TECHNOLOGY

PLUG-IN ELECTRIC VEHICLES: LITERATURE REVIEW

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

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INTRODUCTION

The U.S. transportation system relies on oil for 94 percent of delivered energy with no substitutes currently available at scale. This complete dependence on a single fuel has its origins in a time when oil was an inexpensive and exclusively domestic resource, but over time, it has created serious economic and national security vulnerabilities for the United States. In addition to highly volatile and economically damaging prices, petroleum fuels carry high environmental costs. With nearly 50 percent of U.S. supplies deriving from foreign producers, high oil prices have also contributed heavily to an expanding trade deficit and national security concerns.

Electrification of the transportation system with plug-in electric vehicles (PEVs) has the potential to decrease the United States' dependence on oil and the risks associated with its production and use. Using electricity as a fuel also has benefits for the average consumer, as it is less expensive than gasoline, and electricity prices are less volatile than gasoline prices (MIT 2010). From 1976 to 2008, the price of residential electricity decreased 0.1 percent in real terms while gasoline prices increased by 75 percent in real terms (EIA 2009). In the United States, petroleum accounts for less than one percent of electricity generated, almost all electricity is from domestic fuels, and electricity can be made from sources with almost no greenhouse gas emissions (EIA 2011). Therefore, electrification has the potential to mitigate some of the negative consequences of oil dependency on the economy, national security, and the environment (MIT 2010).

This paper reviews the current literature on PEVs with a focus on issues and solutions related to vehicle deployment and integration with the U.S. electrical grid. It is a companion to C2ES' "Plug-in Electric

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Vehicles Market: State of Play." Material covered in that white paper is not duplicated here. The subjects covered here include vehicles, electricity, the passenger vehicle market, and public policy. This paper relies on the most recent research from government, private business, academia, and research institutions; peer-reviewed literature was used wherever possible. The paper's purpose is to provide a foundation for overcoming some of the major hurdles to PEV deployment in the United States both currently and in the future.

Throughout this paper, the term PEV refers to plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). BEVs and PHEVs are different in many ways including battery pack size, overall system cost and complexity, vehicle range, and more. Despite these differences, both face similar challenges to market growth, and both require similar solutions to overcome barriers. This paper distinguishes between the two vehicle types wherever appropriate.

PLUG-IN ELECTRIC VEHICLES

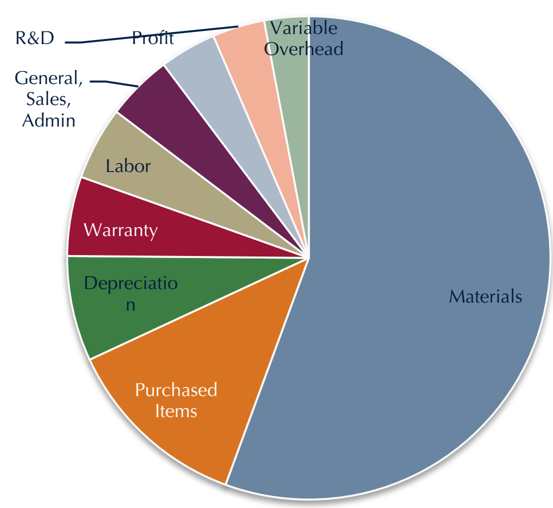
The high cost of PEVs relative to conventional vehicles, PEVs' limited range, battery charging time, and battery durability concerns challenge the growth of widespread consumer demand (MIT 2010). Current PEVs use lithium-ion batteries, which were originally developed for use in consumer electronics. While lithium ion-batteries are more expensive than the nickel-metal hydride batteries used in hybrid electric vehicles (HEVs), they offer substantial performance advantages (Indiana University 2011).

COST REDUCTIONS NEEDED FOR VEHICLES

The principal challenge PEVs face to becoming competitive with conventional vehicles is the high initial cost of purchasing the vehicle, which is in large part due to the high cost of the battery system. The cost to auto manufacturers of current PEV lithium-ion batteries is around $600 per kilowatt-hour (kWh) of total energy or nameplate capacity, while the cost of consumer home-use lithium-ion batteries has been reduced to $250 per kWh (Ener1 2010, BCG 2010).[1] Prices for large-format automotive-grade batteries[2] are expected to drop, with the potential to reach $500 per kWh by 2015 (BCG 2010). However, PEVs may not become cost-competitive with conventional vehicles until battery costs reach $300 per kWh[3] (MIT 2010).

The United States Advanced Battery Consortium has set a cost target of $250 per kWh, but a Boston Consulting Group analysis of battery costs estimates the cost will remain above that target through 2020. The analysis concluded that between 2009 and 2020 the cost that original equipment manufacturers (OEMs) pay for batteries would decrease by 60 to 65 percent. And the price of 15 kWh battery that costs

FIGURE 1: Components of the unit cost of a battery pack (Nelson, Gallagher, & Bloom, 2011 (DRAFT)).



$990 to $1,220 per kWh in 2009 would drop to $360 to $440 per kWh in 2020, with a total cost of the battery at around $6,000 (BCG 2010).

TABLE 1: Predicted Energy Capacity and Cost of Lithium-Ion Battery Packs for PEVs (Santini, Gallagher and Nelson 2010).*

	ELECTRIC DRIVE RANGE (MILES)	TOTAL ENERGY (KWH)	USEABLE ENERGY** (KWH)	TOTAL COST ($)	TOTAL ENERGY COST ($/KWH)
PHEV	20	10.3	7.2	2,058	200
EREV***	20	9.6	6.7	2,741	285
EREV	40	18.7	13.1	3,604	193
BEV	100	33.3	25	4,848	146

*Assuming a production rate of 100,000 per year. Cost is for manufacturing, not the retail price.

** PEVs do not use the system's total battery capacity to ensure a long usable life. See *Uncertain Battery Lifespan and Durability*.

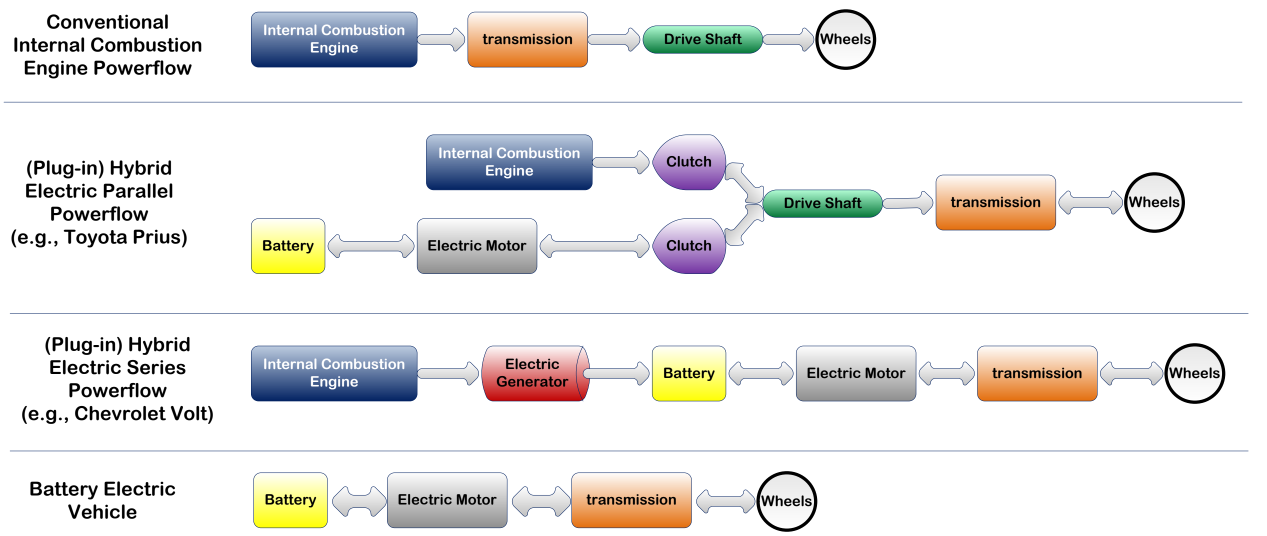
*** EREV or extended range electric vehicle is an electric drive vehicle that contains an internal combustion engine (ICE) to charge the battery system when its energy is depleted (e.g., Chevrolet Volt). It is similar to a PHEV except the ICE does not power the wheels (see Figure 2).

