Technological, Market and Policy Drivers of Emerging Trends in the Diffusion of Plug-in Electric Vehicles in the U.S.

It has only been over the past decade that key technologies advanced sufficiently to enable the development of viable electric vehicles. This article explores the remaining barriers, the cost trajectory for electric vehicles and for conventional vehicles, differentiating and unique features of electric drive, and the lowered barriers to entry for new firms created by electric powertrains.

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I. Introduction

There are a number of societal motivations for the adoption of plug-in electric vehicles (PEVs): reduced emissions, a more diverse mix of fuel types and sources, reducing the dependence on unstable regions with the greatest oil reserves, reducing petro-dollar funding of activities counter to national interests, increased economic security from a more assured continuity of fuel supplies plus more balanced trade, and fuel price stability (Sperling, 1989; Srivastava, 2010). Until recently, these national motivations and societal benefits have not led to significant adoption of any type of alternative fuel vehicle in the U.S. The characteristics of electric drive can enable the creation of

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mass-market viable alternative fuel vehicle that have numerous advantages over a conventionally powered internal combustion engine (ICE) powertrain fueled by gasoline or diesel and not simply a different fuel type consumed. If deployed adeptly, these characteristics can provide advantages to the actual vehicle purchasers, and not only benefits for a nation as a whole. Drivers can benefit directly from significantly lower operating costs given the higher vehicle efficiency of electric drive as well as the likely continuation of substantially less volatility in electricity costs than retail gasoline prices (NPC, 2012). In addition, electric powertrains can provide better noise, vibration, and harshness (NVH) characteristics that are attractive to consumers, the convenience of home refueling, reduced maintenance, lower emissions, and improved performance.

While the concept of electric vehicles is well over a century old, relatively recent technological advancements in batteries, power electronics, computer controls, and powertrain architectures have enabled the first wave of mass-market viable and luxury/performance PEVs. Modern hybrid electric vehicle (HEV) technology was introduced into the U.S. market in 1999. While HEVs still use gasoline as their fuel, and hence are not considered alternative fuel vehicles, they still demonstrated the potential of advanced electrified powertrains with sophisticated computer controlled three-phase AC motors, modern power electronics, and large non-lead-acid batteries that are also used in PEVs.

Given the advanced nature of hybrid powertrains and adoption dynamics, a number of studies have used the past HEV adoption rate as a baseline to compare or project future PEV adoption. Before the introduction of the Tesla Roadster, Chevrolet Volt, Nissan LEAF, and other PEVs starting in the 2008–2010 timeframe, there were no modern mass-market-viable electric vehicles for sale. While still limited, a growing number of PEV models are available from a progressively greater variety of manufacturers. The number of modern PEVs on U.S. highways increased from virtually zero to about 300,000 in four years. This adoption rate is faster than the rate observed of HEVs from year 2000 (Chamberlain, 2014). But to gain perspective, there are about 231 million U.S. light-duty vehicles on the road. These vehicles have an average age of over 11 years. PEVs are still a small fraction of the vehicles on the road today and it will take a number of years to replace the existing vehicle fleet.

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Some of the more interesting PEV-related discussions are included in each of this article's sections. Section II discusses the status of PEV offerings in the market today. Section III describes the factors affecting adoption. Key technology trends that affect adoption are included in Section IV. Section V explores the advanced vehicle capabilities that PEVs can provide and finally, Section VI describes potentially disruptive auto industry dynamics that may arise over the next decade.

II. PEVs Today

Since 2010, PEV models have evolved into four general categories that usefully describe the different types of electric vehicles: long-range battery electric vehicles (BEVs), limited-range BEVs, range-extended plug-in hybrids (PHEVs), and minimal-PHEVs (NAS, 2015). BEVs are the simplest PEVs to conceptually understand. The vehicle has a large (or very large) battery that is charged from the grid and the traction motor is driven entirely from this stored electricity. Range-extended PHEVs are driven by electricity until the battery charge is depleted; then, the on-board computers seamlessly switch to

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gasoline-powered hybrid propulsion. Minimal-PHEVs provide blended electric plus gasoline propulsion given their much smaller battery sizes. Very importantly, all PHEVs eliminate the century-old range anxiety problem of BEVs and substantially simplify charging infrastructure needs. Depending upon a driver's commuting pattern and the model, a PHEV can electrify a substantial portion, if not all, of a driver's typical daily commuting needs (Khan and Kockelman, 2012) simply by charging at home from a common 120 V electrical outlet. The larger the PHEV battery, the more miles that can be electrified and the less often the gasoline engine is deployed, typically providing a more satisfying driving experience.

Long-range BEVs include the family of Tesla Model S luxury/performance sedans with over 240 miles of range (Tesla, 2015a). Limited-range BEVs include the Nissan LEAF, BMW i3, Ford Focus BEV, Fiat 500e, VW eGolf, and Kia Soul EV, generally with an 80- to 100-mile range. Range-extended PHEVs include the 2011–2015 Chevrolet Volt and the second-generation 2016 Chevrolet Volt with 50 miles of electric range (InsideEVs, 2015). Minimal PHEVs include the Ford Fusion Energi, Ford CMAX Energi, Honda Accord PHEV, and Toyota Prius PHEV, with 11 to 20 miles of electric range and varying speeds of EV operation (DOE, 2015a). While some of these PEVs are offered across the entire U.S. (Model S, Volt, LEAF, i3), many of the remaining models have been described as ''compliance cars'' (Honda FIT EV, SmartED, Fiat 500e, Chevy Spark) available either in limited numbers, sometimes only through leases, and only in California or some of the nine other states that have adopted the California emissions or ZEV regulations (Voelcker, 2015; Halvorson, 2014).

