion) and nickel-metal hydride (NiMH) battery types. Li-Ion batteries tend to have higher energy densities, and longer lives in terms of available charges and discharges. NiMH batteries have approximately the same energy density as Li-Ion, but are generally cheaper to produce. The gasoline consumption chart is useful in evaluating the financial tradeoffs of fuel savings for increased overall vehicle costs. For a more accurate comparison, this metric needs to be measured against both the total increased EV cost and the associated electricity fueling costs.

Figure 3: Comparative Gasoline Consumption



Source: (Sanna, 2005)

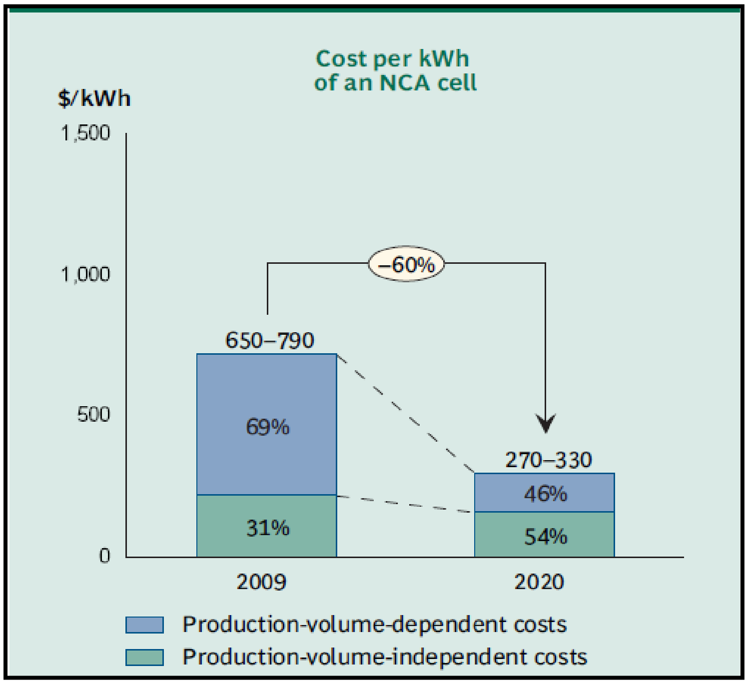
Figure 4: Decline in Battery Costs



Source: (Sanna, 2005)

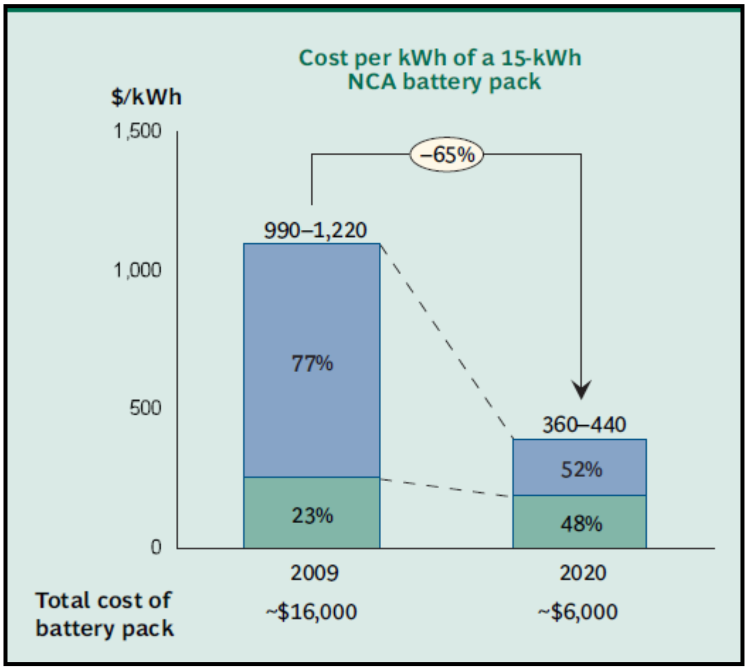
The Boston Consulting Group study (Dinger, et al., 2010) looks closely at batteries and their implications for future development of EVs. The study evaluates lithium-nickel-cobalt-aluminum (NCA) battery types, which are one of the more prevalent battery technologies currently being used in EV applications. It is also asserted in the study that batteries have a strong impact on EV prices, range, and performance relative to other options on the market. Additionally, batteries provide the majority of interaction between the vehicle and grid, so their development will be pivotal to building a grid infrastructure that supports EV charging. Figure 5 provides an estimation of changes in the battery costs, which are expected to decline 60 to 65 percent from 2009 to 2020.

Figure 5: Battery Costs per kWh of NCA Cells from 2009 to 2020



Source: (BCG, 2010)

Figure 6: Battery Costs per KWh of 15-kWh NCA Battery Pack from 2009 to 2020



Source: (BCG, 2010)

The Boston Consulting study presents several economic projections for battery cost, capacity, and technology. The report also draws implications from its projections of EVs and battery technology, as well as potential barriers to the realization of those projections. Much of this analysis is drawn directly from battery suppliers, and does not take into account potentially significant shifts in technology in the battery industry.

Another report (Hauffea et al., 2009) notes that battery manufacturing alone can emit 2 to 5 percent of the lifecycle GHGs of the vehicle assuming the battery can last the life of the vehicle. This sizable emissions value reflects the energy intensity of mining and manufacturing of advanced batteries such as Li-Ion. Battery manufacturing is estimated to represent an approximately 20 to 30 percent increase in vehicle energy manufacturing cost as compared to the cost of CVs.

One of the most significant issues from a consumer and grid operator perspective is that out of all the battery configurations (7-, 20-, 40-, and 60-mile battery capacity) analyzed in the Hauffea et al. report, the 7-mile battery capacity is shown to be both cost effective and net GHG emissions reducing in urban driving cycles. All larger battery configurations did not provide compelling cost-benefit trade-offs.

If a smaller, 7-mile-capacity battery configuration became the norm, the positive impact for grid operators is that the duration of peak demand may not be as excessive as with larger capacity batteries. While the power draw is likely to be reduced somewhat, advances in faster-charging batteries are likely to reduce this grid benefit in favor of consumers who would prefer more convenience. It should be noted that a 7-mile-capacity battery would likely be unappealing to consumers who do not live in dense urban areas, as the incremental cost of an EV drivetrain and battery would likely outweigh the benefits of such a short electric VMT capacity.

PHEV battery optimal sizing is also highly dependent upon the average distance the vehicle will be driven between charges. For the 20-, 40-, and 60-mile capacity, there is a net GHG reduction; however, the cost is prohibitive and a traditional hybrid electric is more economical.

4.1.3 Innovative Policies to Enhance Feasibility

The creation of innovative and supportive policy regimes aimed at facilitating the market development of EVs will be crucial to their success. This includes policy stipulations that allow for increased emissions from utilities that generate electricity used to fuel the EV fleet. In other words, any regulation aimed at capping GHG emissions from electric utilities nationwide will need to allow for a distinct set of increases in emissions coming from electricity generated to charge EVs. This would most likely require the use of special in-home meters for EV charging. Since emissions caps will likely be based on historical demand and associated projections, the new and highly uncertain demand coming from EVs will be difficult to model. This conundrum could result in complex accounting requirements from the utilities to segregate generation used by EVs. However, with the increasing penetration of renewable energy sources and their intelligent pairing with EV charging patterns (e.g., wind power), the overall emissions increases will not correspond directly to increases in traditional generation sources such as coal and gas turbines. Further, the current regulatory environment in the United States presents a unique opportunity to construct legislation that would favor the EV fleet nationwide, since California is currently the only state with GHG emissions caps in place.

The Economic Impact of Electrification Roadmap (2010), created by the Electrification Coalition in Washington, DC, highlights key actions that would support a transition to an electrified LDV transportation environment. The report identifies seven key policies to increase the market adoption of EVs:

- Stationary battery applications to increase the early-stage market size
- Loan guarantees to retool vehicle assembly factories
- Guaranteed residual value for automotive batteries
- Instant vehicle tax credits at point-of-sale to negate the price differential of EVs
- Commercial-scale charging infrastructure tax credits to business at 75 percent cost
- Home charging infrastructure tax credits
- Utility Smart Grid information technology tax credits at 50 percent

Many of the key economic growth and impact calculations are based upon the University of Maryland “Inforum LIFT” economic model. Limitations of this model could impact the ultimate results of the economic forecasts, particularly in the hard-to-model future scenarios beyond 2015.

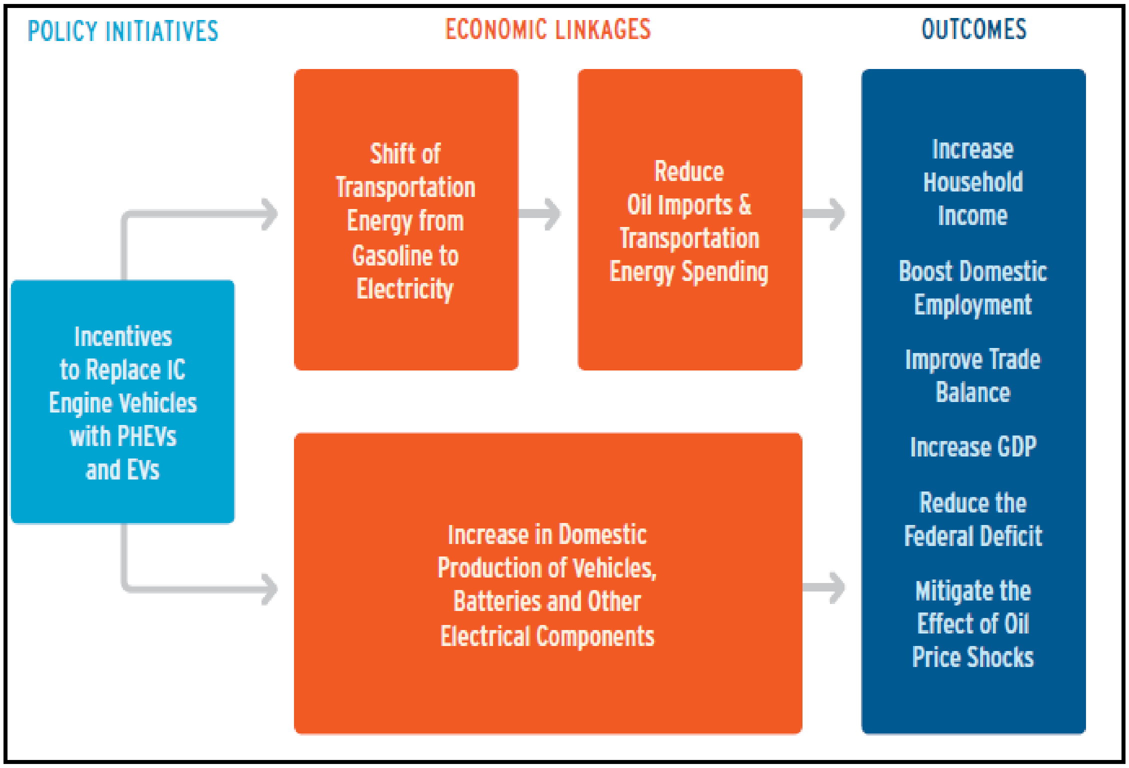
Geographic locations are also developed for early adoption of EVs, referred to as “electrification ecosystems.” This approach was recently included in the legislation by House and Senate leaders, called “Electric Drive Vehicle Deployment Act of 2010” (HR 5442, 2010). This legislative effort is requesting funding of $11B to support 5 to 8 electrification ecosystems (locations) across the United States. The policies are outlined with an emphasis on proof of concept and validation of economic benefits, with 50,000–100,000 vehicles per location by 2013, and 400,000–500,000 per location by 2018.

