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PLUG-IN ELECTRIC VEHICLE DEPLOYMENT AND INTEGRATION WITH THE ELECTRIC GRID

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PLUG-IN ELECTRIC VEHICLE DEPLOYMENT AND INTEGRATION WITH THE ELECTRIC GRID

by

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Dedication

This work is dedicated to my wife and children: Mary Clair, Robert, and Mary Elizabeth. Their support and patience has been exceptional.

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by

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Abstract: Key battery, semiconductor, and software technologies have sufficiently progressed over the past few decades to enable viable plug-in electric vehicle (PEV) alternatives to conventional vehicles. Alternatives to petroleum-based fuels for transportation are sought to address concerns over energy security, foreign oil derived U.S. trade deficits, oil related geopolitical entanglements, and emissions.

The various types of PEVs have substantially different characteristics. The types and key attributes of PEVs, charging standards, and charging locations are described. The likely scenario for PEV-Grid interactions over the next decade is synthesized from the analysis of the technologies available to and circumstances of vehicle manufacturers, utilities, and supplier firms.

PEV adoption considerations are evolving. Many lessons have been learned from the first generation of PEVs that were introduced starting in late 2010. Technology, market, and policy drivers of emerging trends in the diffusion of PEVs are explored more in-depth.

PEVs as electric loads are unique in that they are large, flexible, and intelligent. These attributes can not only provide utilities a new source of revenue, but also improve

grid stability and economics. Actions, technologies, and policies that utilities can deploy to increase adoption are discussed. Actions are explored to make the overall PEV ownership experience superior to a conventional vehicle.

This dissertation also describes research of the capability for PEVs in Vehicle to Home (V2H) scenarios, where the vehicle acts as a residential battery storage system and/or a backup generator in a residential microgrid configuration during a grid outage. Residential energy data collected from a smart grid testbed is used with a custom PEV model to assess the performance (in terms of duration and power output) of a BEV or PHEV used for backup power. Our earlier results quantify the extent to which photovoltaic (PV) generation and the characteristics of a PEV (battery size, gasoline availability) affect the backup duration during an electric grid outage. Strategies to further increase backup duration and non-continuous self-sustaining off-grid alternatives were found in our early V2H research. Varied amounts of load curtailment and PHEV engine-generator control improvements are modeled in subsequent research.

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PART I: PLUG-IN ELECTRIC VEHICLES

Chapter 1: Background

The motivations for developing alternative energy sources and associated vehicle powertrains[1] is to reduce a widespread dependence on oil (particularly foreign oil), imported oil-driven trade deficits with oil imbalances constituting close to half of the U.S.'s trade deficit, [BEA 2008], oil related costs [Greene 2010], and environmental concerns (including climate change and oil spills) while improving energy security, and air quality [Siosanshi and Denholm 2008, Thompson et al. 2009, EPRI and NRDC 2007].

Vehicle manufacturers have an interest in developing emerging technologies to demonstrate leadership (and improve brand image), while ensuring strategic capabilities in key alternative fuel/powertrain technologies critical for success in global vehicle markets. These alternative powertrains may, in the end, be more pervasively deployed in non-U.S. markets even after being pioneered and/or first sold in the U.S. Long-term average U.S. gasoline prices have generally stayed under $3 per gallon (in 2010 dollars), and do not reflect negative externalities [Delucchi and McCubbin 2010]. While oil prices are likely to rise over the long term [ECB 2008, Deffeyes 2002], low fuel prices (both in the past and currently) have not encouraged consumer demand for highly fuel efficient or alternative-fuel vehicles, which then would encourage more active investment by manufacturers. In fact, even though some hybrid-electric vehicles (HEVs) now provide the lowest overall total cost of ownership, hybrids have enjoyed less than 3% of new U.S vehicle sales [Green Car Congress 2010].

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[1]A vehicle powertrain includes the components associated with the source of propulsion (such as a gasoline engine or electric motor), transmission driveshaft(s), differential(s), and axles.,

During the last few decades, advanced technology was deployed to increase power, performance, and vehicle size instead of fuel economy. A combination of relatively recent events has contributed to new investments in alternative fuel and efficient powertrain technologies. These include spot fuel shortages in 2005 from Hurricane Katrina, substantial oil and gasoline price spikes in 2008, the passing of more stringent Corporate Average Fuel Economy (CAFE) and emissions regulations, California ZEV (zero emissions vehicle) mandates, and Tesla Motors' demonstration of a high-performance long-range full-function battery electric vehicle (BEV). Tesla's BEV demonstrated the potential of the technology and inspired competitive response by other vehicle manufacturers. Several new vehicle options are emerging in the U.S. market, as described below and Chapter 2. Moreover, several foreign markets have substantially higher gasoline and diesel prices, and thereby offer strong near-term (and long-term) incentives for alternative vehicle technologies to reduce the near- and long-term private and social costs of personal mobility.

In 2010, mass-market-viable PEVs became available from several global vehicle manufacturers. A variety of PEV models are emerging each successive year from an increasing number of vehicle manufacturers. There are distinctly different types of PEVs and it is useful to define these while assessing their strengths and weaknesses. Essentially, grid-enabled or plug-in electric vehicles (PEVs) can be categorized into pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), with a special variant of a PHEV commercially named an eREV (extended-range electric vehicle). These categories are discussed in the following sections.

I. BEVs (Battery Electric Vehicles)

BEVs incorporate a large on-board battery, charged from the electric grid while parked via a cord (or through wireless power transfer from the grid). This battery then wholly provides the energy for the electric traction motor to propel the vehicle. BEVs are not a new concept. Thomas Edison designed a BEV a century ago. However, the relatively short range (leading to the term "range anxiety") was one of the many reasons the petroleum fueled internal combustion engine (ICE) became the dominant powertrain by the 1920's. Given range anxiety, existing technology Lithium batteries, and other consumer considerations today's mass-market BEVs with \$25,000 to \$35,000 retail prices typically have 80-100-mile nominal range targets. An advantage for BEVs is powertrain simplicity and expected very low maintenance costs.

BEVs have a relatively simple all-electric powertrain that can reduce non-battery-related costs. Vehicle manufacturers also avoid the costs of emissions testing, certification, and warranties since the vehicle has no tailpipe emissions control system. However, range limitations, greater battery weights, and longer charge times can be problematic in BEV vehicles. Without a range-extending back-up (or a very large battery plus a pervasive ultra fast charging network), BEVs may also force a greater dependence upon public charging infrastructure, better trip planning by the driver, or access to a conventional second car for longer-distance commuting needs.

Tesla Motors has introduced two generations of performance BEVs with equivalent (or near equivalent) 200 to 265 miles of range using modern Lithium Ion batteries, lightweight construction, and low aerodynamic losses. The price of the latest Tesla vehicle, the Model S, is competitive with its luxury performance sedan competitors. Independent reviewers, the automotive press, and owners also consider the Model S very well executed. However, the very large battery sizes required to provide this long range contribute to a retail price well above the average U.S. vehicle transaction price of approximately $33,560 [PRNewswire 2015]. At two to three times this U.S. average vehicle transaction price, the Tesla should not be considered a mass-market vehicle but with its long range combined with Tesla's proprietary "SuperCharger" DC-Fast Charging (DCFC) intercity network Tesla is attempting to further demonstrate the viability of all-electric driving as a fully capable alternative to conventional gasoline/Diesel vehicles (even for longer trips).

II. eREVs (Extended Range Electric Vehicles)

eREVs are conceptually BEV-derived vehicles with an on-board internal combustion engine (ICE) generator that provides electrical energy to the motor once the initial battery charge is exhausted. This configuration solves the century-old "range anxiety" problem of a BEV [Markel 2010] by providing an overall range on par with a traditional gas or diesel vehicle. Once its initial charge from the grid is depleted, or if the vehicle is never plugged into the grid, the eREV should operate like a series hybrid electric vehicle (HEV). Extended range electric vehicles can be considered a special type of plug-in hybrid electric vehicle.

III. PHEVs (Plug-In Hybrid Electric Vehicles)

PHEVs effectively are HEVs with larger batteries and a charging cord to access grid power. PHEVs can operate in "EV mode" under some circumstances: less than 11 miles range, under 62mph, and under light acceleration for the Prius PHEV or for 21 miles under 80mph for the Ford CMAX Energi. When not operating in EV-mode, PHEVs typically operate in a "blended" mode, using the gas engine and electric motor together, to substantially reduce gasoline consumption while operating in battery charge depletion (CD) mode [Vyas et al. 2009]. PHEVs also solve the range anxiety problem and should operate similar to a traditional HEV if never plugged into the grid or once the battery is depleted of charge from the grid.

PHEVs operating in blended or mostly electric mode have the potential to achieve impressive liquid fuel economy of over 100 mpg-e ("mpg-equivalent") for some travel distances while the battery is in charge depletion (CD) mode [Vyas et al. 2009]. Since the gas engine and electric motor work cooperatively to propel the vehicle, the motor may be smaller than that of a comparable eREV design. Blended-mode designs also enjoy a wide array of design strategies, to optimize the balance of battery size, weight, cost, engine size, and overall efficiency. Such design options may reduce vehicle price, thereby encouraging sales volumes and economies of scale in production.

Without the gasoline engine running, the smaller PHEV motor size and reduced motor or battery-cooling capacity may limit top speeds, limit electric-only range, and limit acceleration rates depending on battery design and size, powertrain control algorithms, and other parameters. These limitations may reduce the attractiveness (and hence sales) to potential buyers of PHEVs designed with these tradeoffs. However, drivers with low-speed needs and short daily commutes may still find having a small all-electric-range (AER) PHEV can fulfill their desire to drive without consuming any petroleum and at a lower vehicle purchase price. Many will continue to refer to both eREVs and PHEVs simply as PHEVs, since the differences can be subtle for some owners. Meaningful differences in design and operation of eREV and PHEV powertrain technologies exist [Tate 2008], even if, from a user's perspective, they appear to operate somewhat the same. New models of different powertrain configurations are still emerging from varied manufacturers. For example, eREVs are fully functional in electric mode across the entire operating range -- from being stationary at a stoplight to operating at maximum speed without any dependence on gasoline. This architecture may provide a marketing advantage by creating a product which satisfies drivers who desire to drive "petroleum free," even with a modest all-electric range (AER) while still having a gasoline backup generator (which is deployed automatically after the initial charge is depleted). An eREV owner could conceivably never put gas in the tank and simply use the vehicle as a BEV. Nevertheless, in an analysis of driving pattern data from a Southern California regional travel survey, Tate and Savagian [Tate 2008, Tate 2009] concluded that PHEVs may rarely operate in EV mode over a full day's driving, while a majority of eREV drivers will experience a full day of driving without consuming gasoline.

While eREV/PHEV owners can drive in a fashion to avoid gasoline use and maximize electric drive, the manufacturers will likely advise that owners need to keep a few gallons of gasoline in the tank to let the engine occasionally operate to lubricate the gasoline engine's bearings and seals. Blended-mode-PHEV manufacturers will also likely recommend that drivers have gas in the tank to ensure full functionality (e.g., traveling further than 11 miles range, above 62 mph, or under hard acceleration in the case of the Prius PHEV). While these operational nuances are important for drivers, they may be inconsequential to overall liquid fuel consumption if a motivated driver modifies their driving patterns to maximize the miles that are electrically driven, with little gasoline consumed over the course of a year.

Conventional-range-equivalent eREV and PHEV architectures leverage the energy density of petroleum to solve the problem of range anxiety at the cost of incorporating a more complex hybrid electric-plus-gasoline powertrain. Along with the energy density advantage of petroleum, a pervasive refueling infrastructure is leveraged when longer trips are taken. Range-extension capabilities enable the eREVs and PHEVs to serve as a household's primary or sole vehicle. This petroleum-based backup allows downsizing of the most expensive PEV component, the battery (as compared to a BEV) while providing a range on par with those of conventional and hybrid-electric vehicles.

Real world electric range will vary (sometimes significantly) for all types of electric vehicles with the "three T's": driving Temperament, Terrain (hills), and Temperature (weather) given relatively heavy electrical loads such as passenger cabin heating and air conditioning [Tuttle 2012b]. As with conventional vehicle mileage estimates, "your actual (electric vehicle) mileage will vary" (typically, but not always in a negative fashion compared to the EPA test results).

The advertised electric range for PEVs will be based upon a particular objective test cycle, such as the U.S. EPA's LA4/UDDS drive cycle [EPA 2010] for conventional vehicles. While these test cycles are useful for purchase comparisons, the effective ranges experienced in practice typically will differ from estimates stated on a new-vehicle's required window sticker or on the U.S. government's official website (www.fueleconomy.gov). The actual electric range achieved by relatively modest range BEVs (such as the Nissan LEAF), in particular, will likely affect their adoption rate. The U.S. test procedures were updated in 2008 to reflect more realistic driving conditions making official estimates more representative of owner-experienced fuel economies [EPA 2010]. It is expected that future advances in battery cost, capacity and durability will result in the installation of smaller and, hence, less expensive batteries to allow PHEVs/eREVs to be sold at progressively lower initial cost premiums over conventional vehicles, to increase the range of today's modest range BEV, and to substantially reduce the price of long range BEVs.

This dissertation will discuss PEV designs and research carried out on grid-vehicle and off-vehicle interactions.

IV. Organization of Subsequent Chapters:

As the discussion in the previous section has shown, all PEVs are not alike. In fact, the various powertrain configurations create widely varied performance, range, cost, and driving experience characteristics. Chapter 2 describes in detail the various types of PEVs available.

Chapter 3 describes the different charging locations and standards deployed or likely to be deployed as well as impacts to the grid. Over the past century two distinct energy systems have been created: the electric grid for stationary applications (such as buildings) and a parallel petroleum based network for transportation. Since they are charged from the grid, PEVs form a new intersection of transportation and the grid with grid energy stored in batteries for later use[2].

Technological advances, market dynamics, and policy decisions affect the rate of adoption of PEVs. The factors that affect the diffusion are discussed in depth in Chapter 4.

After the oil shocks of the 1970's, the use of oil to generate electricity substantially declined and the interaction of oil and grid electric power became more decoupled. However, oil is still used as a fuel for electricity generation for certain island or remote microgrids. Electric vehicles remained popular until the 1920's when a number of factors made gasoline/Diesel the dominant transportation fuel. By the late 1920's, internal combustion engine powered vehicles dominated the sales of new vehicles

[2] Note that electric trains and trolleys do use grid electricity for transportation, however they typically do not store energy with on-board batteries.

and the electric powertrains were relegated to small niche applications. The more than 240 million vehicles in the U.S. have had no consequential interactions with the grid as a load[3]. The interactions of PEVs as a transportation load with the grid brings together a mix of industries that have not interacted closely in powering large numbers of vehicles. The various participants include vehicle manufacturers, utilities, and supplier firms who operate with radically different business models, regulatory and legal environments, geographical scope, and technical capabilities developed over the past century. From an analysis of these factors this report provides a likely scenario for PEV-Grid interaction over the next decade in Chapter 5.

As key energy providers to electric vehicle drivers, utilities not only benefit from additional PEV electricity sales, but also can meaningfully affect the adoption rate of electric vehicles. The actions that utilities can take to increase PEV adoption and/or provide a more convenient or superior vehicle ownership experience are discussed in Chapter 6.

Chapter 7 describes research related to the capability for Plug-in electric vehicles (PEVs) in Vehicle to Home (V2H) scenarios, for which the vehicle acts as a residential battery storage system and/or a backup generator during a grid outage or more frequent short duration distribution system fault. In this chapter, we use residential energy data collected from a smart grid test bed in Austin, Texas with a custom PEV model to assess the performance (in terms of duration and power output) of a PEV used for backup power. Our results quantify the extent to which photovoltaic (PV) generation and the characteristics of a PEV (battery size, gasoline availability) affect the backup duration of

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[3] Gasoline/Diesel vehicles plugged into the grid to power their engine block heaters during extremely cold weather could be argued to have been a previous vehicle-grid interaction, but the total energy consumed was small, the energy was not used to propel the vehicle, and the interaction was not intended to create a powertrain using an alternative fuel.

a PEV based V2H system during an electric outage. From the insights gained from this early research, strategies are formulated to increase back-up duration (BUD).

We use the insight gained from our early modeling and research results to explore optimal engine-generator control for PV-enabled V2H, and other strategies to further increase backup duration in more recent research discussed in Chapter 8.

Electric vehicles are new loads for the grid that present unique opportunities for intelligent and symbiotic interactions with the grid. PEVs grid loads are unique in that they are large, flexible, and intelligent. Chapter 9 describes future work investigating the ability for PEVs to become a symbiotic load with the grid mitigating the effects of renewable generation intermittency, contributing to improved grid stability, and improving grid economics (particularly of renewable generation).

Many technology trends will affect the adoption and use of PEVs in the future. Appendix 1 provides an overview of the technologies likely to be impactful. These technologies include batteries, power electronics, charging infrastructure, and grid-PEV communications.

Over time it is expected that technology costs will decline such that the price premium for the purchase of a PEV over a conventional vehicle will decline substantially and purchasers may expect a positive payback for the incremental purchase price without tax credits or other incentives (as they have progressed for Hybrid vehicles over the past decade). Appendix 2 includes comparisons of some PEVs with their conventional equivalent given recent prices. An accurate cost-benefit analysis depends upon the particular electric vehicle and its conventional equivalent, and the year of the comparison given declining PEV component costs and increasing conventional vehicle costs. The comparison involves considerable effort to determine the purchase price increment between a PEV and a conventional equivalent and then also estimate operating, maintenance, and depreciation costs differences over the life of the vehicle. To provide the most valuable insights to the reader, it is useful to calculate the net present value using varied gasoline prices and battery replacement costs given the difficulty in projecting these prices over the long term [Tuttle 2012b]. Sample comparisons for the first generation Chevrolet Volt, Nissan LEAF, and the Prius PHEV are provided in Appendix 2. Depending upon usage patterns, gasoline and electricity prices, and battery replacement, the financial payback can be positive to buyers even in low fuel-cost regions such as the U.S. given substantial tax incentives presently offered [Tuttle 2012b]. Over time, PEV technology costs will decline. An overview of total cost of ownership differences in 2025 is also included.

Chapter 2: Plug-In Electric Vehicle Designs

I. New Vehicle Designs

The Chevrolet Volt eREV, the Nissan LEAF BEV, and the $109,000 Tesla Roadster were the most popular PEVs available in 2011. Tesla created a BEV with its Roadster (now out of production) which not only sold out its limited production run of 2500 units but also demonstrated to other vehicle manufactures that battery technology and electric drive had progressed sufficiently to create a compelling vehicle. Since 2011 an assortment of new PEVs have been in production or previewed including the Tesla Model S performance sports sedan, Ford Focus BEV, Mitsubishi iMIEV, Toyota Prius PHEV, Ford CMAX Energi PHEV, Ford Fusion Energi PHEV, Cadillac ELR, Honda Accord PHEV, the BMW i3 and i8, and the upcoming Chevrolet Bolt, Tesla Model X, and Tesla Model 3. At this time there are multiple strategies that vehicle manufacturers are deploying. Most of the vehicle manufacturers appear to be targeting drivers seeking vehicles that dramatically improve fuel economy and which have much less impact on the environment while potentially permitting petroleum-free travel. A second strategy is to create electric vehicles that have compelling performance, styling, NVH (noise, vibration, and harshness) attributes combined with a premium sales and service experience. A third strategy deployed by a few incumbent manufacturers to invest the least amount of resources in PEVs to meet minimal governmental mandates. The PEV powertrain architectures and vehicle characteristics vary considerably and are as varied as vehicle styling and brands images. The Tesla Model S stands out for its long range, high performance, and poor weather handling while deploying a pure battery-only BEV powertrain. The very large battery size incorporated to achieve this long range contributes to the relatively high price of the Model S. This extremely long range combined with Tesla's proprietary "SuperCharger" DCFC network contribute to a changing attitude about BEV range anxiety and the past perception that a BEV would not be capable of long intercity travel.

The number and types of electric vehicles available is continuously increasing and evolving in a way that makes any static list out of date relatively quickly. Plug-In America's updated list of emerging (worldwide) vehicle models (http://www.pluginamerica.org/vehicles) notes whether a vehicle is available for purchase, under development, or a concept vehicle (with no committed production date).

A summary of the vehicles from global vehicle manufacturers available for near-term purchase in the U.S. and with the greatest potential for market impact can be divided into range-extended PHEVs/eREVs and pure BEVs (sometimes simply referred to as "EVs"). **Table 1** describes key features of these various models (including estimates of the manufacturer's suggested retail price (MSRP) and state of charge (SOC) window, where SOC refers to the percentage of battery capacity that can actually be used to power the vehicle while maintaining long-term battery durability

Table 1: PEV available in the U.S. market (2014 update)

Make & Model	**Release Date**	**Estimated Retail Price** (After Federal Tax Credit)	**Body Type**	**Gross Battery Size (kWh)**	**Estimated State of Charge Window**	**All Electric Range (miles)**
Range-Extended PEVs						
BMW i3 REX	2014	$33,850	4-door Hatchback	22	86%	72
BMW i8	2014	$127,500	2-door Sports Car	7.1	86%	14
Cadillac ELR	2014	$67,500	2-door Coupe	16.5	70%	37

Table 1 Continued

Chevy Volt eREV Gen1	2010	$33,500	4-door Hatchback	16	65%	38
Chevy Volt eREV Gen2	2015		4-door Hatchback	18.4	90%	53
Ford CMAX Energi PHEV	2013	$29,995	4-door Crossover -Utility Vehicle	7.6	90%	21 (at speeds under 80mph)
Ford Fusion Energi PHEV	2013	$35,745	4-door Sedan	7.6	90%	21 (at speeds under 80mph)
Honda Accord PHEV	2014	$37,750	4-door sedan	6.7	65%	13
Toyota Prius PHEV	2012	$29,500	4-door sedan	5.3	70%	11 (at speeds under 62mph)
Non-Range-Extended (BEVs)						
BMW i3	2014	$33,800	4-door Hatchback	22	90%	81
Chevrolet Spark EV	2013	$26,685	4-door sedan	28	90%	82
Ford Focus	2012	$31,700	4-door sedan	23	90%	100
Fiat 500e	2013	$32,600	2-door hatchback	29	90%	87
Mercedes Smart Car ED	2012	$17,500	2-door sedan	17.6	90%	68
Mitsubishi iMiEV	2011	$21,625	4-door sedan	16	90%	62
Tesla Roadster (Out of Production)	2009-2012	$101,500	2-door sports car	53	90%	240
Tesla Model S	2013	$62,250-$110,250	4-door sedan	70,85,90	90%	240/ 270

Note: All details shown here have been found at the manufacturer's websites: bmwusa.com, chevrolet.com, fiatusa.com, honda.com, toyota.com, teslamotors.com, nissanusa.com, ford.com, mitsu-motors.com, and smartusa.com. Volt, LEAF, Focus, i3, and iMiEV prices are after a federal $7,500 tax credit, Ford Fusion/CMAX are after $3,750 tax credit, and the Prius-PHEV reflects a $2,500 tax credit (for the first 200,000 such vehicles sold in the U.S. by each manufacturer). All range-extended PEVs evaluated here are gasoline fueled (in order to meet strict U.S. particulate matter emissions standards without the higher costs of Diesel emissions control systems which would further increase the price premium over conventional vehicles).

II. PEV Adoption

An area of considerable debate is the projected PEV adoption rate [Vyas et al. 2009, KEMA 2010]. For example, KEMA's 2010 aggressive forecast meets the goal of one million U.S. PEV sales by 2015, and its slow case hits the one-million-units target in 2019. The KEMA penetration curves are based on the Toyota Prius experience.

The PEV adoption rate could be less than the HEV adoption rate over the past 10 years (dominated by the Toyota Prius), due to additional complexities involving grid charging, higher purchase costs (though lower operation costs), less certain technologies (e.g., battery life), concern over safety (real or perceived), and more uncertainty regarding long-term maintenance costs and support. Conversely, the adoption rate could be far greater than that of the Prius HEV, given gas-price jumps, rising fuel economy requirements, climate change legislation, increasing number of models with unique attributes available from a progressively larger number of global auto manufacturers, and other factors.

Since range-extended PEVs operate very similar to conventional HEVs – even if never plugged into the grid – they are a natural successor to advanced HEVs. Additionally, the potential of driving "petroleum free" is alluring to some, and perhaps many. Avoiding the risks of oil supply disruptions and price spikes, and helping mitigate concerns over oil-related environmental, security, and economic concerns may outweigh the effort required for almost daily charging for many potential owners. Presently, PHEVs with the very highest levels performance (e.g. BMW i8) are expensive and not mass-market vehicles. Some may also prefer the convenience or safety of home refueling instead of regularly stopping at the gas station. Such factors may well lead to a U.S. PEV adoption rate that matches or exceeds that of the Prius HEV over the past decade. Concerns over the actual range achieved by drivers in different climates on different highway types, under different topographical conditions and speeds may also impact adoption.

Total U.S. year 2020 PEV market share projections similar to HEV sales – with approximately 2.5% market share [Vyas et al. 2009] – may be achieved if manufacturers avoid serious early technology safety and quality problems. Battery thermal management and durability are a clear risk, especially for the deep cycled and conductive-cooled battery packs that Nissan has incorporated into its aggressively priced LEAF. PEV sales may increase more rapidly if manufacturers expand their product offerings over the next decade to include a greater diversity of PEV platforms, such as minivans and sport utility vehicles, or performance PEVs – ideally all with targeted marketing to highlight the positive social externalities (and personal benefits) or attractive driving experience of PEV ownership.

When PEVs use their electric motors to save petroleum consumption costs, they obviously are consuming electricity. The average retail residential price for electricity is $0.1250 per kWh in the U.S. [EIA 2014]. The amount for the cost of the electrically driven miles traveled will vary by vehicle, driver, location, and season. To gain a rough estimate of the cost, the second generation Chevrolet Volt will nominally consume 31kWh to travel 100 miles with a resulting electricity cost of $0.03875 per mile [GM 2010c][GM, 2015]. Assuming a comparable conventional vehicle achieves 30 mpg, a gasoline price of $3.00 per gallon yields a cost of $0.10 per mile (or two and a half times higher than electrically driven miles).

Chapter 3: Charging Standards and Charging Locations

Different standards for charging PEVs have been coordinated by several organizations around the world. When defining the standards, organizations consider the safety, reliability, durability, rated power, and cost of the charging methods. The following charging standards, which are also shown in **Table 2**, are commonly accepted protocols in the U.S. and with roughly similar standards elsewhere globally.

The ingrained model of conventional vehicle refueling has been familiar for many generations. Drivers travel periodically to a centralized fueling location which may (or may not) be fairly close by their home or which is on the route to/from work or other regular trips. The actual energy transfer rate in terms

of Joules/minute is very high while the liquid fuel is dispensed into the vehicle, but the overall gasoline/diesel refueling time can typically take from 5-30 minutes depending upon such factors as the traffic to/from the gas station, the number of vehicles in line, the functionality of the pump credit card reader, the flow rate of the fuel, and the

Table 2: Charging Standards Description

	Voltage (V) to the PEV from EVSE	Phase	Maximum Current to the PEV (A)	U.S. Standard
Level 1	120Vac	Single	16A (AC)	SAE J1772
Level 2	240Vac	Single	80A (AC)	SAE J1772
DC Fast Charging (DCFC) (Sometimes called "Level-3", but the Technical Standards nomenclature is "DC-Level-2")	300 – 500Vdc	N/A (Note: The DCFC off-vehicle EVSE typically requires 480V 3-phase input)	200A (DC)	CHAdeMO SAE J1772 CCS, Tesla SuperCharger

functionality of the receipt printer. To summarize, with this traditional refueling model, one must make a special stop at a centralized refueling location with varied levels of convenience, but at least the refueling action itself typically does not take a considerable amount of time.

Recharging PEV batteries with electricity can be accomplished in a variety of rates and methods. In addition to the petroleum-like fast refueling model enabled by DC-Fast Charging (DCFC) and battery swapping, electric vehicles offer additional models of refueling for example at a location where the driver will naturally be parked or by deploying autonomous wireless charging. DCFC offers charging at very high rates from 50kW to 135kW. CHAdeMO and SAE CCS/Combo specify a maximum of 100kW and Tesla supports 120kW DCFC today with 135kW claimed in the future. While this recharging power rating is extremely large relative to typical residential home electrical loads (e.g. 3kW for an HVAC system or 6kW for a clothes dryer), it is considerably slower than the energy transfer rate possible with conventional liquid fuels. However, a 30-minute BEV refueling stop on an intercity trip every 3 hours is likely similar to the effective conventional gasoline refueling time when considering the need to stretch, purchase refreshments, or visit the restroom. High DCFC electricity energy transfer rates imply that only large power sources (e.g. 480V 3-phase service with over 120A per phase) similar to the ones available in commercial and industrial ("C&I") locations can be used. This huge electric service requirement precludes higher rate DCFC from virtually all homes in the U.S. (which typically have 240V 1-phase service). Fortunately, most vehicles are parked more than 22 hours per day with a long dwell time particularly at home overnight hence DCFC is neither needed (nor possible at the highest DCFC rates) at homes. DCFC could be deployed at homes but with much lower power levels, perhaps used to support two-way power flow (for example for V2H applications described in Chapters 7 and 8). The high power rating of DCFC also creates a larger financial hurdle for non-utility businesses to create a centralized electric vehicle charging station deploying multiple DCFC pumps similar to a traditional gasoline station.