The drivers of the PEVs are typically very satisfied. The Tesla Model S has the highest owner satisfaction of any vehicle offered in the U.S. market (Consumer Reports, 2014). The Chevrolet Volt had achieved the highest owner satisfaction for two prior years.

> *It is relevant to note that many of the same questions concerning long-term durability and financial payback were raised when HEVs were first introduced over 15 years ago.*

Presently, the *average* transaction price of a new car sold in the U.S. is $33,560 (Kelley Blue Book, 2015) and the vast majority of vehicles are still powered by petroleum. The manufacturers' suggested retail price (MSRP) for a non-luxury PEV is typically higher than comparable conventional vehicles. The price premium can be reduced by a $2,500–$7,500 federal tax credit and any additional state or local incentives offered (DOE, 2015b). After federal tax credits, non-luxury PEVs are generally priced below this average conventional vehicle transaction price. Tesla's Model S variants are priced about on par with their luxury/performance competitors today. Leases offered by manufacturers may be beneficial for those who cannot take advantage of the federal tax credit since the tax credit claimed by the leasing company can be used to reduce the lease payments.

Long-term durability has yet to be proven. However, it is relevant to note that many of the same questions concerning long-term durability and financial payback were raised when HEVs were first introduced over 15 years ago. Since its introduction, the Toyota Prius has proven to be very reliable and now is one of the most popular models sold in a number of markets. The Prius has also proven to have one of the lowest total costs of ownership (TCO) (Consumer Reports, 2011).

Today, the general public does not have a good understanding of the differences between a PHEV and a BEV (nor HEV), the varied range or driving experience attributes, and the types of charging infrastructure or charging needs of these different types of PEVs. Not only do PEVs present a different refueling paradigm to drivers, they are rapidly evolving. The improving technologies and new PEV models further contribute to this a lag in understanding.

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Presently, purchasing a PEV is more complex than the equivalent purchase/decision process for conventional vehicles and there are far more limited electric vehicle choices offered. While the purchase process may be more complex, the typical operation of any PEV does not differ greatly from a conventional vehicle: simply push the start button, drive the vehicle as one would any other vehicle with an automatic transmission, and typically charge the vehicle conveniently at home.

Historically, factors that were believed to most influence PEV adoption included range, refueling infrastructure, charge time duration, and price. More detailed summaries of factors commonly stated as affecting PEV adoption are included in numerous studies (NAS, 2015; Tsang et al., 2012).

III. PEV Adoption: Accelerants and Impediments

There are two chicken-and-egg scenarios associated with alternative fuel vehicles that affect adoption rate. The first and most fundamental couples the sale of vehicles with the availability of refueling infrastructure (Sperling, 1988; Melaina, 2002; Melaina and Bremson, 2008). The second chicken-and-egg scenario is related to such factors as the auto manufacturers ability to create compelling alternative fuel vehicles, competitive response, R&D investment focus or technology strategy, organizational inertia, skills base, tooling sunk costs, and supplier network.

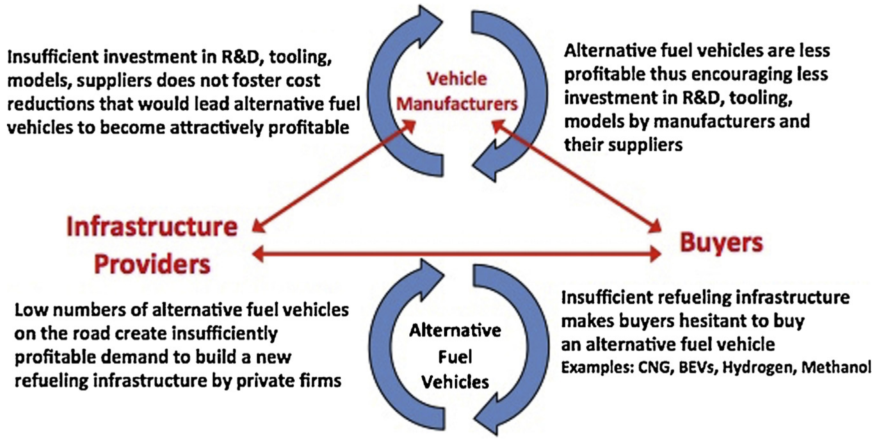

Figure 1: Historical Alternative Fuel Vehicle Adoption Dynamics

Since the 1973 Arab Oil Embargo, there have been numerous attempts at fostering the adoption of a variety of alternative fueled vehicles. Some of the dynamics of adoption are summarized in Figure 1. Potential customers are not likely to buy an alternative fueled vehicle unless there is a convenient and price competitive network of refueling stations available. But, private businesses may not develop a pervasive refueling station network unless there are enough alternative fuel vehicles on the road to create profitable sales volumes of the alternative fuel. These two dynamics create the first chicken-and-egg problem.