Detailed policy and macroeconomic projections (trade deficit impact, federal revenue, employment benefits, global oil demand reduction, annual household income) of PHEVs and EVs are outlined in this document. Two key projections, based upon the University of Maryland “Inforum LIFT” model, are that by 2030 annual household income will rise by $2,800 and that households will experience a $4.6 trillion (2008 dollars) increase in aggregate income during the 2010 to 2030 period.

Such sizable figures indicate large potential impacts of electrification and warrant further investigation. The planned “electrification ecosystems” would be the first step in proving the benefits of electrification. When presented with both government policy and tax incentives, such as fixed trade-in values for batteries, the Electrification Coalition takes a practical approach and straightforward path to drive the early adoption of EVs, despite current economic competitiveness issues with conventional petroleum-powered vehicles.

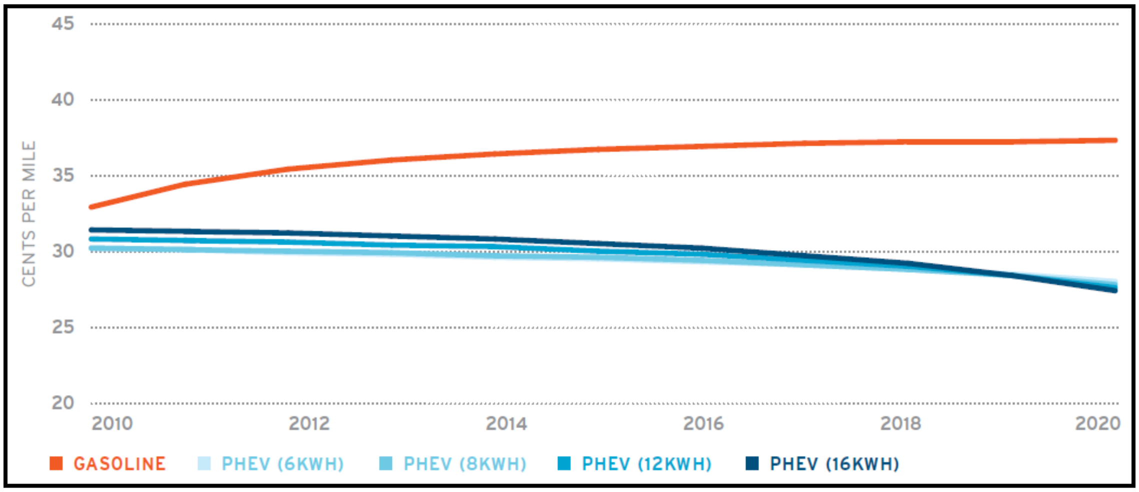
Figure 7 through Figure 9 present the findings from the report in terms of the effect of electrification coalition policies, and total cost of ownership for PHEVs and EVs (including the American Recovery and Reinvestment Act [ARRA] tax credit).

Figure 7: Effects of Electrification Coalition Policies



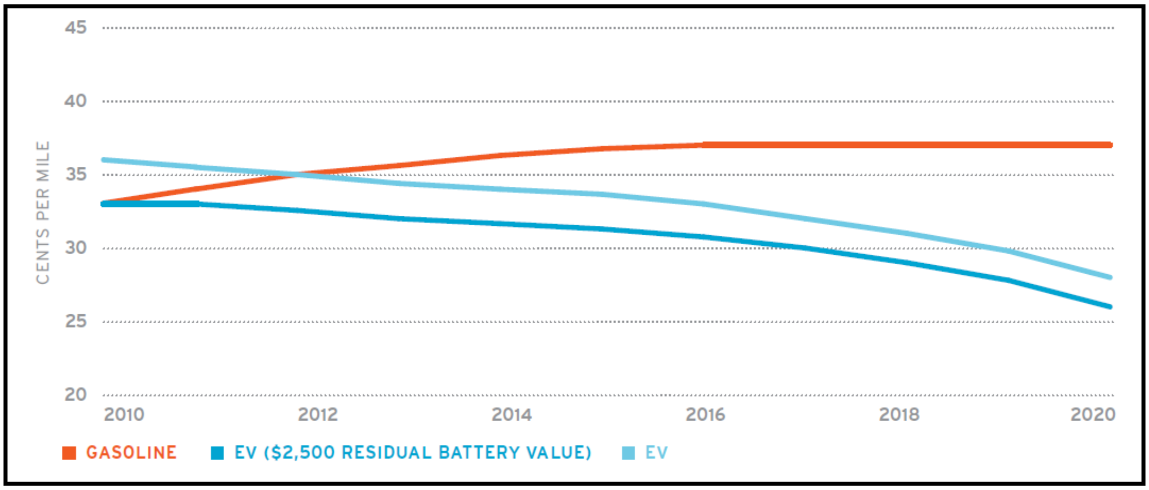
Source: (The Electrification Coalition, 2010)

Figure 8: PHEV Total Cost of Ownership, Including ARRA Tax Credit



Source: (The Electrification Coalition, 2010)

Figure 9: EV Total Cost of Ownership, Including ARRA Tax Credit



Source: (The Electrification Coalition, 2010)

The Electrification Coalition report primarily focuses on policymakers, providing an economic/macroeconomic overview. It provides a simplistic view of deployment that leaves out required infrastructure improvements necessary to support such deployments. The study seems somewhat pessimistic on the overall budget impact of the policies proposed—namely, that it would take several decades to pay back the initial government investment in policies. The authors believe that this is due to the metrics selected by the study, and with externalities accounted for, the picture would look much more positive.

4.1.4 Consumer Surveys on EVs

An extensive report by Axsen and Kurani (2008) surveyed 2,400 individuals who were widely dispersed across the United States and qualified as “new vehicle buying households.”[5] Notable results from the study indicate a large degree of consumer confusion on current hybrid EVs and PHEVs.

The survey results indicate significant confusion about the key attributes most desired by consumers as they examined potential PHEV performance attributes. The key attributes identified are:

- Fuel efficiency in charge-depleting mode
- Charge-sustaining mode efficiency
- Blended versus all-electric efficiency
- All-electric range
- Battery recharge speed

The highest-ranked attribute, however, was the greatest overall fuel efficiency (MPG). The lowest-ranked attribute was battery recharge speed. This provides insight into consumer preference for minimized operating expenses, through lowest perceived cost per mile.

With reference to infrastructure assumptions, the survey estimates that 50 percent of the new-car-buying population has the existing home infrastructure to support an EV or PHEV, at 110V minimum. This is in contrast to other studies that cite only 33 percent of the new-car-buying population having the infrastructure and desire to have an EV.

The final analysis in the Axsen and Kurani report combines information from the survey respondents (driving habits, recharge potential, and PHEV design priorities) to estimate the energy impacts of the respondents’ existing travel and understandings of PHEVs under a variety of recharging scenarios. The results indicate that peak load occurs around 6 p.m. weekdays with a more traditional “plug and play” approach, where the respondents charge between 6 p.m. and 8 p.m. on weekdays. A smart charging approach that defers charging between 8 p.m. and 6 a.m. (next day) on weekdays will offset existing peak demands on the electric grid, and utilize the non-peaking resources available during nighttime. The difficulty with the traditional “plug and play” grid approach is that the PHEV consumption peak closely corresponds to the current load dispatch peak, which implies a requirement for greater generation and transmission capacity. Using a "smart charging" approach to vehicle charging allows for potential pricing incentives during low-demand evening hours.

