Electric Vehicle Charging Infrastructure Deployment: Policy Analysis Using a Dynamic Behavioral Spatial Model

by

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B.A. Mathematics and Political Science
Williams College, 2009

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Abstract

The United States government is committed to promoting a market for electric vehicles. To ensure that this electrification program does not result in the same failure that has come be associated with its predecessor programs, Freedom Car and the Partnership for a New Generation of Vehicles, charging infrastructure must be available.

At this point, however, it is unclear what the balance will be between industry and government involvement in enabling the distribution of electric vehicle service equipment (EVSE). A number of companies in the private sector have begun initial deployment projects, and municipalities, utilities and other commercial players are beginning to look into the provision of this equipment. However, little is understood about this market where uncertainties about vehicle sales, costs and government support abound.

This thesis analyzes the economics of the infrastructure market and explores the internal logic for the companies involved through a dynamic behavioral spatial model to draw policy recommendations for the roles of the government and the private sector in vehicle electrification. Because of the low cost of electricity and high costs of charging infrastructure capital, it will be difficult for EVSE providers to earn a profit selling electricity. Model simulations demonstrate the importance of a public sector infrastructure roll out strategy and investment innovation in the EVSE market toward faster and cheaper charging options. Policies to stimulate electric vehicle adoption must focus on R&D for charging stations and deploying infrastructure.

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Title: Jay W. Forrester Professor of Management
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# Table of Contents

Abstract ........................................................................................................................................2
Acknowledgements ...................................................................................................................3
List of Tables .............................................................................................................................5
List of Figures ...........................................................................................................................6
List of Abbreviations ................................................................................................................7
Introduction ................................................................................................................................8
The alternative fuel vehicle infrastructure problem ..........................................................12
Charging infrastructure economics ......................................................................................16
  Charging Options ..................................................................................................................16
  The EVSE Vendor Business Model .....................................................................................17
  The Prospects for EVSE Providers .......................................................................................21
  The Government's Role ........................................................................................................27
  The Role of the Electric Utility ............................................................................................29
A Dynamic Spatial Behavioral Model .................................................................................32
Model Analysis .......................................................................................................................34
  Electric Vehicle Base Run .....................................................................................................35
  Electric Vehicle Optimistic Scenario ..................................................................................41
  Electric Vehicle Extreme Conditions ....................................................................................45
     EV simulation conclusion: The effects of exogenous infrastructure deployment ..........48
     EV simulation conclusion: The effects of fast charging price ..........................................48
  Plug-In Hybrid Electric Vehicles .........................................................................................49
  EVs vs. PHEVs ......................................................................................................................53
  Future Research ...................................................................................................................58
Policy Recommendations .......................................................................................................59
  Policy Continuity ..................................................................................................................62
Conclusion ................................................................................................................................63
References .................................................................................................................................64
Appendix One: Interview Questions ....................................................................................68
List of Tables
Table 1: The Marginal Profit of EVSE System Production .............................................. 20
Table 2: Total Cost of EVSE Deployment ........................................................................... 24
Table 3: Break-even Electricity Price Mark-up .................................................................. 25
Table 4: Model Fuel Parameters ...................................................................................... 38
Table 5: Model Platform Parameters ................................................................................ 38
Table 6: Favorable Policy Conditions for EV Simulation .................................................. 39
Table 7: EV Fuel Parameters .......................................................................................... 43
Table 8: EV Platform Parameters .................................................................................... 43
Table 9: EV and PHEV Fuel Parameters ......................................................................... 51
Table 10: EV and PHEV Platform Parameters ................................................................... 51
Table 11: Federal Government Policy Portfolio ................................................................ 61
List of Figures

Figure 1: Electric Vehicle Base Run .......................................................... 40
Figure 2: Electric Vehicle Optimistic Scenario ........................................... 44
Figure 3: Electric Vehicle Extreme Conditions ......................................... 47
Figure 4: PHEV Simulation ........................................................................ 53
Figure 5: EV with PHEV and EV Extreme Conditions Comparison .......... 57
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ARRA</td>
<td>American Recovery and Reinvestment Act</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>dmnl</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>EV</td>
<td>Pure Electric Vehicle</td>
</tr>
<tr>
<td>EVSE</td>
<td>Electric Vehicle Service Equipment</td>
</tr>
<tr>
<td>gge</td>
<td>gasoline gallon equivalent</td>
</tr>
<tr>
<td>HFCV</td>
<td>Hydrogen Fuel-Cell Vehicle</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>kWh</td>
<td>kilowatt-hour</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>MITei</td>
<td>MIT Energy Initiative</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SOx</td>
<td>Sulfur Oxides</td>
</tr>
<tr>
<td>TEPCO</td>
<td>Tokyo Electric Company</td>
</tr>
<tr>
<td>WA</td>
<td>The State of Washington</td>
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**Introduction**

Over the last decade, significant improvements in battery chemistries have enabled the recent wave of electrification in the light-duty passenger vehicle fleet. In 2011, General Motors and Nissan released their variations on the electric vehicle, to be followed by other automakers in subsequent years. While gains in battery technology are still necessary to bring down overall vehicle costs, uncertainties abound as to how vehicles will be charged, who will provide the charging infrastructure, and who will pay for all of it. This paper addresses these questions through the lens of a dynamic behavioral spatial model of the transportation system with respect to the light-duty vehicle fleet.

This paper considers the deployment of battery electric vehicles (BEVs) such as the pure electric Nissan Leaf or the plug-in hybrid electric, extended-range, Chevy Volt. A plug-in hybrid electric vehicle (PHEV) differs from a pure electric vehicle (EV) in that after the depletion of the battery, the vehicle will switch to a series-hybrid internal combustion engine that derives its energy from gasoline (or other liquid fuel). On the one hand, the Volt, a PHEV, has a nominal range of 40 miles on electric from a 16 kWh battery and 300 miles on the internal combustion engine. The Leaf, an EV, on the other hand, has a nominal range of 100 miles on electric from a 24 kWh battery (Kenderdine, Kearney and Parness, 2011). The Volt and the Leaf carry sticker prices of $41,000 and $33,720, respectively.
As a policy initiative, vehicle electrification allows the United States an opportunity to capitalize on environmental benefits within the transportation sector and to enhance energy security. With respect to energy security:

- In 2008, the United States consumed $900 billion worth of gasoline, diesel and other refined products, of which $388 billion was imported (Minsk, 2010). This reliance on oil is harmful for a few reasons. First, $388 billion in imported oil represents greater than 50 percent of the United States trade deficit, which results in the loss of economic potential (Minsk, 2010). This is money that is not reinvested into the United States economy, infrastructure or services (Minsk, 2010).

- Second, oil prices often fluctuate dramatically, and this variability results in significant economic loss (Greene, 2009). Oil production is concentrated in the Middle East, and despite extensive oil-exploration efforts in North America (particularly relative to the minimal exploration in the Middle East), the estimates of oil reserves indicate that this production trend will continue in perpetuity (Minsk, 2010). Additionally, this production is concentrated in the hands of National Oil Companies in the Middle East. These regimes often have interests hostile to those of the U.S. as a result of religious, cultural and institutional differences, and are frequently plagued by poverty, corruption and/or political instability (Minsk, 2010). These factors allow for dramatic price variability as a result of geopolitical crises (EIA, 2009), and this price variability inhibits consumers', individuals' and large businesses' ability to
plan their spending, resulting in the misallocation of resources and economic loss (Greene, 2009).

- Third, the oil market is not a free market. National Oil Companies that control such large fractions of production and reserves form an oligopoly. The concentrated market power of the National Oil Companies in addition to the low short-run elasticity of the demand for oil, allows these firms to be price-setters, artificially inflating the price of oil and resulting in economic loss here in the United States (Greene, 2009).

The transportation sector is responsible for 70 percent of oil consumption in the United States, with half of that consumption coming from the light-duty vehicle fleet (Minsk, 2010). Transitioning from oil to electricity as a transportation fuel minimizes the economic loss reported above. Because electricity is generated domestically, profits would be reinvested at home rather than abroad. Government regulation protects electricity consumers from artificially high prices. Finally, at the retail level, consumers are not subject to uncertain price volatility.

Well-to-wheels analyses also suggest that vehicle electrification would result in lower CO₂ emissions and reduced particulate emissions in cities. In the United States, the transportation sector is responsible for 34 percent of total emissions (Electrification Coalition, 2009). Though coal fuels about 45 percent of electricity generation in the United States, the electric-vehicle drive train enables a more efficient consumption of that energy, relative to the internal combustion engine (ICE). While a conventional vehicle produces about 450 g of CO₂ per mile, a plug-in electric vehicle (PHEV) operating on electricity generated at an old coal plant will
emit roughly 325 g of CO2 per mile, and as electricity is generated from cleaner sources, the well-to-wheel emissions from the PHEV drop significantly to 150 grams per mile for a PHEV operating on electricity generated by wind or solar (EPRI/NRDC, 2007). Relative to an internal-combustion-engine vehicle, reductions by generation are as follows:

- 33 percent reduction for conventional hybrids;
- 50 percent reduction for PHEVs operating on combined cycle natural gas generation;
- 66 percent reduction for PHEVs operating on carbon-free electricity - nuclear, biomass and other renewable (Kenderdine, Kearney and Parness, 2011).

These figures correspond to the emissions from a PHEV with 20 miles all-electric range. After 20 miles, the vehicle will operate on gasoline, resulting in tail-pipe emissions.

Additionally, BEVs could significantly reduce NOx and particulate tail-pipe emissions. Utilities expect consumers to charge their BEVs off-peak at night. This demand will be met by the dispatch of larger, more efficient generation units (Kenderdine, Kearney, and Parness, 2011). However, if the electricity required by EVs is drawn exclusively from coal generation – particularly a concern in regions with concentrated coal generation – then higher loads could increase SOx emissions (EPRI/NRDC, 2007). Nonetheless, shifting emissions from the tailpipe to the generating plant could reduce the particulate emissions in cities as generating plants are typically in more suburban locals.
Though vehicle electrification offers these environmental and security benefits, there are a couple significant hurdles to wide-spread BEV market penetration. While battery costs have fallen significantly in the last decade, further reductions are necessary to allow the market to exist without governmental assistance (Cheah and Heywood, 2010). The development and deployment of charging infrastructure is equally important for the success of the industry, and will be the focus of the rest of this paper.