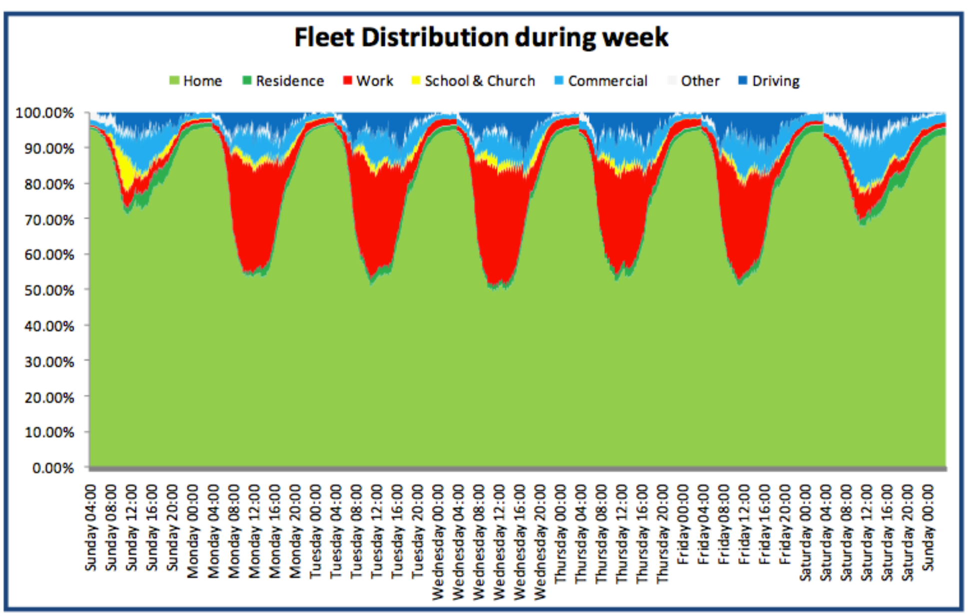
For commercial and industrial customers, particularly in cases with relatively low average-to-peak ratio loads, utilities can receive more revenue from "demand charges" (sometimes also referred to as "capacity charges") than they receive from per kWh energy charges. These demand charges are needed compensation for the fixed capital investment in distribution lines and transformers needed to provide adequate power at peak demand and extra potential costs. For example, in Texas, there is a demand charge based on a utility's "4CP" (four coincident peak) transmission cost allocation. Note that U.S. homes typically do not pay a demand charge. Homeowners pay only on the basis of the energy consumed that includes some allocation of some allocation of demand charges (perhaps plus some modest fixed cost allocation for meters and overhead). Compared to the relatively low fixed capital investment of low-power slower charging (particularly at home with inexpensive EVSE equipment and without any residential demand charge) more charging sessions per day are required to foster sufficiently high DCFC asset utilization to support an independently owned gas-station-like business model unsubsidized by governments, utilities, or vehicle manufacturers. The eventual return on investment could turn positive in the future as DCFC equipment costs decline, methods to reduce installation costs are learned, strategies to reduce/share/mitigate demand charges are created, and many more PEVs are on the road. It should be noted that anecdotal data suggests that conventional gas stations typically do not have compelling profitability on gasoline sales alone. Gas stations are said to only make sufficient profits by the sale of other convenience items (e.g. drinks, lottery tickets, fast food) [EIA 2001][NPR 2007].

The now defunct Better Place firm has demonstrated Battery swapping technology with pilots in Denmark and Israel as well as by Tesla on its Model S. A driver pulls into a battery swapping station, a robot underneath the vehicle orchestrates the actual swapping of the heavy battery pack, and the driver pulls away with a different fully charged pack. The inventory of battery packs at the battery swapping facility can be opportunistically charged during times of lower energy costs, can generate revenue by providing grid ancillary services, be shared to reduce peak energy costs, or can await service. Battery swapping can be useful to enable intercity travel or support for PEV owners who live in multifamily dwellings without nighttime parking capability. Challenges with the battery swapping model include the high fixed costs of the robotic swapping stations, inventory costs of the batteries, difficulty in achieving sufficient commonality of battery designs, and concerns over the quality of the swapped battery received by the PEV owner. It is unclear when a critical mass of vehicle manufacturers will cooperate sufficiently to create a common battery pack standard for plug-in passenger vehicles given the diverse set of requirements for varied vehicle types, the different technologies and suppliers the vehicle manufacturers may use, and the integral nature of the battery design to the vehicle. Boxy fleet vehicles perhaps have a better opportunity to foster standardized battery form factors. A PEV driver who leases their vehicle or who owns their vehicle but leases their PEV battery (a model more prevalent in Europe) may be less concerned about the quality of the swapped battery they receive.

The costs and characteristics of DCFC and battery swapping mean that they will remain niche applications in the near future. Overnight charging at a much more modest power level is sufficient for a very large number of U.S. drivers which have a typical daily driving need of less than 40 miles per day (**Figure 1**).

Figure 1: Personal Vehicle Miles Driven Daily

Approximately 16.7kWh of energy is needed per day to meet 80% of U.S. drivers' daily needs (assuming a 3miles/kWh consumption rate, which appears typical) [DOT 1990]. Virtually all U.S. homes are equipped with 240V/120V electrical service. Assuming a 200A/240V residential service and 80% maximum continuous load, approximately 38.4kW would be available of which only 1.44kW to 7.7kW of this power would be needed for PEV charging. Over the course of a day, this 200A 240V service could provide 921.6kWh of energy of which only 16.7kWh (1.8%) of this energy would be needed for vehicle charging. With a relatively low power 240V-16A circuit, the vehicle could be recharged for the next day's 50-mile drive in about 5 hours. Using the familiar 120V-12A wall outlet providing a modest 1.44kW power level (similar to a coffee maker), the vehicle could be fully charged in about 11.6 hours. Given the vehicle may typically be parked at home at night for long periods of time, over 12 to 14 hours, **(Figure 2)** this relatively slow recharging rate is still likely sufficient to provide a full charge by the next day's departure time while providing the convenience and low cost of home refueling. While the most precise comparison of electricity cost versus gasoline would be from two specific vehicles compared on a cost per mile, the $/gallon equivalent of electricity is roughly $1.20 per gallon assuming the $0.1250/kWh EIA U.S. average electricity price and a simplified analysis: $0.1250/kWh x kWh/3.23miles x 30miles/gallon=$1.16 using a 2016 Chevrolet Volt versus its twin Chevrolet Cruze for comparison [DOE 2014][Fueleconomy 2015]. Of course, this $/gallon equivalent depends on the specific regional, seasonal, and time of day (if applicable) energy costs per kWh.



Source of Data - 2001 National Household Travel Survey ; GM Data Analysis (Tate/Savagian) - SAE paper 2009-01-1311

Figure 2: Fleet Distribution During a Sample Week

Workplace charging is the next most popular location [Tate 2009] **(Figure 2)** typically provided by employers who will invest in the charging equipment to attract, motivate, and retain employees and/or to demonstrate their commitment to the environment as part of a corporate sustainability program. Some employers provide workplace charging as a free "de-minimus" non-taxable benefit, others simply try to recover costs so that they, at least, are not losing money on the energy itself. If employers do not decide to provide free charging to their employees, care must be taken to ensure they do not violate laws by reselling electricity in some electricity markets that have utilities with strict service area boundaries. To recover the costs, employers can make arrangements such as charging a fixed fee per day for the parking spot. Workplace charging typically is 3.3kW to 7.7kW (at a nominal 240V) ac using an outdoor capable permanently installed Level-2 EVSE or by providing conventional 120V wall outlets for 1.44kW charging using a BYOC (bring your own cord) ac Level-1 configuration.

Public charging is typically deployed at 3.3kW to 7.7kW ac using a ruggedized permanently installed Level-2 EVSE on a wall or post. Public charging infrastructure at these charge rates typically does not have an attractive enough return on investment to support a business model selling the energy itself considering the fixed capital cost investment and operating & maintenance (O&M) costs given the relatively low cost of electricity. If there is low asset utilization of the EVSE and if full fixed cost amortization plus energy costs are to be recovered, the charging session price could conceivably be above the equivalent price of gasoline. Presently, public charging tends to be installed by stores who wish to attract PEV drivers to shop at their locations, governments who wish to nurture alternative fuels, utilities encouraging electric vehicle adoption to foster future load growth, or electric vehicle charging networks (such as the eVgo network, http://www.evgonetwork.com) which offer public charging locations as a service combined with home charging services. Stores would consider the EVSE and energy costs provided for their customers as a marketing expense with the benefit of keeping their customers shopping longer in their stores. Stores have confidential metrics of the value of additional amounts of shopping time to their incremental revenue. The longer customers stay to charge their vehicle, the more likely they are to spend increasing amounts of money at the store.

In the U.S. a large percentage of the vehicle fleet could be charged using night time charging, with 122M households, 65% homeownership rate, and 1.92 vehicles per home ~ well over half the U.S. vehicle fleet can charge at home [Census 2012, DOE 2009]. Multifamily homes do create more charging issues. Charging at night at multifamily homes is more challenging given the driver may not own the residence and hence may not be allowed to install an EVSE, not be given permission to charge from a common-area outlet nor have a traditional garage or carport to plug into. Many communities are incorporating requirements for electric vehicle charging in their building codes for new construction and streamlining their permitting process to lower the costs for existing building owners to retrofit charging stations. Also a number of utilities provide financial incentives for existing building owners to install EVSEs.

In the future, two technologies may combine to provide a new solution for multifamily residents. Autonomous (i.e. self-driving) vehicle technology has progressed enormously with the advancement of computing speed/density, software algorithms, and lower cost radar or camera sensor technology. Wireless charging using magnetic resonant technologies is already offered by a number of firms. However, common interoperability compatibility standards have yet to be solidified. In the future condo/townhome/apartment dwellers could be dropped off at their door after work with the vehicle driving itself to a centralized wireless electric vehicle charging location. At that location, the PEV could negotiate a reservation, wait for an open charging spot, precisely park above the wireless coil, and then vacate the spot once charging is completed freeing the location for the next PEV. In the morning, the autonomous wireless charging PEV could greet its owner at their front door via a smartphone command.

Reviewing the specific technical charging standards, the SAE International J1772 Conductive Charge Coupler standard is likely to continue to be pervasively used in North American and other countries such as Japan for charging from 0.8kW to 19.2kW. Unlike the inconvenience and costs associated with the prior generation of two incompatible inductive and conductive chargers, the vehicle manufactures appear to broadly support the SAE J1772 conductive charge coupler **(Figure 3)** as the standard for U.S. market vehicles. SAE J1772 presently has two basic charging voltages: single phase AC Level-1 (120 Volt) and AC Level-2 (240 Volt) up to a peak power transfer rate of 19.2kW [SAE 2012]. This common standard fosters lower charging infrastructure costs, as well as improved availability and convenience of public and home charging stations.

Figure 3: Existing SAE J1772 AC Level-1/AC Level-2 Coupler [SAE 2012]

It is likely that the IEC 62196 (International Electrotechnical Commission) standard will be selected for non-North American markets such as Europe. Although the signaling is very similar between the SAE and IEC standards, the IEC standard will likely use the Menekes coupler that has 2 additional power pins to support 1-phase or 3-phase current to the vehicle. Many countries in the western hemisphere and Japan typically favor IEC standards over others. With the SAE J1772 standard, AC current is provided to the on-board charger of a PEV and is converted to DC current for charging the vehicle's high voltage traction batteries (typically over 300V). SAE J1772 defines "AC Level-1 charging" as a single phase 120 Vac with 16A continuous current (80% of maximum current rating) and "AC Level-2 charging" as a single phase 240 Vac with 80A maximum continuous current. The maximum continuous current rating is limited by a combination of the grid wall outlet/circuit rating and the PEV-EVSE coupler rating. The higher voltage 240V Level-2 charging enables proportionally faster charge rate capabilities. When AC Level-2 charging is used instead of AC Level-1 charging, charging time may be reduced by up to ten times [Scientific American 2010] – i.e., 8 hours of charging time may be reduced to 48 minutes (**Table 3**).

Table 3: Power Required for Various Charging Rates

48KWH NET BATTERY CHARGE
(FOR ONE CHARGING STATION, HOLDING ONE HOUR OF CHARGE)

Power Level [kW]	Charging Time [Hrs.]
1	48
2	24
4	12
6	8
24	2
48	1
96	0.5

The charging time can be radically reduced when 100 kW+ of power is used to charge the battery of a PEV. Moreover, it is desirable to use an off-vehicle EVSE/fast-charger (Electric Vehicle Supply Equipment) for DC Fast Charging. An off-board EVSE/fast-charger reduces vehicle cost and weight, increases safety, and reduces cooling and packaging problems. The power is delivered by dc current; in other words, power is directly transferred from the charging station directly to the high voltage vehicle traction battery without an on-board vehicle rectifier. Note that the off-vehicle EVSE/fast-charger will need to support the various DC voltage levels of different vehicles, and PEVs will still likely have an on-board rectifier/charger to support AC level-1 and AC level-2 charging.

Of course, charging time may be again reduced when the charging voltage and current are increased further. However, as the power transfer increases, the PEV charger must also be increased in capacity. This increase in the charger's capacity, size, cost, and weight may be the limiting factors for the charging rate. Technical efforts by organizations such as SAE, IEC, CHAdeMO, and Tesla have defined various DCFC charging methods to avoid these limitations and increase the charging rate substantially. CHAdeMO is an association established by Nissan, Mitsubishi Motors, Fuji Heavy Industries, Tokyo Electric Power Company (TEPCO), and Toyota which defined DC Fast Charging (DCFC) as 500 Vdc maximum voltage with 200 Amp maximum current [ChaDEmo 2013] which may provide electrical power up to 100 kW. The SAE International J1772 CCS/Combo DCFC specification has similar capabilities but while still providing compatibility with the universally standard J1772 AC Level-1/Level-2 coupler mentioned previously. Tesla has a proprietary DCFC standard defined and productized which supports 120kW today with a stated future capacity of 135kW. In addition, Tesla has recently announced some of its SuperCharger Stations will be outfitted with liquid cooled charging cords to reduce the bulkiness of the cable. It is expected that liquid cooling will also further increase the maximum charge rate but data on any charge rate improvement has not been made available publicly. Tesla vehicles are equipped with a SAE J1772 Level-1/Level-2 adapter so that they can be charged from any SAE AC EVSE. There is also a CHAdeMO to Tesla adapter so that their vehicles can DC fast charge from CHAdeMO DCFC as well as the Tesla proprietary SuperCharger DCFC network.

PART II: DIFFUSION OF PEV TECHNOLOGY

Chapter 4: Technological, Market, and Policy Drivers of Emerging Trends in the Diffusion of Plug-in Electric Vehicles in the U.S.[4]

Abstract

While there are a number of motivations to encourage alternatives, no alternative fuel has meaningfully displaced petroleum for powering transportation in the U.S. to date given price, refueling infrastructure, and other impediments. While an old concept, it has only been over the past decade that key technologies advanced sufficiently to enable the development of viable electric vehicles. Given the many barriers to entry and high capital requirements, the automotive industry in the U.S. has been consolidating with few new entrants for a number of decades. The vehicles that demonstrated the potential of electric drive using these new technologies were from a new firm, entirely dedicated to building electric vehicles. These pioneering modern electric vehicles importantly stimulated competitive responses of a small number of incumbent global manufacturers. Today, the key technology costs, particularly from batteries, typically still lead to a purchase price premium for a plug-in electric vehicle compared to an equivalent mainstream conventional vehicle. This chapter 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 over the next decade.

[4] Tuttle, D., Baldick, R., Technological, Market and Policy Drivers of Emerging Trends in the Diffusion of Plug-in Electric Vehicles in the U.S.. Electr. J. (2015), The co-author provided insights and supervision, http://dx.doi.org/ 10.1016/j.tej.2015.07.008,

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 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 that the rate observed of HEVs from year 2000 [Chamberlain, 2014]. But, to gain perspective there are about 231M 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.

Some of the more interesting PEV-related discussions are included in each of this chapter's sections. Section 2 discusses the status of PEV offerings in the market today. Section 3 describes the factors affecting adoption. Key technology trends that affect adoption are included in Section 4. Section 5 explores the advanced vehicle capabilities that PEVs can provide and finally, Section 6 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. The on-board computers then seamlessly switch to 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, 2012] simply by charging at home from a common 120V 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, 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 other states that have adopted the California emissions or ZEV regulations. [Voelcker, 2015][Havorson, 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.

Presently, the average transaction price of a new car sold in the U.S. is $33,560 [PRNewswire, 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 $2500-$7500 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 tern 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.

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, 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].

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.

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 4**. 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.

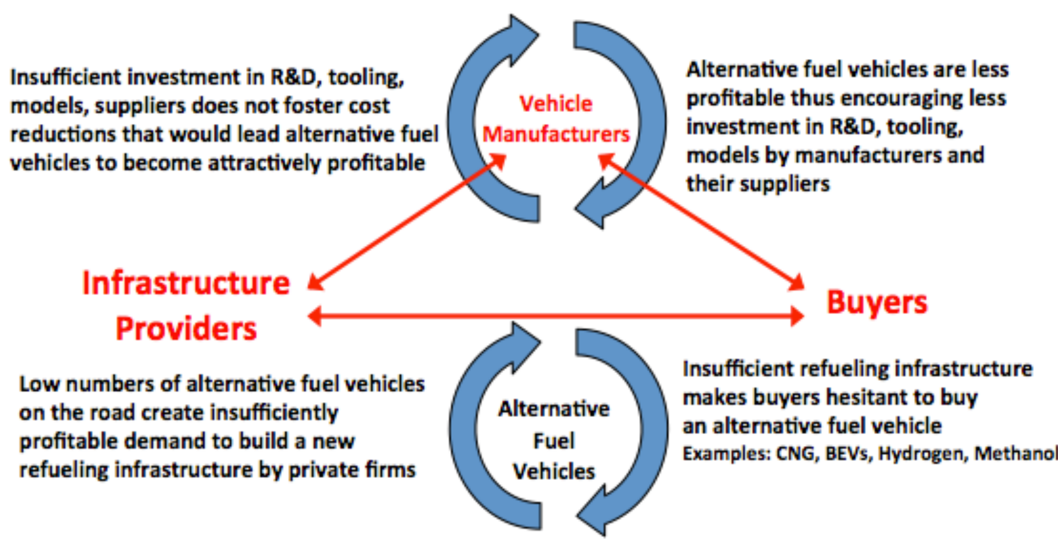


Figure 4: Historical Alternative Fuel Vehicle Adoption Dynamics

The second chicken-and-egg cycle is related to the state of auto manufacturers themselves and is summarized in **Figure 5**. Modern PEVs are still in the early stage of development with only a modest 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.

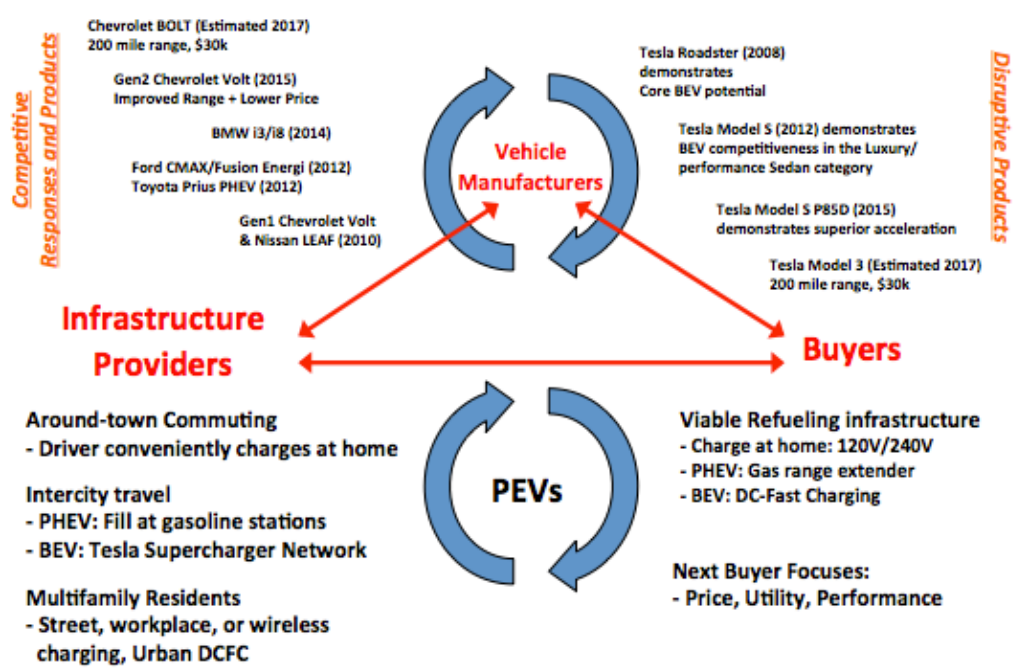


Figure 5: Recent PEV Adoption Dynamics

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 and P90D. 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.

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% 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 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 4**).

Table 4: 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 & 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 & Driving dynamics	
Refueling time, location, convenience	
Leading Edge Technology	
Resale value	
Sales & Service experience	

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 in the U.S. 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 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.

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 significantly 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 6** shows the PEV charging hierarchy [ANL, 2012].

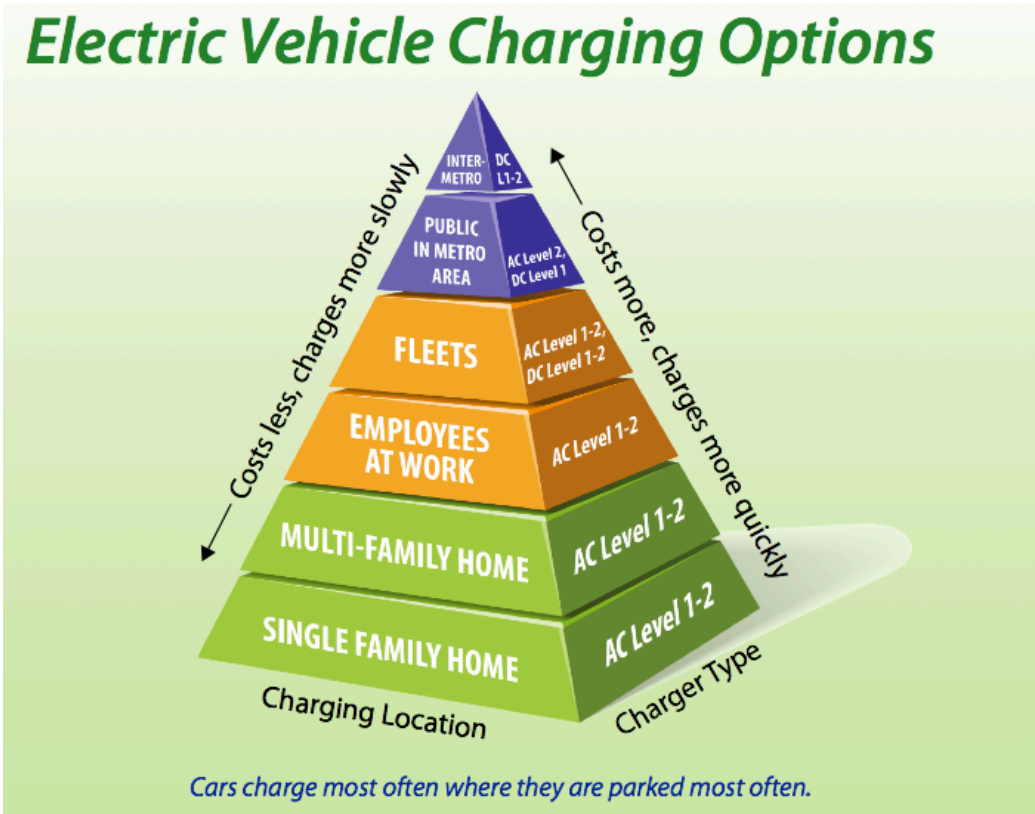


Figure 6: PEV Charging Hierarchy
Source: ANL 2012

Electricity typically provides the lowest cost and most convenient means to re-fuel at home of any transportation fuel. About 40% of US households exhibit the lifestyles amenable to today's PEV [NAS, 2015] leading to an estimate of about 80M 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 120V 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 120V Level-1 AC charge cord included with their vehicle or they can upgrade their home to have a faster permanently installed 240V 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 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, battery swapping is probably more viable for local commercial delivery vehicles and DCFC is likely to be the most popular option to support long distance BEV travel for a number of years.

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% state-of-charge (SOC) in less than 30 minutes. 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-minute 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, 2015]. Tesla has offered to make their 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 (120kW presently, up to135kW 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 and Sales Channels

Given the lack of understanding by the general public of the types of electric vehicles, the education of vehicle 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 taking 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, 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 7**). In 2010 the price of batteries was estimated to be about $1000/kWh. Today, some manufacturers are likely buying batteries at $300/kWh [Nykvist, 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 53 mile electric range with a similarly sized but lighter weight battery pack [GM, 2015].

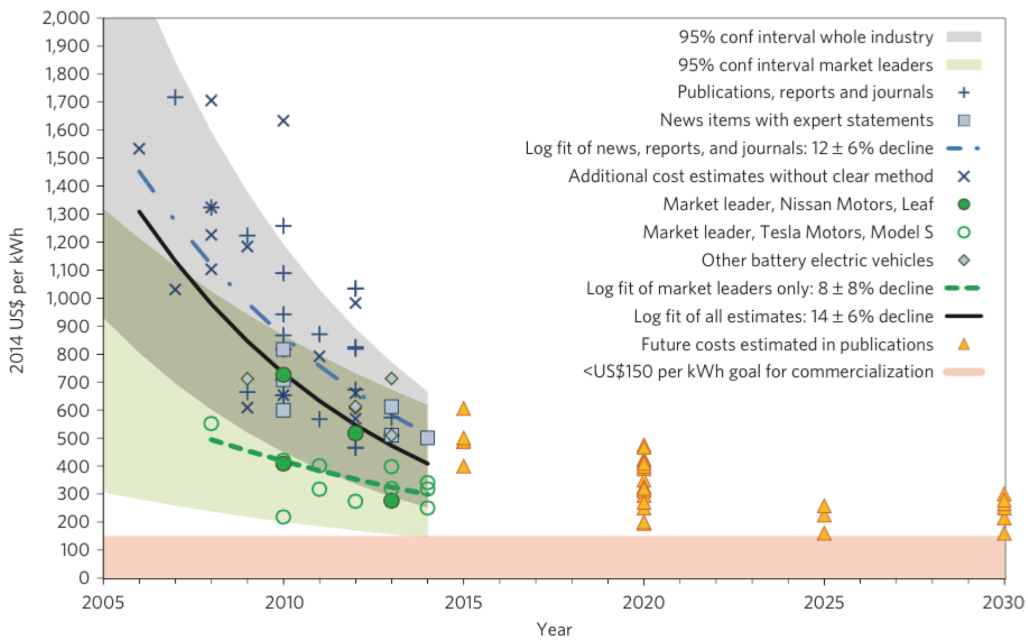


Figure 7: Lithium Battery Price Improvements
[Source: Nykvist & Nilsson 2015, Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change]

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. 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-$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 $3000 to $5000 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 8**). Battery costs have been improving at an average of 7 to 14% yearly [Nykvist, 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.

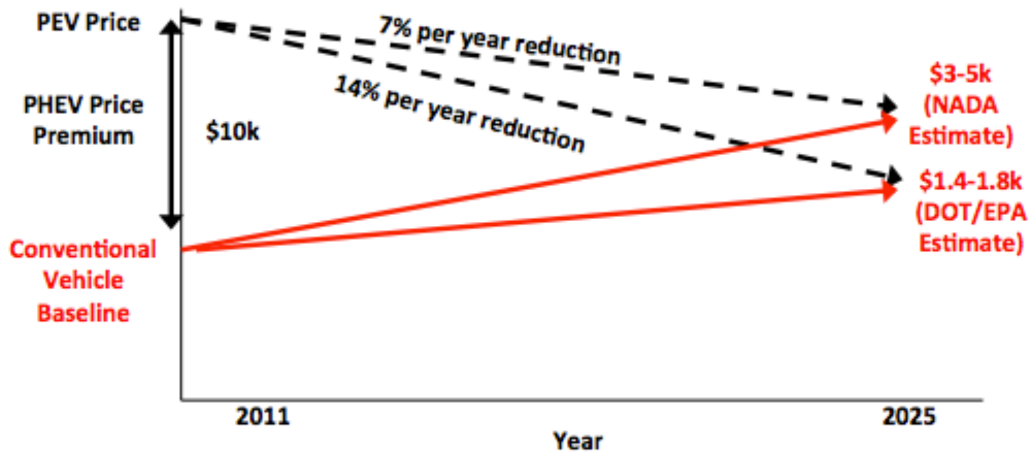


Figure 8: PEV and Conventional Vehicle Price Trends
Plug-In Vehicle battery/power electronics costs are declining while conventional vehicle costs are increasing from more strict emissions and fuel efficiency requirements.

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.

B. 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, 2013]. The home and PEV together are isolated to create a microgrid. In Vehicle-to-Grid (V2G) 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, 1997]. There are varied estimates for the revenue opportunities for PEV owners for providing these grid services [Quinn, 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 approximately 84% of the U.S. light duty vehicle fleet could be charged with existing grid resources [Kintner-Meyer, 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].

C. 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.

V. CONCLUSION

Pervasively available energy from the electricity grid, 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.

PART III: GRID-VEHICLE AND OFF-GRID INTERACTIONS

Chapter 5: The Evolution of Plug-in Electric Vehicle-Grid Interactions[5]

I. INTRODUCTION

PEV-grid interactions comprise a mix of industries that have not interacted closely in the past. A number of these commercial participants have utilized the same basic business model for nearly a century. The various participants include vehicle manufacturers, utilities, and supplier firms who have radically different business models, regulatory and legal environments, geographical scope, and technical capabilities. From an analysis of these factors this chapter synthesizes and provides a likely scenario for PEV-Grid interaction over the next decade.

As described in Chapter 1, BEVs and PHEVs have substantially different range capabilities. As with conventional vehicles, PEVs models need to have a compelling combination of attributes to be commercially successful. The critical attributes typically include functional capabilities, range, styling, performance, cost, driving dynamics, reliability, brand image, fuel consumption, low environmental impact, dealer reputation and convenience. The relative priority order of these attributes is very much particular to an individual driver. The highest priority for vehicle manufacturers is likely making safe and reliable PEVs, driving down the cost premium of a PEV, and achieving profitability rather than advanced Grid-PEV interactions. Nevertheless, this chapter will forecast the likely evolution of PEV-grid interactions.

Given the thousands of different utilities in the U.S., with varied level of technical sophistication and resources to invest in PEV-Grid communications and charging

[5] Tuttle, D, and Baldick, R., "The Evolution of Plug-In Electric Vehicle-Grid Interactions", IEEE Transactions on Smart Grid, Vol 3, No 1, March 2012, The co-author provided insights and supervision.

coordination and the many vehicle manufacturers, it will take a meaningful amount of time to have common, low-cost communications and demand response (DR) standards to support the progression of more sophisticated PEV-grid interactions.