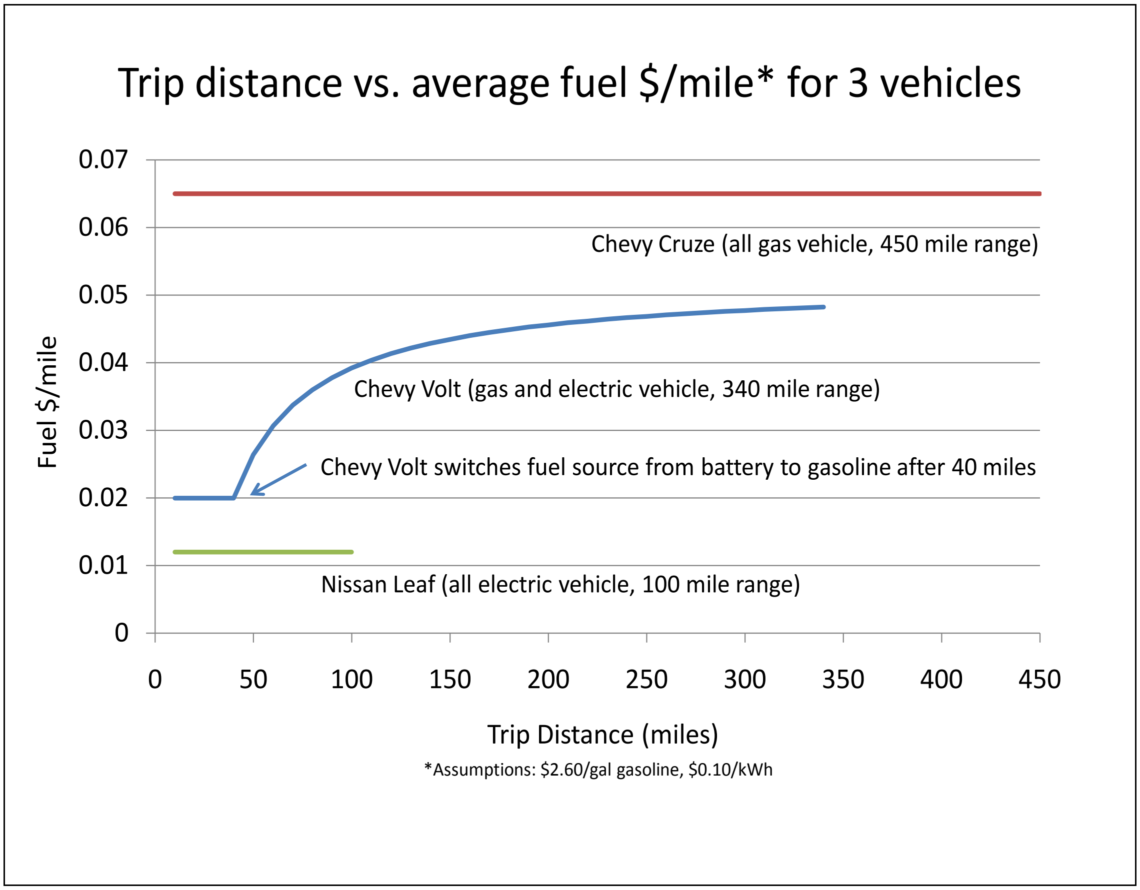
---

[5] These are households that are currently actively looking to purchase a new automobile.

4.1.5 Case Study

There are two EVs that will be available to the American public starting in 2011. The first is the Chevy Volt, a PHEV that runs from battery power for the first 40 miles before switching to an ICE. The second is the Nissan Leaf, an all-electric vehicle that will have an urban range of 100 miles. For purposes of comparison, the Chevy Cruze is included as a representative CV. In Figure 10, it is evident that the Nissan Leaf has the lowest $/mile fuel expense of the three vehicles due to its all electric range and relative performance efficiency per unit of energy used. As the Volt only runs on battery power for the first 40 miles, the cumulative fuel expense gradually increases as the length of the trip increases, and more of the journey is spent utilizing gas power versus battery power. Both EV options are preferable to the Chevy Cruze in terms of fuel expense per mile due to the distinct advantage of battery power on decreasing operating costs.

Figure 10: Trip Distance vs. Average Fuel $/Mile for the Three Sample Vehicles



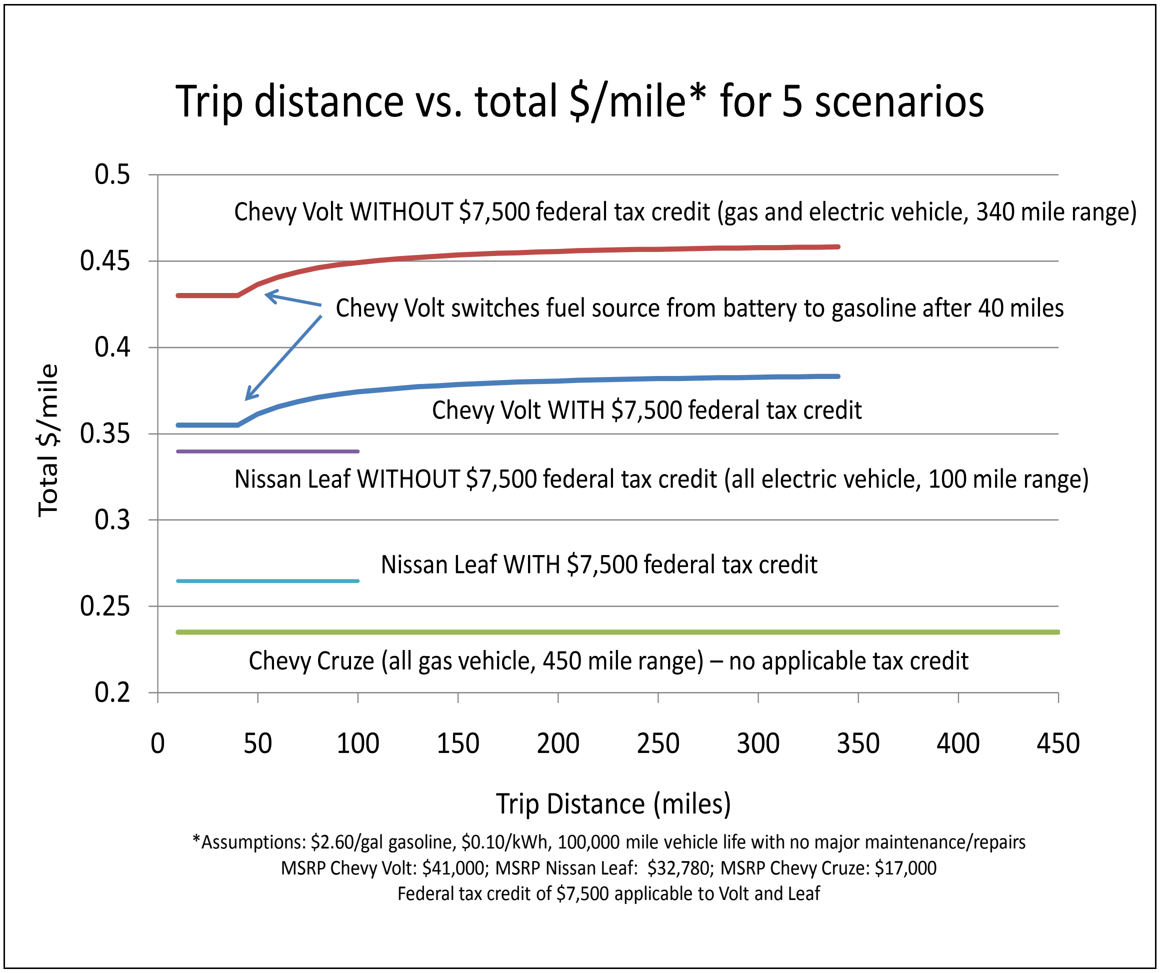
Hybrid and electric vehicles are more expensive than ICE systems due to the relative newness of the technology and the absence of a long history of research and development into equipment and commercial production efficiency. Figure 11 lists the manufacturer's suggested retail price (MSRP) as well as a $7,500 tax credit that is available to US consumers for the Volt and the Leaf. Both EVs have a battery warranty that guarantees 8 years or 100,000 miles. For the purpose of comparison, the vehicle purchase price, minus any applicable tax credits, is spread over the assumed 100,000 mile life of each vehicle.

Figure 11: Capital Expenses of the Three Vehicle Options

	MSRP	Tax Credit	Price after tax credit	Warranty	Assumed life of the vehicle	Capital Cost $/mile
Chevy Volt	$41,000	$7,500	$33,500	Battery: 8 years, 100,000 miles	100,000 miles	$0.335/mile
Nissan Leaf	$32,780	$7,500	$25,280	Battery: 8 years, 100,000 miles	100,000 miles	$0.252/mile
Chevy Cruze	$17,000	$0	$17,000	Powertrain: 5 years, 100,000 miles	100,000 miles	$0.17/mile

In order to get a clear picture of the expense and advantages/disadvantages of these three vehicles, the total cost per mile of travel must be calculated from a combination of both the per mile fuel expense and the per mile capital cost. Figure 12 plots the total per mile cost for each vehicle. In this graph, both the Volt and the Leaf are more expensive than the Chevy Cruze, due to the higher vehicle prices. The advantages in smaller operating expenses is negated by the upfront purchase cost. Figure 13 lists the actual $/mile capital and operating expenses of the three vehicles. The advantage of the Volt over the Cruze in terms of $/mile operating expense is $0.045/mile while under battery power. But at the same time, the price premium that a consumer must pay for a Volt is $0.165/mile in excess of the upfront cost for a Chevy Cruze.

Figure 12: Trip Distance vs. Per Mile TOTAL Cost for Each Vehicle



*Assumptions: $2.60/gal gasoline, $0.10/kWh, 100,000 mile vehicle life with no major maintenance/repairs
MSRP Chevy Volt: $41,000; MSRP Nissan Leaf: $32,780; MSRP Chevy Cruze: $17,000
Federal tax credit of $7,500 applicable to Volt and Leaf

Figure 13: Table of $/Mile Expenses for Three Vehicle Examples

	Capital Cost $/mile	Average $/mile fuel expense	TOTAL cost $/mile
Chevy Volt	$0.335/mile	Variable: $0.02 - $0.048/mile	Variable: $0.355 - $0.383/mile
Nissan Leaf	$0.252/mile	$0.012/mile	$0.264/mile
Chevy Cruze	$0.17/mile	$0.065/mile	$0.235/mile

4.1.6 Summary

Significant barriers to EV adoption remain. It is a fledgling industry supported by government subsidies and will have difficulty competing with existing technology in the near term based upon simple economics. Battery vehicles do exhibit a strong advantage in terms of operating expense, or fuel $/mile. The Chevy Volt has an initial operating expense while under battery power of $0.02/mile, compared to $0.065/mile for the gas-powered Chevy Cruze. But the upfront cost of the vehicle more than eliminates this advantage. With basic assumptions about the life of the vehicle (100,000 miles, no major maintenance/repairs), a consumer should expect to pay $0.335/mile for the Chevy Volt to cover the purchase price, while only $0.17/mile is necessary to cover the price of the Cruze. This is in part because conventional internal combustion vehicles have a 100-year head start including billions of dollars in industry research and development. Key influencing factors for EVs' success will be the existence of carbon legislation, consumer preferences that put pressure on auto manufacturers and electric utilities to help drive the market, and the overall production and fueling economics of the vehicle fleets.

