CHAPTER THIRTEEN
ELECTRIC

EXECUTIVE SUMMARY

There are several advantages to the use of electricity as a transportation fuel—notably, high vehicle efficiency, lower operating costs, and zero tailpipe emissions. Because of the high efficiency of an electric motor, plug-in electric vehicles (PEVs) can be two to three times more efficient than a comparable gasoline vehicle, and electricity as a fuel is in most cases less expensive per mile than gasoline. The high vehicle efficiency plus low "fueling" cost provides a lower cost of operation compared to a conventional gasoline vehicle. Additionally, electricity rates have been historically less volatile than gasoline prices, and this pattern is likely to continue. Battery electric vehicles (BEVs)—and plug-in hybrid electric vehicles (PHEVs) when driving in electric mode—also emit zero tailpipe emissions, which is becoming increasingly important in congested urban areas. Compared to conventional gasoline vehicles, these vehicles can reduce well-to-wheel greenhouse gas (GHG) emissions, and there is opportunity to reduce GHG emissions even further by using renewable electricity or through the use of carbon capture and sequestration in electricity generation. As electricity can be produced from a variety of primary energy sources, its use as a fuel helps to diversify energy use.

Arguably as important as the reasons above, the use of electricity as a transportation fuel has the advantage of being able to use existing infrastructure, as there is already a ubiquitous electricity supply chain in the United States. Over 60% of all housing units in the United States have an attached garage or carport, and adding a dedicated circuit for a 110V outlet to charge a vehicle has minimal cost. In terms of electricity supply—i.e., generation capacity—electric supply entities already have existing long-term asset planning processes to prepare for future electricity demand. Thus, any capacity additions that would be needed for vehicle charging can be planned for in these long-term capital plans.

These advantages, however, do not come without challenges—both at the vehicle level and at the infrastructure level. The challenges at the vehicle level are centered on the battery—cost, energy density, degradation, and longevity.

- Cost. As stated above, PEVs—which include both BEVs and PHEVs—provide operating cost savings, but the cost of the battery leads to a higher up-front vehicle price when compared to a conventional vehicle.
- Energy Density. The lower energy density of batteries relative to liquid fuels is compensated to some extent by the high efficiency of electric motors, and for PHEVs by the addition of a gasoline engine, but for BEVs, the lower energy density leads to a limitation in vehicle range.
- Degradation & Longevity. There are two facets to battery longevity. The first is the actual calendar life of the battery. It is currently unknown whether batteries used in PEVs will last for the life of the vehicle, and battery replacement is likely to remain a significant expense. The second facet of longevity is the degradation of power and energy storage capacity that occurs over time. The gasoline engine in PHEVs can compensate for this, but BEVs will experience reduced power and vehicle range. Battery innovation, therefore—improved energy density, reduced degradation, and predictable calendar life—is most likely necessary for the wide-scale adoption of BEVs.

For vehicle charging, while PHEVs can easily recharge the battery overnight using a standard 110V outlet, drivers of BEVs will most likely need to charge at a higher power level (240V). This requires the purchase and installation of a separate charging unit, which could be a barrier to vehicle purchase if the expense is high—e.g., if new panel capacity is needed, or there is no existing 240V connection in the garage. For both PHEVs and BEVs, drivers in urban areas with on-street parking and drivers who live in multiple dwelling units such as apartments, both types of charging (110V and 240V) will be difficult to realize, as the installation cost can be high and the driver typically lacks the authority to install a charging unit.

As these vehicles have just begun to enter the market, market acceptance of a limited-range vehicle is uncertain. For BEVs, it is possible that "range anxiety" and the inability to use the vehicle for all trips will prove to be a barrier to adoption, but it is also possible that the advantage of home refueling and lower operating costs will outweigh the range limitation.

CHAPTER INTRODUCTION

The Electric Subgroup of the National Petroleum Council's Future Transportation Fuels study was tasked with evaluating the wide-scale use of electricity as a transportation fuel. This evaluation included the vehicles, the electricity supply chain, and the infrastructure for "fueling" the vehicles. While niche markets exist, and "wide-scale" was not precisely defined, it was understood that the market penetration would need to be significant enough to materially impact the petroleum usage and GHG emissions of the transportation sector. This chapter describes the electricity supply chain (including charging infrastructure), the core battery technology, and the vehicle technology and infrastructure requirements that are necessary for significant market penetration of PEVs. The current state of, challenges to, outlook for, and solutions (where identified) to these requirements are then discussed.

It should be noted that throughout the study period, the ecosystem surrounding PEVs was—and still is—extremely dynamic, which added to the already-difficult task of making assessments about the future. Throughout the chapter, many uncertainties are highlighted, including consumer acceptance, the desire and business case for public charging, the type of charging that consumers will prefer, and the extent of the impact to the electricity distribution system.

Additionally, given the nascent state of the core vehicle-level technology—lithium-ion-based battery systems—the subgroup did not have the benefit of significant historical data. As projections further into the future—e.g., 2035 and 2050—are based on expert opinion versus hard data, key variables such as battery costs are presented in ranges.

As this study focuses on the transportation sector, the scope of the Electric Subgroup was to address the potential impacts to the electricity supply chain from vehicle charging. This did not include projecting the trajectory of electricity generation, nor did it presume potential developments in grid modernization—i.e., "smart grid."

INFRASTRUCTURE SUPPLY CHAIN AND VEHICLE SEGMENT SCOPE

This study looked at the entire transportation sector, including both heavy-duty and light-duty vehicles, and to a lesser extent, rail, air, and marine sectors. The rail, air, and marine sectors are addressed in Chapter One, "Demand," and medium- and heavy-duty vehicles in Chapter Three, "Heavy-Duty Vehicles," as well as Chapter Ten, "Heavy-Duty Engines & Vehicles." The Electric Subgroup, therefore, focused on the evaluation of PEVs in the light-duty sector. Additionally, as the infrastructure supply chain for a given fuel-vehicle system can have many different configurations, each subgroup focused on the configuration that was deemed most feasible for the vehicle classes being evaluated. The vehicle classes and infrastructure configurations that are the focus of this chapter are illustrated in Figure 13-1.

As shown Figure 13-1, BEVs in the pickup and large SUV vehicle classes were not included in the scope of the discussion of PEVs. As explained in the section on energy density of batteries, a pickup or large SUV would require a very large battery, resulting in a very-high-priced vehicle. Additionally, a vehicle with a limited range would not align with the typical duty cycles and use cases for pickups and large SUVs—towing, hauling several

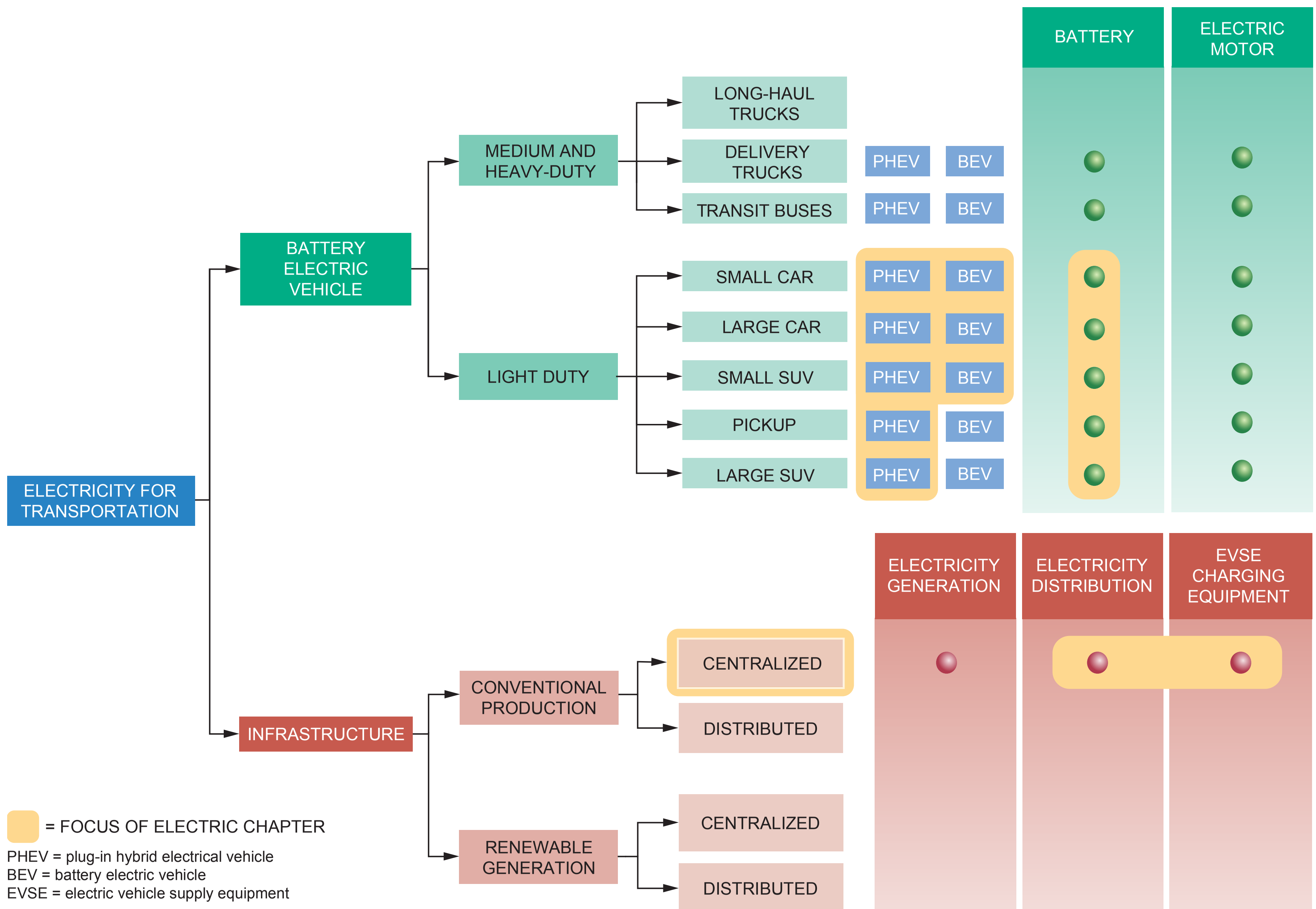


Figure 13-1. *Vehicle Classes and Infrastructure Configurations Considered in This Study*

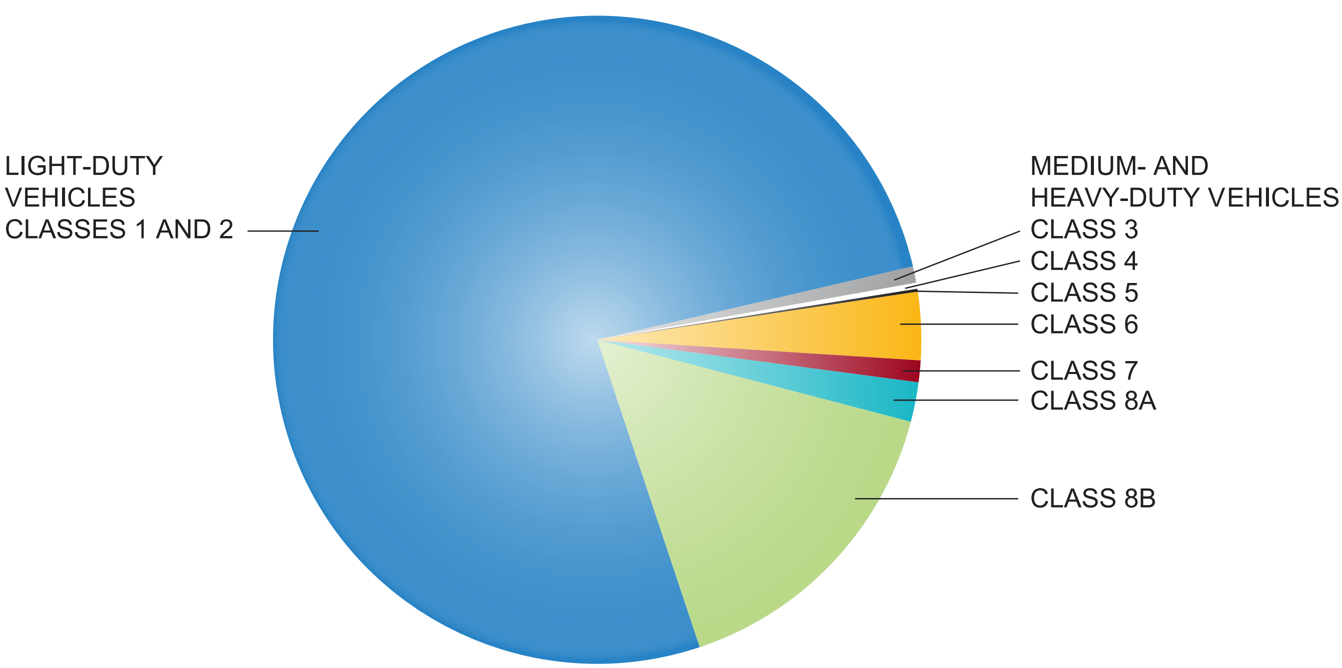
AEO	% of New Vehicle Sales (2010)†	NPC Study	VISION
Two Seater Car	1.0%	Small Car	Car
Mini-compact Car	0.5%		
Subcompact Car	5.1%		
Compact Car	12.4%		
Midsize Car	19.7%	Large Car	
Large Car	9.3%		
Small Van	1.4%	Small Utility	Truck
Small Utility	16.8%		
Large Utility	13.8%	Large Utility	
Large Van	3.8%		
Small Pickup	2.8%	Pickup	
Large Pickup	10.6%		
Commercial Light Truck*	2.8%		
Total	100.0%		

* Commercial light truck is not a light-duty vehicle in AEO but is in VISION.

† Percentages remain relatively stable over the AEO projection period (to 2035).

Source: Energy Information Administration, *Annual Energy Outlook 2010: With Projections to 2035,* 2010, Reference Case.

Table 13-1. *Vehicle Segments and Fractions of U.S. Light-Duty Vehicle Sales*



Note: Plug-in vehicles would be a sub-subset of these low-fuel-use vehicle classes (Classes 4, 5, 8a).

Source: National Research Council of the National Academies, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles,* 2010.

Figure 13-2. *Percentage of Total Transportation Fuel Use* passengers, and long-distance recreational driving. The category of "pickup" does include small-sized pickup trucks, and while a BEV might be more feasible from a size and duty cycle standpoint, this market segment is very small—as shown in Table 13-1—and is expected to decrease further over time.

While medium- and heavy-duty trucks are addressed in other chapters, the potential for electrification of this sector, particularly for medium-duty vehicles, is often mentioned. Thus, the Electric Subgroup thought it helpful to include a brief note here. These classes consume an extremely small portion of national transportation energy, as illustrated in Figure 13-2. Further, due to the unique requirements of commercial customers, the feasibility of plug-in powertrains is further constrained to a handful of niches within these classes of vehicles. The sum total of such applications is small, and the fuel usage even smaller.

INDUSTRY OVERVIEW

Vehicle Technology

This study examined two distinct vehicle types that are offered for sale today, and which represent categories of PEVs. The first type is a pure BEV that is propelled by an electric motor that uses electricity stored in a battery that is recharged from the grid. The next vehicle type is a PHEV that is propelled by both a gasoline internal combustion engine and an electric motor that uses electricity stored in a battery that is recharged from the grid. Within the PHEV category, there are two configurations. PHEVs typically have a maximum speed at which the vehicle can operate in electric mode. If additional power is needed—e.g., for quick acceleration—the gasoline engine activates. Once the battery is depleted to a predetermined level, the gasoline engine and the electric motor work in concert to operate as a conventional hybrid electric vehicle. Most BEVs and PHEVs are also able to recapture energy from braking and deceleration, but not at a rate sufficient to fully recharge the battery.

The three representative vehicles evaluated are as follows, and are shown in Figure 13-3:

- PHEV10—a shorter-range PHEV with a parallel/series design that enables up to 10 miles of driving in electric mode, and a total driving range of 300+ miles
- PHEV40—a mid-range PHEV with a series architecture that enables up to 40 miles of driving in electric mode, and a total driving range of 300+ miles
- BEV100—a battery electric vehicle with up to 100 miles of total driving range.

Miles Traveled Using Electricity

While the all-electric range for these vehicle types give the maximum number of miles each can travel under electric power in a single trip, it is important to understand that the total number of vehicle miles traveled (VMT) using electricity is not a linear function of the all-electric range—for example, a BEV100 does not electrify 10 times the number of VMT as a PHEV10. For instance, if a driver travels 20 miles to and from work each day (and does not drive on the weekend), she would electrify 50% of her VMT with a PHEV10 (driving the first 10 miles to work using electricity and 10 miles home with gasoline), 100% with a PHEV40, and 100% with a BEV100, under certain driving conditions.

Figure 13-4 shows the calculated "utility factor" across drivers and driving days, based on an Electric Power Research Institute (EPRI) analysis that uses the 2009 National Household Travel Survey (NHTS) data, under different charging scenarios, for PHEVs with different electric ranges. The utility factors in this figure, representing the percentage of VMT that can be driven using electricity instead of gasoline, were calculated using a simplified simulation of the driving data from NHTS. In the simulation, each vehicle starts each travel day with a full battery and drives on electricity until the battery is depleted, at which point the vehicle switches to the gasoline-fueled engine. If the vehicle stops at a location where charging is available, it recharges at 3.3 kilowatts until the battery is full or the next trip begins. For BEVs, this methodology presents some challenges, as one must assume either (1) a recharge at the end of every X miles (X being the electric range of the vehicle), or (2) that an alternate vehicle is used for trips that exceed the range of the BEV. This is explained more fully in the section entitled "Utility Factor" at the end of this chapter. The results of this simulation for PHEVs are listed in Table 13-2.

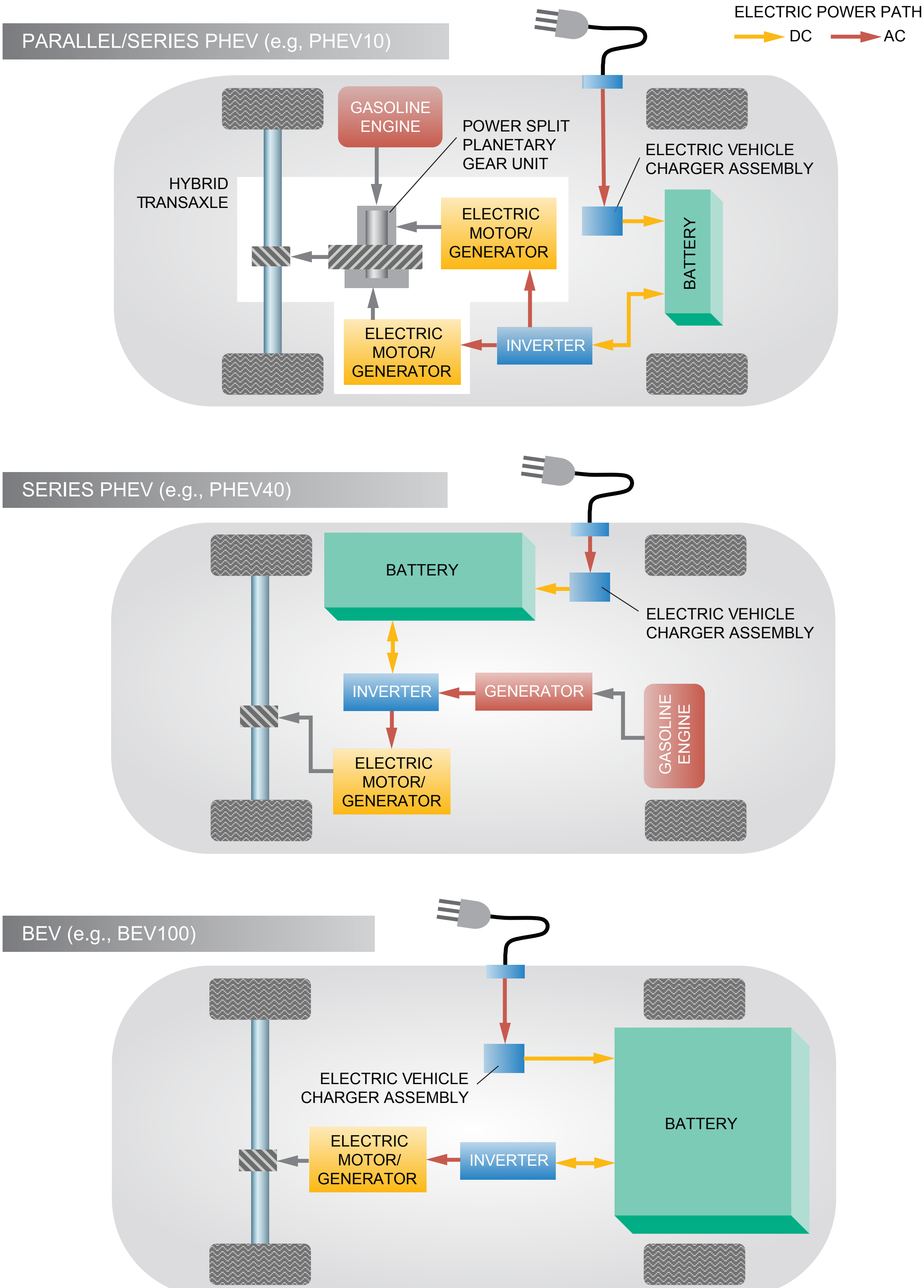
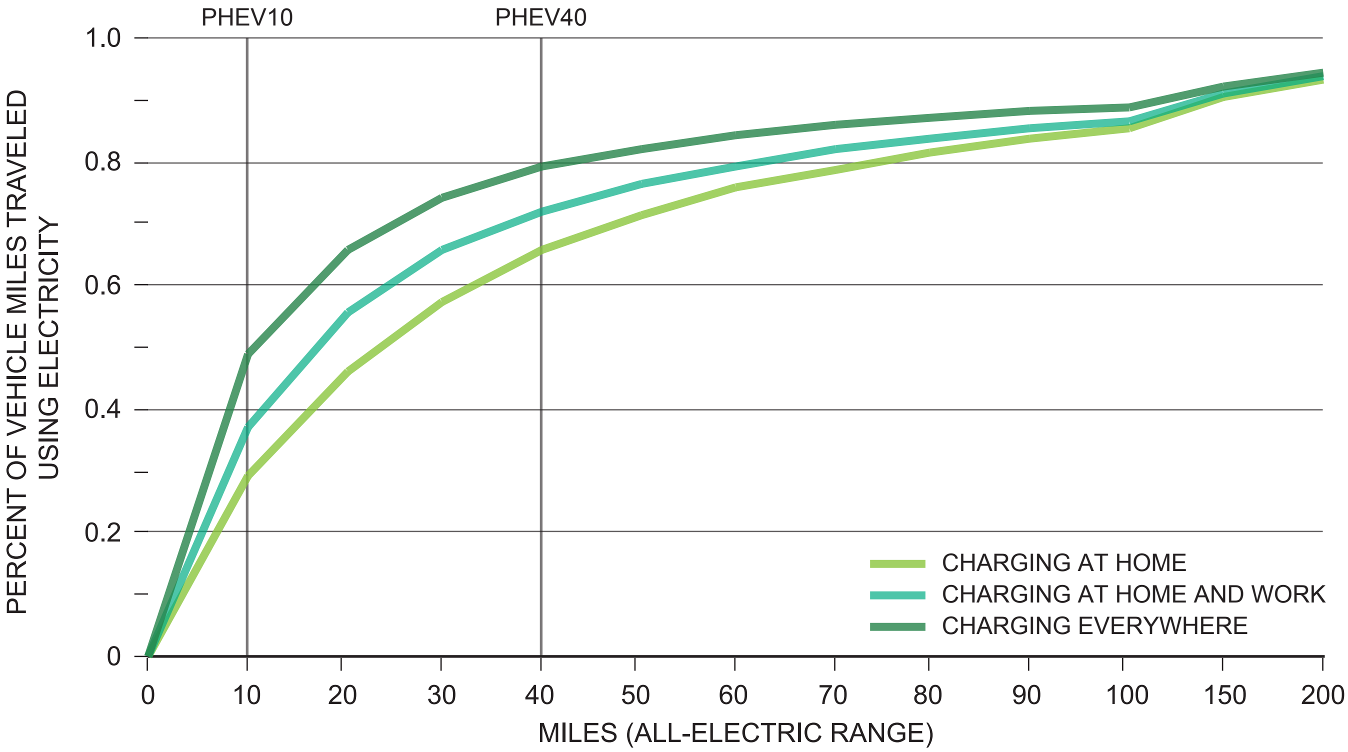


Figure 13-3. Vehicle Types and Configurations



Source: Electric Power Research Institute analysis, based on data in National Household Travel Survey 2009.

Figure 13-4. *Utility Factors for Various Vehicle Ranges and Charging Scenarios*

Vehicle Type	Where Vehicle Was Charged		
	Home	Home and Work	Everywhere (home, work, and commercial locations)
PHEV10	27%	36%	50%
PHEV40	65%	73%	80%

Note: This is a simulation using the test-mode electric range of the vehicle. Real-world range and charging availability can vary widely and thus the percentage of vehicle miles using electricity will vary.

Table 13-2. *Percentage of Vehicle Miles Traveled Using Electricity Instead of Gasoline*

Battery Technology

Battery Basics

A battery is an energy storage device that converts the chemical energy contained in its active materials directly into electric energy via an electrochemical oxidation-reduction reaction where electrons are transferred from one material to another through an electric circuit. In rechargeable batteries, the battery is recharged by reversing the process.

The major components of a battery cell are:

1. The *anode* or negative electrode—which is oxidized during discharge and reduced during recharge.
2. The *cathode* or positive electrode—which is reduced during discharge and oxidized during recharge.
3. The *electrolyte*—an ionic conductor that provides the medium for transfer of charge, as ions, inside the cell between the anode and cathode. The electrolyte is typically, but not necessarily, a liquid such as water or other solvents, with dissolved salts, acids, or alkaloid to impart ionic conductivity. Some batteries use solid electrolytes, which are ionic conductors at the operating temperature of the cell.
4. The *separator*—an electrical insulator placed between the anode and cathode to prevent

shorting, but of sufficient microporosity to allow efficient charge transfer.

5. The *cell mechanical components*—container, cover, terminals, sensors, safety features.

To scale up to the hundreds of volts required for automotive powertrain use, many cells are assembled in series to form a battery pack, which connects and contains the cells, and also includes a battery management system (BMS)—an electronic control system that uses various sensors to monitor the state of each cell within the pack (e.g., for voltage, temperature, internal resistance) and to control electrical flows to and from the battery. Most packs include an integrated thermal management system to moderate the pack temperature. The most basic thermal management uses passive air-cooling of the pack from the outside, while more sophisticated systems employ liquid or refrigerant cooling.

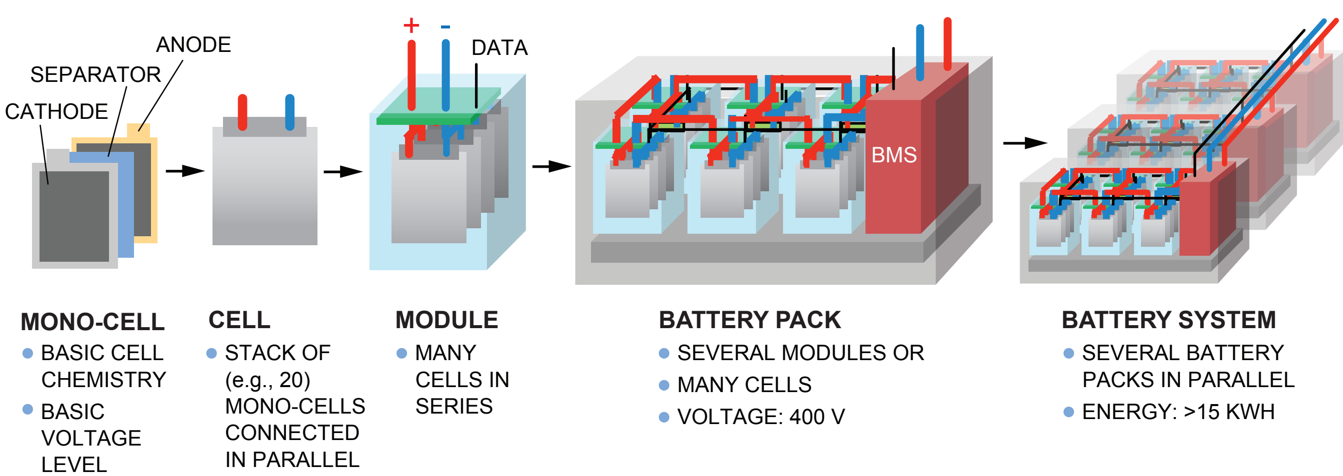
While individual cells can be of different format (e.g., cylindrical, pouch) and there are different ways to assemble the cells into packs, an example of the elements that comprise a complete battery pack are shown in Figure 13-5.

Lithium-Ion Batteries

Of the predominant battery chemistries employed by automakers today, nickel-metal hydride and lithium-ion, the latter is the chemistry of choice for PEV applications, due primarily to its superior specific energy and power density—attributes that are critical to vehicles that use grid-supplied power for driving.

Rather than any one particular combination of materials, however, the term *lithium-ion* refers to a family of chemistries that operates on the principal of the transfer of lithium ions between the *anode* and *cathode* during discharge and charge cycles. In contrast to the "lithium" cells that utilize elemental lithium metal as the anode, lithium-ion chemistries contain no elemental metallic lithium, but rather there are ionic lithium cations (Li^+) that are intercalated/de-intercalated in and out of the electrode structures during use. Specifically, during charge, lithium transports from the cathode to the anode, and upon discharge it returns to the cathode. The fundamentally stable nature of intercalation reactions greatly enhances the abuse tolerance of this chemistry. A carbon graphite anode is most commonly used, though alternatives to graphite have emerged that improve battery performance (examples include lithium alloy systems such as Li-Si and Li-Sn-Co-Carbon that are arranged in nanocomposites such that they are stable over many use cycles). Similarly, the lithium-iron-phosphate battery, also commonly referred to as a lithium-ion battery, combines lithium-iron-phosphate as the cathode active material and a graphite anode.

There are a number of performance trade-offs within the family of lithium-ion chemistries among the primary battery performance attributes of



Source: Alexander Otto, Fraunhofer Institute for Electronic Nano Systems ENAS, presentation of May 30, 2012, "Battery Management Network for Fully Electrical Vehicles Featuring Smart Systems at Cell and Pack Level."

Figure 13-5. *Battery Pack Components and Assembly* *specific energy density, power density, cycle life, safety, and costs.*

For example, cobalt oxide cathodes, $LiCoO_2$, emerged as the chemistry of choice in the consumer and portable electronics industries, but have proven unsuitable for automotive-grade applications due to cost and less stable thermal characteristics that can lead to thermal runaway (industry parlance for fire). Consequently, a number of new lower-cost chemistries have been developed to production capability in recent years with more stable thermal characteristics. These include Nickel Cobalt Aluminum, Lithium Iron Phosphate, and Lithium Manganese Oxide Spinel. Table 13-3 provides a summary of common lithium-based combinations currently at or near production.

Note that there is no one "silver bullet" chemistry that achieves all key battery performance targets.

Currently, no dominant lithium-ion chemistry has emerged for automotive-grade applications from the set of competing chemistries. Table 13-4 provides a representative subset of chemistries chosen by auto manufacturers for models that are either in production or slated for production at the time of this writing.