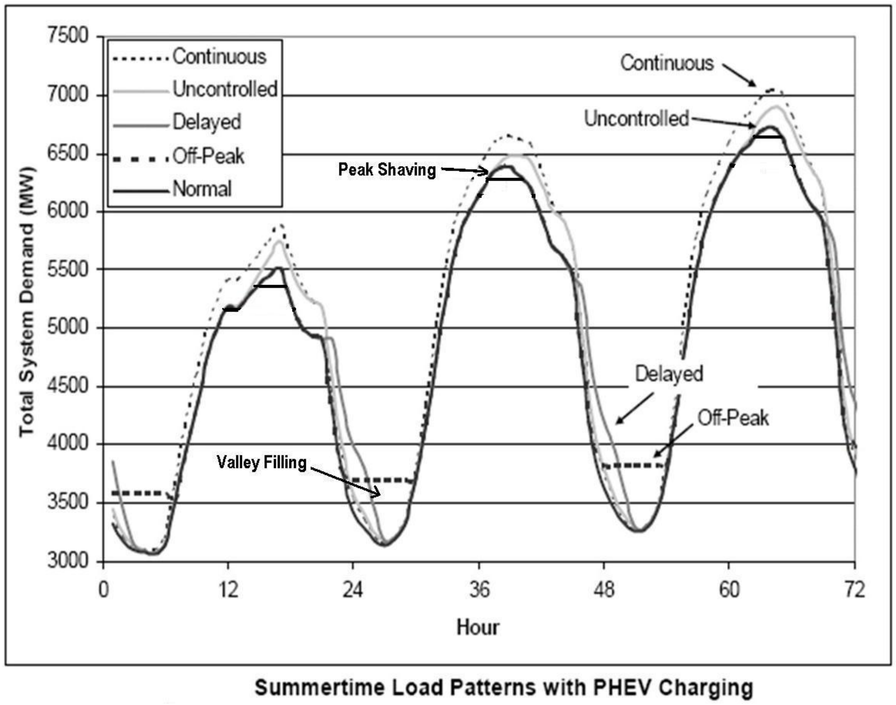
Electric grid participants consist of generators, transmission and distribution firms, retailers, and, in the near future, aggregators, which are defined here to be a type of retailer that communicates to and controls a sufficiently large number of demand-side resources such as PEVs to effectively create a single controllable resource for the grid operator. All participants are typically motivated by increased vehicle-specific energy sales. Most of these participants also prefer avoiding the aggravation of critical peak demand.

II. Impact on the Electrical Grid

Various studies have determined that even with considerable adoption of PEVs in the vehicle fleet, the deployment of off-peak charging can drastically limit the impact on the grid. However, DCFC stations that have multiple 100kW+ charging cords can create distribution issues if not properly provisioned to avoid voltage/current droops or spikes. Some utilities have a concern about local distribution transformers, which typically provide 240V service to 4-10 homes, if there is "PEV clustering." As electric vehicle sales increase over time, multiple homes served by a single grid distribution transformer that must solely support the charging of a cluster of new PEVs may force distribution firms to divert a portion of their incremental revenues to selectively upgrade these transformers.

To encourage PEV adoption to create this demand, grid participants will be focused on safe, convenient, and cost effective access to charging stations. In order to avoid aggravating peak demand, grid participants will likely encourage grid friendly charge windows **(Figure 9**) through simple peak/off-peak pricing programs combined with manual driver inputs to the PEV on-board computer, the offer of subsidized installation of home electric vehicle supply equipment, (EVSE, commonly called a charging station) in return for demand response control, or rudimentary signaling of CO_2 and/or prices to the PEV to vary charge rate over various communication pathways.

Many regions have substantial spare off-peak capacity in their transformers, particularly if the homes also have rooftop PV and are in locations with heavy air-conditioning load (which is lessened at night). PEV clustering in moderate climate regions with large amounts of community heating and low air conditioning loads may also drive distribution upgrades (e.g. some parts of Europe), encourage slow residential vehicle charging rates (<2kW), foster greater numbers of DCFC or battery swapping stations, or wireless charging methods. In the U.S. the grid has been upgraded repeatedly over the last century after the first installation of lighting, next from later additions of new home appliance loads, then air conditioning, then modern electronics loads. Similarly, future upgrades needed for PEV clusters is not expected to be a widespread problem nor a significant technical challenge in regions with high peak to average ratio loads and/or with upgraded distribution systems. In certain areas with substantial PEV adoption in the future, utilities may need to divert a portion of their incremental revenue from electric vehicle charging to selectively upgrade feeders that are subject to PEV clustering.



Source: NREL TP-640-41410: Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory

Figure 9: Typical Daily Variation in Grid Load

III. Four generations: Method and rationale

A wide variety of sources from research universities, national labs, standards-setting bodies, and the automotive and utility industries are drawn on to assess the likely progression of technologies, critical priorities and constraints, and business/regulatory environment to identify and articulate a likely scenario of PEV-Grid interactions over the course of the next decade. Since the scope of key participants is so broad, subjected to substantially different operating paradigms for many decades, and the technology so new this scenario provides a useful framework for focusing resources to the most potentially relevant areas of research as well placing "a stake in ground" to foster further debate on the likely progression.

IV. RESULTS AND DISCUSSION

A. First Generation

First generation PEVs are available today. The first-generation PEVs will establish "green" technology leadership and build brand equity for their manufacturers, help the vehicle manufacturer meet increasingly strict government fuel economy or emissions standards across many regions, drive R&D/manufacturing/supplier base learning, and provide test beds to better understand the durability of batteries and other key components. Volumes are expected to be modest, but meaningful. These PEVs will likely sell at low or negative profit levels depending upon sales volumes, financial accounting for the basic technology R&D amortization, sales price, tax incentives, and battery warranty costs. The first generation of PEV manufacturing will mainly demonstrate market leadership, while attempting to maintain the extremely high levels of reliability, safety, and convenience that conventional vehicles provide today. Meeting these expectations could be a challenge given PEV technology is new and unproven in large-scale customer deployments, which tend to surface problems not easily found despite manufacturers' rigorous validation tests.

The global vehicle manufacturers likely perceive enough safety and durability risks with these first generation vehicles that they will avoid including two-way powerflow capability for the near term. The vast majority of PEVs will likely include only Grid-to-Vehicle (G2V) power flow and the driver will have on-board vehicle programmability to manually set the charge window. Modest integrated communication capabilities will be included, which will enable diagnostics and status from the vehicle, such as charge control to set "grid-friendly" charging windows, and control of passenger cabin pre-heating or pre-cooling.

Range extended eREVs and PHEVs typically have smaller (but still considerable) batteries that can charge overnight through a standard AC Level-1 120V wall outlet. BEVs will more typically need a more expensive AC Level-2 240V high-speed charger that may have an installed cost between $1000 and $3000 [EV-Project 2014]. Regional efforts to create a large supply of qualified electrical contractors, a streamlined permitting and inspection process, or Level-2 charger rebates contingent upon off-peak charging will be useful in substantially driving down the cost of these permanently installed high-speed Level-2 chargers in residences. While a meaningful additional initial cost, these SAE J1772 Level-2 chargers can be used with vehicles from all manufacturers and will effectively upgrade a home to have its own permanently installed "personal refueling station" for electric vehicles.

B. Second Generation

Second generation PEVs will be developed with far greater amounts of field and lab experience enabling improvements particularly in cost. Enhancements in battery control and efficiency will improve range or maintain range at decreased costs. Hence, second generation PEVs are likely to have a more attractive financial payback and be somewhat less dependent upon tax incentives. As PEV powertrain components gain scale production economies and become less expensive (or if oil supplies are disrupted or gasoline/Diesel prices increase substantially) relative total cost of ownership improvements will drive further waves of adoption.

Grid to Vehicle (G2V) SAE J1772 AC Level-1 (120 Volt) and AC Level-2 (240 Volt) charging capability will remain but likely be improved with more substantial communication capability such as power line communications (PLC) between the Electric Vehicle Supply Equipment (EVSE) and PEV, ZigBee™ wireless communications between the smartmeter and EVSE/PEV, vehicle integrated wireless capability typically over digital cell phone networks, or 802.11 WiFi ™ wireless communications between the PEV and a home energy management system (HEMS). These enhanced communications will enable more sophisticated Grid-PEV interactions and more intelligent charging with CO_2/energy-price signaling or perhaps limited regulation-up/regulation-down grid ancillary services, which may generate revenue for the PEV owner. Ancillary services can be supported by intelligent PEV G2V charging by setting the baseline charge rate at half of the maximum and then increasing or decreasing the charge rate (**Figure 10**) [Sortomme, 2011].

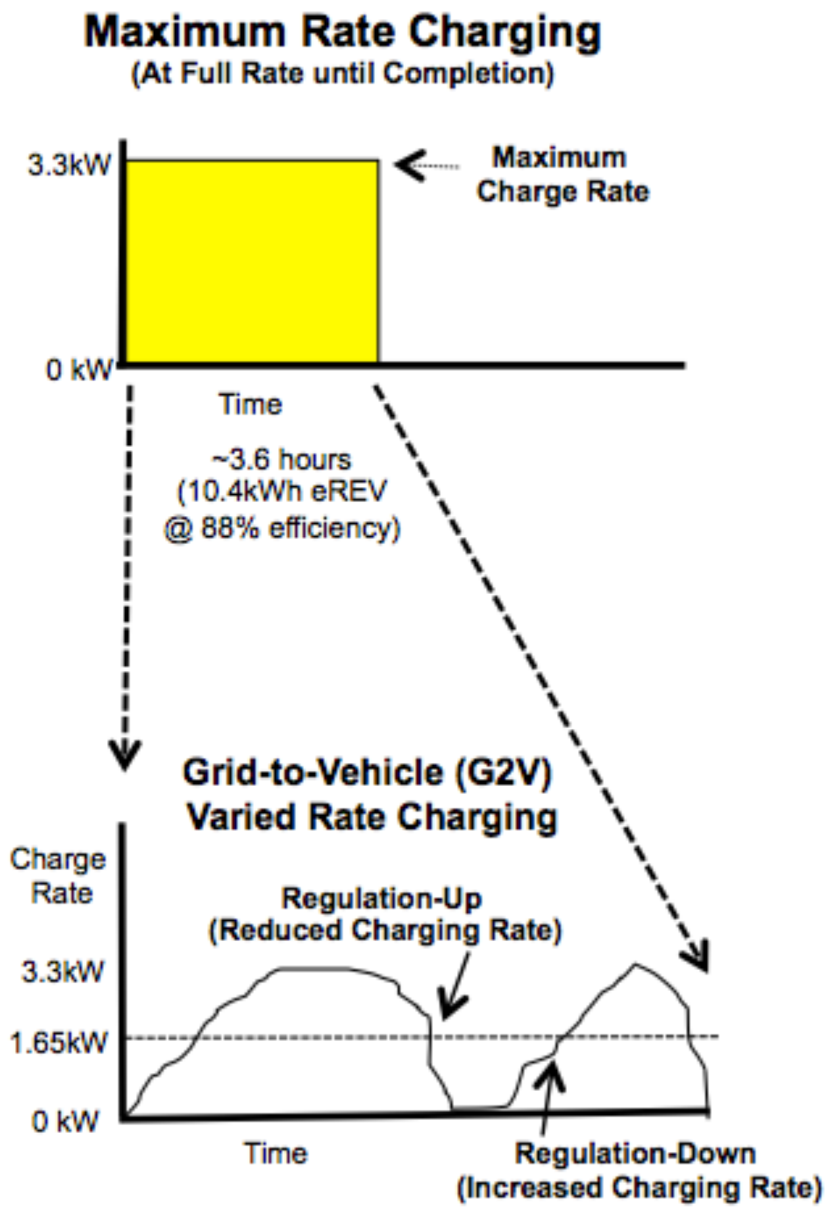


Figure 10: G2V Varied-Rate Charging Support of Ancillary Services

Regulation-up would be accomplished by reducing the charge rate. Conversely, regulation-down would be accomplished by increasing the charge rate. Algorithms to implement G2V AS would take into account such parameters as the initial battery state of charge, the maximum charge rate, and the vehicle departure time target when the battery is expected to be fully charged.

Importantly, additional communications and control capabilities will likely enable more sophisticated charging control which can increase the effective yield and lower costs of incorporating wind, solar, or other intermittent renewable generation sources by creating a flexible load resource which can varied to reduce the variation in wind, load, or NETLOAD (load minus wind). To best support grid stability, these PEV-based load resources may be most beneficially deployed as ancillary services such as emergency load resources or fast ramping responsive reserves to dampen wind, load, or NETLOAD variations. The availability of these more sophisticated communications and control are one of the defining characteristics of the second generation. These extra capabilities create the potential for PEVs to provide the most flexible, large scale, and effective demand response capability ever developed for the grid. It is likely to take more than 3 to 4 years to have PEV-based grid-advised charging or demand response to be deployed in significant amounts. At the very least, it will take this amount of time to begin to have meaningful numbers of PEVs on the road.

Additional standards efforts (such as SAE International J2847) are underway to enable more sophisticated communications between the PEV, the home area network, home energy management system (HEMS), and the meters/utility. Also, AC Level-2 charging speed may be improved further by increasing the typical current capability to 32A or up to the maximum 80A limit where supported by the premise electrical infrastructure. For example, an increase of maximum Level-2 charge rate from 3.3kW to 6.6kW would reduce the time required for a full 10kWh eREV charge to about 2 hours.

By the second-generation timeframe, the relative advantages of the various PEV architectures will become increasingly clear to customers, the technology will have advanced further, and costs/performance will likely have been improved. Vehicle manufacturers may have enough knowledge about technologies and PEV consumer behaviors and preferences to offer an increased diversity of vehicle platforms using the same basic electric powertrain components or derivatives. For example, given the strong torque capabilities of electric motors, a larger selection of differentiated performance PEVs will likely be announced. Performance cars traditionally have a higher sales price and provide larger profit margins for vehicle manufacturers. These greater margins can more profitably recover the additional costs of the electric powertrain and batteries by providing the customer with "guilt-free performance" (the Tesla Model S is a case in point). Increased number of PEV types and performance, lower costs, more familiarity with PEVs may then increase PEV adoption rates.

C. Third Generation

Third generation PEVs may be substantially defined as vehicles with two-way powerflow capabilities to an isolated load. To meet cost, safety, and efficiency goals this two-way powerflow capability may be combined with the inclusion of a DCFC interface to the vehicle (beyond the AC Level-2 interface ubiquitous today) supporting a higher maximum powerflow of approximately 50kW to 100kW (135kW and higher for Tesla). While reverse power flow is possible in principle through an ac Level-2 (or even Level-1) interface and on-board charger circuitry augmented with an inverter, it is not supported with currently hardware available. In addition, there is likely a better combination of cost and weight to support reverse power flow directly through a DCFC port to the high voltage traction battery using an off-vehicle EVSE. The inclusion of a DCFC port is of modest cost and weight compared to substantially upsizing the on-board 3.3kW to 7kW Level-1/2 charger/inverter.

The first reverse powerflow configuration may be Vehicle to Load (V2L) [Scholar 2012b]**.** V2L capability will enable the PEV to act as a construction-site generator to an isolated load. An example of this configuration would be a PEV pickup truck that would include an on-board charger, converter, and pickup-bed mounted power outlets.

The PEV could act as a home backup generator in a vehicle-to-home (V2H) configuration. V2H capabilities are explored more in depth in **Chapters 7 and 8**. Multiple PEVs acting in concert with a local coordinator could support a larger isolated building/mobile command center/Military mobile hospital in a Vehicle-to-Premise (V2P) configuration. In V2P, there is no coordination with the grid system operator, but instead there is local communication and control of the PEVs as an independent cluster of generation resources not tied to a larger electricity grid.

Given there is little or no coordination needed with the grid, it is possible that some vehicle manufacturers may introduce third generation V2L, V2H, or V2P capability much more quickly than fourth generation PEVs (to be discussed in the next section and that requires not only two-way powerflow but also sophisticated grid coordination). This timeframe for third generation PEVs could still be more than 5 years. By that timeframe, major vehicle and battery manufacturers will have gained considerable field experience with battery durability, battery costs will have declined substantially, PHEV pickup trucks may be introduced in addition to the common small four-door sedan PEV, or projected profitability for this niche vehicle feature becomes financially attractive. Note that V2H capability is a microgrid concept different than Vehicle to Grid (V2G), where the vehicle provides two-way power flow from/to a functioning electric power grid for peak shaving or grid ancillary services [Kempton 2005].

Basic Vehicle-to-Grid (V2G-net-metered or V2G-NM) interactions could leverage the PEV as a distributed storage node to capture locally generated energy from photovoltaic panels or store low-cost off-peak energy for later release back to the grid at higher peak rates through "net-metering". Net-metering capability enables a home's electric meter to effectively run backward to credit the customer's account when their local generation (such as rooftop solar panels) produce more energy than their home demands. The excess energy is fed back into the grid. Unlike residential photovoltaic panels that may provide excess power back to the grid simply based upon total sunlight available and the local load, the increased communication and control of PEV can provide greater coordination and optimization of reverse power flow to the grid.

Additional configurations of two-way power flow to the grid with both G2V charging combined with Vehicle-to-Home/Vehicle-to-Premise/Vehicle-to-Grid capability will likely require an off-vehicle EVSE /power outlet/transfer switch designed to meet the required premise building electricity codes (such as "islanding" when the grid power is off) and perhaps an industry standard high-capacity V2P interface if large amounts of energy flow are required.

To recover their incremental R&D, manufacturing, and warranty costs the vehicle manufacturers will likely charge an additional premium for a two-way powerflow capable interface and an off-board charger/power outlet/transfer switch box.

D. Fourth Generation

Compared to third generation PEVs, fourth generation vehicles have such attributes as assured/secure two-way grid-vehicle communication and control, additional software, and grid aggregators that enable full integration of two-way powerflow (V2G) between the vehicle and the grid. Since they can provide reverse powerflow to the grid, fourth generation PEVs may be enabled to be a more capable source of grid ancillary services than second generation G2V-based AS systems. This additional capability can generate increased revenue (or reduce energy costs) for the owner compared to previous generations. PEVs may act as a distributed storage node with their large battery storing less-expensive off-peak energy from the grid or locally generated renewable energy from rooftop solar panels, providing power for the premise, or releasing excess energy back to the grid during higher priced peak demand [Kempton 2005, Brooks 2002]. Estimates for the revenue potential for the PEV owner from ancillary services vary. A large portion of the variation in estimates appears to be from varied market price assumptions for ancillary services in the different regions, and differences in assumptions on the costs of aggregation and vehicle availability to the aggregators. V2G capability and aggregators would be required to support the most capable PEV-based ancillary services such as regulation up, regulation down, emergency load curtailment, and spinning reserves for the grid independent system operator [KEMA 2010, Quinn 2009]. All of these functions can technically be provided with two-way power flow combined with communications and control. As discussed earlier, somewhat more limited, but still useful G2V based ancillary services can be provided with 1-way powerflow (varied charging of the vehicle) combined with communications and aggregators. The limitations to using the PEV for advanced V2G will likely be related to the challenge of implementing assured and secure communications particularly between the aggregator and the large number of PEVs, the amount of the potential income, the additional wear on the PEV battery, and the degree of inconvenience to the driver. Given these challenges, meaningful adoption of reverse powerflow V2G is likely to take more than 8 to 10 years (approximately two vehicle generations).

The use of PEV range extending engines to generate energy (and create compensating revenues for the PEV owner) which is then fed back to the grid to reduce grid peak demand has questionable likelihood of achieving mass adoption given the complexities of control, and unattractive economics and emissions compared to traditional very large scale grid generation.

Another concept is to use coordinated PEVs as a grid feeder backup. The need for assured communication and the complexity of coordination make the use of PEVs for feeder backup extremely challenging. Orchestration of this concept would require coordinated isolation of the feeder through grid protection and isolation devices such as relays, breakers, and fuses. The concept would likely require a large number of sophisticated coordination activities related to frequency, voltage, reactive power, cold start, feeder configurations, and shutdown.

Significant investment and interest in advanced V2G PEV-Grid interactions will likely require policy action or regional specific circumstances that create sufficient financial incentives.

Using PEVs as synergistic grid storage will be more compelling to utilities when new sources of fast ramp/zero-CO_2 generation, spinning reserves or regulation ancillary services are needed to enable greater deployment of intermittent renewable generation. This increased thrust for greater renewable generation and hence sophisticated PEV storage control may be most strongly accelerated by increasing renewable portfolio credits, renewable fuel credits, production tax credits, carbon taxes, or other policy actions.

Total PEV fleet size is likely to not be a meaningful fraction of the total number of vehicles (approximately 240 million) on U.S. highways for a number of years. To assess the likely timeframe when a total of 1 million PEVs would be on U.S. highways, KEMA [KEMA 2010] assumed that the PEV adoption curve for the next ten years would be similar to the Toyota Prius adoption rate of the past ten years. Assuming the "target" adoption rate stated in the KEMA study with 1M PEVs on U.S. highways by 2017 and nearly 2M by the end of 2020, PEV sales should be approximately 2% of new vehicle sales by 2020, nearly equivalent to the 2.5% Hybrid new vehicle market share today in the U.S. Assuming 13 million vehicles sold per year, an estimated 300,000 PEVs would be sold yearly in 2020. A further projected breakdown of these 2M PEVs into BEVs, eREVs, and PHEVs is highly speculative given that the eventual mix may likely be dependent upon many factors. Those factors include the popularity of a particularly styled PEV, brand preference and reputation, one brand and/or type of PEV having better or worse battery durability experiences, technical breakthroughs, oil prices, and battery cost and gasoline range extender cost declines over the course of 9 years.

V. SUMMARY

The first generation of Mass-market viable PEVs are now available but still in their infancy. PEV-grid capabilities will be defined not only by the rate of technology development but will likely also be guided, accelerated, or limited by the regionally unique financial incentives, regulatory structure and requirements, and values of each participant. It is possible that incremental or breakthrough technology progress may accelerate the progression, but other factors such as communications standards, long vehicle development cycles, and the required grid-side communications and control infrastructure may be constraining factors which may keep the progression of PEV-grid interactions in the same approximate order.

Vehicle manufacturers are fundamentally driven to create PEVs with compelling design, image, and features that will create profitable vehicle sales. Safety and durability are, of course, also critical and fundamental objectives. The additional software cost to enable "grid friendly" charge window programming is negligible and hence expected to be incorporated into all PEVs. More advanced grid-advised or renewable generation coincident charging can be enabled by relatively simple broadcast of emission or price related information to PEVs. Algorithms programmed into the PEV on-board computer can then deduce the optimal charging profile. With more advanced communications and grid aggregators, the sale of ancillary services such as regulation up/regulation down could produce revenue for the PEV owner by regulating G2V charging of the vehicle.

Enabling basic two-way power flow for V2L, V2H, or V2P adds extra hardware costs, adds risk of stress and failure to PEV components and battery, and increases product liability exposure. An extra cost V2L contractor site generator or V2H/V2P backup generator option that avoids the need for sophisticated external communication and coordination could be profitable for vehicle manufacturers. PEVs enabling V2L, V2H, V2P, or basic V2G-Net-Metering capability can likely be profitably offered as an extra cost option once sufficient field experience has been gained to understand and address key technology failure mechanisms. Given there are few dependencies upon advanced external communications and control or industry standards development, this option holds promise of commercialization as soon as vehicle manufactures can profitably engineer a sufficiently robust hardware and software solution.

V2G with limited communication could be useful and financially attractive in regions with substantial time-of-use price differentials or premise solar or wind generation that is net-metered back to the grid. Over the next ten years, introduction of the most advanced V2G capability which supports the sale of the most rich set of ancillary services is expected to be limited by the availability of assured PEV-Grid communications, two-way power flow capability, and control on the PEV. The varied communication and control pathways, reliability requirements, other performance parameters, and financial payback are complex and all areas worthy of further research. Vehicle manufacturers may also be hesitant to offer this capability for a number of years until the wear mechanisms and risks are well known and they understand how to profitably offer this feature.

Grid participants are typically motivated by increased vehicle-specific energy sales while also avoiding the aggravation of critical peak demand. To encourage PEV adoption to create this demand, grid participants will be focused on safe, convenient, and cost effective access to charging stations. Also, in order to avoid aggravating peak demand, grid participants may offer lower cost off-peak tariff programs or subsidize EVSE installations in return for demand response control. Installation of intelligent EVSEs with demand response may then provide the capability to beneficially align PEV charging with intermittent renewable generation output.

Regionally specific circumstances may create compellingly high prices for ancillary services or other special PEV-Grid interactions. Otherwise, the most advanced V2G PEV-Grid interactions may require policy actions to foster the needed investments by the relevant participants. An increased policy thrust for deployment of greater amounts of intermittent renewable generation on the grid may provide the needed financial incentives to create the communication and control systems to use PEVs as synergistic grid storage, fast ramping reserves, or for regulation ancillary services

This chapter is an attempt to articulate the most important factors that affect PEV adoption, characteristics, capabilities, and interactions with the grid over the next decade. While there will be differences in the types of PEVs, the evolution of their interactions with the grid is likely to be fairly similar given the required development and investment in grid-side communications and control functions to enable each successive generation of PEVs, and because of the common battery durability knowledge that will be gained from an increasing number of PEVs on the road, and a greater number of years of expertise accumulated. A likely, or at least possible, progression of PEV-grid interactions is synthesized and summarized in **Table 5**. While the timeframes for the introduction of each generation are likely to be different for various regions, a combination of limiting and interdependent factors may prove the progression to be a durable framework across multiple regions. In particular, various G2V configurations will be developed well before the advent of V2G and this chapter articulates a progression of beneficial PEV-grid interactions.

Table 5: Progression of PEV-Grid Interactions

PEV Generation	**Power Flow**	**Communications Characteristics**	**PEV-Grid Interaction Characteristics**
First Generation	Grid-to-Vehicle (G2V)	Over cell phone network (if any)	G2V with manual driver programmed "grid friendly" charge window
Second Generation	Grid-to-Vehicle (G2V)	Real-time broadcast of CO_2 and price information to PEVs Grid-to-PEV communications via aggregator	G2V with advanced intelligent charging aligned with renewable generation G2V with limited regulation up/down & load curtailment ancillary services
Third Generation	Grid-to-Vehicle (G2V) plus Vehicle-to-Load (V2L) Grid-to-Vehicle (G2V) plus Vehicle-to-Home (V2H) Grid-to-Vehicle (G2V) plus Vehicle-to-Premise (V2P) Grid-to-Vehicle (G2V) plus Vehicle-to-Grid-Net Metered (V2G-NM)	EVSE-PEV communication only (no external communications) EVSE-PEV communication only (no external communications) EVSE(s)-PEV(s) communication only (no external communications) EVSE-PEV communication only (no external communications)	V2L for construction site generator V2H for home backup generator (isolated through premise transfer switch) V2P as building backup generator (isolated through transfer switch and coordinated by a local aggregator) V2G-Net-Metered: Local generation (such as rooftop photovoltaics) with reverse power flow of excess energy and net-metering.
Fourth Generation	Grid-to-Vehicle (G2V) plus Advanced Vehicle-to-Grid (V2G-Advanced)	Assured secure two-way Grid-PEV communication	V2G-Advanced: Grid Ancillary Services provided by two-way power flow of PEV battery energy and/or local generation (such as rooftop photovoltaics)

Chapter 6: The Electric Vehicle Utility 2.0[6]

I. INTRODUCTION

How can utilities help accelerate the adoption of plug-in electric vehicles and why should drivers consider buying or leasing an electric vehicle? In Austin, the equivalent price of electricity powering a plug-in electric vehicle (PEV) is approximately $1 per gallon significantly below gasoline prices of $2.00 to $3.50 per gallon. There are many other benefits for the adoption of PEVs including:

- reduced emissions,
- decreased U.S. trade deficit,
- reduced dependence on unstable regions with the greatest oil reserves,
- fewer petro-dollars potentially funding activities counter to national interests,
- improved energy security, and
- fuel price stability.

PEVs also provide many direct advantages for the driver over a conventional gasoline or diesel vehicle, including:

- lower operating costs,
- improved noise-vibration-harshness characteristics within the vehicle,
- convenience of home refueling,
- reduced maintenance, and
- improved performance.

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[6] Dave Tuttle and Ross Baldick, City of Austin Rethink Austin Whitepaper, http://www.austintexas.gov/sites/default/files/files/Sustainability/Rethink_-_SAA/Electric_Vehicle_Untility_White_Paper_-_FINAL_8-20-15.pdf. The co-author provided insights and supervision

The concept of electric vehicles is well over a century old, but only in the past decade have technological advancements in batteries, power electronics, computer controls, and powertrain architecture enabled the first wave of mass-market viable and luxury/performance PEVs. PEVs represent new unique loads (and potential energy storage) for the electric grid: they are large, flexible, and intelligent. Given these characteristics, electric vehicles not only provide real benefits to the U.S. as a whole and to the individual driver, but they can also synergistically interact with the grid. By deploying Smartgrid technology, intelligent electric vehicle charging has the potential to increase grid stability, improve electrical grid fixed asset utilization, and provide the ability for utilities to incorporate more renewable generation on the grid.

In addition to promoting PEVs and educating their customers on the benefits of electric drive, utilities are uniquely positioned to increase PEV adoption and unlock many of the advantages of electric vehicles by focusing on areas related to 1) charging infrastructure installation and costs, 2) intelligent charging capabilities and re-charging costs, and 3) autonomous charging infrastructure and convenience.

II. INTELLIGENT, FAST, AND MORE PERVASIVE CHARGING INFRASTRUCTURE

One of the advantages with PEVs is the ability to charge/refuel at home. Home charging is the dominant charging location today and is expected to remain so in the future. As an example, PEV charging flexibility can be leveraged since a vehicle may need only 4 hours to fully charge but be plugged in for over 12 hours at home (say, 7pm to 7am). The vehicle could be charged at a pace slower than its maximum rate, thus taking advantage of nighttime wind production, while further reducing the demand on the distribution grid. As long as the process is automated and still charges the vehicle by the departure time, such managed charging does not create an inconvenience to the driver.

Home charging stations are now being introduced that allow utilities and their customers to work together to enable smart charging while still ensuring the electric vehicle is charged when needed. The core communications and computing technologies needed to implement intelligent charging are known and mature. The home charging station can be equipped with WiFi communications and a relatively modest embedded computer. The WiFi equipped charging station could coordinate with the utility through the Internet just as a NEST thermostat does today.

An interesting example would be to align PEV charging with the availability of wind energy from West Texas that tends to peak at night. Utilities could also include vehicle charging in their Demand Response (DR) programs to reduce stress on the grid and minimize CO2 emissions just as their thermostat, water heater, or pool pump DR programs can today. For example, Austin Energy conducted one of the first demand response pilot programs in the U.S. that successfully integrated electric vehicle charging into a uniform platform with thermostat vendors to curtail charging during peak demand periods. With residential solar panel electricity production growing rapidly, intelligent PEV charging is being considered as a means to increase grid stability when there is excess solar power or a rapid change in solar panel output.