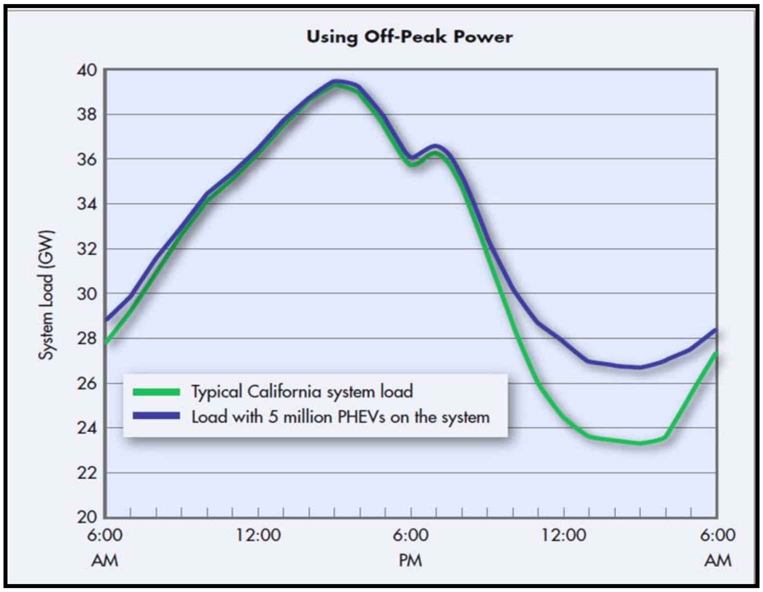
4.2 Utility Perspective on EVs

The increased concern about the environment and recent advances in EV technology will enable growth for various types of EVs. Due to their high energy capacity, mass deployment of EVs will have significant impact on the power system network. This impact will dictate the design of vehicle interface devices and the way future power system networks will be designed and controlled. In addition, the influence of the major power generation and transmission utilities will have a significant impact on the rollout of EVs as they determine the capability to realize the ancillary benefits of EV ownership, such as V2G.

4.2.1 Opportunistic Charging Schemes

Various opportunistic charging schemes exist that utilize off-peak, idle generation capacity for EV battery charging. These methods are effective in the current dispatch curve, but are increasingly difficult to achieve as EV adoption rates increase. As the number of vehicles increases and user behavior is better understood, , effectively managing charging patterns could prove difficult. If done improperly, there could be significant ramifications for electric utilities in terms of generation requirements and costs. However, with effective, Smart Grid-enabled charging dispatch, EVs could deliver energy costs savings to consumers and increased profits to electric utilities, not to mention reductions in GHG emissions and overall environmental impact from the transportation sector.

Figure 14: Power System Loading with PHEVs Using Off-Peak Power



Source: (Sanna 2005)

Off-peak charging, though attractive on the surface, presents some major issues from a utility perspective. Perhaps most important, distribution equipment is utilized longer, reducing its lifetime through more sustained high-temperature-related stress. Recent research (Gerkensmeyer et Al., 2010) indicates possible reductions in transformer life from 60 to 40 years. Utilities that make significant long-term investments in power infrastructure will be hesitant to sacrifice the longevity of their equipment unless the economic incentives are sustainable. However, the average energy consumer with limited awareness of appropriate charging durations uses electricity to charge EVs at any time during the day. This presents a scenario where the utilities are unable to avoid the resulting system stress from PHEV charging, in absence of refined Demand Response (DR) capabilities such as delayed and variable voltage regulation charging schemes. Additionally, if utilities have some control over EV charging, the overall capital investment costs for utility baseload generation will be lower than those of peaker units, making off-peak charging the likely candidate selection from the utility's perspective for EV powering.

4.2.2 Vehicle-to-Grid Applications

Vehicle-to-grid (V2G) describes the concept of using an EV's battery to provide regulation services for electricity markets when the vehicle is plugged in during the daytime. This could enable greater renewable power by supporting the electricity output swings and acting as a distributed storage source. This may become the only realistic form of opportunistic charging that has true long-term potential when scaled to ~100+ million vehicles. If consumer incentives are high enough, drivers may alter behavior significantly to reap revenue benefits from selling their battery's energy to the utility.

This would align consumer EV charging behavior with renewable energy generation utilization—which is a desirable outcome when renewable energy percentages increase past current state mandates of around 10 to 15 percent.

A study *("A Conceptual Framework Design for Implementation of Vehicle to Grid")* by George Cross (2009) from the Department of Electrical Engineering at University of Illinois-Urbana Champaign explores potential design considerations in implementing V2G configurations with battery vehicles (BVs). The study looks at potential charging needs for BVs and proposes frameworks for aggregating them into smarter loads that can also provide services. The study also outlines potential implementation issues around metering communication control needs, and design of an incentive program.

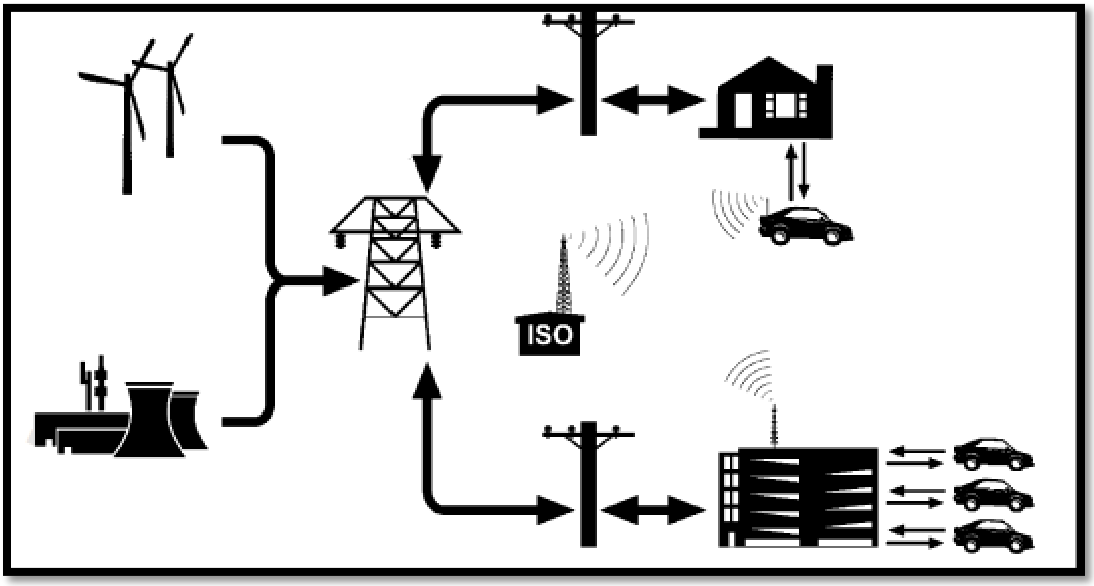
Cross provides a V2G conceptual framework that focuses on:

- Issues related to aggregating BVs and their interaction with the electric grid through the Independent System Operators (ISOs) / Regional Transmission Organizations (RTOs).
- Exploring the role of the aggregator as the market maker for V2G services.
- Providing implementation challenges that could be encountered while setting up a V2G market.

The study provides useful technical parameters of electric use patterns and their impact with the introduction of BVs. It looks into issues specific to the use of BVs for grid services while focusing on the perspective of the aggregator, which is an imaginary entity. It is clear that this entity can exist conceptually as a sort of "broker," but in the real world it is not clear who would occupy this role. It could possibly be an independent business organization or an extension of an existing stakeholder such as a utility or the ISO/RTO. However, the study does not explore the BV owner's perspective on how their vehicles interact with the grid.

Another study (Tomic and Willet, 2007) provides a broader V2G concept using fleets of battery-EVs to provide ancillary services. Figure 15 provides a schematic of connections between the EVs and the electric power grid.

Figure 15: Illustrative Schematic of Power Lines and Wireless Control Connections between Vehicles and the Electric Power Grid



Source: (Tomic, 2007)

The Tomic and Willet study also discusses potential economic value and payment schemes for grid regulation services provided by EVs. The study demonstrates variance across vehicle types and market setups with factors such as the value of ancillary services in the area, the power capacity of the vehicle, and the energy capacity of the vehicle.

This report provides information on a methodology by which the vehicles can contribute to the grid, and a rough quantification of the value that service can provide. Additional technical dimensions of V2G and its implementation with respect to dynamics of charge controllers for vehicle owners and various payment schemes are in early development stages and hold great promise.

Probably the most concerning aspect of the current state of V2G is that the recently established electrical connection standard between vehicle and charger to be used by all major automotive manufacturers (Society of Automotive Engineers SAEJ1772) does not include a communication standard that supports direct V2G communication. Only limited charge-specific data are communicated between the vehicle electronics and charging system. This likely means that the first generation of EVs may not have real-time communication ability with grid operators.

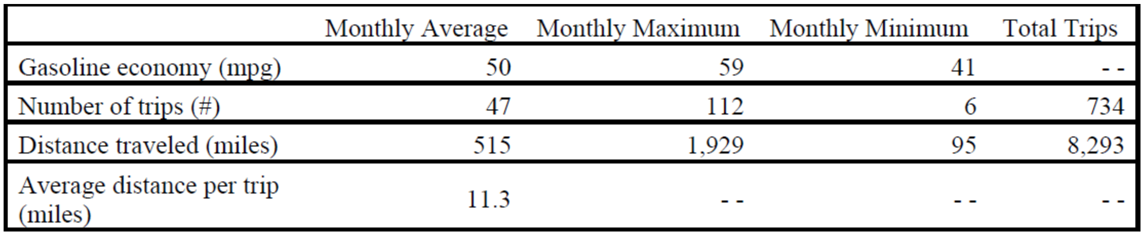
4.2.3 Consumer EV Demand Impacts on Power Grids

Utility infrastructure requirements and associated costs will be driven by consumer behavior, early adopters of PHEV technology, and state/federal mandates. The study by US DOE Battelle Energy Alliance (Morrow et al., 2008) looks at typical driving behaviors, derived from information about current drivers as well as early PHEV adopters, and uses those behaviors to extrapolate PHEV charging parameters such as charge power, charge energy, and charge times.