As production volume increases, the cost of batteries will decrease due to economies of scale. Through the American Reinvestment and Recovery Act (the Recovery Act), the U.S. Department of Energy (DOE) has funded efforts to increase production rates so battery manufacturers can benefit from economies of scale. DOE estimates that if a battery plant expands production from 10,000 units per year to 100,000 units per year, it can reduce battery costs by 30 to 40 percent (DOE 2010). In addition to economies of scale, the price of PEV batteries is expected to drop due to learning curve improvements such as decreased cost of battery materials, increased manufacturing expertise, and advancements in battery design (BCG 2010). However, about 25 percent of the battery cost, mainly standard parts and raw materials, will remain independent of scale, limiting the potential for overall cost reduction (BCG 2010).

As lithium-ion chemistries are developed, improved, and produced on a large scale (100,000 battery packs per year), the cost per kWh to manufacture batteries could drop significantly. Importantly, almost half the cost of manufacturing a battery pack is expenses is not related to manufacturing or materials, so advancements will need to go beyond battery chemistry (see Figure 1). If broad improvements are achieved, costs could reach below $300 for PHEVs, and below $200 for BEVs, as seen in Table 1 (Santini, Gallagher and Nelson 2010).

In the case of plug-in hybrid electric vehicles (PHEVs), the cost challenge is further complicated by the fact that they require a battery pack as well as an internal combustion engine (ICE) and associated components (see Figure 2). The ICE system in a PHEV, including the drivetrain and fuel tank, can add $4,000 per vehicle. However, PHEVs require less energy capacity from the battery—and therefore a lower cost battery pack—than BEVs, so the addition of the ICE system does not necessarily make them less economically competitive (IEA 2009).

FIGURE 2: Power flows for different vehicle types. External electricity can be used to provide energy to the batteries in a PHEV, while it cannot do so in a hybrid electric vehicle. A plug-in hybrid series vehicle is also known as an EREV.

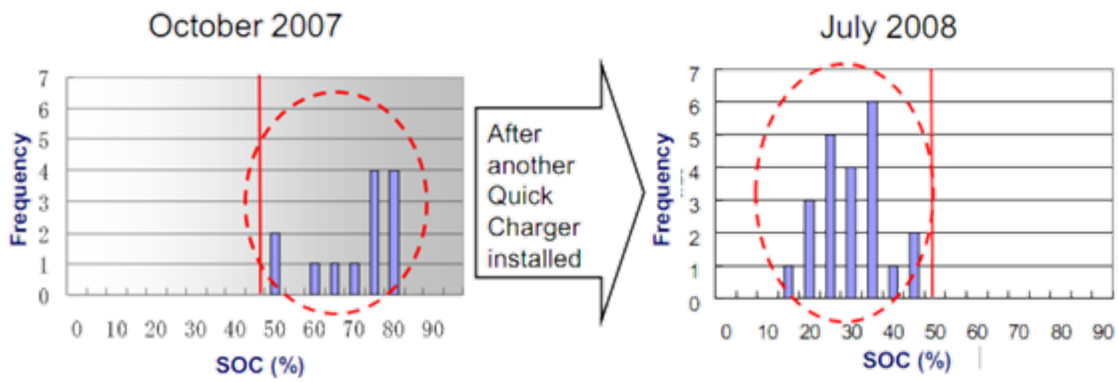


LIMITED DRIVING RANGE AND RANGE ANXIETY

Range anxiety, a common consumer concern about BEVs, is the worry that a vehicle has an insufficient range for a driver to reach his or her destination and will leave the driver "stranded." Although the average daily drive range in the United States is 33 miles, many consumers are concerned about the limited range of BEVs (Accenture 2011, Kintner-Meyer, Schneider and Pratt 2007). A recent survey by Deloitte Global Services found that 90 percent of U.S. respondents drive 75 miles or less per day, which is the expected range of the 2011 Nissan LEAF. Since many drivers occasionally drive beyond this distance, the same study showed that the "expected range" of 63 percent of respondents was around 300 miles on a single charge, which is not currently available in any BEV model (Deloitte 2011). PHEVs overcome this "range anxiety" altogether, as they are capable of running fully on gasoline when the battery becomes discharged (Benecchi, et al. 2010). For this reason, they are currently a more popular choice among consumers surveyed, who rank the insufficient battery range of BEVs as the number one reason to choose a PHEV over a BEV (Accenture 2011).

The installation of public charging infrastructure can also help reduce range concerns and spur BEV sales. The amount of public charging infrastructure needed, however, is still unknown. A trial program by the Tokyo Electric Power Company (TEPCO) suggests that even with minimal fast-charging infrastructure, BEV drivers become more comfortable driving further and approaching their maximum range (Aoki 2010). Some public and private stakeholders believe a thorough network of public charging infrastructure is necessary to overcome range anxiety while one study predicts that as few as one public charging station per 100 PEVs would be sufficient. In that case, the majority of PEV charging would take place at private residences (Benecchi, et al. 2010). In a different study, General Electric estimates that 1.4 public and private charging stations are desirable for each PEV (General Electric 2011).

Figure 3: Impact of the strategic installation of public charging stations. State of charge (SOC) is the amount of energy in the battery (Aoki 2010).



The range of a BEV or the all-electric range of a PHEV is determined by the specific energy density[4] of its battery. The specific energy density of today's lithium-ion batteries is only 1 percent that of gasoline, which limits range because large—and therefore heavy—battery systems are needed.[5] Without a major breakthrough in battery technology, batteries will continue to limit the driving range of most BEVs to approximately 160 to 190 miles between charges (BCG 2010). Future lithium-ion batteries will likely employ advanced technology and materials that will increase energy density and lower cost (DOE 2011b). Further, technological breakthroughs with new battery chemistries such as lithium-air would allow BEVs to attain a range equal to ICE vehicles (Greene and Plotkin 2011). However, conventional vehicle technology will also advance, and the system-level energy density for conventional vehicles can improve significantly through efficiency improvements (see Table 2).

TABLE 2: "Tank to wheel" energy density comparison (EPA 2008, Crabtree et al. 2008, Girishkumar, et al. 2010, Greene and Plotkin 2011) .

VEHICLE TYPE		ENERGY DENSITY (WH/KG)	SYSTEM EFFICIENCY	SYSTEM LEVEL ENERGY DENSITY (WH/KG)
TODAY	Conventional Vehicle * (Gasoline)	13,000	21%	2,730
	PEV** (Lithium Ion Battery)	100-250	81%	81-203
FUTURE	Conventional Vehicle*** (Gasoline hybrid)	13,000	42%	5,460
	PEV**** (Lithium Air Battery)	12,000	9%	1,100

* Includes energy loss from internal combustion engine, standby/idle, driveline, and accessories.

** 10% energy loss from electric motor and 10% loss from battery charging. Does not include loss from accessories.

*** Assume doubling of efficiency through advanced drivetrains, engine shut-off when idle, regenerative braking, and more.