Rather than arbitrarily selecting a particular chemistry to represent the class of lithium-ion batteries, the Electric Subgroup chose to cite

Cathode	Anode	Abbrev.	Energy Density	Power Density	Cycle Life	Safety*	Cost
Lithium Cobalt Oxide	Graphite	LCO	High	Fair	Fair	Fair	High
Nickel Cobalt Aluminum Oxide	Graphite	NCA	High	High	Fair	Fair	High
Lithium Iron Phosphate	Graphite	LFP	Low	High	High	Very good	Fair
Lithium Manganese Oxide	Graphite	LMO	High	High	Fair	Very good	Fair
Lithium Manganese Oxide Spinel	Graphite	LMO	High	High	Fair	Good	Low
Lithium Manganese Oxide Spinel Polymer	Graphite	LMO	High	High	Fair	Good	Low
Manganese Nickel Cobalt Oxide	Graphite	MNC	High	Fair	Low	Fair	High
Lithium Manganese Oxide Spinel	Lithium Titanate Oxide	LMO-LTO	Low	Low	High	Good	High
Lithium Nickel Oxide	Graphite	LNO	High	Fair	Fair	Fair	Fair
Lithium Manganese Nickel Oxide Spinel	Graphite	LMNS	High	High	Fair	Fair	Low
Lithium Manganese Nickel Oxide Spinel	Lithium Titanate Oxide	LMNS-LTO	Fair	High	High	Good	Low

* "Safety" refers to the thermochemical reactivity of the specific cathode/anode couples. Beyond this, (1) the reactivity with the electrolyte must be considered and (2) system-level safety is primarily determined by the battery management system, which includes thermal management.

Source: Shmuel De-Leon, "High Power Rechargeable Lithium Battery Market," presented at IFCBC Meeting, February 4, 2010.

Table 13-3. *Comparison of Lithium-Ion Battery Chemistries Across a Sampling of Key Performance Attributes*

Vehicle OEM	Model	Battery Supplier	Drivetrain	Drivetrain Architecture	Battery Chemistry	Format	Thermal Management
Chevy (GM)	Volt	Compact Power/ LG Chem	PHEV	Series	LMO Spinel Polymer	Prismatic	Liquid
Nissan	LEAF	AESC (NEC/ Nissan)	BEV	Series	LMO	Prismatic	Air
Fisker	Karma	A123	PHEV	Series	LFP (Nanophos-phate)	Cylindrical (26650)	Liquid
Mitsubishi	"I"	GS Yuasa	BEV	Series	LMO-NMC/ Hard Carbon	Prismatic	Air
Prius (Toyota)	PHEV	PEVE	PHEV	Parallel/ Powersplit	NCA	Prismatic	Liquid
Smart (Daimler)	fortwo ED	Duetsche ACCUmotive (Daimler & Evonik)	BEV	Series	*	*	Liquid
Tesla	Model S	Panasonic Samsung	BEV	Series	LMO	Cylindrical (18650)	Liquid
Volvo	C30 EV	Enerdel/Ener1	BEV	Series	LMO-NMC/Hard Carbon	Prismatic	Air
BMW	ActiveE	S8 LI Motive (BMW, Bosch, Samsung)	BEV	Series	NMC	Prismatic	Liquid
Toyota	Rav4 EV	PEVE	BEV	Series	LMO Spinel Polymer	Cylindrical (18650)	Liquid
Scion (Toyota)	IQ-EV	PEVE	BEV	Series	LMO Spinel Polymer	Prismatic	Liquid
Ford	Focus	Compact Power/ LG Chem	BEV	Series	LMO Spinel Polymer	Prismatic	Liquid
Honda	Fit EV	GS Yuasa	BEV	Series	LMO-NMC/ Hard Carbon	Prismatic	Liquid
Coda Automotive	CODA	Lishen/LIO Energy Systems	BEV	Series	LFP	Prismatic	Liquid
Ford	C-Max Energi	Compact Power/ LG Chem	PHEV	Parallel/ Powersplit	LMO Spinel Polymer	Prismatic	Liquid
Fiat	500 EV	*	BEV	Series	*	*	*
Chevy (GM)	Spark EV	A123	BEV	Series	LFP	Prismatic	Liquid
Fisker	Nina	*	PHEV	Series	*	*	*
Honda	Accord	GS Yuasa	PHEV	Parallel	LMO-NMC/ Hard Carbon	Prismatic	Liquid
Tesla	Model X	Panasonic Samsung	EV	Series	LMO	Cylindrical (18650)	Liquid
BMW	I3	SB LI Motive (BMW, Bosch, Samsung)	(1) BEV (2) PHEV	Series	NMC	Prismatic	Liquid
BMW	I8	SB LI Motive (BMW, Bosch, Samsung)	PHEV	Series	NMC	Prismatic	Liquid
Ford	Transit Connect	Johnson Controls	BEV	Series	NCA	Cylindrical	Liquid
Azure	Balance	Johnson Controls	PHEV	Parallel	NCA	Cylindrical	Liquid

* Unknown or not available.

Note: Data current as of February 2012.

***Table 13-4.** Representative Subset of Battery Chemistries Considered by Current Automobile Manufacturers* figures that represent an average of all chemistries in this class. Therefore, *references in this report to lithium-ion batteries should be interpreted more generally as representative of the average characteristics of the set of chemistries that comprise the lithium-ion family.*

Energy Density

The term "energy density" is often used as a generic reference to the mass or volume that the cells or battery system occupy within the vehicle compared to the gross number of energy units, typically watt-hours (Wh), that can be stored in them. In reality, two different energy metrics must be considered when selecting the appropriate electrochemistry and battery size for a particular application, as either metric can be the key design driver.

1. Specific, or gravimetric, energy refers to the amount of stored energy per unit mass, typically watt-hours per kilogram.
2. Energy, or volumetric, density, refers to the amount of stored energy per unit volume, typically watt-hours per liter.

In PHEV applications, for example, the battery *volume* rather than mass tends to be more critical to the design because these platforms are usually modified conventional vehicles that carry an internal combustion engine, transaxle, and fuel tank in addition to a battery pack, electric motor(s), and power control electronics. In BEVs, however, the battery *mass* can become the primary constraint as it becomes a substantial fraction of the total vehicle mass, significantly affecting energy requirements and overall vehicle dynamics.

Figure 13-6 illustrates conceptually the specific energy challenges of batteries in automotive applications. For a pure BEV, as driving range is extended by increasing the battery size, the vehicle mass increases significantly. Even with advances in battery energy density, the curb weight for a small BEV with a driving range comparable to a conventional vehicle (~300+ miles) would be substantially greater than that of the comparable gasoline internal combustion engine (ICE) vehicle.

The Nissan LEAF and Versa were used as the basis for the chart in Figure 13-6. The LEAF as sold

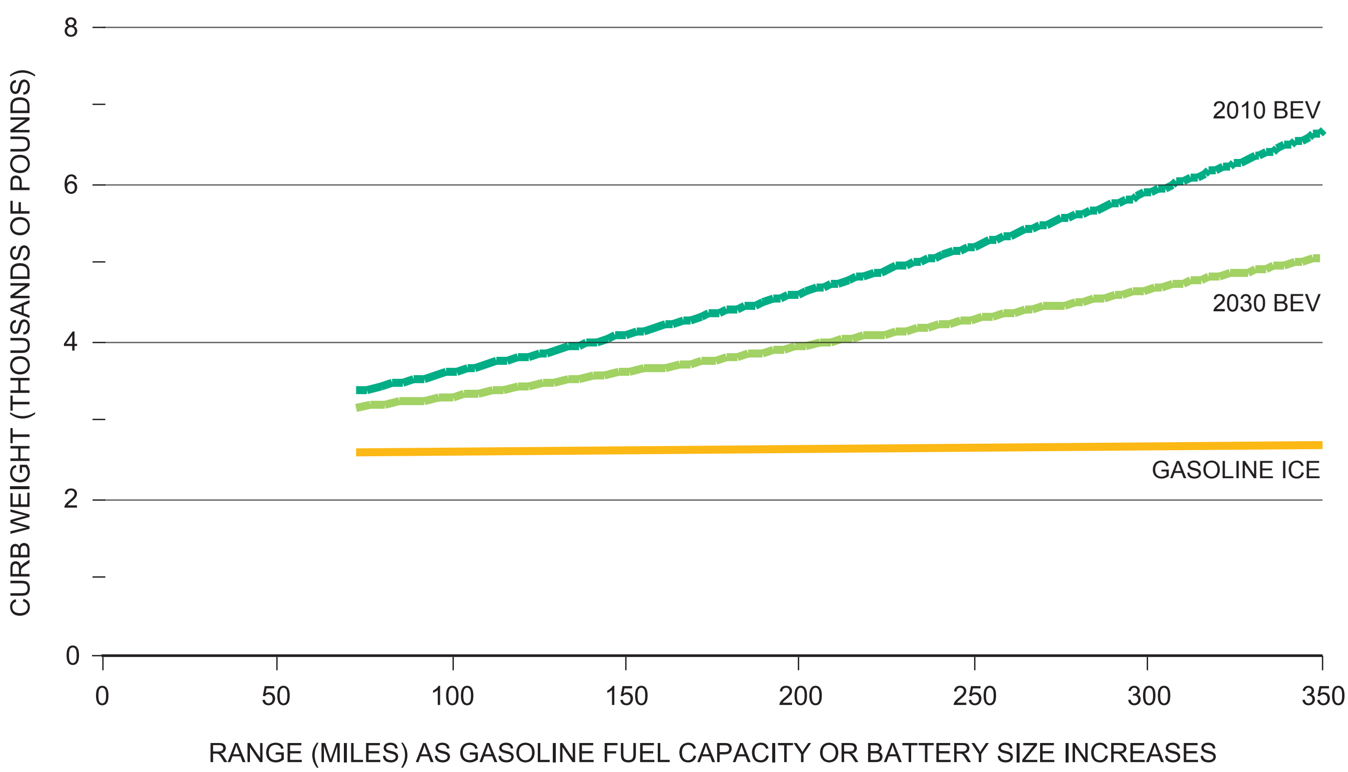


Figure 13-6. *Vehicle Weight vs. Vehicle Range*

currently has a range of 73 miles as rated by the Environmental Protection Agency (EPA). Gasoline mass was subtracted from the Versa to reduce its range to an equivalent 73 miles for comparison. To construct the 2030 BEV line, the LEAF battery mass was reduced to reflect projected improvement in energy density. Points on the BEV lines were generated by adding battery energy in 1 kilowatt-hour (kWh) increments. A factor of 1.5 was used as an estimate for mass compounding, meaning that for each pound of battery added, the vehicle curb weight increases by 1.5 lbs.[1,2] For the BEV, energy consumption per mile was increased by 1% for every 2.5% increase in vehicle mass,[3] and the resulting range was then computed for each battery energy level. It should be noted that the LEAF and Versa are both based off of conventional vehicle platforms. Optimization of the conventional vehicle platform, reducing weight by using lighter-weight materials, for example, was not part of this analysis. Under the presumption that platform-level advancements would apply to both a conventional vehicle and a PEV, the comparison illustrated above would be directionally similar.

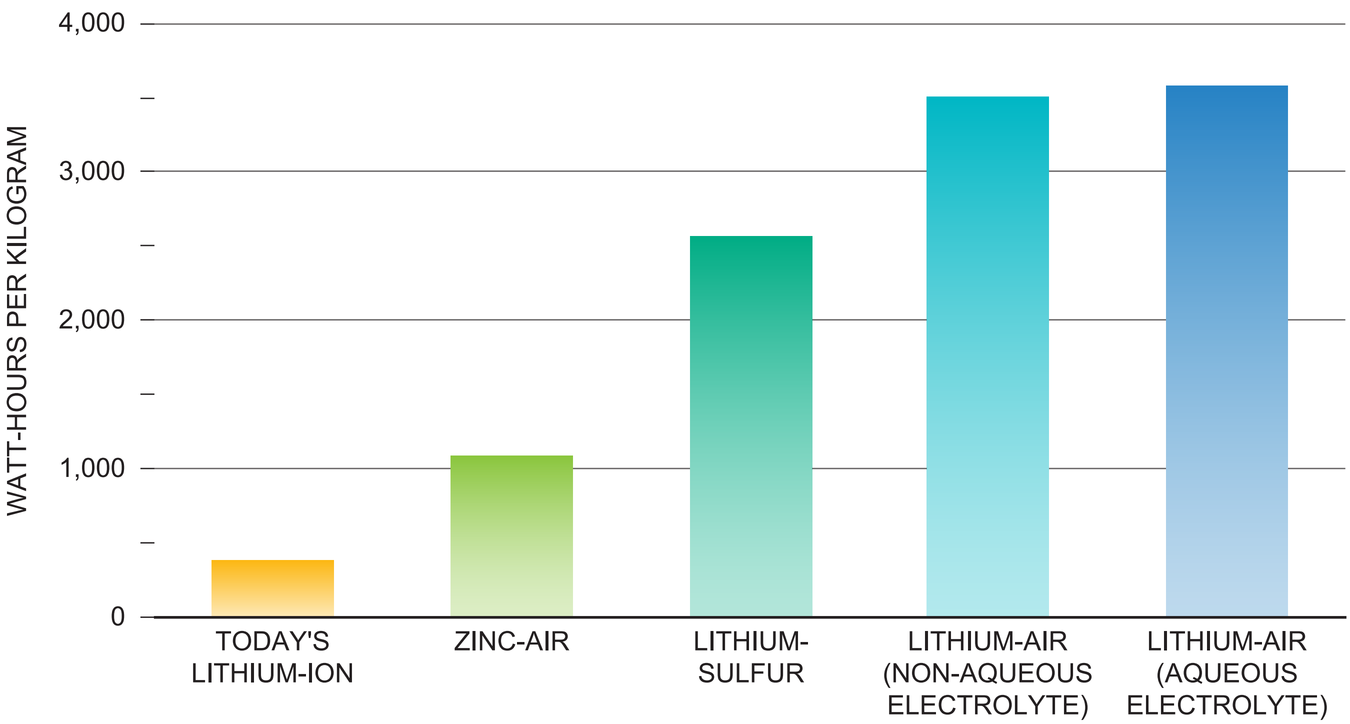
In order for PEVs to be feasible in vehicle classes beyond the small vehicles currently offered, improvements in specific energy density beyond those that are expected for lithium-ion chemistries are most likely needed. Figure 13-7 shows electrochemistries with higher performance characteristics than current lithium-ion batteries. As indicated, the theoretical specific energies of electrochemistries such as zinc-air, lithium-sulfur, and lithium-air, are well beyond that of lithium-ion. This optimism must be tempered, however, with the reality that:

1. Theoretical specific energy at a cell level is not achievable.

1 Catarina Bjelkengren, "The Impact of Mass Decompounding on Assessing the Value of Vehicle Lightweighting," Masters Thesis, Massachusetts Institutes of Technology, June 2008.

2 Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* LFEE 2007-03 RP, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, May 2007.

3 Value based on literature review; see Chapter Nine, "Light Duty Engines & Vehicles," page 9-33, for additional information.



Source: P. G. Bruce et al., "Li-O_2 and Li-S Batteries with High Energy Storage," *Nature Materials* 11, January 2012.

Figure 13-7. *Theoretical Specific Energy for Current and Future Lithium-Ion Batteries*

2. System level burdens will further reduce these performance metrics.

In addition to new chemistries, research and development is also needed on higher-capacity anode and cathode materials for lithium-ion batteries. Potential improvements include alternative anode materials with greater energy density, such as silicon and tin, or novel cathode materials such as lithium vanadium phosphate fluoride ($LiVPO_4F$) that operate at higher voltage, thus also increasing energy density. *These higher-capacity materials, along with energy storage technologies that have potential for use in PEV applications, are discussed in Topic Paper #17, "Advanced Batteries: Beyond Li-ion," and listed in Table 13-5.*

Materials for Next Generation Lithium-Ion Batteries	
Advanced Cathode Materials	**Advanced Anode Materials**
• Oxygen Release Cathode Materials • "Two-Lithium" Cathode Materials • High-Voltage Spinels	• Graphite • Tin • Silicon

Electrochemical Energy Storage Beyond the Lithium-Ion Paradigm
• Elemental metal anodes
• Metal-Air systems
• Lithium-Sulfur battery
• Displacement reaction lithium cathodes
• Non-lithium rocking chair systems
• Organic lithium storage materials
• Flow systems

Table 13-5. *Advanced Energy Storage Technologies for Plug-In Electric Vehicle Application*

Power vs. Energy Batteries

Battery designs strive to strike a balance between the energy and power requirements of the battery. In a vehicle application, power density is needed to provide sufficient acceleration as well as optimal ability to capture regenerative braking energy, while specific energy is the primary determinant of the vehicle's all-electric range. Both specific energy and power density are fundamental to optimal battery pack design. Depending on the context of the discussion, power density may reference power delivered by mass or by volume, measured in watts per kilogram and watts per liter, respectively. The former, specific power, is typically referenced when discussing battery performance while the latter is relevant in the context of vehicle packaging.

As the gasoline energy provides the necessary driving range, the battery packs of PHEVs with shorter all-electric range or with blended-mode operation, are generally optimized to meet peak power demands. Conversely, BEV packs are optimized around the vehicle's energy demands. This may, however, come at the expense of power. Specific energy, rather than specific power, is the primary determinant of total battery cost.[4]

The total amount of energy that a particular battery technology can deliver or accept is a function of the rate (power) requirement on discharge, recharge, or during energy recuperation—e.g., regenerative braking events. Therefore, in addition to understanding the energy density versus specific energy capabilities, the vehicle designer must also understand the functionality between power and energy for a particular battery type (chemistry). A conventional graphic method used to illustrate the relationship between power and energy for a particular battery type is the Ragone plot, which is a logarithmic curve of the energy available versus power demand. The Ragone relationship can be expressed on a gravimetric or volumetric basis.[5] As shown in Figure 13-8, compared to other chemistries, lithium-ion is relatively insensitive to power demand, while for LiM Polymer, increasing specific energy comes with a significant decrease in specific power.

System-Level Considerations

Ragone plots express cell level performance. The mass and volume of the cells and the incremental mass and volume, or burden, of the non-cell battery

4 Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* LFEE 2007-03 RP, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, May 2007.

5 While typically used to compare different cell designs, different points on a plot can also represent the same cell under different operating conditions.

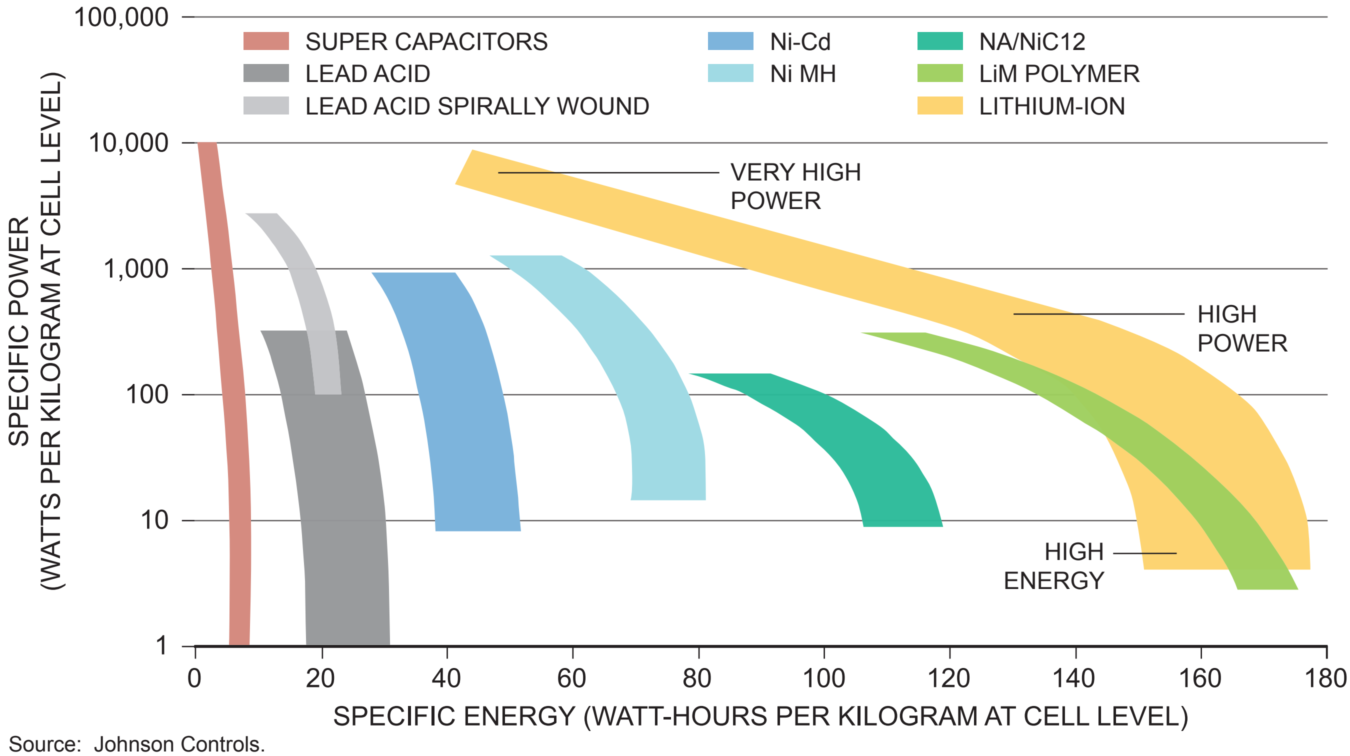


Figure 13-8. *Ragone Plot of Different Battery Chemistries*

system components (battery casing, thermal management system, etc.), however, are extremely important in determining whether or not the targeted goals for battery system energy density and specific energy are achievable.

Although there is no universally accepted convention for calculating burden, it is typically defined as the ratio of the non-cell mass or volume to the cell mass or volume.

Example: If a battery system has a cell mass of 40 kg and a non-cell mass of 40 kg, the mass burden is 100%. Therefore, if the cell-based specific energy is 200 Wh/kg, the actual metric the vehicle designer must consider is 200/2.00 or 100 Wh/kg. It is not unusual for a battery system volume burden to be well in excess of 100%.

Example: *A doubling of battery pack gravimetric performance requires not only a 2X improvement in cell based specific energy but also a 50% reduction in the mass of non-cell components.*

Optimal battery system design and supporting R&D requires focus on five key areas:

1. The thermal characteristics of the cells and the corresponding size, mass, complexity, and cost of the requisite thermal management subsystem.
2. Advanced thermal management technologies/devices to improve heat transfer rate, temperature uniformity, and volume/mass burden.
3. Uniformity of performance from cell to cell (manufacturing quality), which to a large extent will determine the cost, complexity, mass, and volume of subsystems to monitor and control cell operation during discharge and recharge.
4. Cell geometric format, module packaging, and battery enclosure technology and design. There is a myriad of opportunities to improve battery system level performance, but to a certain extent these opportunities are tied to the choice of electrochemistry.
5. Strategies for battery monitoring and control, including the hardware burden for sensors, signal wiring, and signal processing.

Total Energy versus Useable Energy

A typical vehicle battery is controlled so that it never discharges fully, thus the total installed, or nominal, capacity is greater than the capacity actually used. This approach:

- Extends battery life
- Allows for sufficient power at low states of charge (important for BEVs)
- Mitigates the risk associated with cell-to-cell variation in high-voltage packs
- Builds in engineering margin to enable the original equipment manufacturer (OEM) to promise a certain driving range for a certain time period.

Currently, the depth of discharge for a BEV is in the 70% range, with the battery's state of charge (SOC) ranging from, for example, 20 to 90%. The effect of this is that a cost figure derived from useable capacity is greater than a cost based on total energy.

Example: A $600/kWh cost based on total capacity would translate to a $857/kWh cost based on useable capacity when used in a BEV with a 70% SOC swing ($600 divided by 0.7).

Battery Degradation and Longevity

All batteries experience power and capacity fade over time as functions of cycling, time, and temperature. The mechanisms that degrade battery power and capacity vary with battery chemistry, the operating profile and ambient conditions. Instead of *calendar* life—the age of the battery in years—battery life is typically described by the number of times the battery can be charged and discharged, referred to as *cycle life.* Some battery chemistries are more sensitive than others to the number of charge-discharge cycles.

The cycle life of a battery is fundamentally determined by the reversibility of the electrochemical reaction(s) that are responsible for the energy storage function. In other words, the degradation of the battery life is the result of loss of the electrochemical reaction reversibility upon charge-discharge cycling. The key factors responsible for the cycle life, which are more pronounced at elevated temperatures are:

- Mechanical/structural fatigue or failure of the active materials, especially at the microscopic level. Materials deteriorate due to stress, especially cyclic stress-induced fatigue upon charge-discharge cycling.
- Side reactions of positive and negative electrodes with the electrolyte, which results in the formation of highly resistive interfacial layers that impede the electrochemical reaction(s) and a loss of active materials (lithium, anode material, cathode material, and electrolyte), which leads to loss of capacity.

In most commercial lithium-ion chemistries, the primary cause of the decrease in battery function is the undesirable side reactions between the electrolyte and active materials on the electrodes. These reactions consume lithium, thereby limiting the lithium available to participate in the desirable discharge/recharge reactions. These irreversible side reactions also result in the formation of films on the active materials that impede ionic and interfacial transfer.

In laboratory "accelerated cycle" testing, current lithium-ion battery technologies have been shown to provide several thousands of deep cycles. The number of cycles before end of life is different for each chemistry. Lithium Manganese Oxide, Lithium Iron Phosphate, and Lithium-Nickel Cobalt Aluminate have demonstrated over 1,000, 5,000, and 4,000 cycles respectively. If used in a BEV100, these levels of cycle life could translate into 3 to 15 years of useful battery life. In real-world driving, however, it is difficult to apply the notion of a "cycle." In addition to the broad charge-discharge cycles, there are also millions of "micro" cycles associated with regeneration and acceleration, which in some chemistries, are equally as impactful in the degradation of battery performance.[6]

The vehicle performance ramifications of year-to-year decreases in capacity and power are most significant for BEVs. As battery capacity decreases over time, the allowable SOC swing must increase in order for the battery to deliver the same number of all-electric miles. As explained in the previous section, expanding the SOC swing can accelerate the degradation and decrease battery life. Further, at a low SOC, the battery may not

6 Scott B. Peterson, Jay Apt, and J. F. Whitacre, "Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization," *Journal of Power Sources* 195, no. 8 (2010): pages 2385-2392.

be able to deliver sufficient power to the vehicle. For PHEVs, the ramification of reduced power from the electric motor is not as noticeable to the driver, because as the battery loses capacity and power, the gasoline engine takes on more of the power requirements.

Example: Consider a 20 kWh battery with a 60% SOC swing at beginning of life, which equates to 12 kWh of useable energy. Assuming 3 miles of electric driving range per kWh, 12 kWh of useable energy would provide 36 miles of electric driving range. If 10 years later, the total capacity has degraded by 30% to 14 kWh, in order for the battery to deliver the same 36 miles of driving range, the SOC swing must increase to over 85% (12 kWh needed capacity for 36 miles, divided by the total capacity of 14 kWh).

Temperature Effects

Battery life is extremely sensitive to the time–temperature characteristics of the vehicle environment during both operation and storage, i.e., when the vehicle is parked. Battery life versus temperature is functionally described by the Arrhenius equation, which is logarithmic. *A "rule of thumb" employed by battery engineers is that for every 10°C increase in average temperature, battery life will be reduced by 50%.*

Example: A battery operated at an average temperature of 70°F (21°C) that demonstrates 15 years of calendar life will, if operated at an average temperature of 106°F (41°C), yield at best 3.8 years of calendar life.

It is imperative that the battery cells within a pack be exposed to the same thermal history. If some cells in a string degrade more rapidly than others due to temperature non-uniformities, the entire pack will be compromised and life will be negatively affected. Further, extreme heat or sustained temperatures over 120°F can be fatal to the battery.

It is important to note that thermal management for temperature control is not a one-way function. In cold operating environments, it can make sense to "heat" the battery to ensure good power (acceleration/regeneration during braking) and range.

Vehicle Countermeasures

Thermal Management. For the reasons articulated above, battery packs commonly have a thermal management system that is designed to keep all cells within a pack at acceptable and similar temperatures.

There are several viable methods to thermally manage a battery pack:

- Use battery energy (a parasitic load) to power the heating and cooling functions.
- When plugged in, use grid energy to power the heating and cooling functions.
- In operation, forced air or liquid coolant can be used. In some cases, a vehicle A/C refrigerant line can be routed to the battery if the cooling requirements are substantial.

Limiting SOC Swing. The predominant countermeasure being employed by automakers to ensure battery longevity is to counter the expected degradation by increasing the nominal (total) capacity of the battery and limiting the SOC swing, as discussed in the previous section on total energy versus useable energy.

While sufficient laboratory cycle life has been demonstrated for some of the commonly used chemistries for batteries in automotive use, much uncertainty remains about the calendar life of these batteries when used in real-world driving and conditions. Battery management systems, power controls, and thermal management techniques can extend the life of the battery, but substantial investment in research and development is needed to accurately evaluate and improve the calendar life of batteries.

Effects of Extreme Temperatures on Battery Performance

Battery degradation and longevity is affected more by extreme heat than by extreme cold, and was discussed in the previous section. *Battery performance*, however, is more affected by extreme cold.

In extreme cold weather, the power capability of batteries decreases. This occurs because the ionic and chemical processes that govern the internal battery processes are "thermally motivated." Thus the key chemical reactions and ionic transport mechanisms happen more slowly at lower temperatures, thereby limiting both the amount of instantaneous power available as well as the overall amount of energy that can be delivered. The driver experiences reduced power and greatly reduced vehicle range. This issue is most significant for BEVs, as they are entirely dependent on the battery for propulsion. PHEVs are affected to a lesser degree due to the fact that the internal combustion engine can be relied upon to achieve vehicle range and performance requirements (although the displacement of gasoline through the use of batteries will be reduced).

It is possible, through "smart" thermal management systems, to self-heat the pack (whereas the default design of thermal management systems is for heat rejection) to enable greater functionality, but this can take sixty minutes or more. The ability to self-heat, however, is regulated by the power-to-energy ratio of the battery—larger BEV packs, because of the higher "energy battery" designs (see earlier section on power vs. energy batteries), will self-heat at a much slower rate than smaller PHEV packs, unless heating elements are added to the pack thermal management system. Other methods include using a fuel-fired heater, extracting waste heat from the internal combustion engine (if the vehicle is a PHEV), and using grid electricity to pre-heat the battery pack while the vehicle is plugged in.

Battery Costs

The cost of the battery is the primary cost driver for PEVs. This section will review existing studies that address current and projected future battery costs, and determine a range for the future battery costs used in the integrated vehicle analysis of this study.

Prior to a discussion of battery costs, however, it is necessary to specifically define what "cost" represents, as the generic term "battery cost" is imprecise. Many cost references are at the individual cell level, but moving from the cell to the module to the battery pack increases the cost—anywhere from 25 to 65%.[7] Vehicle OEMs generally expect to purchase a battery pack from a supplier, integrate this battery with the vehicle, and provide it to their retail sales channel.[8] Consequently, in addition to understanding the basic cost components of a battery pack, it is important to differentiate whether "costs" are based on the manufacturing costs for the battery cells, the costs for the battery pack supplier, the price the vehicle OEM would pay the battery supplier for the pack, or the amount of cost the vehicle OEM passes on to the retailers or end consumers, as each level within the supply chain adds costs. The "battery" could be a cell or a pack; the "cost" could be the cost to the OEM, the retailer, or the end consumer; the "cost" per kilowatt-hour could refer to either useable capacity or total capacity; and the pack may or may not include an active thermal management system.

From this point forward, "battery cost" will refer to the complete battery pack, including the battery management system but not including an active thermal management system, at the battery supplier-to-vehicle OEM level, on the basis of total capacity.