The study provides analysis for potential customer needs for PHEVs and infrastructure required to support those individual needs. It suggests that a 40-mile range is sufficient for most users, but looks at a variety of vehicle charge time and energy/capacity combinations.

The Idaho National Laboratory (INL), as part of the DOE Advanced Vehicle Testing Activity, collected data from nine Toyota Prius's converted by HyMotion to PHEVs that operated in five different states during the months of January and February 2008. The vehicles were designed with a charge-depleting range of approximately 30 miles. Table 4 and Table 5 along with Figure 16 and Figure 17 present the data collected from those nine Toyota Prius vehicles.

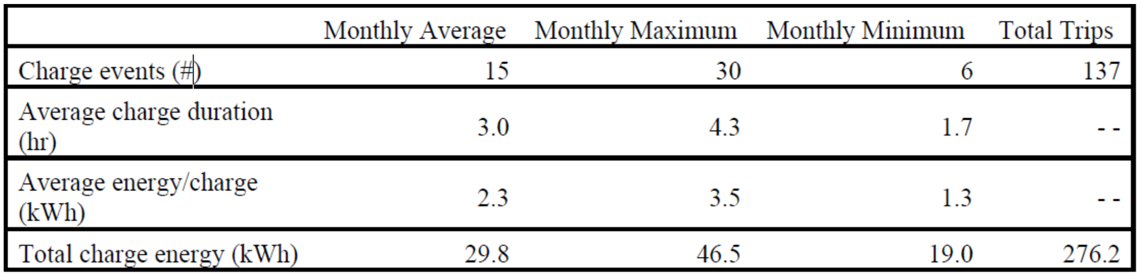
Table 4: Vehicle Trips in January and February 2008



	Monthly Average	Monthly Maximum	Monthly Minimum	Total Trips
Gasoline economy (mpg)	50	59	41	- -
Number of trips (#)	47	112	6	734
Distance traveled (miles)	515	1,929	95	8,293
Average distance per trip (miles)	11.3	- -	- -	- -

Source: (Morrow, 2008)

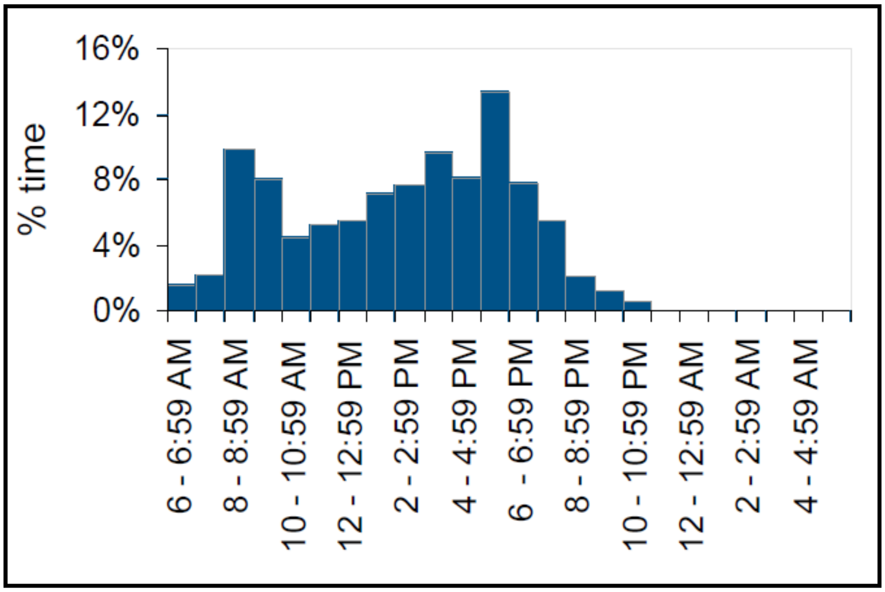
Table 5: Charging events for January and February 2008



	Monthly Average	Monthly Maximum	Monthly Minimum	Total Trips
Charge events (#)	15	30	6	137
Average charge duration (hr)	3.0	4.3	1.7	- -
Average energy/charge (kWh)	2.3	3.5	1.3	- -
Total charge energy (kWh)	29.8	46.5	19.0	276.2

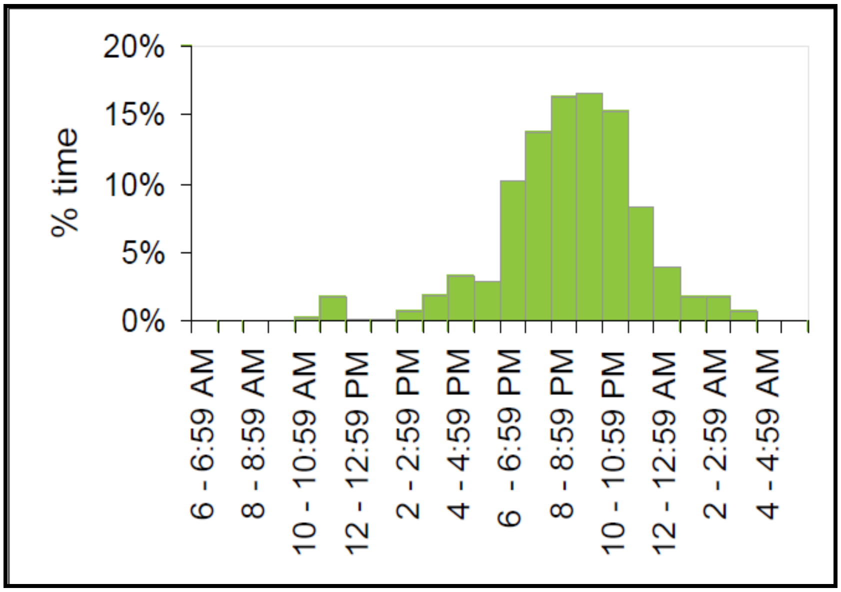
Source: (Morrow, 2008)

Figure 16: Time of Day When Driving for January and February 2008



Source: (Morrow, 2008)

Figure 17: Time of Day When Charging for January and February 2008



Source: (Morrow, 2008)

The study also analyzes apartment and single-family-home-based users, and assesses costs to install infrastructure at individual locations with various electrical configurations. The study distinguishes between level 1 (basic, 120 V plug), level 2 (conductive or inductive, 240 V), and level 3 (fast charging, 480 V, 3 phase) charging station types.

These factors have a major impact on the shape of the dispatch curve for utilities, since fast charging could minimize the long-term demand spikes peaking between 8 and 10 p.m.

4.2.4 Transmission and Generation Infrastructure Requirements of EVs

A study by Kintner-Meyer et al. (2007) shows that 52 percent of U.S. petroleum imports can be replaced by PHEVs without upgrading the current electrical grid ("upper limit of the PHEV penetration without requiring new investment in generation and Transmission & Distribution capacity expansions"). This equates to the fueling of 158 million vehicles and a 27 percent overall reduction in CO_2 emissions. This is a "fill the valleys" method. Any additional T&D capacity and generation increase is described as "icing on the cake." SO_X emissions and particulates increase significantly in most regions. However, NO_X emissions are highly regionally dependent. Notably, there is a shift of emissions from urban to rural locations. These calculations were performed using the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

It is assumed that the T&D system can run at full capacity (with coal and natural gas running at a 0.85 capacity factor, to include outages) to deliver electricity to the maximum number of PHEVs at the upper limit of penetration. It is also assumed that the average commute is 33 miles round-trip (data available from the Transportation Research Board).

The Kintner-Meyer study shows that the electrical grid can take far more PHEV penetration than is likely based on market and technological forces such as plug types, building upgrades, charging infrastructure, and competing vehicle technologies.

A study by PNNL (Schneider et al.) explores the impact of a widespread deployment of PHEVs on the electric power distribution system, using the Pacific Northwest as a case study. The study looks at the charging patterns of PHEVs under slow- and quick-charge scenarios. These charging patterns have significant impact on the electric power distribution system in the Pacific Northwest. It estimates that the Northwest distribution system can support up to an 18 percent penetration of PHEVs in its current form.

As this study focuses primarily on Pacific Northwest as a case study, generalizations of its results are limited. One of its limitations is that it focuses only on the technical potential for managing PHEV charges, rather than including the market adoption and economic arguments. Since the technical potential boundary is based purely on the technological resource capacity that could support this penetration of PHEVs, and it does not address the realistic, economically viable penetration rates, the study is limited to defining the best-case scenario under the capped-generation investment framework. The authors believe that the study would benefit from more analysis of the costs of providing support infrastructure to increase desired penetration levels. It could also benefit from a more in-depth exploration of smart chargers and smart grid as a method for alleviating some of the strain on the distribution system caused by a potential widespread PHEV deployment.

4.2.5 Generation Impact Analysis

A study by Oak Ridge National Laboratory (ORNL) (Hadley and Tsvetkova, 2008) attempts to quantify the effect of driver choice on the grid from a technical and economic perspective. The study involves 91 scenarios each for 2020 and 2030, based on 13 NERC regions, 3 charging rates (1.4 kW, 2 kW, 6 kW), two times to plug in (evening = 5 p.m. or night = 10 p.m.), plus one business as usual (BAU) (no PHEV) case. It projects 25 percent market penetration of PHEVs by 2020.

For each region, grid reliability is examined with respect to substation or line overloading. Dispatch is affected if there are a number of PHEVs, or if a significant percentage recharge exists during the day or evening. In the presence of load shaving, consumers recovering from demand response events on a hot day and consumers plugging in their PHEVs after work could stress the power system network.

The study shows that coal is mostly used as a percentage of new generation if the charging is done slowly and at night (i.e., 1.4 kW), and PHEVs compare favorably with 40-mpg HEV vehicles. In the ideal charging scenario (nighttime), PHEVs are estimated to have fueling costs of approximately 25 percent that of HEVs, with higher emissions of NO_X and SO_2. CO_2 emissions increase about 10 percent. This is because renewables such as wind are not assumed to be integrated. Evening charging is shown to cause a risk to the reserve margins for some regions, while nighttime charging may change dispatch if there are enough PHEVs.