**** Includes loss due to battery system, electric motor, and battery charging.

VARIABLE BATTERY CHARGING TIME

One of the major differences between PHEVs and BEVs is charging time. While a standard 120-volt electrical outlet can charge a BEV, the required time (about 17 hours) may be inconvenient for consumers (see Table 3 for a description of the three charging standards). In order to fully charge a BEV overnight (when the majority of charging is expected to take place), many BEV owners would need to install a Level 2 charger in their homes. A Level 2 charger requires a system upgrade, as 240-volt outlets are not common in most household garages (NAS 2010). On the other hand, a 120-volt charge socket is suitable for PHEVs, which could negate the need for the installation of special hardware. However, regulations in some areas could require a separate circuit installation for a Level 1 or Level 2 charger.

TABLE 3: Charging levels included in Society of Automotive Engineers (SAE) J1772 standard (SAE 2011). The Level 1, 2, and 3 charging standard refers to the electric power characteristics detailed in the table below.

LEVEL	CURRENT	ELECTRIC POTENTIAL DIFFERENCE (V)	CURRENT (A)	POWER (KW)	BEV CHARGING TIME** (MINUTES)			
					3.3kW charger	7kW charger	20kW charger	45kW charger
Level 1	AC	120	12/16	1.4/1.92	1,020			
Level 1	DC	200-450	80	36	-	-	72	-
Level 2	AC	240	80	19.2	420	210	72	-
Level 2	DC	200-450	200	90	-	-	-	20
*Level 3**	DC	200-600	400	240	-	-	-	<10

* There is no official Level 3 today. This is the proposed standard by the SAE.

** Assumes 25kWh of usable capacity beginning at 20 percent state of charge (SOC). If power provided can charge the battery in less than one hour, then charging stops at 80 percent SOC. AC charging uses an on-board charger. DC charging uses an off-board charger.

For BEVs, charging can be done faster using a higher voltage charging station (e.g., 480-volt), where a 100-mile battery can be recharged to 80 percent of its capacity in 30 minutes. These units can be very expensive to install for households and will likely only be available in public spaces, such as parking lots, parking garages, and shopping centers. This technology is also more expensive than Level 1 or Level 2 charging stations, which may dissuade governments and businesses from installing it (NAS 2010). Also, PHEVs may not include the power electronics to support these high-power chargers. Furthermore, even with "quick chargers," the recharging time is much longer than the time it takes to refuel a conventional vehicle, which can be inconvenient for vehicle owners (J.D. Power and Associates 2010). Battery switching stations, which swap batteries in the same amount of time it takes to refuel at a gas station, could ultimately overcome this problem (Becker, Sidhu and Tenderich 2009).

UNCERTAIN BATTERY LIFESPAN AND DURABILITY

Battery lifespan can be defined in two ways: battery age (in years) or the number of charge-and-discharge cycles until the battery is degraded so it can no longer power the vehicle adequately (MIT 2010).[6] Charge rates, depth of discharge swings,[7] and temperature make it difficult to determine how batteries will age (Lipman and Williams 2011). Most OEMs are requiring batteries that will meet PEV energy storage needs over the lifetime of a vehicle, or approximately 10 years.[8] In order to accomplish this, OEMs are specifying batteries with a capacity that is larger than initially necessary, so they will still have a high enough capacity for normal operation as they degrade. Larger capacity increases the size, weight, and cost of a battery, which reduces efficiency (BCG 2010). Enhancing the "second-life" of these batteries could be a great opportunity for business innovation (see *Competitiveness in the Automobile Market*).

As more real-world testing is done and confidence in battery life increases, the amount of excess capacity is expected to decrease (DOE 2011b). OEMs could choose an alternate business model, by installing smaller batteries with a shorter life span, and replacing them every 5 to 7 years with more current technology. A battery leasing model, such as that proposed by Better Place, decouples the battery life span from the vehicle life span, and reduces the high initial cost of buying a BEV (BCG 2010). However, the DOE estimates that by 2015, domestic manufacturers will be able to produce batteries with a lifespan of up to 14 years (DOE 2011b).

INTEGRATION WITH THE U.S. ELECTRICAL GRID

Integrating PEVs into the U.S. electrical grid raises several key issues, including the installation of charging infrastructure, managing electricity supply and demand, and enabling business innovators. There are several ways to overcome these challenges, including stakeholder collaboration, financial incentives to promote off-peak charging, and the deployment of smart grid technology. A significant business opportunity results from addressing these issues. Stakeholder collaboration is key to overcoming many challenges, including residential and non-residential charging infrastructure and regulating supply and demand.

COORDINATION NEEDED FOR CHARGING INFRASTRUCTURE

One challenge PEV integration faces is charging infrastructure, which research suggests will be concentrated in residential areas at the outset (CAR 2011). Residential charging infrastructure offers several benefits, including convenience and access to off-peak charging.[9] Off-peak charging is less expensive and can help maintain the reliability of the grid. However, home charging stations also face challenges, including cost, time, and access. Consumers will want access to Level 2 charging stations for BEVs, which can be costly without incentives (see *Public Policy* and *Enabling Business Innovation*), and consumers may be unaware of relevant financial incentives.[10] The installation of Level 2 charging stations may also be very time consuming, as consumers will need to coordinate with multiple stakeholders including automakers, charging equipment providers, inspectors, electricians, and the local electric utility. The process could become more complicated for those living in multi-dwelling units, where consumers may not have reserved parking or the authority to install charging infrastructure (California PEV Collaborative 2010).

Non-residential charging infrastructure is also important for developing PEV markets. It may be vital for those without access to residential charging services, such as for people living in some multi-unit dwellings; and it provides other benefits, such as extending daily all-electric driving range, providing comfort for early adopters, and increasing the visibility of PEVs (California PEV Collaborative 2010). Though initial adopters of PEVs will rely mainly on residential charging, non-residential infrastructure will be important to expand the market further (CAR 2011). Non-residential infrastructure presents several challenges, including the strategic placement of charging stations, potential impacts on peak demand and the electrical grid as adoption increases, and investment risk in charging infrastructure because the future of the PEV market is largely unknown (California PEV Collaborative 2010).

To facilitate the deployment of residential charging infrastructure, government and stakeholder collaboration is needed to streamline the installation process, reduce cost, minimize homeowner inconvenience, and develop solutions for multi-dwelling units. Some local governments, automakers, and charging equipment providers are already working together to expedite the process by simplifying paperwork, reducing the steps necessary for infrastructure installation, and forging strategic partnerships (California PEV Collaborative 2010).

Overcoming the challenges facing non-residential charging infrastructure will require strategic planning primarily based on where PEV use and charging demand is the highest. Public and private stakeholders could coordinate their efforts to maximize the coverage and access to their combined charging infrastructure networks. They could also provide information to businesses regarding the installation process and to consumers on the location and type of charging infrastructure and the cost of charging (California PEV Collaborative 2010). An example of information sharing is the program the DOE launched with Google in April 2011 to identify vehicle charging station locations (DOE 2011c).

To better prepare for changes in demand, automakers and charging infrastructure providers should notify utilities when and where charging infrastructure will be installed and estimate the predicted impact on demand. This information will also help utilities plan for necessary upgrades and additions to the electrical grid, particularly the distribution infrastructure (California PEV Collaborative 2010).

MANAGED VEHICLE CHARGING NOW AND IN THE FUTURE

Another major challenge for the successful integration of PEVs with the electrical grid is balancing supply and demand. If a large number of PEVs are deployed, this could put stress on the grid by increasing the demand for electricity. This stress largely depends on the type of charging system used (Level 1, 2, or 3); the greater the power, the more instantaneous demand is put on the electrical grid. In some cases, this may be desirable in order to remove loads from the grid as quickly as possible. In other cases, high power loads can cause grid integrity problems.