The second chicken-and-egg cycle is related to the state of auto manufacturers themselves and is summarized in Figure 2. Modern PEVs are still in the early stage of development, with only a modest

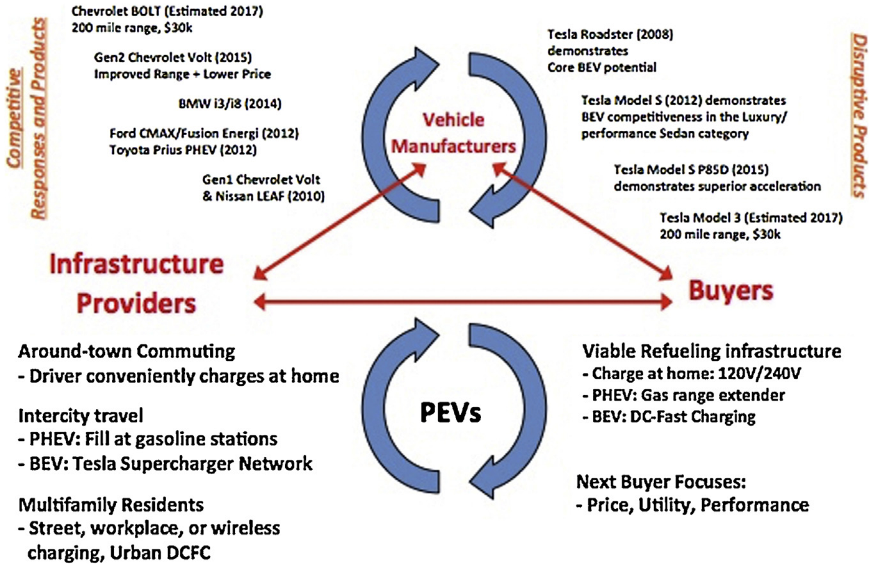

Figure 2: Recent PEV Adoption Dynamics

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number of well-regarded or broadly available PEVs for sale in all 50 states. The limited selection of PEVs available implies that some manufacturers do not see profitable demand for such electric vehicles at this time and hence may not substantially invest in the technology. At the same time, a manufacturer may only eventually achieve profitable sales over the longer term with investment that drives down costs, builds organizational core competency, and learns how to create vehicles that are compelling to consumers. Today, there is a spectrum of PEV manufacturers, from those producing compelling PEVs to those offering compliance cars.

Combining key technological advancements, a new entrant (Tesla) was able to substantially influence the dynamics of the PEV market. For many decades such attributes as performance, comfort, or styling has differentiated vehicles. The potential of luxury/performance electric vehicles was first demonstrated with the Tesla Roadster in 2008, the Tesla Model S in 2012, and more recently with the Models S P85D. A premium global brand and highly rated vehicles were built by focusing solely on the development of expensive high-performance long-range BEVs, reducing impediments to adoption, and leveraging a number of inherent characteristic advantages of electric drive. Given the considerable investments required and the financial risks of a failed product, a production vehicle that demonstrates a significant new capability can have a high impact on the investments of other manufacturers. Having an ''existence proof'' in the form of a competitor's vehicle to physically drive and analyze is extremely valuable to lower perceived risks and foster greater investment in PEV product development by key executives and boards of directors that make multi-billion dollar investment decisions. It is documented that some vehicle manufacturers decided to make an earnest effort to develop PEVs in part because of the potential demonstrated by Tesla's original Roadster (Lutz, 2011) and later the Tesla Model S.

The limited selection of PEVs available implies that some manufacturers do not see profitable demand for such electric vehicles at this time.

While arguably not betting the financial survival of their respective companies, GM, Nissan, and BMW are examples of firms that have invested significantly (billions of dollars by each) to create innovative PHEVs, mass-market, limited-range BEVs, or advanced lightweight construction PEVs with attractive driving dynamics. Other manufacturers (such as Ford, Toyota, VW) created their first-generation modern PEV powertrains that can be installed in their existing vehicle platforms. While sometimes compromising the range or performance of the PEV, this strategy provides some participation in the PEV market, meets regulatory requirements, and fosters the building of their organizational capabilities, while reducing R&D and tooling costs. Finally, a number of incumbent manufacturers are laggards that produce low-volume compliance cars with very limited availability (typically in California) and actively discourage drivers from leasing them (Beech, 2014).

Incumbent manufacturers' past and present success is largely a result of their ability to deliver conventional gas or diesel-driven vehicles that had some compelling combination of direct benefits to the buyer. These manufacturers have considerable expertise, skills, and tooling to create profitable conventional vehicles. This same success can lead to organizational inertia and a biased view of new innovations (Christensen, 1997) that may open the door for new entrants. As a reflection of the modest market opportunity for vehicles that deliver mainly societal benefits, only 5 percent of buyers would pay more for a ''green vehicle'' (NAS, 2015) and buying a green vehicle is a factor generally prioritized behind price, quality, and function. To increase adoption substantially, manufacturers would need to

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Table 1: Factors that may be considered in Consumer Purchase Decisions.