4.2.6 Economic Considerations of EVs

An article by Rocky Mountain Institute (Swisher et al., 2010) looks at the potential economic and policy implications of a PHEV deployment from a utility perspective. In particular, it explores the impact of decoupling rate structure reform on eliminating a disincentive for PHEV deployments. Rate decoupling provides a disincentive for load growth because it rewards utilities for measures that reduce overall energy generation. This is at odds with development of the EV industry, since EVs would require load growth with increasing market penetration.

The article explores issues regarding the deployment of PHEVs and incentive structures for utilities to either encourage or discourage PHEV deployments. A separate PHEV metering infrastructure is proposed to create transparency in emissions accounting and use of electricity for PHEVs. A separate rate structure for PHEVs that could accommodate and promote these vehicles is proposed.

This study focuses on the California market, which serves as a specific scenario with decoupling rules. Other markets with different decoupling rules or no decoupling rule may reach different conclusions about the appropriate treatment of PHEVs. The study would benefit from more in-depth discussion on how utilities would affect the rate of deployment of PHEVs, other than the rate structure, which is primarily decided by regulators. Examples of these include decisions to build charging infrastructure, treatment of households with PHEVs, and financial incentive payments. Further research on utility revenue models and other key variables that influence revenue collection would help for a national-scale implementation.

4.2.7 Summary

Currently, PHEV technology is not seen as competitive, but rather complementary, to CV technology, with PHEVs penetrating deeper into suburban markets and CVs maintaining market share in rural areas. As fuel economy standards for CVs increase substantially over the next five years, CVs will be more competitive both economically and environmentally. This has substantial implications for the electrical grid in the United States because it lowers PHEV market penetration estimates relative to studies based on the assumption that PHEVs will replace CVs. Even if there was a mass transfer of CVs to PHEVs, research shows (Kintner-Meyer, 2007) that 52 percent of U.S. petroleum imports can be replaced by PHEVs without upgrading the current electrical grid. The transmission and distribution system (T&D) can run at full capacity to deliver electricity to the maximum number of PHEVs at the upper limit of penetration. Another important note is that PHEVs are estimated to have fueling costs of approximately 25 percent that of HEVs, with higher emissions of NOx and SO2, and CO_2 emissions increases of about 10 percent. In the absence of opportunistic charging schemes managed and choreographed by the utility, the impact of EVs on the grid could be substantial and result in increased capital investment and overall emissions. However, with effective V2G and DR programs, the utilities could realize significantly increased profits with minimal additional capital investments. This includes the potential opportunity to shift away from costly and inefficient peaking plant generation sources and an increased ability to efficiently integrate and dispatch intermittent renewables. Further, the primary impact on the utility from well-managed EV charging will be an increased nighttime utilization of idle baseload capacity, primarily from coal generation.

4.3 Environmental Impacts of EVs

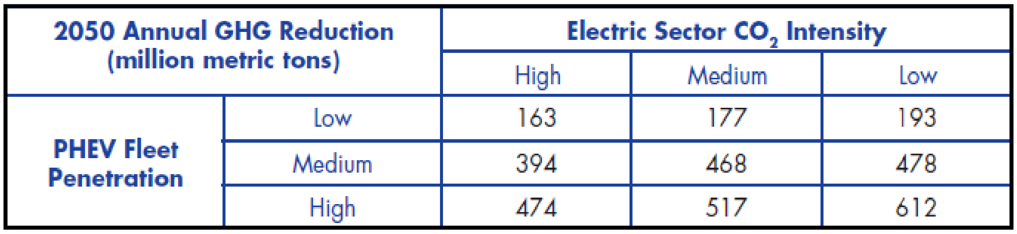
Significant emissions reductions are possible through EVs, which are relatively costly compared to reducing emissions from other vehicle efficiency technologies, such as using lightweight materials and optimizing engine performance for increased gas mileage. Recent studies (BCG, 2009) note that CV technology will continue to dominate the auto market in 2020, but that hybrid sales may reach 11 million per year, while EV/Extended Range Electric Vehicle (EREV) sales may reach 3 million per year in 2020.

A major factor in realistic environmental impacts will be geographic deployment rates of EVs. Projected sales of different types of powertrain models in 2020 will vary geographically over various regions, but to make measurable impacts, usage will need to be concentrated in existing high GHG emissions areas, primarily where coal is the main power generation source. A number of competing fuels and drivetrain technologies exist, with tradeoffs in terms of total cost of ownership for the buyer as well as emissions benefit to society. There are no simple answers to the environmental impact of EVs, particularly since Li-Ion battery manufacturing can account for 2 to 5 percent of a vehicle's lifetime GHGs. Appropriate analytical boundaries are critical to understanding the environmental impacts of EVs from a holistic, life-cycle perspective.

4.3.1 U.S. Greenhouse Gas Impact Projections

A study by EPRI (2005) analyzes the GHG emissions of PHEVs between 2010 and 2050. The projections (see Table 6) support the understanding of the affects of PHEVs on the air quality of the United States. Throughout the projections, it is clear that a wide variety of adoption scenarios can significantly affect the overall GHG impacts.

Table 6: Annual Greenhouse Gas Emissions Reductions from PHEVs in the Year 2050



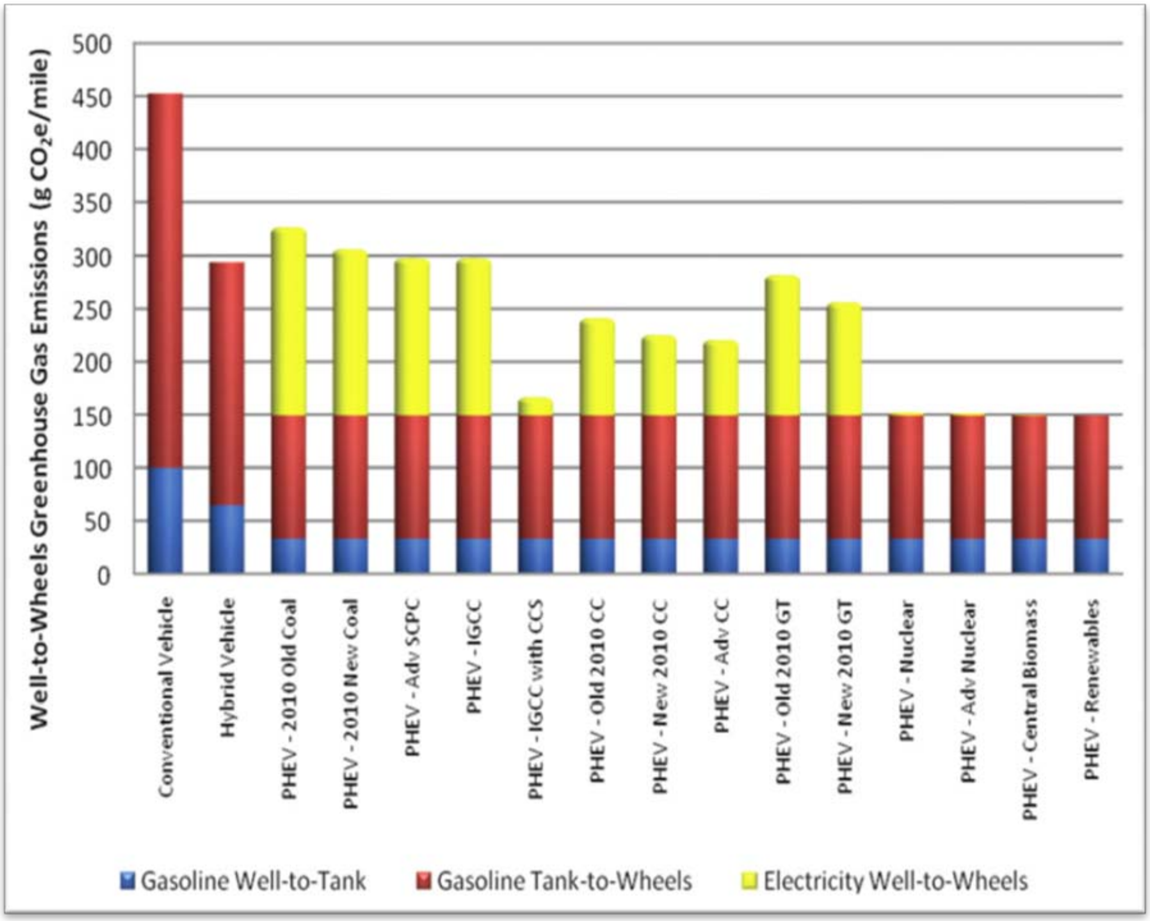
2050 Annual GHG Reduction (million metric tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

Source: (EPRI, 2005)

Several specific themes are identified, including market share and GHG impacts. The assumptions regarding market share of PHEVs and hybrids are not clear. The assumption that 50 percent of the market is PHEVs by 2025 is critical, and at the high end of expected range. The study looks at various options for hybrid, PHEVs, or CVs on CO_2 emissions/mile. A "well-to-wheel" approach was used for analysis of economic performance.