A study conducted by the Institute of Electrical and Electronics Engineers (IEEE) concluded that unmanaged charging of PEVs could lead to negative impacts on the electricity distribution system of a U.S. utility at only 5 percent vehicle market penetration. Managed charging prevents those impacts on most of the system until up to 30 percent penetration.[11] Impacts include the potential for overloaded distribution transformers, overloaded conductors and cables, and consequently, reduced voltage to consumers. Studies suggest that the greatest impacts will occur in the afternoon to evening, when consumers return home from work and other daily activities outside the home (Dow et al. 25-29 July 2010).

Another study, conducted by the University of California-Berkeley (UC-Berkeley), examined the impacts of PEVs on electricity demand in California. The study found that unmanaged charging would increase peak electricity demand by over 5 percent with a moderate PEV market penetration level of 10 percent. This higher peak demand would last 3.5 hours if consumers have access to only residential charging infrastructure, and two hours if consumers have access to both residential and non-residential charging infrastructure. In the former case, many vehicles would begin charging in the evening when people get home from work, adding significantly to peak load. In the latter case, charging can also take place during the day; therefore, the increase in demand is more evenly distributed. With reduced rates for off-peak charging, however, demand does not exceed the baseload during peak load hours. This is true for penetration levels from two to 25 percent, and for cases in which off-peak charging is done 50 or 100 percent of the time (DeForest, et al. 2009).

Impacts on the electrical grid may be less significant depending on the battery size of the PEVs in the area. A study by the Pacific Northwest National Lab estimates that a PHEV fleet (with an all-electric range of 33 miles) equal to 84 percent of all cars and light trucks in use in 2001 could be supported without adding new capacity if charged during off-peak hours (Kintner-Meyer, Schneider and Pratt 2007).[12] However, this finding would change if vehicles were charged during peak hours, when the addition of the PHEV load could necessitate an increase in generation capacity. For example, a study conducted by Southern

California Edison concluded PHEVs could account for up to 11 percent of its system load by 2020, which would increase peak loads by thousands of megawatts if charging were unmanaged (NAS 2010). Importantly, these studies pertain to PHEVs, and not BEVs, which require much more energy from the grid due to their higher battery capacity.

While such studies are useful as initial analyses, the impacts of charging will undoubtedly vary by region, depending on PEV market penetration, the types of PEVs sold, the electricity generation mix, and seasonal variations in electricity use. In certain scenarios and regions, additional capacity will be necessary to meet the increase in demand created by charging PEVs, which will require capital investment from utilities and may increase electricity prices (Hadley and Tsevotka 2008).

One way to manage the increase in electricity demand due to PEVs is to offer reduced electricity rates during off-peak hours, or time of use (TOU) rates, in order to create a financial incentive for PEV owners to charge at night (Dow et al. 25-29 July 2010).[13] Daytime charging, especially during peak hours, may cause demand to exceed the supply provided by existing generation and distribution capacity.[14] However, off-peak charging may allow electricity providers to benefit from selling electricity produced by otherwise unused capacity, and consumers will benefit from lower, off-peak rates (NAS 2010).

In addition, the deployment of smart grid software technology would be beneficial for managing an increase in demand. This software includes both charging software and network software. Charging software manages communication between the PEV and the grid, including the state of charge, the time the battery needs to be fully charged, and consumption and billing information. Network software enables utilities to manage demand by recognizing how many PEVs are connected to the grid and if and where reinforcement needs to occur (Narich et al. 2011). However, this method requires installing new technology, such as new meters and a significant capital investment from utilities (Dow et al. 25-29 July 2010).

In the future, smart grid technologies such as vehicle-to-grid (V2G) could also help mitigate demand issues. PEVs could then act as distributed storage units allowing for reverse power flow from a PEV battery to the grid. This type of smart grid technology could actually aid in regulating the grid, by providing electricity for peak power demand and acting as a demand-response resource. One study suggested V2G could be most useful for two fast-response, short-duration ancillary services: helping to regulate imbalances in supply and demand[15] and serving as spinning reserves.[16] However, V2G reverse power flow capabilities may be limited by the capacity of the plug circuit, the capacity of the vehicle's battery, the state of charge when the vehicle is plugged in, and requirements to limit the effects on battery degradation (Letendre, Denholm and Lilienthal 2006).

Another study suggests V2G could be used for smoothing variable generation from renewables, peak load shifting, and providing distributed energy storage. One issue with current distributed storage is that single-use storage facilities are used infrequently if demand does not regularly exceed supply, and therefore these facilities make minimal revenue or even go unused. V2G has the potential to overcome this inefficiency because it relies on the idea of dual-purpose batteries, where storage is a secondary use because the battery is purchased for transportation purposes. Even if V2G is not highly profitable to PEV owners, it requires minimal upfront investment in controllers[17] and converters[18], some of which need to be installed anyway to facilitate off-peak charging (Peterson and Whitacre 2009). While V2G offers several opportunities, it also faces serious barriers and unknowns, including the installation of expensive two-way meters, uncertain impacts on battery life and performance, and unproven economic justification for utilities and consumers (DeForest, et al. 2009).

ENABLING BUSINESS INNOVATION

Several private sector companies are turning the obstacles facing PEV integration into opportunities, by developing new business models and forming strategic partnerships. These stakeholders are aiming to capture the emerging market, and include auto manufacturers, charging infrastructure providers, power companies, utilities, and third-party investors. Many of these efforts focus on creating a network of accessible charging stations and making charging simple and inexpensive for consumers.

One of greatest opportunities in the PEV market is the provision of charging infrastructure. The supply chain for charging infrastructure is vast, including hardware (e.g., PEV supply equipment), software to manage PEV charging, and support services (e.g., electrical grid infrastructure maintenance) (Narich et al. 2011). This mingling of new and traditional businesses is a great opportunity for innovation, similar to the opportunities the Internet provided a decade ago, if at a smaller scale.

Companies are currently implementing different business models involving charging networks and/or battery-switch stations.[19] Together, they have raised hundreds of millions of dollars in private capital to realize those visions. In some cases, companies have proposed owning the battery inside the PEV,[20] and in others, the company will install the charging station in a customer's home at no cost, but may charge the customer for the electricity.

Subscription services can offer monthly pricing plans, which include the installation of in-home charging stations, as well as unlimited use of networked charging stations and free off-peak charging depending on the plan.

Software developed by these companies aims to make it easy for customers to monitor and manage battery charging in real-time. This offers a clear value proposition to utilities, as it allows them to manage demand and fill off-peak valleys in electricity use without large investments in infrastructure (DeForest, et al. 2009).

An innovative approach to battery ownership also could dramatically decrease the high up-front cost of purchasing a PEV. In one business model, a customer purchases a PEV but does not own the battery. Instead, infrastructure network operators offer pay-per-mile contracts that finance the cost of the battery, a network of charging and/or battery switching infrastructure, and the electricity used for charging. In addition to reducing the purchase price of a PEV, this model overcomes range concerns, uncertainty regarding battery durability, and the cost of electricity. A study by the UC-Berkeley concluded that such a service-based battery ownership model could result in a market share of 64 to 86 percent of new light-vehicle sales by 2030 (Becker, Sidhu and Tenderich 2009). Such a large and rapid shift in the passenger vehicle market would be unprecedented. Further, there is a tremendous amount of intellectual property inside a PEV's battery system. Developing a common, removable battery system poses significant challenges, both technical and financial.