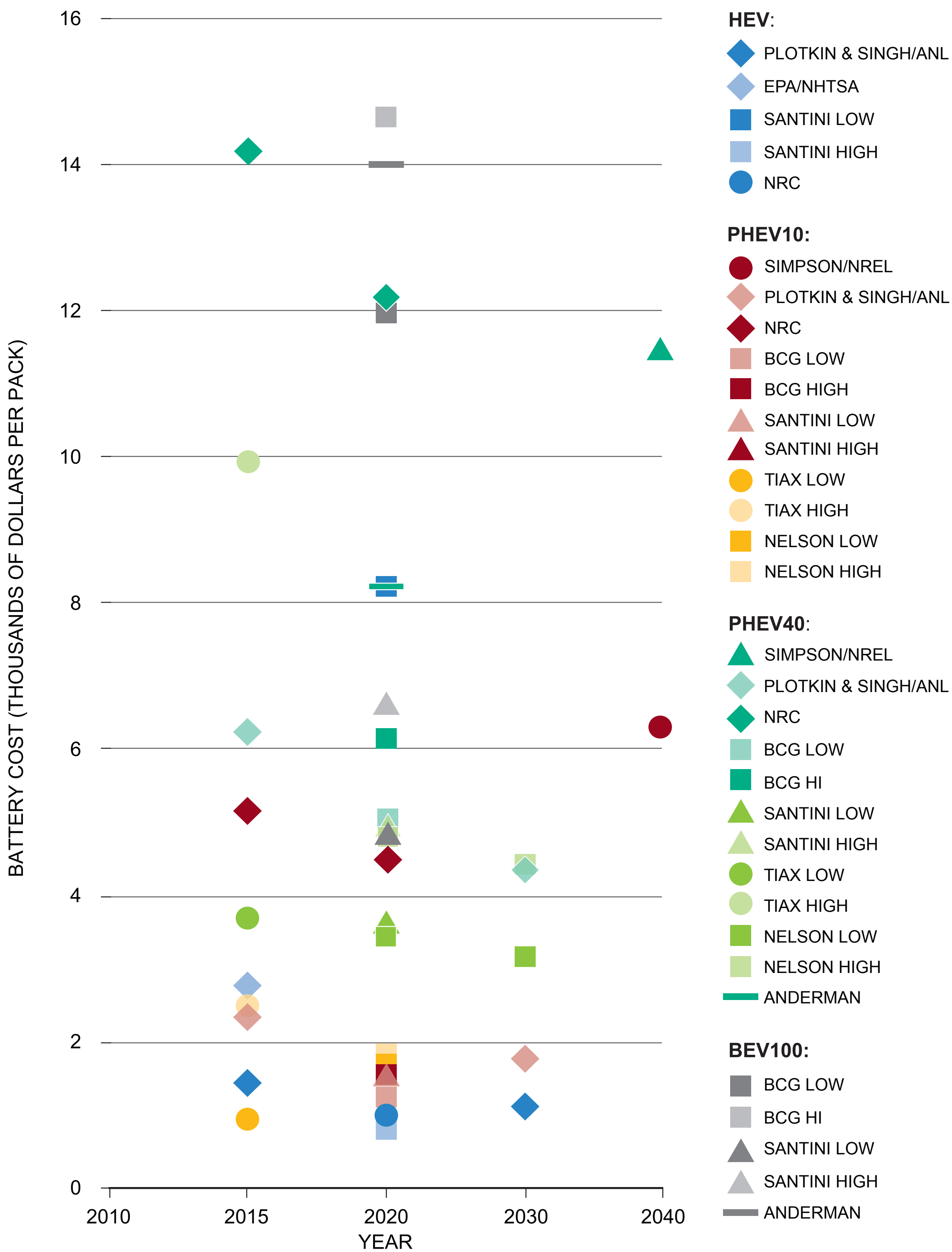
There are many available studies of current and projected lithium-ion vehicle battery costs, which at first glance vary so widely that it seems impossible to draw conclusions. In order to compare the studies, the Electric Subgroup (1) differentiated by vehicle type, (2) used a common battery pack size, and (3) standardized costs by the level of cost within the value chain. The results are shown in Figure 13-9.

A subset of these studies was then selected, using the following criteria:

- Bottom-up approach—Studies were prioritized based on their ability to build battery costs up from materials, components, capital, and labor costs, as opposed to market surveys or manufacturers' press releases.
- Supported by specific literature—Priority was given to well-referenced studies and studies that are publicly available.
- Reasonable in light of the results of other studies—Despite a broad variability from source to

7 F. R. Kalhammer et al., *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007,* Prepared for State of California Air Resources Board, Sacramento, California, April 13, 2007.

8 In some cases, OEMs are pursuing models other than purchasing packs from outside suppliers—such as purchasing cells and integrating them into a pack, as GM has done for the Chevy Volt; or securing packs from a venture in which it has partial ownership, as Nissan does with Automotive Energy Supply Corporation, a JV between Nissan and NEC. However, considering pack costs to the OEM provides the most consistent way to judge the impact of the battery on overall vehicle costs and to make apples-to-apples comparisons.



Note: Most projections shown are for pack-level battery cost to OEM. To make this a component of vehicle cost, upward adjustment (margin) is required in most cases. In cases where costs were provided in $/kWh, the following pack sizes were assumed: 33.3 kWh for BEV, 14 kWh for PHEV40, and 3.5 kWh for PHEV10.

Sources: See Bibliography for data sources.

Figure 13-9. *Estimates of Pack-Level Battery Cost to Original Equipment Manufacturer* source, some studies fell far outside the mainstream range of opinion, and were therefore not included.

The resulting subset of studies, and the rationale for selection, is shown in Table 13-6.

The projected battery costs—to the vehicle OEM, per kilowatt-hour of total capacity, for a battery supplied at the pack level—of this subset of studies are shown in Figure 13-10. Note that there are major differences in costs based on the type of vehicle (BEV, PHEV40, or PHEV10).

These studies and estimated costs indicate that:

- Battery costs are currently high, but are expected to decrease substantially in the next several years, primarily due to mass production and economies of scale, improved production efficiency through learning, and improved cell and packaging design.
- By 2020, battery costs will likely be in the range of $200 to $500 per kWh.
- Costs will drop further past 2020, but not at the pace of cost reduction between 2010 and 2020.

A number of pathways are being pursued to reduce battery costs. Today's lithium-ion vehicle batteries are expensive in part because they are built at relatively low volumes. Simply increasing scale from today's sales volumes (well under $500 million of total sales worldwide in 2010) to anticipated volumes in 2020 (projections range from $2.3 billion[9] to over $5 billion[10] worldwide) will inevitably drive down per-unit costs substantially, partly from economic advantages of scale manufacturing, and partly from the improvements in productivity and yields that will come with manufacturing experience and process optimization.

9 Lux Research, *Small Batteries, Big Sales: The Unlikely Winners in the Electric Vehicle Market,* March 2011.

10 H. Takeshita and H. Mukainikato, "Worldwide Market Update on Secondary Batteries for Portable Devices, Automobiles, and ESS," Presented at the 28th Annual Battery Summit, Ft. Lauderdale, FL, March 14, 2011.

Study	Rationale for Selection	Notes
Santini*	Thorough and credible bottom-up estimation for a range of battery chemistries and applications. Viewed as state-of-the-art accurate predictions by some; seen as overly optimistic regarding labor and overhead costs by others.	Controversially low regarding EV100 battery pricing, and generally lower than other studies; therefore the high-end range from Santini was typically used.
BCG†	Bottom-up approach was used, although few details were published. Consistent with other studies and credible in the business community.	Used as a higher and less controversial source for EV100 battery cost.
Nelson‡	Credible, bottom-up approach similar to that of Santini, and developed by the same group of experts at Argonne National Laboratory.	Documents a simplified method for projecting out to 2030. Used for PHEV40 projections.
Anderman§	Simpler underlying cost calculations, but performed by a credible source with up-to-date industry knowledge.	Highest PHEV40 battery cost projections for 2020.
Tiax¶	Highly credible, detailed bottom-up study; however, no specific timetable was defined in the work. Uncertainty analysis leads to a wide range of estimates.	2015 timetable prescribed to the data for this study.

Sources:

* Danilo Santini, Kevin Gallagher, and Paul Nelson, "Modeling of Manufacturing Costs of Lithium-Ion Batteries for HEVs, PHEVs, and EVs," presented at EVS25 (Electric Vehicle Symposium), Shenzhen, China, November 5-9, 2010.

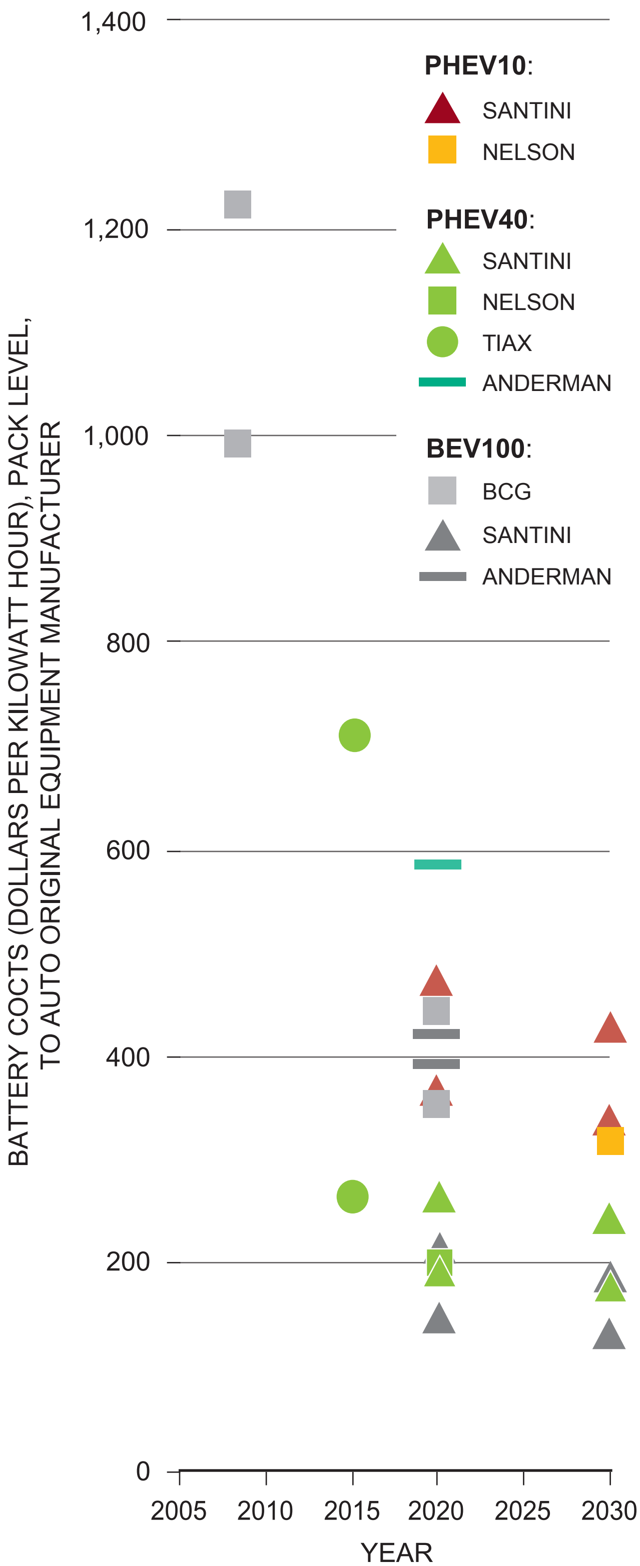
† The Boston Consulting Group, *Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020,* 2010.

‡ Paul Nelson, Danilo Santini, and James Barnes, "Factors Determining the Manufacturing Costs of Lithium Ion Batteries for PHEVs," presented at EVS24 (Electric Vehicle Symposium), Stavanger, Norway, May 13-16, 2009.

§ Menahem Anderman, "World EV/PHEV/HEV Market and Corresponding Battery Technology and Market," presented at the SAE International Vehicle Battery Summit, Shanghai, China, September 2010.

¶ TIAX LLC, "PHEV Battery Cost Assessment," presentation by Brian Barnett et al., June 2010.

Table 13-6. *Subset of Studies of Lithium-Ion Vehicle Battery Costs*



Note: 2030 projections are made using the method of Perry, as cited by both Nelson and Santini, over 10 years and a tenfold increase in plant capacity, using each author's 2020 projections as a starting point.

Sources: See Table 13-6 for data sources.

Figure 13-10. *A Summary of Projected Costs of Batteries Over Time from Several Sources*

Cell electrochemistry is also evolving, and may lead to cost reductions in lithium-ion batteries via new materials. Many of the new materials under development are still in the laboratory phase, however, and it is extremely difficult to project commercialization timelines and costs. *The battery cost projections used in this study, therefore, do* ***not*** *assume commercial adoption of advanced battery chemistries or other energy storage technologies.*

Vehicle Charging Infrastructure

Charging Levels

Plug-in electric charging infrastructure is categorized by the power rate at which electricity is delivered. Table 13-7 describes the various charging configurations, ratings, and terminology according to the Society of Automotive Engineers (SAE).

For the purposes of this report, charging is defined as follows:

- Level 1 Charging—Level 1 (L1) charging is low-power charging at 120 volts (V) of alternating current (AC) at a rate of approximately 1.4 kW.

Alternating Current (AC)	Direct Current (DC)
AC Level 1 – 120V AC 1 • Rated current 12A or 16A • Rated Power 1.44W, 1.92kW • J1772 connector	**DC Level 1 – 200-450V** • Rated Current <=80A • Rated Power <=19.2kW • J1772 connector
AC Level 2 – 208/240V AC 1 • Rated Current <= 80A • Rated Power <=19.2kW • J1772 connector	**DC Level 2 – 200-450V** • Rated Current <=200A • Rated Power <= 90kW • J1772 hybrid connector
AC Level 3 – TBD; AC 1 or 3 • Connector is TBD†	**DC Level 3* – 200-600V** • Rated Current <=400A • Rated Power <=240kW • Connector is TBD†

* The industry is shifting to the term "DC" or fast charging to replace the previously common term "Level 3" charging.

† The connector standards for DC and AC Level 3 are still in process, so they are subject to change.

Table 13-7. *Various Charging Configurations, Ratings, and Terminology from Society of Automotive Engineers*

On the grid side, L1 is supplied by the NEMA 5-15R receptacle that is ubiquitous in North American homes and businesses. Providing L1 charging requires a connector cord and an EVSE (Electric Vehicle Supply Equipment), which includes a charging circuit interrupting device to provide personal protection, and a ground monitor interrupter to confirm a complete ground circuit prior to charging the vehicle. The alternating current supplied by the grid is converted on the vehicle into the direct current needed to recharge the battery. As the EVSE does not supply electricity directly to the battery, it is incorrect to refer to it as the "charger." (See Figure 13-11.)

- Level 2 Charging—Level 2 (L2) charging is medium-power charging at 240V AC at a rate of approximately 3 kW, up to 19 kW. An L2 EVSE is larger than an L1 EVSE, and includes more sophisticated circuitry in order to ensure safety. (See Figure 13-12.)
- DC (Direct Current) Fast Charging —"DC Fast Charging" is high-power charging, with the electricity supplied by an off-board (off-vehicle) charger at variable DC voltages and currents. There are different power levels possible with DC, but for vehicle charging, the power is typically supplied at 200–450V, at a rate of up to 90 kW, depending on the requirements of the vehicle. Charging is controlled by the vehicle's battery management system, which ensures that the battery is not charged at a rate in excess of predetermined limits. (See Figure 13-13.)

Note: Leviton L1 16A Residential charging unit and GFCI outlet.

Figure 13-11. *Example of a Dedicated GFCI Outlet and Level 1 EVSE*

Note: Leviton L2 Residential charging units, 32A and 40A.

Figure 13-12. *Examples of Level 2 EVSEs*

Note: A 25 kW DC Quick Charging Station.
Source: Fuji Electric Corporation of America.

Figure 13-13. *Example of a DC Fast Charger*

Figure 13-14 shows the approximate charge times (in minutes or hours) for the three different vehicle types at different power rates. An "average charge" is for a trip of 25 miles, which is the average distance traveled by all vehicles that were driven on a given day in the United States.[11]

Charging Infrastructure Requirements

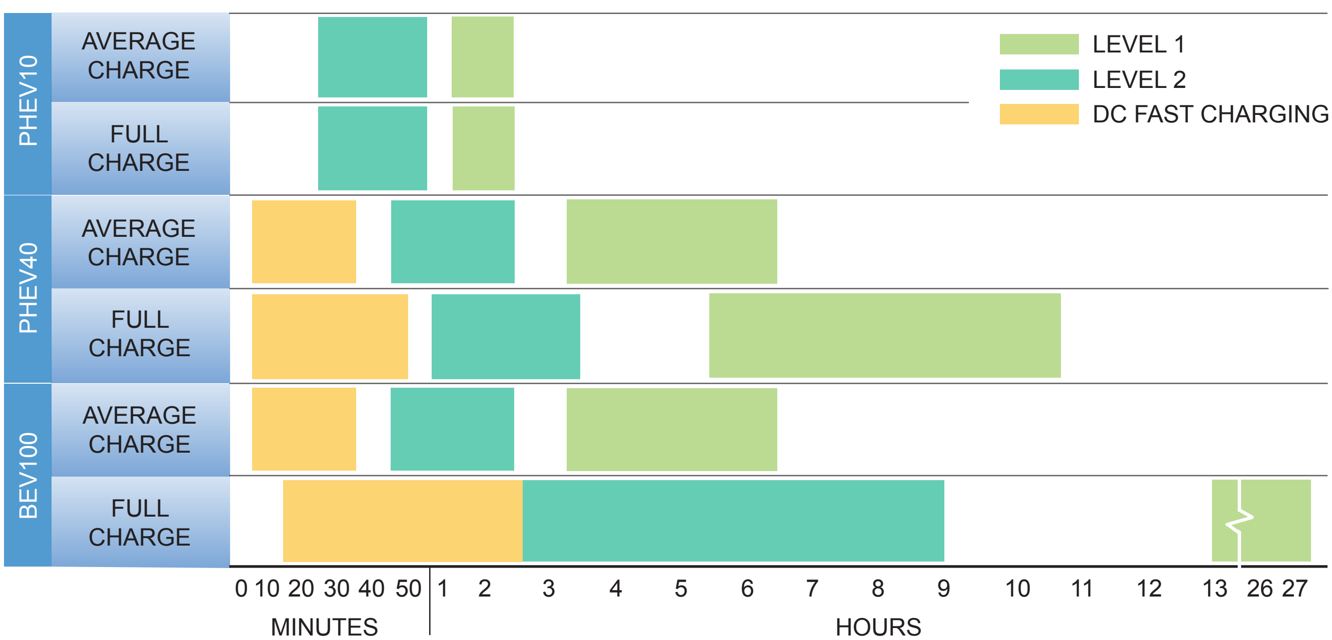
In order for PEVs to be practical, drivers must have convenient access to charging, at an adequate charging rate for their vehicle use. For most drivers, this will likely occur at home, where most driving days originate and where vehicles typically have the longest "dwell" time during a day. Additional charging will likely occur at the workplace and at commercial locations such as stores and restaurants.

Few well-described forecasts for residential and non-residential charging infrastructure requirements exist in the literature. Complicating matters is the need to project needs for both the location of charging infrastructure (residential, workplace, and public/commercial installations) and the type of charging required (Level 1, Level 2, or DC Fast Charging). Of the literature that does attempt to answer "How many? What type/level? Where?", most either focus exclusively on the needs of BEVs, or do not explicitly distinguish between requirements specific to BEVs, PHEVs, or both. Additionally, many of the reports offer little transparency to the assumptions underlying the forecasts. A 2011 California Energy Commission report cited a wide disparity among recommendations, ranging from 0.6 to 3.5 charging units per PEV, depending on the source.[12] Appendix 13A (at the end of this chapter) describes the detail and methodology underlying several of these recommendations.

An internal analysis performed by the Electric Power Research Institute (EPRI) using general

11 Lucy Sanna, "Driving the Solution: The Plug-in Hybrid Electric Vehicle," *EPRI Journal,* Fall 2005.

12 Charles Smith and Miles Roberts, *2011-2012 Investment Plan for the Alternative and Renewable Fuel and Vehicle Technology Program,* California Energy Commission, Staff Draft Report CEC-600-2011-006-SD, February 2011.



Notes: Level 1 charge time assumes a rate of 1–2 kW, Level 2 assumes a rate between 3–10 kW, and DC Fast Charging assumes a charging rate between 11–90 kW. The vehicle efficiencies used are 290 Wh/mile for the PHEV10, 360 Wh/mile for the PHEV40, and 340 Wh/mile for the BEV100. (EPA fuel economy label values for the Toyota Prius Plug-in Hybrid, Chevrolet Volt, and Nissan LEAF, respectively.)

Source: Electric Power Research Institute calculation.

Figure 13-14. *Approximate Charge Times at Different Power Rates* vehicle driving statistics attempted to provide detail of vehicle charging requirements for both PHEVs and BEVs, at multiple charging locations, and at multiple charging levels. There were two primary elements to the analysis: benefits test and charging station occupation.

Benefits Test

The benefits-based approach examines each individual vehicle, under different charging scenarios. If the total number of electric miles accumulated from charging outside the home is greater than the total number of electric miles from charging at home only, then the vehicle is perceived to have some benefit to charging outside the residence. Charging is presumed to have enough of a "cost" that the consumer would only charge if they received some benefit in terms of increased miles driven electrically. Thus, a BEV100 that only drove 10 miles to work and is expected to drive 10 miles home would not charge at work.

This methodology reduces the number of chargers occupied by individuals who would achieve no benefit from charging, so it assumes that some cost trade-off would drive the decision as to whether or not to charge. Note that "cost" does not need to be monetary—it could be the inconvenience of having to walk from a distant parking lot to reach the final destination. Finally, the analysis assumes optimal charging station location—i.e., the charging station is at the right location at the right time. This same logic is used to determine the benefit achieved from increasing charging rates from Level 1 (1.44 kW) to Level 2 (6.6 kW).

The results of the benefits-based methodology provide an idea as to the number of chargers that would be in use at any given time if charging had some associated cost, which is likely in the future. At this time it is unclear if free charging or paid charging will dominate in public-access (commercial) and limited-access locations such as lots for employees (workplace). If the cost of paid charging is substantial, however, then the benefits-based methodology would overestimate charger utilization.

Charging Station Occupation

- The "vehicle occupies parking" case assumes that once the vehicle is parked it is not moved until the vehicle leaves on its next trip.
- The "vehicle occupies charger" case assumes that the vehicle occupies the charger only until it is full and is then moved to free up the charger for another vehicle.

The matrix of "benefits test" and "charging station occupation" yielded recommendations for the four scenarios listed in Table 13-8.

	Charging is free	Charging only with benefit
Vehicle occupies parking	A	B
Vehicle occupies charger	C	D

Table 13-8. *Charging Cost and Usage Scenarios*

The resulting EPRI recommendations are for Scenario B, and are illustrated graphically in Figure 13-15.[13] For low-range vehicles with relatively small batteries but a high benefit to charging, such as the PHEV10, the peak number of charging stations is relatively high. A high number of Level 1 charging stations is beneficial for these vehicles due to longer dwell times at work and short refueling times. For the BEV100, and to a lesser extent the PHEV40, vehicles are less likely to need to charge, but if they do need to charge they are more likely to benefit from higher-power charging.

Table 13-9 lists EPRI's recommendation by charging level for Home, Workplace, and Public locations, as well as the recommendations from various other sources, as described in Appendix 13A.

DC Charging

DC Fast Charging has many potential benefits, but also has many uncertainties and challenges, as described below.

DC Charging Benefits

DC Fast Charging allows vehicle batteries to be charged significantly more quickly than can be achieved with on-board vehicle chargers. This

13 Because the dataset used is limited in nature, and does allow simulation of actual position-based destinations, this methodology does not represent how the position of chargers and the needs of vehicles align. It is likely that vehicles would not be able to charge at every destination desired, but the vehicles would more intensively use chargers at the destinations that do have charging. The case is not necessarily a high or a low estimate for the total number of chargers that will need to be installed, but does represent plausible long-term charger requirements.

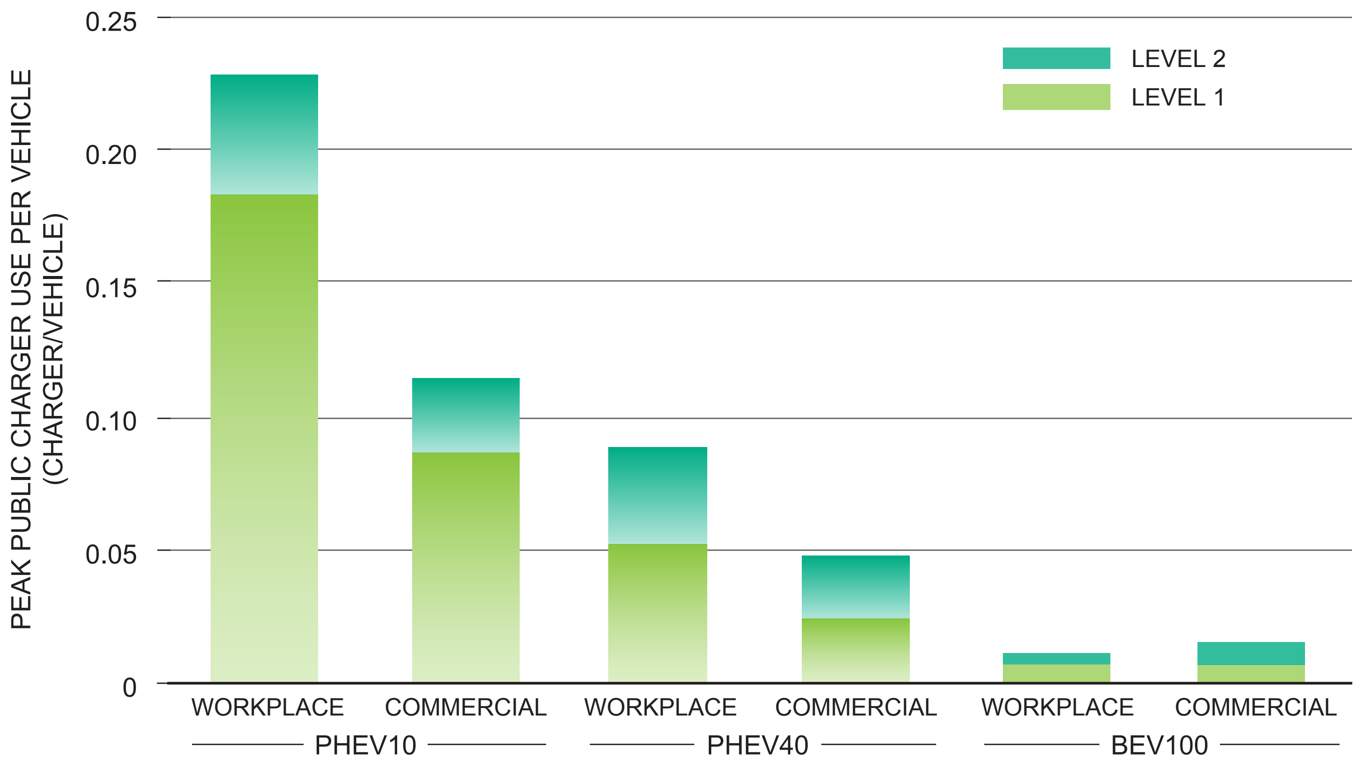


***Figure 13-15.** Results of the Shared-Benefit Based Approach to the Number of Chargers per Vehicle*

reduced charge time could provide a significant benefit in use cases such as long-distance travel for BEVs, as well as for vehicle owners who do not have access to overnight charging—for example, those who live in urban areas with on-street parking. DC Fast Charging has the potential to improve customer perceptions of vehicle capability, particularly for BEV owners, as widely available fast charging could reduce fears of being stranded—commonly referred to as "range anxiety." Another potential benefit is an increase in the amount of vehicle miles traveled by BEVs.[14] As explained in the section on utility factor at the end of this chapter, the existence of DC Fast Charging may allow for more trips taken with the BEV, instead of using another vehicle for trips longer than the BEV range.

Because of these potential benefits, several automakers including Nissan, Toyota, Subaru, Honda, Volvo, Peugeot, Mazda, Suzuki, and Mitsubishi are pursuing DC Fast Charging.[15] For example, Nissan sells DC charging equipment today in Japan and offers a DC charge port on the LEAF. In addition, Volkswagen, Audi, Daimler, Ford, GM, Porsche, and BMW are proposing an international standardized approach to fast charging BEVs in the United States and Europe that would be backward compatible with the J1772 system used in the United States and would allow a single charging interface on the vehicle.[16]

Uncertainties for Vehicle Manufacturers

There are a number of uncertainties for vehicle manufacturers concerning DC Fast Charging, however, including the impact on batteries and the overall system efficiency of PEVs (as more of the charging energy is lost to heat), the potential for more than one type of DC charging standard to

14 A study by Tokyo Electric Power Company found that even if BEV drivers did not use the fast chargers, the chargers provided a psychological "insurance" against being stranded, and the drivers increased the number of miles driven.

15 The CHAdeMO Association includes 826 companies, http://www.chademo.com/.

16 Green Car Congress (website), "Seven Auto Manufacturers Collaborate on Harmonized Electric Vehicle Fast Charging Solution," October 13, 2011, http://www.greencarcongress.com/2011/10/harmony-20111013.html.

Reference	Timing		Home		Total Home	Workplace			Total Work	Public			Total Public	Total EVSE
			L1	L2		L1	L2	L3/DC		L1	L2	L3/DC		
EV Project/ECOtality	Early Market		–	1.00	1.00					–	0.64	0.03	0.67	1.67
ECOtality/eTec	Mature Market		–	0.48	0.48					–	0.63	0.01	0.64	1.12
EV Project Curve Fit			–	0.49	0.49					–	0.08	0.01	0.09	0.58
Electrification Coalition/PRTM	Early Market													1.5–2.5
	Mature Market													0.5–1.5
WCCC	Early Market													
	Mature Market													0.20
SCE/CPUC (CEC)	Early Market		0.40	0.60	1.00								0.20	1.20
	Mature Market													
EPRI	Early Market													
	Mature Market													
	PHEV 10	Residential Charging Scenario	1.00	–	1.00	–	–	–	–	–	–	0.01	0.01	1.01
		“Ubiquitous” Charging Scenario	1.00	–	1.00	0.18	0.05	–	0.05	0.09	0.03	–	0.03	1.08
	PHEV40	Residential Charging Scenario	0.60	0.40	1.00	–	–	–	–	–	–	0.01	0.01	1.01
		“Ubiquitous” Charging Scenario	0.60	0.40	1.00	0.05	0.04	–	0.04	0.03	0.02	–	0.02	1.06
	BEV100	Residential Charging Scenario	0.20	0.80	1.00	–	–	–	–	–	–	0.01	0.01	1.01
		“Ubiquitous” Charging Scenario	0.20	0.80	1.00	0.01	0.01	–	0.01	0.01	0.01	0.00	0.01	1.02
	Average				1.00	0.04	0.02		0.02	0.02	0.01	0.00	0.01	1.01
eTec/Source 1	Early Market		0.19	0.81	1.00									
Research	Mature Market													
RMI (CEC)	Early Market												0.60	
	Mature Market													
Bay Area Corridor (CEC)	Early Market												0.1–0.2	
	Mature Market													
OEMs (Nissan, Ford, GM, Chrysler) – CEC	Early Market				1.00								0.30	
	Mature Market													

Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

***Table 13-9.** Summary of Infrastructure Density Recommendations for PEVs – Ratio per Vehicle* develop, and the impact it would or would not have on market adoption.

One of the largest uncertainties for vehicle manufacturers is the impact of DC Fast Charging on battery life. Charging at high rates will likely increase the rate of battery degradation for near-term chemistries, which will increase the likelihood of warranty replacements and negative customer perceptions. Additionally, potential charge patterns, such as fast charging at high ambient temperatures or charging multiple times per day will likely have an additional negative impact on battery life. Real-world data will be needed to measure the magnitude of the impacts from fast charging.

Vehicle manufacturers also face uncertainty in determining the potential impact on consumer adoption for vehicles with and without the ability to fast charge. The uncertainty and lack of data on vehicle usage patterns (BEV vs. PHEV, or occasional vs. frequent fast charging) means that vehicle manufacturers have a difficult time assessing whether fast charging capability is truly beneficial for market adoption. Finally, there is not yet a universally agreed-upon standard for DC Fast Charging. This creates the risk of designing a vehicle with a DC charge port that would need to be retrofitted in the future should a different standard emerge, or worse yet, needing to design vehicles that can accommodate two standards, which would add complexity and cost to the vehicle.

Uncertainties for Infrastructure Providers

Infrastructure providers contend with two key uncertainties: (1) the lack of a U.S. DC Fast Charging standard and (2) an uncertain business case. Although the U.S. SAE standard is expected to be finalized by late 2012, DC charging equipment manufacturers must then receive compliance approval from certifying organizations such as the Underwriter Laboratories. Additionally, it is uncertain whether or not DC charging devices currently being deployed under other standards can be retrofitted to the new standards. This creates significant near-term uncertainty about which devices can be installed without the risk of becoming obsolete.