The alternative fuel vehicle infrastructure problem

There are a number of studies within the literature that demonstrate the importance of fueling infrastructure for alternative fuel vehicle platforms. Yeh (2007) looks at the coevolution of refueling infrastructure with the natural gas vehicle platform. Yeh demonstrates that the market growth for natural gas vehicles increases in tandem with the deployment of refueling stations, i.e. the growth rate in fuel stations matches the growth rate in the CNG fleet, but the market fails when the ratio of refueling station to 1000 vehicles fails to pass 0.2 (Yeh, 2007). Consistent with Yeh’s work, Greene (1997), through a series of surveys, illustrates that consumer choice for an alternative fuel vehicle is a function of fuel availability (Greene, 1997). However, perhaps the most apt case study is that of the first electric vehicle deployment.

The Electric Vehicle has a long history in the United States that can provide valuable insight when considering vehicle electrification today. The history of the EV
dates back to 1834, when Thomas Davenport invented the first non-rechargeable electric car (Frost and Sullivan, 2009). Gaston Pante improved upon this first generation vehicle with the invention of the rechargeable lead-acid battery. The first vehicle with power-steering hit the road in 1897, a BEV (Frost and Sullivan, 2009). In 1900, the vehicle market was split into thirds between steam cars, BEVs and gasoline cars (Frost and Sullivan, 2009). At first, many people were concerned with the high costs, noise, danger and high speeds of ICE vehicles (Struben and Sterman, 2008). Nonetheless, by 1912, BEV registrations maxed out at 30,000, lagging significantly behind the thirty-times larger ICE vehicle fleet (Struben and Sterman, 2008).

The evolution of driving preferences allowed the internal combustion engine vehicle to dominate the market. Drivers took to exploring the countryside and travelling more frequently between cities (Struben and Sterman, 2008). Between 1921 and 1922, the Federal Highway Act appropriated significant funds for the creation of a national highway system to facilitate mail delivery, and increased the need for longer-range vehicles (Frost and Sullivan, 2009). However, these roads predated rural electrification, and thus, the ability to provide charging infrastructure outside of the city was minimal (Struben and Sterman, 2008). Instead, relatively cheap gasoline distribution points, made possible by the expansion of the automobile, became the norm and drove the industry forward through a reinforcing feedback (Struben and Sterman, 2008). These factors lead to Struben and Sterman’s conclusion:

Thus social exposure to the auto, word of mouth among nondrivers, emerging preferences for and the improving convenience of long-distance travel, growing
scale, experience, installed base and infrastructure, and innovation spillovers all interacted to spell the doom of the early market leaders.... Over a hundred years later, alternative vehicles face a mature industry, fully articulated infrastructure, powerful vested interests, and a society, economy, and culture tightly bound to ICE (Struben and Sterman, 2008).

These examples from the early days of the automobile demonstrate the importance of charging infrastructure to consumer acceptance of a vehicle platform. However, this is not the whole story. In a more recent scenario, the Tokyo Electric Power Company (TEPCO) deployed BEVs as part of its vehicle fleet, offering charging stations at the home fleet depot (Electrification Coalition, 2009). Concerned about the range of their vehicle, drivers would bring the BEVs back to the fleet depot with 50 percent of the battery capacity remaining (Electrification Coalition). To alleviate this range anxiety, TEPCO placed a network of chargers throughout Tokyo (Electrification Coalition). After the implementation of the additional driving stations, drivers began returning to the fleet depot with far less battery capacity remaining. Drivers became much more confident, employing broader driving patterns. However, the additional charging stations were infrequently utilized. Rather than increasing the driving distance by topping-off, drivers simply drove farther and longer knowing that they could top off (Electrification Coalition). TEPCO's experience with their EV fleet suggests that infrastructure deployment is most important from a behavioral standpoint, but perhaps, not from a physical or technical standpoint. An average driver in the U.S. only drives about 33 miles per day, well below the 40 miles per charge and 100 miles per charge of the Volt and the Leaf, so it is likely that these dynamics exist in the United States, as well.
Does this mean that the government should not invest in public charging infrastructure? The work of Morrow, Karner and Francfort (2008) suggests that this is the wrong lesson to learn from the TEPCO experience. Morrow, Karner, and Francfort (2008) analyze the trade off in the vehicle electrification system, today, between the costs of a larger battery in the vehicle to reduce range anxiety and the costs of deploying a rich charging infrastructure. They found that overall costs to the transportation system would be reduced by the deployment of a rich charging infrastructure rather than expensive increases in battery size within each vehicle (Morrow, Karner, and Francfort, 2008).

There are many parameters interacting in the vehicle electrification system. Some of these are economic – how much does a vehicle cost? How much does a charging station cost? Who pays? Some of these are behavioral – when does a consumer gain enough trust in the platform to make a purchase? Some of these are spatial – what is the distribution density of the charging infrastructure? How far out of my way do I have to drive to reach a charge point? All of these interact within the system in non-linear ways. These interactions suggest that non-intuitive lessons could be learned from a dynamic behavioral spatial model with a broad model boundary.
**Charging infrastructure economics**

In order for consumers to be comfortable buying an electric vehicle they must first have a place where they can charge their car. This poses a significant problem for the diffusion of the electric vehicle – drivers won’t buy vehicles unless charging infrastructure is available, but governments, utilities and the private sector will not invest in electric vehicle service equipment (EVSE) without market potential – a chicken and egg problem (Struben and Sterman, 2008). Many stakeholders are involved in the deployment of charging infrastructure – the driver, the automobile manufacturer, the local utility, the federal government, the municipal government, the EVSE vendor and the EVSE provider (shopping malls, hotels, apartment buildings, etc.). This section identifies the roles of each of these stakeholders and their economic motivations for vehicle electrification.

**Charging Options**

There are three options available for electric vehicle charging – Level 1, level 2 or level 3 (Fast Chargers) EVSE. Level 1 EVSE entails a unique cord from the EV that can plug into a traditional 110-volt (AC) plug with a dedicated 15-amp circuit. Using this option, a vehicle with a 24-kWh battery, such as the Leaf, can attain a full charge in 8 to fourteen hours depending on the initial state of charge (TechNews Daily, 2010). Level 2 EVSE utilizes 220-V (AC) with a dedicated 80-amp circuit and appears as a standalone box that can be mounted to a wall and wired directly to an electrical panel. Using a level 2 charger, the same electrical vehicle can charge in six
to eight hours. Level 3 chargers, or Fast Chargers, carry a charge of 480-volt (DC) using a 60-amp, dedicated breaker with special grounding equipment (State of Washington, 2010). Fast Chargers can reduce the charging time from hours to minutes.

The location of these charge points will vary by level. Consumers are being encouraged to deploy level 1 and level 2 charging in their garages at home. Municipal governments, hotels, apartment buildings and shopping malls are considering the deployment of level 2 charging in their parking lots. The Federal and California State governments are looking into the deployment of Fast Chargers on highways. However, a number of concerns remain to be answered with regard to Fast Chargers. What will be the impact of the high voltage, direct current on EV battery life? Can an EVSE provider recoup the $53,000 investment necessary to deploy a level 3 charger (Gogoana, 2010)?

**The EVSE Vender Business Model**

A number of EVSE venders have entered the California market, including but not limited to companies such as Coulomb, Better Place, Aerovironment, General Electric and ECOtality. These venders target two primary market segments – (1) at home charging and (2) commercial availability/public charging. A third segment would be for highway charging, but Aerovironment, Coulomb and General Electric are the only companies at this point targeting this niche (TechNews Daily, 2010). In targeting the first two segments, the companies provide a variety of technical devices and services.
Two business models for EVSE vendors look promising. The first is the battery-swap model implemented by Better Place in Israel and Denmark. The second is a charge-point and service model implemented by Coulomb and other players.

Though Better Place has made its name off of the innovative battery-swap business model, the company is prepared to set up a network of electric car power stations in California for EV charging with an investment of $1 billion (Frost and Sullivan, 2009). Better Place has stated its intention to include battery swap stations among its charging points (Frost and Sullivan, 2009). Consumers will hold subscriptions to Better Place that grant them access to their charging stations (Frost and Sullivan, 2009).

Coulomb similarly offers a charge-point technology (both Level 1 and Level 2), but supplements it with an infrastructure of connected charge-points called the ChargePoint Network (Frost and Sullivan, 2009). The network allows consumers to find the nearest available charging-point through a smart-phone or internet application. An RFID tag identifies consumers to the charge-points. Like Better Place, Coulomb's profits will be driven by the marginal profit per charge-point sale and the annual subscription fee. As a result, the RFID tag eliminates the need for payment at the charge-point (Frost and Sullivan, 2009). For public charging infrastructure, Coulomb then pays the EVSE owner for the electricity that is purchased during a given charge. It is expected that roughly 80% of subscription revenues will be paid to EVSE owners for electricity and maintenance (Frost and Sullivan, 2009).
However, already regulators are balking at the exclusivity of public charging stations. The government does not want to subsidize the deployment of a public good that is not available for use by all willing consumers. As a result, EVSE providers, rather than venders, will most likely be stuck paying for the electricity consumed at their charge-point, and it will be in their purview to charge EV drivers to “fill up” (Kenderdine, Kearney and Parness, 2011). These EVSE providers will be the EVSE vender’s primary customers - cities, fleets, utilities, hotels, apartment complexes and corporations.

Production cost data for EVSE at this point is proprietary and difficult to ascertain. However, total costs to the EVSE vendor include unit production, installation, network creation and maintenance. In the near term, it is likely that there are low profit margins on the EVSE itself due to low order volumes, but as orders increase, this could change. One level 2 charging unit will be sold for roughly $1000, plus a $900 installation fee. (Note: This installation fee goes directly to the EVSE vendor and covers only the actual installation for the EVSE, not the preparatory work that could be necessary, including highly expensive installations of new electric lines and panels.) For installation, an electrician, that makes about $75 / hr may need, liberally, four hours to complete the work for a total labor cost of $300 – though installation costs can grow significantly if additional wiring needs to be permitted and installed.

An EVSE vendor will charge a $100 subscription fee per year (though some companies are offering a subscription for free during the first year) to utilize public charging infrastructure, and take advantage of the network benefits like the ability
to make reservations on given charge-points and ensure timely maintenance. The network creation is an upfront fixed cost with small maintenance charges thereafter. Thus, much of this $100 subscription fee will be profit.