Utilities are generally enthusiastic about the ability to grow revenue by selling more electricity for PEV charging and at the same time advancing grid reliability. These benefits are leading many utilities to offer rebates for charging station installation to encourage PEV adoption in their service area. The ability to temporarily throttle down PEV charging is of great economic value to a utility when wholesale electricity prices spike or when the grid is stressed. To not strand a driver, a PEV owner should be able to manually override the utility signal and enable full charging of their vehicle so they can still drive to their desired destination.

Given the large number of single-family homes in the U.S., some estimate that over 80 million of the 231 million vehicles in the U.S. could be charged at home. However, residential charging is more of a challenge for those drivers who rent an apartment, live in a multi-family complex, or who must park on the street. To address this challenge, some regions are implementing building code changes that will eventually require landlords or condo associations to accommodate electric vehicle charging.

Some utilities are also creating programs that encourage landlords to install PEV charging. Austin Energy has been working with pioneering apartment complexes to install their first chargers. Light post charging using cords with embedded wireless smartmeters is another useful concept that utilities could implement to support PEV drivers who park on the street.

Some utilities, including Austin Energy, have implemented workplace-charging programs that reduce the costs and complexity for firms to install PEV charging equipment for their employees. These programs can help companies achieve their environmental sustainability goals as well as attract and retain employees.

As battery prices decline over the next few years, more 200+ mile range Battery Electric Vehicles (BEVs) will be introduced. Utility installation of the highest capacity urban Direct Current Fast Charger (DCFC) would be useful for BEV taxis, BEV car sharing, street-parkers, or multifamily residents. The general rule of thumb is that DCFC can provide an 80% charge in less than 30 minutes. While charging takes longer than gasoline refueling, a driver does not need to stay with their vehicle while it charges. It would be attractive to co-locate these DCFC stations in innovative ways with grocery stores, retail shopping, coffee shops, bakeries, movie theaters, or taxi stands so that the drivers can take care of other errands while their vehicle charges.

While individual utilities may already have payment methods that are convenient and low cost for drivers from their own service area, the cost of charging an electric vehicle outside a driver's home utility service can be far greater than the equivalent cost of gasoline and less transparent than the prices posted on a gas station pump. Eventually, a nationwide charging infrastructure should be created with transparent prices that are more comparable to home charging (or at least not punitively high), and with convenient payment methods similar to self-service gas stations.

III. INNOVATIVE PRICING PROGRAMS TO GUIDE INTELLIGENT CHARGING

Intelligent charging must have signals to automatically reduce or vary the charge rate. Time-of-use (TOU) rates are published electricity tariffs that vary by the time of day. The simplest form of TOU rates can be structured to have peak and off-peak rates. Peak rates in Austin occur during the heat of the day. Off-peak rates offer lower retail prices when the grid is less stressed in the night. However, classically structured TOU rates may provide little ability to dynamically signal grid stress. In addition, some homeowners may not select TOU rates for electric vehicle charging if this forces their entire home to adopt a TOU rate structure. Today, some utilities are already providing a second meter specifically to offer special "TOU-EV" (Time of Use-Electric Vehicle) rates separate from the rate for the rest of the house.

Utilities can provide more dynamic signals that can be transmitted at specific times of grid stress or high wholesale prices. Given the flexibility of PEV charging to potentially increase or decrease charging, it is possible to create new signals from the utility that could be called “CO2-EV” rates if they are based upon emissions or “RTP-EV” (real time prices) rates if they are based upon real time wholesale prices. Acceptable implementations may need to include price caps or a baseline rate with a varied rebate mechanism.

IV. Deploying advanced infrastructure & autonomous PEVs

Wireless PEV charging eliminates the charge cord by deploying matching inductive coils: one on the underside of the PEV and the other on or under the ground. Autonomous or self-driving vehicle capabilities have been under development for a number of years. Google self-driving cars have been testing their autonomous driving capabilities for number of years in California and now are also observed driving on Austin streets. While initially raising some concerns about computer driven cars, new generations of radar and cameras, laser sensors, and more powerful computers and algorithms have demonstrated considerable capabilities today. In 10 to 15 years manufacturers may offer wireless autonomous PEVs that allow street parkers or multifamily PEV owners to have their car automatically drop them off at their front door, negotiate a wireless charging reservation, drive to a temporary parking spot until a wireless charging spot is open, vacate that spot after charged, and then pick up their owner in the morning with a full charge. The electric vehicle utility of the future could create automated wireless parking lots that create a far more convenient parking and refueling experience than a conventional vehicle.

IV. CONCLUSION

The combination of commonly available affordable energy from the electricity grid, advances in Lithium batteries, semiconductor based power electronics, and embedded computing have created viable PEVs. To date, the basic electric powertrain technology is proven and the PEVs on the road have demonstrated that they are safe, reliable, and satisfying to drivers. While adoption at a large scale may take a number of years, there are many actions that utilities can take to increase adoption rates and support the increasing number of electric vehicles locally.

First, utilities can create a more convenient vehicle ownership experience compared to a conventional gasoline/Diesel vehicle, lower costs of charging stations and fuel for drivers, and use intelligent charging to improve grid stability, emissions, and economics. Far-sighted utilities will develop intelligent, fast, and more pervasive charging infrastructure. Secondly, utilities can create innovative emissions or cost-variant signals to guide intelligent charging and leverage flexible PEV charging. Finally, to unlock the advantages of PEVs, utilities and planners should invest in innovative urban PEV infrastructure designs to support wireless autonomous charging.

Chapter 7: Plug-In Vehicle to Home (V2H) Duration and Power Output Capability for Residential Electricity Backup[7] (Early Research)

I. Introduction

As discussed in Chapter 5, Vehicle to Home (V2H) capability describes a scenario in which a plug-in electric vehicle (PEV) not only receives charge from the grid to power the vehicle, but also provides backup power to an islanded load such as a home during an outage, similar to a stand-alone emergency generator [Bertold, 2011, Tuttle, 2012a]. Because of the value that V2H can provide during sustained grid outages, interest in BEV V2H has increased greatly in Japan after the Fukushima disaster [Nissan 2013]. In other scenarios, a V2H capable vehicle may provide seamless backup power for more frequent, but typically shorter duration, distribution system faults.

V2H systems with rooftop photovoltaic (PV) generation combined with electric vehicles have been explored to improve the utilization of PV generated electricity [Yoshimi 2011]. With today's conventional operational standards, a typical home with residential PV generation must shut down if the grid power is lost [IEEE 2005]. The requirement for a PV system to shutdown is to ensure that the PV system does not backfeed to the grid creating safety problems for linemen repairing the distribution system and to avoid microgrid stability problems given the lack of storage or a stiff grid to effectively regulate voltage, reactive power, and current surges. However, solar PV systems combined with local storage can remain operational even during an outage.

[7] Tuttle,D.P, Robert L. Fares, Ross Baldick, Michael E. Webber, 2013, *Plug-In Vehicle to Home (V2H) Duration and Power Output Capability*, IEEE iTEC-2013 Conference Proceedings, The co-authors provided substantial contribution, insights, and/or supervision.

Thus, a V2H capable vehicle connected to a PV equipped home could enable fully off-grid operation or the vehicle to power a home or other isolated load as a convenient, safe, and powerful backup generator.

As discussed in Chapters 1 and 2, PEVs are offered with and without an internal combustion gasoline/diesel engine range-extender. A PEV without an internal combustion engine (a BEV) relies entirely on its battery to provide energy for its traction motor; therefore its on-board battery tends to be much larger than a PHEV/eREV. A PHEV/eREV has a gasoline engine/generator incorporated and inherently has the ability to generate considerable power from its on-board gasoline engine/motor-generator powertrain.

One advantage of PHEV/eREV systems (in contrast with traditional generators) is that to achieve their typical 350+-mile range, these vehicles have a sufficiently large gasoline tank that could fuel the engine-generator for a meaningful period of time. Unlike a conventional stand-alone backup generator which may require an owner to inconveniently store gasoline containers for long periods of time, dispose of stored gasoline that has become stale during storage, or carry heavy hand-carted gasoline containers repeatedly from the gasoline station to the generator, a homeowner with a V2H capable PEV could simply unplug with a few gallons of gasoline remaining in the PHEV fuel tank, drive to a remote gas station, conveniently refill the vehicle gasoline tank, and then return to the stricken location to again power the home.

Additional advantages of a PHEV over a conventional backup generator include more efficient operation of the engine-generator given the large battery storage to buffer transient load conditions, and a lower emissions and higher efficiency engine given advanced automotive technology such as fuel injection and catalytic converters required to meet emissions or fuel economy requirements compared to, typically less efficient, carbureted backup generators that are not required to meet the same standards. Residential backup generators also can be susceptible to clogged fuel systems from infrequent use. PHEVs may also exhibit quieter operation compared to a standard backup generator.

In this chapter we simulate a PEV used for backup power during an outage. We use residential energy data collected from a smart grid test bed in Austin, Texas to conduct the following analyses: 1) quantify the duration (in hours) of backup power that could be achieved with BEV or PHEV based V2H system and for a representative load, 2) determine how the time of an outage may affect the duration, 3) model the energy conversion efficiency of the PHEV generator, 4) identify more optimal engine-generator control for PV enabled V2H with a PHEV, and 5) identify strategies to further increase backup duration and non-continuous self-sustaining off-grid alternatives.

In Section II, we introduce the smart grid test bed from which the residential energy data utilized in this report originates. Section III describes the PEV system model and the derivation of the PHEV gasoline generator energy conversion efficiency. Section IV briefly describes the interfaces with the vehicle to enable V2H capabilities. Section V discusses the results of backup duration simulations from the numerous PHEV and BEV configurations considered, as well as insights learned from this study. The final section includes the conclusions.

II. Representative Load and PV Data

To estimate the instantaneous load on a PEV used in a V2H application, we use data collected by Pecan Street Inc. [Pecan Street 2014] of Austin, Texas as part of their ongoing smart grid demonstration study. The overall Pecan Street study utilizes a test bed of more than 250 modern, green-built homes constructed after 2007, and 160 other homes ranging from 10-92 years in age [Rhodes 2013]. The homes are instrumented with various forms of energy metering equipment, which tracks electricity, natural gas, and water use. Of the homes in the study, more than 185 have rooftop PV panels. The power production from rooftop PV is metered separately from electric demand. These Mueller Community Pecan Street homes (**Figure 11**) homes were selected given their one-minute resolution data availability for the entire year and installation of rooftop PV (which can be effectively turned-off in simulation to provide insights for scenarios with and without PV).

Figure 11: Mueller Community SmartGrid Test Bed

A small number of data dropouts were found (<1.5%) in the data. Because the majority of these dropouts appeared at common times across multiple homes, they were most likely caused by routine firmware updates carried out by the electricity monitoring equipment. Missing data points were patched with the prior day's data from the same home and time. Given typically low loads and no PV generation at these dropout times, patches from the prior day were assumed to be sufficiently representative of the originally lost data. The homes considered in this report have PV systems ranging from 4 kW to 6.9 kW in rated capacity. The homes range in size from 1200 ft^2 to 2700 ft^2. We use PV production and electric demand data from these homes as the input to a PEV model, which is described in Section III.

III. SYSTEM AND VEHICLE MODELS

A. System Model

Models to simulate V2H performance in response to an unplanned outage were constructed for both BEV and PHEV configurations using MATLAB. The model components consisted of the vehicle battery providing energy to the home load in conjunction with any PV energy provided and an engine-generator for a PHEV. **Figure 12** shows the diagram for the V2H system model.

For the purposes of this report, we utilize PV production and whole house electric demand data collected on a one-minute time interval from 20 homes over the year 2012.

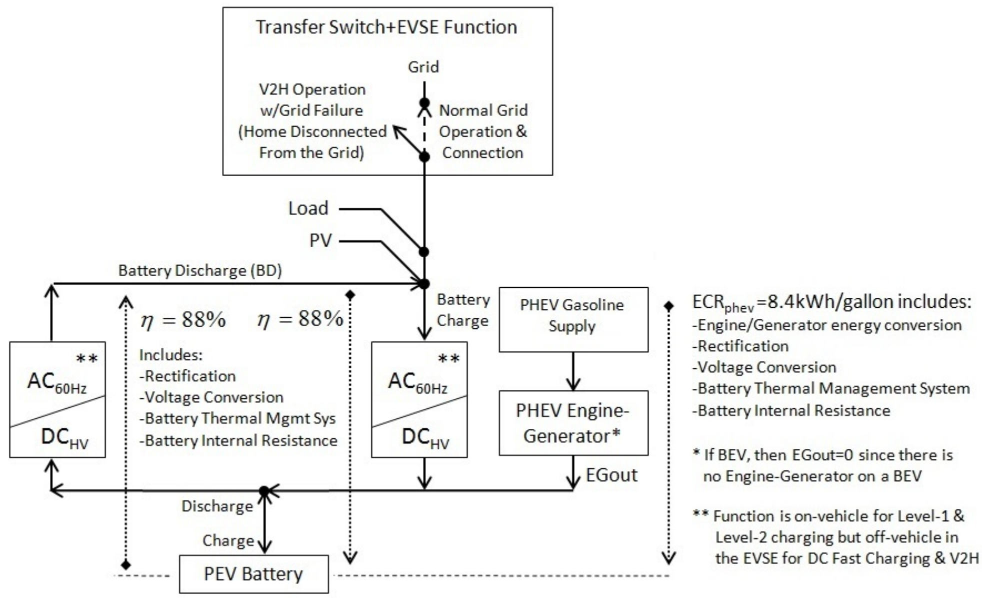

Figure 12: V2H System Model

Note: For the BEV model, the generator output is forced to zero. BEV battery sizes are 19.2kWh and 32kWh; PHEV battery sizes are 3kWh and 10.5kWh.

If the PV output was greater than home load demands, the battery was assumed to be charged until it reached full state-of-charge (SOC). In this analysis, the home is assumed to have lost grid power and at that time began using its electric vehicle based V2H system. Simulations were run to assess the impact of 24 different starting hours during a day. Given the relatively large battery size of BEVs and the large amount of energy stored in gasoline per gallon for PHEVs, the outage start time did not meaningfully affect the overall backup duration given a large PEV battery (and/or gasoline store) served only a single home. This finding contrasts to community energy storage configurations where a single 25kWh battery is shared by multiple homes analyzed in [Fares 2013] where the start time significantly affected backup duration. With this insight, the outage start time was assumed to be midnight on the first day of each month to simplify the analysis. Any excess PV energy that could not be stored in its fully charged PEV battery was assumed to be "spilled" and lost. In the BEV model, PV energy is consumed first to power the home load (with any excess charging the battery). If there is insufficient PV output to power the load, then the battery is used until its stored energy is exhausted.

For the PHEV model, PV energy is consumed first, then battery energy is used to power the home, and then finally the engine-generator is deployed to power the load and recharge the battery until the gasoline supply is exhausted. The backup duration was calculated as the time duration when the battery was terminally exhausted and could no longer support the home's load.

Using specifications of battery size, usable battery SOC window [GM 2010a], and measurements of input energy from the grid the overall charging efficiencies (η) were calculated during varied temperature conditions **(Figures 13,14)** for a Chevrolet Volt PHEV according to equation (1).

$$\text{Battery Size} \bullet \text{SOC Window} \bullet 1/(\text{Input Grid Energy}) = \eta \quad (1)$$

With:
Battery Size = 16kWh [GM 2010a]
SOC Window = 65% [GM 2010a]
Input Grid Energy = 11.2kWh (temperate weather)
Input Grid Energy = 11.8kWh (hot weather)

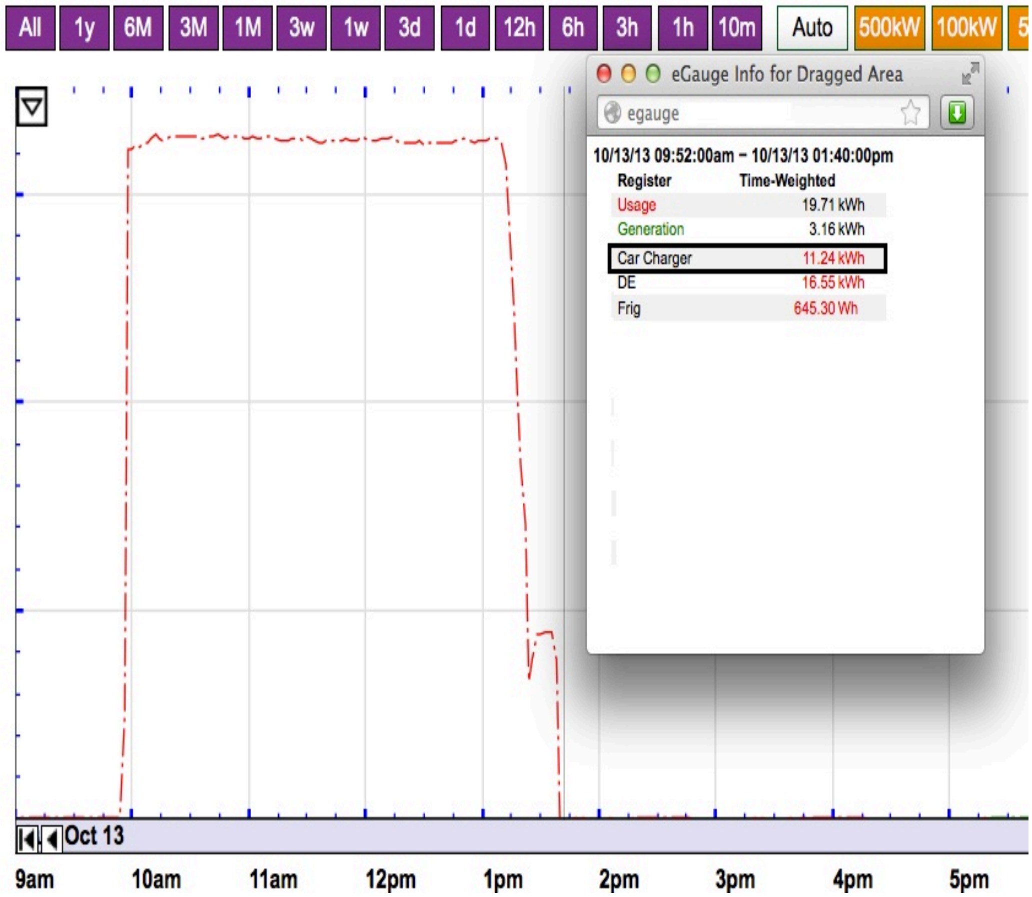

Figure 13: Energy Required for Full Charge during Moderate Temperatures

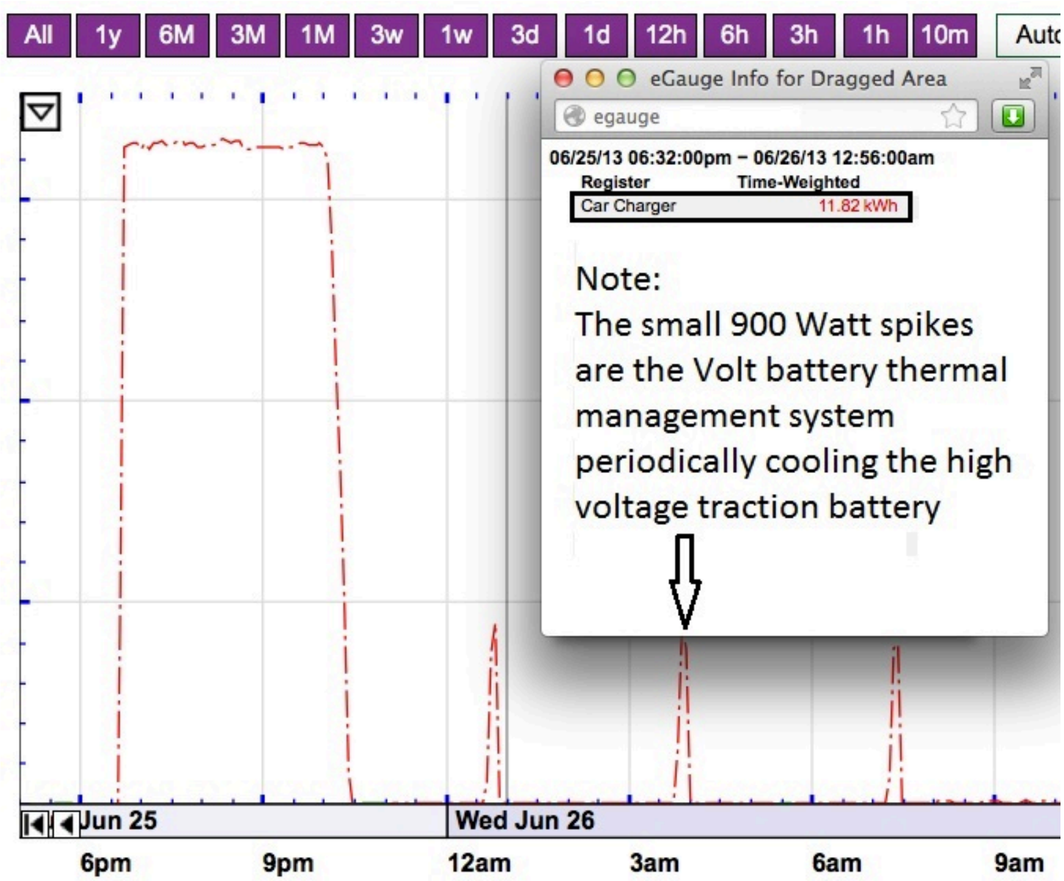

Figure 14: Energy Required for Full Charge during Hot Ambient Temperatures

Input energy was measured using an eGauge energy monitoring system measuring the dedicated 240V circuit for an AC Level-2 charger for a Chevrolet Volt[8]. This 1-way conversion efficiency includes rectification, step-up to the traction battery voltage of over 370V DC, battery internal resistance, and energy for the battery thermal management system. This measurement and calculation was useful as an estimate for the V2H off-grid configuration which would also deploy similar (but off-vehicle) stages of

[8] One of the Chevrolet Volts is the personal car of the author. The second Volt was owned by a colleague of the author.

circuitry, utilize the same battery thermal management system, and exhibit the same battery internal resistance.

A conservative 88% conversion efficiency is assumed from measurement of charging during hot weather (with regional weather station data indicating 92 to 96 degrees Fahrenheit during the charging period) on the Volt. During more moderate temperatures (weather station data indicating 67 to 71 degrees) the efficiency is observed to reach a calculated 93%. The 5% efficiency loss appears to be consumed by the battery thermal management system to cool the battery during hot weather. Given this efficiency parameter is set conservatively in the model, the backup duration times could be somewhat longer in moderate temperature conditions. The same 88% efficiency factor is used for both BEV and PHEV models since the battery technology, battery thermal management, and power electronics are assumed to be similar. The 1-way charging and 1-way discharging efficiencies are assumed to be equal yielding a round trip efficiency of 77% (88% x 88%).

B. Energy Conversion Efficiency of PHEV Generator

An advanced automotive diagnostic tool (the Autoenginuity Enhanced Interface for GM Family EI02 (**Figure 15)** which can read the battery state of charge in real time through the OBDII diagnostic port, (**Figure 16**) allowed estimation of the gasoline to electricity kWh output energy conversion ratio. Two Chevrolet Volts (2011 and 2013 models) were used for data observation and acquisition. The data indicated on the 2011 Volt that the net SOC window was typically from a low level of 19% to a high level of 85%, consistent with prior GM public statements of a 65% net SOC window. The Volts were driven until the battery was depleted confirmed by the range extending engine generator turning on. The vehicle was immediately parked with all accessory loads turned off and placed into "Mountain Mode" [GM 2010b]. Mountain Mode is a special setting which forces the engine generator to charge the battery well above the typical operating threshold to enable the vehicle to maintain speed while climbing a very long grade. Measurements were made of time, fuel used, and SOC in "Mountain Mode" (**Figure 17**) until the engine generator turned off (**Figure 18)**.

With knowledge of the battery size, the change in SOC, and the fuel used at the observed Mountain Mode steady state 1700RPM engine operating speed, the energy conversion ratio (ECR_{phev}) of approximately 8.4kWh/gallon was calculated according to equation (2).

$$\text{Battery Size} \bullet \Delta\, SOC \bullet 1/(\text{Gas Consumed}) = ECR_{phev}\ (kWh/Gal) \quad (2)$$

With:
Battery Size = 16kWh
Final SOC = 40%
Initial SOC = 19%
Gas Consumed = 0.40 gallons

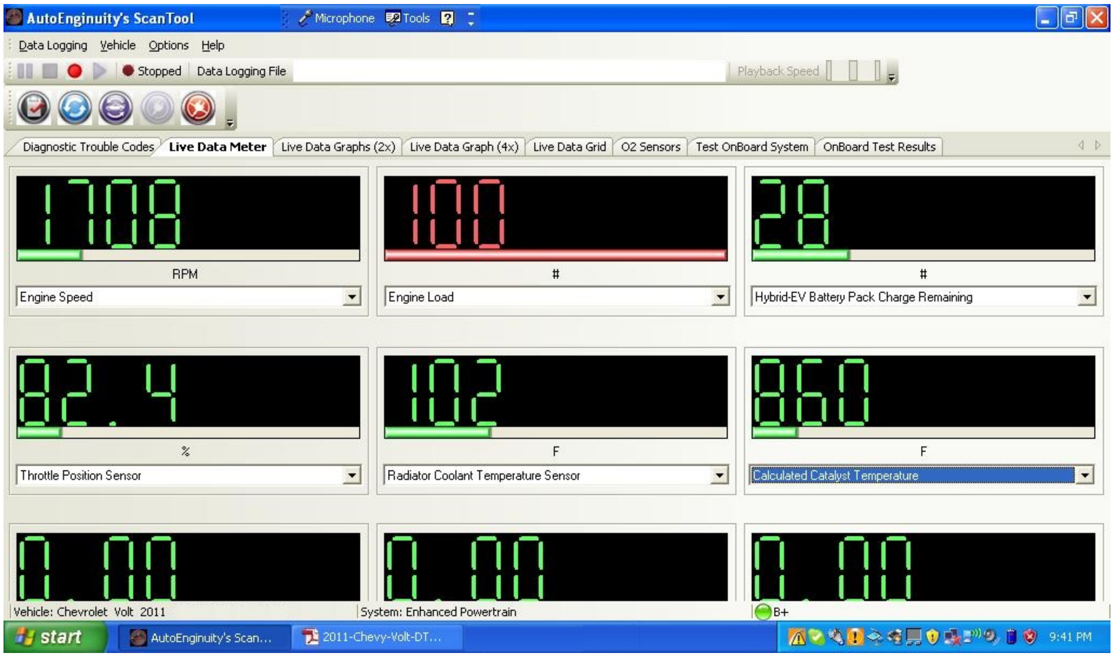

Figure 15: AutoEnginuity reading RPM, Load, SOC/Charge Remaining

Figure 16: OBDII port and communications cable

Figure 17: Chevrolet Volt “Mountain Mode”

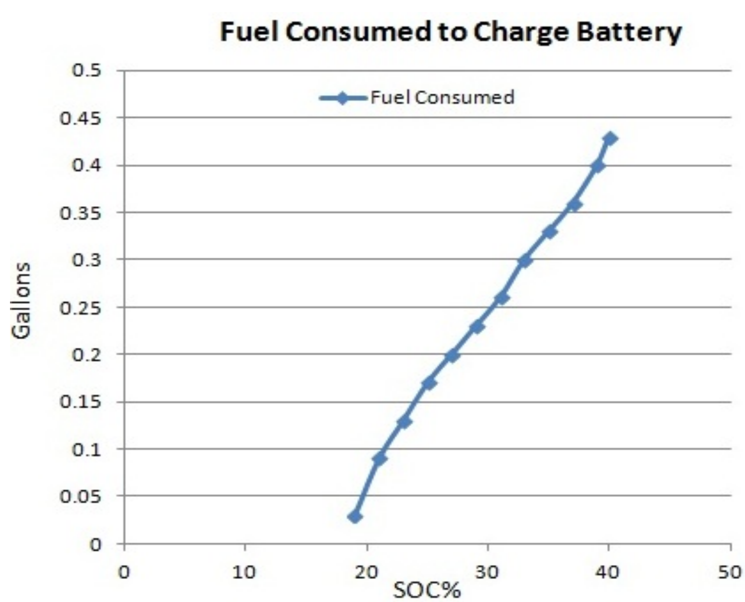

Figure 18: PHEV Fuel Consumed versus SOC (2011 Volt)

The average power output at the steady state engine operating speed of 1700rpm was calculated to be approximately 12.4kW according to equation (3).

Energy (kWh) /Elapsed Time (h)= Average Power (kW) (3)

With:
Energy = 3.36kWh
Elapsed Time = 0.27h

The engine output maximum is stated as 63kW SAE Net power, well above the observed 12.4kW output level even with conversion to equivalent metrics. The Volt's traction motor is quoted at over 110 kW maximum [GM 2010b]. Hence, the battery output is assumed to be capable of providing 110kW power output, well beyond the needs of a residential load.

For a rough comparison, an additional calculation was made to estimate the gasoline to electrical kWh output conversion ratio of a large, commercial-scale backup generator using heat rate data [EIA 2013] for a diesel electric generator and the heating value of gasoline [DOE 2013]. For these commercial grade large-scale generators, a conversion ratio (ECR_{lsg}) of 10.7kWh/gallon was calculated according to equation (4).

$$1/HR\ (kWh/Btu) \bullet HV\ (Btu/Gallon) = ECR_{lsg}\ (kWh/Gal) \quad (4)$$

With:
HR=Large Scale Generator Heat Rate = 10,800 Btu/kWh
HV=Gasoline Heating Value (Lower) = 116,090 Btu/gallon

This ECR_{lsg} includes only the conversion of energy fed into the grid in real time, not into a battery storage system. For a more accurate comparison, this 10.7kWh/gallon must be further de-rated to include equivalent rectification, voltage conversion, and battery internal resistance. Using the same 88% (η) grid-to-battery conversion efficiency from equation (1), the large-scale generator would produce 9.4kWh/gallon. This approximately 12% better efficiency over the PHEV engine-generator is plausible given that the large-scale generator is a purpose built design and can be expected to have higher efficiency. Furthermore, there may be more efficient operating points for the engine generator than the particular 1700rpm level observed during the experimental measurement. Therefore, the 8.4kWh/gallon PHEV energy conversion ratio is assumed to be reasonable, but perhaps conservative.