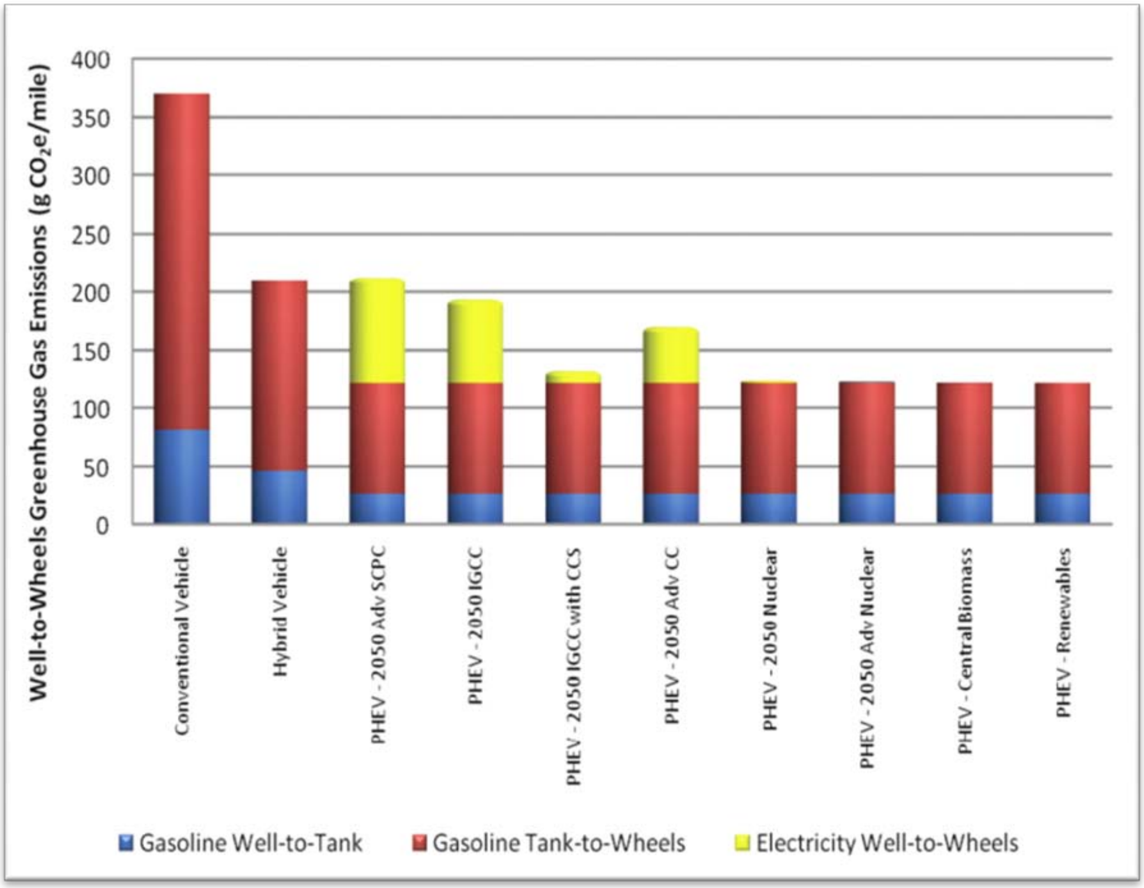
Figure 18 and Figure 19 highlight the various impacts of generation technology on GHGs for PHEVs. Note that the first chart is a 2010 baseline, while the second chart is a 2050 scenario, with advanced emissions control technology:

Figure 18: Year 2010 Comparison of PHEV 20 GHG Emissions When Charged with Electricity from Specific Power Plant Technologies, 12,000 Miles Driven per Year



Source: (EPRI, 2005)

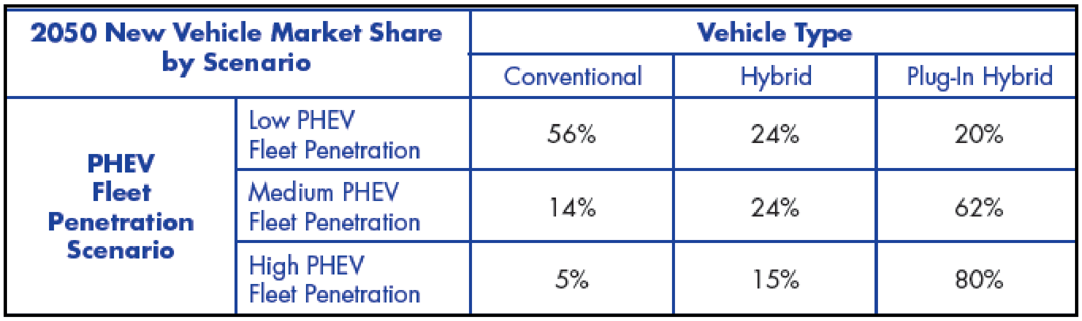
Figure 19: Year 2050 Comparison of PHEV 20 GHG Emissions Charged Entirely with Electricity from Specific Power Plant Technologies, 12,000 Miles Driven per Year



Source: (EPRI, 2005)

The analysis and graphs are useful if the assumptions are reasonable, but the forecasts are subject to wide variability. The graphs support an accurate cross-walk evaluation of generation options with various vehicle powertrains. Table 7 below provides the PHEV market penetration potential for three PHEV adoption scenarios.

Table 7: Peak New Vehicle Market Share in 2050 for the Three PHEV Adoption Scenarios



2050 New Vehicle Market Share by Scenario		Vehicle Type		
		Conventional	Hybrid	Plug-In Hybrid
PHEV Fleet Penetration Scenario	Low PHEV Fleet Penetration	56%	24%	20%
	Medium PHEV Fleet Penetration	14%	24%	62%
	High PHEV Fleet Penetration	5%	15%	80%

Source: (EPRI, 2005)

Another key observation from recent studies is that the Natural Resources Defense Council (NRDC) has expressed support for the introduction of PHEVs as long as power plant emissions are well controlled—demonstrating key support from a leading environmental advocacy group.

4.3.2 Summary

PHEVs will not act as a replacement for CVs in the near term, but rather will be complementary, filling niches where their characteristics fit market needs well. The upper-income, suburban niche seems to fit PHEV technology well. On the other hand, the rural niche will likely be better filled in the short term by emerging clean and more efficient CV technologies, because of longer distances traveled per day at relatively high speeds. These CV fuels will not directly expand upon the impacts on the grid, since they operate and fuel independently of the electric generation sector. While PHEVs and CVs are complementary, there are measurable impacts on emissions. EPRI reports that even a low PHEV fleet penetration in a low electric sector CO_2 intensity would decrease GHGs emissions by 193 million metric tons by 2050. High PHEV fleet penetration increases this amount in a low electric sector CO_2 intensity to 612 million metric tons of GHGs.

4.4 Modeling Tools for EVs

Significant research has been performed on appropriate modeling tools for PHEVs. The analytical results of these models sometimes give conflicting results; however, some convergence has occurred with standardized models and has significant utility for those interested in understanding the nuances of PHEV impacts.

From a big-picture perspective, life cycle analysis (LCA) modeling methods are not adequate for comparing the myriad options for transportation. A combination of LCA with cost-benefit (CB) analysis would be an ideal modeling approach that could help analysts compares all types of vehicles with respect to their total energy usage and GHGs in the context of cost effectiveness. The GREET, ORCED, and PSAT models are discussed below, but are not considered to be a comprehensive list of models involving EV performance.

4.4.1 GREET Model

The GREET model, developed by Argonne National Laboratory, is introduced as a way to combine LCA and CB methods. The GREET model includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems.[6] It considers the PHEV choices from the perspective of economic (cost), environmental (emissions), and performance considerations. It uses a life cycle analysis approach in an attempt to allow in-depth comparisons between different drive trains. Cost, in addition to technical feasibility, must be a factor in comparing different vehicle technologies.

---

[6] http://www.transportation.anl.gov/modeling_simulation/GREET/

The GREET model takes a more general and high-level analytical approach. PHEV powertrains can be categorized according to battery chemistry, level of capability to run all electric based (i.e., PHEV-40, PHEV-10), type of baseline hybrid power-train, type of vehicle model, and fuel type. A significant contribution is the model's consideration of the source of energy (e.g., tar sands oil, instead of just "oil"), which allows the analyst to use economic projections for availability of fuel by type and source. One important motivating factor for this approach is that tar sands oil is more carbon intensive through its life cycle than light crude.

The GREET model makes simplifying assumptions, but considers the vehicle cycle to include raw materials extraction, processing, fabrication, assembly and disassembly, recycling, and disposal of the vehicle and its powertrain. Therefore, the GREET model incorporates the best features of LCA.

Efficiency figures were not obtained from corporate average fuel economy (CAFE), but from road testing. GREET assumes each vehicle is driven the same number and type of miles. An article by Vyas and Santinil (2010) mentions that this is not a complete perspective, so performance should be expressed on a "per mile" basis. The difference in usage patterns between urban and rural users is a complicating factor.

4.4.2 ORCED Model

The Oak Ridge Competitive Electricity Dispatch (ORCED) model provides a way to model generation dispatch and its relation to emissions and PHEV market penetration. Use of this tool requires the input of a large amount of data available from EIA or the Ventyx Energy Velocity suite.

The main model impacts are the effect on the grid from many PHEVs, or from untimely (evening)charging. These impacts include the possibility of changing the generation mix to meet evening demand, and the associated increase in emissions. The ORCED model can be used for region-by region-analysis.

4.4.3 PSAT Model

Another battery and vehicle interaction modeling capability is the DOE Argonne Powertrain System Analysis Toolkit (PSAT). It allows dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. A driver model attempts to follow a vehicle driving cycle, sending a power demand to the vehicle controller, which, in turn, sends a demand to the propulsion components (commonly referred to as “forward-facing” simulation). PSAT can be used to model all vehicle types, including CVs and various forms of EVs.

Dynamic component models react to the demand (using transient equation-based and physics-based models) and feed back their status to the controller. The process iterates on a sub-second basis to achieve the desired result (similar to the operation of a real vehicle). The forward architecture is suitable for detailed analysis of vehicles/propulsion systems, and the realistic command-control-feedback capability is directly translatable to PSAT-PRO control software for testing in the laboratory. Capabilities of the model include transient performance, efficiency and emissions (conventional, hybrid, and hybrid fuel cell vehicles), optimization of control strategies, and identification of transient control requirements

5.0 Topics for Further Research

There are numerous opportunities to perform additional analysis and research to complement and, in many cases, expand the body of literature on the EV subject. This assessment helps put in perspective the analytical tools, methodologies, and general scope of much of the significant work to date.

In general, much of the current work does not explicitly analyze and parse out the marginal impacts of Smart Grid infrastructure and how it will affect EV fleet integration. The value of Smart Grid technologies is implied throughout the literature, as the management of these mobile, distributed-storage-and-generation devices is likely to be complex and best approached using advanced grid technologies. However, focused analyses are scarce, particularly those centering explicitly around particular technology portfolios that could mitigate and/or manage the impact of EVs on the electric grid. The literature covered in this report gives numerous clues and indications as to what key impacts take precedence in an intelligent design of the Smart Grid. Namely, these include DR capabilities that can control the times and rates at which vehicles are charging, and the technology necessary to manage V2G capabilities.