Table 1 below shows projected marginal profits for an EVSE vender under three scenarios. The first scenario assumes that EVSE vendors see no profit on the production of the EVSE itself, instead only earning a $600 marginal profit for the whole system from the $500 difference in installation fee and installation costs in addition to the $100 EVSE service charge. The second and third scenarios assume a $250 and $500 profit margin, respectively on EVSE production, corresponding to $850 and $1,100 marginal profits for the whole system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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<tbody>
<tr>
<td>EVSE production</td>
<td>($1,000)</td>
<td>($750)</td>
<td>($500)</td>
</tr>
<tr>
<td>EVSE installation</td>
<td>($400)</td>
<td>($400)</td>
<td>($400)</td>
</tr>
<tr>
<td>EVSE Price</td>
<td>$1,000</td>
<td>$1,000</td>
<td>$1,000</td>
</tr>
<tr>
<td>EVSE Service Charge</td>
<td>$100</td>
<td>$100</td>
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</tr>
<tr>
<td>EVSE installation fee</td>
<td>$900</td>
<td>$900</td>
<td>$900</td>
</tr>
<tr>
<td>Marginal Profit</td>
<td>$600</td>
<td>$850</td>
<td>$1,100</td>
</tr>
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Table 1: The Marginal Profit of EVSE System Production

If EV sales reached one million by 2015, the optimistic goal set by the Obama administration (Washington Post, 2011), EVSE vendors would net between $600 million and $1.1 billion in revenues. These revenues would be used to pay off the necessary fixed costs – manufacturing facility, network creation, network maintenance, marketing and administration fees. More data about the manufacturing processes for EVSE are necessary to analyze the sustainability of the
business model. For these EVSE vendors then, the key is selling the charging stations to EV owners and EVSE providers (municipalities, hotels, apartment buildings, and shopping malls).

The Prospects for EVSE Providers

A number of other variables enter into the business calculation for EVSE providers. These providers must take into account additional electrical wiring, permitting and signage. The installation costs are the most variable, not because consumers will owe EVSE vendors more money, but rather because significant structural work may be necessary to add electrical lines and panels to a desired EVSE location. The Department of Energy, Vehicle Technologies Program (Morrow, Karner and Francford, 2008) released a study in 2008 summarizing the costs to EVSE providers as the following:

- Residential garage charging
  - Level 1 $878
  - Level 2 $2,146
- Apartment complex charging
  - Level 1 $833
  - Level 2 $1,520
- Commercial facility charging
  - Level 2 $1,852

These costs include labor, materials, permits and signage, but they are misleading. These estimates assume that the EVSE is located within 40 feet of a breaker panel and that apartment complexes and commercial providers will install five to ten charge-points at one time, respectively. Additionally, these estimates don’t include the necessary administration and maintenance costs that would be required to own and operate an EVSE.
Perhaps, it is fair to assume that residential customers will put a charge-point within 40 feet of a breaker panel as, in many cases, the breaker panel is located in or near the garage. However, commercial providers do not have the luxury of putting a charge-point near a breaker panel. In some cases the breaker panel is not in a vehicle accessible location. More importantly, if commercial providers want to recoup their investment in the EVSE, a high utilization rate for the charge-point is necessary. This requires that the EVSE be in a high priority parking spot and thus, minimizes the flexibility in EVSE placement.

A variety of considerations go into the placement of EVSE. First, firms are looking at hybrid vehicle use, as those groups of people are likely to be the same as electric vehicle first-movers. Second, firms look at population density and commuting patterns. It is likely that there will be more electric vehicles along densely travelled urban corridors. Third, firms are looking at high volume destinations such as office buildings, shopping malls and airports. These high priority locations are those where drivers would stop to top-off, and leave the space, allowing another vehicle to occupy the space. This enables a high utilization rate for the EVSE. As a result of these considerations, charge-points could be farther than 40 feet from breaker panels and appropriate wiring, necessitating significant additional installation expenses, on the order of $4000 to $5000 a unit.

Moreover, the study also assumes that 10 level 2 charge-points will be installed at once in commercial applications for a total cost of $18,519, and five level 2 charge-points will be installed at once in apartment complex applications for a total cost of $7,597 (Morrow, Karner and Francfort, 2008). Again, with utilization
such a high priority, it is unlikely that firms will take the risk of adding so many all at
once with such high costs. Adding additional charge-points in one installation
significantly reduces the cost per charger as extensive structural costs can be spread
across the charge-points.

A different view of the costs for EVSE providers is displayed in table 2 below.
The fixed costs for an EVSE provider include all of the inputs to EVSE deployment –
cost of the charge-point, installation of new charge-point, annual maintenance costs,
annual administration costs, permitting costs, signage and a 50% EVSE purchase tax
credit from the Federal Government. The cost of the charge-point and the
installation by the EVSE manufacturer is equivalent to the $1000 and $900 from
above. However, additional EVSE installation costs in scenario 2 are projected to be
$3,000, a low estimate concurrent with significant electrical and perhaps,
construction work. Annual maintenance costs of $300 are expected for various
failures in the electrical and/or networking system. Administration costs entail any
costs that are incurred in setting up the payment scheme by which drivers will
charge on the EVSE, and the personnel necessary to manage it. $2,000 is, again, a
low estimate, as it may be necessary to hire additional employees for this job, which
could cost a firm $50,000. Indeed, there is a lack of understanding about the
transactional costs involved in the resale of electricity. Finally, signage and
permitting costs are set equivalent to those in Morrow, Karner and Francford
(2008), which are representative of the experience in California. Scenario 1
represents the installation of one charging station near the breaker panel, and
scenario 2 represents the installation of one charging station that requires electrical lines and panel upgrades.

Table 2: Total Cost of EVSE Deployment

These numbers more realistically project the first-year costs that firms will have to incur to deploy initial EVSE units. Despite these costs, there are a number of reasons why hotels, apartment buildings, office buildings, gas stations and shopping malls would still make this investment. In California, the PUC is expected to allow these firms to sell electricity, a right previously only allotted to utilities. Table 3 indicates the mark-up price at which EVSE owners in these locations would need to sell electricity in order for the revenues to cover the EVSE costs in the given time period. This price is in addition to the retail electricity price and is determined by

<table>
<thead>
<tr>
<th>EVSE Commercial Providers</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVSE Level 2 Cost</td>
<td>$1,000</td>
<td>$1,000</td>
</tr>
<tr>
<td>EVSE Installation</td>
<td>$900</td>
<td>$900</td>
</tr>
<tr>
<td>Additional EVSE Installation costs</td>
<td>$0</td>
<td>$3,000</td>
</tr>
<tr>
<td>Annual Maintenance Costs</td>
<td>$300</td>
<td>$300</td>
</tr>
<tr>
<td>Annual Administration Costs</td>
<td>$2,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>Permitting Costs</td>
<td>$165</td>
<td>$165</td>
</tr>
<tr>
<td>Signage</td>
<td>$350</td>
<td>$350</td>
</tr>
<tr>
<td>50% Tax Credit for EVSE purchase</td>
<td>($500)</td>
<td>($500)</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$4,215</strong></td>
<td><strong>$7,215</strong></td>
</tr>
</tbody>
</table>

the utilization rate of the EVSE (hours per day) with the expected utilization rate occurring 365 days of the year. 50% is a high estimate for utilization as most vehicles will be looking for a charge at one of these locations either during the evening, at an apartment building, for example, or during the day, at an office
building, but it is unlikely that one driver would charge during the day and during the evening in one location.

<table>
<thead>
<tr>
<th>Total Cost Scenario</th>
<th>50% Utilization 12 hrs / day</th>
<th>33% Utilization 8 hrs / day</th>
<th>25% Utilization 6 hrs / day</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One Year Payback Period</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 ($4,215)</td>
<td>$0.96 / kWh</td>
<td>$1.44 / kWh</td>
<td>$1.92 / kWh</td>
</tr>
<tr>
<td>Scenario 2 ($7,165)</td>
<td>$1.63 / kWh</td>
<td>$2.45 / kWh</td>
<td>$3.27 / kWh</td>
</tr>
<tr>
<td><strong>Two Year Payback Period</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 ($6,515)</td>
<td>$0.74 / kWh</td>
<td>$1.12 / kWh</td>
<td>$1.49 / kWh</td>
</tr>
<tr>
<td>Scenario 2 ($9,465)</td>
<td>$1.08 / kWh</td>
<td>$1.62 / kWh</td>
<td>$2.16 / kWh</td>
</tr>
<tr>
<td><strong>Three Year Payback Period</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 ($8,815)</td>
<td>$0.67 / kWh</td>
<td>$1.01 / kWh</td>
<td>$1.34 / kWh</td>
</tr>
<tr>
<td>Scenario 2 ($11,765)</td>
<td>$0.89 / kWh</td>
<td>$1.34 / kWh</td>
<td>$1.79 / kWh</td>
</tr>
<tr>
<td><strong>Four Year Payback Period</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 ($11,115)</td>
<td>$0.63 / kWh</td>
<td>$0.95 / kWh</td>
<td>$1.26 / kWh</td>
</tr>
<tr>
<td>Scenario 2 ($14,065)</td>
<td>$0.80 / kWh</td>
<td>$1.20 / kWh</td>
<td>$1.61 / kWh</td>
</tr>
<tr>
<td><strong>Ten Year Payback Period</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 ($24,915)</td>
<td>$0.56 / kWh</td>
<td>$0.85 / kWh</td>
<td>$1.14 / kWh</td>
</tr>
<tr>
<td>Scenario 2 ($27,865)</td>
<td>$0.63 / kWh</td>
<td>$0.95 / kWh</td>
<td>$1.27 / kWh</td>
</tr>
</tbody>
</table>

Table 3: Break-even Electricity Price Mark-up

This analysis poses some particularly vexing questions. Even if firms were willing to invest conditioned upon a ten year payback period, the electricity would have to be resold at a price $0.56 per kWh more than the price at which the electricity is being purchased. The price of electricity on peak in California can reach $0.55 per kWh, meaning that the EVSE owner would have to resell the electricity at $1.11 per kWh. A high price for electricity would be a disincentive to charging at a public EVSE, resulting in a decreased utilization time and an increased payback...
price, creating a dangerous reinforcing feedback loop. Moreover, at such high electricity prices, the fuel expense savings relative to gasoline are significantly diminished. At $1.11 per kWh, a consumer would pay $26.64 for 100 miles or $106.56 for 400 miles. This compares to $80 that a consumer would pay for 20 gallons of gas at $4 a gallon in a car that gets a low 20 miles to the gallon for a total of 400 miles.