Direct Buyer Interests and Benefits:	Social Interests and Benefits:
Functional utility: the number of passengers, towing or hauling capability	Reduced Emissions
Purchase Price or Total Cost of Ownership (TCO)	National Energy Security
Styling and Brand Image	Oil Related Trade Deficit reduction
New Functions: Vehicle-to-Home, Vehicle-to-Grid. At-home charging, wireless charging	Fewer petro-dollars funding organizations with interests counter to U.S. national interests
Safety	
Reliability	
Performance and Driving dynamics	
Refueling time, location, convenience	
Leading Edge Technology	
Resale value	
Sales and Service experience	

invest sufficiently to produce PEVs that provide a superior combination of attributes than a comparable conventional vehicle in ways that are visible and directly benefit the buyers (**Table 1**).

Given the general lack of knowledge and relatively little field experience of PEVs, it is difficult for potential buyers of PEVs to weigh the potential likelihood or cost of battery replacement with experience they may have had with the replacement costs of expensive transmission, engine, or other key component repairs on conventional vehicles as they age. It may also be difficult for potential buyers to formulate an accurate comparison of PEV prices compared to an equivalent conventional vehicle with the same features, noise/vibration/harshness (NVH) attributes, or performance attributes.

Other concerns that may impact adoption are related to the safety of the lithium batteries and crash worthiness of the vehicle itself. To a certain extent, all lithium batteries are under a cloud of suspicion given a small number of highly publicized (but resolved) computer laptop or airliner lithium battery issues over the past decade. It may be difficult for potential buyers to gauge the relative safety of high capacity PEV batteries and home charging compared to the 160,000 conventional vehicles fires every year (Ahrens, 2010) and the occasional gas station fire.

From a crash-worthiness perspective, thus far there do not appear to be any fundamental technological issues that proper design and manufacturing cannot address. The Tesla Model S has the highest 5-Star safety ratings in all categories (NHTSA, 2015) and the Chevrolet Volt is a ''Top Safety Pick'' by safety ratings agencies such as IIHS (IIHS, 2015). Potential buyers may also not be able to discern the relative safety of PEVs compared to conventional vehicles given the record number of conventional vehicle recall campaigns during 2014 (Plungis, 2015).

A. Policy actions to accelerate adoption

The combination of California regulations, U.S. Federal CAFE fuel economy requirements, greenhouse gas emissions (GHG) regulations, and similar requirements in other substantial markets such as China and Europe have led to increased R&D investments in PEVs and hydrogen fuel cell vehicles (H2FCV) by manufacturers. The $2,500 to $7,500 federal tax credit enacted to create demand for electric vehicles will be phased out for each individual manufacturer's electric vehicles after that firm sells 200,000 PEVs. The intention with this limited volume of vehicles eligible for the tax credit is to provide a subsidy

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to allow present-day PEVs to be price competitive while nurturing the nascent technology so that, over time, the manufacturers and their suppliers can substantially reduce the price premium of electric vehicles. The preferred outcome is that manufacturers develop cost effective new technologies that deliver the efficiency and emissions outcomes desired without restricting consumer choice or increasing the total cost of ownership.

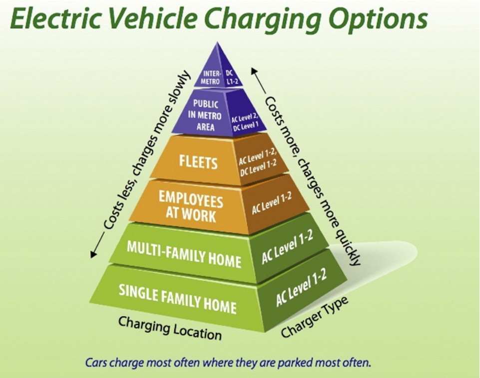

Figure 3: PEV Charging Hierarchy
Source: ANL (2012).

B. Charging infrastructure

Electric vehicles have the meaningful advantage of refueling at a far wider array of locations than gasoline stations. The more than 168,000 gas stations in the U.S. (DOE, 2015c) must be carefully located to achieve scale economies to pay for expensive sturdy buried fuel storage tanks, environmental and safety protection methods, and gas pumps. In contrast, PEVs can charge at millions of potential home, work, or public locations. However, for the foreseeable future even with the fastest PEV DC-Fast Chargers (DCFC), sometimes also called ''Level-3 Chargers,'' the maximum energy transfer rate to the vehicle for electricity will still be meaningfully slower than gasoline. The main disadvantage of longer refueling/charging time is likely not an issue when drivers can simply plug in and charge at a variety of locations where they would naturally park their vehicle for long periods of time, such as home or work. Home charging will likely remain the most important and highest priority infrastructure in the U.S. (DOE, 2015d). **Figure 3** shows the PEV charging hierarchy (ANL, 2012).

Electricity typically provides the lowest cost and most convenient means to refuel at home of any transportation fuel. About 40 percent of U.S. households exhibit the lifestyles amenable to today's PEV (NAS, 2015) leading to an estimate of about 80 M PEVs. This estimate is far higher than any reasonable projection for PEV adoption in the next decade barring a drastic petroleum supply shock.