For businesses to compete on a level playing field in this new market, they will require regulatory certainty, including whether regulators will treat them as utilities. In some markets, government is already providing support to stimulate growth (see *Public Policy*). In these cases, using public support to leverage private capital could increase overall investment.

PASSENGER VEHICLE MARKET

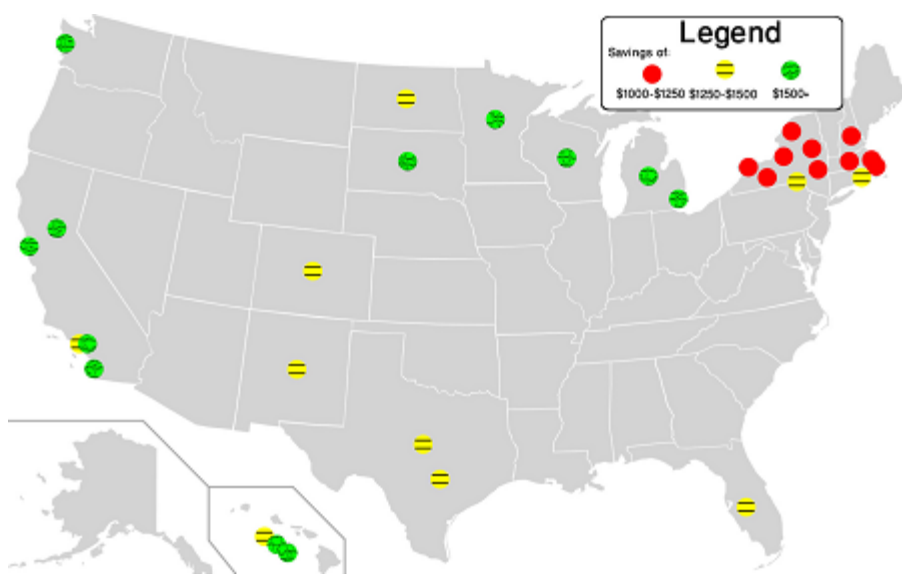
COMPETITIVENESS IN THE AUTOMOBILE MARKET

To date, PEVs are not competitive with conventional vehicles for the average consumer, primarily due to their higher upfront costs. In some scenarios, however, PEVs may already be cost-competitive on a total cost-of-ownership (TCO)[21] basis. However, a survey conducted by Deloitte Global Services demonstrates consumers are not willing to pay much of a premium, if any, to purchase a PEV over a conventional vehicle (Warrier, Osborne and Odama 2009, Deloitte 2011). In order to help overcome the cost issue, a number of incentives are currently available to subsidize the production of PEVs and PEV components for manufacturers, as well as the purchase of PEVs, installation of charging infrastructure, and operating costs for consumers. Private investors will ultimately drive the growth of the PEV market, but public policy can help spur the growth of PEVs by overcoming existing market failures (see *Public Policy*). The federal government and states have been investing in this market for some time, providing almost $4 billion in direct support from the Recovery Act (MIT 2010). Meanwhile the private sector has recently invested or committed to invest over $10 billion in the PEV market, with much of it coming after the recession started in late 2008.[22]

Since the most expensive component of a PEV is the battery system, research and development (R&D) to reduce the cost of producing battery systems can help reduce the overall cost of production (see *Cost Reductions Needed for Vehicle*). Further, *Enabling Business Innovation* describes business models that could remove the upfront cost of the battery altogether. This type of creative battery ownership model could be especially useful if second-life applications of PEV batteries are developed. As a PEV battery is charged and discharged, its storage capacity will eventually decrease to a level that is not sufficient for vehicle use. However, the battery will still have enough capacity for other purposes, and will therefore maintain some level of value (Witkin 2011). Examples of second-life uses could be telecommunications back-up power storage, transmission support, and residential and commercial load following to help enable distributed generation from renewable sources (Cready, et al. 2003). These second-life uses can lower the purchase cost of a PEV by offsetting or splitting the cost of the battery between stakeholders (NREL 2011).

Consumers can also benefit from financial and non-financial incentives to help offset the currently high initial cost of purchasing a PEV. Financial incentives include grants, loans, tax credits, rebates, and registration fee exemptions. Non-financial incentives include the use of High Occupancy Vehicle (HOV) Lanes, discounted or convenient parking, and exemptions from vehicle emissions testing and inspections (CAR 2011). See *Public Policy* for details of federal, state, and local government policy on PEVs.

FIGURE 4: Relative annual fuel cost savings from switching to PEVs based on estimated gasoline prices in July 2008 (Lidicker, Lipman and Shaheen 2010).*



*Assumes 10,000 electric miles per year; savings are in comparison to a gasoline vehicle that averages 23 mpg.

A study by UC-Berkeley examined the annual cost savings of using a PEV instead of a conventional vehicle in 2008 and 2009, given a range of gasoline and electricity prices from around the United States. The results show the average annual savings was $1,447 during peak gasoline prices in July 2008 for a driver traveling 10,000 electric miles per year instead of driving a vehicle with the national average of 23 miles per gallon (mpg). However, the average saving dropped to roughly $100 per year when gasoline only cost an average of $1.90 per gallon in January 2009. The actual annual savings varies significantly by location, depending on local gas prices and electricity rates, as seen in Figure 4 (Lidicker, Lipman and Shaheen 2010). Further, fuel economy for conventional vehicles – especially hybrid electric vehicles – will continue to improve; for instance, a BEV would have annual savings of about $700 compared to a Toyota Prius during the peak gasoline prices in 2008.

FORECASTING CONSUMER DEMAND

Consumer demand will ultimately make or break PEVs. While there is already some consumer demand, much of it is concentrated in markets with specific characteristics. This market of "early adopters" is generally characterized by an enthusiasm for new technology or concern for the environment that outweighs the risks of purchasing a vehicle powered by emerging technology (Indiana University 2011). For these consumers, the value proposition is being the first to own a PEV, with its perceived environmental benefits and image, despite the higher cost (Tuttle and Baldick 2010). While PEVs will likely experience an initial phase of high growth in sales, it is unlikely that rate will be maintained, and does not necessarily indicate PEVs can reach a stage of mass commercialization (Indiana University 2011). In order to reach more mainstream consumers, PEVs will need to overcome certain obstacles related to technology, charging infrastructure, and vehicle range. The PEV value proposition will also have to shift towards one with clear financial benefits, so the average consumer will see PEVs as an economical form of transportation (Tuttle and Baldick 2010).

A recent survey conducted by Deloitte Global Services found there is considerable interest in PEVs from consumers, as 12 percent of respondents in the United States identified themselves as "potential first movers," and another 42 percent as "might be willing to consider." Further, a recent survey by Accenture found 57 percent of Americans would consider purchasing a PEV for their next vehicle (Accenture 2011). However, potential consumers also have high expectations regarding price, range, and charging time, which are not met by PEVs on the market today (Deloitte 2011).

Consumer demand is highly sensitive to price, and consumers are often hesitant or unwilling to pay more for a good if they can get something similar for less. This unwillingness is coupled with an insensitivity to fuel savings, as consumers have a discount rate of around 20 percent for fuel savings while society's discount rate would be closer to 4 percent (Greene and Plotkin 2011).[23] Even if fuel savings over the lifetime of a vehicle outweighs the difference in initial cost, it may not be enough to convince consumers to pay more upfront (Indiana University 2011).

The Deloitte survey found that as gas prices rise, consumer interest in PEVs increases. With gas prices at $3.50 per gallon, around 30 percent of respondents would be more likely to purchase a PEV, while at $5 per gallon this statistic increases to 78 percent (Deloitte 2011). However, the impact of fuel prices on vehicle purchasing decisions is slow to affect change, modest in scale, and is often based more on the availability of gasoline and the rate of change in price than the absolute price (Tuttle and Baldick 2010).