Additionally, in order to keep the EVSE spaces utilized, vehicles will have to depart immediately upon the charge completion. For example, if a driver parks his car at work and begins charging, he would have to relocate his vehicle in the middle of the day when the car is done charging, so that a new vehicle could take its place. As a result, EVSE owners will likely charge customers for the time spent in the parking space, rather than just the time spent charging.

The absence of ancillary revenue hinders the economics of EVSE deployment, relative to the conventional gasoline distribution system. Gas stations can sell fuel at a very low profit margin as a result of the profits made from associated convenience store sales. EVSE providers will not have this flexibility if the charge points are located in parking structures at workplaces, shopping malls, etc., because people will not linger near the vehicle while it is charging. A gas station can make $80,000 in profits from ancillary sales in a given year (Gogoana, 2010). With such profits, an EVSE provider could allow charging for free, incurring a cost of $28,382.40 in a year at an EVSE with 50% utilization all of which occurs on peak at $0.27 per kWh, charging an EV with a completely depleted 24 kWh battery capacity.
However, EVSE providers would not need to make too much money on ancillary sales in order to recoup the price of the EVSE. If EVSE providers resell electricity at its initial retail price, then the only costs that need to be recouped are capital and installation costs for the EVSE, $4,215 or $7,165.

One opportunity that EVSE providers could pursue to realize ancillary revenues is advertising. Early EV adopters will likely be a combination of higher income individuals and/or individuals that consider themselves to be "green." As a result, recharge points would be an ideal place for targeted advertising. EVSE providers could sell space for advertising. If the parking space is indoors, an EVSE provider could maximize the space with monitors that rotate advertisements.

Additionally, apartment buildings, office buildings, shopping malls, hotels and gas stations may profit from ancillary services stemming from the added attractiveness of the venue derived from the presence of EVSE. For instance, an EV driver may be more likely to live in an apartment building with EVSE than one without. At this point, though, these profits are hard to quantify.

The Government's Role
Vehicle Electrification has become a priority at all levels of government. The federal government has enacted policies to spur vehicle purchases and infrastructure deployment. As part of the American Recovery and Reinvestment Act, (ARRA) the Plug-In Electric Vehicle Tax Credit offers a $7,500 tax rebate to consumers who purchase an electric-drive vehicle. ARRA also provides a 50% tax credit for EVSE purchases, and $100 million in direct investment for EVSE
deployment (Kenderdine, Kearney, and Parness, 2011). As the market progresses, targeted government support will be necessary.

State and municipal governments are also playing a role. Municipal governments are a primary purchaser of EVSE, and importantly, control the permitting process for EVSE installations. This process varies by city, but the expectations in California are that the permitting process will take about one month or more for regions that should expect a lot of EVs. If a bidding process is required, the process could take up to a year. As more EVSE is deployed, the permitting process will take longer because cities will have to adjust to the new volume. Unfortunately, if this process isn’t handled well, these dynamics could hinder EV diffusion as the experience for individuals becomes more burdensome.

In addition to permitting, the state and municipal governments will be responsible for the roll out of EVSE on public streets and parking lots. This will require adequate zoning, lighting and signage (WA Department of Commerce, 2010).

The state government also plays an important role in regulating the sale (and resale) of electricity. In California, the Public Utilities Commission (PUC) is currently ruling on whether to allow an unregulated resale of electricity for public charging stations. Indications are that this will be allowed, and EVSE owners will be able to charge for the provision of the EVSE and the electricity purchased. The PUC will be responsible for monitoring this situation to ensure that EVSE owners do not take advantage of consumers by price gauging.
Governments at all levels will play a role in ensuring that all elements of vehicle electrification are completed on the basis of standards. Enabling the compatibility of equipment and improving the user experience, standards play an important role in consumer acceptance for EVs. Though the government doesn’t set the standards, their support for platforms that abide by the standards is critical. International Standard Development Organizations within specific fields are responsible for setting standards in that field (Brown, Pyke, and Steenhof, 2010). The Society of Automotive Engineers (SAE) set the standard for EV charging equipment (J1172), dictating the physical, electrical and performance requirements for EVs (Brown, Pyke, and Steenhof, 2010). However, standards do not only focus on technical compatibility. They also regulate management practices (Brown, Pyke and Steenhof, 2010). Today, concern remains over the management desire for subscription exclusivity over public charging stations.

The Role of the Electric Utility

As the providers of the fuel for EVs, California’s electric utilities play an important role in preparing the system for EV deployment and maintaining the system after vehicles are on the road. This latter role is critical as a result of the added strain to the electricity infrastructure in the state attributable to EVs. If charged overnight at home, an EV will draw the same amount of electricity from the grid (kWh) as an additional house during the time in which it is charged (Jonathan Fahey, 2010). Though utilities seem less concerned with generation and transmission issues, local distribution systems, made up of a network of neighborhood transformers, will sustain the bulk of the strain. Three to six houses
draw electricity through a given transformer, and adding an EV to this transformer would reduce its life expectancy and add to maintenance costs. The worst-case scenario for utilities would come to fruition if “clustering” occurred, where one neighborhood, and thus, one transformer, is home to multiple EVs. Clustering would damage the transformer, resulting in significant costs for the Utility. Such costs and disruptions to EV owners and non-EV owners, alike, would result in negative word of mouth that could stymie EV diffusion. However, utilities in California are proactively updating these neighborhood transformers in an effort to avoid these disruptions, and the utilities are paying for these upgrades as part of their regular maintenance schedule.

The electric vehicle first appeared on California roads in the mid 1990s. Since then, the Utilities have had to adjust to their presence, not only in terms of preparing neighborhood distribution capabilities, but also in terms of electricity rates. California consumers have two electricity rate options. The first is the standard tiered residential rate, which adjusts the cost of electricity by the amount consumed. A consumer that uses less electricity pays less per kWh, and the price increases as consumption increases – there are three tiers. The second is a whole-house time-of-use rate where prices are modeled on the marginal cost of electricity dispatch. With this scheme, there are two time intervals in the spring, fall and winter (the more expensive on peak consumption and the less expensive, off peak consumption), and three time intervals in the summer (on peak, off peak and super off peak). EV owners will have the option of staying on the tiered residential rate and adding a separate meter specifically for their EV or switching to the whole
house time-of-use rate. The separate meter for the EV would set prices according to a two-time interval (27 cents / kWh on peak and 11 cents / kWh off peak) time-of-use rate. Meter updates, though necessary, will be costly, as utilities may need to upgrade the service infrastructure around location. However, as smart-meter technology is deployed, the utilities will be able to closely monitor the status of electricity consumption and the surrounding distribution infrastructure to proactively prevent problems (California Public Utilities Commission, 2010).

The time-of-use rate for EVs is critical to insure that owners charge their vehicles off-peak. Independent system operators call for dispatch from electricity generating plants, and the first plants to be called upon are those with the lowest marginal cost of production. As electricity demand increases, independent system operators call for dispatch from those plants with higher marginal production costs, the inefficient, dirtier coal-fired power plants. On-peak charging would result in greater dispatch from these plants, resulting in increased particulate and carbon emissions. Additionally, on-peak charging would result in increased capital costs throughout the system that would be spread to all electricity consumers, not just EV owners. These extra costs could result in the same negative word of mouth as discussed above. If managed correctly though, vehicle electrification offers utilities an opportunity to level out demand curves and increase efficiency and load factors, all of which could result in reduced rates in the long term.
**A Dynamic Spatial Behavioral Model**

The model used in this paper depicting the electric vehicle system is a variation on the one offered by Struben and Sterman (2008) for the generic alternative-fuel vehicle, and Supple (2007) for hydrogen fuel vehicles. The literature highlights a couple key elements in the intersection between the transportation and electricity systems. First, significant time lags in the turn-over of the vehicle fleet limit the rate at which alternative fuel vehicle diffusion can occur (Leiby and Rubin, 2000; Leiby and Rubin, 2001; Greene and Schafer 2003). Indeed, the median lifetime for a light-duty passenger vehicle is 16.9 years (Supple, 2007). Second, high costs of infrastructure development and deployment are impediments to alternative fuel vehicle diffusion (Yeh, 2007; Supple 2007; Thomas, Kuhn et al., 1998; Mintz, Molburg et al., 2000). Additionally, previous models have been used to address alternative fuel vehicle diffusion, for the purpose of climate-policy analysis. These include a bottom-up dynamic market allocation model (Schafer and Jacoby, 2006) and a general equilibrium, *Emissions Predictions and Policy Analysis* (EPPA) model (Paltsev, Reilly, Jacoby, Eckaus, Mcfarland, Sarofim, Asadoorian, Babiker, 2005).

The model used here derives the diffusion of the electric vehicle taking into account behavioral, spatial and dynamic system analyses. From a behavioral perspective, the model captures the learning curve of consumers as they become comfortable with the vehicle range and less likely to use infrastructure as illustrated by the TEPCO example. From a spatial perspective, the model endogenously determines the distribution density of charging infrastructure based on profitability (Struben and Sterman, 2008). Station density feeds back to the queue length for a
given refueling point and the station-balking fraction, i.e. the consumers that forgo
refueling because the lines are too long. A large queue length and high station
balking fraction both lead to unfavorable word of mouth about the utility of
alternative vehicles, which feeds back to undermine adoption.

The model represents California as a case study for electric vehicle
deployment. California is divided into patches of 352 mi², and the deployment of
refueling infrastructure, charging stations in this case, is endogenously determined
by the expected profitability within each patch (Struben, 2006; Struben, 2007;
Supple, 2007). The profitability of the charge points within each patch is, of course,
the revenue they generate less costs; revenue is determined by the demand for
charging in a given patch and the price charged per kWh delivered to the EVs; costs
are determined by the number of charging stations in each patch (Struben, 2006;
Struben, 2007; Supple, 2007). Demand for power from charge stations is a function
of the number of EVs driving in or through that patch (whose drivers require
charging in the patch), the number of miles driven per vehicle per day, and the
efficiency of the vehicles (thus determining how may kWh per vehicle per day are
required. The size of the EV fleet in turn depends on the attractiveness of the
electric vehicle platform, which itself depends on the availability of charging
infrastructure (the chicken-and-egg problem previously referenced).