The incorporation of a gasoline range extender in a PHEV combined with the ability to fully charge at home overnight with a common 120 V outlet has largely solved electric vehicle charging infrastructure and range issues for plug-in hybrids potentially driven by millions of homeowners. BEVs have the advantage of a simple powertrain without any gasoline engine but still present a greater challenge for long-range travel with longer charge times than a conventional vehicle during intercity travel.

With the purchase of a PEV, an owner can either continue to use the 120 V Level-1 AC charge cord included with their vehicle or they can upgrade their home to have a faster permanently installed 240 V Level-2 AC charging station. Some utilities offer substantial rebates to lower the cost of the Level-2 charger installation and/or will install a separate meter to measure energy purchased as part of a time-of-use electric-vehicle (TOU-EV) charging tariff. These special EV tariffs can further lower the cost of charging the vehicle. Once installed, the home then has its own permanent home refueling station that can likely be used with all future PEVs.

There are charging solutions developing (but certainly not universal) for residents of multifamily homes or drivers who park on the street. A number of communities are now incorporating charging provisions in their multifamily home building codes. Some apartments are beginning to

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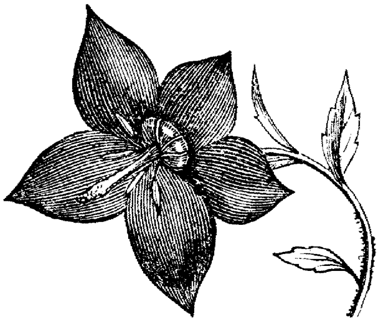
install PEV charging in their parking lots for residents. Charging cords with wireless revenue-grade meters that plug into street lights are now offered for drivers who park on the street in dense urban areas (Ubitricity, 2015). Urban DCFC stations can be installed in the parking lots of shopping malls, grocery stores, restaurants, coffee shops, or movie theaters to support PEV drivers who cannot charge at their multifamily residence. In the future, autonomous wireless charging enabled PEVs may be able to drop off their owner, negotiate a reservation at a wireless charging spot, drive themselves to the charging parking lot, align themselves precisely over the inductive charging coil, and then pick up the owner when desired. For long trips beyond the range of a BEV, DC Fast Charging, battery swapping, or dynamic wireless charging is required. For a variety of reasons, DCFC is likely to be the most popular option to support high-mileage around-town driving or long distance BEV travel for a number of years. Battery swapping may find an application niche in commercial delivery vehicles.

Long-distance travel of large-battery/long-range BEVs combined with a DCFC station network has been demonstrated across the U.S. (Tesla, 2015b) but is not yet universal. A 265-mile range BEV, such as a Model S, can recharge its battery to 80 percent state-of-charge (SOC) in less than 30 min. These DCFC stations can be installed at attractive locations such as specialty bakeries or premium malls where drivers can find activities to occupy their time for a 30-min charge. Given the flexibility of electricity delivery, electric vehicle recharging can be placed at waypoint locations that drivers find more attractive to stop or conveniently located at a destination.



In early 2015, reports surfaced that Apple is developing an electric vehicle (Wakabayashi and Ramsey, 2015). Tesla has offered to make its Supercharging network available to other manufacturers. It is plausible that Apple could adopt the Tesla charging coupler standard given it has the highest DC charging rate (120 kW presently, up to 135 kW in the future) and a single coupler for both AC and DCFC, while still providing standard SAE J1772 Level-1 and Level-2 charger compatibility. New entrants, such as Apple, may importantly be able to provide the resources to radically increase the number of urban and intercity DCFC stations installed.

While there is a single AC Level-1 and Level-2 charging standard in the U.S., there are three competing standards for DCFC. To resolve this issue, the DCFC equipment suppliers have developed ''multi-standard'' DC fast charging stations that incorporate both the CHAdeMO and SAE J1772 Combo DCFC standard cords just as gas pumps have multiple handles for gasoline or diesel or multiple grades of gasoline. Presently, the nationwide Tesla DCFC network is free to Tesla vehicle owners that purchased the Supercharger option with their vehicle. The network is reserved exclusively to charge only Tesla vehicles.

The combination of relatively low asset utilization of DCFC, installation costs, and utility capacity demand charges will continue to make the unsubsidized business case for public DCFC financially unattractive until there are many more PEVs on the road or new business model innovations are developed for DCFC stations (EPRI, 2014; NAS, 2015). The issue of public refueling station profitability is not unique to PEVs. Gas stations are carefully located to increase sales and are typically dependent upon non-gasoline sales to improve profitability (EIA, 2001; NPR, 2007).

C. Distribution channels

Given the lack of understanding by the general public of the types of electric vehicles, the education of vehicle

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buyers by the sales channel would likely increase PEV adoption rates. However, the financial incentives for traditional auto dealerships in the U.S. may instead slow adoption (NAS, 2015). PEVs generally involve a more complex sales process that takes more time to complete the sale while requiring increased levels of training of the sales staff. Salespeople must understand buyers' commuting needs, the types of PEVs (BEVs vs. PHEVs), the different types of charging, home charger installation, rebates, tax credits, and other regional incentives (e.g. HOV access). Dealer employee turnover and the potential loss of service revenue can also make PEVs less attractive to sell than a gasoline vehicle for U.S. car dealers (Consumer Reports-Dealer Survey, 2014; Cahill, 2015) given the lower expected maintenance costs of electric vehicles. Manufacturers can provide training and assistance, but they do not have direct control over dealers to ensure the sales staff remains fully trained given U.S. dealers are independently-owned private businesses typically protected by strong state franchise laws. Despite these dynamics, there are dealers who have focused, well trained, and effective PEV sales staff.