C. Scenarios

The homes selected have rooftop PV, PV output data, and whole home load data on a per minute basis for 2012. The simulation models were constructed to enable analysis without and with PV output extending the backup duration. BEV useable net battery capacities were assumed to be 19.2kWh and 32kWh, representative of two commercially available BEVs: a Nissan LEAF [Nissan 2012] and entry-level Tesla Model S [Tesla], respectively. The PHEV usable net battery capacities were assumed to be 3kWh and 10.5 kWh, representative of a Toyota Prius PHEV [Toyota 2012] and a Chevrolet Volt PHEV [GM 2010a] (slightly larger than a 2011 Volt, slightly smaller than a 2013 Volt), respectively. The PHEV gasoline quantities available were assumed to be 3.5, 7, and 17 gallons.

The 3.5-gallon quantity represents the minimal amount of fuel that a PHEV owner may have in their tank under many circumstances. The 7 gallon quantity reflects the amount of gasoline a representative PHEV owner would have in a full tank with a few gallons remaining to drive the PHEV to a distant gas station for refueling (e.g. 2.3 gallons remaining in a 9.3 gallon Chevrolet Volt fuel tank). The 17-gallon quantity represents a

PHEV with a large on-board fuel tank or a Volt-sized fuel tank plus additional gasoline stored in two common 5-gallon containers.

IV. Key Interfaces With The Vehicle

As discussed in Chapter 3, the common vehicle power interface for PEVs in the U.S. is the SAE J1772 [Bohn 2011]. This standard provides for both AC and DC interface capabilities with various power capacities. The AC interface standard supports grid-common 120V or 240V 60Hz AC power with the vehicle incorporating on-board rectification, voltage step up to the appropriate DC battery charging voltage (typically above 300V DC), and all battery related control functions. The AC Level-2 interface defined supports up to 19.2kW.

The DC interface described in Chapter 3 provides a more direct connection to the vehicle's high-voltage/high-capacity traction battery. The DC Level-1 specification supports up to 40kW and the DC Level-2 interface supports 100kW, well above any typical residential home load (typically less than 20kW). Other regions around the world have functionally similar but physically typically different vehicle connectors [IEC 2011, CHAdeMO 2013]. It is likely that PEV manufacturers will prefer to provide V2H support through a DC interface [Nissan 2013] to provide sufficient power capacity, avoid the complexity of dealing with a large number of regional variations in electrical code and equipment, limit adding additional weight and cost to the vehicle, and a variety of other reasons. Either a CHAdeMO or SAE J1772 Combo/CCS connector could provide the DC interface. Utilizing the universal U.S. SAE AC Level-2 connector for V2H with DC power flow may be possible using the SAE DC Level-1 configuration or for a greater power transfer capability, a SAE DC Level-2 "Combo" connector can be deployed [SAE 2013]. Associated communication, use case, and interoperability standards that enable control of the V2H session are also under development [IEEE 2013, Scholar 2011a, Scholar 2011b].

Home AC power could be provided by standard electrical receptacle outlets mounted on the vehicle, electrical receptacle outlets mounted in a weatherproof enclosure mounted on a pole or bollard, or through an EVSE plus transfer switch function mounted in the residence. Transfer switches are common devices used in conjunction with backup generators to isolate the home from the grid, switch the desired circuits to be fed by the backup generator, and then switch back once the grid restores power. The EVSE+Transfer switch function would provide the most seamless integration to the home for an off-grid backup power V2H scenario.

V. RESULTS

Simulation models used Pecan Street home load and PV data, calculated energy conversion ratios, power output levels, conventional PHEV control algorithms, and a variety of battery (BEV: 19.2kWh and 32kWh, PHEV: 3kWh and 10.5kWh) and gas supply sizes (3.5, 7, and 17 gallons). The simulations showed that the PHEVs and BEVs could provide considerable backup capability, particularly during seasons with modest load, for homes with PV installed and with strong PV output. **Figure 19** shows the backup duration of a BEV V2H system with and without PV and the substantial benefit of rooftop PV for a V2H system. It is interesting to note that the 32kWh battery (67% larger than the 19.2kWh BEV battery) did not provide commensurately greater backup duration in the PV BEV V2H system. The battery size is the most important factor for the BEV system throughout the year. When the battery is fully charged and the PV is fully serving the load, the opportunity to capture any additional PV energy is lost. This loss is named “spillage” in this dissertation and accounts for why the 32kWh battery did not provide commensurately more backup than the 19.2kWh battery. By reducing spillage, improved load control, curtailment, or shifting may be much more valuable than a considerably more expensive battery under some circumstances.

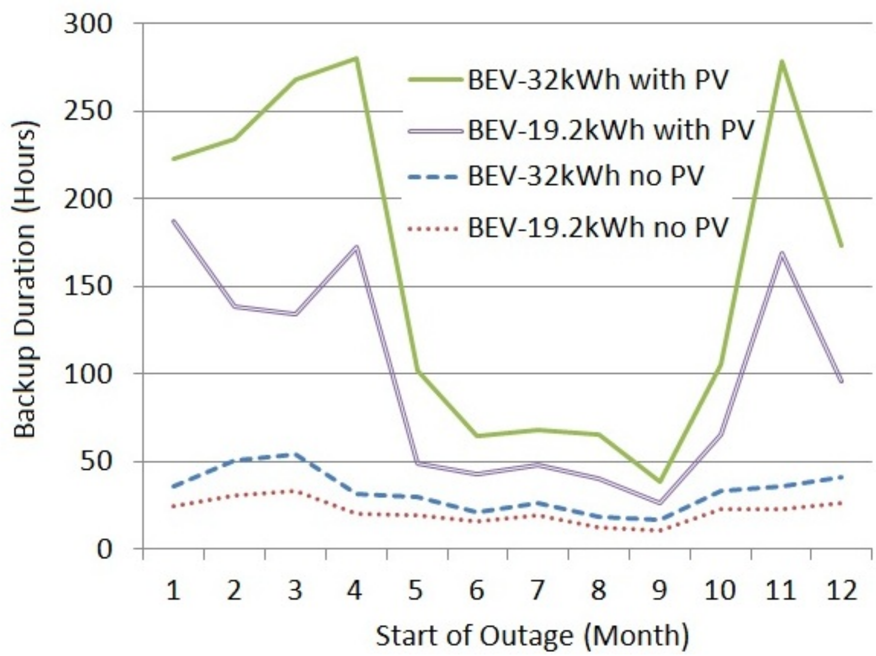

Figure 19: BEV Backup Durations
(20 home average, with and without PV for outages starting the 1st day of each month With 32kWh and 19.2kWh battery sizes)

The volume of gasoline available for PHEVs is the most important determinant of overall backup duration given the considerable energy storage provided by each gallon of gasoline, effectively 8.4kWh per gallon. During off-peak months, the PV output complements the PHEV generator to substantially extend backup durations from a few days to nearly 25 days (**Figure 20).**

Prior studies of community level storage [Fares 2013] have shown that the time at which an outage begins for homes with PV can be a large determinant of the backup duration. The storage must have enough energy to maintain the load until the PV can start producing.

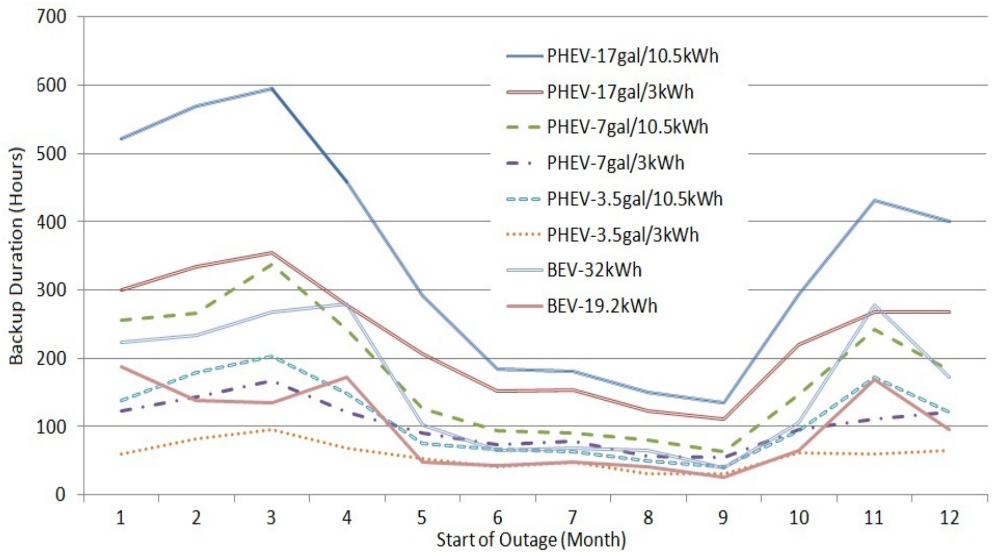

Figure 20: PHEV and BEV Backup Durations

(20 home average, with PV for outages starting the 1st day of each month with varied battery and gasoline tank sizes)

The initial charge understandably would have the greatest effect on a BEV-V2H system without PV. However, PV needs a working storage system to not shut down. Therefore, if the initial SOC is low, a BEV with PV system backup duration could be meaningfully shortened if the battery is exhausted before the PV production can ramp up.

Given the relatively large energy potential of storage gasoline, PHEV based V2H is relatively insensitive to the initial battery charge, even with only modest amounts of gasoline available. This analysis assumed initial state of charge was 100% given that i) lower initial levels can be approximated as smaller BEV battery sizes, ii) initial SOC having negligible impact on PHEVs, and iii) the need to reduce the complexity of the analysis.

For advanced systems, it is conceivable that a home energy management system (HEMS) and PEV could coordinate using weather service information to modify the charge rate of the PEV (i.e., if a storm is approaching, then charge the vehicle as rapidly as possible to increase the possibility of reaching 100% SOC before a grid outage).

A possible optimal control strategy for cases where the initial BEV state of charge is low may be to shut off load support during the remaining portion of the night and later use the remaining BEV battery charge to support the single home residential microgrid equivalent of blackstart [ERCOT 2013] once the rooftop PV energy production has increased sufficiently to be greater than or equal to the home load.

Small battery PHEV configurations suffered disproportionate PV spillage compared to their overall backup duration. A Home Energy Management System (HEMS) to shift load would be particularly useful for this circumstance to maximally extend the backup duration.

The simulation model developed for this analysis used a conventional algorithm for PHEV engine-generator control. This algorithm typically allows the battery SOC to drop to a lower control bound with the engine off, then deploys the engine-generator until the battery is charged to a higher control bound to achieve efficient operation and low emissions. In this simulation model, 0% SOC of the net usable battery capacity was the lower control bound and 100% SOC of the net usable battery capacity was the upper control bound. For a PHEV V2H system without PV, this control algorithm was a good fit. However, it was discovered from the simulation data that for a residential PHEV V2H system with PV, there are periods where this control system is a poor fit. In certain cases the battery becomes fully depleted early in the morning immediately before the sun rises and PV begins production. When the engine-generator commences operation using the conventional control algorithm it will then fully charge the battery. If the PV generation is strong and/or the load is low, the battery then has limited capacity to capture this PV energy, and the energy is spilled, as shown in **Figure 21**. A more optimal engine-generator control strategy may be to charge the battery to some lesser upper SOC control bound for PV-V2H systems to save gasoline, provide just enough spare capacity in the battery to capture the excess PV energy, and extend overall backup duration. Ideally, this engine-generator algorithm could be fully optimized with time of day, PV production history and projections, load projections/HEMS coordination, and weather forecasts.

With additional improvements of the generator control and intelligent load shifting, the amount of PV energy spilled could be reduced and the overall backup duration could be extended. **Table 6** illustrates the amount of PV energy lost to spillage. In a number of cases the potential to extend backup duration is considerable.

Another possible improved control strategy might provide blocks of usable PV enabled backup. This algorithm would cease supporting load by the battery before the battery is fully depleted. By doing so, the remaining battery charge would be available to restart the PV system so that it can again provide power to the home load once PV production resumes. This configuration effectively provides a single home residential microgrid blackstart. While this method would not provide continuous uninterrupted power, it has the potential to indefinitely provide sustainable power for blocks of time every day that the PV is providing output.

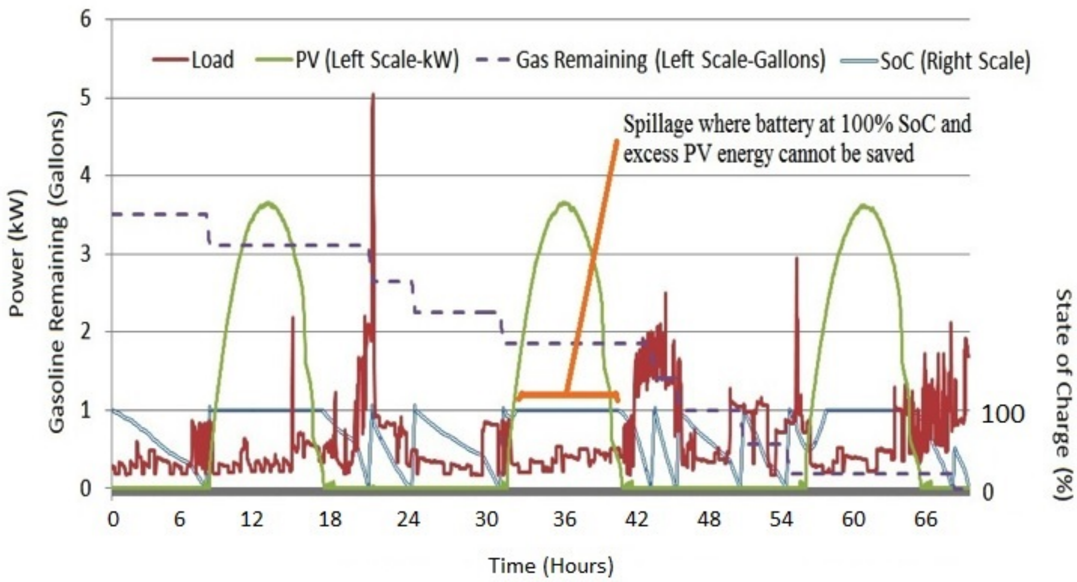

Figure 21: PHEV SOC, Load, PV, & Remaining Gas Over a Backup Event (Note spillage during high PV output where SOC is at the maximum 100%)

Table 6: PHEV PV Spillage (kWh of energy lost)

	Fuel Tank Size/Battery Size					
Outage Start	17gal/ 10.5kWh	7gal/ 10.5kWh	3.5gal/ 10.5kWh	17gal/ 3kWh	7gal/ 3kWh	3.5gal/ 3kWh
Jan	147.9kWh	89.0	50.6	127.5	63.4	34.6
Feb	153.0	56.7	37.0	110.9	34.8	20.0
Mar	194.0	111.5	62.2	150.1	81.3	50.9
Apr	161.0	93.3	51.4	139.0	64.1	36.1
May	68.4	25.2	16.4	71.3	29.8	18.8
Jun	30.2	18.2	15.0	40.3	24	17.1
Jul	25.9	14.1	10.4	34.7	20.4	12.4
Aug	26.9	16.4	10.5	36.3	18.7	11.0
Sep	24.0	9.5	4.9	28.5	12.8	7.3
Oct	66.2	40.8	30.7	79.4	47.9	34.6
Nov	127.4	78.7	57.1	120.3	54.8	31.7
Dec	91.0	32.7	21.6	82.8	36.4	16.9

Large BEV batteries can provide considerable backup duration combined with PV. The simulation results show the batteries became fully depleted once a period of poor PV production and/or large load occurred (**Figure 22**), terminally exhausting the battery.

During a grid outage, a V2H system, particularly with PV, has the ability to have considerable backup power duration extension with selective load level changes. In a simulation using one of the home load/PV profiles, the worst case backup time period (September start month, a PHEV with a 3kWh battery and only 3.5 gallons of gas was extended from to 18.7 hours to 26.7 hours with a crude 50% reduction in load. It is interesting to note that with a 50% reduction in load, the duration was increased less than twice due to the non-advantageous timing between PV and this particular load, which resulted in considerable spillage of PV energy. Load shifting by the HEMS or behavior changes by the residents (e.g. washing clothes during PV production periods where PV would otherwise be spilled) could extend the backup duration.

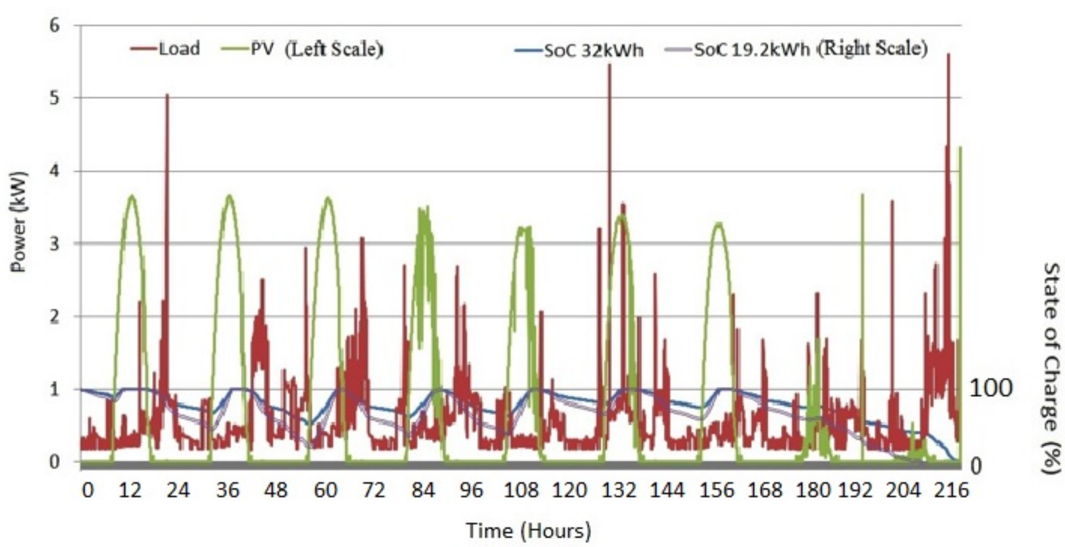

Figure 22: BEV SOC, Load, PV Output Over a Backup Event
(Note the longer duration with the larger 32kWh battery)

Various control strategies could be devised for different outage scenarios. If an outage occurs from a localized distribution fault with modest outage duration, the HEMS could decide to simply use the PEV for seamless backup without any load modifications. If a large storm creates an outage and weather alerts have been issued, the system could be programmed to significantly limit loads to essential functions only (e.g. refrigerator, lights, pumps, communications) to maximize backup duration until the home occupant overrides the system or indicates an estimated restoration of grid electrical service. With this estimate of restored service, the HEMS could then optimize the load automatically in the case of intelligent devices or provide guidance to the occupant on optimal times to deploy particular loads (e.g.: HVAC, clothes washing, electric hot water heating)

VI. Summary

Combining a BEV or particularly a PHEV with a PV system provides the opportunity to create a single home microgrid with considerable capabilities to provide backup power. PV systems typically must turn off their inverter output if the grid power is lost (or if there is no energy storage to create an off-grid microgrid). With an electric vehicle based storage node, the V2H system can create an off-grid microgrid that has the sufficient voltage regulation, energy storage, and safety disconnects. Our results indicate that a residential V2H system coupled with rooftop PV could provide backup power for approximately 19-600 hours, depending on the time of year and the precise vehicle configuration. Particularly with curtailed or shifted load during a grid emergency situation, an electric vehicle based V2H-PV microgrid system could provide considerable backup duration capability supporting the conventional home load. Improved microgrid control systems, better-optimized PHEV engine generator control algorithms, and selective load curtailment could further extend backup duration. Furthermore, sophisticated V2H control systems could save a modest portion of remaining battery power to blackstart the PV system to enable self-sustaining non-continuous power indefinitely.

In the next chapter, the ability to increase the back-up duration through load control and PHEV engine/generator control algorithm improvements is explored.

Chapter 8: Load Management and Control Algorithm Improvements to Extend Plug-In Vehicle to Home (V2H) Back-up Duration

This chapter extends the analysis in the last chapter of the capability for Plug-in electric vehicles (PEVs) in Vehicle to Home (V2H) scenarios. In this chapter, we use updated residential energy data collected from the Pecan Street smart grid test bed in Austin, Texas with an updated custom model to assess the performance in terms of back-up duration of a PEV V2H system used to provide power. In the previous chapter, we have quantified the extent to which photovoltaic (PV) generation and the characteristics of a PEV (battery size, gasoline availability) affect the backup duration of a PEV based V2H system during an electric outage. In this chapter, we use the insight gained from these prior results, new higher resolution load data, and an enhanced model to further explore the effect of load modification and improved engine-generator control for PV-enabled V2H strategies to further increase backup duration.

I. INTRODUCTION

In this chapter, using the insights gained from prior V2H research, we further explore methods to lengthen the backup duration of a PEV used in a V2H configuration to provide for backup power to a home during a grid outage. High resolution residential energy data collected from the Pecan Street smart grid test bed in Austin, Texas was used to conduct the following analyses: 1) quantify the baseline duration (in hours) of backup power that could be achieved with a newer generation of BEVs or PHEVs incorporated in a V2H system powering a representative home load, 2) derive the HVAC heating and cooling parameters used in the model to assess the value of modifying interior temperature thermostat setpoint targets to extend backup duration, 3) estimate the backup duration time improvement potential by modifying the temperature setpoint of the

HVAC system to reduce the home load while maintaining a reasonable comfort level for the residents, and 4) assess improved engine-generator control algorithms for PV enabled V2H with a PHEV to further extend backup duration.

In Section II, we introduce the smart grid test bed from which the residential energy data utilized in this chapter originates. Section III provides an overview of the PEV system model, the PHEV gasoline generator energy conversion efficiency, the interfaces with the vehicle to enable V2H capabilities, and the scenarios simulated. Section IV describes the derivation of HVAC heating and cooling parameters used in the model to assess the value of modifying inside temperature thermostat setpoint targets to extend backup duration. Section V discusses the results of backup duration simulations from the numerous new PHEV and BEV configurations and improvements considered. The final section concludes.

II. REPRESENTATIVE LOAD AND PV DATA

To estimate the instantaneous home and HVAC load and PV output on a PEV used in a V2H application, we use updated data collected by Pecan Street Inc. **[Pecan Street, 2013]** of Austin, Texas as part of their ongoing smart grid demonstration study. The overall Pecan Street study utilizes a test bed of over 250 modern, green-built homes constructed after 2007, over 250 homes ranging from 10-92 years in age **[Pecan Street, 2015],** 140 apartments, 25 small commercial properties, and three public schools. Of the homes in the study, over 185 have rooftop PV panels. The homes that provided data for this V2H study are instrumented with various forms of energy metering equipment, which tracks electricity, natural gas, and water use.

For the purposes of this study, we utilize PV production, whole house electric demand, and detailed HVAC load data collected on a one-minute time interval from 8 homes over the year 2013. The study described in Chapter 7 by the authors used 2012 data that only provided whole house load and PV output data. These homes were selected given their high-resolution data availability for the entire year, installation of rooftop PV (that can be effectively turned-off in simulation to provide insights for scenarios with and without PV), natural gas heating, and availability of detailed HVAC load data for the entire year.

The homes considered in this chapter have PV systems ranging from 4 kW to 6.9 kW in rated capacity. The homes range in size from 1200 ft^2 to 2700 ft^2 **[Rhodes, 2013].** We use PV production, overall home load, and HVAC load data from these homes as the input to a PEV model, which is described in Section III.

III. SYSTEM AND VEHICLE MODELS

A. System Model (Updated)

The core model used to simulate V2H performance in response to an unplanned grid outage were constructed for both BEV and PHEV configurations using MATLAB and used in a prior study **[Tuttle, 2013]** but updated with additional functionality for this study. The model components consisted of the vehicle battery of varied sizes providing energy to the home load in conjunction with any PV energy generated by the rooftop PV system, and an engine-generator for a PHEV. **Figure 12** in Chapter 7 shows the diagram for the V2H system model, however in this chapter the BEV battery sizes are updated to 19.2kWh and 72kWh and the PHEV battery sizes are 3kWh and 16.4kWh.

In this analysis, the home is assumed to be isolated by a transfer switch in a single-vehicle/single-home microgrid once grid power is lost. When the PV output was greater than home load, the battery is charged until it reached full state-of-charge (SOC). Excess PV energy that could not be stored in the fully charged PEV battery is assumed to be "spilled" and lost, hence methods to reduce spillage can lead to improved backup duration.

The V2H simulation model assumes PV energy (if any) is consumed first, then battery energy powers the home, and then finally the engine-generator (if equipped) is deployed to power the load and recharge the battery until the gasoline supply is exhausted. Since a BEV has no engine-generator, only the initial stored battery energy and PV output can power the home. Using specifications of battery size, usable battery SOC window [GM, 2010a], and measurements of input energy from the grid the overall charging efficiency (η) shown in **Figure 12** were calculated during varied temperature conditions for a Chevrolet Volt PHEV. We continue to assume the conservative 88% hot weather conversion efficiency (derived when regional weather station data indicated 92 to 96 degrees ambient temperature). A 5% conversion efficiency improvement is expected during more moderate temperatures (67 to 71 degrees ambient temperature) from a reduced parasitic loss from the battery thermal management system deployed to cool the battery during hot weather. Given the battery technology, battery thermal management, and power electronics are assumed to be similar between BEVs and PHEVs, the same 88% efficiency factor is used for both types of vehicles. Also, the charging and discharging efficiencies are assumed to be equal. The energy conversion ratio (ECR_{phev}) of approximately 8.4kWh/gallon and average power output of 12.4kW at the steady state engine operating speed of 1700rpm are again assumed from prior derivations **[Tuttle, 2013]**.

B. Scenarios

The homes selected have rooftop PV output data, whole home load data, and detailed HVAC load data on a per minute basis for every minute of 2013 enabling the exploration of a variety of scenarios. The simulation models were constructed to enable analysis of the following:

a) A *baseline with rooftop PV* back-up duration (BUD) scenario, new PEV models (2016 Volt and 2015 Tesla Model S both with a larger batteries), and 2013 measured Load/PV/HVAC data.
b) A *modestly less comfortable* interior temperature scenario with a 6-degree (F) warmer thermostat set-point when cooling or 6-degree (F) cooler setpoint when heating.
c) An *extremely less comfortable* interior temperature scenario with the HVAC entirely shut off.
d) A *baseline without rooftop PV* BUD scenario.
e) An *enhanced control algorithm* PHEV engine-generator scenario in comparison to the baseline PHEV scenario.

BEV useable net battery capacities were assumed to be 19.2kWh and 72kWh, representative of two commercially available BEVs: a Nissan Leaf [Nissan, 2013b] and a 2015 Tesla Model S with the largest battery available [Tesla, 2013], respectively. The PHEV usable net battery capacities were assumed to be 3kWh and 16.4 kWh, representative of a 2015 Toyota Prius PHEV [Toyota, 2012] and a 2016 Chevrolet Volt

PHEV [GM, 2015], respectively. The PHEV gasoline quantities available were assumed to be 3.5 and 17 gallons.

IV. Derivation of HVAC Parameters

There are a number of methods available to derive the cooling and heating parameters that can be used to estimate the amount of energy required to maintain a given interior thermostat setpoint temperature. One could derive the parameters from a detailed bottom-up analysis of all the components, design, construction, and orientation of the homes [Yoon, 2014]. Another method is to estimate the parameters using an assumed default cooling and heating setpoints, ambient exterior air temperature data, and empirical data on each home's HVAC load as measured by the data collection system. Given access to the detailed construction, equipment, and other key data for the homes was not available, we chose to derive the parameters from empirical energy consumption data of the heating/cooling system during periods of sustained cold or hot weather assuming a 70 degree (°F) heating thermostat setpoint and a 74 degree (°F) cooling setpoint. The cold weather reference period included the 5 days (7200 minutes) from December 6th through 10th, 2013 when the temperature varied from 26.4 to 46.3 degrees (°F) and the average temperature was 33.7 degrees (°F). The hot weather reference period included 5 days from August 6th to 10th, 2013 when the temperature varied from 74.6 to 102.97 degrees (°F) and the average temperature was 88.9 degrees (°F).

For the heating period, for each minute of the five-day period, the difference between the 70-degree setpoint (Tsph) and the ambient air temperature (Tamb) was calculated. Given the activities of the occupants, sunlight striking the home, as well as the ambient temperatures can affect the energy consumption, each day was divided into three time periods: midnight to dawn (sleeping), daylight, and sunset to midnight (evening). For each of these three periods, the cumulative energy consumed by the HVAC system alone was divided by the total differences in the Tsp and Tamb across all 8 reference homes. Taking into account the varied time durations of each of these periods, a weighted average of these sums was calculated to derive a coefficient that describes the power in kW required to maintain this temperature differential.

The same method was used to calculate the summer coefficient of kW/(Tsp-Tamb). Given all eight homes used natural gas heating, the electrical energy consumed to heat the home was substantially less than the electrical energy to cool a similar temperature differential in the summer. During heating, the HVAC system only consumed electricity to power the fan that circulates air through the vents and to power the control system while the natural gas burners provided the heat source.