Even if a charging standard is quickly ratified with compliant devices that quickly follow, infrastructure providers face uncertainty about the business case. Fast chargers will be expensive to install, and capital and maintenance costs must be recovered during usage. Additionally, in many areas the power draw of fast chargers will incur power-based “demand charges.”[17] It is uncertain whether consumers will pay the higher cost that will need to be charged for the electricity. As has been stated numerous times within this chapter, only real-world market data will inform the uncertainties of whether and how consumers use DC Fast Charging, and the value it provides to both the consumer and the charging station provider.

Ultra-Fast Charging

The benefits of DC Fast Charging have led some to conclude that even higher charging rates would be beneficial, so that charge times could be reduced to be similar to refueling of current gasoline vehicles, about 5 minutes. In addition to the vehicle- and battery-related issues that would need to be solved, much higher charge rates would pose significant challenges to the grid. Ultra-fast charging of a 25 kWh battery pack in 5 minutes would require a power flow rate of approximately 300 kW, which is approximately equivalent to the peak power requirements for a 100,000 square foot office building.[18] The power use for this load would have a sharp profile similar to an industrial load like a sawmill. Achieving the same charge time for larger batteries, such as those for a heavier or longer-range BEV, would require even more power. Although loads of this type can be provisioned, the equipment to supply this load without disrupting surrounding loads would be bulky and expensive, and the low utilization of these assets would make cost recovery difficult except in very high-traffic areas. It would be possible to use on-site energy storage to reduce the grid demands for this load, but this equipment is also bulky and expensive, particularly if the station is designed to accommodate back-to-back recharges.

Current State of Activity Related to Grid-Connected Vehicles

Government Investment

Over the past few years, there has been significant interest and investment in PEVs. Incentives

17 Demand charges are separate from the consumption charges, and reflect the peak-use rate of electricity during any given billing period.

18 Electric Power Research Institute, *Commercial Building Energy Efficiency and Efficient Technologies Guidebook,* Report 1018313, November 2008.

and programs aimed to increase the penetration of PEVs in the light-duty vehicle fleet include the following:[19,20]

- The American Recovery and Reinvestment Act of 2009 (ARRA)
  - Provided $2.4 billion in loans to three electric vehicle factories in Tennessee, Delaware, and California.
  - Provided $2 billion in grants (with 100% matching funds by private industry) to support 30 factories that produce batteries, motors, and other electric vehicle components. These grants are intended to build the capacity to produce 50,000 BEV/PHEV batteries annually by the end of 2011 and 500,000 batteries annually by December 2014.
  - Provided $400 million in grants (with 100% matching funds by private industry and/or state/municipal entities) to install 22,000 EVSEs in 20 U.S. cities.
  - Created tax credits for the purchase of BEVs and PHEVs. The amount of the credit is based on the size of the battery, and ranges from $2,500 to $7,500 per vehicle. These tax credits begin to sunset (phase out) when each automaker sells 200,000 BEV/PHEVs.
  - Funded the "EV Project," which included approximately 400 DC fast chargers.
- Over 40 U.S. states have adopted other measures promoting electric-drive vehicle usage, including access to high occupancy vehicle lanes (with a single occupant BEV or PHEV), waived emission inspections, tax credits, rebates, and other programs.
- The U.S. government and some U.S. state governments also fund extensive R&D efforts on batteries and other electric vehicle components.
- Other regulatory programs, such as the Zero-Emission Vehicle program that applies in over 10 U.S. states, mandate the sale of substantial numbers of BEVs, PHEVs, and Fuel Cell Electric Vehicles (FCEVs).

19 U.S. Department of Energy, *One Million Electric Vehicles by 2015*, February 2011 Status Report.

20 U.S. Department of Energy (website), Alternative Fuels Data Center, "Laws & Incentives," http://www.afdc.energy.gov/afdc/laws/matrix/tech.

Vehicle Announcements

The majority of global automakers is active in PEV development, either currently offering vehicles or with plans to introduce one or more models in the next couple of years, as shown in Table 13-10.

Toyota, Ford, and Volvo will offer their plug-ins on platforms common to their conventional offering, while Mitsubishi and BMW are pursuing dedicated (unique platform) vehicles. There are also several start-up companies that are entering the market. Many start-ups, however, face tremendous hurdles to successful commercialization, not the least of which is the availability of suppliers willing and/or able to meet the aggressive timing and relatively low volume production levels targeted by start-ups. These companies compete with established automotive manufacturers that are delivering plug-in models of their own and at volumes more appealing to suppliers that place greater priority on the security and assurance that only established automotive OEMs have the resources to provide.

Charging Equipment Companies

In response to the release and announcement of many PEV models, and the anticipated market growth of PEVs, many companies have entered the business of supplying electric vehicle supply equipment. These include both start-up companies and established multinational firms, and many of them have partnered with automakers to help ensure compatibility with PEVs and drive the market for their offerings. (See Table 13-11.)

Electricity Supply Chain

The electricity supply chain comprises the generation, transmission, and distribution of electricity, as depicted in Figure 13-16. Electricity **generation** typically occurs at central plants distant from load centers, and is fueled by a variety of primary fuels. Electricity **transmission** is the long distance transfer of electricity from central plants to load centers. This transfer occurs at high voltages—typically greater than 100 kilovolts (kV)—in order to reduce the current and consequent resistive losses during the transfer. Electricity **distribution** is the transfer of electricity from transmission endpoints, typically

U.S. Market Intro	Make	Model	Drive-train	All-Electric Range (miles)	Total Range (miles)	Fuel Econ-omy (MPGe)	MSRP (pre-subsidy)	Targeted Annual U.S. Volume	Vol-ume Target Date	Status
2008	Tesla	Roadster	BEV	225	225	120	$109,000	1,000	2009	In Production
2011	Chevy (GM)	Volt	PHEV	40	379	93	$39,980	120,000	2012	In Production
2011	Nissan	LEAF	BEV	73	73	99	$35,200	100,000	2014	In Production
2012	Fisker	Karma	PHEV	32	230	52	$102,000	10,000	2012	In Production
2012	Mitsubi-shi	"I"	BEV	62	62	112	$29,125	*	*	In Production
2012	Prius (Toyota)	PHEV	PHEV	14.3†	475	95	$32,760	15,000	2013	In Production
2012	Smart (Daimler)	fortwo ED	BEV	63	63	87	*	20,000	2013	In Development
2012	Tesla	Model S	BEV	160/230/300	160/230/300	*	$57,400	20,000	2013	In Development
2012	Volvo	C30 EV	BEV	70-100 (est.)	70-100 (est.)	*	$2,100	100	2012	Demo Program
2012	BMW	ActiveE	BEV	100 (est.)	100 (est.)	*	$2,250 + $499 / mo. x 24 months	700	2012	Demo Program
2012	Toyota	Rav4 EV	BEV	80-120 (est.)	80-120 (est.)	*	*	*	*	In Development
2012	Scion (Toyota)	IQ-EV	BEV	50 (est.)	50 (est.)	*	*	*	*	Demo Program
2012	Ford	Focus	BEV	80	80	100	$39,995	*	*	In Development
2012	Honda	Fit EV	BEV	70	70	*	*	*	*	In Development
2012	Coda Automo-tive	CODA	BEV	<150 (est.)	<150 (est.)	*	$37,250	*	*	In Development
2012	Ford	C-Max Energi	PHEV	500	500	*	*	*	*	In Development
2012	Fiat	500 EV	BEV	80-100 (est.)	80-100 (est.)	*	*	*	*	In Development
2013	Chevy (GM)	Spark EV	BEV	*	*	*	*	*	*	In Development
2013	Fisker	Nina	PHEV	*	*	*	$47,490	75,000	2014	In Development
2013	Honda	Accord	PHEV	10-15†	*	*	*	*	*	In Development
2013	Tesla	Model X	EV	230/300	230/300	*	*	15,000	2014	In Development
2013	BMW	I3	(1) BEV (2) PHEV	80 (est.)	80 (est.)	*	*	*	*	In Development
2013	BMW	I8	PHEV	20 (est.)	*	*	*	*	*	In Development

* Unknown or not available.

† Blended-mode operation; 14 miles all-electric range only possible under 62 mph.

Note: Data current as of February 2012.

Table 13-10. *U.S. Market Timing for Grid-Connected Vehicles*

Company	Product	EVSE/Station type (L1, L2, DC)	Auto OEM partners	Other partners
ABB	EVSE	Level 2, DC	GM	ECOtality
Aerovironment	EVSE	Level 2, DC	BMW	Gov't entities
Aker Wade	EVSE, Software	DC	Toyota, Chrysler, GM, Honda	Coulomb Technologies, Better Place
Avcon	EVSE	Level 1/2	Ford, Honda	
Better Place	Charging Service Provider	Swap battery, Level 1/2, DC	Renault-Nissan	GE
Coulomb Technologies	EVSE, Installer	Level 1/2, DC	Ford, BMW	
Eaton	EVSE, Simulator, Software	Level 1/2, DC	Mitsubishi	
Ecotality	Charging Station Provider	Level 2, DC		ABB, Cisco
EV-Charge America	EVSE	Level 1/2		
GE	EVSE	Level 2		
Leviton	EVSE	Level 1/2	Ford, Toyota	Azure Dynamics, Coulomb
Panasonic	EVSE	Level 1/2, DC		IKEA
Schneider Electric	EVSE	Level 1/2, DC		City of Fort Collins
Shorepower	EVSE	Level 1/2		

Note: Data current as of February 2012.

Table 13-11. *Sampling of Companies Active in EVSE Production, Installation, and Operation*

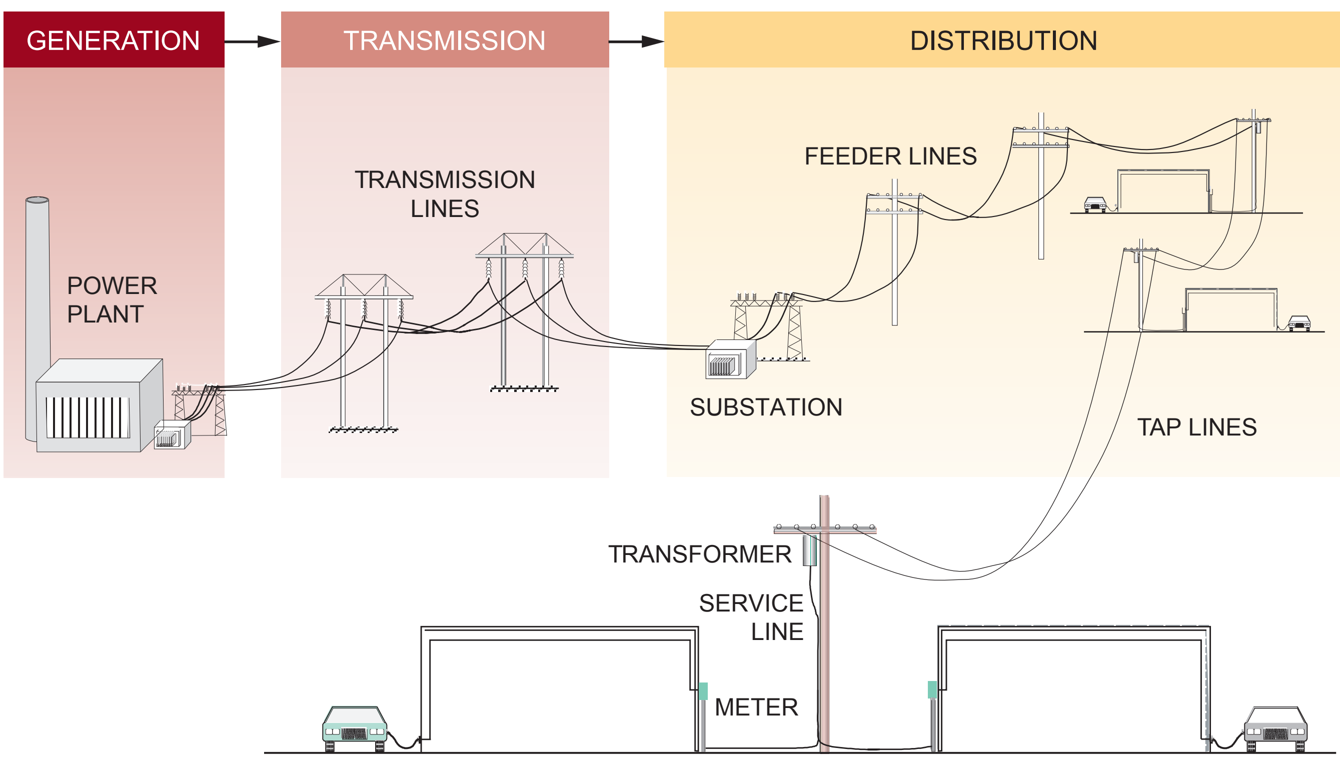


Figure 13-16. *Pathway of Electricity from Generation Source to Vehicle Charging*

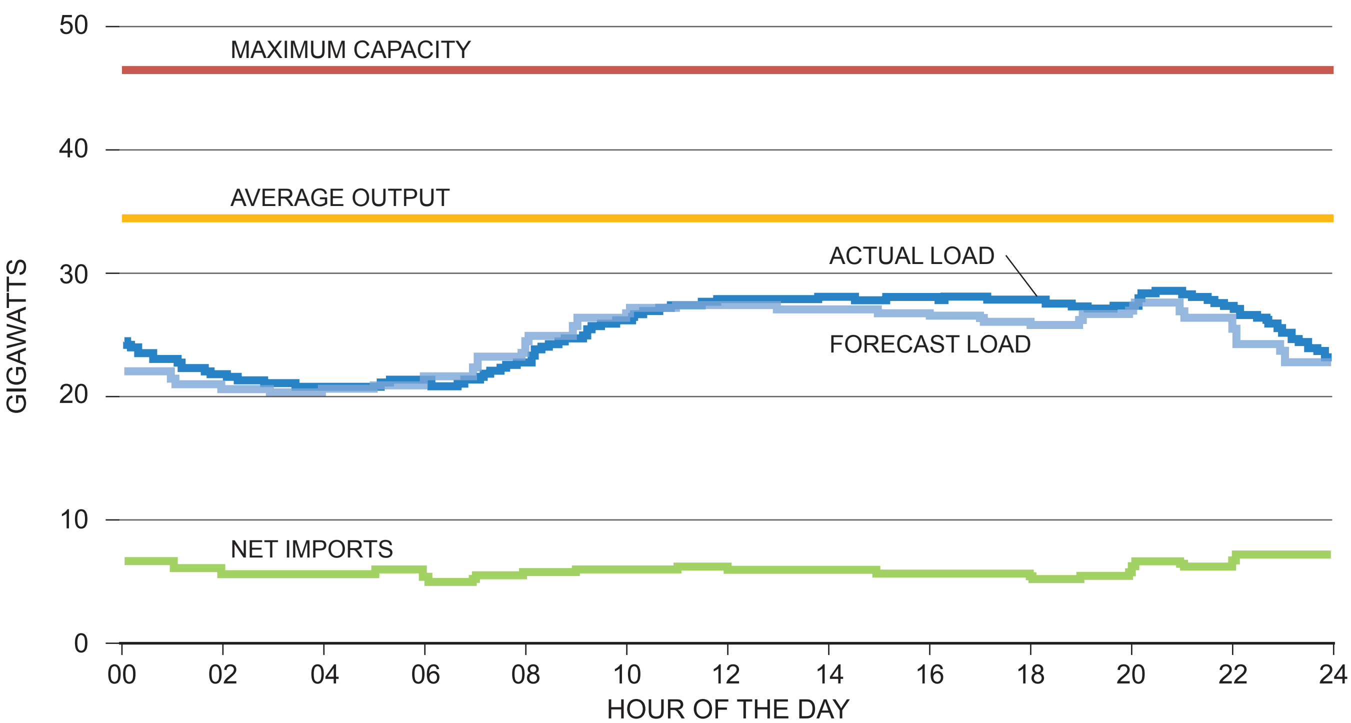
substations, to customers. Distribution occurs at a variety of voltages far lower than for transmission—4 kV to 35 kV—as the transfer distances are much shorter.

These different stages of the electricity supply chain, and the impacts of vehicle charging, are discussed in the sections that follow.

Electricity Generation and Transmission and Impacts of Vehicle Charging

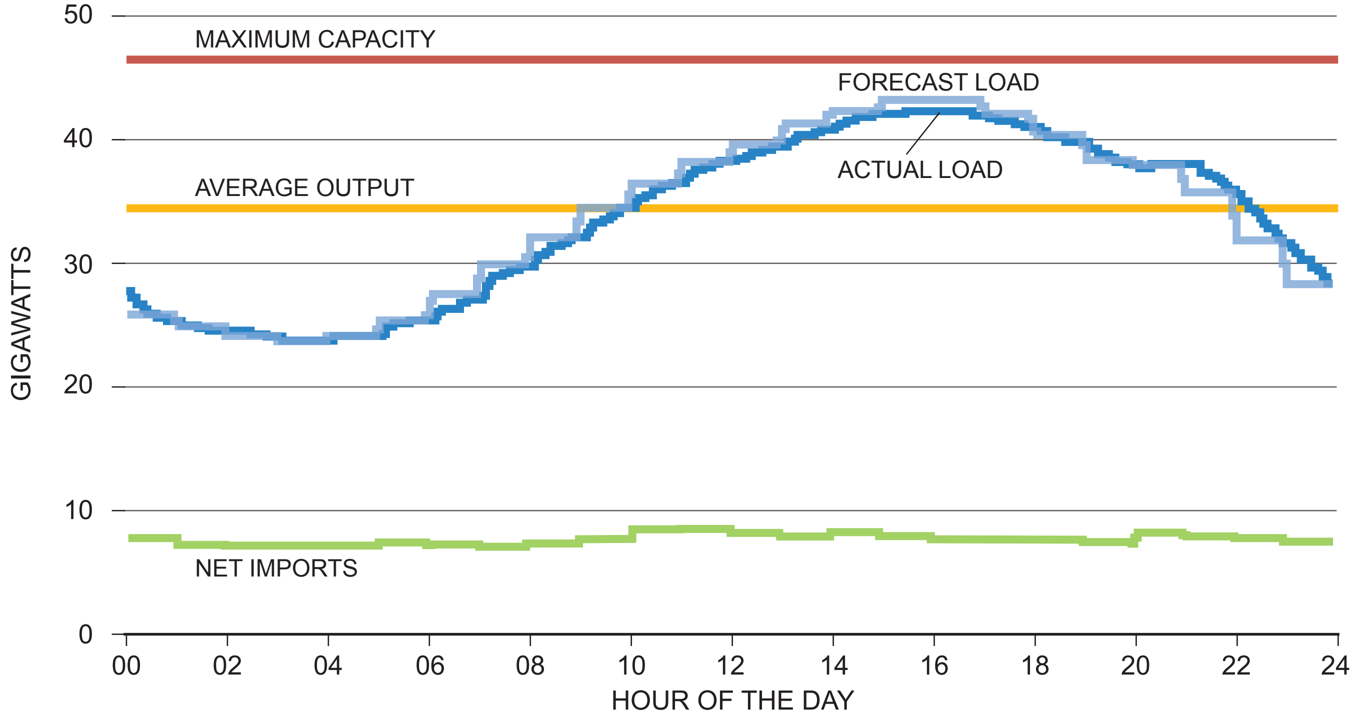
The impact to "the grid" (e.g., to generation capacity) from wide-scale vehicle charging has been estimated by various studies. The answer to the key question, "How much new generation capacity will be needed?" is complex. The short answer, as discussed in the narrative that follows, is that new generation capacity will likely be needed, but that a long-term planning process for addressing capacity additions already exists, therefore the additional capacity needed for vehicle charging can be planned for in existing business practices.

The primary challenge at the generation and transmission level is that electricity must be produced at the same time that it is used—there is very little energy storage capability on the grid. The real-time total amount of electricity demand, or use, referred to as electricity "load," varies significantly throughout the day and from month-to-month. "Peak" load refers to the time of day that the maximum amount of electricity demand occurs. In many regions, the peak loads occur in the late afternoon during the summer, due to air conditioning use. In addition to the daily peak load, many areas have a higher critical or "needle" peak that occurs a few times per year, typically on the hottest summer weekday afternoons. Graphs from the California electricity system help to illustrate this. Figure 13-17 shows a "typical" day, where demand never exceeds average system output. Figure 13-18 shows a "high-use" day, where system demand exceeds average system power for approximately half the day (common during summer months, it occurs approximately 30 times per year). And Figure 13-19 shows a "peak" day,



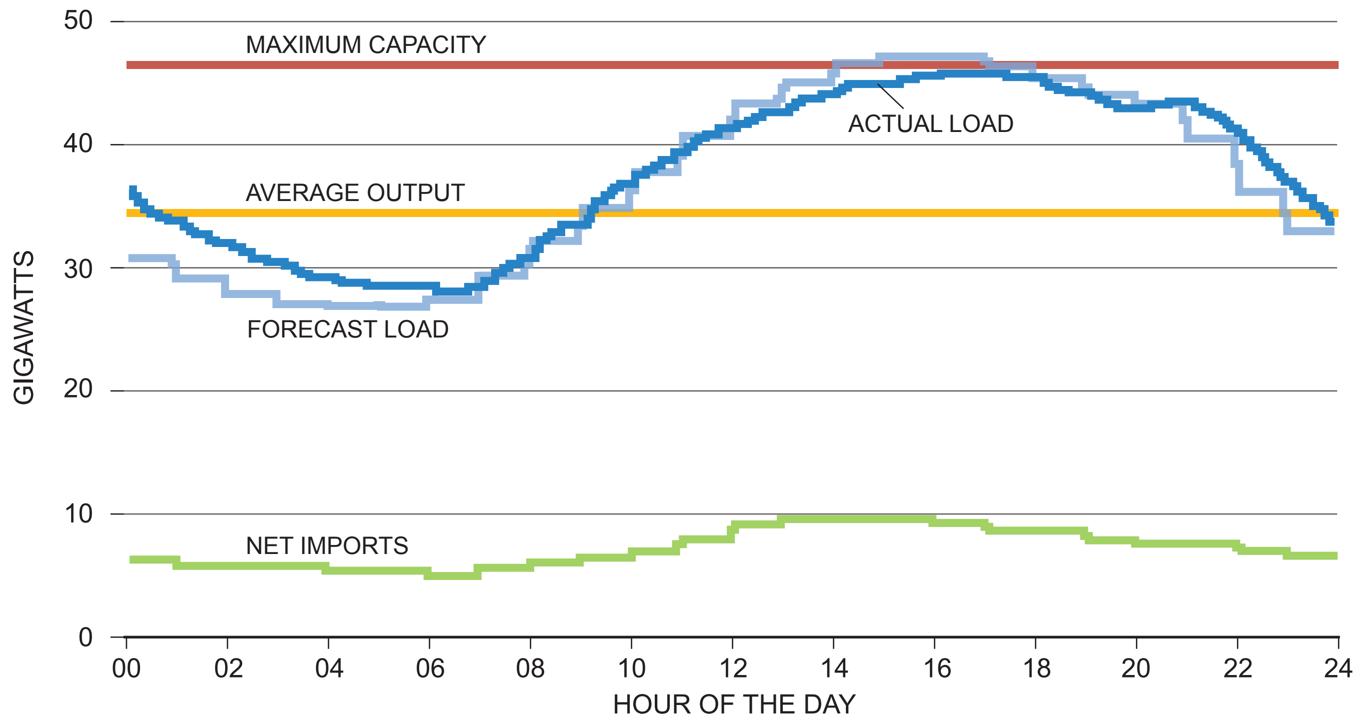
Source: Current Energy (website), "Supply of and Demand for Electricity for California."

Figure 13-17. *California Electricity System Load for Saturday, May 20, 2006 – Typical Day*



Source: Current Energy (website), "Supply of and Demand for Electricity for California."

Figure 13-18. *California Electricity System Load for Thursday, June 22, 2006 – High-Use Day*



Source: Current Energy (website), "Supply of and Demand for Electricity for California."

Figure 13-19. *California Electricity System Load for Sunday, July 23, 2006 – Peak Day* where peak consumption[21] exceeds average system power for most of the day and threatens to exceed system capacity.[22] Peak days occur approximately 7 times per year.

Figure 13-20 represents the number of hours per year that the load was below a given threshold of gigawatts.

Impact to Electricity Generation Capacity from Vehicle Charging

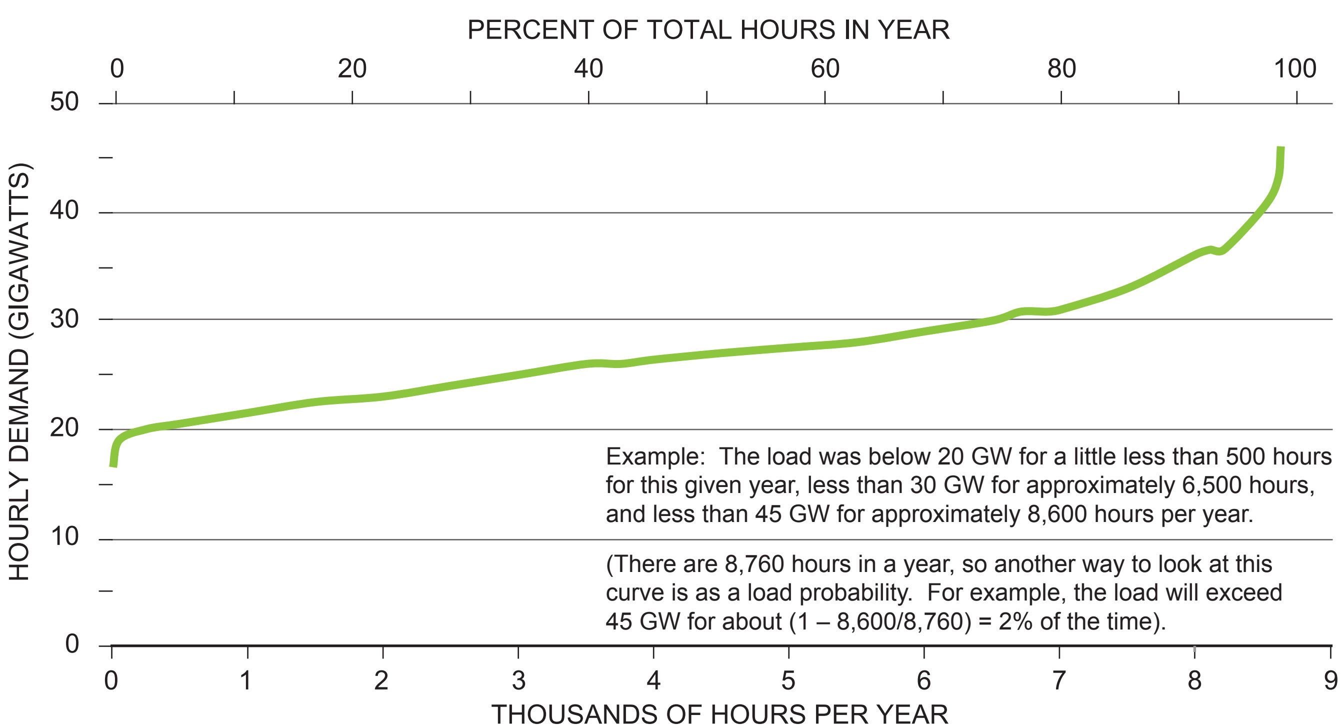
The existing electricity generation and transmission systems are quite large and robust today, both in terms of energy use and power, and are expected to grow in capacity in the future due to natural demand growth, independent of whether PEVs are introduced. Figure 13-21 shows historical capacity additions over the past 40 years, by primary energy source.

Changes in capacity to the electricity generation and transmission systems are anticipated and planned for under the current *North American Electricity Construct*. North American Electric Reliability Corporation (NERC)[23] standards are intended to evaluate and ensure preservation of reliability of the electricity system. This reliability standard ensures that there are adequate resources, including generation and transmission capacity, to provide electricity to consumers, and is based on long-term peak demand and energy forecasts from all loads, including PEVs. NERC's most recent reliability assessment finds that "The electric industry has

21 The actual maximum generation capacity varies over time based on plant availability, instantaneous renewable generation, and other factors. If the load approaches available supply, additional margin can be created through activating emergency generators, increasing importation into the region, or calling on demand response resources to reduce load.

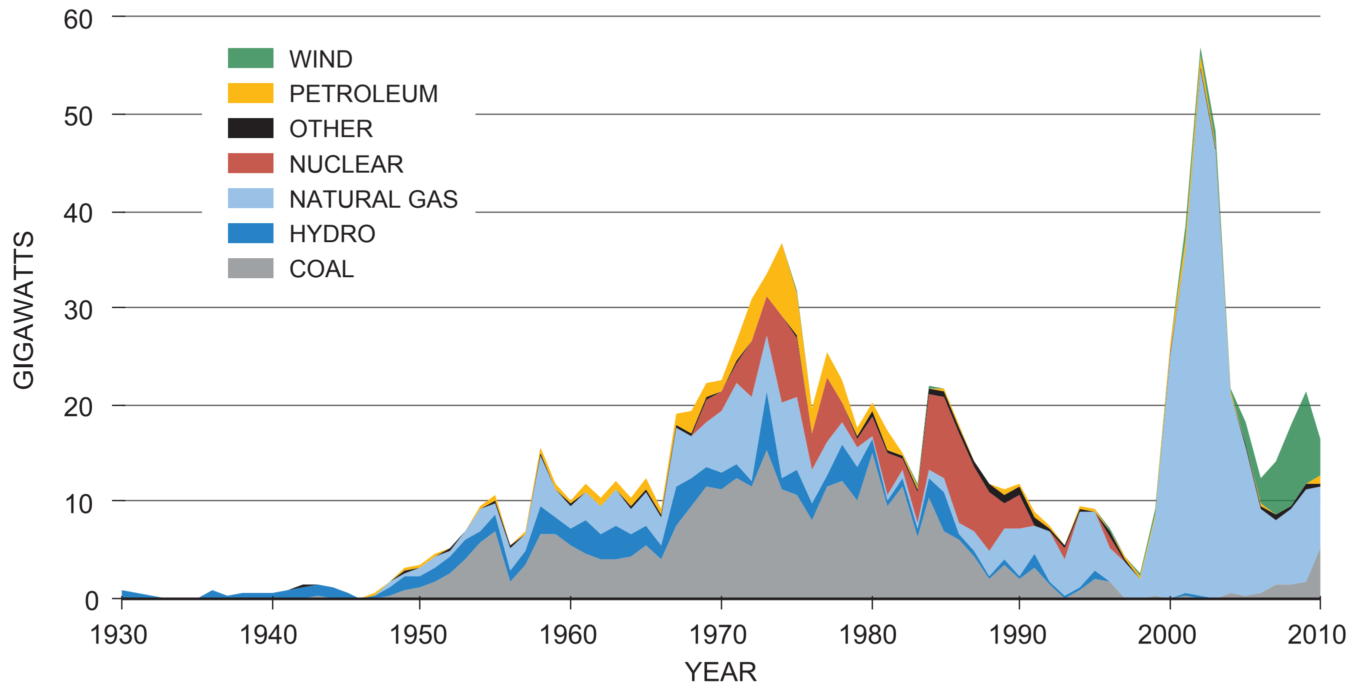
22 Capacity is the capability of meeting a given power demand, and is expressed in gigawatts. Capacity is related to the maximum peak power load that could be handled by the grid, but due to maintenance requirements, geographic separation, reserve requirements, and intermittency of some resources, the capacity must exceed peak power capability. When this capacity is used, the generated energy can be calculated based on the power generated and the duration of generation. This generated energy is measured in gigawatt-hours or terawatt-hours.

23 NERC is the electric reliability organization certified by the Federal Energy Regulatory Commission to establish and enforce reliability standards for the bulk-power system. NERC assesses resource adequacy annually via a 10-year forecast, and summer and winter forecasts.



Source: California Independent Systems Operator (CAISO), OASIS database, Reuters calculations.