To address these concerns, new entrants have pioneered a direct and Internet sales process. In states that allow manufacturers to directly own outlets, buyers can buy their vehicle on the Internet or in a Tesla store. In the remaining states, the vehicles can be purchased on the Internet with delivery directly to the buyer's home. While generally unwelcomed by traditional dealers, direct sales may also provide better control of the buying experience, more effectively support the greater consumer education generally needed for PEV'S compared to conventional vehicles, yield more rapid feedback for future enhancements or product issues, and lower the cost of the vehicles to the consumer compared to a traditional dealer structure. This distribution strategy may also align better with the demographics of the customers that would be most likely to purchase a PEV.

IV. Key Trends

One of the most important factors affecting PEV prices is the cost of batteries. Battery prices have declined faster than expected (**Figure 4**). In 2010 the

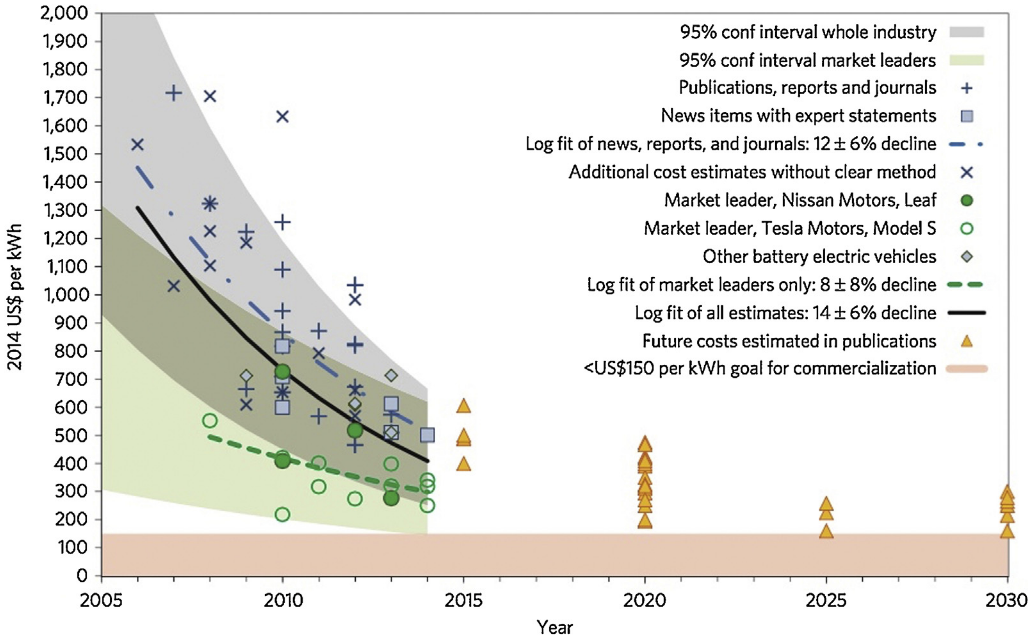

Figure 4: Lithium Battery Price Improvements
Source: Nykvist and Nisson (2015).

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price of batteries was estimated to be about $1,000/kWh. Today, some manufacturers are likely buying batteries at $300/kWh (Nykvist and Nisson, 2015). These cost reductions are a combination of lower battery prices and improved energy density. Demonstrating this progress, the original 2011 Volt provided 35 miles of electric range while the recently announced 2016 Volt has a 50-mile electric range with a similarly sized but lighter-weight battery pack (GM, 2015).

While continued improvements in batteries are expected, there are other methods to reduce the need for battery capacity to further lower costs. Improved vehicle weight, cabin HVAC efficiency, vehicle controls, aerodynamic drag, and tire rolling resistance decrease the size of the battery needed. In addition, the decoupling of the engine from the drive wheels in a PHEV can provide significant opportunities to further improve and optimize the engine-generator used as the range-extender (Kosaka et al., 2014). Additional cost reductions and efficiency improvements are likely over time as the vehicle manufacturers progressively refine these gasoline (or Diesel) engine-generators.

A. Declining PEV costs and increasing conventional vehicle costs

Over the next decade the cost of conventional vehicles is projected to increase as advanced technologies are incorporated to meet more strict emissions and efficiency requirements. Government estimates for these increased costs vary from $1,461 to $1,616 per vehicle to meet the 2025 CAFE regulations and $1,836 to meet the GHG standard (Federal Register, 2012). The National Auto Dealers Association (NADA) estimates an increase of $3,000 to $5,000 per vehicle to meet these regulations (NADA, 2012).