For heating:

$$\delta_{sleeping} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes) / [8 \cdot \sum_{k=1}^{7200} (Tamb - Tsph)] \quad (5)$$

$$\delta_{daylight} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes) / [8 \cdot \sum_{k=1}^{7200} (Tamb - Tsph)] \quad (6)$$

$$\delta_{evening} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes) / [8 \cdot \sum_{k=1}^{7200} (Tamb - Tsph)] \quad (7)$$

$$\begin{aligned}\Delta_{heating} = [&\delta_{sleeping} * sleeping\ min/day \\ &+ \delta_{daylight} * daylight\ min/\mathrm{day} \\ &+ \delta_{evening} * evening\ min/day]/1440\ min/day\end{aligned} \quad (8)$$

With:
Tamb = Ambient air temperature
Tsph = 70 °F *Thermostat heating setpoint*
kWminutes = Energy consumed by HVAC blower fan

$\delta_{sleeping}$ = *kW / (Tamb-Tsph) from midnight to dawn*
$\delta_{daylight}$= *kW / (Tamb-Tsph) during daylight*
$\delta_{evening}$= *kW / (Tamb-Tsph) from sunset to midnight*
$\Delta_{heating}$ =*0.005411 kW / (Tamb-Tsph) weighted average*
Energy savings = 0.0325 kWh per hour for a 6 degree less comfortable heating setting

For cooling:

$$\delta_{sleeping} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes)/[8 \cdot \sum_{k=1}^{7200} (Tamb - Tspc) \quad (9)$$

$$\delta_{daylight} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes)/[8 \cdot \sum_{k=1}^{7200} (Tamb - Tspc)] \quad (10)$$

$$\delta_{evening} = \sum_{m=1}^{7200} \sum_{h=1}^{8} (kWminutes)/[8 \cdot \sum_{k=1}^{7200} (Tamb - Tspc)] \quad (11)$$

$$\Delta\delta_{cooling} = [\delta_{sleeping} * sleeping\ min/day + \delta_{daylight} * daylight\ min/day + \delta_{evening} * evening\ min/day]/1440\ min/day \quad (12)$$

With:
Tamb = Ambient air temperature
Tspc = 74 °F *Thermostat cooling setpoint*
kWminutes = Energy consumed by HVAC compressor & fan
$\delta_{sleeping}$ = *kW / (Tamb-Tspc) from midnight to dawn*
$\delta_{daylight}$= *kW / (Tamb-Tspc) during daylight*
$\delta_{evening}$= *kW / (Tamb-Tspc) from sunset to midnight*
$\Delta_{cooling}$ =*0.07884 kW / (Tamb-Tspc) weighted average*
Energy savings = 0.473 kWh per hour for a 6 degree less comfortable cooling setting

V. RESULTS

The simulation models used Pecan Street home load, HVAC, and PV data, calculated energy conversion ratios, power output levels, conventional and improved PHEV control algorithms, full HVAC load, a six degree less comfortable HVAC setting, and HVAC off. The effect of a variety of battery sizes (BEV: 19.2kWh and 72kWh, PHEV: 3kWh and 16.4kWh) and gas supply sizes (3.5 and 17 gallons) on BUD were analyzed. The simulations showed that the PHEVs and BEVs could provide considerable backup capability, particularly with rooftop PV during seasons with modest HVAC load or if the residents purposely lessen HVAC load.

Figure 23 shows the backup duration of a BEV V2H system with PV and two considerably different battery sizes (72 vs. 19.2kWh). It is interesting to note that under low-load and high PV output conditions, the 72kWh battery provided a 4.8x to 12.4x extension of BUD for a 3.75x increase in battery size. With a 72kWh BEV-PV-V2H system with full comfort HVAC settings, the longest average BUD was nearly 2 months. For months with heavier loads and good PV output, the BUD was extended from 2.7x to 3.3x with the 3.75x battery size increase. During the hottest weather month with unmodified consumption behavior (e.g. maintaining full comfort HVAC), the average BUD was slightly under 1 day for a 19.2kWh BEV-PV system and nearly 3 days with a 72kWh BEV-PV V2H system.

The batteries are assumed to be fully charged when the grid outage occurs. The larger 72kWh battery capacity provided a much larger initial store of energy as well as the ability to spill less PV energy. These two factors enabled the system to ride through longer periods of poor PV output to provide longer back-up durations before the battery was terminally exhausted.

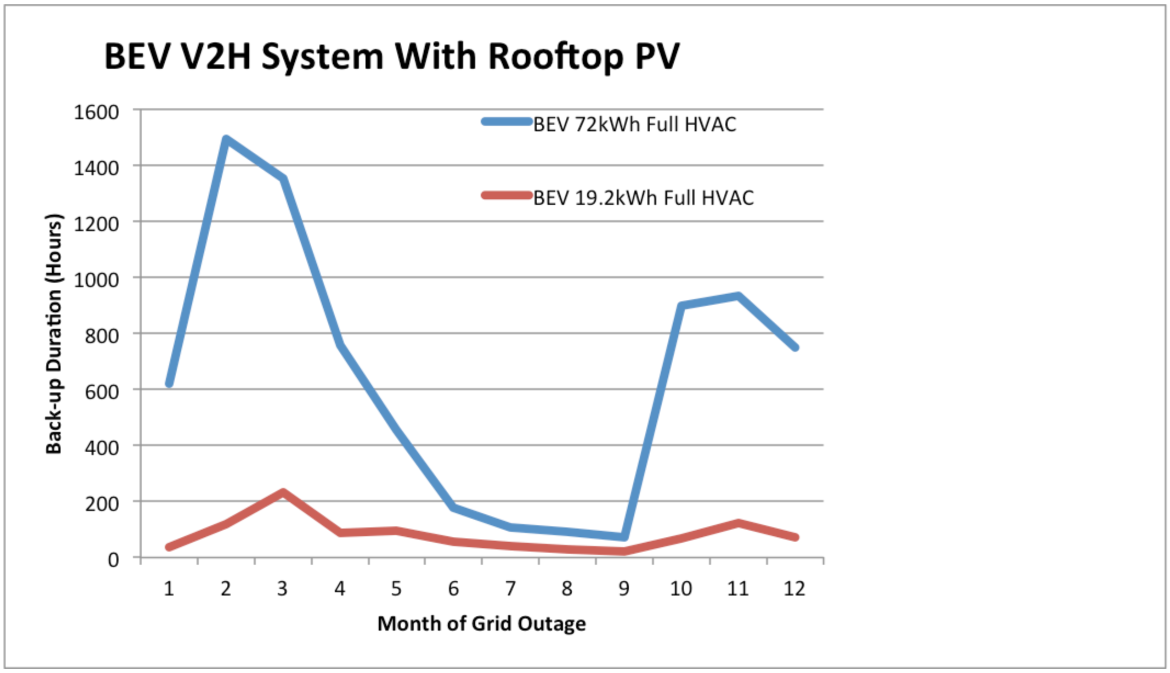

Figure 23: BEV Backup Durations (BUDs) with PV
8 home average, for outages starting the 1st day of each month with
72kWh & 19.2kWh battery sizes

The BUD results for the baseline PHEV V2H system with PV deployed for two battery sizes and two initial gasoline quantities are shown in **Figure 24**. While the battery size is the most important factor in determining the BUD for a BEV V2H system, the volume of gasoline available for PHEVs is generally the most important determinant of overall backup duration given the considerable energy storage provided by each gallon of gasoline (effectively 8.4kWh per gallon) except for cases where the load is low and the PV output is high such as month 3. In month 3, the average BUD benefited more from the reduced spillage from a larger 16.4kWh (vs. 3kWh) battery than the much greater amount of initial gasoline (17 gallons vs. 3.5 gallons). During more moderate ambient temperature months, the PV output can complement the PHEV generator and gasoline store to extend backup durations to nearly 50 days even with a full comfort interior HVAC thermostat setting.

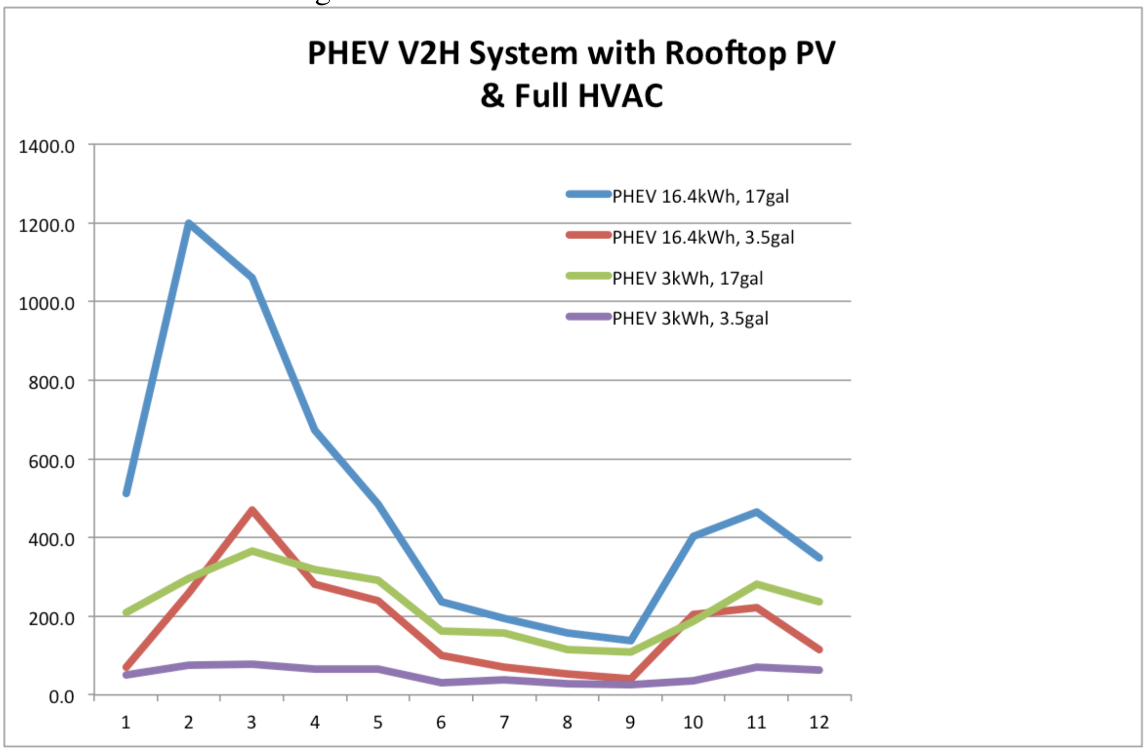

Figure 24: PHEV Backup Durations (BUDs) with PV
8 home average starting the 1st day of each month with 16.4kWh & 3kWh battery sizes and 17 & 3.5 gallon initial gasoline stores.

In the Southern region where the home load, HVAC, and PV data was acquired, HVAC cooling load was typically the largest load. The ability for residents to extend their BUDs during long term grid power outages (e.g. in the aftermath of a super-storm or a large scale grid cyber attack) was explored by deriving the energy savings of a six degree less comfortable HVAC thermostat setting or turning off the HVAC entirely. By sacrificing interior temperature comfort levels, the residents have the ability to maintain power to critical loads such as refrigeration, lighting, and communications for potentially much longer periods of time. **Figure 25** shows the potential to extend the

BUD for a BEV V2H system with rooftop PV with a six degree less comfortable thermostat setting and also with the HVAC turned off.

There are a number of observations that can be made from the results of varied HVAC load. In the scenario where the HVAC is completely turned off, the very large 72kWh BEV battery combined with the substantially reduced load could provide a BUD of about two months to nearly a half-year. Secondly, with the HVAC turned off, the smaller 19.2kWh battery BEV produced BUDs that generally increased with increased PV output and produced shorter BUDs when PV production was weaker (i.e. in January or February). Thirdly, the benefit of a 6-degree less comfortable change in interior thermostat setpoint can, in many circumstances, have a substantial benefit on the BUD. Deeper analysis of the individual homes showed that the average was skewed by one of the homes having a BUD extend to the entire year. In other words, for that specific home, their combination of a 72kWh battery, their PV system size, and load profile created a sustainable off-grid system. For the other homes, the benefit of a 6 degree thermostat change provided an average BUD extension of 47.7% for a 72kWh BEV V2H system and 58.0% for a 19.2 BEV V2H system.

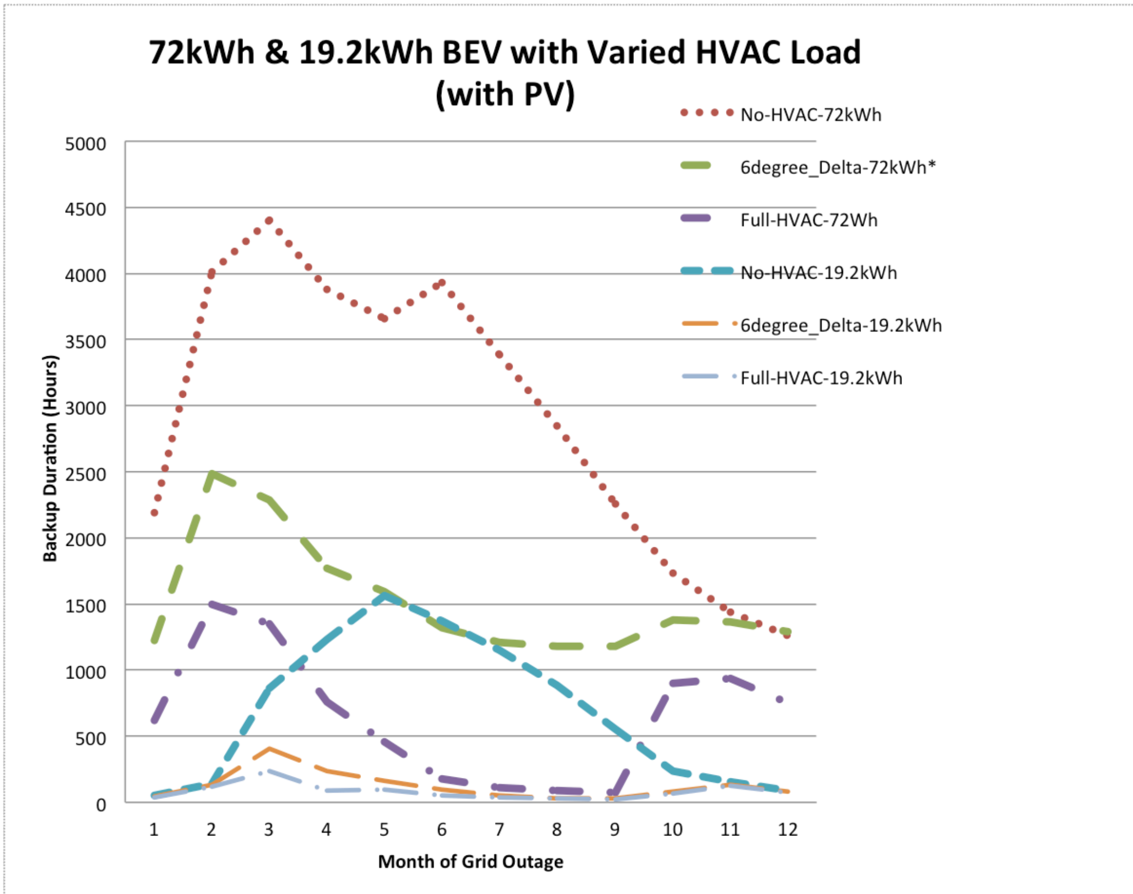

Figure 25: BEV BUDs with PV, full HVAC load, 6°(F) change, & HVAC off
8 home average, starting the 1st day of each month with 72kWh & 19.2kWh battery sizes

The benefit of a 6-degree less comfortable thermostat setting is shown in **Figure 26**. In this BEV V2H system where the full HVAC load is maintained, the battery is terminally exhausted in hour 165. However, with a 6 degree Tsp adjustment, the rooftop PV system provides enough cumulative energy to support the home's load given the substantial 72kWh battery provides enough storage to ride through periods of weak PV production.

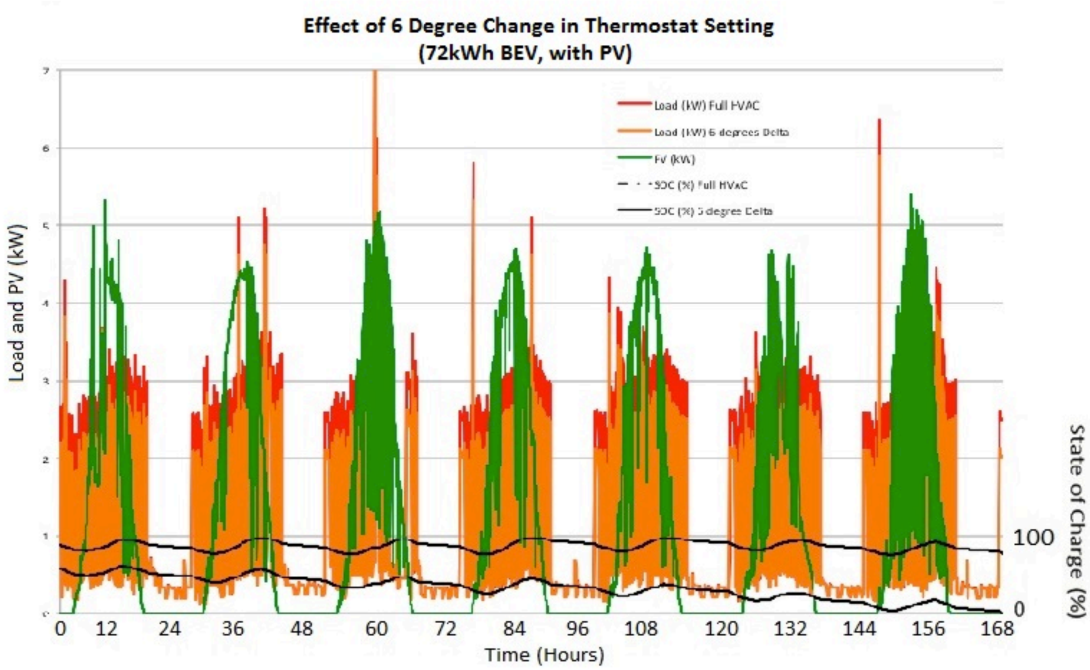

Figure 26: BEV battery SOC, Load, & PV output, full HVAC & 6°(F) change

Figure 27 and **Figure 28** show the potential to extend the BUD for a 16.4kWh and 3kWh PHEV V2H system (respectively) with rooftop PV with a six degree less comfortable thermostat setting and also with the HVAC turned off. The benefit of a much larger battery can be observed by comparing the 72kWh BEV no-HVAC data in Figure 4 with the 16.4kWh/17gallon PHEV no-HVAC data in Figure 6. Even without the relatively large 17-gallon store of gasoline, the 72kWh BEV V2H system provides longer average BUD times.

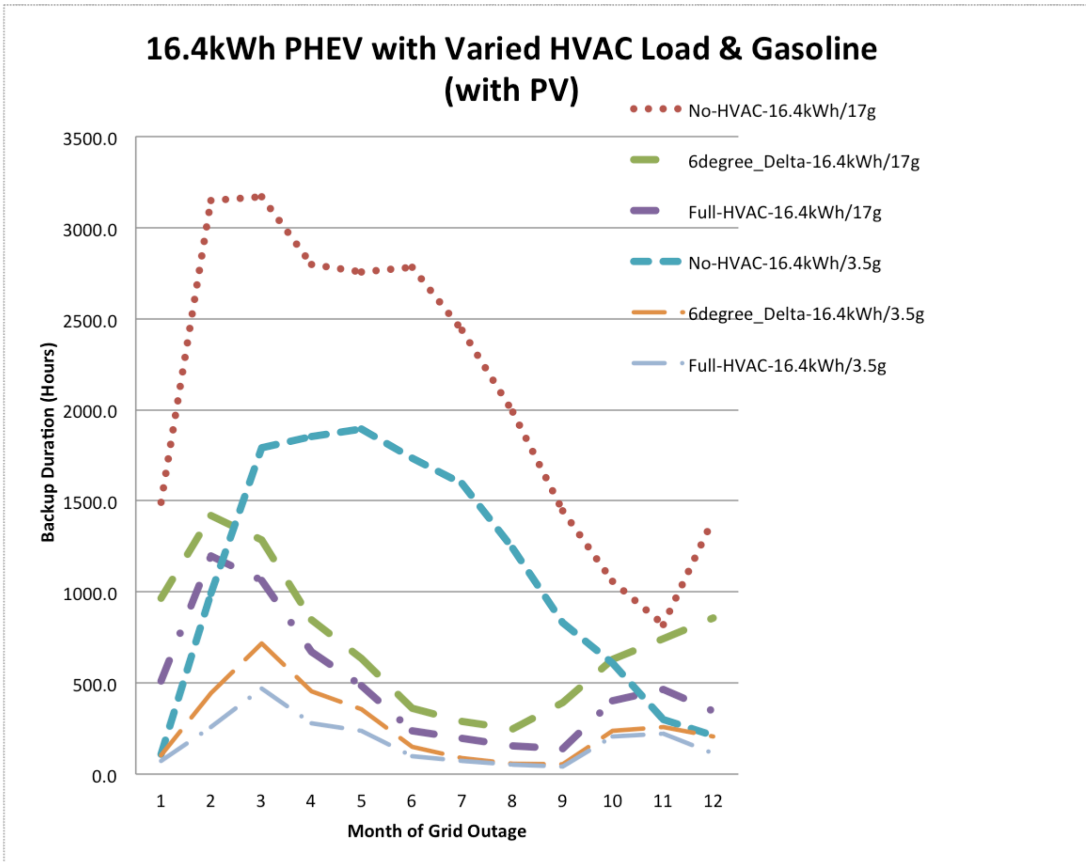

Figure 27: PHEV BUDs with PV, full HVAC load, 6°(F) change, & HVAC off 8 home average for outages starting the 1st day of each month, with 16.4kWh battery size, 17 & 3.5 gallon initial gasoline stores

In the scenario with the smaller 3kWh PHEV shown in Figure 23, the amount of initial gasoline store and turning the HVAC off provide the longest BUDs. Even with the relatively small 3kWh battery, with 17 gallons of fuel over 25 days of power can be provided. Reducing the HVAC load via a 6-degree less comfortable setting increases the backup by a little over a day. Given the relatively small battery size, with no-HVAC load, the BUD generally follows the amount of PV output generated.

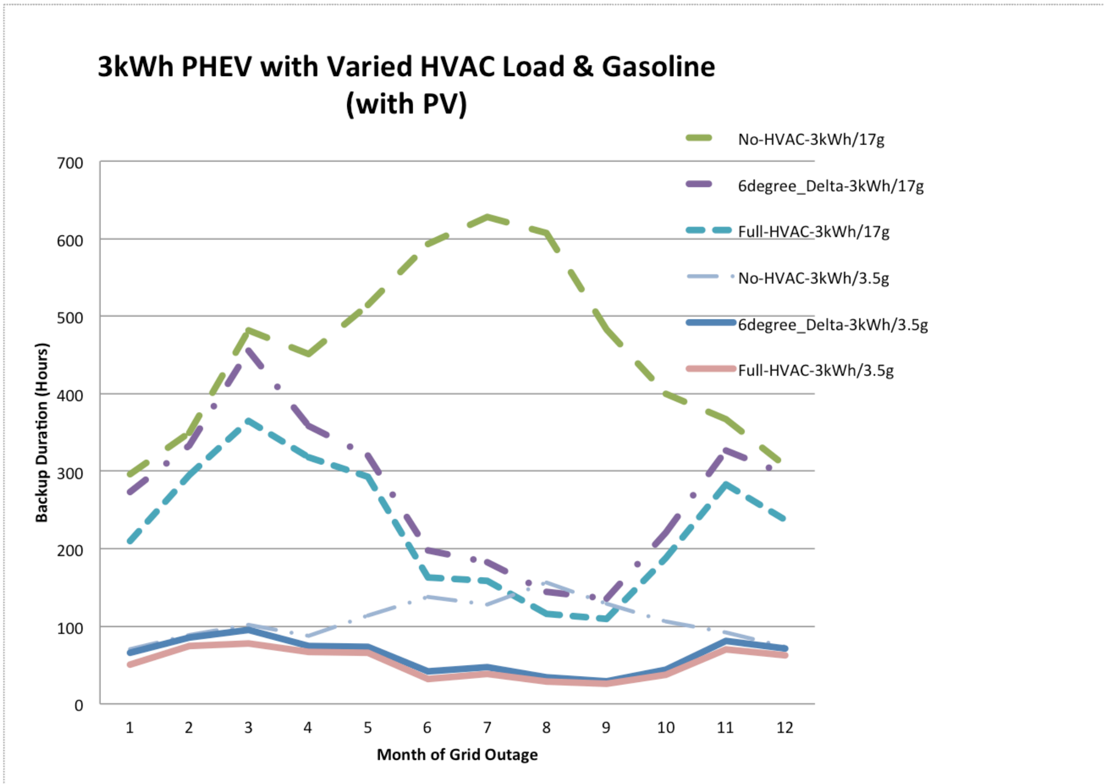

Figure 28: PHEV BUDs with PV, with full HVAC, 6°(F) change, & HVAC off 8 home average for outages starting the 1st day of each month, with 3kWh battery size, 17 & 3.5 gallon initial gasoline stores

The considerable benefit from rooftop PV generation is clear by the modest BUDs for BEV and PHEV V2H systems without PV in **Figure 29** and **Figure 30**.

Without PV, the average BEV V2H BUD is entirely dependent upon the size of the battery and the initial battery SOC. For a given battery size and initial SOC, the only means to extend the BUD is by reducing load. With the smallest 19.2kWh BEV battery and full HVAC, the BUD is slightly more than a half day. For the worst month, this BUD can be extended to nearly a day and a half by turning off the HVAC. From this data, a V2H system without rooftop PV would tend to be more valuable for shorter grid disruptions (such as distribution faults) and be of far less value (particularly with a BEV) during an extended disruption in the aftermath of a super-storm or massive grid cyber attack.

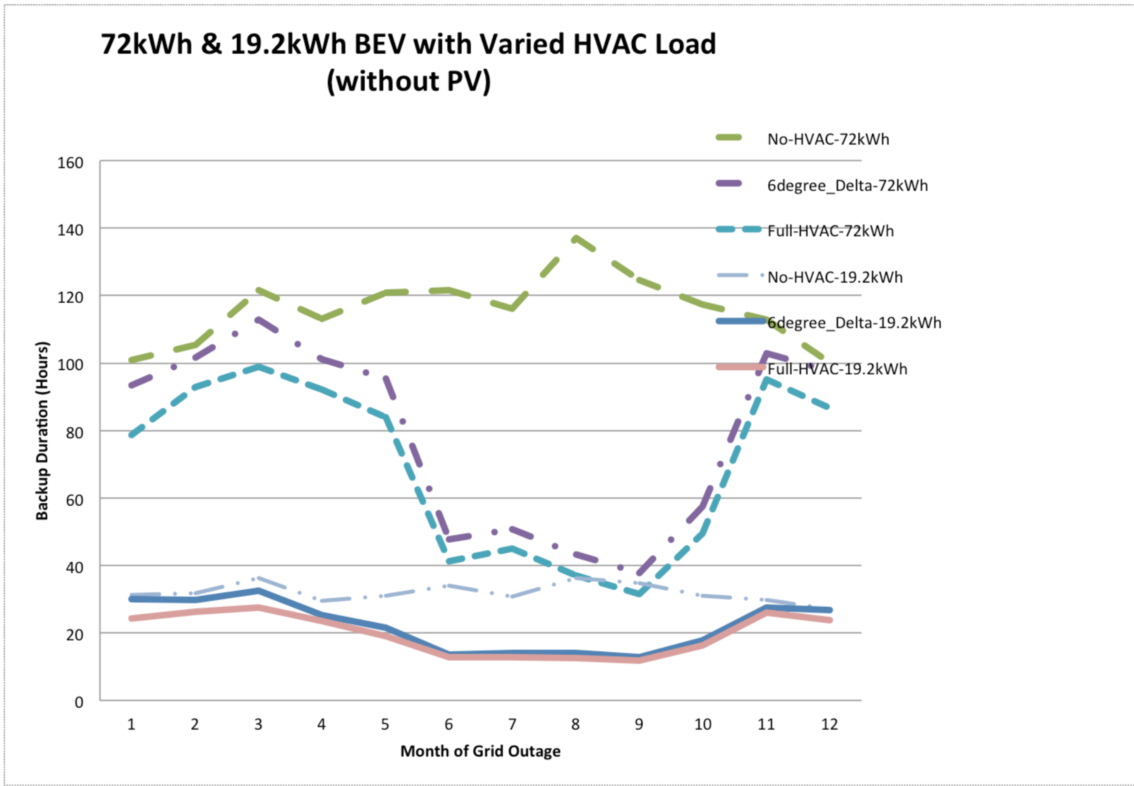

Figure 29: BEV BUDs w/o PV with full HVAC, 6°(F) change, & HVAC off
8 home average for outages starting the 1st day of each month,
with 72kWh & 19.2kWh battery

If no PV is installed on the home, a PHEV V2H system typically has the potential for much longer BUD than a BEV V2H system. The energy density of gasoline is considerable. Even with a modest amount of gasoline and the smallest battery size PHEV, nearly a day of backup can be achieved. By turning the HVAC off, this same PHEV V2H system could extend the BUD to about 3 days.

Without rooftop PV, a PHEV V2H system BUD is most affected by the amount of gasoline stored at the time of grid outage and the load. Also, the PHEV can be disconnected from the home and driven to a gas station to fully refill with a modest amount of residual gasoline held in reserve.

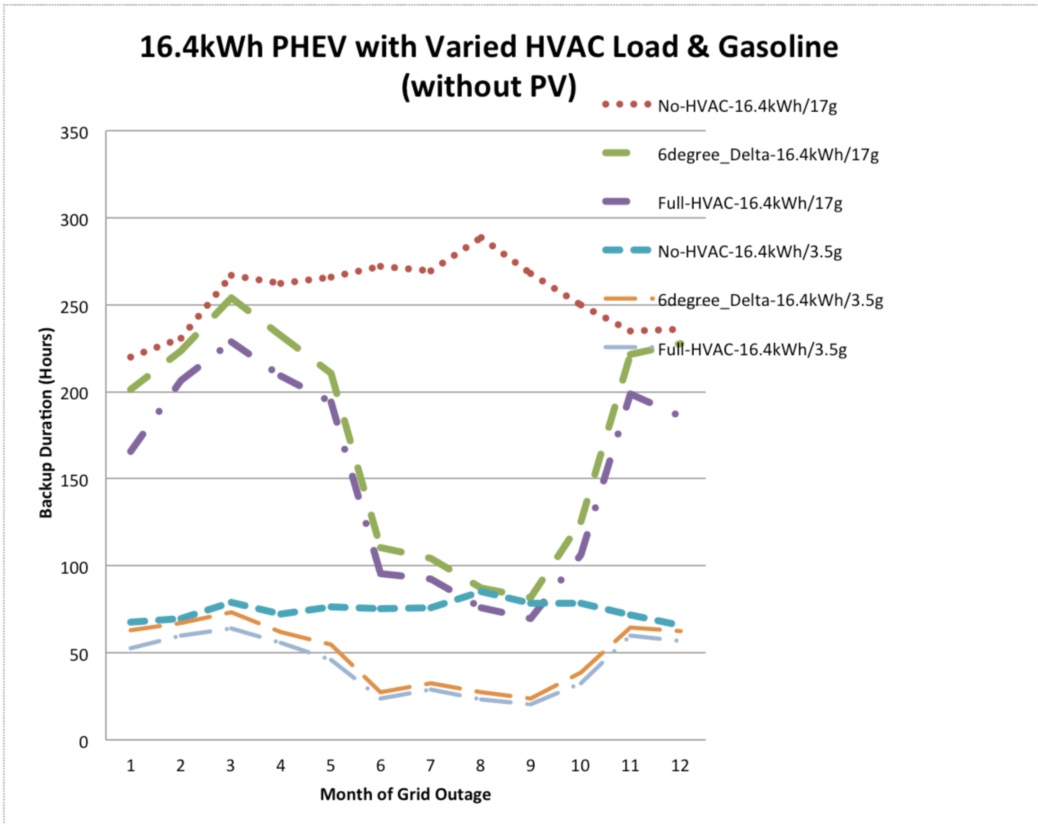

Figure 30: PHEV BUDs w/o PV, with full HVAC, 6°(F) change, & HVAC off
8 home average for outages starting the 1st day of each month, with 16.4kWh battery size, 17 & 3.5 gallon initial gasoline stores

The simulation model was updated for this analysis to assess the potential benefit of deploying enhanced control algorithms for a PHEV V2H system with rooftop PV. The conventional algorithm typically allows the battery SOC to drop to a lower control bound (0% net SOC) with the engine off, then deploys the engine-generator until the battery is charged at a higher control bound (100% net SOC) to achieve efficient operation and low emissions. The original control algorithm is still a good fit for driving or PHEV V2H systems without PV. However, in the morning immediately before the PV production commences, the original engine-generator algorithm deploys to fully charge the battery. With a fully charged battery, if the PV output is greater than the load, the battery cannot store the excess energy. The excess energy is spilled and wasted, reducing the potential BUD. A number of potentially more optimal engine-generator control strategies were formulated that reduce upper SOC control bound in an attempt to improve back-up duration. The upper SOC control bound was set to 100% (baseline), 50%, 20%, and 10% and re-simulated to determine the benefit. The most aggressively modified control algorithm (10% upper bound SOC) improved the average back-up duration a maximum of 8.4% to 43.2% with 16.4kWh/17gallons or 3kWh/3.5gallon PHEV V2H configurations, respectively. **Figure 31** shows the benefit of various improvements to PHEV engine generator control algorithm to reduce spillage and better utilize the initial gasoline stores.