Finally, the model calculates miles driven per day as a function of fuel
availability and consumers’ willingness to travel out of their way to find fuel.
Considering this, the model accounts for congestion that builds up at charge points
as a function of the number of vehicles in a given patch, travel distance, and the
extent to which consumers top-off in response to low availability of refueling infrastructure. This congestion creates a negative feedback loop by reducing the profitability of the infrastructure, beginning with the reduction in vehicle miles driven by owners of the alternative vehicle in fear of not being able to find fuel/charge points. The drop in demand for charging limits charging infrastructure deployment, reducing the overall attractiveness of the electric vehicle platform.

Model Analysis

The scenario analysis that follows is divided into four sections. The first section (Electric Vehicle Base Run) simulates EV deployment using best-guess model parameters derived from the literature and interviews with various stakeholders. The second section (Electric Vehicle Optimistic Scenario) simulates a more optimistic scenario that includes a much more aggressive policy regime, the deployment of fast-charging infrastructure and reduced vehicle costs. The third (Electric Vehicle Extreme Conditions) simulates vehicle electrification using a set of radical conditions necessary to create a sustainable market for EVs. These simulations bring to light the significant hurdles that threaten vehicle electrification, particularly those revolving around infrastructure deployment. The fourth section analyzes different dynamics offered by the growth of PHEVs as an alternative to EVs.

All simulations assume the non-exclusivity of recharging infrastructure, i.e. all vehicles are compatible with all charging equipment at no additional cost. There is one standard for vehicle-to-infrastructure interface. In reality, the issue of
standardization remains open. The Society of Automotive Engineers adopted the J1772 conductive charging standard for EV infrastructure interface, but standards have yet to be resolved for Level 3 fast charging.

Additionally, unless explicitly stated, the simulations assume that EVs are the lone-entrant competing against internal combustion engine vehicles, an optimistic assumption. The model enables multiple alternative vehicles to enter and compete against one another. However, to focus on the issues facing EVs, we assume, optimistically, that there are no other types of alternative vehicles simultaneously competing against conventional ICE vehicles (such as hydrogen fuel cell vehicles or natural gas vehicles).

**Electric Vehicle Base Run**

The model used in this paper (Struben, 2007) was applied to Hydrogen Fuel Cell Vehicles (HFCV) by Supple (2007). This section will look at vehicle electrification under the current policy regime, highlighted in table 6, and best-guess technical parameters for EVs and the corresponding infrastructure. Table 4 below lists the parameters.

The EV parameters were compiled from a literature review and interviews with various stakeholders. Confidential interviews were conducted with select stakeholders in the California EVSE market. These included government bodies, both regulatory and administrative, EVSE vendors, EVSE providers both from commercial sources and municipalities, and utilities. The interview questions for the different category of stakeholder can be found in Appendix One, and the results have
been incorporated into the discussion of EVSE economics above and the parameters listed below.

EVSE vendors assert that planning and site selection could be accomplished in one visit from an EVSE vendor representative. As a result, planning and site selection earlier on may only take a week. However, as more orders are placed, time and personnel constraints will limit EVSE vendors' ability to respond to requests in a timely manner. Additionally, potential EVSE providers will need time to consider and accept EVSE purchase proposals. Combined, these times for planning and site selection should not take longer than three months, 0.25 years.

Similarly, in the early stages, permitting times could be less than one week, until EVSE sales pick up and more permitting is required. As more people purchase EVSE, it can reasonably be expected that these permitting times will increase as a result of personnel constraints. Nonetheless, the permitting time for a charge point will be significantly less than that for a gas station, rarely surpassing two months.

EVSE installations rarely require the magnitude of capital investment and construction required for a gas station. Also relative to gas distribution, there are currently few EVSE vendors in the market. These factors reduce the bidding and construction times for EVSE purchases. Regulators and EVSE vendors expect these times to be between four and five months once the market is off the ground. However, this time could actually be shorter if the EVSE installation will be near an existing electric panel, thus limiting the need for construction and bidding.

Unlike gasoline stations, charge-points will exist in isolated locations in parking lots and on streets, occupying minimal space. These characteristics also
dramatically affect the economics for EV charge-points and gas stations. The EV parameters depicted in table four utilize the lower end of estimates for EVSE capital cost parameters, $1,900 for the charge-point with $2,490 in annual levelized fixed station costs. These costs are significantly lower than the $1,000,000 in capital costs and $296,000 in annual levelized fixed costs for a gas station (Supple, 2007).

Revenue generators for EV charge-points and gas stations are also different. Individual charge points will be distributed geographically, unlike gas refueling positions, which are typically clustered in groups of eight at a gas station. At 33.4 kWh to one gasoline gallon equivalent (gge) and an eight hour charge time for one 24 kWh EV battery, one charge-point has an average daily station sales volume of 2.15 gge compared to the 4000 gge for a gasoline refueling position. These simulations assume (optimistically) a $0.11 per kWh electricity price, concurrent with off-peak prices in California, and a 100-mile range for a 24 kWh battery. Concurrently, one gge equivalent (33.4 kWh) will allow 139 miles per gallon equivalent in fuel economy (Department of Energy, Energy Efficiency and Renewable Energy Alternative Fuels Data Center).

Finally, the initial cost of an electric vehicle is set in accordance with that of the Nissan Leaf, $32,720 manufacturer’s suggested retail price. These costs, along with those for EVSE, represent the capital costs prior to the application of federal and state subsidies.

Very little is known about the lifespan for an EV or EVSE. How long will the battery last? How quickly will the EVSE deteriorate? For simplicity, these parameters are set equal to those of the ICE platform at 16 years and 10 years,
respectively. However, these are optimistic assumptions. An EV battery may
deteriorate faster as a result of constant charge and discharges under real-world use
conditions. It is possible that the lives of these instruments may be shorter.

<table>
<thead>
<tr>
<th>Fuel Parameter</th>
<th>Units</th>
<th>GAS</th>
<th>EV Base Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning &amp; Site Selection Time</td>
<td>years</td>
<td>0.5</td>
<td>0.250</td>
</tr>
<tr>
<td>Permitting Time</td>
<td>years</td>
<td>0.5</td>
<td>0.160</td>
</tr>
<tr>
<td>Bidding and Construction Time</td>
<td>years</td>
<td>0.75</td>
<td>0.400</td>
</tr>
<tr>
<td>Fixed Area</td>
<td>acre/station</td>
<td>0.12</td>
<td>0.001</td>
</tr>
<tr>
<td>Variable Footprint Area per Fueling Position</td>
<td>acre/position</td>
<td>0.02</td>
<td>0.001</td>
</tr>
<tr>
<td>In-Store Sales Revenue/Fuel Revenue</td>
<td>dmnl</td>
<td>0.2</td>
<td>.2</td>
</tr>
<tr>
<td>Depreciable Overnight Station Capital Cost</td>
<td>$/Station</td>
<td>1000000</td>
<td>1,900</td>
</tr>
<tr>
<td>Annual Levelized Fixed Station Costs</td>
<td>$/year/station</td>
<td>296000</td>
<td>2,490</td>
</tr>
<tr>
<td>Fueling Positions/Station</td>
<td>position/station</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Average Daily Station Sales Volume</td>
<td>gge/day/station</td>
<td>4000</td>
<td>2.15</td>
</tr>
<tr>
<td>Average Annual Station Sales Volume</td>
<td>gge/year/station</td>
<td>1500000</td>
<td>785</td>
</tr>
<tr>
<td>Levelized Fixed Cost/Daily Sales Volume</td>
<td>$(gge/day)</td>
<td>74</td>
<td>1,158.14</td>
</tr>
<tr>
<td>Design Daily Capacity per Fueling Position</td>
<td>gge/position/day</td>
<td>3750</td>
<td>2.15</td>
</tr>
<tr>
<td>Total Fill-Up Time (Fixed &amp; Variable)</td>
<td>hour/refill</td>
<td>0.08666</td>
<td>8.00</td>
</tr>
<tr>
<td>Daily Operating Hours</td>
<td>hours</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Unit Variable (Wholesale Fuel) Cost</td>
<td>$/gge</td>
<td>3.00</td>
<td>0.153</td>
</tr>
</tbody>
</table>

Table 4: Model Fuel Parameters

<table>
<thead>
<tr>
<th>Platform Parameter</th>
<th>Units</th>
<th>ICE</th>
<th>EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Size</td>
<td>gge</td>
<td>20</td>
<td>0.718</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>miles/gge</td>
<td>21</td>
<td>139</td>
</tr>
<tr>
<td>Range</td>
<td>miles</td>
<td>420</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle Cost</td>
<td>$/vehicle</td>
<td>25,000</td>
<td>32,720</td>
</tr>
<tr>
<td>Average Vehicle Life</td>
<td>years</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5: Model Platform Parameters

These parameters were used to simulate the markets for EVs under the
current policy conditions displayed in Table 6. Current federal subsidies include tax
credits for $7,500 for the purchase of an electric vehicle and $500 for the purchase
of a charge-point, both set to expire after five years. At this point, there aren't any federal subsidies for infrastructure operation or electricity purchasing, so the duration of those subsidies has been set to 0.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vehicle Subsidy</th>
<th>Infrastructure Capital Subsidy</th>
<th>Infrastructure Operation Subsidy</th>
<th>Fuel Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>$7,500</td>
<td>$500</td>
<td>$2,490</td>
<td>$0</td>
</tr>
<tr>
<td>Start Time</td>
<td>T=0</td>
<td>T=0</td>
<td>T=0</td>
<td>T=0</td>
</tr>
<tr>
<td>Duration</td>
<td>5 years</td>
<td>5 years</td>
<td>0 years</td>
<td>0 years</td>
</tr>
</tbody>
</table>

Table 6: Favorable Policy Conditions for EV Simulation

The EV market rises in the early stages of the market but collapses despite favorable policy initiatives. In Figure 1, the graph of Expected Relative Profitability for Infrastructure and Profitability from Ancillary Sales shows the challenge faced by EV infrastructure providers relative to their counterparts for ICE. The business economics for EVSE providers are not favorable. Without any direct source for ancillary sales there are few economic incentives for apartment buildings, shopping malls, and hotels to purchase and deploy these devices. For this simulation, in store sales revenue was set to 20% of fuel revenue, a generous setting for level 2 EVSE. As one consumer occupies an EV charge-point for up to eight hours at a time, there would be little traffic through an associated convenience store relative to the traffic through a convenience store associated with a gas station.
Figure 1: Electric Vehicle Base Run
As EVs enter the market, infrastructure providers deploy charging points, even though they are doing so at a loss. Early on, the expectation in the industry is that profitability is rising, encouraging deployment. This deployment is responsible for the growth in station density. However, the deployment of charging infrastructure is not enough because station balking fraction and average queue length spike. Without investment in more charge points, the station density does not reach a level that can sustain the market. Congestion grows, further impeding EV adoption and correspondingly, deteriorating the economics of EVSE deployment.