During the same period, it is expected that battery and power electronics costs will continue to decline (**Figure 5**). Battery costs have been improving at an average of 7 to 14 percent yearly (Nykvist and Nisson, 2015). In late 2010, when the first generation mass-market viable PEVs were first offered for sale, the PHEV cost premium over an equivalent conventional vehicle was estimated to be $10,000 (Higgins, 2013). A meaningful amount of the development cost of the original Chevrolet Volt was the development of 10 million lines of control software running on about 100 control units (Merritt, 2011). The ability to reuse or leverage this code also decreases the cost of the vehicle in future generations. Precise cost estimates are proprietary to firms and difficult to predict, but over the next decade the price premium of a PEV compared to an equivalent conventional vehicle is likely to decline substantially.

Battery energy storage has considerable opportunities outside the automotive market. Large-scale economic storage for the electric grid is a disruptive technology that has the potential to enable the integration of more renewable generation on the grid over the long term. The high volumes, high reliability, strict safety requirements, and low costs demanded by the automotive industry are a powerful force that can drive battery storage advancements that also make batteries more competitive for grid applications. These additional volumes from grid applications may then drive higher volumes and lower costs for PEVs.

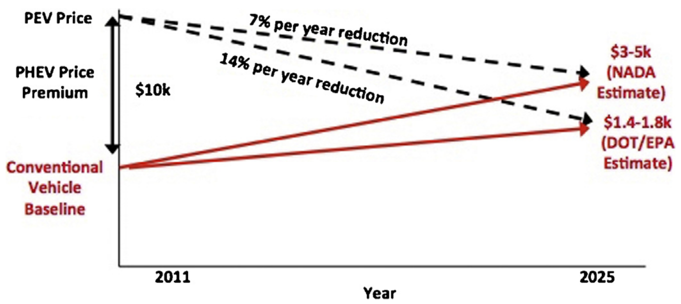

Figure 5: PEV and Conventional Vehicle Price Trends
Plug-In Vehicle battery/power electronics costs are declining while conventional vehicle costs are increasing from more strict emissions and fuel efficiency requirements.

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V. Advanced Vehicle Capabilities and Grid Impacts

PEVs are new and unique loads for the electric grid given they are large, flexible, and intelligent. Manufacturers can also incorporate functions into their PEV to not only avoid additional stress on the grid from PEV charging, but also to enable synergistic vehicle integration with the electric grid. Intelligent charging of PEVs can reduce grid generation emissions, charging costs, or stress on the grid (EPRI, 2001; Parks, 2007; Sioshansi, 2009; Anderson, 2014). The additional flexible PEV load could enable regions to incorporate increased amounts of renewable generation on their local grids (Markel, 2009).

Intelligent charging is a logical and useful extension of the simple programming of charge windows available on the first generation of PEVs. PEVs are excellent candidates for utility demand response (DR) programs (Denholm, 2006). Products are being developed (but not broadly deployed) to allow PEV charging to participate in utilities DR programs. The fundamental computing and communications technologies to support PEV-based DR is mature. The pace of implementation of PEV-DR is typically limited by the economics of DR for a particular utility and the number of vehicles. For example, if a utility is experiencing negative load growth from more efficient homes and businesses, DR could be uneconomic given excess generation, transmission, and distribution capacity.

PEV-unique capabilities include vehicle-to-home (V2H) and vehicle-to-grid (V2G). V2H applications use the PEV as a storage node and electricity generator (in the case of a PHEV) to provide an alternative to a traditional home backup generator in the case of a grid outage or off-grid applications (Tuttle et al., 2013). The home and PEV together are isolated to create a microgrid. In vehicle-to-grid scenarios, the PEV is connected to the grid and uses its battery (and/or generator) to generate revenue from grid ancillary services or energy arbitrage (Kempton and Letendre, 1997). There are varied estimates for the revenue opportunities for PEV owners for providing these grid services (Quinn et al., 2010). These advanced PEV-unique functions are not implemented in any broadly sold production PEV to date. Over the next decade, as manufacturers gain sufficient field experience with batteries, grid interfaces, and electrified powertrains they may become more apt to offer V2H or V2G capabilities as an extra cost PEV feature.

Wireless charging at home can further simplify the PEV ownership experience. The driver could not only avoid trips to the gasoline station, but also avoid the task of plugging-in their PEV for charging. The automated parking capability that is becoming more common on new vehicles today can guide the PEV for precise alignment above the inductive charging coil unit. Combining wireless charging with autonomous driving capability can create compelling new solutions for residents of multifamily residents or dense urban areas.

Over the past decade, a number of research efforts were launched to assess the potential impact of PEVs to the electrical grid (Electric Vehicles, 2012). Two main concerns surfaced: the impact of charging PEVs during peak grid load and clusters of PEVs stressing common feeder distribution transformers (Hadley, 2006, 2009; Kim, 2012). With the basic levels of intelligent charging capabilities already incorporated in the first-generation PEVs to avoid aggravation of the peak grid load or to automate charging when electricity rates are low, Pacific Northwest National Labs estimated that nearly 70 percent of the U.S. light-duty vehicle fleet could be charged with existing grid resources (Kintner-Meyer

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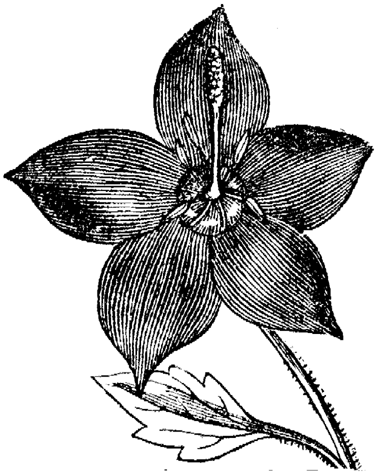
et al., 2007). Some utilities have already implemented rebate programs for residential Level-2 charging stations. In return for this rebate, the owner might be asked to allow the utility to reduce charging during periods of grid stress. The PEV owner has the ability to override this curtailment if needed.