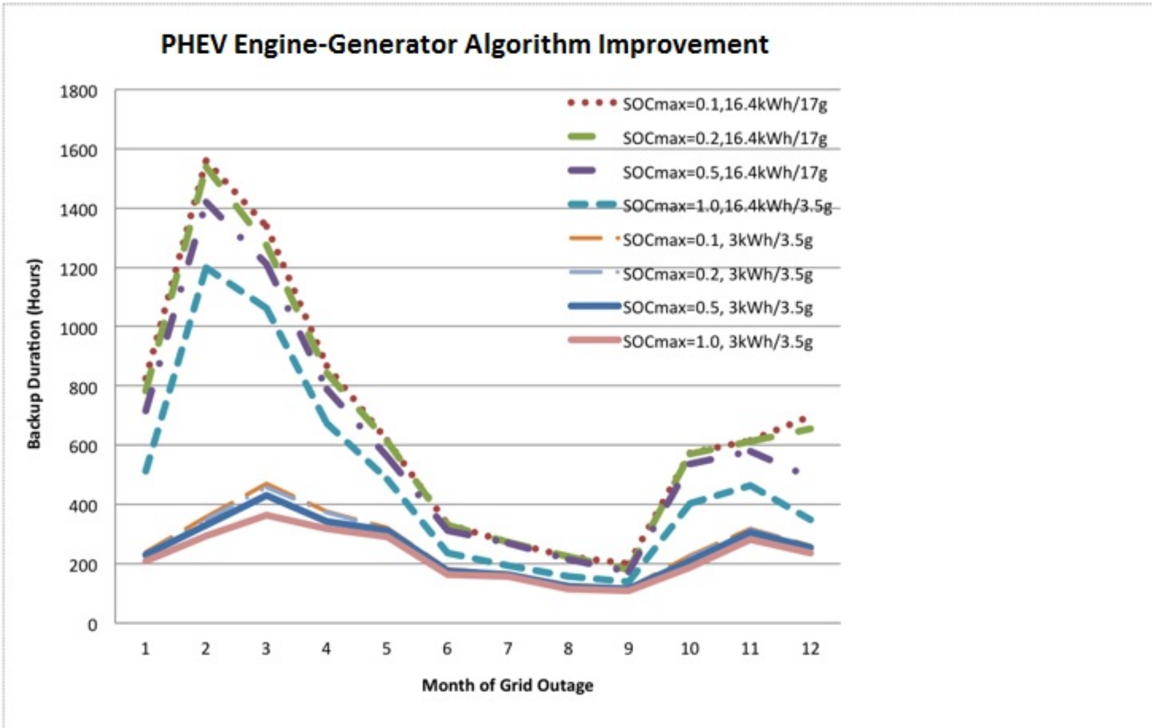

Figure 31: PHEV BUDs with PV, full HVAC, & varied PHEV algorithms
8 home average for outages starting the 1st day of each month, with 16.4kWh & 2kWh battery sizes, 17 & 3.5 gallon initial gasoline stores

Various HEMS load control strategies could be devised for different outage scenarios. If a localized distribution fault with modest outage duration is detected, the HEMS could simply provide seamless backup without any load modifications. If a super-storm or massive grid cyber attack has occurred, the system might significantly shift or limit loads to support essential refrigerator, lighting, pump, communications loads, and provide some level of HVAC conditioning when the energy is otherwise spilled while still maximizing the backup duration until restoration of grid electrical service can occur. Also, intelligent load control may be much more valuable than a considerably more expensive battery under some circumstances.

This analysis assumed initial state of charge was 100% given the lower initial SOC (0) levels can be approximated as smaller BEV battery sizes, the initial SOC can have a negligible impact on the PHEV based V2H system BUD given the relatively large energy stored in gasoline, and the need to reduce the complexity of the analysis. Advanced home energy management system (HEMS) could leverage weather service information to modify the charge rate of the PEV. If a storm is approaching, the HEMS could charge the vehicle as rapidly as possible to achieve 100% SOC before a grid outage.

PHEV based V2H system's relative insensitivity to the initial battery charge level, even with only modest amounts of gasoline available, is an advantage over community level storage solutions that share a battery across multiple homes where the total energy stored may not be sufficient to maintain the load until the rooftop PV can begin production [Fares, 2013].

Battery degradation was ignored in this analysis given the model assumed that the PEV's battery management system (BMS) was used to maintain the vehicle battery state of charge and temperature within typical ranges, two critical factors that can impact battery life. In addition, the V2H system is intended to be an emergency backup during the occasional distribution fault or in the rare aftermath of a long duration grid outage from a super-storm or grid cyber attack. During V2H system activation, the vehicle battery may experience a full cycle of charge from PV and discharge during the night. This single charge/discharge cycle is assumed to be sufficiently equivalent to the regular single day charge/discharge cycle the vehicle may experience while being driven in normal use.

Another observation is that small battery BEV or PHEV configurations suffered higher relative levels of PV spillage. In a small battery V2H implementation, load shifting by a Home Energy Management System (HEMS) would be particularly useful to maximally extend the backup duration.

Some rough system configuration rules of thumb could be created with greater experimentation with the model and more specific load and PV profiles. For example, for continuous load service, the cumulative rooftop PV production would need to be over 124% of the cumulative home load given the round trip system losses assuming a very large BEV battery that experiences minimal spillage.

An indefinitely long BUD could be supported by sophisticated HEMS-V2H system coordination of discontinuous blocks of backup power supported by PV output. Before the battery is fully depleted, the HEMS would shut down the system in order to reserve enough energy to restart the system once PV production resumes (a microgrid equivalent of grid blackstart [ERCOT, 2013]). Also, clever shifting of load to periods that would otherwise have spilled excess energy may be able to lengthen the periods with power.

VI. CONCLUSIONS

Constructing a V2H system with a BEV or PHEV and rooftop PV provides the opportunity to create a self-sustaining single home microgrid with considerable capabilities to provide backup power. For a variety of reasons, grid tied PV systems today must shut down during a grid outage. The vehicle battery function can be combined with a PV systems to allow the continued energy production from the PV system while there is a grid outage to support the home load. The vehicle based storage node and V2H control system can create an off-grid microgrid with appropriate voltage and current regulation, and safety disconnects.

Our latest results indicate that a residential BEV-V2H or PHEV-V2H system coupled with rooftop PV could provide backup power for a considerable amount of time, depending on the time of year and the precise vehicle configuration. With curtailed HVAC load, there were a few large battery configurations where the cumulative PV energy produced could wholly support the remaining while the home was off-grid.

Also, the results of the analysis showed that varying levels of load curtailment and improved PHEV engine generator control algorithms were able to meaningfully extend backup duration of a PEV based V2H system.

Chapter 9: Conclusions and Future Work

I. Summary of Completed Work

The first three chapters provide background on plug-in electric vehicles (PEVs). Despite the common category descriptor of "PEVs," there are substantially different types of electric vehicles with meaningfully varied attributes. A framework for describing these types of vehicles was developed to better guide research into potentially positive and negative interactions with the grid, charging infrastructure, deployment based on potential owner driving habits/needs, and to gain a more clear understanding of where (and when) the vehicles can play a viable role in synergistic interactions with the grid. Given the network effects of vehicles and their related refueling/charging infrastructure combined with the ubiquitous availability of electricity, it is useful to understand that the dominant charging location is expected to be at home overnight, followed by workplace charging, and then public charging. Residential charging is typically extremely convenient since it means having one's own "personal home refueling station" and a supply of fuel at about $1.20 per gallon equivalent.

The different types of PEVs can be most easily categorized as pure battery electric vehicles (BEVs) and petroleum range-extended electric vehicles called PHEVs (plug-in hybrid electric vehicles). The subcategories of BEVs include modest-range 70 to 100-mile range BEVs (such as the Nissan LEAF) and long-range BEVs (such as the Tesla Model S) with up to 265 miles of range. Even with 80% of U.S. drivers daily commuting distances less than 50 miles, modest-range BEV configurations likely require a more substantial investment in the type of home charging infrastructure, the number and power rating of public chargers, and the availability of workplace charging infrastructure to achieve far greater adoption. Modest-range BEVs do not lend themselves to long intercity travel even with the most powerful DC Fast Charging infrastructure. Stopping once every hour to charge for 20 minutes is not likely to be acceptable for most drivers (barring serious petroleum supply interruptions). Long-range BEVs with huge (and presently expensive) battery packs appear to provide more than sufficient range capabilities to eliminate range anxiety for daily commuting. Their large battery enables the ability to avoid the need to seek public charging infrastructure for daily in-town commuting needs and to depend wholly on convenient nighttime charging at home. With large amounts of battery storage on-board, the typical charging focus becomes more related to the daily miles traveled instead of the total battery capacity. That is, with a huge battery, if a driver needs 50 miles of range even a Level-1 120V 1.44kW cord may provide sufficient charging of the battery over night while still meeting occasional additional demands given the usual 12+ hour dwell time at night. Charging deficits can be made up over successive nights given the large size of the battery particularly if 240V Level-2 charging is installed at a home (3.3 to 7.7kW). Long-range BEVs also present a more viable possibility for supporting intercity travel. A 3 hour interstate highway drive with a 30 minute recharge at a 120kW-135kW DC Fast Charger station is nearly on par with realistic long distance travel patterns of conventional vehicles when stretching one's legs, buying refreshments/food, and a visit to the restroom during a long distance trip are taken into account. The limiting factors of this model involve the considerable cost of the batteries (and hence vehicle) at this time and the availability of 120kW+ DCFC stations on intercity travel routes. Tesla demonstrates the technical viability of the long-range BEV with its Model S combined with their "SuperCharger" DCFC network strategically placed on numerous U.S. interstate highways, which facilitates viable travel between typically large cities. As the battery price per kWh continues to (slowly) decline over time, the vehicle manufacturers will have the opportunity to offer long-range BEVs at progressively lower prices. Note that these progressively lower battery prices will also allow manufacturers to increase the range of today's modest-range BEVs, perhaps beyond a threshold of comfort to relieve the century old "range anxiety" of BEVs for typical around-town commuting.

Conventional range equivalent PHEVs (and a specific derivative commercially called an eREV) can provide mostly (or all) electric driving capability for a daily commute combined with an automatic gasoline engine backup to fully support long distance travel on par with today's gasoline vehicles. This combination of electric-plus-gasoline powertrain solves the BEV range anxiety problem at the cost of additional powertrain complexity and cost. The continued advancement of battery/power electronics/range-extender technologies and DCFC networks will lead to an interesting technological race over the next 3 vehicle generations (each generation being 4 to 5 years) to see the evolution and market acceptance of range-extended PHEVs compared to BEVs. The PHEV/eREV powertrain architecture eliminates the need to depend upon public charging infrastructure to meet inter-city travel distance needs (while at the cost of sometimes not driving purely on electricity). This electric-plus-gasoline backup combination lessens the need for very high power DCFC infrastructure (and its demands on grid distribution) and allows drivers to predominately charge conveniently at home overnight just as they charge their mobile phones. Given the shorter electric range with commensurately smaller battery, the charge time or charge rate demands are also much reduced. These factors can make PHEVs more benign to distribution transformer loading from electric vehicle clustering. The gasoline engine backup can also provide drivers who live in multifamily dwellings the opportunity to substantially electrify many or most of their driving if they have workplace charging available, have desired retail establishments that provide charging, or can join charging network providers (such as eVgo) to provide non-home charging facilities

Our research has also included analysis of the technological, market, and policy drivers of emerging trends in the diffusion of PEVs as explored in Chapter 4 and also prior surveys in key technologies to determine which are most likely to be impactful on PEV adoption and use as well as the potential for creating disruptive technological shifts in non-PEV related areas (e.g. PEV adoption enabling grid economic storage). Appendix 1 also includes material discussing the specific technologies.

Chapter 5 included developing a framework for the likely types of PEV-grid interactions and the likely progression of the successively more sophisticated interactions over time. This work is an attempt to articulate the most important factors that affect PEV characteristics, capabilities, and interactions with the grid over the next decade with the progression of function limited by such factors as grid-side communications and control functions, economic grid-vehicle communications, and large-scale/long-term battery experience in extreme customer environments. A likely, or at least possible, progression of PEV-grid interactions is summarized in **Table 4** earlier in this dissertation. In particular, various G2V configurations with 1-way powerflow are likely to be developed well before the advent of full fourth generation two-way powerflow V2G. While the timeframes for the introduction of each generation are likely to be different for various regions, the combination of limiting and interdependent factors described previously may prove the progression to be a generally durable framework.

The framework created four main generations of PEV-Grid interactions. The first generation of mass-market viable PEVs are now available but still in their infancy. PEV-grid capabilities will be defined not only by the rate of technology development but will likely also be guided, accelerated, or limited by the regionally unique financial incentives, regulatory structure and requirements, and values of each participant. It is possible that incremental or breakthrough technology progress may accelerate the progression, but other factors such as communications standards, long vehicle development cycles, and the required grid-side communications and control infrastructure may be constraining factors which may keep the progression of PEV-grid interactions in the same approximate order.

Vehicle manufacturers are fundamentally motivated to create profitable automotive products. Similar to any other vehicle, PEVs will need a compelling combination of design, image, and features while maintaining traditionally high levels of safety and durability to be successful. Some of the advanced two-way communication or two-way powerflow capabilities described in Chapter 5 may not be a priority for the vehicle manufacturers to incorporate for a number of years.

The additional software cost to enable "grid friendly" charge window programming is typically included in the first generation of PEVs available today, adds negligible incremental hardware cost to the vehicle, and provides basic charging start-time or stop-time programming. More advanced grid-advised or renewable generation coincident charging can be enabled in second generation PEVs by more advanced communications capabilities which can relay emission or price related information to the vehicles or deliver grid operator commands to PEVs. In these second generation PEVs, deploying more advanced communications and grid aggregators, the sale of ancillary services such as regulation up/regulation down or emergency load curtailment could produce revenue for the PEV owner by regulating G2V charging of the vehicle.

Third generation PEVs enabling basic two-way power flow for isolated loads in vehicle-to-load (V2L), vehicle-to-home (V2H), or vehicle-to-premise (V2P) configurations adds extra costs, increases the use or stress on the vehicle components, and may increases product liability exposure for the vehicle manufacturer. In V2L, the PEV acts as a contractor site generator with on-vehicle power outlets. A V2H configuration can provide backup power to a home. Multiple PEVs in close proximity could potentially coordinate together to provide a higher aggregate output in a V2P configuration. While supporting two-way powerflow, third generation PEVs avoid sophisticated grid-PEV communication and coordination since they may typically be used in isolated microgrid applications. Free of the dependency upon advanced longer distance external communications and coordination with the grid, third generation PEVs with 2-way powerflow holds promise of commercialization for V2H applications as soon as vehicle manufactures can profitably engineer a sufficiently robust hardware and software solution. V2H was explored in depth in Chapters 7 and 8.

Fourth generation PEVs with full vehicle-to-grid (V2G) capabilities could be useful and financially attractive in regions with high AS prices, with substantial time-of-use price differentials, or deploying premise solar or wind generation that is net-metered back to the grid. The most advanced V2G capability which supports the sale of the most capable set of ancillary services is likely to be limited by the availability of assured PEV-Grid communications as well as the availability of two-way powerflow capability.

Grid participants are typically motivated by increased vehicle-specific energy sales while also avoiding the aggravation of critical peak demand that could force additional capital investments. In order to avoid aggravating peak demand, grid participants may offer rebates for DR enabled EVSEs and attractive tariff programs that encourage off-peak charging. DR-enabled EVSE may also provide the capability to align PEV charging to mitigate the effects of renewable generation intermittency. To encourage PEV adoption will likely first focus on safe, convenient, and cost effective access to charging stations.

Regionally specific circumstances may create compelling economics for certain PEV-grid interactions. Locations with constraints in transmission, distribution, or limited generation may have sufficiently high ancillary services prices that foster PEV-based AS. Otherwise, the most advanced V2G PEV-Grid interactions may require policy actions to foster the needed investments by the relevant participants. Policies which encourage substantially larger deployment of intermittent renewable generation may provide the needed financial incentives to create the communication and control systems to use PEVs as grid storage, fast ramping reserves, or for regulation ancillary services

Chapter 6 includes a discussion of the short and long-term actions that utilities can take to increase the adoption of PEVs. These actions include building charging infrastructure, synergistic tariff design that improves grid costs or emissions while maintaining or improving the costs or convenience for the PEV owner.

As described in Chapters 7 and 8, with their large capacity battery and generator (in the case of PHEVs/eREVs), PEVs also have the potential to provide unique capabilities for their owners for microgrid applications or synergistic grid tied interactions. With V2H/V2P, PEVs can provide high value grid backup to homes or premises as an isolated microgrid. Chapter 7 describes research related to combining a BEV or a PHEV with a PV system to provide the opportunity to create a single-home microgrid with considerable capabilities to provide backup power. PV systems typically must turn off their inverter output if the grid power is lost (or if there is no energy storage to create an off-grid microgrid). With an electric vehicle based storage node, the V2H system can create an off-grid microgrid that has the sufficient voltage regulation, energy storage, and safety disconnects. Our early results indicate that a residential V2H system coupled with rooftop PV could provide backup power for approximately 19-600 hours, depending on the time of year and the precise vehicle configuration. The research shows that particularly with curtailed or shifted load during a grid emergency situation, an electric vehicle based V2H-PV microgrid system could provide considerable backup duration capability supporting the conventional home load. More recent research discussed in Chapter 8 explored the benefits of improved PHEV engine generator control algorithms and selective load curtailment could further extend backup duration. Furthermore, sophisticated V2H control systems could save a modest portion of remaining battery power to blackstart the PV system to enable self-sustaining non-continuous power indefinitely.

Understanding the financial costs or payback (higher up-front purchase price, but lower operating and maintenance costs, for example) compared to a conventional vehicle are relevant to better understand the adoption rate, essential cost sensitivity of key technology underpinnings, the rate at which the initial cost disadvantage is likely to decline, and where PEV-Grid interactions may have compelling non-conventional applications (such as V2H). This research (summarized in Appendix 2) is useful to understand when PEVs adoption may accelerate up the “S-Curve” with a total cost of ownership on par or superior with conventional vehicles (without government subsidies), the costs of the different PEV architectures, and the possible (if not probable) direction of PEV architecture directions which can have implications to PEV-grid interactions. From this research, our best estimate is that there will be a plethora of range-extended PHEVs offered with substantially different attributes, modest range BEVs will gain more range as battery prices decline, and long-range BEVs will potentially decline in price (however their price may still only decline to the lower-end of the luxury segment by 2025).

In summary, the research shows that PEVs are a viable long-term alternative powertrain technology and that connected to the grid, PEV charging can be intelligently controlled to improve the emissions, grid stability, or improve economics of the electric grid.

II. FUTURE WORK

V2H

In our early V2H research, it was discovered that a commonly used PHEV engine/generator control algorithm could contribute to PV energy spillage. As the battery supports the load overnight, the SOC can drop below the lower SOC control bound triggering the engine/generator to be deployed until the battery is charged to the upper SOC control bound. The most inopportune time for this event to occur is the early morning immediately before PV production starts. Once PV production starts in the morning, the battery can be nearly fully charged leading to meaningful amounts of PV-produced energy being spilled (and wasted) since there is little spare battery storage capacity. In the later research, a number of alternative control algorithms that may increase overall backup duration are explored and assessed for their benefit. The first alternative involves reducing the battery SOC upper control bound to reduce PV spillage. This mode would reduce the period of time the engine/generator is deployed after reaching the battery SOC lower control bound that triggers the engine/generator to start. This strategy was shown to reduce spillage, however the cost of additional engine start-up efficiency loss due to "cold start over fuel" while the engine is cold was not assessed. Further analysis would incorporate the efficiencies lost from over-fueling during the cold start until the engine is sufficiently warmed until the injected fuel quantities reach levels associated with normal engine operating temperatures. Consideration for the length of time the engine control can avoid repeating cold-start-over fuel from cooling while the engine is off should be considered in the algorithm and simulation.

Another more complex strategy to explore would involve reducing the round-trip energy losses (generator-power electronics-battery and then battery-power electronics-home load) and reduce spillage by operating the engine/generator at a varied output to match the home load when the PV system cannot serve the home load by itself. With the 1-way losses estimated to be about 12% (24% round trip), as long as the varied control reduces overall engine efficiency by less than 24%, then the backup duration might be further improved. Since engine/generator efficiency versus RPM/Load data may be confidential to PEV manufacturers or difficult to obtain without expensive automotive testing equipment, clever methods to estimate these values are likely required.

The model developed for the V2H research described in this dissertation could be further enhanced in a number of ways. A PV output scaling factor and variable battery size parameter could be incorporated to assess the combinations of larger (or smaller) rooftop PV systems along a wider variety of battery sizes on the back-up duration. This additional flexibility would be helpful for a user to tune a system for their desired BUD and hardware cost objectives. In addition, the model could be extended to include more sophisticated load analysis and management techniques [Perez, 2015] to extend the BUD in continuous back-up mode or to minimize the microgrid power unavailability during non-continuous operation.

Commercial availability of V2H systems will likely depend upon a number of developments. Vehicle manufacturers will need to offer the V2H function as an additional cost option on their PEVs. These manufacturers are more likely to offer this function after they have considerable field experience over a number of years with their electric vehicles in harsh or abusive customer usage environments. They may also wait until common interfaces, couplers, communications protocols, and safety standards needed to enable interoperability between different vehicles and V2H equipment manufacturers are developed. An electronic unit that contains the combined functions of an EVSE (likely to be a relatively modest power DCFC version), an inverter to convert the PEV high voltage traction battery's output to 240V ac, the overall microgrid control system, and a transfer switch would provide the fundamental hardware building blocks for the V2H system. A further enhancement may be to also incorporate the PV inverter function with the EVSE, PEV inverter, controller, and transfer switch. Future research could include prototyping or detailed circuit simulation of the V2H components together to characterize the overall system performance and gain insights on additional improvements.

APPENDIX 1: RELATED TECHNOLOGY TRENDS

Key Technology Trends Affecting PEV Adoption and Use

The rate of PEV adoption and use, as well as their environmental and other implications, will depend on a variety of trends that are expected, but with uncertain rates. These include battery technology, power electronics, charging infrastructure, and Grid-PEV communications. These technologies are discussed briefly in turn here.

Automotive-grade Batteries

Battery costs are the most significant contributor to the price premiums of PEVs over conventional vehicles. A number of factors lead to the expectation that battery costs will decline over time.

As well as improvements in battery cell chemistry, cell manufacturing cost reductions, and competition driving down the costs of the batteries themselves, automotive engineers can improve the vehicle designs so there is a lesser demand for the total amount of energy storage. Engineers are expected to enhance control algorithms, which will improve efficiency and enable battery downsizing as more is learned about battery wear mechanisms from field experience. Electrical energy required for cabin heating and cooling directly reduces PEV range, so weather conditions become relevant. It is reasonable to expect efficiency improvements in electrically driven PEV heating and air conditioning systems and cabin insulation to further reduce demands on the battery. Traction motor energy demands can be further improved by reducing vehicle mass. Vehicle "light weighting" is a concept that is likely to be increasingly deployed on all types of vehicles to improve efficiency. A lighter vehicle mass from aluminum or carbon fiber construction would reduce the size and cost of the batteries needed. Also, improved energy recapture through advances in regenerative braking is likely, through innovations like ultracapacitor/battery combinations.

PEV batteries appear to have substantial potential for cost reductions as production volumes increase [Santini et al. 2010], perhaps to $150/kWh with large volumes from $1000/kWh a few years ago. The overall incremental price of a PEV driven by the battery cost is likely to decline from a combination of lower battery prices and an ability to use smaller battery pack size while maintaining range and through other vehicle innovations mentioned previously. A decade ago Hybrid vehicles had similar cost disadvantages to conventional vehicles as PEVs do today. Advanced battery technology has improved such that today's hybrids are now cost competitive (**Figure 32**). As battery prices per kWh decline further, vehicle manufacturers will have the ability to incorporate a greater degree of powertrain electrification while maintaining competitive vehicle retail price levels. The continuum of powertrain electrification includes mild hybrids, strong hybrids, PHEVs/eREVs, modest range BEVs, long range BEVS (and perhaps Hydrogen Fuel Cell vehicles).

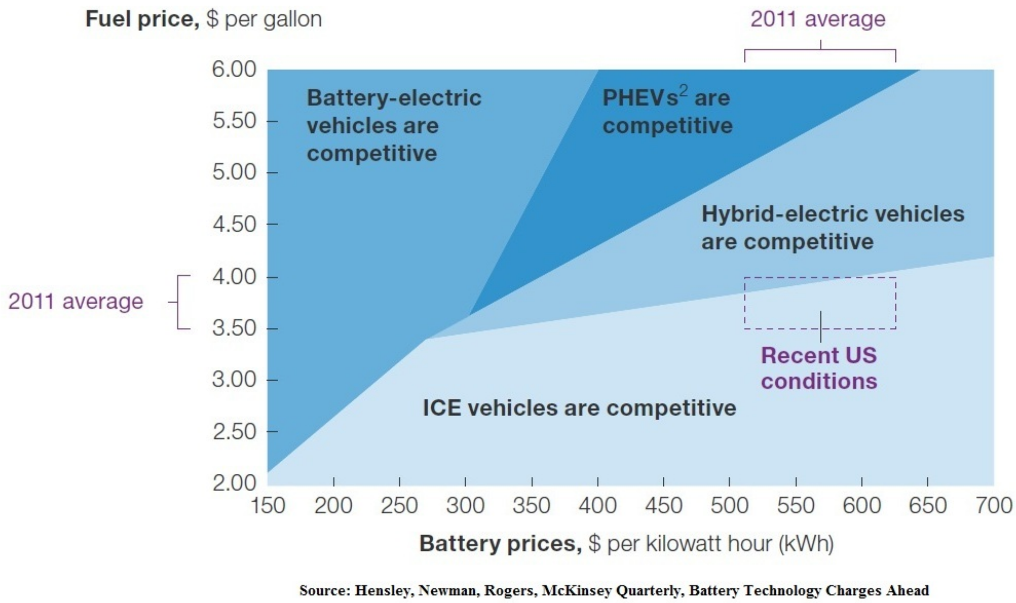

Figure 32: Battery & Gas Price effect on PEV/HEV Cost Competitiveness

There are two dominant form factors of Lithium batteries used in automotive applications today. Cylindrical 18650 cells used by Tesla (and in powertrains that are licensed from Tesla) and prismatic cells used by most other PEV manufacturers. Cylindrical 18650 cells (18mm x 650mm, slightly bigger than a AA battery) are used in laptop computers with considerable production volumes worldwide (**Figure 33**). Prismatic cells (approximately the size of an iPad) are asserted by some engineers to be better optimized for automotive applications (**Figure 34**).

Figure 33: 18650 Battery

Figure 34: Automotive Prismatic Form Factor Battery

Of great interest is the technology competition between 18650 and prismatic cell formats. The combination of laptop and automotive applications can drive further commoditization and lower prices of 18650 cells. Compounding this improvement over time implies that unsubsidized deployment of PEVs may occur within 10 to 15 years at costs near equivalent to conventional vehicles. There is speculation that Tesla cell cost is already near $250/kWh. Automotive-grade prismatic Lithium batteries have relatively small amounts of global sales at this time but as more vehicle manufacturers incorporate prismatic cells in a greater variety of models, the increased volumes will likely reduce prices over time. Importantly, this battery competition may eventually reduce the overall cost of energy storage to a level that makes grid-level storage cost competitive. Credible sources estimate the rate of cost/energy-density improvement to average 5% per year [Voelcker 2012]. DOE studies [DOE 2013b] discuss a $250/kWh near term system cost target and a $150/kWh long-term target for viable deployment.

Power Electronics

While the mechanical systems of a PEV can be much more simple (and potentially more reliable) than a conventional vehicle, the power electronics content of a PEV (or Hybrid) is typically far greater than a conventional vehicle. With each successive 4 to 5 years generation of PEV/HEV, the power electronics advance to become a combination of more volumetrically dense, more efficient, capable of more power delivery, and/or lower cost. While power electronics may not be improving at a Moore's Law equivalent rate, they are expected to continue to improve in costs and capabilities similar to other semiconductor based technologies over time. Anecdotal data from a number of vehicle manufacturers suggests that over the course of 2-3 vehicle generations the power electronic advancements will contribute to substantially reduce the initial purchase price premium of PEVs.