Second generation charging stations are not purchased after the expiration of the first wave between year 10 and 12. Between year 12 and 15, most charging stations are withdrawn from the market, and the market collapses. While charge-points can function beyond their expected life-span, most cannot function beyond 125% of their expected lifespan, expiring at 12 years or shortly there-after.

**Electric Vehicle Optimistic Scenario**

The Electric Vehicle Optimistic Scenario changes the parameters for electric vehicles to make the EV system more competitive. The parameters for the Electric Vehicle Optimistic Scenario differ from those of the Electric Vehicle Base Run in a few important facets captured in Table 7 and 8 below. First, I assume vehicle price parity between EVs and internal combustion engine vehicles. Realistically, the EV carries a price tag of $32,720, not $25,000.

Second, the Electric Vehicle Optimistic Scenario assumes that all charging infrastructure will be level 3, fast chargers that enable a complete recharge in 15 minutes. These fast chargers carry a price tag of $50,000 (Gogoana, 2010).
Third, the Electric Vehicle Optimistic Scenario incorporates a 40-year subsidy regime for infrastructure capital costs, operating costs and vehicle price.

Lastly, rather than having one charge-point comprise a refueling station, it is assumed that there will be eight, as would be the case for ICE vehicle refueling stations. Ancillary revenues remain 20% of gas revenues. Despite a longer charge time (15 minutes) relative to a five-minute refueling time for a gas vehicle, it is unlikely that customers will buy more. Instead, customers would buy a certain amount of goods per stop. However, shortening the recharge time, relative to a Level 2 charger, allows for greater traffic through the station and corresponding convenience store and thus, greater revenues. As a result, the charging infrastructure economics begin to resemble the economics of gas stations, characterized by high capital costs and low fuel margins with more opportunity for ancillary sales.
### Table 7: EV Fuel Parameters

<table>
<thead>
<tr>
<th>Fuel Parameter</th>
<th>Units</th>
<th>GAS</th>
<th>Electric Vehicle Base Run</th>
<th>Electric Vehicle Optimistic Scenario</th>
<th>Electric Vehicle Extreme Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning &amp; Site Selection Time</td>
<td>years</td>
<td>0.5</td>
<td>0.250</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>Permitting Time</td>
<td>years</td>
<td>0.5</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>Bidding and Construction Time</td>
<td>years</td>
<td>0.75</td>
<td>0.400</td>
<td>0.400</td>
<td>0.400</td>
</tr>
<tr>
<td>Fixed Area</td>
<td>acre/station</td>
<td>0.12</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Variable Footprint Area per Fueling Position</td>
<td>acre/position</td>
<td>0.02</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>In-Store Sales Revenue/Fuel Revenue</td>
<td>dmnl</td>
<td>0.2</td>
<td>2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Depreciable Overnight Station Capital Cost</td>
<td>$/Station</td>
<td>1000000</td>
<td>1,900</td>
<td>400,000</td>
<td>1,900</td>
</tr>
<tr>
<td>Annual Levelized Fixed Station Costs</td>
<td>$/year/station</td>
<td>296000</td>
<td>2,490</td>
<td>42,300</td>
<td>2,490</td>
</tr>
<tr>
<td>Fueling Positions/Station</td>
<td>position/station</td>
<td>8</td>
<td>1</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Average Daily Station Sales Volume</td>
<td>gge/day/station</td>
<td>4000</td>
<td>2.15</td>
<td>551.86</td>
<td>551.86</td>
</tr>
<tr>
<td>Average Annual Station Sales Volume</td>
<td>gge/year/station</td>
<td>1500000</td>
<td>785</td>
<td>201,427.55</td>
<td>201,427.55</td>
</tr>
<tr>
<td>Levelized Fixed Cost/Daily Sales Volume</td>
<td>$(gge/day)</td>
<td>74</td>
<td>1,158.14</td>
<td>76.65</td>
<td>76.65</td>
</tr>
<tr>
<td>Design Daily Capacity per Fueling Position</td>
<td>gge/position/day</td>
<td>3750</td>
<td>2.15</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Total Fill-Up Time (Fixed &amp; Variable)</td>
<td>hour/refill</td>
<td>0.08666</td>
<td>8.00</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Daily Operating Hours</td>
<td>hours</td>
<td>18</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Unit Variable (Wholesale Fuel) Cost</td>
<td>$/gge</td>
<td>3.00</td>
<td>0.153</td>
<td>0.153</td>
<td>.0153</td>
</tr>
</tbody>
</table>

### Table 8: EV Platform Parameters

<table>
<thead>
<tr>
<th>Platform Parameter</th>
<th>Units</th>
<th>ICE</th>
<th>Electric Vehicle Base Run</th>
<th>Electric Vehicle Optimistic Scenario</th>
<th>Electric Vehicle Extreme Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Size</td>
<td>gge</td>
<td>20</td>
<td>0.718</td>
<td>0.718</td>
<td>0.718</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>miles/gge</td>
<td>21</td>
<td>139</td>
<td>139</td>
<td>139</td>
</tr>
<tr>
<td>Range</td>
<td>miles</td>
<td>420</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle Cost</td>
<td>$/vehicle</td>
<td>25,000</td>
<td>32,720</td>
<td>25,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Average Vehicle Life</td>
<td>years</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

---

**Table 7:** EV Fuel Parameters

**Table 8:** EV Platform Parameters
Figure 2: Electric Vehicle Optimistic Scenario
Even with these optimistic parameters, however, the market for electric vehicles fails to develop sustainably, as shown in figure 2. Like the base run, the Optimistic Scenario rises gradually, surpassing the base run and peaking at year 15. This scenario allows for more growth as a result of the fast-charging infrastructure. The gap in expected relative profitability between the Optimistic Scenario and the Base Run stems from the difference in ancillary sales. The decrease in charging time allows for more vehicles to utilize the charging station, and more ancillary sales accompany greater utilization.

However, these added profits do not provide enough of a boost to push the EV over the tipping point. Profitability is not high enough to warrant more investment in another generation of charging infrastructure, and as a result many stations leave the market as the life expectancy for the charge-point (10 years) passes. As stations leave the market, station balk fraction and queue length spike, driving down adoption, and the market fails.

**Electric Vehicle Extreme Conditions**

The Electric Vehicle Extreme Conditions scenario alters additional technical and economic parameters on top of those modified in the Electric Vehicle Optimistic Scenario (Tables 7 and 8).

First, instead of a co-evolution of vehicle and infrastructure deployment, infrastructure for EVs is exogenously deployed at the beginning of the simulation such that the station density of charge-points or HFCV fuel distribution points equals 15 percent that of gasoline distribution initially. After initiation, station density is allowed to grow or decline endogenously. This circumvents the previously
discussed chicken-and-egg problem, as a number of public charging options will be available at the outset.

Second, it is assumed that level 3 fast chargers will cost the same amount as level 2 chargers ($1,900). In reality, a fast charger could cost up to $50,000, as established in the Optimistic Scenario (Gogoana, 2010).

These extreme conditions result in a sustainable electric vehicle market. After 30 years, EVs reach 40 percent market share as depicted in the Vehicle Adoption graph in Figure 3. However, as a result of negative infrastructure-industry returns, the build out of charging infrastructure does not occur until year 20. Until that point, EVSE providers do not see fit to add to the station capacity beyond replacement of the stations that had been exogenously deployed at the beginning. However, since the expected profitability continues to rise, the replacement does occur, allowing for the development of familiarity of the EV platform and the positive feedbacks that follow for platform adoption as a result.

The high Average Pump Utilization indicates that the lack of a compelling investment in the infrastructure holds the market back, resulting in a high station balk fraction and a growing queue length. Nonetheless, cumulative vehicle production increases and the market sustains EV penetration at 30%.

Comparing the Electric Vehicle Base Run, Optimistic Scenario and Extreme Conditions scenarios highlights the importance of infrastructure development and deployment for electric vehicle market penetration. Without exogenous deployment and significantly reduced costs for fast charging EV infrastructure, the market for
EVs collapses. The next sections analyze the dynamics surrounding these infrastructure issues.

Figure 3: Electric Vehicle Extreme Conditions
EV simulation conclusion: The effects of exogenous infrastructure deployment

In the Electric Vehicle Extreme Conditions simulation, charging infrastructure is exogenously deployed prior to the simulation such that the geographical dispersion of EV charge-points, i.e. the number of charge-points per square mile, is 15 percent that of ICE refueling stations. The government covers the total cost of this deployment, allowing EVSE providers to forgo the initial upfront capital costs. Concurrently, the availability of infrastructure reduces consumer anxiety over range, allowing for more rapid growth in sales. Growth in sales pushes the market past the tipping point, allowing for industry improvements as a result of learning and experience, demonstrated by improvements in new vehicle performance in Figure 3.

In the Electric Vehicle Optimistic Scenario simulation, EVSE providers must buy infrastructure up front. Initial deployment increases past the Extreme Conditions scenario as EVSE providers take advantage of the station capital subsidy and the station-operating subsidy. However, vehicle sales never get the initial spike necessary to initiate positive word of mouth and learning feedback loops.

EV simulation conclusion: The effects of fast charging price

The Extreme Conditions simulation assumed that Level 3 fast chargers would cost the same as Level 2 chargers: $1,900 including installation. However, these chargers may cost $50,000 (though none are on the market right now). The charger will also have significant installation costs due to the high current flux it must handle.