A number of studies have been performed to better understand the impact to feeder distribution transformers (SCE, 2013; Pyper, 2013). To date, few problems have surfaced in charging the 300,000 PEVs on U.S. roads. If a specific distribution transformer is overloaded, the solution is generally simple. The utility dispatches a crew to the site and upgrades the transformer. Over the past century, distribution grids have been repeatedly upgraded as new loads (with associated increases in utility revenue) successively presented themselves in the form of home appliances, televisions, air conditioning, and consumer-electronics. In addition, some utilities are experiencing a decline in their loads and have excess capacity to handle PEV loads from reduced industrial loads combined with the adoption of substantially more efficient CFL and LED lighting, more efficient HVAC systems, and home energy efficiency measures. These utilities welcome the additional revenue from PEV charging that can increase their revenue and improve the asset utilization of their capital stock.

Anecdotally, the few areas with potential transformer issues appear to be coastal or mild climate areas that have been able to defer transformer upgrades for many years given minimal HVAC load from mild sea breezes or cool average temperatures. In some of these areas, the introduction of large amounts of rooftop PV generation has created a more significant problem for the local distribution system. Intelligent charging of PEVs has been proposed as a method to reduce the voltage control and ramping problems in these systems (CAISO, 2013; SCE, 2013).



VI. Reduced Barriers to Entry for New Manufacturers

Capital-intensive industries with a relatively few large-scale long-established firms can be highly resistant to adopt significantly different core technologies such as electric drive. New entrants to the industry can be essential to encourage broad adoption of a potentially superior, but disruptive, new technology. However, becoming a successful auto manufacturer is a considerable challenge. Many firms that tried over the years have failed. Electric powertrains can substantially reduce the barrier to entry for new firms by reducing the high cost of traditional powertrain development, validation, and manufacturing tooling. While substantially more efficient than gasoline engines, electric motors are relatively simple, inherently reliable, and powerful devices. Three-phase AC motor control is well developed with modern power semiconductors and software control. Also, a small number of motor designs are needed to create a wide range of rear wheel drive, front wheel drive, or all-wheel drive combinations across multiple vehicle types further saving R&D, tooling, and manufacturing costs.

A BEV powertrain further reduces costs by eliminating the need for emissions systems design, stringent emissions validation testing, and warranty coverage across multiple regions with varied regulations and significantly different fuel qualities. Note that PHEV powertrains continue to require emissions systems development similar to conventional vehicles.

VII. Conclusion

Pervasively available energy from the electricity grid,

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advances in lithium batteries, improved semiconductor-based power electronics, and modern embedded computing have been combined to create viable mass-market PEVs. To date, the basic electric powertrain technology appears to be proven and the PEVs on the road have demonstrated that they can be safe and reliable.

Regional variation in adoption will likely continue due to differences in such factors as fuel prices, dominant home structure (owner-occupied detached home versus multifamily or rented residence), incentives, commuting patterns, further infrastructure build-out (particularly for BEVs), or vehicle type preferences. PHEVs already have minimal infrastructure needs and no range anxiety. BEV manufacturers (some new) may stimulate demand by substantially increasing the rate at which the charging infrastructure is constructed.

There is a spectrum of auto manufacturers creating a modest variety of PEVs that can be described as ‘‘compelling to compliance cars.’’ The most fundamental impediments to adoption today include a combination of the relatively limited variety of new PEV model types available, a relative lack of understanding of the different types of PEVs and how each may fit drivers needs, a ‘‘wait and see attitude’’ to let others be early adopters of radically new technology to make sure it is reliable and safe, the relatively short electric range of today’s mid-priced BEVs, a lack of a nationwide DCFC network for BEVs (not needed for PHEVs), and generally higher PEV prices.

Looking forward to the next decade, it is likely that petroleum will remain the dominant transportation fuel but also that conventional vehicles will have a continued steady increase in costs to meet more strict emissions and efficiency requirements while PEVs will likely experience continued improvements and a decline in costs. Hence, the price premium of PEVs compared to conventional vehicles is likely to shrink, perhaps substantially, leading to greater adoption. If adeptly deployed, a number of superior attributes of electric drive and lowered barriers to entry may combine to create a wider variety of PEVs with compelling combinations of attributes by incumbent manufacturers and disruptive opportunities by new auto firms.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tej.2015.07.008.

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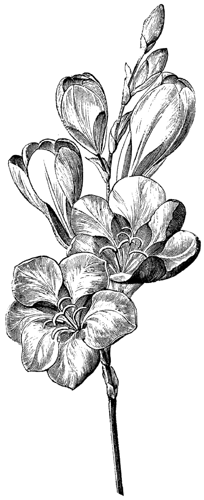

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