Charging Infrastructure

While Level-1 120V charging at home typically requires no initial investment, there still are advantages to the permanent installation of a 240V Level-2 EVSE. A Level-2 charger will have its own dedicated circuit. A recent installation will allow a licensed electrician to assess the condition of the home's wiring, breakers, and service and upgrade equipment as safety and budget dictates. And a Level-2 EVSE with communications capability may enable the PEV to participate in Demand Response (DR) programs that then qualify for an equipment rebate or lower energy prices. Generally, the focus for home charging will be reducing the cost of Level-2 charger hardware and installation costs while also eventually providing inexpensive communications to enable DR. Home charging rates will likely stay below 7.7kW (240V x 32A nominal).

Workplace charging is presently offered to attract, motivate, or retain "creative class" employees who may also happen to be PEV early technology adopters or as part of a corporate sustainability program. As PEV adoption grows, businesses will likely decide that if they are effectively competing with gasoline stations as a refueling location, they should at least break even financially or perhaps make a small fee as they do for their on-site vending machines or cafeterias. The relatively long dwell time and broader demand for workplace charging may foster a greater adoption of slow (but sufficient) lower-cost Level-1 charging with transaction systems which compensate the employer but avoid the legal issue of reselling electricity.

The many varied challenges of public charging include lower-cost Level-2 EVSEs for retail shopping locations, lower cost DCFC installations (and methods to mitigate demand/capacity charges), convergence of wireless charging standards for stationary charging (both by non-autonomous and autonomous PEVs), dynamic wireless charging where the vehicle picks up charge from conductors in the road, and battery pack standardization to improve the economics of battery swapping.

Homes are expected to be the predominant charging location [PUCT 2010]. More charging points are expected to be installed over time to support potential PEV buyers who do not have a home garage. Work, apartment building, and public charging options are far more important for modest range BEVs than for eREVs and PHEVs. It is likely that PEV drivers without garages will favor eREVs/PHEVs, have reasonable charging options at work, and/or live in a community with strong commitment to (and investment in) public charging. With more pervasive deployment, shorter daily commuting distances, and better mass-transit systems alternatives, European and Japanese markets may experience much greater shares of BEVs (as compared to eREVs/PHEVs) than in the U.S. and much greater PEV adoption rates overall.

Grid-PEV Communications

The first generation PEVs available today typically have on-board communications capabilities integrated in the form of OnStar, CarWings and other proprietary cell phone based communications systems designed into the vehicle by the manufacturer. This two-way communications technology can enable the manufacturer to run diagnostics of the vehicle, download software updates to the vehicle computers, provide battery and charging status, and participate in demand response programs. However, the cost of these telematics services through the vehicle manufacturer may strongly encourage the utilities to create alternative methods to intelligently manage the charging of the vehicles. Viable alternative communications pathways include WiFi enabled EVSEs that leverage a homeowner/PEV driver's existing broadband connection, or a ZigBee equipped EVSE, which communicates through a ZigBee enabled SmartMeter to the utility. The deployment of more advanced communications will likely be driven by the economics of DR programs for the utility. A mix of cost reduction of the hardware, installation, and utility management software combined with an increased value of peak-shaving DR, for example, may eventually trigger much greater deployment.

Residential Energy Pricing

Electricity is an essential good and hence typically served by utilities with oversight from public utility commissions, self-owned co-operatives, and/or other forms of democratically elected oversight bodies (in the case of municipally-owned utilities). For the foreseeable future, retail energy prices (and customers) are unlikely to be subjected to real-time price fluctuations (with a market clearing price determined every five to 15 minutes, for example) as wholesale power prices are today. Time-of-Use (TOU) rates presently differ from real-time rates in that they typically offer just two rates per day: peak and off-peak. Time-of-use rates also may have different peak/off-peak rates for summer and winter seasons, to provide incentives for efficiency during the most stressful, seasonal peaks, and to encourage load shifting to off-peak periods.

The ability to improve the effectiveness of incentives for energy efficiency have been moderated in the past by the relatively low price of energy, and an inability to precisely estimate the benefits of energy-saving behaviors and investments given the only data available is a total-energy bill received at the end of each month. Time-of-use rates which are expected to continue to provide attractive energy costs during the expected dominant night time PEV's charging period. Regulating entities are highly unlikely to support substantially raising off-peak retail rates as a policy as they are typically resistant to allowing any rate increase. Experience has shown that even in the highest electricity cost regions, nighttime electricity energy rates can still be relatively low. Prior studies have shown that using manual human intervention in order to foster substantial consumer electricity demand shifting, substantial rate differences are required between the higher cost peak time periods and the lower cost off-peak times. With automation and a large flexible PEV load, this impediment becomes far less problematic. It is important to note that a significant portion of the grid's value to customers for the past century has been providing as much energy as a homeowner desires, whenever they want it, at an attractively low cost (relative to other energy options) and importantly delivered with great simplicity: Customers simply plug their devices into the wall. Given the compute power already incorporated into PEVs and the relatively low compute intensity of intelligent charging programs, the major impediment to deploying progressively more sophisticated and synergistic charging are the generation of signals from grid operators, and communications pathways to the vehicles.

Utilities face an inherent dilemma: lower CO_2 emissions imply either lower carbon content generation (generally more expensive or sometimes intermittent) and/or lower energy sales with resultant lower revenues. Lower energy sales lead to greater challenges covering fixed costs, which can strain the utilities finances or force it to seek higher rates from regulators (where applicable). PEV energy sales provide a means for utilities to offset their residential energy sales lost to structure energy efficiency improvements while improving overall (vehicle plus generation) CO_2 emissions. The incremental costs to lower generation emissions can be reduced by deploying intelligent PEV charging which can mitigate the intermittency and associated costs of low/zero emissions renewable generation.

In order to optimize the charging of vehicles, it would be instrumental for regional independent grid operators (ISO) to provide either real time emissions or price information for utilities to use as signals to intelligently manage PEV charging.

Travel Patterns/Modes/Planning

While both PHEVs and BEVs are grid connected, BEVs will likely foster a greater variety of behavioral changes. Even with a 100-mile claimed AER, more planning for the day's travel will be required for a modest-range BEV that can typically travel about 70 miles in real world conditions. This overhead will be driver specific and may not be meaningful if daily travel distances (e.g., the work commute) do not vary greatly or are short. When the daily drive is less predictable rental or ownership (and use) of a second conventional vehicle or the ability to conveniently search for available public charging stations may be essential. BEV owners may be much more "interconnected" through the use of their vehicle telematics (communications plus navigation) systems that can guide them to pre-reserved public charging stations. It is possible that this overhead may decrease (or vacillate) over time, with improvements in the availability of public charging stations but then worsen with more PEVs on the road competing for these stations. Long-range (but expensive) BEVs greatly reduce if not eliminate, daily commuting range anxiety concerns, but still required significant long-trip planning.

The range anxiety of a BEV might also be solved via non-technological solutions. For example, manufacturers may sell BEVs with attractive car rental arrangements at their dealerships for longer range and or less conventional vehicle types. Rental options are very likely to include SUVs, pickup trucks and minivans, for example, to accommodate less regular – but important – trip making, including weekend camping trips or furniture moving days. Such strategies can help a variety of U.S. households – and others around the globe – "downsize," offering a potentially dramatic long-term gasoline savings, by moving household ownership trends away from the light-duty-truck fleet. This strategy may also provide less risk of remote repair. If an accident or break-down occurs, the renter simply and quickly gets another vehicle to continue their trip without the need to search for a reputable repair shop or wait for the repair. Also, dealer rental programs may have the advantage of bringing the PEV owner into the dealer for service, enhancing the dealer-consumer and manufacturer-consumer relationships.

APPENDIX 2: PEV FINANCIAL PAYBACK TODAY AND 2025

FINANCIAL ANALYSIS OF PEVs AND COMPARABLE CONVENTIONAL VEHICLES TODAY[9]

As U.S. and other consumers now enjoy the choice of a BEV and eREV, full-cost accounting becomes a factor in new-technology adoption rates. There are many factors to consider beyond base price and fuel costs. The durability of PEVs' advanced Lithium batteries is a justifiable concern, given the technology's relative immaturity. A total-cost-of-ownership analysis should also include likely maintenance or repair costs and potential battery replacement costs.

A key assumption for asset payback comparisons is lifetime use, or vehicle miles traveled in the case of PEVs. A National Highway Traffic Safety Administration report [Lu 2006] finds average U.S. personal-vehicle lifetimes of 156,000 miles. This average lifetime is skewed high by pick-ups and SUVs, which tend to be used over more time and for greater distances (and thus average closer to 180,000 lifetime miles). Mid-size and compact cars, such as these PEVs and their conventional twins, typically are used less. To reconcile such statistics, the following calculations assume consumers evaluate range-extended PEVs (like the Volt eREV and the Prius PHEV) over a 15-year, 150,000-mile horizon (typical of the average U.S. light-duty vehicle). Given their shorter range and longer charge times, BEVs are likely to achieve higher adoption rate among households with lower-distance needs. The base BEV analysis thus assumes a 15-year, 100,000-mile life. Included in the cash flow are estimates of expected maintenance costs from interviews with Chevrolet, Nissan, and Toyota service managers. While informal, such data provide insight and fairly accurate estimates on the differences in relevant costs. For

[9] Tuttle, D., K.Kockelman, *ELECTRIFIED VEHICLE TECHNOLOGY TRENDS, INFRASTRUCTURE IMPLICATIONS, AND COST COMPARISONS*, Transportation Research Forum 51 No.1: 35-51, 2012.

example, HEV experience suggests that vehicles with regenerative braking exhibit substantially less brake wear than their conventional counterparts. Many Prius owners never experience the need for expensive brake service. This analysis assumes that the front and rear brakes are replaced at 40,000 and 60,000-mile intervals, respectively, on conventional vehicles. These assumptions imply that the comparable conventional vehicle will require three sets of front brakes and two sets of rear brakes over the 150,000-mile lifetime. For the BEV comparison, the Nissan Versa was assumed to have two front brake replacements and one rear brake replacement over its 100,000-mile lifetime.

Chevrolet and Nissan have both announced eight-year/100,000-mile battery warranties on their respective PEVs. For this analysis, if a battery is replaced, it is expected to occur during the ninth year, immediately after the warranty expires, which is a conservative assumption (in favor of conventional vehicles). Given the likelihood of second-use applications for such batteries (e.g., grid power and computer backup power storage devices) and falling battery costs (thanks to scale economies in production and accelerating competition), net replacement costs may lie close to Argonne National Laboratory's recent higher volume projection of $150/kWh [Santini et al., 2010]. Continued improvements in battery energy density are expected over time. These improvements can be applied to achieving greater range or reducing ownership costs. If customers indicate a satisfaction with 73 to 100 miles of AER, future battery packs may be smaller with fewer cells, and therefore less expensive.

This chapter provides the net present values (NPVs) of the *differences* that will emerge in cash flows for a PEV *relative to its conventionally fueled counterpart*. A positive NPV should be interpreted as the higher initial PEV purchase price is fully offset by the future savings from lower operating and maintenance costs. A negative NPV implies that the future savings do not offset the higher PEV purchase price. NPV calculations involve standard accounting equations to find the present-day value of a series of current and (discounted) future costs (and revenues or other benefits, when those exist). Since future gasoline and Lithium battery prices are unknown, NPV values were computed for each PEV/conventional vehicle comparison over a wide range of price assumptions, as shown in **Tables 6 through 9**. Table values illuminate the impact of higher or lower fuel prices and battery replacement costs on the net, long-term monetary benefits of buying a PEV over a conventional vehicle. As one would expect, higher gasoline prices and lower battery replacement costs result in a higher NPV of a PEV over its conventional counterpart.

Table 6's values assume a 5% discount rate and 100,000-mile vehicle lifetime for the Nissan LEAF BEV over its comparably equipped conventional twin, the Nissan Versa. With the $7,500 federal tax credit included and no battery replacement required, the NPV remains positive for gasoline priced as low as $2.75/gallon. The BEV LEAF avoids not only brake replacement costs but also regular oil and filter changes, which should generate greater savings for its owners. By looking at NPV entries in **Table 6** close to $7,500 (the assumed tax credit), it can be deduced that without a tax credit, the LEAF is estimated to offer cost savings (i.e., have a positive NPV) at gasoline prices between $5.50 and $6/gallon (again assuming no battery replacement). If battery replacement is required post warranty, the break-even gasoline price (where the LEAF offers no long-term owner savings or cost over the Versa) is estimated to increase by approximately $0.66/gallon for each $100/kWh increase in battery replacement cost. The implications of increased battery replacement-costs and their effect on higher gasoline prices to maintain the same NPV can be seen by simply examining pairs of similar NPV values in the table (e.g., values of $1,969 and $1,927 in **Table 7**). Thus, for every

$100/kWh increase in battery replacement cost, the gasoline price must rise approximately $0.66/gallon to maintain the same NPV

Similar calculations with a discount rate of 10% (which can be common among consumers who have short term focus or who greatly discount future savings) reduces the benefit of the BEV's future fuel and maintenance savings (but also battery replacement cost implications) such that the NPV becomes slightly negative (-$932) with the tax credit in place and gasoline at $3.00/gallon. When discounting at 10%, a gas price of about $8 per gallon (still below that in many EU countries) is required for the LEAF to break even with the Versa (i.e., zero NPV) without any tax credit and with a relatively low lifetime vehicle miles traveled (VMT) of 100,000 miles, as stated earlier and noted in the table.

Given its lower travel-distance assumptions, the LEAF's fuel and maintenance cost *savings* are reduced. 100,000 miles over 15 years averages to less than 19 miles per day, well below the 100-mile nominal range (and below its worst-case harsh-weather range). If this short range does represent the typical driving pattern, then this very low reliance on the battery's capacity could lead to far lower stresses and failures and contribute to greater durability and battery life. If the miles driven are increased, the fuel and maintenance costs savings over the conventional Versa also increase, improving the NPV for the LEAF (**Table 8**). A lowest-cost scenario would maximize miles driven while avoiding battery replacement. Noting that the eight-year/100,000-mile battery warranty expired from age (not mileage) after eight years one may expect the battery to last the 15-year/100,000-mile life of the vehicle (since the battery would then be lightly stressed in this scenario).

Table 7: Net Present Values of Nissan LEAF vs. Versa (100k-mile life)

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$10,042	$7,721	$6,174	$4,627	$3,080
$6.50	$8,889	$6,568	$5,021	$3,474	$1,927
$6.00	$7,735	$5,415	$3,868	$2,321	$774
$5.50	$6,582	$4,262	$2,715	$1,167	($380)
$5.00	$5,429	$3,108	$1,561	$14	($1,533)
$4.50	$4,276	$1,955	$408	($1,139)	($2,686)
$4.00	$3,122	$802	($745)	($2,292)	($3,840)
$3.50	$1,969	($352)	($1,899)	($3,446)	($4,993)
$3.00	$816	($1,505)	($3,052)	($4,599)	($6,146)
$2.50	($338)	($2,658)	($4,205)	($5,752)	($7,299)

Assumptions: 5-% (real) discount rate; 100,000 miles over 15 years; Versa: 30 miles/gallon; LEAF: 73-100 miles AER, 2.94 miles/kWh (electric); 6,667 miles/year; electricity cost: $0.1175/kWh; battery replacement in year nine (after eight year warranty's expiration); 2011 LEAF price of $25,280 (after $7,500 U.S. federal tax credit); 2011 Versa at $19,840 (comparably equipped to LEAF); Terminal values of both vehicles assumed equal.

Table 8: Net Present Values of Nissan LEAF vs. Versa (150k-mile life)

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$18,128	$15,807	$14260	$12,713	$11,166
$6.50	$16,398	$14,077	$12,530	$10,983	$9,436
$6.00	$14,668	$12,347	$10,800	$9.253	$7,706
$5.50	$12,938	$10.617	$9,070	$7,523	$5,976
$5.00	$11,208	$8,888	$7,340	$5,793	$4,246
$4.50	$9,478	$7,158	$5,611	$4,063	$2,516
$4.00	$7,748	$5.428	$3,881	$2,333	$786
$3.50	$6,018	$3,698	$2,151	$604	($944)
$3.00	$4,288	$1,968	$421	($1,126)	($2,673)
$2.50	$2,558	$238	($1,309)	($2,856)	($4,403)
Assumptions: 5% (real) discount rate; 150,000 miles over 15 years; Versa: 30 miles/gallon; LEAF: 73-100 miles AER, 2.94 miles/kWh (electric); 6,667 miles/year; electricity cost: $0.1175/kWh; battery replacement in year nine (after eight year warranty's expiration); 2011 LEAF price of $25,280 (after $7,500 U.S. federal tax credit); 2011 Versa at $19,840 (comparably equipped to LEAF); Terminal values of both vehicles assumed equal.					

Table 9 contains the NPVs calculated using a 5% discount factor for the Chevrolet Volt over its comparably equipped conventional twin, the Chevrolet Cruze. With the $7,500 tax credit included and no battery replacement required, its NPV becomes positive when gas costs $3.00/gallon or more and reaches a maximum at $7.00/gallon (the highest gas price assumed in the U.S., but can be relatively common abroad). As with other PEVs and hybrids, the Volt should avoid brake replacement costs but will still require oil and filter changes at least every two years, according to the Volt owner's manual (compared to the Cruze's twice-a-year or every 5,000-8,000 miles recommendation). The table's NPV entries are $7,500 at slightly more than $5.00/gallon (without battery replacement), suggesting that without the tax credit, the Volt enjoys a

positive NPV advantage at gas prices above the $5/gallon price level. Interpolating from **Table 9** entries $5601 and $5699, if battery replacement is required post warranty, interpolating across table entries the gasoline price must increase approximately $0.29/gallon for each $100/kWh increase in battery replacement cost to maintain the same NPV. This $0.29/gallon is much lower than the $0.66/gallon computed for the LEAF/Versa comparison, due to the fact that the Volt's battery is 33% smaller than the LEAF's and fewer annual miles were assumed for the range-limited LEAF. As discussed earlier, discounting at 10%[10] reduces the benefit of future fuel and maintenance savings (but also the cost of the battery replacement in the out years) such that the NPV is a negative $928 with the Federal Tax Credit, no battery replacement, and gasoline at $3.50/gallon. A gas price of about $6.60/gallon is required for zero NPV (where the Volt and Cruze have equal long-term costs) without any tax credit using a 10% discount rate.

The fuel and maintenance costs savings for the Volt extend to 150,000 miles. This total vehicle life yields an average daily usage of less than 29 miles per day – and thereby within the Volt's 35-38 mile all-electric range. Hence, all 10,000 yearly miles traveled are assumed to be electrically driven. GM has indicated that the battery failure mode may be a degradation of storage capacity instead of a sudden total failure. If all 10,000 miles traveled are electrically driven, the battery may last the entire 15-year/150,000-mile life of the vehicle and still meet the 29-mile average daily driving need.

Table 9: Net Present Values of Chevrolet Volt (eREV) Over Chevrolet Cruze

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$14,869	$13,322	$12,291	$11,259	$10,228
$6.50	$13,205	$11,468	$10,437	$9,406	$8,374
$6.00	$11,162	$9,615	$8,584	$7,552	$6,521
$5.50	$9,308	$7,761	$6,730	$5,699	$4,667
$5.00	$7,455	$5,908	$4,877	$3,845	$2,814
$4.50	$5,601	$4,054	$3,023	$1,992	$960
$4.00	$3,748	$2,201	$1,170	$138	($893)
$3.50	$1,894	$347	($684)	($1,715)	($2,747)
$3.00	$41	($1,506)	($2,538)	($3,569)	($4,600)
$2.50	($1,813)	($3,360)	($4,391)	($5,422)	($6,454)
Assumptions: 5-% (real) discount rate; 150,000 miles over 15 years; Cruze: 28 miles/gallon; Volt: 40 miles AER, 2.78 miles/kWh (electric); cost of electricity: $0.1175/kWh; Battery replacement in ninth year (after eight-year warranty's expiration); 2011 Volt price of $33,500 (after $7,500 Federal Tax Credit) vs. 2011 Cruze at $25,100 (comparably equipped to Volt); Terminal values of both vehicles assumed equal.					

Table 10 contains the net present values calculated using a 5% discount factor for the Toyota Prius-PHEV over a comparably equipped conventional twin, the Toyota Corolla. With the $ 2,500 tax credit included and no battery replacement required, the NPV is positive for gasoline values nearing $3.75/gallon. As with other PEVs and HEVs, the Prius-PHEV should avoid brake replacement costs but will likely still require yearly oil and filter changes (compared to the recommended twice yearly/5,000-8,000 mile interval for the Corolla). Looking for NPV values near $ 2,500 in the table, the lower-cost benefit of the relatively small 5.3kWh battery is apparent, since NPVs become positive – even without this PHEV's $ 2,500 tax credit – at gas prices of just slightly less than $3.25/gallon (again assuming no battery replacement). From **Table 10**, given lower battery replacement costs overall (due to smaller battery size), for each $100 increase in

Prius PHEV replacement battery costs increases the gasoline price by only \$0.15/gallon to maintain the same NPV (versus \$0.66 in case of the LEAF and \$0.29 for the Volt). As before, annual discounting at 10% (for more risk-averse or myopic buyers) will reduce the benefit of future fuel and maintenance savings (but also reduces the present value of battery replacement) such that the NPV of the Prius PHEV (over a Corolla) offers a positive at about \$3.10 per gallon, with a tax credit and assuming no battery replacement. A gas price of about \$5.90/gallon is required for a break-even condition, without any tax credit (and no battery replacement).

The fuel and maintenance costs savings for the Prius-PHEV extend to 150,000 miles. As noted earlier, this assumption implies an average daily usage of 29 miles per day. Given Toyota's initially announced intention of a 15 mile AER, just 15 miles are assumed to be driven electrically, and the remainder uses gasoline to provide a reasonable approximation of fuel consumption. It is interesting to note the lower gasoline-price break-even points without tax credits given the Prius-PHEV's smaller battery and modest AER, but lower purchase price premium. These results are consistent with prior PEV architecture cost studies [Vyas, et al 2009]. In addition, if a replacement battery is required, it should be considerably less expensive, given the smaller size.

Table 10: Net Present Value of Toyota Prius-PHEV Over Toyota Corolla

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$8,548	$8,035	$7,693	$7,352	$7,010
$6.50	$7,237	$6,725	$6,383	$6,041	$5,700
$6.00	$5,927	$5,414	$5,073	$4,731	$4,390
$5.50	$4,617	$4,104	$3,762	$3,421	$3,079
$5.00	$3,306	$2,794	$2,452	$2,110	$1,769
$4.50	$1,996	$1,483	$1,142	$800	$459
$4.00	$686	$173	($169)	($510)	($852)
$3.50	($625)	($1,137)	($1,479)	$($1,820)	($2,162)
$3.00	($1,935)	($2,448)	(2,789)	($3,131)	($3,472)
$2.50	($3,245)	($3,758)	($4,100)	($4,441)	($4,783)
Assumptions: 5% (real) discount rate; 150,000 miles over 15 years; Corolla: 29 miles/gallon; Prius-PHEV: 15 miles AER, 49 mpg (gas), 3.8miles/kWh (estimated electric); 5,475miles/year (electric) + 4,525miles/year (gas); cost of electricity: $0.1175/kWh; Battery replacement in ninth year (after eight-year warranty expiration); 2012 Prius-PHEV announced price at $29,500 ($32,000 MSRP - $2,500 federal tax credit), vs. 2011 Corolla: $19,244 (comparably equipped but Navigation not available on Corolla); Terminal values of both vehicles assumed equal.					

Interestingly (but perhaps not by accident, given manufacturer and government sales aspirations and likely cooperation in defining the structure of the Federal Tax Credit policies), for all three vehicles, the U.S. battery-size-based tax credit results in positive (though slight) NPV values at fuel costs of under $3.75, if the owner doesn't face battery replacement costs. Of course, as driving distances, future-cost discounting, recharge frequencies, gasoline prices, battery prices, power prices, and other attributes or assumptions change, the NPV values can go either way. A sensitivity analysis was performed to estimate the price of fuel required for breaking even between each PEV and its comparable conventional vehicle. Assuming no battery replacement *and no credits*, the NPV would also be positive with gas prices above approximately $5.90, $5.00, and 4.70 per gallon for the LEAF (assuming a 100,000-mile life), Volt (150,000 lifetime), and Prius-PHEV (150,000 lifetime), respectively.

The relative cost analysis was repeated to observe the effect of increasing the LEAF's lifetime miles to that of the other PEVs (150,000 miles). If the LEAF is driven an average of 29 miles per day (150,000 over its 15-year vehicle life, instead of 100,000 miles), the breakeven fuel price (without tax credit and without battery replacement) drops to less than $4.00 per gallon. This 29 miles-per-day distance lies well within the range of a BEV, such as the LEAF (and well within the round-trip commute of most workers), even in harsh weather conditions with reduced range. If vehicle manufacturers succeed in engineering and manufacturing PEVs with batteries to last the vehicle's lifetime, their financial attractiveness, particularly in higher fuel cost regions (including China), seems very solid, especially at moderate discount rates. If one were to price the social costs of the various vehicles, the comparisons should land more heavily in favor of PEVs [Lemp and Kockelman, 2008].

Analysis was also performed to compare the payback for the 2010 Prius HEV to the 2010 Toyota Corolla, and then to the Prius PHEV described earlier. Given its higher purchase price, but slightly lower maintenance costs and much lower fuel costs, the NPV of a Prius HEV over a Corolla is positive at gas prices below $2.50 per gallon (assuming no battery replacement, 150,000-mile life, 5% real discount rate and no tax credits). Using a 10% discount rate, the HEV Prius enjoys a positive payback over a Corolla at gas prices below $3.10 per gallon. Given the recently announced pricing of the Prius PHEV at only $2,205 over a comparably equipped Prius III HEV, gas price estimates must reach only $3.50/gallon to generate a positive return on the Prius PHEV, over the Prius III HEV, but nearly $ 4.75 per gallon without its $2,500 Federal tax credit.

These results rely on actual retail prices and EPA efficiency data. There are some observations that can be made that are consistent with previous studies that used bottom-up component cost and efficiency estimates [Kromer and Heywood 2007, Vyas 2009, and Shaiu et al. 2009] in that the most attractive purchase conditions without tax credits are typically achieved when the expensive battery's size is as small as possible to provide no spare electric drive range capacity and the electric driving range is somewhat less than the driver's average driving needs.

Projection of 2025 Cost Comparison

A relevant question is whether PEV technology will ever progress sufficiently such that the total cost of ownership (TCO) will be comparable (or superior) to a conventional vehicle. Comparisons for today's vehicles can be performed using publically available retail pricing and performance data. However, accurately projecting future costs depend upon detailed and typically confidential component cost data and trends. A Bernstein/Ricardo [Bernstein 2011] study projects that with increasingly strict emissions and fuel economy requirements, conventional vehicle powertrains are expected to increase in cost through 2025. Over the course of the next three PEV vehicle generations (each generation being roughly 4-5 years), major component costs such as batteries are expected to decline such that the total costs of ownership (TCO) will be increasingly similar between the various powertrain/fuel alternatives. From the bottom-up component based comparison for the European market that included much higher fuel costs, the savings by a U.S. driver in fuel costs may be similar given higher average U.S. vehicle miles traveled per year and lower electricity prices. It is noted that given the relatively similar 2025 TCO estimates, such long-range projections can be meaningfully affected by the compounding effect of minor changes in assumptions such as fuel costs or key component price declines (such as batteries).

SUMMARY

PEV related technologies have progressed sufficiently to enable the introduction of mass-market-viable vehicles by mainstream global manufacturers. With the advent of the Chevrolet Volt and Nissan LEAF PEVs the industry has been set in motion and consumers have some serious choices to make.

Assuming a discount rate of 5%, the estimated net gains for owners of these early PEV models (compared to comparably-equipped conventional vehicles) is small in low-gas-price regions like the U.S., but still positive, when U.S. tax credits are included, assuming no battery replacement is required by owners. Without such credits, the relative NPVs are negative at current U.S. gas prices. Nevertheless, cost savings may be substantial for longer-distance drivers who electrify their miles and is estimated to be strongly positive for those in higher-fuel-cost regions (e.g., Germany at $7 to $8 per gallon). Gas prices above approximately $5.90, $5.00, and $ 4.70 per gallon are estimated to make the LEAF, Volt, and Prius-PHEV attractive from a purely financial standpoint, respectively, than their conventional counterparts, without any credits and with today's PEV component and retail prices, using a 5% discount rate. Gas prices above approximately 8.00, $6.60, and $ 6.50 per gallon are required when using a discount rate of 10% for a positive NPV without tax credits.

PEVs are expected to sell well to innovators and early adopters despite potentially higher overall costs in low-fuel-cost regions, just as HEVs have enjoyed some niche-market success. Early purchase opportunities, greater personal wealth, and pent-up demand for such innovative vehicles may trigger the greatest markets for PEVs initially in the U.S., with long-term total sales highest abroad, thanks to higher fuel prices settings elsewhere, higher base-level charging voltages, shorter commutes, and/or a greater focus on transportation environmental impacts (and potentially stronger government incentive programs relative to the U.S.).

The higher component costs (such as Lithium batteries) which lead to higher purchase prices for PEVs are likely to decline over time, as they have for HEV related components and past automotive innovations (such as fuel injection, electronic engine management, and air bags). Continued component price declines and fuel cost increases will lead to a higher NPV for PEVs, relative to comparable conventional vehicles. Even in relatively low-fuel-cost countries, such as the U.S., the HEV Prius has a positive NPV over a similar conventional vehicle. The experience with the HEV Prius over the past decade demonstrates the trends and factors that may lead to PEV cost parity with conventional vehicles over the coming decade.

Charging infrastructure build-out also may also proceed more rapidly in the U.S. over the short term, but then accelerate relatively rapidly in regions with higher fuel prices (such as Europe and Japan). Over time, the share of BEVs in European and Japanese markets may become much greater than in the U.S., due to shorter daily commuting distances, the presence of better mass-transit systems, and potentially more pervasive charging infrastructure deployment.

The U.S. grid is expected to continue to become more “green” over time [EIA 2001], and the deployment of larger numbers of PEVs has the potential to accelerate grid-emissions reductions, through the synergistic coordination of PEV charging with renewable generation sources (such as wind and solar). More meaningful PEV architectures and battery-technology competition are expected, with many viable combinations that offer a variety of optimization opportunities, reducing battery costs and PEV prices over time.

Interestingly, the introduction of PEVs may stimulate a competitive response that may accelerate advances in conventional powertrain efficiency, biofuels, or hydrogen fuel-cell vehicles as well. As long as energy security, air quality, trade deficits, and other concerns remain a concern, all such innovations bode well for the world at large.

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