In the first ten years, expected profitability for the full cost, Optimistic Scenario simulation exceeds the expected profitability for the reduced-cost Extreme
Conditions simulation, as seen in Figure 3. Much of the fast-charger installation cost could be amortized over a group of fast chargers, all within one refueling station. (Note: This amortization is unlikely for level 2 chargers, in reality, because EVSE providers will not want to buy more than one at a time because their profits will be derived from utilization.) As a result, relative station density grows faster at the outset with vehicle sales alongside it. As the first set of stations begin to wear out, additional investment is necessary to maintain the station density. However, these additional costs reduce profitability, and when profitability drops, station density follows soon thereafter. When the station density drops, the Balk Fraction increases, indicating that the market is in a tailspin, and concurrently, the adoption fraction declines unable to sustain its growth.

**Plug-In Hybrid Electric Vehicles**

To this point, all simulations have modeled pure electric vehicle adoption. However, the presence of plug-in hybrid electric vehicles significantly alters the market by negating the needs identified above for cheaper infrastructure prices and exogenous infrastructure deployment. A PHEV can capitalize on the benefits of an electric vehicle – cheaper input fuel and better fuel efficiency – without the corresponding constraints – range anxiety and limited battery capacity. The next simulation analyzes the adoption of a PHEV as the lone incumbent against the internal combustion engine to get a sense for the dynamics of PHEV diffusion. Afterward, PHEVs will be simulated against EVs and ICE to analyze the technological and familiarity spillovers between the two alternative platforms.
In modeling PHEV adoption, a few assumptions about consumer behavior must be made. First, consumers are likely to charge their vehicles at nights at their homes. This will allow for a full 40-mile range at the beginning of each day. After the battery is depleted, the consumer can drive on gasoline. While consumers likely would want to charge at work, they will only be able to do so if the appropriate infrastructure is in place. The simulation assumes that there is no public charging infrastructure for PHEVs. Such an assumption will result in a lower PHEV adoption than might otherwise be the case. The cost of a level 2 home charger has been built into the vehicle price, so that while a Chevy Volt carries a $40,000 price tag, the vehicle cost is inflated by the $1,900 cost and installation for an EVSE to $41,900.

Second, the fuel economy for a PHEV is set to 93 miles per gasoline gallon in congruence with the EPA ruling for corporate average fuel economy (CAFE) standards, which produces a range of 865 miles (Environmental Protection Agency, 2010). However, these fuel economy ratings are still in flux. 93 miles per gasoline gallon and 865 miles of range are optimistic parameter settings for the PHEV and favor PHEV adoption in the simulations. In reality, the average miles driven per day will determine the real values for the fuel economy and range parameters. If consumers drive less than 40 miles per day, 93 miles per gasoline gallon with an 865-mile range will be feasible. However, if consumers are driving more miles, they will be using the ICE engine more frequently, and the fuel economy and range will be significantly lower.

Similarly, it must be noted that another significant hurdle to PHEV market penetration is not captured in this model. The fuel economy benefits of a PHEV can
only be achieved under the assumption that a driver can charge his vehicle at night off-peak. However, in large cities most people will not have garages in which they can charge their car. They will be forced to charge at public EVSE. In that case, diffusion will begin to look more like those of the EV, hindered by the requirement of public charging infrastructure deployment.

The PHEV simulation is conducted under the same policy and model parameter framework as the Electric Vehicle Base Run. The policies in place correspond to the current policy regime as depicted in Table 6.

<table>
<thead>
<tr>
<th>Fuel Parameter</th>
<th>Units</th>
<th>GAS</th>
<th>Electric Vehicle Base Run</th>
<th>PHEV Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning &amp; Site Selection Time</td>
<td>years</td>
<td>0.5</td>
<td>0.250</td>
<td>0.5</td>
</tr>
<tr>
<td>Permitting Time</td>
<td>years</td>
<td>0.5</td>
<td>0.160</td>
<td>0.5</td>
</tr>
<tr>
<td>Bidding and Construction Time</td>
<td>years</td>
<td>0.75</td>
<td>0.400</td>
<td>0.75</td>
</tr>
<tr>
<td>Fixed Area</td>
<td>acre/station</td>
<td>0.12</td>
<td>0.001</td>
<td>0.12</td>
</tr>
<tr>
<td>Variable Footprint Area per Fueling Position</td>
<td>acre/position</td>
<td>0.02</td>
<td>0.001</td>
<td>0.02</td>
</tr>
<tr>
<td>In-Store Sales Revenue/Fuel Revenue</td>
<td>dmnl</td>
<td>0.2</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Depreciable Overnight Station Capital Cost</td>
<td>$/Station</td>
<td>1,000,000</td>
<td>$1,900</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Annual Levelized Fixed Station Costs</td>
<td>$/year/station</td>
<td>296000</td>
<td>$2,490</td>
<td>296,000</td>
</tr>
<tr>
<td>Fueling Positions/Station</td>
<td>position/station</td>
<td>8</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Average Daily Station Sales Volume</td>
<td>gge/day/station</td>
<td>4000</td>
<td>2.15</td>
<td>4000</td>
</tr>
<tr>
<td>Average Annual Station Sales Volume</td>
<td>gge/year/station</td>
<td>1500000</td>
<td>785</td>
<td>1500000</td>
</tr>
<tr>
<td>Levelized Fixed Cost/Daily Sales Volume</td>
<td>$(/gge/day)</td>
<td>74</td>
<td>$1,158.14</td>
<td>74</td>
</tr>
<tr>
<td>Design Daily Capacity per Fueling Position</td>
<td>gge/position/day</td>
<td>3750</td>
<td>2.15</td>
<td>3750</td>
</tr>
<tr>
<td>Total Fill-Up Time (Fixed &amp; Variable)</td>
<td>hour/refill</td>
<td>0.0866</td>
<td>8.00</td>
<td>0.0866</td>
</tr>
<tr>
<td>Daily Operating Hours</td>
<td>hours</td>
<td>18</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Unit Variable (Wholesale Fuel) Cost</td>
<td>$/gge</td>
<td>$3.00</td>
<td>$0.153</td>
<td>$3.00</td>
</tr>
</tbody>
</table>

Table 9: EV and PHEV Fuel Parameters

<table>
<thead>
<tr>
<th>Platform Parameter</th>
<th>Units</th>
<th>ICE</th>
<th>EV</th>
<th>PHEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Size</td>
<td>gge</td>
<td>20</td>
<td>0.718</td>
<td>9.3</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>miles/gge</td>
<td>21</td>
<td>139</td>
<td>93</td>
</tr>
<tr>
<td>Range</td>
<td>miles</td>
<td>420</td>
<td>100</td>
<td>865</td>
</tr>
<tr>
<td>Vehicle Cost</td>
<td>$/vehicle</td>
<td>25,000</td>
<td>32,720</td>
<td>41,900</td>
</tr>
<tr>
<td>Average Vehicle Life</td>
<td>years</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 10: EV and PHEV Platform Parameters
The extended range and shared infrastructure dramatically improve the adoption dynamics for the PHEV. Figure 4 below shows the PHEV sustainably diffusing into the market with a total adoption fraction above 90% after 30 years. A couple of years after the vehicle enters the market, sales pick up, elevating the profitability of refueling infrastructure, increasing familiarity and leading to more adoption. As more vehicles are adopted, institutional learning occurs that improves driving performance, initiating another positive feedback.
This simulation doesn’t tell the entire story, however. PHEVs will be competing in the market with EVs in addition to ICE vehicles. The next simulation analyzes the interplay between EVs and PHEVs in the market.

**EVs vs. PHEVs**

This simulation considers the interplay between EVs and PHEVs when they are deployed alongside one another. The PHEV parameters are the same as those used above, and the EV parameters match those of the Extreme Conditions.
simulation. These parameters were used to spur a sustainable EV market in order to best gauge the interaction between EVs and PHEVs.

Struben (2007) and Supple (2007) explain that the model differentiates between incumbents and entrants based on their compatibility with ICE refueling infrastructure. The fact that PHEVs share infrastructure with ICE vehicles allows the PHEV to be modeled as the incumbent with the EV as the lone entrant. While this may not perfectly represent reality, it is not unrealistic to assume that consumers will decide first whether to purchase an alternative fuel vehicle or an ICE vehicle. If the decision is made to purchase an alternative fuel vehicle, then consumers will decide between alternative platforms, in this case the EV or PHEV. Moreover, this simulation is not meant to be predictive. Rather, analysis is required to best understand the interplay between the two platforms, the spillovers in technical innovation and co-evolution of consumer familiarity.

The EV vs. PHEV simulation carries a couple of other assumptions. First, I assume that the PHEV and EV share charging standards, such that EVs and PHEVs can recharge on the same infrastructure. Both the Volt, a PHEV, and the Leaf, an EV, use the Society of Automotive Engineer J1772 standard for charge plug, and this trend is likely to continue with other makes and models. Different charging standards for different makes and models would significantly impair market penetration because all vehicles wouldn’t be able to charge at all EVSE locations.

Second, strong feedbacks exist as a result of technological spillovers between the EV and PHEV, such that improvements in one platform can be utilized by the other platform. Strong feedbacks are likely to favor PHEV deployment. For example,
if battery technology improved to enable a 150 all-electric range for an EV on the same 24 kWh battery, similar improvements would be available for a PHEV range. At this point, 150-mile all-electric range may not sufficient to alleviate consumer range anxiety. However, some all-electric range should be enough to alleviate those concerns. When battery capacity improves to reach that range, EVs may be able to capture all of the benefits, pushing PHEVs out of the market. Until then though, it is likely that PHEVs will capture the benefits of spillovers.

Figure 5 compares the EV vs. PHEV simulation to the EV (Extreme Conditions) vs. ICE simulation. EVs attain a greater total adoption fraction initially when simulated against PHEVs, but in the last five years, its growth is stagnant. Eventually, total adoption is greater for the EV vs. ICE simulation. The outcome seems counterintuitive because the expected relative profitability and, accordingly, the relative charging station density is greater for the EV vs. PHEV simulation. However, because PHEVs utilize the charging infrastructure in addition to the gasoline infrastructure, station profitability increases, enabling a higher station density. However, these additional charge-point users increase congestion, spiking the average queue length. Increased average queue length creates unfavorable feedback to reduced sales and stagnated adoption.

It might be expected that the EV would benefit from technical spillovers from the PHEV, but the reality is that the negative feedbacks discussed above from the infrastructure side dominate the dynamics. Platform familiarity and exposure from drivers are roughly equivalent between the high spillover scenario (EV vs. PHEV)
and a lower spillover scenario (EV vs. ICE). Similarly, new vehicle performance, representative of technical spillovers, remains largely unchanged.