Figure 13-20. *Twelve-Month Load Duration Curve for California*



Source: U.S. Energy Information Administration (website), "Today in Energy," 2011, http://www.eia.gov/energy_in_brief/age_of_elec_gen.cfm.

Figure 13-21. *Construction Date of Operating Capacity*

prepared adequate plans for the 2010-2019 period to provide reliable electric service across North America," including approximately 131 gigawatts of planned new generation resources.[24]

Due to the size of existing generation and transmission systems, the impact of vehicle charging will primarily be determined not by the total incremental amount of electricity used for vehicle charging, but by the impact to the existing peak load.

In examining the impacts of vehicle charging on the existing electricity supply chain, EPRI has found that vehicle charging has characteristics similar to existing load, meaning that peak demand from unconstrained vehicle charging would occur at roughly the same times as peak demand from other loads.

Further analysis performed by EPRI attempted to estimate the impact of different charging methods:

- **Home-Night** charging includes only nighttime residential charging, except for some non-residential charging during the day to allow BEVs to complete their daily trips.
- **Home-Anytime** charging is similar to Home-Night, except that charging is allowed whenever the vehicle is home (vs. being restricted to nighttime hours).
- **Ubiquitous** charging enables charging every time the vehicle is parked, regardless of the time of day.

In this initial analysis, Home-Anytime charging had about seven times the impact of Home-Night charging, since without load control the Home-Anytime charging scenario applies vehicle load to the grid when vehicles arrive home from work (between 5:00 and 6:00 pm), which generally coincides with the non-vehicle load peak. This increases total peak demand, which then increases the need for additional capacity. In the Home-Night case, peak load is only increased by daytime charging that cannot be deferred, so the need for additional capacity is much lower. In the Ubiquitous charging case, more charging is performed earlier in the day, so less additional

24 North American Electric Reliability Corporation, *2010 Long-Term Reliability Assessment,* October 2010. http://www.nerc.com/files/2010%20LTRA.pdf.

capacity is needed than in the Home-Anytime case.

To illustrate the need for additional capacity in relative terms, the EPRI modeling described above was used to calculate the capacity impact from aggressive vehicle deployment scenarios. Table 13-12 shows the estimated percentage increase in grid capacity relative to the overall system capacity in the AEO2010 Reference Case, shown in Figure 13-22, for various vehicle penetration scenarios.

Even if half of the vehicle fleet is electrified, capacity demands can be mostly mitigated by charging vehicles at night.

It should be noted that in a widespread adoption scenario it is almost certain that new rates and "Smart Grid" programs would encourage the use of managed charging to offset incremental electricity demand by shifting electricity demand from vehicle charging to times of the day where excess capacity occurs, so impacts would likely be closer to the Home-Night scenario.

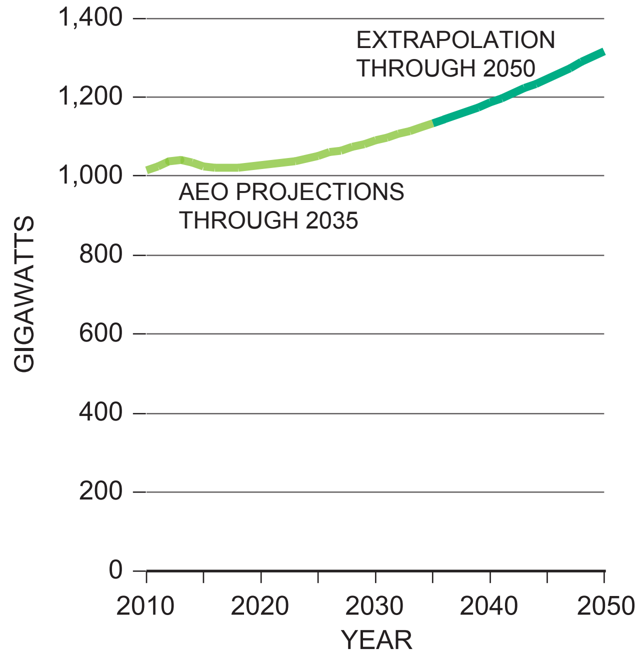
Electricity Distribution and Impacts of Vehicle Charging

While existing asset planning processes for generation and transmission are most likely adequate to address the impact of increased electricity load from vehicle charging, there is caution in the near term for the distribution system.

Figure 13-19 showed the total system load on a peak day in California. To help understand the potential impact of vehicle charging on the distribution system, it is helpful to look at peak load for an

Percentage of Total Vehicles that are PEVs	20%	30%	40%	50%
	2035	2050	2035	2050
Home-Anytime	6%	10%	12%	18%
Home-Night	1%	1%	2%	2%
Ubiquitous	5%	8%	11%	14%

***Table 13-12.** Added Capacity for Vehicle Charging for Different PEV Penetration Scenarios, In Different Charging Scenarios*



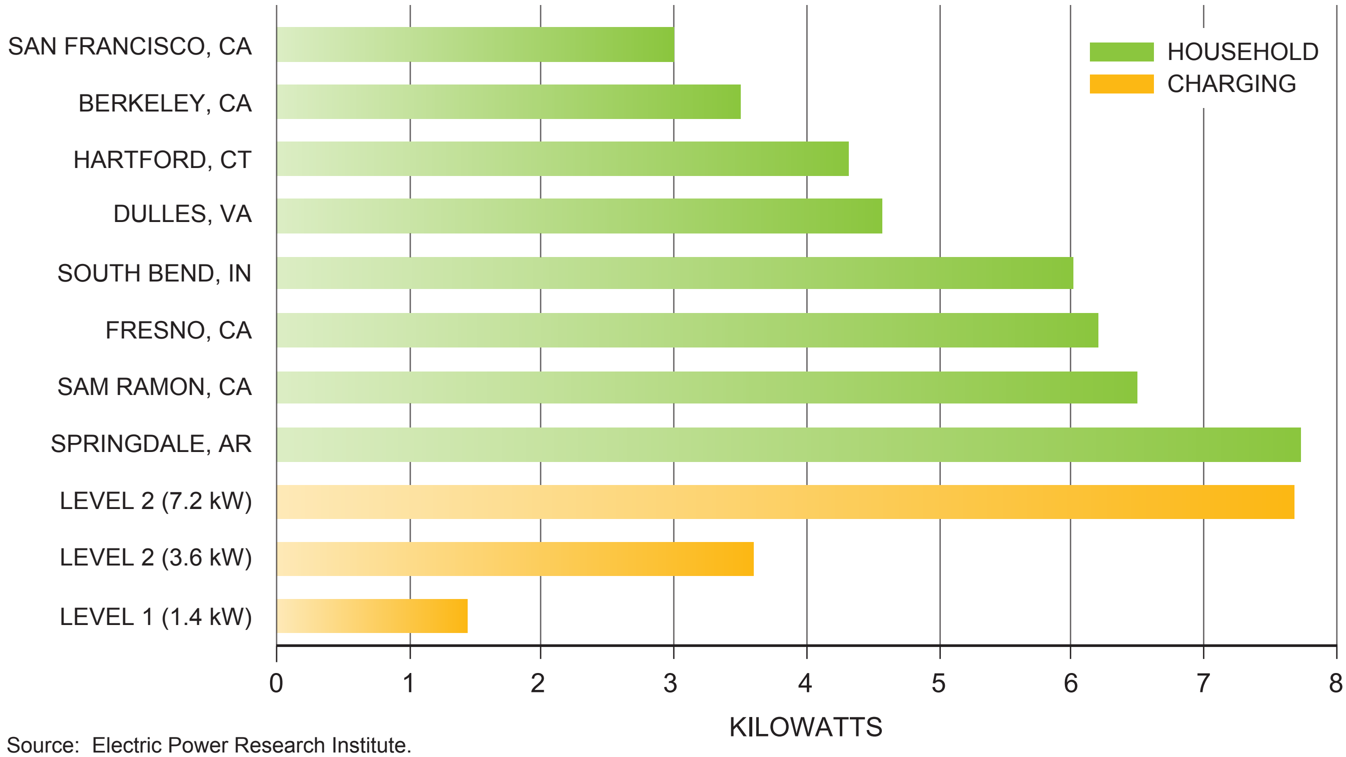
Note: AEO2010 electricity generating capacity data from 2008 through 2035, extrapolated to 2050.

***Figure 13-22.** Projected Generation Capacity in the United States Through 2050 Without Additional Vehicle Load*

individual household. Figure 13-23 shows example Level 1 and Level 2 peak vehicle charging loads, compared to peak household loads for various U.S. cities. As evident in the graph, in certain areas of the country, Level 2 charging can be equivalent to the peak load for an entire house.

Should the demographics of early adopters for PEVs mimic those of early hybrid vehicle adopters, there is a potential for geographic (e.g., neighborhood) clusters of vehicles that could increase the peak load and potentially overload local distribution systems, depending on the design of the utility system (e.g., size of the transformers). For example, the pole-mounted transformers common in suburban neighborhoods typically serve 5 to 7 households, and in some regions of the country Level 2 vehicle chargers can have a peak load impact roughly similar to adding a new house to a circuit, so a relatively small number of similar customers could cause a significant localized load increase.

The magnitude of the potential impact will depend both on the number and type of vehicles and on the Level of charging (i.e., Level 1 versus Level 2), with



Source: Electric Power Research Institute.

Figure 13-23. *Peak Vehicle Charging Load vs. Peak Household Loads for Various U.S. Cities*

Level 2 posing a much more significant challenge than Level 1. Some electric utilities have already developed plans to anticipate this potential "clustering effect" by working with automakers, customers, and others to get advance data (such as the type of vehicle purchased and the address of the vehicle purchaser) to allow them to examine the distribution system prior to the customer receiving the PEV and upgrade the transformer serving the neighborhood/cluster if needed.

Understanding all of the impacts and effects of vehicle charging requires complex analysis, in which many in the electricity industry are currently engaged. It is likely that some areas will experience initial problems due to high penetrations of PEVs in areas with susceptible distribution systems. In general, however, negative impacts will primarily occur on distribution circuits that are already close to their capacity limit. As transformers and other distribution system assets are continuously replaced for a variety of reasons, vehicle charging load is more likely to cause system upgrades to occur sooner than would have been required without PEVs. Additionally, overloaded transformers will more likely need to be replaced due to power quality concerns rather than failure. During rapid load increases that have occurred in the past, such as due to the introduction of air conditioning or more recently plasma TVs, transformers were often replaced due to reports of light "flicker" in neighboring houses. In cases such as this, the transformer would be upgraded to one with a higher rating, and the loss of service would be relatively short. In the long term, these effects will be addressed through modifications to distribution system design standards, so that the system accommodates vehicle charging loads as it does the introduction of other new loads.

Introduction to "Requirements for Reaching Wide-Scale Commercialization"

As described in Chapter Four, "Priorities for Technology Investment," each fuel-vehicle group within this study identified the requirements for the wide-scale commercialization of their particular fuel-vehicle system. For PEVs, the requirements were evaluated for each of the three representative vehicle types—PHEV10, PHEV40, and BEV100. These requirements could be related to fuel or vehicle technology, infrastructure, or codes and standards, and were assessed against the following rating/readiness scheme:

- (blue) "Minimal/No Barriers" (Technical roughly corresponds to DOE TRL 8+)
- (yellow) Technical: "Pathway for success has been demonstrated and significant testing has been performed. Will take sustained effort for wide-scale commercialization." (roughly corresponds to DOE TRL 5-7) and/or Non-technical: "Barrier today, but pathway for success has been identified. Will take sustained effort for wide-scale commercialization."
- (red) Technical: "Requires invention OR high uncertainty" (roughly corresponds to DOE TRL 5) and/or Non-technical: "Significant barrier OR high risk OR high uncertainty OR requires breakthrough or invention."
- (green) Priority Focus Area to enable wide-scale commercialization

It is important to note that the evaluations are based on a snapshot of what is known today, across all vehicle classes (sizes).

The evaluation of many of the requirements is expected to change over the next few-to-several years, based on recent development efforts and investment underway. For those requirements that are either high-priority or currently "red," the expected trajectory is discussed within the narrative of the section that discusses the requirement.

As the objective of this study is to describe wide-scale commercialization of fuel-vehicle systems, *projected battery advances were translated into cost reduction and vehicle efficiency improvements instead of increased electric range.* Additionally, BEVs with ranges longer than 100 miles that would be comparable to a conventional vehicle—e.g., a BEV300—were not considered because battery packs large enough to support 300 miles of travel pose several major technical, economic, and infrastructure challenges that include:

- From an economic standpoint, larger battery packs are underutilized, and there are diminishing returns to carrying additional range-increasing battery capacity. It is unlikely that the fueling cost savings of using electricity instead of gasoline will offset the price premium for vehicles with battery packs large enough to support 300 miles of range, even if Department of Energy battery cost and life targets are achieved.[25]
- Larger battery packs are heavy, requiring additional structural support in the vehicle body and chassis and more heavy-duty components to accommodate the additional weight, creating a compounding weight effect. The additional weight can significantly reduce vehicle efficiency.[26]
- Negative impacts to cargo, luggage, and passenger space would be much greater for a BEV300 than for a BEV100. A tripling of range would require more than a tripling of battery size because of the structural changes to the vehicle to accommodate the weight of the battery.
- A BEV300, while having sufficient range for longer-distance travel, would require DC fast charging to fill the battery overnight, which is neither feasible at a residence nor feasible from a cost-to-fuel perspective.

The requirements for the wide-scale adoption of PEVs are separated into two sections—Vehicle Requirements, and Infrastructure and Regulatory Requirements.

Vehicle Requirements for Plug-in Electric Vehicles

The assessment of the three vehicle types is shown in Figure 13-24, and discussed in the sections that follow.

Battery Energy Density

	PHEV10	PHEV40	BEV100
BATTERY ENERGY DENSITY	(blue)	(yellow)	(red)

The battery is able to meet the vehicle energy requirements under normal/real-world driving cycles and ranges without compromises in vehicle cost, weight, or range

– *The PHEV10 is rated "blue" because the shorter all-electric range of the vehicle, as well as the ability of the gasoline engine to propel and provide additional power when needed, requires*

25 Steve Plotkin and Margaret Singh, *Multi-Path Transportation Futures Study: Vehicle Characterization and Scenario Analysis,* Energy Systems Division, Argonne National Laboratory, July 2009.

26 C.-S. N. Shiau et al., "Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles," *Energy Policy* 37 (2009): pages 2653-2663.

a relatively small battery that causes minimal vehicle compromises.

– *The PHEV40 is rated "yellow" because the battery is slightly larger than that of the PHEV10, with attendant vehicle compromises (e.g., vehicle cost, weight, etc.).*

– *The BEV100 is rated "red" because of the large size of the battery, the limited driving range, and the cost of the vehicle.*

Battery Degradation and Longevity

The battery lasts the life of the vehicle (~15 years), and the degradation does not materially impact the customer

The longevity of lithium-ion batteries in automotive use is highly uncertain at this point in time, as the vehicles have only recently been introduced, and as such, there is a lack of empirical data. In spite of this uncertainty:

– *The PHEV10 and PHEV40 are both rated "yellow" because the decrease in the electric range from natural battery degradation is made up for by the gasoline engine.*

– *The BEV100 is rated "red" because the calendar life of the battery is unknown and additionally, battery degradation leads to a further decrease in vehicle range that impacts the consumer.*

It is important to note that most PEVs on the market today have battery warranties of 8–10 years, which is most likely acceptable to the first vehicle purchaser, but does not meet the requirement of lasting the life of the vehicle (14–17 years).

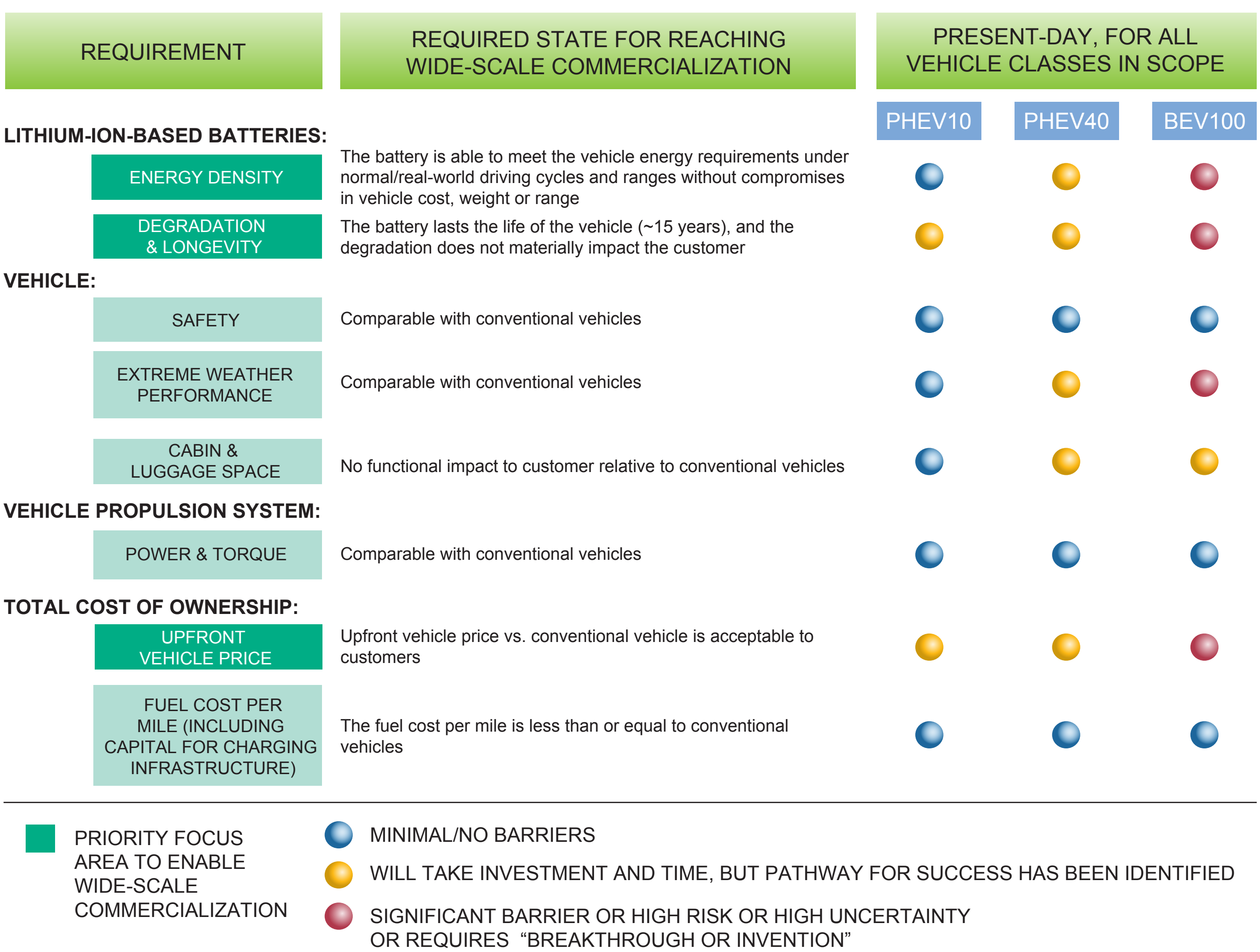


Figure 13-24. *Vehicle Requirements for the Wide-Scale Commercialization of PEVs*

Uncertainty of battery life poses a risk to buyers of used PEVs that may reduce the resale price. Additionally, while advanced thermal management systems can help increase longevity by controlling the temperature of the battery pack, these systems add further cost to the vehicle.

Vehicle Safety

Comparable with conventional vehicles

The safety of lithium-ion batteries relies upon good cell design, thermal management of the pack, and crash safety. All three vehicle types are rated "blue" because automobile and battery manufacturers have done extensive design and testing of these features and are confident in their safety.

Impact of Extreme Weather on Vehicle Performance

Comparable with conventional vehicles

As discussed in an earlier section of this chapter, extreme temperatures have a significant impact on batteries—both in terms of calendar life (for heat), and vehicle performance and range (for cold).

- *The PHEV10 is rated "blue" because the impact of extreme weather on a PHEV10 is minimal, as the gasoline engine compensates for any decrease in the battery performance due to cold ambient temperatures.*
- *The PHEV40 is rated "yellow" because although the gasoline engine can compensate for a decrease in performance, the electric range of the vehicle is reduced.*
- *The BEV100 is rated "red" because lacking an alternate propulsion system, this vehicle experiences both a decrease in performance and a significant decrease in electric range.*

Vehicle Cabin and Luggage Space

No functional impact to customer relative to conventional vehicles

The impact to vehicle cabin and luggage space for PEVs is directly correlated to the size of the battery, which is primarily determined by the battery energy density. The size of the battery is roughly proportional to the all-electric range of the vehicle. As all-electric range increases for a fixed vehicle platform, compromises in vehicle cabin and luggage space will at some point become necessary.

- *The PHEV10 is rated "blue" due to the small battery, which has minimal impact on vehicle cabin and luggage space.*
- *The PHEV40 and BEV100 are rated "yellow" because the larger battery size requires compromises in vehicle cabin and/or luggage space.*

It is important to recall that the assessment for the requirements is across all vehicle classes within scope. For smaller vehicles, the impact to cabin and luggage space is likely to be greater than in larger vehicles. Additionally, vehicles that are based on "clean-sheet" designs,[27] versus the modification of an existing vehicle, will be able to better accommodate the battery in the vehicle "packaging," which will lessen the impact to cabin and luggage space.

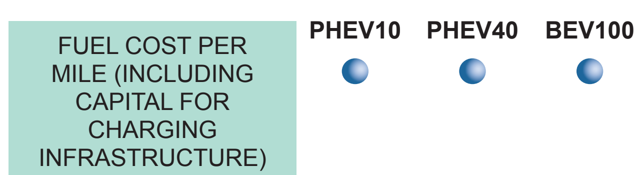
Power and Torque

Comparable with conventional vehicles

All three vehicle types are rated "blue" because of the inherent efficiency of electric motors in converting energy to power, and their ability to provide substantially higher torque on demand, resulting in enhanced acceleration performance of the vehicle.

Upfront Vehicle Price and Fuel Cost per Mile

Upfront vehicle price vs. conventional vehicle is acceptable to customers



The fuel cost per mile is less than or equal to conventional vehicles

27 See Chapter Nine, "Light-Duty Engines & Vehicles," for a description of "clean-sheet" design.

To achieve widespread adoption, PEVs need to offer consumers a financial value proposition that is at least as competitive with conventional internal combustion engine (ICE) vehicles, without subsidies. The financial value proposition for the consumer depends largely on two factors: the upfront vehicle price, and the fuel cost per mile (which makes up the majority of the operating costs of the vehicle).

Upfront Vehicle Price

This study considered vehicle price as the actual cost to produce a vehicle.[28] While vehicle manufacturers may pursue pricing strategies that factor in corporate and/or marketing strategies and/or regulatory compliance, these are outside the scope of this report. By these standards, all PEVs are currently more costly than the comparable ICE vehicles, due largely to the cost of the batteries.

The upfront cost of these vehicles, however, does not necessarily need to be at parity with a conventional vehicle to offer a positive financial value proposition to the consumer, primarily due to the lower fuel costs of operating the vehicle that can offset the higher up-front cost of purchasing the vehicle. Assuming that the fueling cost savings of the vehicle do at some point in time exceed the upfront vehicle price premium, the "payback period" (the amount of time it takes for fuel cost savings to offset the additional upfront cost) may be too long for consumers to consider worthwhile, and the "sticker shock" from comparing PEV prices to those of comparable conventional vehicles may deter consumers from choosing the costlier vehicle. Additionally, financing vehicles that have a longer payback period can be difficult for fleet owners and may require them to borrow at higher interest rates. Higher risk due to uncertainty over residual values is also a major consideration for fleet managers, as vehicles are turned over at a faster rate than are consumer vehicles.

The length of time over which the fuel savings is considered is a critical variable in assessing the upfront cost premium of a vehicle. Consumer research has attempted to quantify this variable and has indicated a relatively short consideration time frame (between 3 and 5 years).[29]

- *The PHEV10 and PHEV40 are rated "yellow" because battery costs are expected to decrease with scale manufacturing (see section on battery costs at the end of this chapter), with the potential for the upfront vehicle price premium to be acceptable to consumers.*
- *The BEV100 is rated "red" because given the larger battery, even with projected cost decreases, the upfront vehicle price premium will still be significant, requiring either a breakthrough beyond those expected for lithium-ion batteries or a change in how consumers consider and value efficiency in the vehicle purchase.*

Fuel Cost Per Mile

Electricity is relatively inexpensive as a transportation fuel, compared to gasoline. Light-duty vehicles powered by electricity generally require from 300 to 400 watt-hours to travel one mile, while an ICE vehicle averaging 33 mpg requires 0.03 gallon of gasoline to travel that same mile. While electricity rates can be variable (see section on electricity rates later in this chapter), and gasoline prices fluctuate, if one considers the average U.S. residential electricity rate of $0.10/kWh and a gasoline price of $3.00/gallon,[30] the gasoline cost to drive one mile is $0.09, versus $0.03 for electricity. While ICE vehicles will continue to improve in fuel economy, it is unlikely that these improvements will make up for the fuel cost advantage of electricity, and historically electricity price has been more stable relative to gasoline. Additionally, many advances that improve ICE fuel economy will also make PEVs more efficient at using electricity.

In sum, using average electricity rates, the fueling costs for PEVs currently provide a strong, positive financial value to the consumer, and will most likely continue to do so in the near future. Lower, off-peak, and/or specific rates for PEV charging could further increase this positive financial value. Thus, all three vehicle types are rated "blue" on fuel cost per mile.

Infrastructure and Regulatory Requirements for Plug-in Electric Vehicles

The deployment of electric charging infrastructure presents numerous challenges for wide-scale

28 Current tax credits were not included due to their uncertain continuation and the long time horizon of this study.

29 David L. Green, *TAFV Alternative Fuels and Vehicles Choice Model Documentation,* ORNL//TM–2001/134, Oak Ridge National Laboratory, July 2001.

30 Electricity rate assumes a residential rate that does not include costs for vehicle charging equipment or for equivalent road tax, although the electricity rate does include other taxes that are not included in gasoline taxes, such as municipal fees.

vehicle adoption. This section discusses the key challenges for the development of charging infrastructure for PEVs. Similar to the vehicle-level requirements, the challenges are discussed and assessed for different vehicle configurations, as the infrastructure requirements and challenges vary by vehicle type. (See Figure 13-25.)

Electricity Generation Capacity

Sufficient, cost-effective fuel production capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices

All vehicle types are rated "blue" because, as discussed in the Electricity Supply Chain section, the additional capacity that would be needed for vehicle charging represents a small percentage over the capacity additions that will occur over the next four decades, independent of demand from vehicle charging. This expected load growth can be included in the normal, ongoing long-term asset planning processes currently employed by electricity generators and utilities.

Electricity Distribution Capacity

Sufficient, cost-effective fuel distribution capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices

- *The PHEV10 and PHEV40 are rated "blue" under the assumption that they will be charged at Level 1. As discussed in the Electricity Supply Chain section, there may be local distribution issues that occur in the short-term. In the longer-term, however, existing asset planning processes will accommodate the distribution system changes required to support wide-scale vehicle charging.*
- *The BEV100 is rated "yellow" because it is assumed that it will need to be charged at a higher power rate for longer durations, which may necessitate managed charging to accommodate the additional load.*

Charging, Residential (Single Unit) – EVSE Installation Process and Cost

The installation process for the electric vehicle supply equipment (EVSE) is quick and easy and is not a deterrent to vehicle purchase

The cost of the EVSE plus installation is not a deterrent to vehicle purchase

For successful market introduction, consumers must be able to economically and conveniently prepare their residence for vehicle charging.

- *The PHEV10 and PHEV40 are rated "blue" based on the assumption that Level 1 charging will be utilized at the residential level.*
- *The BEV100 is rated "yellow" because it is assumed that Level 2 charging will be used, bringing with it the costs and challenges of a more complicated installation process, described below.*

Installation Process

The installation process for a Level 2 EVSE is currently immature, non-standardized, and subject to wide variations in cost and timing due to the involvement and coordination of many different entities—the local utility, a certified electrician, a qualified building inspector, and the municipal permitting office. Codes governing the permitting process vary on a state-by-state and even city-by-city basis. These processes are required to ensure that charging equipment is suitable for its application, safe for its intended use, properly installed, and integrates appropriately with utility infrastructure.[31] Whereas in some regions, this permitting process can be "over-the-counter," in other regions, permitting alone can take as many as 35–60 days.[32] The complexity and time requirements of these processes may discourage some consumers.

31 Electric Power Research Institute, *Transportation Electrification: A Technology Overview,* July 2011.

32 Enid Joffe, "Lessons Learned, Evaluation of Prior EVSE Installations," Plug-in 2010 Conference, July 2010.

REQUIREMENT		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	PRESENT DAY, FOR ALL VEHICLE CLASSES IN SCOPE: PHEV10	PHEV40	BEV100
ELECTRICITY GENERATION & TRANSMISSION:					
	CAPACITY	Sufficient, cost-effective fuel production capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices	blue	blue	blue
ELECTRICITY DISTRIBUTION:					
	CAPACITY	Sufficient, cost-effective fuel distribution capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices	blue	blue	yellow
CHARGING:					
RESIDENTIAL (SINGLE UNIT)	**EVSE INSTALLATION PROCESS**	The installation process for the electric vehicle supply equipment (EVSE) is quick and easy and is not a deterrent to vehicle purchase	blue	blue	yellow
RESIDENTIAL (SINGLE UNIT)	EVSE INSTALLED COST	The cost of the EVSE plus installation is not a deterrent to vehicle purchase	blue	blue	yellow
RESIDENTIAL (MULTI-UNIT)	EVSE INSTALLED COST	The cost of the EVSE plus installation is not a deterrent to placement of EVSEs	red	red	red
RESIDENTIAL (MULTI-UNIT) / COMMERCIAL/ PUBLIC	**BUSINESS MODEL**	Business models, regulations, codes and standards are aligned to allow 3rd-party providers to install and charge for public charging	yellow	yellow	yellow
COMMERCIAL/ PUBLIC	UNIVERSAL ACCESS	All chargers are useable by all customers	yellow	yellow	yellow
COMMERCIAL/ PUBLIC	CHARGING AVAILABILITY	Sufficient charging locations exist to support all trips	n/a	n/a	red *
COMMERCIAL/ PUBLIC	ELECTRICAL STANDARDS (DC)	Standards developed and implemented for high-voltage DC charging (“Level 3”)	n/a	n/a	yellow
	SYSTEM DIAGNOSTICS & REPAIR	If vehicle charging fails and the vehicle cannot operate, a seamless system exists to diagnose and repair the problem	blue	blue	yellow
	TIME REQUIRED TO CHARGE BATTERY	Does not result in greater inconvenience for consumers relative to conventional vehicles	blue	blue	red *
GRID INTEGRATION:					
	MANAGED CHARGING TO MINIMIZE NEGATIVE IMPACT TO GRID	Communication and/or Management systems are standardized and capable of controlling charging to minimize negative impacts to the grid	yellow	yellow	yellow
	REGULATORY CERTAINTY	A sufficient level of regulation exists in jurisdictions across the country to allow EVSE installation/operation (including revenue generation) to support wide-scale PEV adoption	yellow	yellow	yellow
FUEL ECONOMICS:					
	CAPITAL REQUIRED FOR CHARGING INFRASTRUCTURE	Capital required for dispensing infrastructure to support all trips can be accommodated within existing business practices	n/a	n/a	red *
	DISPENSED FUEL COST	Fuel cost per mile is less than or equal to conventional vehicles	blue	blue	blue

(Dark green box) PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

(Blue) MINIMAL/NO BARRIERS

(Yellow) WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

(Red) SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES “BREAKTHROUGH OR INVENTION”

* There is a minority view within the Electricity Subgroup that BEVs do not need to be one-to-one substitutions for conventional vehicles. The argument is that if households adjust their driving behavior, such as using the BEV only for trips where the limited range is not an issue, then (1) battery charging time is not an issue, and (2) away-from-home charging infrastructure is not needed, thus, the capital required to enable such infrastructure is not an issue. Additionally, as described in this chapter, there are potentially non-economic factors included in the purchase decision that could outweigh any perceived vehicle limitations.