In addition to price issues, the average consumer's interest may be limited by a lack of knowledge of or experience with PEVs, which can be overcome by increasing consumer awareness of and familiarity with PEVs. Only 36 percent of American consumers claim to know enough about PEVs to consider one for their next purchase, although even that low level of consumer awareness is second only to that of China (Accenture 2011). Increasing awareness could include education campaigns that clearly identify the benefits and convenience of using PEVs, as well as events or PEV fleets that enable consumers to have individual experiences with PEVs (California PEV Collaborative 2010).

While the persistence of consumer demand is unknown, interest in recently released PEVs is growing and automakers are likely to respond. GM recently increased the production levels for the Chevrolet Volt due to customer demand to 16,000 in 2011 and 60,000 in 2012 (GM 2011). Nissan has even more aggressive production level targets, as it plans to produce 20,000 Nissan LEAFs in 2011, the first year of production, and up to 500,000 BEVs by 2012 (Indiana University 2011). In contrast, the Toyota Prius (a hybrid electric vehicle) sold just 300 units in limited production in its first year. When sales expanded from Japan to the North American and European markets in 2000, sales rose to 19,000 and then to 29,500 the following year (TMC 2010).

MARKET GROWTH WITH BUSINESS AND GOVERNMENT DEMAND

The business community and governments have the potential to play a major role in the deployment of PEVs by purchasing them for their vehicle fleets. This provides an early market for PEV manufacturers and increases the visibility of PEVs to potential consumers. Success in fleet markets can help bridge the gap between early adopters and mass commercialization, as this type of "lead by example" program increases the visibility of PEVs, and can increase consumer awareness, interest, and confidence in PEVs (California PEV Collaborative 2010). For instance, General Electric has committed to purchasing 25,000 PEVs by 2015 for its own fleet and its Capital Fleet Service Business (General Electric 2010). The purchase of fleet vehicles played an important role in the deployment of hybrids and has the potential to do the same in the case of PEVs (CAR 2011).

One reason fleet buyers are showing interest in purchasing PEVs is in order to reduce the environmental impact of their operations. Fleet purchases can help companies and governments develop a reputation as "green" and reduce greenhouse gas (GHG) emissions to align with their overall sustainability strategies or goals. For these reasons, entities may be willing to purchase PEVs even if the financial case is not strong (Indiana University 2011).

Finance-oriented fleet managers may also be convinced to purchase PEVs if the fuel and maintenance savings outweigh the higher initial cost of the vehicle (Indiana University 2011). Fleets generally have a higher utilization rate than personal vehicles, which decreases the payback period, which depends on mileage.[24] Some fleets also have highly predictable routing, which can minimize range anxiety and allow for battery "right-sizing," thereby reducing capital costs.[25] Fleets may also benefit from commercial or industrial electricity rates, which are often lower than those of residential customers. PEVs also have lower maintenance costs, further reducing their lifetime cost compared to conventional vehicles (CAR 2011). Fleet buyers are often risk-averse and work under limited budgets, so if the TCO is below a conventional vehicle, they will be able to make the business case for such a purchase (California PEV Collaborative 2010).

One type of fleet that shows potential for the use of PEVs is urban delivery vehicles, a part of the large commercial truck and van sector. This type of fleet generally runs on fixed routes, which could be designed to incorporate centralized recharging infrastructure (Indiana University 2011). These fleets may be ideal for PEV use, given the predictability of the vehicle's electricity use, reduced operating costs, and capability to charge overnight in a consistent location (California PEV Collaborative 2010).

GEOGRAPHIC MARKETS DISPARITY

The demand for PEVs, as well as types of PEV models offered, will vary geographically. On a large scale, studies suggest that there will be greater demand for PEVs in certain cities and states than in others, as seen with hybrid electric vehicles. The demand in different markets will depend largely on the make-up of the population, as well as the commitment and collaboration of entities such as the local governments and utilities. To that end, Ford indicated that when selecting initial markets for PEV deployment, it looked at hybrid purchasing trends, utility collaboration, and the local government's commitment to vehicle electrification (CAR 2011).

One determining factor in the demand for PEVs in a given location is the consumers. Several personal factors drive consumer demand, including concern for the environment, above average wealth, personal image importance, and the perceived benefit of ownership. While demand concentrations are still unknown, it is expected that PEV purchasing will be clustered in areas where people share these characteristics,[26] and hybrid penetration can be used as a model for demand patterns since many of the considerations are the same. There are also external factors, such as the TCO savings, other transportation options, and impact on local pollution (Benecchi, et al. 2010).

Another important factor in determining the demand for PEVs is the involvement and support of local governments and utilities. A study by Roland Berger Strategy Consultants says cities can play an important role in the deployment of PEVs. This includes encouraging an infrastructure network, creating hospitable regulatory and operational environments, forming partnerships with stakeholders, and educating consumers. Local governments can also provide monetary and non-monetary incentives, including grants, rebates, tax credits, registration fee exemption, reduced electricity rates, parking benefits, vehicle inspection exemptions, and HOV lane access (Benecchi, et al. 2010).

Within separate geographic markets, the demand for different types of PEVs, mainly BEVs and PHEVs, will vary depending on the needs and priorities of consumers. Given their limited driving range, BEVs are likely to be most popular in cities, where daily driving distance is limited (Narich et al. 2011). However, a recent study shows that BEVs are most financially beneficial compared to conventional vehicles for those who drive longer distances each day (100+ miles), as the payback period is reduced when more electric miles are driven (Santini, Vyas, et al. 2011). One concern with relying on BEVs for long distances is that owners will have range anxiety, though there are ways of alleviating this problem (see *Limited Driving Range and Range Anxiety*). While PHEVs may also appeal to city drivers, they are likely to be attractive to suburban and rural drivers as well given their dual fueling option. Furthermore, PHEVs have the potential to serve as transition vehicles, while BEV battery capacity and driving range are increased, charging infrastructure becomes more widespread, and consumers become more comfortable with PEVs (Narich et al. 2011).

PRIVATE MARKET PLAYERS

PEV private market players include those involved in the production and deployment of PEVs, as well as their operation. As the market for PEVs develops, these stakeholders face several challenges in establishing their respective roles in the value chain and will need to work together to ensure the success of the PEV market (BCG 2010, Narich et al. 2011).

On the production and deployment side, battery manufacturers, vehicle manufacturers, and the federal, state, and local governments play important roles in bringing PEVs to the market. Battery manufacturers and automakers are competing to develop products that maximize a wide range of consumer needs, and in doing so, must consider what differentiates their product from the competition and how to best allocate limited financial resources. Federal and state governments are providing financial support for manufacturing and R&D, enabling the industry to reach technological maturity and cost viability (BCG 2010).

Electricity retailers, charging station owners and operators, and information technology (IT) service providers are key to deploying and making the daily operation of PEVs possible. Electricity retailers, primarily utilities, must consider how PEV market penetration will affect electricity demand, and how they will manage the increase in demand while maintaining grid reliability (Narich et al. 2011). PEVs also create opportunity for electricity providers that successfully manage demand, as they may see an increase in profits driven by the increase in electricity sales (Tuttle and Baldick 2010).

Charge point owners and operators, as well as IT service providers, are primarily responsible for the consumer's experience with charging infrastructure. In some cases, municipalities or utilities will take on this responsibility, but there is also the opportunity for other private-sector market players to fill this role with new business models (Narich et al., 2011).

As the market for PEVs develops, market players will need to collaborate in order to create new strategies and business models. As new business models emerge, the roles and responsibilities of key players may be different depending on the local market. For example, in some markets, government and utilities may play a central role in driving demand, while competition and consumer preferences may drive other markets (Narich et al. 2011).