The V2G supporting Smart Grid technologies will, at a minimum, need to be capable of receiving and processing signals from individual vehicles. In this information exchange, electric vehicles will need to be able to communicate the current level of charge, the quantity available for discharge (i.e., purchase by the utility), and prices to determine whether it is beneficial to charge or discharge to the grid. Further, system operators will need to know the amount of energy flowing into the system from EVs, pointing to the need for a Smart Grid network in order to accurately assess the generation requirements. It is precisely this information exchange and management that makes feasible the distributed storage and generation (from regenerative braking) capabilities of EVs. Herein lies an opportunity for analysis where the technology investments and information processing and management can be assessed to quantify the displaced peak energy generation and the additional potential penetration from wind power to fuel these distributed storage sources.

The same case can be made for the role of Smart Grid technologies in controlling and managing utility DR. It will be critical for the realization of the upsides of EVs while mitigating the potential downsides to actively manage their drain on the grid during various times throughout the day. If consumers instinctively plug their EVs in upon returning home after work, the utility will want to have intelligent system technology in place that can delay this charging until more favorable load periods. This will require the ability to compare excess generation capacity and costs with actual and estimated charging needs of an EV fleet within a utility's T&D network. However, in some instances consumers may not be willing to delay the charge of their vehicles (perhaps emergency and trip requirement arose necessitating immediate charge), at which point the utility would need to offer some sort of "emergency override" capability. Similar mechanisms are currently being tested and implemented for traditional DR programs with household appliances. Additional research here could take the form of analyzing consumer willingness and motivations to delay charging until nighttime, and the value that advanced DR grid technologies would have on managing this utility/customer relationship.

Another notable opportunity for additional research is to provide a detailed analysis of the differences between an all EV fleet versus a PHEV fleet. The pure EV fleet will need to get all of its energy for mileage travel from the grid and thus will add increased burden on the utilities. Since PHEVs have a conventional motor for backup, the charging requirements (both from relative battery size and consumer charging preferences) will be very different. Research to date has not broken down the analysis to quantify the incremental differences between these two EV technologies. Since the consumer behavior profile will be different, as consumers will not have the “back up” of the CV motor to rely on, even short-distance commuters will likely require greater “reserve” margins for their batteries in order to hedge against unexpected driving requirements.

Further research in the area of utility perspectives on off-peak charging also has significant potential for innovative analysis. Claims that 52 percent of our petroleum consumption can be replaced with existing grid and generation infrastructure implies our petroleum security and supply issues could be improved dramatically by developing this industry. However, it is likely that a much more complex system integration issue, with many geographically dependent factors, such as regional differences between utilities, would make this claim of 52 percent reduction more complex. The research opportunity is to perform an in-depth study of all regional electricity areas and their associated grid infrastructure capabilities. Further, extensive interviews with actual utility operators, grid independent system operators (ISOs), infrastructure developers (wire, transformers, generation, etc), and other key players should be performed to provide an integrated perspective on what would be required to practically achieve such a large increase in electricity demand. This level of analysis would help put in perspective the more granular infrastructure barriers to large-scale EV deployment and integration.

The composition and costs and benefits of a non-residential charging infrastructure are also particularly interesting topics of research that have not been extensively addressed. Since there are many issues associated with this infrastructure investment, such as financing, development responsibilities, ability to facilitate V2G distribution, accounting methodology, and consumer acceptance, a thorough quantitative and conceptual analysis of these dynamic factors could prove useful for the literature. There are many support analyses that could be drawn upon and integrated to form a clearer, more comprehensive picture of this major infrastructure component of EVs’ interaction with the grid. It would also be particularly useful to understand the value of the potential distributed storage offered by EVs and weigh it against the cost to develop the necessary plug and discharge infrastructure. This analysis could include charging technology standardization issues, as well as accounting methods that would be applicable within different utility service areas.

Demand dispatch is another new concept, where resources like EVs and PHEVs could actually adjust their loads (varying their charging rates) to follow variation in intermittent resources (wind, solar). Large numbers of EVs operating in this mode could be a great asset for enabling the integration of renewables. An analysis could be performed to quantify the impact and value of this variable charging rate control. This would include a technology portfolio analysis necessary to support this option, as well as a realistic scenario analysis that incorporated consumer charger preference and behaviors with the optimal charging variation schemes to ascertain viability.

6.0 Conclusions

In summary, among the suite of alternative transportation technologies currently available or being developed, EVs hold perhaps the most significant promise for future development, particularly in the context of a Smart Grid supplied with renewable energy. Although technologies such as CAVs offer many of the electric grid-related costs and benefits, EVs present the most complete overall package in terms of economics, performance, usability, and environmental sustainability.

The time phasing of deployment is likely to favor PHEVs first and pure EVs second. The significant cost hurdles of battery packs alone (not to mention charging infrastructure) are prohibitive to the mass market that prefers a sub-$20,000 vehicle. For example, even though the Nissan Leaf, at $32,780 MSRP ($25,280 after tax rebate), is currently viewed as an inexpensive full EV, from a consumer perspective it is a very expensive mid-size vehicle that may have trouble competing with conventional vehicles.

Unfortunately, until EVs can meet cost and feature parity with CVs, market adoption rates will be slow and grid impacts minimal. Market adoption will be fueled by not only pure economics, but by government support and relevant legislation that drives industry and consumers towards cleaner transportation. As EVs begin to increase in market share, advances in grid technology will likely provide the intuitive responses that both consumers and grid operators expect. The opportunity with a gradual deployment is that it gives the electric power sector time to optimize massive infrastructure investments for the unique demands of an electrified light-duty transportation sector.

In addition, there are numerous grid infrastructure engineering challenges that will need to be addressed for an effective development of this market. The impact on load profile and the required infrastructure investments to facilitate the effective integration and utilization of EVs are both examples of complex and uncertain variables that accompany this industry. The Smart Grid will certainly play a crucial role in the effective management of an EV fleet, including utilizing its data management capabilities to further incorporate clean energy generation and minimize the grid impacts from the increased load demand created from EVs.

This report highlights and summarizes these central issues and elaborates on opportunities for unique, follow-up research that can further contribute to the current body of knowledge surrounding this nascent transportation technology.

7.0 References

"A Conceptual Framework Design for Implementation of Vehicle to Grid (V2G)", George Gross, ECE Seminar Series, Carnegie Mellon University, Nov 2009.

Axden, J., Kurani, K. "The Early U.S. Market for PHEVs: Anticipating Consumer Awareness, Recharge Potential, Design Priorities and Energy Impacts", University of California at Davis, 2008.

"Batteries for Electric Cars, Challenges, Opportunities, and the Outlook to 2020", The Boston Consulting Group, Jan 2010.

"Economic Impact of the Electrification Roadmap", The Electrification Coalition, April 2010.

Electric Power Research Institute (EPRI). "Environmental Assessment of Plug-In Hybrid EVs", 2007.

Gardner, M. "Gaining Traction: A Customer View of Electric Vehicle Mass Adoption in the U.S. Automotive Market", Deloitte Automotive, May 13, 2010.

Gerkensmeyer, C., Kintner-Meyer, M.C.W., DeSteese, J.G. "Technical Challenges of Plug-In Hybrid EVs and Impacts to the US Power System: Distribution System Analysis", Pacific Northwest National Laboratory, April 30, 2010.

Hadley. S.W. "Impact of Plug-in Hybrid Vehicles on the Electric Grid", Oak Ridge National Laboratory, November 2006.

Ho, H., Zhang, Q., Streets, D., Wang, M., Binhe, K. "Environmental Implication of EVs in China", Environmental *Science & Technology*, May 2010.

H.R. 5442: Electric Drive Vehicle Deployment Act of 2010 (Introduced in House - IH) May 27, 2010.

ICF International. "Compressed Air Vehicles: A Drive Cycle Analysis of Vehicle Performance, Environmental Impacts, & Economic Costs", 2010.

Kintner-Meyer, M., Schneider, K., Pratt, R. "Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids", Pacific Northwest National Laboratory, 2007.

Morrow, K., Karner, D., Francfort, J. "Plug-In Hybrid Electric Vehicle Infrastructure Review", US DOE Battelle Energy Alliance, November 2008.

"Plug-In Hybrid EVs: How Does One Determine Their Potential for Reducing U.S. Oil Dependence?" Proceedings of the Electric Vehicle Symposium No. 23, Anaheim, CA, Dec. 2–5, 2007.

Sanna, L. "Driving The Solution: The Plug-In Hybrid Vehicle", *EPRI Journal*, 2005.

Santini, D., Vyas, A. "How to Use Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains", Argonne National Lab, April 30, 2010.

Schneider, K., Gerkensmeyer, C., Kintner-Meyer, M., Fletcher, R. "Impact Assessment of Plug-In Hybrid Vehicles on Pacific Northwest Distribution Systems", PNNL, 2008.

Shiaua, C.-S., Smarasb, C., Hauffea, R., Michalek, J. "Impact of Battery Weight and Charging Patterns on the Economic and Environmental Benefits of Plug-in Hybrid Vehicles", Carnegie Mellon University, 2009.

Smart Grid Basics; available at http://www.smartgrid.gov/basics; accessed July 2010.

Stanton, H., Tsvetkova, A.A. "Potential Impacts of Plug-in Hybrid EVs on Regional Power Generation", Oak Ridge National Laboratory, January 20008.

Swisher, J., Hansen, L., Mims, N., Taylor, Z. "Plug-In Hybrid EVs and Environmentally Beneficial Load Building: Implications on California's Revenue Adjustment Mechanism", Rocky Mountain Institute, January 2010.

The Comeback of the Electric Car? How Real, How Soon, and What Happens Next", The Boston Consulting Group, January 2009.

Tomic, J., Kempton, W. "Using Fleets of Electric Drive Vehicles for Grid Support", University of Delaware, March 2007.

Westcott, R., Werling, J. "Economic Impact of the Electrification Roadmap", Electrification Coalition, April 2010.