Figure 13-25. *Infrastructure and Regulatory Requirements for Grid-Connected Vehicles*

Efforts to streamline and simplify the installation process are critical for BEV adoption.

The 2008 and later National Electrical Code standard covers Level 2 EVSE installation, but it is not yet universally adopted by the many thousands of code districts in the United States. Localities should at minimum update this section of their electrical code to the current standard in order to reduce uncertainty for vehicle purchasers and electricians. Further, a national EVSE installation certification program could create a ready pool of qualified electricians. Aggregation of these processes by third parties or by utilities, including direct contracting with or employment of qualified electricians, could reduce bidding and permitting time for installations.[33] Finally, pre-wiring of new construction through programs similar to LEED (Leadership in Energy and Environmental Design) certification could facilitate Level 2 EVSE installation by ensuring housing units are equipped with properly sized breaker boxes and wiring that terminates at the garage or carport.

Additional actions that would help to streamline and simplify the installation process are:[34]

- Streamlining service planning and customer interface with new PEV customers by electric utilities.
- Developing national training (websites, industry events, curriculum, etc.) for industry professionals (e.g., installers, inspectors, electricians) that answers common code interpretation questions from inspectors and permit desk staff, provides "best practices" for streamlined city permits, plan-checks, and inspections, provides a residential EVSE plan check-list, lists all EVSEs listed by nationally certified testing laboratories, and provides information on utility issues and customer choices (utility rate, meter, and charge level options).
- Encouraging best-in-class actions by cities and counties to speed the process (e.g., on-line permitting, handheld field computers for inspectors that allow instant utility notification) or lower costs (e.g., use of transfer switches so the PEV can use the electric dryer circuit when the dryer is not in use).

33 Ibid.

34 Consensus Action Items for PEV Charging Infrastructure Deployment, October 2010, GM, Nissan, SCE, PG&E, NRDC, Coulomb, Ecotality, Better Place.

An example of a major utility that has worked on streamlining the installation process is Southern California Edison. Over the last two years, Southern California Edison has reached out to the city and county building permit jurisdictions within their service territory, and has found that most have developed a streamlined experience for PEV owners, including over-the-counter permits, inspections within 24 hours, and prepared samples of needed forms for electricians.

Installation Costs

For Level 1 charging, the installation cost is the cost to install a dedicated circuit, if one is not located near the vehicle parking location. According to the 2009 American Housing Survey,[35] 66% of U.S. residences have a garage or carport, and assuming that there is existing electricity supply to the garage or carport, the cost to install a dedicated circuit is relatively inexpensive.

The installation cost for Level 2 charging at the residence, however, can be high, and is primarily driven by whether a dedicated 240V circuit is available near the vehicle parking location, and whether there is sufficient electrical panel capacity. If capacity and a new circuit need to be added, the cost can be several thousands of dollars.

When looking at actual installation costs, the lowest costs were recorded by utilities that streamlined and simplified installation processes, and in regions with relatively lower labor rates. Direct employment of electricians performing the work and the elimination of bidding and permitting times also contributed to lower average installed costs.

New construction and turnover of existing stock can play a large role in reducing costs over time. Pre-wiring during construction is less expensive than a retrofit. A residence, for example, pre-wired with 200-amp capacity in the circuit box could dramatically lower the installation cost. Local authorities could amend building codes to recommend or require such pre-wiring. Movable home charging stations could lower the installation cost and make the units similar to an appliance such as an electric clothes dryer.[36]

35 U.S. Census Bureau (website), American Housing Survey (AHS), AHS Tables 2009, Table 2-7, Additional Indicators of Housing Quality—Occupied Units.

36 Level 2 residential EVSEs listed by UL (Underwriters Laboratories), such as those offered by Leviton, are movable and not hard-wired to the home. Many jurisdictions interpret National Electric Code (NEC) article 625 as allowing this, while others do not.

Charging, MDU/Commercial/Public – EVSE Installed Costs

MDU/COMMERCIAL/ PUBLIC EVSE INSTALLED COST	PHEV10	PHEV40	BEV100
	● (red)	● (red)	● (red)

The cost of the EVSE plus installation is not a deterrent to vehicle purchase

All vehicle types are rated "red" for the reasons discussed below.

- *Residential — For rentals, multiple dwelling units (MDUs) such as condominiums and apartment buildings with parking lots or on-street parking, the vehicle purchaser often lacks direct ownership of the parking structure and/or property. Lack of alignment between customers and parking structure/lot owners is compounded by the complexity of the installation, which may require far higher costs, even for Level 1 charging used by PHEVs (e.g., in a parking garage structure where conduit is not currently run). This issue is particularly problematic for urban areas considered well suited for BEVs, where a large percentage of the population uses on-street parking.*
- *Workplace and Commercial — The installed EVSE costs in workplace and commercial settings can be quite high. While it may be possible to "cherry pick" low-cost sites in the short-term, in the longer-term, and for wide-scale vehicle adoption, particularly BEVs, costs will need to decrease significantly.*

The Electric Subgroup collected actual EVSE installed costs for various types of installations. The installed costs vary widely. For example, Residential Level 2 total installed costs (EVSE + Installation) ranged from approximately $1,500 to $4,000, and for Commercial Level 2 from approximately $2,700 to more than $30,000. The wide variance in the total installed costs are based on a number of factors, including the following:

- Regional labor costs
- Whether trenching and concrete or asphalt cutting or boring is required to prep the site
- What grid-side investments are needed, such as new conduit, increased panel capacity and upgrading the transformer
- The number of EVSE units installed in each location
- The proximity of the transformer relative to parking location
- Whether renewable charging is included.

Installation costs are at least as significant as equipment costs, and present a large source of variability in total installed EVSE costs. Included in labor are any costs for site evaluation, preparation, installation, and inspection. There are regional differences in labor rates, varying process requirements, and fragmented jurisdiction of the involved parties. The number of charging stations per site also impacts per-unit costs. In most cases, per-unit labor costs fall with increasing charging station installations per site, but this is not always the case. For example, existing parking garages typically do not have a large electrical distribution capacity (mainly just surface lighting and signage). Such installations, particularly if spread across multiple levels, would be quite expensive due to transformer upgrades and conduit placement.

It is likely that experience will inform the matching of EVSE installations with appropriate locations and facilities. For example, while parking garages may seem like a reasonable place for charging stations, the cost of retrofitting parking garages for EVSE installations on multiple levels of the structure may prove very high; conversely, clustering the chargers on a single deck or in a large parking lot, or having one multi-port charge station serve two to four parking stalls may ultimately prove more cost effective.

Charging, MDU/Commercial/Public – Business Model

MDU/COMMERCIAL/ PUBLIC BUSINESS MODEL	PHEV10	PHEV40	BEV100
	● (yellow)	● (yellow)	● (yellow)

Business models, regulations, codes and standards are aligned to allow 3rd-party providers to install and charge for public charging

- *All three vehicle types are rated "yellow" because the alignment of business models, regulations, and codes and standards that would allow third-party providers of charging stations the incentive to install charging equipment and the ability to charge a fee that will provide cost recovery for the EVSE purchase, installation, and ongoing operational costs has only recently* *begun. This is not only an issue for non-residential charging, but also for residential charging in the significant percentage of housing units that do not have an attached carport or garage.*

Commercial and Public

Many business models for providing charging stations have been launched and/or proposed, but it is too early in the PEV market to determine which model provides the most value to consumers while providing for an appropriate financial return to the provider. Business models for public infrastructure are further complicated by the relatively high cost of infrastructure installation. Recovering the capital cost of the charging equipment through a user fee in most cases makes the cost of charging higher than at home.

The most common models under consideration are generally a variation of one or more of the following categories:

- Third-party independent electric vehicle service provider (EVSP). The charging station is installed, owned, and managed by a third-party EVSP[37] that receives payment for the supply of transportation electricity or for access to the charging station.
- Utility ownership. The charging station is owned by an electric utility, which recovers its costs through regulated tariffs.
- Host facility ownership. The charging station is owned by the facility that is hosting the charging station (e.g., retail store, employer). The facility owner may choose to charge for the service or provide it at no cost as an incentive to create other value streams (e.g., encourage customers to shop longer.)
- Civic Ownership. Charging stations are owned by a city/county government in a similar model to street lighting or parking meters.

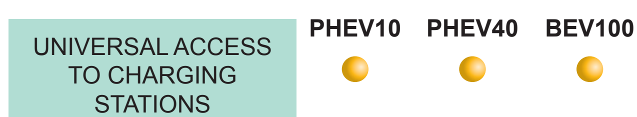
The business models under consideration may be affected by the regulatory structure within certain jurisdictions. For example, in the state of California the investor-owned utility ownership model is currently not allowed. In some states, charging station owners can require payment based on the amount of energy consumed, while in other states this would be considered "re-selling of electricity," which can only be done by a regulated utility. Some business models, such as those for RV parks and marinas or other host-site ownership of charging stations, can be implemented without regulatory change. Similarly, workable business models for some municipal utilities have already been established, especially in situations where the city has sole jurisdiction to act on its own or award a franchise. Additional discussion on this topic can be found in Topic Paper #18, "Emerging Electric Vehicle Business Models," on the NPC website.

Multiple Dwelling Units

While the percentage varies greatly depending on geography, the national average for housing units that do not have a carport or garage is around 40%. These include apartments and condominiums, as well as homes in dense urban areas where parking is on the street. For example, apartment dwellers typically have an assigned parking space, but they do not have the authority to install a charging unit. The landlord or owner of the building or lot must make the necessary infrastructure modifications, which entails issues ranging from the costs associated with installation, the distance of the power source to the parking location, the assignment of liability, the logistics challenge of re-aligning parking if/when the tenant moves, to the lack of ability by the building/lot owner to isolate the amount of electricity used at a particular parking spot (charging station).

Unlike workplace and commercial locations, the MDU owner often lacks potential additional value propositions for installing charging stations, such as attracting customers for retail business or creating an employee benefit. Given that urban areas are a potentially attractive market for PEVs, particularly with early adopters, concerted effort needs to be undertaken by multiple stakeholders to overcome this barrier to adoption.

Charging, MDU/Commercial/Public – Universal Access to Charging Stations



All chargers are useable by all customers

37 EVSP is becoming a regulatory term and implies the charging station operator who provides a service that includes electricity bundled with other services. The charging station operator could be a non-utility, third party, the host facility, or a utility.

- *All three vehicle types are rated "yellow" because while the market is moving in the direction of allowing all drivers of PEVs to have access to any charging station, this has not yet occurred.*

As charging stations are deployed in public spaces, it is important that all drivers have the ability to access these stations. While some business models are based on subscription services, if provisions are not made for access by all drivers, a large number of disparately owned charging stations may be needed for a given area. This will result in a higher public charging station cost per vehicle, which may create unintended negative consequences on vehicle adoption. Additionally, a BEV driver who is unable to charge (due to not being a member of the particular charging provider's service) may be "stranded." Each EVSE provider may adopt individual access control methods (RFID, touch pads, etc.), but as long as there is a back-up method that allows all consumers to use the charging station on an as-needed basis (e.g., a phone call to central control center that activates the charging station), then universal access can be achieved. In addition, it may be desirable to develop market standards across providers, which would facilitate the deployment and utilization of publicly accessible charging stations.

Charging, MDU/Commercial/Public – Station Availability

	PHEV10	PHEV40	BEV100
MDU/COMMERCIAL/ PUBLIC CHARGING AVAILABILITY	n/a	n/a	●

Sufficient charging locations exist to support all trips

- *The PHEV10 and PHEV40 are rated "n/a" because they do not need away-from-home charging stations to support all trips.*
- *The BEV100 is rated "red" because the development of away-from-home charging infrastructure to support all trips is a significant barrier, due to (1) the cost to install either DC charging infrastructure or a network of Level 2 charging stations and (2) uncertainty related to the need for DC Fast Charging.*

Similar to battery recharge time, there is a minority view that the availability of charging stations to support all trips is not a requirement for wide-scale consumer adoption, as BEVs do not need to be one-to-one substitutions for conventional ICE vehicles. If households adjust their driving behavior, such as using the BEV only for trips where the limited range is not an issue, away-from-home charging infrastructure is not needed.

Charging, MDU/Commercial/Public – Electrical Standards for DC Charging

	PHEV10	PHEV40	BEV100
MDU/COMMERCIAL/ PUBLIC ELECTRICAL STANDARDS (DC)	n/a	n/a	●

Standards developed and implemented for high-voltage DC charging ("Level 3")

- *The PHEV10 and PHEV40 are rated "n/a" because they are not currently, and not likely to be, engineered to accept DC charging.*
- *The BEV100 is rated "yellow" because the standards for DC charging are under development, and implementation will take time, as discussed in the section on DC charging.*

Charging – System Diagnostics and Repair

	PHEV10	PHEV40	BEV100
CHARGING SYSTEM DIAGNOSTICS & REPAIR	●	●	●

If vehicle charging fails and the vehicle cannot operate, a seamless system exists to diagnose and repair the problem

- *The PHEV10 and PHEV40 are rated "blue" because they can still operate even if charging fails. Note that they are not rated as "not applicable" because the driver will still need to take the vehicle to the dealer to determine the cause of the failed charging.*
- *The BEV100 is rated "yellow" for two reasons: (1) if charging fails, the vehicle is inoperable and (2) while it is possible to create a seamless system to remedy the situation, this requires the integration of communication systems, logistics, operational systems, and business models. Such an integrated, seamless system is still in the early stages of development.*

A key lesson learned during the previous period when PEVs were on the market (approximately 1996–2003) is that the inability to diagnose and remedy a situation where the vehicle fails to charge can be a source of tremendous customer dissatisfaction. This is most important for BEVs, as they do not have a secondary power source onboard. The critical need is the ability to identify whether the fault lay with the EVSE or the vehicle, without necessitating the dispatch of a technician. Enabling this requires multiple components:

- A "smart" EVSE—one that includes communications technology
- A service entity to either receive an automatic message or receive the customer inquiry
- Remote access of the EVSE by the service entity to diagnose the fault
- Ideally, the dispatch of either an EVSE service technician, if the fault is with the EVSE, or a tow truck, if the fault is with the vehicle.

Charging – Time Required to Charge Battery

Does not result in greater inconvenience for consumers relative to conventional vehicles

- *PHEVs are rated "blue" because they (1) can operate on a depleted battery and (2) are expected to charge at home using Level 1, which for a PHEV10 requires only a few hours to fully recharge the battery, and for PHEV40s, overnight charging can still yield a full charge.*
- *BEV100s are rated "red" because they cannot operate on a depleted battery thus (1) they require Level 2 charging at home to fully recharge the depleted battery, which carries with it the costs and installation issues described earlier in this chapter, and (2) away-from-home charging is required to fulfill all trips, and the "fueling" time is considerably longer than for a conventional vehicle, even for DC Fast Charging.*

Given the previously acknowledged skepticism about the feasibility of DC Fast Charging, there are potential ways to address battery recharge time for BEVs that are not dependent on DC Fast Charging stations. Charging infrastructure for BEVs can be at multiple power levels, and located at multiple locations. Public-access charging may occur at locations where vehicles are parked for a long time (long dwell times). These locations include locations where people typically stay for many hours (beaches, parks, theme parks, etc.) and also include public parking lots and streets that serve condos, apartments, and mobile homes. Rather than depending on matching the conventional vehicle experience, this solution takes advantage of where drivers park their vehicles today. Thus, there are a variety of forms that away-from-home charging of BEV100s could take:

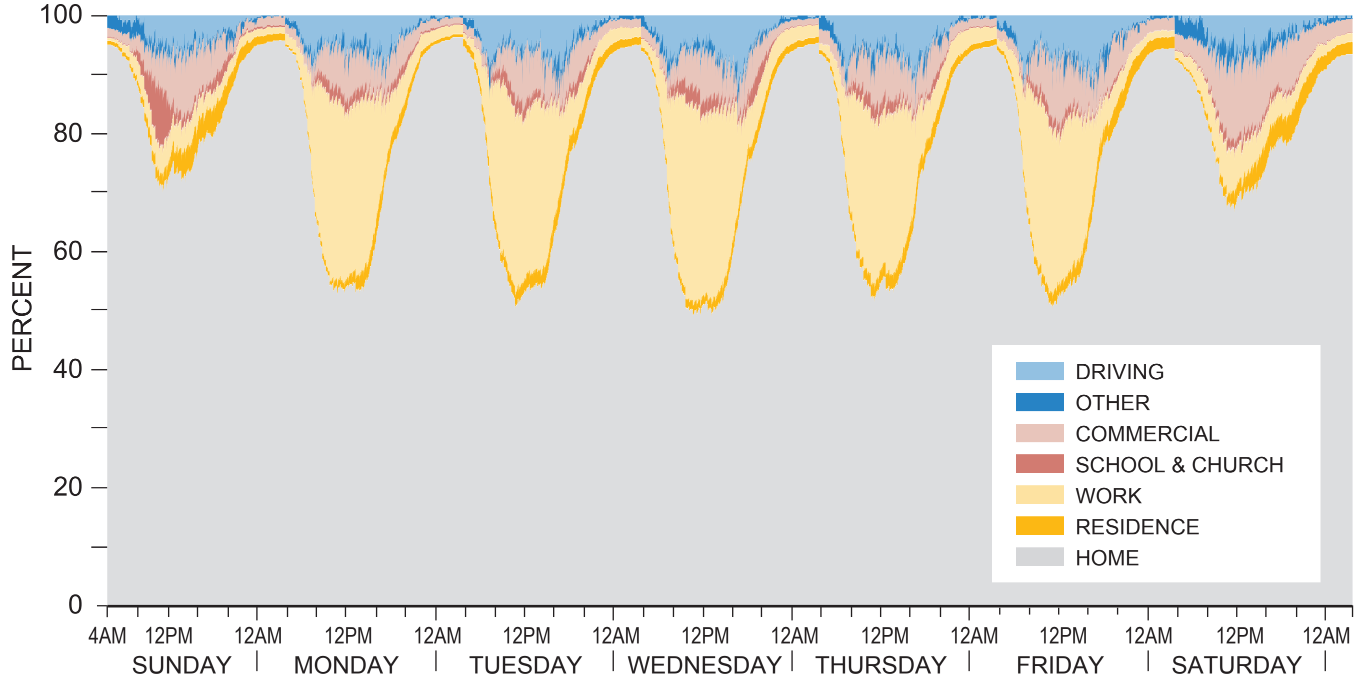
- Workplace, either Level 1 or Level 2
- Public-access
  - Level 1 for longer dwell times, such as theme parks, resorts, and beaches
  - Level 2 or DC for short dwell times, such as a coffee shop or restaurant.

Figure 13-26 shows dwell times based on analysis of 2001 National Household Travel Survey data, which shows that vehicles "dwell" mostly at home, and to a lesser extent at work and other locations.

Real-world data and experience is needed to help inform key questions related to PEV charging:

- Will DC Fast Charging be preferred by consumers over public-access Level 2? At which locations?
- For which dwell types will consumers want to charge—e.g., short stops at the local diner, or long stops at resorts, casinos, and similar locations?
- To what extent will BEV owners change their habits to accommodate limitations of the BEV—e.g., change drive patterns or switch cars for long-trips?
- Will BEV100 owners be willing to pay for public charging, given that the cost may be significantly higher than charging at home?
- Is there significant potential for Level 1 charging for public access and workplaces?
- Will sufficient regulations exist to support public charging business models?

There is a minority view that recharge time for BEVs being comparable to fueling a conventional vehicle is not a requirement for wide-scale consumer adoption, as BEVs do not need to be one-to-one substitutions for conventional vehicles. Data from the 2009 National Household Travel Survey suggests that on a given day approximately 3% of vehicles travel farther than 100 miles. Thus, if



Source: 2001 National Household Travel Survey; Tate and Savagian, *The CO_2 Benefits of Electrification E-REVs, PHEVs and Charging Scenarios*, SAE paper 2009-01-1311, 2009.

Figure 13-26. *Vehicle Fleet Distribution Over a Week*

households adjust their driving behavior, such as using the BEV only for trips where the limited range is not an issue, away-from-home charging infrastructure is not needed, and the time to recharge the vehicle at home is not an inconvenience to the customer.

Grid Integration – Managed Charging to Minimize Negative Impact to Grid

MANAGED CHARGING TO MINIMIZE NEGATIVE IMPACT TO GRID	PHEV10	PHEV40	BEV100

Communication and/or Management systems are standardized and capable of controlling charging to minimize negative impacts to the grid

As discussed in the Electricity Supply Chain section, there are three different peaks in the electricity grid—the daily generation peak for power plants; the critical (or "needle") peak for power plants, which occurs typically on only a few days of the year; and the distribution system peak, which varies by distribution circuit.

Dealing with and minimizing these different impacts to the grid will involve different solutions, all with different costs and benefits. Utilities and their regulators are in an early stage of analyzing actual consumer charging patterns with the associated load impacts, and the costs and benefits of various solutions.

- *All three vehicle types are rated "yellow" because it will take several years to match real-world charging behavior with the appropriate mechanisms to ensure that charging does not have negative impacts to the grid.*

At a basic level, two key strategies can help to lessen additions to peak load from vehicle charging: (1) charging at a lower power level (kW), and (2) charging during off-peak hours. Technical solutions to achieve these strategies can be achieved by the utility, the PEV manufacturer, and in some cases even by smart phone applications. In addition, knowing the location of the charging equipment (especially at homes) is important to minimizing the impact on the distribution system peak.

Charging at a Lower Power Level (kW)

Charging at lower levels than is allowed by the SAE standards could help to minimize vehicle charging loads during peak periods. For example, Level 1 charging is typically at 1.4 kW, but could be at lower levels such as 0.7 kW. Level 2 charging can be at 3.3 kW (20 amps), 5.0 kW (30 amps), 6.6 kW (40 amps), and higher. The charging rate is controlled by the vehicle's battery control system, and vehicle models coming to market may or may not charge on a lower rate, so this countermeasure would require automotive manufacturers to build in flexibility of charging power rate by the EVSE.

Charging Off-Peak

There are many ways to achieve the goal of off-peak vehicle charging, ranging from very simple to highly sophisticated. At the simple end of the spectrum is for the vehicle to have a timer that the customer sets. Vehicles already on or coming to market have this capability. At the more sophisticated end of the spectrum is to have the EVSE communicate with the utility or to be "aware" of the grid conditions and to consequently either allow or disallow charging. This implies some way for the EVSE to recognize parameters related to the local utility tariffs—for example, the interval during which the utility would charge a peak rate for electricity. Eventually, the utility might offer voluntary programs (similar to summer climate-control programs) where it would be financially attractive to the vehicle owner to allow the utility to respond to needle peaks or distribution system peaks by interrupting or delaying charging.

Codes and Standards Under Development

A number of standards are necessary to facilitate the communication between electric vehicles and the supporting infrastructure, extending from the charging station to the transformer and up to the substation. Information to be transmitted can include the rate of charge—corresponding to amperage required from the grid—and the expected duration of the charge, along with any kind of vehicle ID and remuneration information that would be necessary in the case of shared chargers. These standards would provide a means of sharing information in a consistent and reliable fashion such that charging could be allowed or disallowed as necessary to ensure that the local distribution grid is not adversely affected by the vehicle charging and that the vehicle owner can take advantage of any pricing incentives offered by the utility. SAE International is working on two sets of standards as part of the efforts led by the National Institute of Standards and Technology (NIST) and coordinated by the Smart Grid Interoperability Panel (SGIP). The first set of standards, SAE J2836, describes key system elements and use cases. The second set of standards, SAE J2847, establishes requirements and specifications for communications between the system elements. Although the development of J2836 and J2847 provides a solid base for integration between PEVs and the grid, the expectation is that implementation of the standards will lead to further refinements. For example, SAE J2847 specifies that communication is "expected to include a base or fundamental speed." While faster communications provide increased flexibility and value, it is presently unclear what the maximum allowable communications delay between PEVs and the utility grid is to make a system like this usable in practice. Other elements, such as communications between utilities when vehicles roam between different service territories may also require standardization.

Notifying the Utility

As part of managing the distribution system, utilities typically have their planners visit sites with significant new loads (e.g., those that have had panel upgrades at homes and businesses, new homes and businesses, etc.) in order to determine whether upgrades are needed to the distribution system. As discussed in the section on electricity distribution, BEVs can represent a significant new load that may have a long duration. In addition, PEVs can move locations. In order to address this problem, the utility would ideally know early on in the sales process, or even before the vehicle sale, the vehicle type and address of the purchaser. Methods to enable early notification of the utility include:

- Encouraging automakers, cities, and other stakeholders to implement mechanisms to encourage PEV customers and obtain PEV customer consent to provide investor-owned and public utilities with early notification of the location of PEV charging by those customers, so that utilities can address electric distribution system impacts on an expedited basis and help customers "get PEV ready" before they bring their PEVs home.[38]

- Developing scalable solutions to consolidate and simplify the collection and notification of PEV customers' charging needs and locations including notification of the resale and/or relocation of PEVs.[39]

Grid Integration – Regulatory Certainty

REGULATORY CERTAINTY	PHEV10	PHEV40	BEV100
	●	●	●

A sufficient level of regulation exists in jurisdictions across the country to allow EVSE installation/operation (including revenue generation) to support wide-scale PEV adoption

The rules for electric utility operations and the use of electricity vary across state and municipal jurisdictions, while federal regulatory agencies govern transmission system operation between states. Policy priorities and regulations vary greatly among jurisdictions; thus, there are different rules governing vehicle-grid integration across the country. New regulations for PEVs are in varying stages of development and adoption across the country. Some states, such as California and Virginia, are establishing specific regulations governing charging infrastructure, while others are waiting to see how the market develops before proposing new regulation. It will take time for regulating entities to decide whether and how to treat vehicle charging, which, as discussed in the next section, affects the potential business models allowed for the installation of charging stations.

Because of the time it will take to develop appropriate regulations, all three vehicle types are rated "yellow."

The most common regulatory approach across the country is to treat grid connected vehicle load as any other load addition. Over the last half century, utilities have managed the adoption of significant customer load additions such as central air-conditioning, computers and data centers, high power consumer electronics, and other unique loads such as "instant on" water heaters. In each of these cases load additions were managed without significant regulatory changes. While it is not possible for the treatment of vehicle charging to be identical across jurisdictions, the key is for infrastructure providers to "know the rules." If the treatment of vehicle charging is unknown—not yet considered or addressed by the regulating entity—or uncertain, infrastructure providers will be reluctant to install charging stations.

The view of the Electric Subgroup is that regulatory changes may be beneficial in the future, but they should not be rushed. Regulations created while the market is nascent could have unintended consequences that could be detrimental to vehicle adoption and/or charging infrastructure development. Real-world experience is needed to gauge the magnitude and timing of PEV load, and design and develop the appropriate regulations.

Fuel Economics – Capital Required for Charging Infrastructure

CAPITAL REQUIRED FOR CHARGING INFRASTRUCTURE	PHEV10	PHEV40	BEV100
	n/a	n/a	●

Capital required for dispensing infrastructure to support all trips can be accommodated within existing business practices

- *The PHEV10 and PHEV40 are rated "n/a" because they are expected to charge at home using low-cost Level 1 EVSEs, and do not need non-residential charging infrastructure to support all trips.*
- *The BEV100 is rated "red" because of the higher cost of Level 2 EVSE charging equipment, and because without extensive non-residential charging infrastructure to support all trips, customers would need to adjust their driving behavior and it is highly uncertain whether customers will actually do this. Realizing the charging infrastructure to support all BEV trips is also highly uncertain, as discussed in the section on MDU/Workplace/Commercial charging.*

Similarly to recharge time and charging station availability, there are some who believe that the capital required for charging stations to support all trips is not an issue for wide-scale consumer adoption, as BEVs do not need to be one-to-one substitutions for conventional vehicles. The argument is that if households adjust their driving behavior, such as using the BEV only for trips where the limited range

38 Consensus Action Items for Plug-in Electric Vehicles and Charging Infrastructure Deployment, October 2010, by Natural Resources Defense Council, Coulomb Technologies, Ecotality, Southern California Edison, and Pacific Gas and Electric.

39 Ibid.

is not an issue, away-from-home charging infrastructure is not needed, thus the capital required to enable such infrastructure is not an issue.

Fuel Economics – Dispensed Fuel Cost

Fuel cost per mile is less than or equal to conventional vehicles

- *All three vehicle types are rated "blue" because, as discussed earlier in the section on fuel cost per mile, fueling costs for PEVs in most cases provide a positive financial value to the consumer and will most likely continue to do so in the future.*

CONSUMER VALUE PROPOSITION

Throughout this chapter, many areas of uncertainty have been discussed, including charging needs, future battery development, and government regulations. The greatest uncertainty, however, is how consumers will value a PEV. The discussion thus far is based largely on two key assumptions: (1) that potential customers of PEVs will base their purchase decisions on the attributes and performance expectations of conventional automobiles, including (2) a cost-benefit financial comparison of the upfront price premium of the vehicle to the operating cost savings of "fueling" it, as compared to a conventional vehicle.

Consumers of light-duty vehicles are arguably motivated as much by emotional considerations, however, as they are by "rational choice" calculus.[40,41,42] There are non-financial benefits of PEVs that may affect the consumer evaluation. These include the ability to "fuel" at home, near-silent vehicle operation, instant torque and acceleration, potentially reduced standard maintenance costs, and the ability to pre-condition the passenger cabin while the vehicle is plugged in. Additionally, there may be other purely emotional factors involved in the purchase decision, such as the absence of tailpipe emissions, and the perception that PEVs contribute to "energy security."[43,44] There is also the possibility for business-model innovation to impact consumer adoption. This topic is discussed in Topic Paper #18, "Emerging Electric Vehicle Business Models."

There is also the possibility that, for BEVs, consumers will not accept a limited-range vehicle. Though many surveys have attempted to gauge consumer interest in PEVs, it is extremely difficult for consumers to convey the value of experiences they haven't yet had,[45] and it will only be in hindsight that we will know with any certainty what consumers ultimately did or did not value, and what factors entered into the purchase decision.

OTHER MATERIAL CONSIDERATIONS

Emissions from Electricity Generation

Life-cycle GHG emissions attributable to PEVs are proportional to the electric power generation fuel mix. In regions where more of the power is generated with low GHG emission methods such as nuclear, wind, or hydroelectric power, the resulting GHG emissions per mile for PEVs can be relatively low. Conversely, in regions that are dominated by higher emitting methods such as older coal-fired power plants, the emissions per mile ratio for PEVs is significantly higher.

Chapter Six, "Greenhouse Gases and Other Environmental Considerations," addresses the issue of GHG emissions and criteria pollutants for PEVs as well as other fuel-vehicle combinations. The chapter also includes a section specifically addressing lower carbon intensity electricity grid scenarios and their impact on reducing emissions attributable to PEVs.

40 David L. Greene, *How Consumers Value Fuel Economy: A Literature Review,* Report EPA-420-R-10-008, Oak Ridge National Laboratory, prepared for the EPA Office of Transportation and Air Quality. March 2010.

41 Tim Jackson, *Motivating Sustainable Consumption, a Review of Evidence on Consumer Behaviour and Behavioural Change,* Centre for Environmental Strategy, University of Surrey, January 2005.

42 T. Turrentine and D. Sperling, "The Development of the Alternative Fueled Vehicles Market: Its Impact on Consumer Decision Process," in *Methods for Understanding Travel Behavior in the 1990's*, Chateau Bonne Entente, Quebec, 1991, pages 208-227.

43 Todd Woody, "Home Solar Installer SolarCity to Sell Electric Car Charging Stations," *Forbes Technology Blog,* July 27, 2011, http://www.forbes.com/sites/toddwoody/2011/07/27/home-solar-installer-solarcity-to-sell-electric-car-charging-stations/.

44 General Motors, GM News, "Going Pump Free: Volt Owners Go 1,000 Miles Between Fill-ups," April 21, 2011.

45 University of California, Berkeley, Transportation Sustainability Research Center, *Strategies for Transportation Electric Fuel Implementation in California: Overcoming Battery First-Cost Hurdles,* CEC-500-2009-091, prepared for California Energy Commission, Public Interest Energy Research Program, February 2010.