PUBLIC POLICY

There are several barriers to the deployment and mass commercialization of PEVs, as well as their integration with the electrical grid. Without government support, the PEV industry could struggle to become competitive with conventional vehicles. While government involvement is not warranted for all technologies facing market challenges, PEVs mitigate several negative externalities associated with conventional vehicles, which justifies government support. These externalities include tailpipe emissions that contribute to local air pollution and climate change, as well as the transportation sector´s reliance on oil, which affects the United States´ energy security. Public policy to support fuel-efficient vehicles, such as PEVs, will help internalize these externalities (Center for Climate and Energy Solutions 2011).

The extent of government involvement will be influential in integrating PEVs into the electrical grid, as integration presents many high-risk opportunities that the private sector may not take on its own. Recent policies provide evidence that government has already started to address these obstacles in cooperation with the private sector. Most PEV deployment and grid integration projects are public-private partnerships thus far. These partnerships use government support to leverage private capital for investments that may be too high-risk for the private sector alone. The projects aim to encourage innovation in the areas of technology and new business models, so the PEV industry will grow and eventually be self-sustaining. In order to maximize the growth of the PEV market, government support is needed at the federal, state, and local levels (see Table 5). However, as technology costs decline, incentives that favor PEVs, especially financial incentives, should diminish and eventually be retired (California PEV Collaborative 2010).

FEDERAL SUPPORT

In the 2011 State of the Union address, President Obama announced a goal of having one million PEVs on the road by 2015, exemplifying the Administration's support for such technology. At a national level, the deployment of PEVs can help cement the United States´ leadership in technological innovation and reduce the nation's dependence on oil (DOE 2011b). Federal policy options include regulations that promote fuel-efficient vehicles, market-based policies that make fuel-efficient vehicles more competitive, financial incentives for consumer adoption, demonstration projects, and funding to support manufacturing (see Table 4 for the effects of some policies that support PEVs). When possible, technology-neutral policies should be employed to allow the marketplace to determine which fuel-saving technologies are most effective (Indiana University 2011).

The federal government is helping the PEV market with its own purchases. As the operator of the largest vehicle fleet in the United States, the General Services Administration launched pilot projects with over 100 PEVs in May of 2011 (GSA 2011). As mentioned in *Market Growth with Business and Government Demand*, government demand can provide an early market for PEVs and increase visibility to consumers. One type of regulation that promotes low-emission, fuel-efficient vehicles is the National Program for fuel economy and GHG emissions standards. The U.S. government has started increasing Corporate Average Fuel Economy (CAFE) and GHG emissions standards in recent years. Standards are in place to raise the fuel economy for light-duty vehicles to 34.1 mpg (and cut emissions to 250 grams of CO_2 per mile) by model year 2016, a 6.8 mpg increase from 2011 (J.D. Power and Associates 2010). Standards to cover model years 2017 through 2025 vehicles are expected to be announced in the fall of 2011 (Federal Register 2010). If stringent enough, increased fuel economy standards will encourage the expansion of the market for PEVs (DOE 2011b). Accordingly, the Obama Administration announced it would target 54.5 mpg by 2025 (White House 2011).

Several market-based policies could be used to make fuel-efficient cars more competitive with conventional vehicles, including increased taxes on petroleum-based fuels (Indiana University 2011). Increasing taxes on gasoline to account for energy security and environmental externalities, for example, would provide greater incentive for consumers to purchase fuel-efficient and alternative fuel vehicles. Several developed countries already tax petroleum-based fuels heavily, while the United States has not increased its federal gasoline tax since 1993. While this type of policy could be effective in advancing the market for PEVs, it is also unlikely in the United States given that raising taxes in general is a politically charged topic (J.D. Power and Associates 2010).

TABLE 4: For each item, the value indicates the percentage change in energy efficiency relative to the AEO 2010 reference case, which indicates the business-as-usual scenario, from implementing the policy (Greene and Plotkin 2011). While this table does not identify impacts on the PEV market in particular, it does highlight the importance of public policy in promoting changes in the vehicle market.

	2035		
POLICY/MITIGATION OPTION	Low	Mid	High
LIGHT-DUTY VEHICLES			
Change in Energy Efficiency for Total Stock (miles per gallon)			
Fuel Economy/Emissions Standards	15.00%	30.00%	40.00%
Pricing Policies			
Carbon Price	2.44%	2.44%	2.44%
Road User Tax on Energy	0.94%	1.55%	1.88%
Pay-at-the-Pump Insurance	0.00%	4.37%	4.37%
Feebates	0.00%	10.00%	10.00%
Change in Fuel Carbon Intensity for Total Stock (gCO2e/MJ)			
LCFS: 2035 / Increased Hydrogen & Electricity: 2050	-5.00%	-10.00%	-15.00%

Another approach is to offer financial incentives to consumers in order to make purchasing a PEV more affordable. Examples of incentives include rebates, feebates, and tax credits. With a rebate, consumers receive a discount for purchasing a high-mileage vehicle. With a "feebate," consumers purchasing high-mileage vehicles receive a rebate, while those purchasing low-mileage vehicles must pay a fee (Greene and Plotkin 2011). The federal government offers a similar program for PEVs, which is a tax credit of up to $7,500 for purchasing a PEV (DOE 2011b). The credit extends to the first 200,000 PEVs sold by any OEM in the United States, is phased out afterwards, and does not expire at a particular point in time. Since the credit applies to all OEMs and with current sales of PEVs in the low thousands, this credit will likely be available for quite some to come.

When possible, rebates are preferable to tax credits because the consumer receives the discount at the point of purchase (Benecchi, et al. 2010). These types of financial incentives should also be limited in terms of time and/or production volumes, so they are reduced or eliminated as the market matures (Indiana University 2011).

A national demonstration project would address informational barriers that face PEV deployment by taking a "learning-by-doing" approach. This project would deploy vehicle and infrastructure in selected cities, from which data could be gathered from stakeholders such as consumers, utilities, city governments, and charge point owners and operators. The information would then be used to successfully deploy PEVs in other areas (Indiana University 2011). Similar projects are already underway in many cities as public-private partnerships, but to date, there is no nationally coordinated effort.[27]

To facilitate the installation and use of public charging infrastructure, several projects are being executed as public-private partnerships to leverage private funding, including programs such as ECOtality's EV Project and Coulomb Technologies' ChargePoint Network (CAR 2011). In April 2011, the DOE announced $5 million in PEV funding to be distributed to local governments and private companies through an application process. At the same time, DOE announced a partnership with Google and over 80 PEV stakeholders on a project that will help consumers identify charging center locations (DOE 2011c).

Finally, the federal government can provide financial support in the areas of R&D and manufacturing, in order to make PEV battery technology more mature and help automakers reach their short-term PEV production targets. Funding for a wide range of battery R&D projects will increase competition and innovation and help the United States establish itself as a world leader in the industry (Indiana University 2011). Support for manufacturing batteries, other PEV components, and the vehicles themselves, will help manufacturers reach greater production capacities and benefit from economies of scale, thus reducing manufacturing costs. The federal government provided funding for such programs, mostly from the Recovery Act, but it is unclear if those investments will be sufficient to achieve automakers' short-term PEV production targets (DOE 2011a).

STATE AND LOCAL ROLE

State and local governments, as well as utilities, can also adopt policies that facilitate the deployment of PEVs and their integration with the electrical grid. While federal policy focuses on high-level policies that promote fuel-efficient vehicles in general and provides financial incentives to aid initial deployment, state and local governments can adopt policies that will help support PEVs in their region from manufacturing to point-of-sale to once they are on the road. This support may include financial incentives for manufacturers and consumers, as well as planning, coordination, and performance requirements (Benecchi, et al. 2010).