These dynamics may occur because in the EV vs. ICE simulation, the EV moves up the learning curve, already capturing the benefits of experience. It still moves up the learning curve in the EV vs. PHEV simulation, so the added experiential benefits from deploying with the PHEV may be negligible.
Finally, it is important to reiterate that these simulations are not intended to predict market penetration but rather to provide insight into the important interactions between parameters within the vehicle electrification system. This
analysis highlights the importance of the state of infrastructure deployment and recharging options, particularly capital costs and charge time. The PHEV, free of the reliance on electric vehicle charging infrastructure, is able to attain significant market penetration as a market entrant. As a result, when deployed with EVs, the PHEV curtails the growth of the EV market by attracting would-be EV adopters and utilizing EV infrastructure, increasing congestion and initiating unfavorable feedback loops toward less adoption.

Future Research

It is impossible to perfectly simulate a system as large as the one that unites the transportation system and the electricity system. In attempting to model vehicle electrification, there are necessarily a number of shortfalls, and this work is no different.

First, this analysis assumes that EVs and PHEVs are the only alternative fuel vehicles vying for adoption in the market. Natural gas vehicles, flex-fuel vehicles, bio-fuel vehicles, and other alternatives will compete against each other in the market resulting in lower adoption for each platform. This extra competition will limit the adoption of EVs and PHEVs.

Second, the potential dangers to the electricity infrastructure in California as a result of vehicle electrification are not captured in the model. High EV diffusion could result in increased costs of electricity for everyone, a negative feedback loop that is not represented.
Third, most people will charge their EVs in their garages at home. Home charging is not included in the model for EVs and will likely have a significant effect on the market moving forward. The presence of home charging diminishes the range anxiety for consumers looking to buy electric vehicles. However, a home charger will cost $1000 in addition to any installation fees, which would vary by distance to the home’s electricity panel. While this would be an additional price to consumers, it reduces the necessity for infrastructure. However, this in turn minimizes the incentive for providers to deploy EVSE, which increases the range anxiety for drivers. The outcome of these dynamics is uncertain and further research into modeling them is needed.

Additionally, the PHEV simulation assumes that home charging will occur, while the EV simulations don’t take it into account. This discrepancy dramatically favors the PHEV over the EV, as the basis for the PHEV improvement vis a vi the ICE platform is the increased range and fuel economy made possible by the availability of home charging.

**Policy Recommendations**

The numerous stakeholders in the vehicle electrification system paint a particularly complicated political picture. There are a variety of strong concentrated interests held by the oil and gas industry, the electricity industry, the automobile industry, the battery industry and the fledgling EVSE industry. To these groups, the costs and benefits of vehicle electrification are real and significant. However, the
energy security and environmental benefits that would be accrued as a result of vehicle electrification are diffuse. As a result, the voices in the former category resonate the loudest, while those of the latter tend to be stifled. However, unlike other regulations in the energy space, vehicle electrification might untie the strong electricity industry lobbying effort from their counterparts at oil and gas firms, offering a glimmer of hope for vehicle electrification proponents moving forward.

Should governments decide that vehicle electrification is a worthwhile policy initiative, there are a number of policy strategies they can employ. Governments can subsidize electric vehicle purchases, infrastructure deployment and research and development for battery chemistries and smart-grid applications to facilitate charging. Additional options heretofore absent from the policy portfolio include a gasoline tax, corporate average fuel economy standard or a low-carbon fuel standard. Today, the United States government employs a collection of tax credits for EV and EVSE purchases in addition to direct investments in manufacturing facilities and infrastructure deployment. Table 9 below from Kenderdine, Kearney and Parness (2011) illustrates the current policy regime. The first section of the table, Batteries, Infrastructure and Manufacturing Assistance, denotes programs that intend to reduce the price of batteries and/or increase the capacity of vehicle-scale batteries in order to make EVs more appealing to consumers. The second section of the table, EV deployment, denotes programs that intend to reduce the price of the overall vehicle relative to conventional internal-combustion engine vehicles.
Table 11: Federal Government Policy Portfolio

It is important to note that the model runs above are not intended to predict outcomes, but rather to show which policy instruments affect the system in the greatest ways in order to inform policy makers. Thus, policies should aim to push vehicle infrastructure and encourage innovation in the EVSE market.

As demonstrated above, because of the unfavorable economics of charging infrastructure, the deployment of charge-points has a large effect on vehicle adoption. The government has deployed $100 million in charge-points to date, and offers a $500 tax credit for the purchase of EVSE. These policies play an important role in infrastructure roll-out as the business proposition for the private sector remains uncertain.
However, while the government has invested large sums of money in battery technology innovation over the last 15 years for electric vehicles, subsequent investment in charging technology has not followed. As automobile manufacturers adjust the vehicle batteries to the power of fast-charging stations, policy makers will need to allocate more funds to develop fast-charging stations.

**Policy Continuity**

EVs and other alternative fuel vehicles struggle to attain market share for a number of reasons, but a large hurdle revolves around the nature of the incumbent platform, the internal combustion engine, and the incumbent fuel, gasoline. Simply put, gasoline is cheaper and more energy dense than its alternatives. Policies to promote alternatives should be complimented by policies to internalize the externalities of the incumbent, allowing the market to realize the full price of oil consumption. A final policy consideration to stimulate EV adoption is a gasoline tax. From a policy perspective, a gasoline tax is preferable in that it is technology agnostic relative to alternative fuel vehicle options. However, because Congress has struggled to pass economically more efficient regulations like a gas tax to internalize the environmental and security externalities of oil consumption, technologies like electric vehicles are selected against other alternative fuel vehicles resulting in a grab-bag of tax-credits and subsidies for EVs, NGVs, and bio-fuels without any clear policy direction.
**Conclusion**

Significant environmental and security concerns exist to motivate vehicle electrification as a policy initiative. However, at the same time, significant economic barriers exist to wide-spread vehicle electrification. If, as a matter of policy, government officials want to promote vehicle electrification a significant financial commitment is necessary to deploy charging infrastructure and innovate toward faster cheaper chargers, as demonstrated by the dynamic behavioral spatial model used in this work. These initiatives carry a significant price tag and long time horizons that will require a long-term political commitment that is free of the ebb and flow of the standard, short-sited political cycle.
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64


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Appendix One: Interview Questions

For each organization, to start:

- Tell me about your organizations involvement in the market for EVs.

Questions for EVSE vendors and providers:

- How do you view the commercial prospects for electric vehicles? PHEVs?
- How do you view the commercial prospects for electric vehicle supply equipment?
- What are your company's criteria for investment in the EVSE industry / How was this decision made?
- How long of a payback period do you expect on your investment? Do you envision withdrawing EVSE if under-utilized?
- What level charging station are you developing? Deploying? How fast do you expect a battery to recharge on average?
- What are the most important technical barriers to commercialization?
- What are the most important non-technical barriers to commercialization?
- What variable costs do you foresee in EVSE production?
- What are the fixed costs that your firm will incur in production and deployment?
- Do you anticipate an additional price to be added to the rate for charging an EV in your area? What is ‘additional price’ for? Electricity price + margin to pay off recharging point?
- What role should the government play in facilitating infrastructure deployment? Additional regulations? Time-of-use pricing?
- Who is your company’s primary buyer of public charging equipment? Who will own and operate the equipment?
- Where do you expect to locate public charging equipment? More specifically, what indicators will you use to decide where you will install a recharging point and when? Sales? Recent sales? Utilization of existing EVSE infrastructure?
- What distribution density does your company view as adequate? How do you evaluate an adequate density distribution?
- Is it possible that the distribution density employed initially may not be the most convenient station allocation in the eyes of the consumer? (I.e. are there split incentives for consumers and EVSE producers?)
- How many chargers do you expect per station?
- What utilization rate (hours use/day) do you envisage / need?
- What is your target ratio for charging stations per vehicle?
- Will your charging infrastructure be a pay-per-use service or a subscription service?
- What is the lifespan of your product?
• What is the expected installation time for your product? Planning and site selection? Permitting? Bidding and construction time?
• How much space will the charging station occupy? Single EVSE space?

Questions for Utilities:
• How do you view the commercial prospects for electric vehicles? PHEVs?
• How do you view the commercial prospects for electric vehicle supply equipment?
• Is your company involved in development and/or deployment of EVSE?
• If your company is not yet involved, what market signals and/or events might incent your company to get involved?
• What are your company’s criteria for involvement?
• What is your company doing to prepare for an EV roll out?
• Is your company concerned about the impact of EVs on the electricity sector? If yes, how do you plan to manage these impacts? Differential pricing?
• *If* yes, what level charging station are you developing? Deploying? How fast do you expect a battery to recharge on average?
• What opportunities are available to your company as a result of / how could your company benefit from this move toward vehicle electrification?
• What are the most important technical barriers to commercialization?
• What are the most important non-technical barriers to commercialization?
• Do you anticipate an additional price (?) to be added to the rate for charging an EV in your area?
• What role should the government play in facilitating infrastructure deployment? Additional regulations? Time-of-use pricing?
• *If* yes, who is your company’s primary buyer of public charging equipment? Who will own and operate the equipment?
• *If* yes, where do you expect to locate public charging equipment?
• *If* yes, what distribution density does your company view as adequate? How do you evaluate an adequate density distribution?
• Is it possible that the distribution density employed initially may not be the most convenient station allocation in the eyes of the consumer? (I.e. are there split incentives for consumers and EVSE producers?)
• How many chargers do you expect per station?
• In your analysis, what should be the target ratio for charging stations per vehicle?

Questions for Government representatives:
• How do you view the commercial prospects for electric vehicles? PHEVs?
• How do you view the commercial prospects for electric vehicle supply equipment?
• What is your branch of the government doing to speed development and/or deployment of electric vehicle supply equipment?
• What specific incentives are in place for public charging infrastructure deployment?
• What electricity rates and taxes for EV charging are in effect or will be in effect within the next year?
• What are your criteria for involvement in the field?
• How do you evaluate the success of government action with regard to development and deployment of electric vehicles/EVSE? What market signals and/or events do you monitor?
• What distribution density does your government view as adequate? How do you evaluate an adequate distribution density?
• How many chargers do you expect per station?
• What is your target ratio for charging stations per vehicle?