Electricity Rates

It is relatively easy to calculate refueling costs for vehicles that use conventional fuels such as gasoline. While the price may vary by time and location, the basic unit of cost is dollars per gallon, which is clearly posted at the refueling point and remains generally consistent over short periods of time (days to weeks) and in the same geographic area.

For PEVs, however, the cost of "filling the tank" can be difficult for the consumer to determine and can vary considerably depending on the time of day. Utility rates used to calculate electricity costs can be complex. There are thousands of electric rate schemes in the United States, each with its own structure. Utility rates are composed of individual charges for consumption, demand, surcharges, adjustments, tax components, riders, and provisions. The various consumption and demand costs can also change from season to season and between weekdays, weekends, or holidays.

Appendix 13B at the end of this chapter provides a summary of the different types of rate plans commonly used in the United States and the impact on the cost consumers pay for electricity. The complexity and variability of these schemes means that many users will not know at any given time how much they will be paying for electricity when they charge their PEV, thus the fuel cost savings of using electricity as a transportation fuel will not be apparent to many consumers, and it may be difficult for consumers to make good choices to maximize those savings.

Battery Manufacturing Capacity

Battery manufacturing, and specifically lithium-ion battery manufacturing, has been concentrated in Asia for many years—especially in Japan, South Korea, and, increasingly, China. Over the past few years, however, the expected demand for batteries designed for PEVs (as well as for energy storage on the grid) has led to plans for several U.S.-based battery manufacturing plants. This recent trend notwithstanding, the U.S.-based supply chain for vehicle batteries is not as large or as robust as those in Asia.

It is important to note that electrifying a significant number of vehicle miles traveled in the United States does not require that the batteries be manufactured in the United States, especially given that many automotive components are imported today, and lithium-ion batteries are already imported in significant volumes for consumer electronics uses. Additionally, cultivating U.S.-based manufacturing across the lithium-ion battery supply chain is not without risks. Many industry analysts are projecting that the global lithium-ion battery industry could be heading for oversupply,[46] placing new production sites at increased risk of downtime or even failure. Manufacturing sites in Asia, particularly in China, will continue to have advantages in labor and overhead costs, as well as substantial government support, and most of the key material suppliers are currently based in Asia.

Nonetheless, there are many reasons why U.S.-based manufacturing would be desirable, including the following:

- Shipping large volumes of lithium-ion batteries can be problematic (see section on battery supply chain logistics safety) and adds costs, and vehicle batteries are far larger than those used in consumer electronics.
- U.S.-based vehicle battery manufacturing would create jobs and contribute to the tax base.
- Domestic manufacturing will help support U.S. technology leadership in this field.
- As the battery is such a critical component of PEVs, it may be strategically desirable for the United States to foster domestic manufacturing capabilities (especially as, in addition to automotive, there may be military applications for these technologies).

Choosing the appropriate policies toward U.S.-based battery manufacturing will require weighing a complex list of factors that includes, but extends far beyond, a desire to increase the use of electricity as a transportation fuel. Assuming that the United States does want to develop a sustainable domestic battery manufacturing capability, some of the key factors are discussed below.

46 Lux Research, *Using Partnerships to Stay Afloat in the Electric Vehicle Storm,* June 2011; Bloomberg New Energy Finance, *Energy Smart Technologies – Research Note,* September 5, 2011; Roland Berger Strategy Consultants, *Powertrain 2020: Li-ion batteries – The next bubble ahead?,* February 2010.

Development of a U.S. Supply Chain

If an advanced battery industry is to become sustainable in the United States, the following are some key issues that must be addressed:

- Development of a North American supply chain for cell and battery material components and manufacturing equipment. Currently the majority of the processing equipment for making the thin-film electrodes used in lithium and other advanced batteries are made in Japan, South Korea, and to a lesser extent China. As a result, American battery companies find it difficult if not impossible to receive state-of-the-art equipment in a timely manner, compared to on-shore competitors in the countries producing this equipment. Some bright spots are emerging, such as a coating manufacturer in Wisconsin, but a much more robust U.S. equipment industry is needed.
- Electrode active materials and substrates. Currently many of the key cathode and anode materials and precision aluminum and copper foils are sourced offshore. The Department of Energy's American Recovery and Reinvestment Act funding has helped enable suppliers to locate plants in Michigan near their automotive battery customers.
- As discussed earlier in this chapter, the technology needs of a domestically sustainable advanced battery industry go well beyond the cell level. Equally critical to the expertise in developing advanced and improved cell materials is the focused expansion of academic and manufacturing prowess in the United States around system levels technologies such as:
  - Thermal management devices and subsystems, particularly miniaturization and advanced heat transfer media
  - Advanced sensors and deployment methods
  - Lightweight, reusable containment systems
  - Design for remanufacturability and recycling.

Substantial improvements in cell chemistry are demanded if batteries are going to power a significant number of vehicle miles traveled in the United States. As such, a skilled labor force capable of advanced R&D in the fields of electrochemistry, power electronics and materials science, mechanical engineering, and computer science will also be essential for providing the battery volumes necessary for the wide-scale deployment of PEVs.

Battery End-of-Life

Recycling Methodologies

A discussion of the use of batteries for transportation is not complete without addressing the end-of-life consideration of the batteries themselves. Although there continues to be significant debate about the economic value proposition for recycling automotive lithium-ion batteries, there is active discussion within the battery industry about the need to develop such a system.

The process to recycle large format lithium-ion batteries exists in different forms, based on the recycling company and the specific technologies it utilizes. For example TOXCO, Umicore, and RSR are well-established recyclers capable of breaking down complete battery systems and recovering high-value metals and/or metallic compounds, but they do not use identical processes.

The spectrum of recycling methodologies is shown in Table 13-13, listed in descending order of potential economic value. The two methods most widely discussed are "secondary use" and "direct recycling," and are presented in more detail below.

Secondary Use as Stationary Storage

In both the transportation and electric utility industries, there has been significant discussion of the potential to take battery packs that have reached their useable end-of-life in vehicle applications and repurpose them for stationary applications such as providing a storage buffer for intermittent electricity generation sources such as wind and solar, or providing uninterrupted power supply for commercial applications. This potential is based on an aging characteristic that is common to many battery technologies, which is that peak power fades more rapidly than useable energy. The logic is that spent vehicle batteries would not necessarily need to provide the same peak power, useable energy, or cycling efficiency when used in a stationary application. If sold at a discounted price, the logic is that the low power and energy characteristics of the batteries may find a business case because of the less stringent requirements of some stationary applications,

Potentially More Economically Favorable	Secondary use	recovery of functioning sub-assemblies into other applications
	Direct recycling	recycling of contained materials at the value of the manufacturing process
	Recycling	recycling of contained materials at a value equal to the raw material inputs to the manufacturing process
	Downcycling	recycling of contained materials at a value below the raw materials input to the manufacturing process
	Energy recovery	recovery of energy from materials contained within the product (exothermic processes)
Potentially Less Economically Favorable	Hazardous Waste Disposal	not a desirable option for recycling of large format automotive batteries

Table 13-13. *Spectrum of Recycling Methodologies*

relative to automotive applications. The practical application, however, is much more complex, primarily due to the different requirements for and types of stationary storage. Most stationary systems will demand very large energy capacity—in many cases on the megawatt or megawatt-hour level. Hundreds or thousands of small vehicle battery packs would need to be disassembled and then reassembled to achieve these large aggregate electrical capacities. This requires achieving "balance" between battery packs with different calendar lives, cycling histories, and states of health, as well as adding a new battery monitoring and control system and thermal management system to function in a stationary application.

Little empirical data is available to adequately assess the economic or performance suitability and safety of used battery systems. Although substantial progress has been made in the last decade in formulating computational models to predict battery aging behavior and end of life, no model that exists today is sufficiently sophisticated or has been validated for use as a substitute for empirical test data. Because of this uncertainty, significant testing needs to be performed in a controlled environment to assess the reliability, safety, and performance of these devices, before secondary use of batteries would be accepted by energy storage providers.

In addition to the technical difficulties of repurposing vehicle batteries, there are economic hurdles:

- PEV battery costs are expected to come down over time, and new battery costs create a "ceiling" on the value of used batteries.
- As battery performance post-vehicle is unknown, the secondary user will likely discount the price to account for this uncertainty.
- Secondary use would begin years after the initial PEV purchase, and secondary value must accordingly be discounted by the time value of money.
- The cost of the re-engineering to balance the new pack would likely be borne by the secondary user, which would require further discounting.

Because of these technical and economic challenges, it is best to view PEV battery secondary use as an upside potential in the overall vehicle value proposition—one that is unlikely to make or break the value proposition for these vehicles.

Note that the section above on secondary use discusses the use of spent vehicle batteries for energy storage once the battery is removed from the vehicle. The use of batteries while still in the vehicle to flow power from the battery to the grid—vehicle to grid or V2G—is discussed in Topic Paper #20, "Vehicle to Grid (V2G)," on the NPC website.

Direct Recycling

The direct re-use of certain battery materials such as the active materials in cathodes is being explored by several recyclers. The economic value of the resultant materials above the cost of recovering the materials, however, is dependent on the specific metal, as well as market conditions at a given time. It is important to note that a substantial portion of the economic value of finished electrode materials is in the conversion costs incurred to provide the necessary purity and structure to satisfy the battery performance requirements. Even electrode materials that are "cheap" at the elemental level become more costly to produce. The same basic relationship holds true for recycling, to the extent that electrode compounds typically characterized as having a net positive recycled value, such as cobaltates, can represent a net cost to the battery manufacturer. Fluctuations in market prices for key metals affects the final valuations, but generally speaking, the above holds true. While this approach has environmental and potential economic benefits, the processes, as well as the quality of the resultant reprocessed materials have yet to be validated, thus further evaluation is needed.

Ultimately the economics of recycling/recovery will be a function of:

- Volume and mix
- Chemistry
- Process costs and elemental recovery rates
- Prevailing market prices for virgin materials
- Legislative and policy actions.

Much like the recycling legislative model and infrastructure voluntarily proposed and implemented by the lead-acid battery industry in the 1980s, a proactive approach to self-regulation by the lithium-ion battery industry would prevent the need for regulatory action at the federal, state, or municipal level.

Raw Materials Supply

PEVs contain new components (such as the lithium-ion battery), built from new materials not typically produced in automotive quantities. This leads to the question of whether global raw materials supply will become a bottleneck to the implementation of such vehicles. The question has been raised as to whether the United States might become dependent on such materials if there were to be a significant shift to PEVs.

There are two distinct classes of "new materials" contained in a PEV. (In fact, neither of these materials are newly discovered; rather they are new to the specific application of the automotive industry.) One is a group of elements known as rare earth metals, which are used in electric motors, among other things. The second material of interest is lithium itself, for use in lithium-ion batteries (and consumer electronics). Both classes of material will be in demand by the automotive industry as a direct result of PEVs. The question is whether this new demand creates risks and uncertainties to the industry. Each class of material is discussed separately below, as the two materials face very different supply issues.

Rare Earth Metals

Rare earth metals are a classification of metals containing 22 distinct elements. Several of these are of commercial interest to PEVs, including lanthanum, cerium, neodymium, and others. These metals are used in the permanent magnet motors that power the majority of electrified vehicles (including conventional hybrid electric vehicles). They are also used in non-lithium-based batteries (e.g., nickel-metal hydride batteries) currently employed in some hybrid electric vehicles. Demand for such materials, however, is driven by a variety of technologies in addition to vehicles—e.g., wind turbine generators, solar panels, and LED lights.

In the last two decades, the United States has shifted away from being a leading global supplier of rare earth metals. Over the same time period, China has emerged as the dominant global supplier of rare earth metals, providing well over 90% of global supply.[47] The United States has large reserves of rare earth metals, with over 11% of the world's total deposits.[48] Mining operations in the United States, however, have become unprofitable in recent decades, which has led mine operators to cease operations, such that by 2010, none of the commercially utilized rare earth metals was mined in the United States. This trend was reversed in 2011, with dramatically increased exploration and investment activity. Several sites are also under development in Canada, Australia, and elsewhere. A key near-term hurdle is the time and cost of developing new mine sites, which can take five years or longer, and is often drawn out due to the environmentally sensitive process of ore extraction.

If this current interest and investment trend continues, the long-term supply of rare earths seems

47 U.S. Geological Survey, Minerals Information (website), Mineral Commodity Summaries: Rare Earths, January 2011.

48 Ibid.

relatively secure. In the near term, however, China has a near monopoly on global supply, suggesting that the United States and other nations may be vulnerable to supply disruptions. It is not without precedent for China to restrict exports of raw materials in an effort to shift into value-added manufactured parts.[49]

Supply vulnerabilities would presumably be eased if and when new production is brought online, but that time frame is anticipated to be between 5 and 10 years from now.

Lithium

Lithium is a key component of various materials inside a lithium-ion battery pack. Lithium is typically found in the form of a carbonate salt, often dissolved in water to form lithium-rich brine. Globally, the largest concentrations of lithium are found in South America's Atacama Desert, in northern Chile and Bolivia. In combination, these two countries control over half the known reserves worldwide. In contrast, the United States contains an estimated 4 million tons (of an estimated 29 million tons thought to exist worldwide).[50] The search for lithium sources worldwide has not been exhaustive, and other deposits are thought to exist undiscovered at various sites (for example, in Serbia and Afghanistan).[51]

In the case of lithium, there is an emerging consensus that supplies will be adequate in both the short and long term. According to one analysis, "even if, by 2040, all the world's 2 billion cars are EVs, the total lithium used would be 6 million tons, which is equivalent to less than 25% of the world's known reserves."[52] This relative abundance of the material is evident in recent skepticism over new lithium mining projects, with some analysts citing production capacity plans that are double the projected demands in coming years.[53]

49 Keith Bradsher, "China Said to Widen Its Embargo of Minerals," *New York Times,* October 19, 2010.

50 U.S. Geological Survey, Minerals Information (website), Mineral Commodity Summaries: Lithium, January 2011.

51 Gopalakrishnan et al., *Impacts of Electric Vehicles – Deliverable 2: Assessment of Electric Vehicle and Battery Technology,* CE Delft publication number 10.4058, October 2010.

52 Ibid.

53 Edward Anderson, TRU Group Inc., "Shocking Future Battering the Lithium Industry through 2020," Presentation at Lithium Supply & Markets Conference, January 2011.

Battery Supply Chain Logistics Safety

Battery safety during shipment is a concern for large-format lithium-ion batteries. Under normal storage conditions, such batteries are stable and safe. Shipping mishaps could happen, however, causing container punctures, mechanical damage, or other damage that may present a fire hazard. Lithium-ion batteries are flammable when heated to high temperatures. This risk has caused the recall of several such batteries in cell phone and laptop computer applications.

The risks of shipping have become a focus of regulators since the crash of a UPS jetliner in September 2010, which was carrying a large load of lithium batteries. The FAA is investigating the safety of battery shipping methods and materials, and is expected to release more guidance on the topic soon. SAE is also working toward standards for battery shipment. *These efforts are leading to standards and requirements for battery shipments. This represents a near-term risk for the plug-in electric vehicle industry, and a major logistical inconvenience for the emerging market. In the long term, however, battery shipping via approved methods will likely emerge as a commonplace activity, though perhaps with more costly safeguards and/or regulations than exist today*.

INPUTS FOR INTEGRATED ANALYSIS

As explained in Chapter Nine, "Light-Duty Engines and Vehicles," each vehicle-fuel system subgroup provided cost projections for their key vehicle and fuel dispensing components. For the Electric Subgroup, these were projected battery and installed EVSE costs.

Battery Costs

A range of costs was necessary for the integrated analysis, in order to represent the considerable uncertainty in projections of battery costs in the future. For each combination of year and vehicle type, a baseline case was chosen to be similar to the average value implied by the curves shown in Figures 13-27, 13-28, and 13-29. Then a "High" case, which is 25% higher than the baseline, and a "Low" case that is 25% lower than the baseline case were used to represent the range of projected battery costs. The cost ranges used

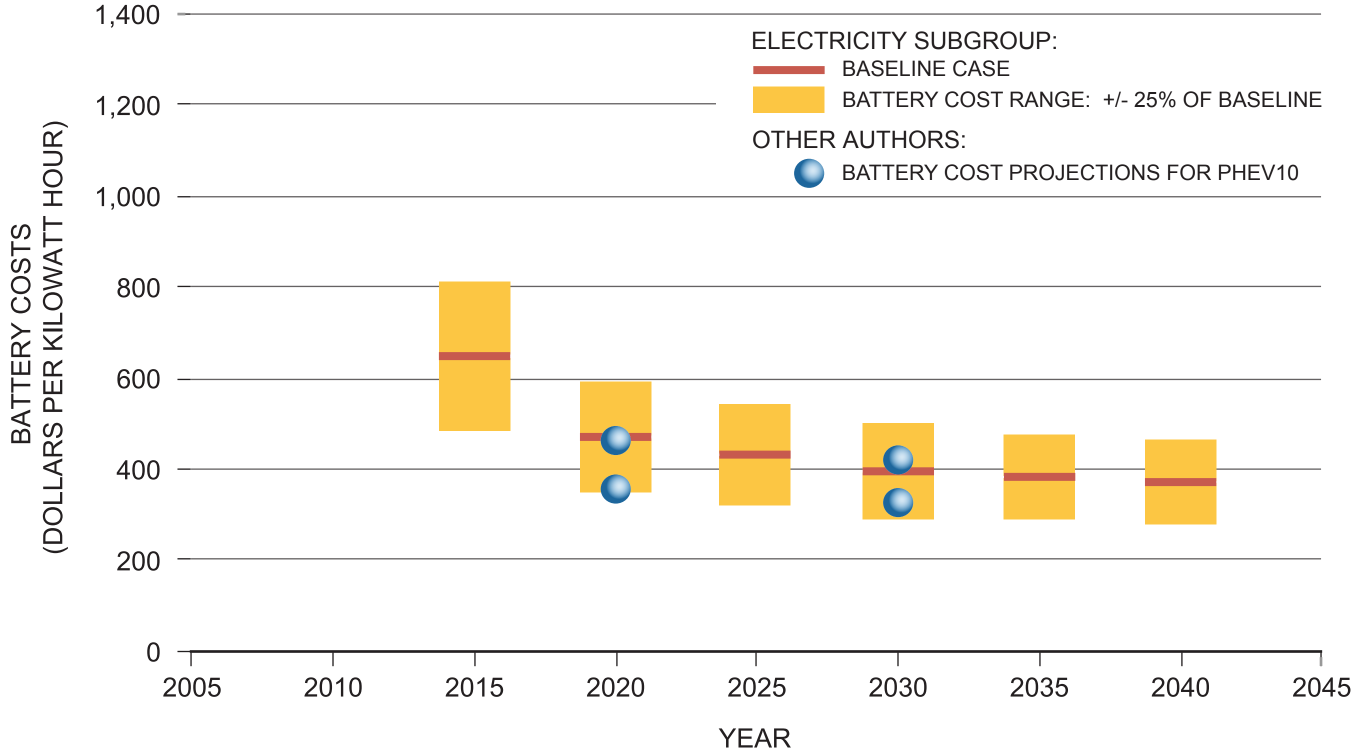


Figure 13-27. *Battery Cost Ranges Used in the Integrated Analysis, Compared to the Projections of Other Authors – PHEV10*

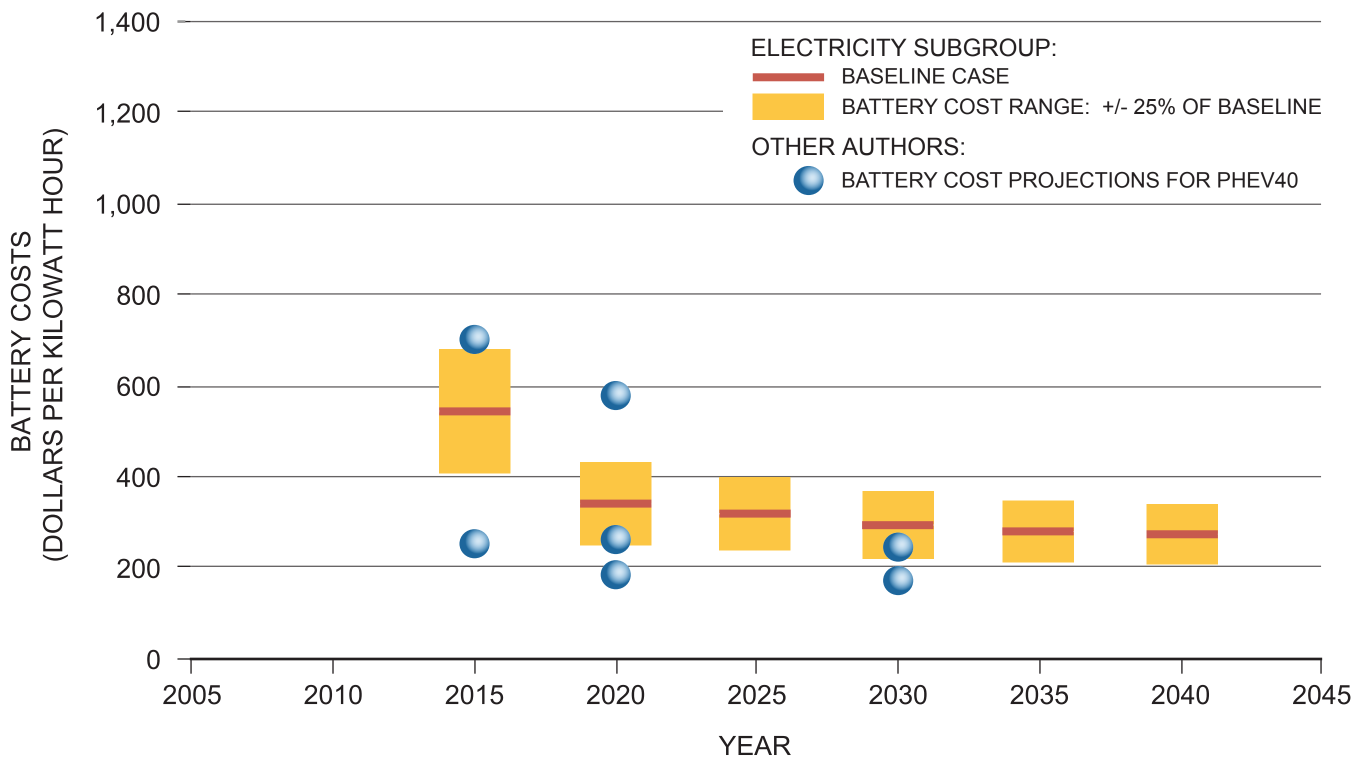


Figure 13-28. *Battery Cost Ranges Used in the Integrated Analysis, Compared to the Projections of Other Authors – PHEV40*

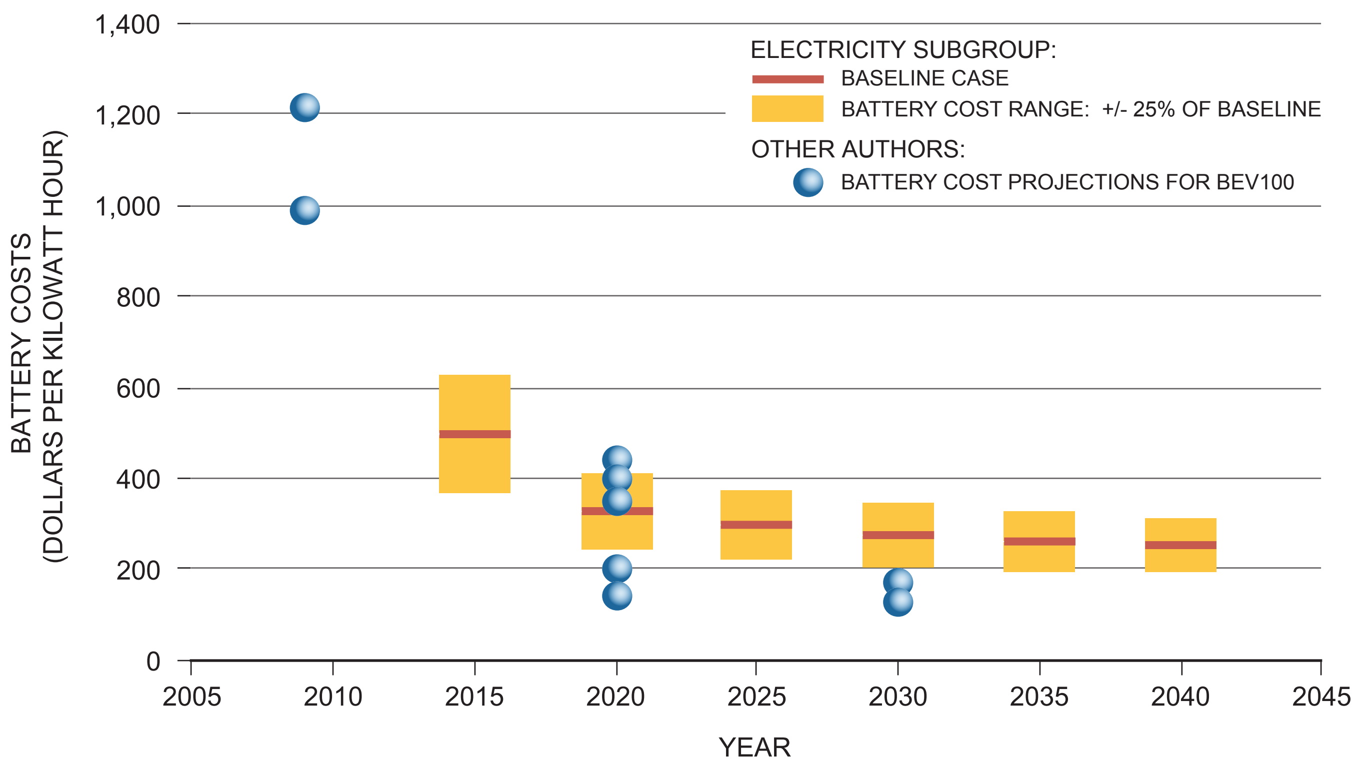


Figure 13-29. *Battery Cost Ranges Used in the Integrated Analysis, Compared to the Projections of Other Authors – BEV100*

in the integrated analysis, are shown in these figures, along with the projections of other authors for comparison.

Installed EVSE Costs

As discussed in the sections on charging, the cost of the EVSE unit and installation can be an obstacle to the wide-scale adoption of BEVs, and for all PEV types in MDU, workplace, and commercial settings. To develop the installed EVSE costs for the integrated analysis, three components were needed:

- Projected EVSE unit costs
- Projected EVSE installation costs
- Density and power level of EVSEs.

Projected EVSE Unit Costs

The basis of the unit cost projections is the average of actual unit costs in the market. Projected costs were based on assumed manufacturing learning and scale, and were calculated from actual costs, discounted over time at rates of 3% annual reduction for five years, followed by 2% annual reduction for five years, and then 1% annual reduction thereafter. This is consistent with the treatment of other immature technologies, as discussed in Chapter Nine.

Projected EVSE Installation Costs

As with the EVSE unit cost projections, the basis for the EVSE installation cost projections is the average of current actual costs in the market, with projections calculated according to the following:

- To account for housing stock turnover that would lead to pre-wiring, installation costs from 2020 on were reduced by the housing stock turnover rate.
- Level 1 residential installation—under the assumption that circuits should be dedicated
  - Assume 50% require upgrade to dedicated
  - Idaho National Laboratory installation cost estimate used, as no actual market cost information was available.

- For Level 2 commercial installation, multiple EVSEs in one location tends to lead to decreased per-unit costs, so the methodology was to use data from Clean Fuel Connection, Inc., showing decrease in costs from 1 unit per installation to 6+ units per installation (a 50%+ cost decrease). The assumption is that by 2025, this would be the case.
- The resulting installed costs are listed in Table 13-14, and as can be seen in Figure 13-30, are expected to decrease substantially over time.

Density of EVSEs

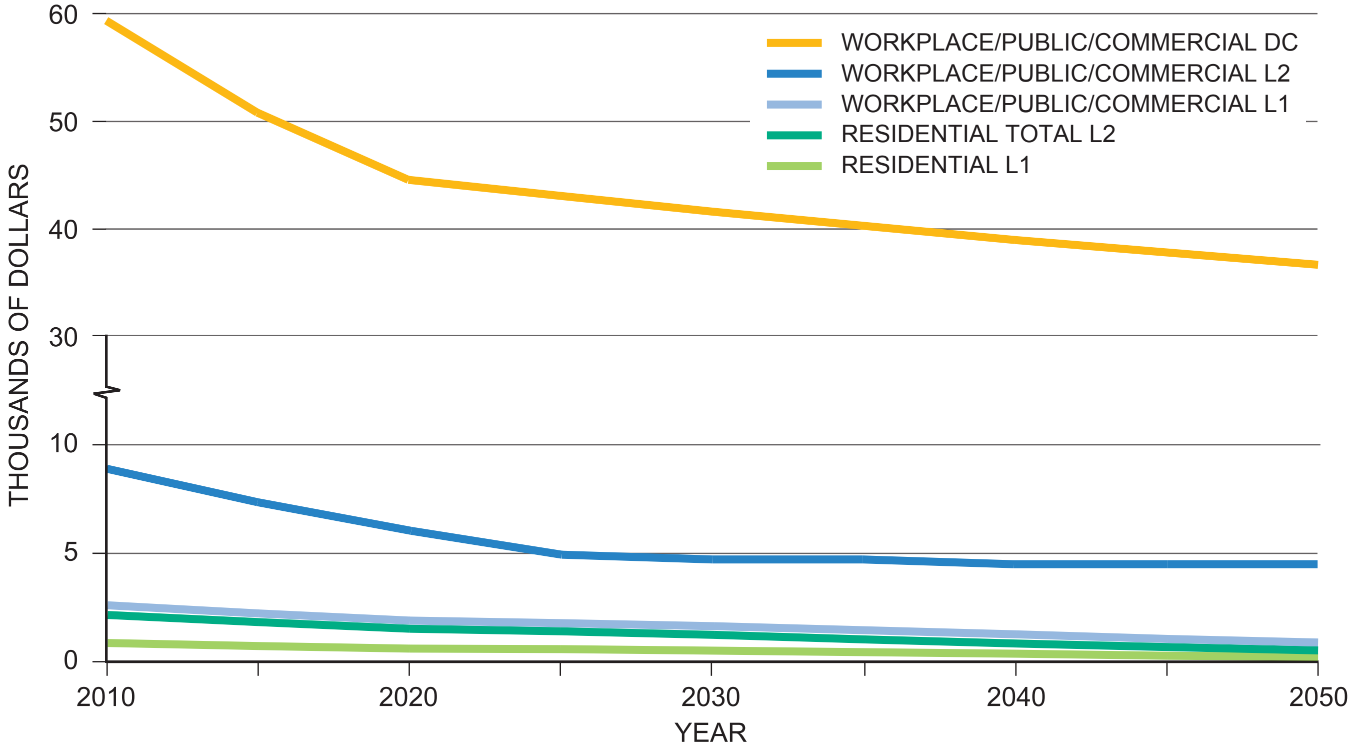
In spite of the considerable uncertainty in any density recommendation, the method for determining density is EPRI's benefits-based

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Residential									
L1 unit	$500	$429	$388	$369	$351	$334	$317	$302	$287
L1 install no turnover	$606	$515	$424	$424	$380	$320	$252	$185	$124
Housing Turnover	1.00	1.00	0.99	0.94	0.90	0.84	0.79	0.73	0.67
L1 install w/ turnover	$303	$257	$210	$200	$170	135	$100	$67	$41
Total L1	**$803**	**$687**	**$598**	**$569**	**$521**	**$469**	**$417**	**$369**	**$328**
L2 unit	$1,100	$945	$854	$812	$772	734	$698	$664	$632
L2 install no turnover	$1,603	$1,363	$1,112	$1,050	$941	793	$626	$457	$306
Housing Turnover	1.00	1.00	0.99	0.94	0.90	0.84	0.79	0.73	0.67
L2 install w/ turnover	$1,603	$1,363	$1,102	$992	$842	669	$493	$334	$205
Total L2	**$2,703**	**$2,307**	**$1,956**	**$1,804**	**$1,614**	**1,404**	**$1,192**	**$998**	**$837**
MDU / Commercial / Public									
L1 unit	$3,000	$859	$776	$738	$702	668	$635	$604	$574
L1 install	$606	$515	$424	$424	$380	320	$252	$185	$124
Total L1	**$1,606**	**$1,373**	**$1,200**	**$1,162**	**$1,082**	**988**	**$887**	**$788**	**$698**
L2 unit	$2,745	$2,357	$2,130	$2,026	$1,927	1,832	$1,742	$1,657	$1,576
L2 install	$6,215	$5,096	$3,977	$2,859	$2,859	2,859	$2,859	$2,859	$2,859
Total L2	**$8,959**	**$7,453**	**$6,108**	**$4,885**	**$4,785**	**4,691**	**$4,601**	**$4,516**	**$4,435**
L3 DC unit	$39,332	$33,775	$30,530	$29,034	$27,611	26,258	$24,971	$23,747	$22,583
L3 DC install	$20,000	$17,000	$14,000	$14,000	$14,000	14,000	$14,000	$14,000	$14,000
Total L3 DC	**$59,332**	**$50,775**	**$44,530**	**$43,034**	**$41,611**	**40,258**	**$38,971**	**$37,747**	**$36,583**

Notes: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

The costs are represented to three significant digits. This is NOT meant to represent precision, but is simply the result of using an average of actual, unrounded costs.