Financial incentives are one form of policy that can help drive the market for PEVs in a specific area. These can be used to encourage manufacturing facilities or increase consumer adoption. On the manufacturing side, several states have already employed policies that attract manufacturing facilities to their states (Center for Climate and Energy Solutions 2011). These include property tax exemptions, tax credits for the purchase of manufacturing equipment, and tax credits based on the capacity of the battery produced. States also offer similar incentives that are available to manufacturing related to all types of alternative vehicles (Indiana University 2011).

Some states and cities also offer consumer incentives to promote the adoption of PEVs. Similar to action at the federal level, some states offer financial incentives to reduce the high up-front cost of purchasing a PEV or associated infrastructure, such as purchase incentives and infrastructure grants (Benecchi, et al. 2010). Several states offer tax incentives in addition to comparable federal incentives, including tax credits and sales tax exemptions for the purchase of a PEV or for the installation of charging infrastructure (Center for Climate and Energy Solutions 2011). Cities can contribute with lower-cost incentives such as special parking access, reduced toll fees, reduced vehicle registration fees, and small-scale infrastructure funding (California PEV Collaborative 2010, Benecchi, et al. 2010). When possible, incentives should be bundled so the process is easier to navigate, and rebates should be provided at the time of purchase or installation (California PEV Collaborative 2010).

Utilities, some of which are regulated and can recover costs from ratepayers, can also offer financial incentives to make PEVs more financially attractive. These include rebates for in-home charging infrastructure and lowered electricity rates for charging (Indiana University 2011). One type of incentive that may be especially important for grid integration is reduced off-peak charging rates, which can help promote nighttime charging in order to manage increased grid demand (Benecchi, et al. 2010).

TABLE 5: Policy options to promote PEV deployment and grid integration

POLICY OPTION	LEVEL OF GOVERNMENT			
	Federal	State	Local	Utility
Financial Incentives				
Funding for R&D	X			
Manufacturing Incentives	X	X		
Public Infrastructure Incentives	X	X	X	
Private Infrastructure Incentives	X	X		X
Purchase Incentives (tax credit, rebate, etc.)	X	X		
Free Parking			X	
Reduced Bridge and Toll Roads		X	X	
Reduced Vehicle Registration Fees		X		
Reduced Electricity Rates for Charging (TOU)				X
Non-Financial Incentives				
HOV Access		X		
Exemption from Vehicle Inspection		X		
Other				
Fuel Efficiency Standard	X	X		
Gasoline Tax	X			
Price on Carbon	X			
Streamline Processes	X	X	X	X
Facilitate Information Sharing	X	X	X	
Lead by Example – Fleets	X	X	X	X

States and cities can also educate consumers by disseminating information, or providing opportunities for citizens to personally experience PEVs. Governments can launch education campaigns or provide forums for consumer information sharing. Such campaigns help consumers learn more about PEVs and how purchasing one may accommodate their lifestyle. In addition, governments can incorporate PEVs into their vehicle fleets so government employees can experience what it is like to drive them. This type of "lead by example" approach would also make PEVs more visible to the public (California PEV Collaborative 2010).

The degree of success for PEVs in the automobile market depends on technological progress, vehicle cost reduction, public and private cooperation, public policy, and ultimately, consumer acceptance. The future of PEVs in the United States is bright with nearly all automakers – and some startups – introducing PEVs in the next two or three years (Plug In America 2011). The opportunity for these vehicles to make a marked improvement on U.S. energy security along with the local and global environment depends on their ability to satisfy consumer demand. In the case of the environment, decarbonizing the electrical grid is also a necessary step in order to reduce PEVs' impact on global climate.

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ENDNOTES

1 Vehicle batteries must meet significantly stricter requirements over consumer batteries in the areas of safety and lifespan.

2 An automotive battery pack consists of a number of battery cells connected together to form modules. Several modules are connected to form the battery pack, which also contains a cooling mechanism and other controls.

3 Based on 2008 average gas price of $3.21 per gallon.

4 The amount of energy a battery can provide per unit of weight.

5 Since the system efficiency of a PEV is much higher than a gasoline-based system, the energy density of a PEV does not have to match gasoline to achieve comparable range.

6 It is estimated that about 80 percent of the battery's capacity will still be available at this point.

7 Depth of discharge refers to the amount of energy used from the battery before it is recharged. Battery life is believed to be degraded when high depth of discharge occurs frequently.

8 Both GM and Nissan are offering 8-year warranties for the Volt and Leaf, respectively.

9 Reduced electricity rates are offered by utilities to encourage more electricity consumption outside of peak usage periods.

10 For PHEVs, consumers may prefer Level 1 charging stations, which could be as simple as a standard 120V outlet. Even then, however, complications and costs could be high if regulations require a separate charging circuit.

11 Managed charging is when utilities use systems such as pricing incentives and smart grid technology to manage electric load.

12 This study assumes vehicles are driven the national average of 33 miles per day on electricity. Driving beyond that range requires the use of the PHEV's ICE. It also assumes charging is done during off-peak hours.

13 Even average U.S. electricity rates of less than $0.10 per kWh are still much less expensive than gasoline by a factor of 3 or 4.

14 Of course, all of this depends on available capacity on the grid, which varies depending on the region.

15 An expensive service provided by generators know as frequency regulation.

16 Spinning reserves are extra generating capacity that is already connected to the power system but only activated when generators are scheduled to go offline or a portion of the transmission or distribution system fails.

17 Manages the PEV's interface with the grid, including the charging time and the flow of electricity in and out of the battery.

18 Makes compatible electronic devices using alternating current, direct current, and differing. In the case of V2G the converter allows electricity from the grid to flow in and out of the battery through a charger.

19 Better Place and NRG Energy are two examples of companies operating in this space. Better Place has raised over $700 million from investors. NRG Energy offers a subscription service. See C2ES' "Plug-in Electric Vehicles Market: State of Play" for details.

20 In this case, the company can charge a subscription fee to access its charging network. For interchangeable battery systems, the company can partner with local utilities to provide energy storage capabilities.

21 The total cost of ownership (TCO) takes into account the cost of purchasing a vehicle, as well as operational costs such as fuel and maintenance. While the cost of purchasing a PEV is currently higher than purchasing a comparable conventional vehicle, lower fuel and maintenance costs could result in net savings to the vehicle owner over the lifetime of the vehicle.

22 Estimating private capital investments in the PEV market can be very challenging. The $10 billion figure only includes venture capital and other direct investments in or by Tesla Motors, ECOtality, Fisker Automotive, Better Place, NRG Energy, Coulomb Technologies, Johnson Controls, A123 Systems, Ener1, Ford Motor Company, General Motors, and Nissan. Details are available from the authors upon request. Nissan alone has committed to invest $5.6 billion (Autoblog Green , 2011).

23 Consumers have tended not to value a dollar of future fuel savings nearly as highly as a dollar spent today for fuel saving technology, though this could change if fuel prices continue to rise and stay high.

24 The cost-per-mile for electric miles is much lower than gasoline miles so BEVs may be preferred for short-route vehicles. In other cases, PHEVs could be suitable if the fleet drivers must occasionally travel long distances in a single day.

25 Right-sizing refers to a custom battery pack that has a range suitable for the vehicle's daily route.

26 This clustering can result in electrical grid instability issues mentioned earlier, such as blown transformers.

27 For example, the Recovery Act includes the Vehicle Electrification Initiative, which is sponsoring the largest PEV deployment project to date.

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