***Table 13-14.** Installed EVSE Costs Used in Analysis*



Note: DC = Direct Current Fast Charging; L2 = Level 2 Charging; L1 = Level 1 Charging.

Figure 13-30. *Installed EVSE Costs Used in Analysis*

occupied parking method (described in detail in Appendix 13A).[54] This method provides density and charging power level values for the three vehicle types addressed in this chapter. The exceptions are the following:

- Methodology did not capture Residential Level 1 vs. Level 2, so 100% Level 1 assumed for PHEV10s and 60/40% Level 1/Level 2 for PHEV40s.
- Methodology calculated Residential Level 2 for BEV as significantly lower than any other source, so 20/80% Level 1/Level 2 was used, which is within the range of other estimates.
- The resulting EVSE densities are listed in Table 13-15.

54 Appendix 13A provides a detailed description of the methodologies used by the various sources to arrive at the recommendations.

	PHEV10		PHEV40		BEV100	
	Home	Ubiquitous	Home	Ubiquitous	Home	Ubiquitous
Residential						
Level 1	1.00	1.00	0.60	0.60	0.20	0.20
Level 2	–	–	0.40	0.40	0.80	0.80
Commercial/Public						
Level 1		0.269		0.077		0.010
Level 2		0.075		0.059		0.018
DC Fast Charging					0.005	0.002

Table 13-15. *EVSE Densities Used in Analysis*

Utility Factor

Modeling the energy use of PEVs is challenging, given presently available data. These vehicles, particularly BEVs, may be used differently than normal vehicles, the availability of charging will change over time, and PHEVs use both electricity and gasoline in ratios that will change with different usage patterns.

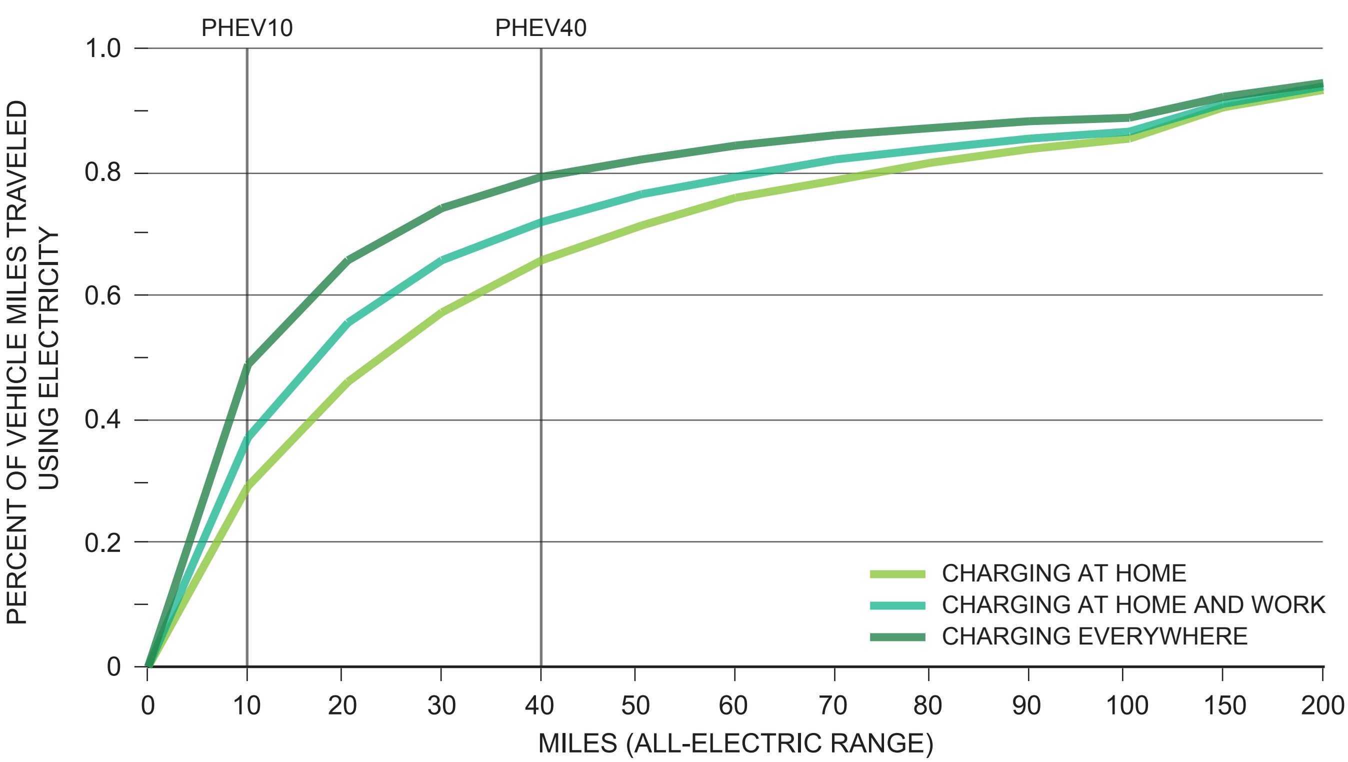
EPRI uses a methodology that is relatively common among energy modelers: a utility factor is calculated for the vehicle that estimates the percentage of vehicle miles traveled that will be driven on electricity. The utility factor is then calculated by using data collected on driving patterns of current vehicles in a simple simulation that calculates how energy would be used by hypothetical vehicles with different ranges and levels of charging availability. The resulting utility factors are those shown in Figure 13-31.

This method provides plausible results for PHEVs, which are beginning to be validated by initial test fleets. BEVs, however, are more complicated to handle in this framework. When the electric range of a PHEV is exceeded, it can switch to using gasoline and continue driving until the gas tank is depleted. If the electric range of a BEV is exceeded during a driving day, the driver essentially has two choices:

1. That driving day could be driven by a gasoline vehicle instead. Much of the VMT above a range of ~100 miles is driven on days with driving significantly longer than 100 miles, so these days are relatively easy to anticipate and can be planned for.

2. The driving day could be driven as planned with the BEV, stopping to charge at a fast charge station when needed.

Method (1) would result in a usage factor similar to the utility factor above, but the remaining mileage would be driven with a different vehicle, so the VMT accumulation per year for the BEV would be lower than for other vehicles, and a replacement vehicle of some type would have to be created to fill in the missing VMT.



Source: Electric Power Research Institute analysis, based on data in National Household Travel Survey 2009.

Figure 13-31. *Utility Factors for Various Vehicle Ranges and Charging Scenarios*

	PHEV10		PHEV40		BEV100	
	Home	Ubiquitous	Home	Ubiquitous	Home	Ubiquitous
Utility Factor	27%	50%	65%	80%	100%	100%

Table 13-16. *Utility Factors Used in Analysis*

Method (2) would result in a usage factor of 1.0, so the vehicle would be driven the same number of miles per year as a conventional vehicle. This scenario is somewhat unrealistic, as it means that on some days drivers would be stopping 2 to 3 times to quick charge. Additionally, an adequate quick charging network does not exist, so this driving pattern would not be feasible. The reality is that the usage factor for BEVs is likely to be somewhere between the calculated utility factor and 1.0. Drivers with intensive transportation needs with frequent long driving days will likely not purchase BEVs. The remaining drivers, with less frequent long driving days, will be able to achieve most days within the range of the vehicle. Medium-distance driving days will likely be achieved with one quick charge or careful trip planning, and long driving days will likely be achieved using a different vehicle or through a different mode (like rail or airplane).

While some version of this combined scenario would probably be the best approach, the data and tools currently available do not provide this capability. Given these limitations, the utility factors calculated for the Electric Subgroup by EPRI use Method (2) above, so it is assumed that the BEV drives the same number of annual miles as a conventional vehicle and quick charges as needed. This assumption approximately doubles the demand for DC Fast Charging, versus one charge per day and then switching to a different vehicle, as in Method (1).

The resulting utility factors used in the integrated analysis are listed in Table 13-16.

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APPENDIX 13A:
METHODOLOGIES FOR DETERMINING CHARGING INFRASTRUCTURE REQUIREMENTS

This appendix describes by source the methodologies used to arrive at plug-in electric vehicle (PEV) charging infrastructure requirements.

ELECTRIFICATION COALITION

The Electrification Roadmap, developed by the Electrification Coalition in cooperation with PRTM, presented the forecast illustrated in Table 13A-1. Most notable is the downward trend of ratios over time, consistent with the view of many analysts that a larger up-front density is required to ease the anxiety associated with the BEV purchase decision. Other assumptions are sparse, but include the requirement that all PEVs require access to overnight charging.[55]

	2010	2020	2030
Expected Public Chargers per Vehicle	2.0	1.5	1.0
Maximum Public Chargers per Vehicle	2.5	2.0	1.5
Minimum Public Chargers per Vehicle	1.5	1.0	0.5

Table 13A-1. *Ratio of Chargers to PEVs*

EV PROJECT

The DOE-funded EV Project involves the deployment of 13,800 public and residential chargers to support up to 5,700 Nissan LEAF BEVs and 2,600 Chevy Volt PHEV40s, in six metropolitan areas. The program intends to gauge the effectiveness of infrastructure deployment, pilot revenue schemes for public and residential infrastructure, and apply lessons learned to future PEV deployment efforts. Project partner Ecotality issued a detailed report that used four primary approaches for determining Level 2 charging infrastructure coverage to support the program through 2020.[56] It is unique in that it details the rationale, methodologies, and underlying assumptions of its projections. A short description of each method follows.

The "Refueling" method targets the recharging needs of "a typical EV community" within the 50-mile radius of a typical metropolitan area, a radius based on the initial range performance of first-generation BEVs. The eTec report adopts the results of a Deloitte study suggesting publicly available EVSEs should at minimum match the coverage afforded by gas station availability today. Further, the EVSE footprint should be sufficient to maintain vehicle throughput such that wait-times are minimized, consequently placing greater emphasis on the number of dispensers (ports) at any given site over the number of recharging sites in a given area.

The "Geographic" method calculates charger density based on geographic coverage around the same 50-mile radius metropolitan area. It further assumes that workplaces are within the round-trip range of the BEV (approximately 100 miles), that no workplace charging exists, and that drivers will use side-trip destinations to recharge. It further assumes that drivers are willing to walk up to a quarter-mile to reach their destination. Density increases from the periphery to the metro center, but averages roughly 0.6 public charge ports per square mile. The report uses this approach to establish minimum infrastructure intensity needed to serve a targeted PEV community.

The "Destination" method attempts to quantify density as a proportion of common destinations such as airports, shopping malls, and theaters in a typical metro area. Using this method, the report arrives at 2.6 charge ports per square mile, which is equivalent to 1.12 public charge ports per BEV. The analysis assumes an initial coverage encompassing two-thirds of the 11,369 destination points cited, with further expansion accommodated by

55 Electrification Coalition, *Electrification Roadmap: Revolutionizing Transportation and Achieving Energy Security,* November 2009, http://www.electrificationcoalition.org/sites/default/files/SAF_1213_EC-Roadmap_v12_Online.pdf.

56 Electric Transportation Engineering Corporation (eTec, an Ecotality company), *Long-Range EV Charging Infrastructure Plan for Tennessee,* April 2010.

Year	Vehicles Fleet	Vehicles Residential	EVSE Fleet	EVSE Residential	EVSE Comm./ Public	EVSE Total	EVSE % EV Total
2011	3,692	14,767	2,474	11,841	41,053	55,340	300%
2012	7,895	48,496	5,289	37,342	113,966	156,598	278%
2013	11,308	130,048	7,577	96,235	256,194	360,005	255%
2014	17,840	252,467	11,953	176,727	416,570	605,250	224%
2015	26,367	420,536	17,666	281,759	609,778	909,203	203%
2016	34,335	652,360	23,004	410,987	815,451	1,249,442	182%
2017	43,782	951,258	29,334	570,755	1,093,946	1,649,035	170%
2018	55,166	1,323,972	36,961	754,664	1,403,411	2,195,036	159%
2019	70,031	1,772,896	57,644	1,151,930	2,349,937	3,559,511	153%
2020	86,036	2,303,860	57,644	1,151,930	2,349,937	3,559,511	149%

Table 13A-2. *Projected Cumulative EV and EVSE Penetration in the United States*

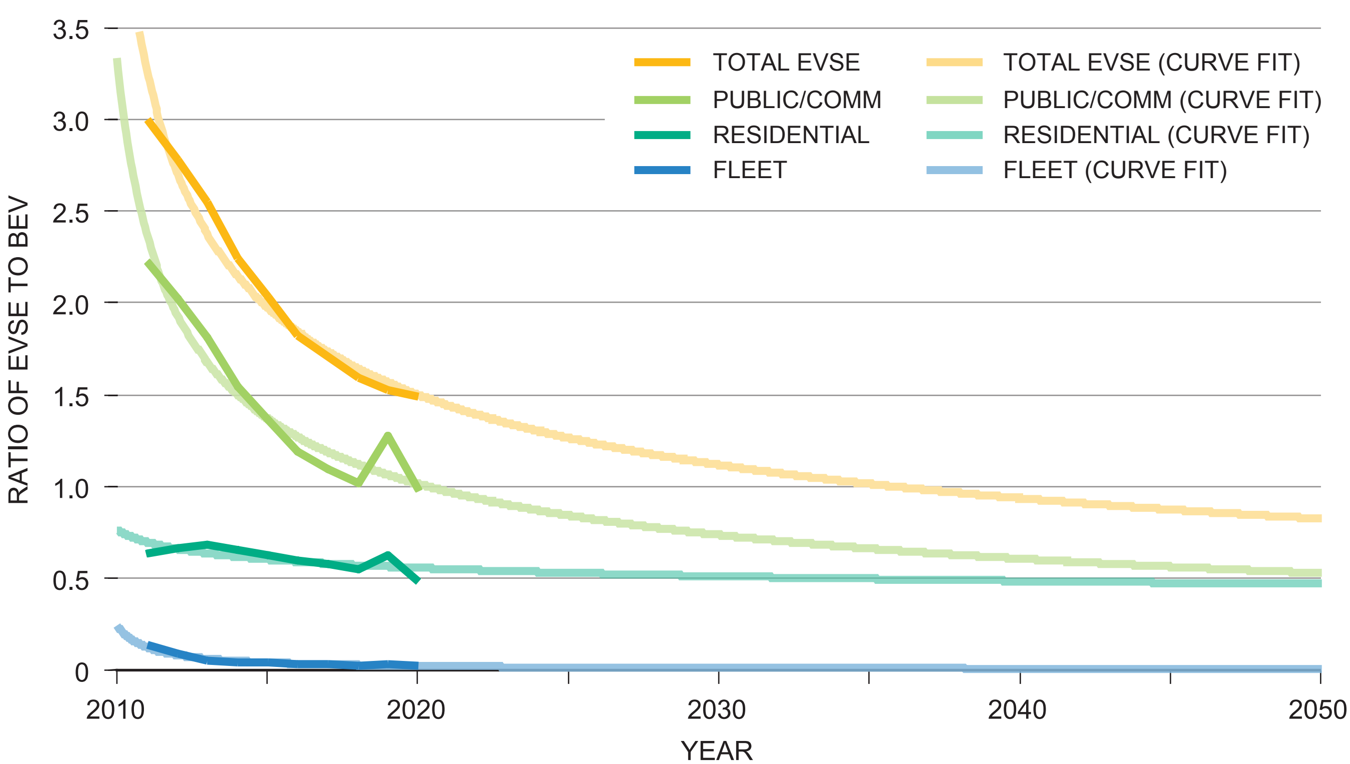

Figure 13A-1. *Projected Charging Supply Curve as a Function of the Ratio of EVSE Ports to BEVs through 2050* adding ports rather than additional refueling sites. The Electric Subgroup adjusted this figure for initial density downward after removing ATM locations from the calculus, as the consensus was that the dwell time would not be sufficient to support any useful charging benefit.

eTec advances a fourth and final approach it calls the “Rich EV Micro-climate” that is derived from the multiple methods discussed above.

To arrive at a supply curve that can be applied at the national level, eTec adapts BEV penetration forecasts derived from multiple available sources. These forecasts are provided in Table 13A-2 and assume that BEV penetration rates rise to approximately 500,000 BEV sales annually by 2020.

Plotting these points yields the suggested public charging supply curve as a function of the ratio of the number of EVSEs to non-fleet BEVs through the year 2020 (Figure 13A-1). Note that infrastructure densities start at relatively intense levels and taper as the market matures. While the quantity of EVSEs deployed increases through 2020, the ratio of EVSEs to PEVs decreases over time.

To establish additional data points for the model inputs, a simple curve fit was applied to the forecasts of each of the EVSE types to extend the trend out to 2050 where mature market conditions are presumed to exist. The result is shown in Figure 13A-1. Note that the “Total EVSE” curve represents the sum of the individual EVSE trend lines.

APPENDIX 13B:
ELECTRICITY RATES

Most residences have a fixed-fee consumption charge that is relatively simple: the cost per kilowatt-hour (kWh) is the same throughout the billing period and throughout the day, regardless of the time of day or how much energy has already been used. Many utilities, however, have shifted, or are in the process of shifting, to non-fixed rate schemes.

Block rates vary the cost of electricity depending on how much electricity has been used in a given period—typically monthly—and usually at an inclining rate, as illustrated in Figure 13B-1.

Time-of-use or time-of-day rates vary the cost of electricity at each hour of the day as illustrated in Figure 13B-2. The highest rates are typically from noon through late afternoon, corresponding with high electricity use for cooling.

There are also combined block and time-of-use rates. For example, the on-peak period may have a block component so that there is block pricing structure that applies between certain hours of the day. Table 13B-1 shows an example of a combined rate structure. Other adjustments on basic consumption charges include day type adjustments (where weekdays and holidays are metered at a different rate than weekdays) and seasonal adjustments where there are summer and winter differences, or four seasonal changes, or even cases where the rate structure changes each month.

Demand charges—the amount billed for the maximum current draw—also have block and time-of-use rates. The demand over a given billing period is usually set by the highest rate of energy consumption during any 15-minute period, although

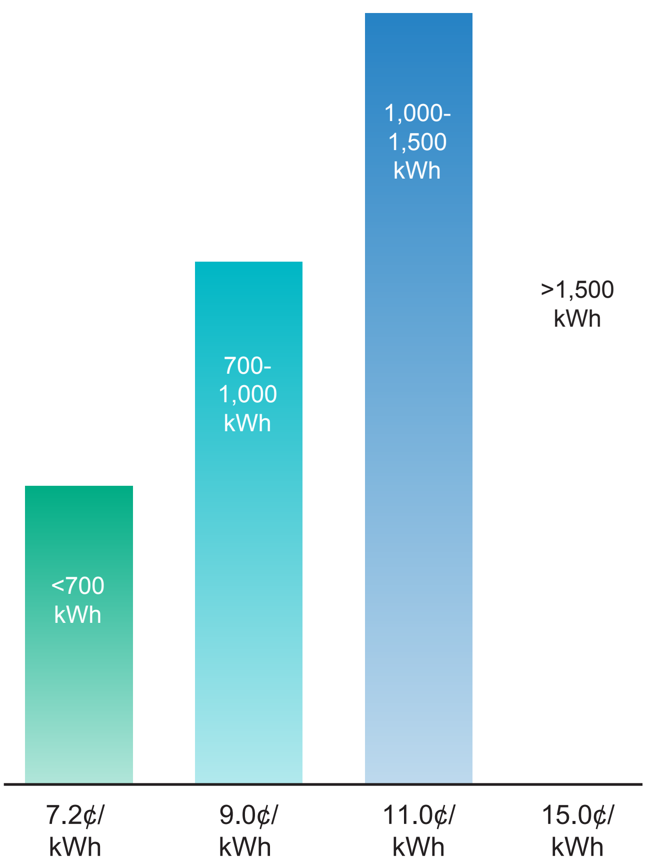

Figure 13B-1. *Example of Inclining Block Rate*

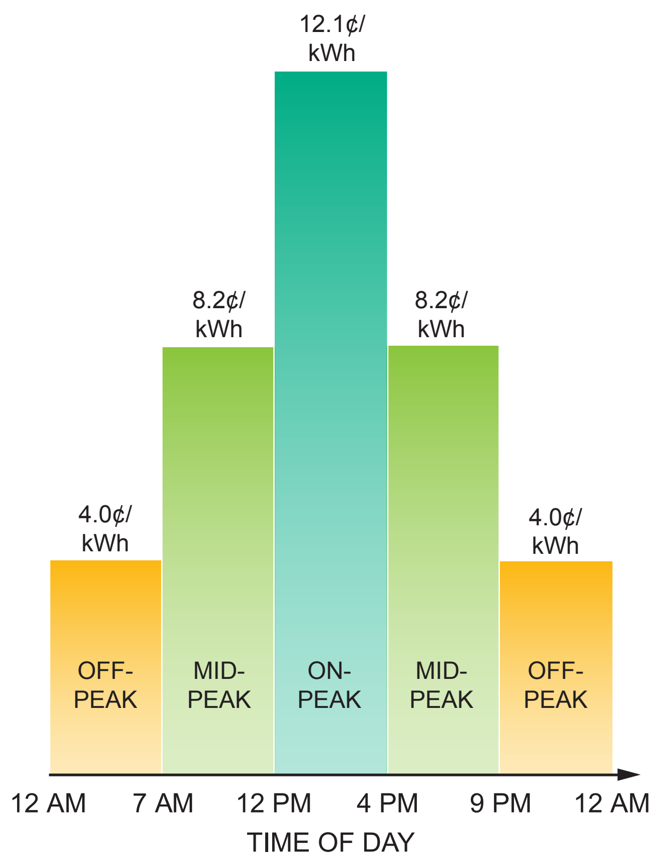

Figure 13B-2. *Example of Time-of-Use Rate* sometimes 30-minute or 60-minute intervals are used. The demand charges for a billing period are set by the highest demand at any point during that billing period. In some cases, the demand charges are ratcheted from month to month. This means that the peak demand charge can carry over from one month to the next, and sometimes even over the next year. There are many variations on this, such as having the demand charge for a given month be the greater of either the measured demand for that month or some percentage of the peak demand for any of the previous 11 months.

PEV specific rates are various rate schemes for PEVs being implemented or planned by many utilities. Table 13B-2 shows a proposed rate from Southern California Edison describing rates for residential customers for PEV charging. Here there are three types of plans available: a single meter with an inclining block rate, a single meter with seasonal combined time-of-use and block rates, and a dual-meter plan with seasonal time-of-use rates. Figures 13B-3 and 13B-4 show two rate options that are currently available to San Diego Gas & Electric customers.

Period	Rate	
On-peak	9.362¢ for first 2,500 kWh	On-peak is 9:30 am – 4:30 pm Monday through Friday except holidays
	12.48¢ for next 5,000 kWh	
	15.66¢ for anything above 7,500 kWh	
Off-peak	5.763¢ for first 1,700 kWh	All other periods are off-peak
	6.311¢ for next 1,300 kWh	
	8.210¢ for anything above 3,000 kWh	

Table 13B-1. *Example of Combined Time-of-Use and Block Electricity Rate*

a. Residential plan, single meter with block rate

Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
12 ¢/kWh	14 ¢/kWh	24 ¢/kWh	27 ¢/kWh	31 ¢/kWh

b. Home and electric vehicle plans, single meter with seasonal time-of-use and block rate

		Summer		Winter	
		Tier 1	Tier 2	Tier 1	Tier 2
On-Peak	10 AM – 6 PM, Weekdays	19 ¢/kWh	55 ¢/kWh	13 ¢/kWh	26 ¢/kWh
Off-Peak	All other hours	13 ¢/kWh	25 ¢/kWh	12 ¢/kWh	23 ¢/kWh
Super Off-Peak	Midnight – 6 AM	10 ¢/kWh	16 ¢/kWh	10 ¢/kWh	16 ¢/kWh

c. Electric vehicle plan, dual meter with seasonal time-of-use rate

	Summer	Winter
On-peak (Noon – 9 PM)	27 ¢/kWh	21 ¢/kWh
Off-Peak (9 PM – Noon)	11 ¢/kWh	11 ¢/kWh

Table 13B-2. *Example of Electric Vehicle Charging Rate from Southern California Edison*

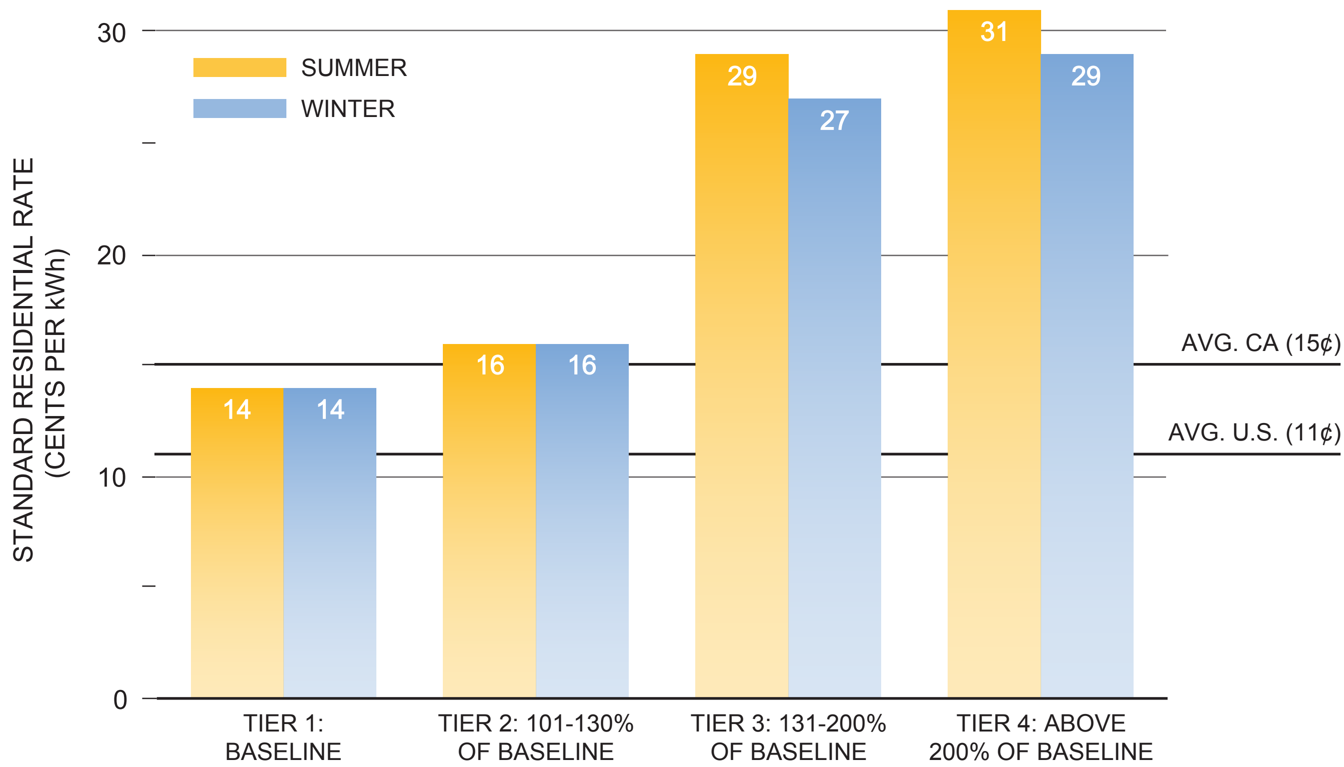

Figure 13B-3. *Example of Standard Residential Rates from San Diego Gas & Electric Company*

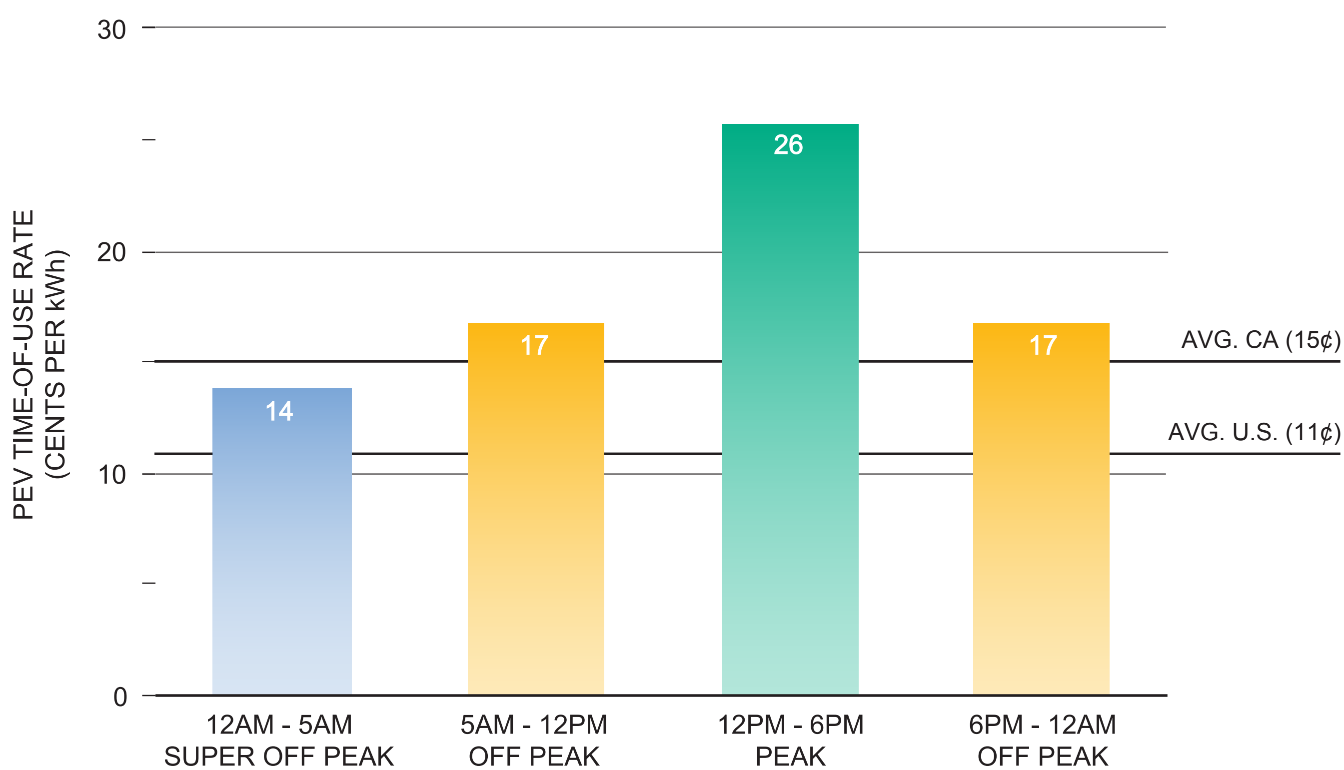

Figure 13B-4. *Example of PEV Time-of-Use Rates from San Diego Gas & Electric Company*