SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 2: The Plug-in Electric Vehicle Pathway

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While biofuels seem to represent the nearest-term answer to the demand for alternative fuels, electricity is closing in as a viable choice. Electric-drive technology continues to pique the imagination of motorists with its promise of clean skies, quiet cars, and plentiful fuel produced from nonpolluting domestic sources. In the designs they have dangled before us, automakers have shown us variations in plug-in electric vehicle (PEV) size, performance, and definition in efforts to overcome the fundamental challenge of electric drive: how to store energy and supply power. PEVs (a category that includes plug-in hybrid electric vehicles or PHEVs as well as battery electric vehicles or BEVs) are powered at least in part by electricity from the grid—a fuel that under certain conditions is less costly and more environmentally friendly than gasoline. Because vehicle electrification can improve the total energy efficiency (MJ/mile) of the vehicle and may allow lowering of the carbon intensity (gCO_2/MJ) of the fuel used in vehicles over time, PEVs offer a form of transportation with the potential for very low greenhouse gas (GHG) emissions.

PEVs have now entered the marketplace with models from several manufacturers. However, PEV technology has yet to achieve widespread market success. In this chapter we sort through the hype and improve understanding of the PEV pathway and what it will take to become competitive with internal combustion engine vehicles (ICEVs). We draw from several streams of research—including testing of battery technology, modeling of the electricity grid, and eliciting consumer data regarding PEV design interests and potential use patterns—to address these questions:

- What is the technical outlook for PEV technology and batteries?
- How will widespread charging of PEVs influence the operation and evolution of the electricity grid, and how does infrastructure need to develop for our transportation system to transition to the PEV pathway?
- What are the expected environmental impacts of electricity use for charging vehicles, and how can we minimize them?
- How do PEVs fit into long-term deep GHG-reduction scenarios?
- What policies and business strategies are needed to support PEVs in both the near and long terms?

CHALLENGES ON THE PEV PATHWAY

These complex technical and logistical challenges must be overcome if an electricity-based transportation system is to become widespread:

- **Technical challenges.** PEVs face high costs and limited all-electric range due to inherent energy storage limitations of batteries. There are also trade-offs among different battery chemistries regarding power, energy, cost, safety, and longevity. The present state of battery technology is sufficient for early market formation, but costs and range may need to improve for markets to expand.
- **Infrastructure challenges.** Current 110-volt recharge potential at home may be suitable for PHEVs and low-range BEVs. However, widespread commercialization of longer-range BEVs will require at-home 220-volt charging, and potentially workplace and public charging at 220 volts or higher. A significant fraction of people, mainly in urban areas, do not have access to off-street parking, which may limit adoption of PEVs.
- **Transition issues / coordination of stakeholders.** The electrification of transportation could start with giving consumers what they want: less technologically ambitious PHEVs. Near-term commercialization of such less-electrified PEVs could pave the way for future sales of longer-range BEVs by increasing manufacturing experience and whetting consumer appetites for PEVs. Utilities will need to provide the appropriate incentives to consumers to charge during less-expensive off-peak hours.
- **Policy challenges.** Policy makers could better support a gradual transition to electric-drive technology—for example, starting with greater hybridization and low-range PHEVs to stimulate further vehicle electrification in the future. However, policy should be sure to address well-to-wheel PEV emissions—that is, account for regional variations and future expectations of electricity grid carbon intensity. The role of PEVs and electricity needs to be examined in the context of a broader suite of vehicle and fuels-related policies (such as CAFE and the LCFS). California policymakers are already developing this portfolio of policies for transportation, as are other regions around the world.

Technology Status and Outlook

PEVs have followed a tortuous pathway of development. Spurred by disruptions in petroleum supply and price, and by policies on air pollution and climate change, much effort and many resources have been devoted to PEVs over the past three decades. In the United States, the Hybrid and Electric Vehicle Act of 1976 laid the groundwork for battery, motor, and power-and-control electronics technologies that emerged during the 1990s.[1] Battery electric vehicles garnered renewed attention in the 1990s, stimulated by General Motors' development of the EV-1 (a.k.a. Impact) and California's zero-emission vehicle (ZEV) mandate. Automakers eventually produced a limited number of BEVs in California to meet the modified ZEV Mandate. Then after years of further technology development and policy debate, policy makers were convinced by automobile manufacturers in the late 1990s that battery technology was not ready to meet manufacturers' EV performance goals. Some battery technologies, namely NiMH, later proved successful in less-demanding hybrid electric vehicles.

Today attention is increasingly turning toward PHEVs, which use both grid electricity and gasoline as fuels. Policymakers are increasingly giving attention to PEV pathways.[2] For instance, President Obama set a national target of 1 million PEVs on the road by 2015, and a federal tax credit is available, beginning in 2009, and will be in place for a number of years.[3] Several states offer additional advanced vehicle rebates and charging infrastructure subsidies.

Battery technology remains the largest technological challenge on the PEV pathway. Although breakthroughs in advanced battery chemistries since 2000 allow for more ambitious PEV designs than those available in the 1990s, important limitations remain. In this section we address those technological limitations and prospects for batteries and then consider them in light of the PEV design preferences expressed by potential PEV buyers in a survey. We also summarize key issues for other PEV components and recharge devices.

Battery technology goals, capabilities, and prospects

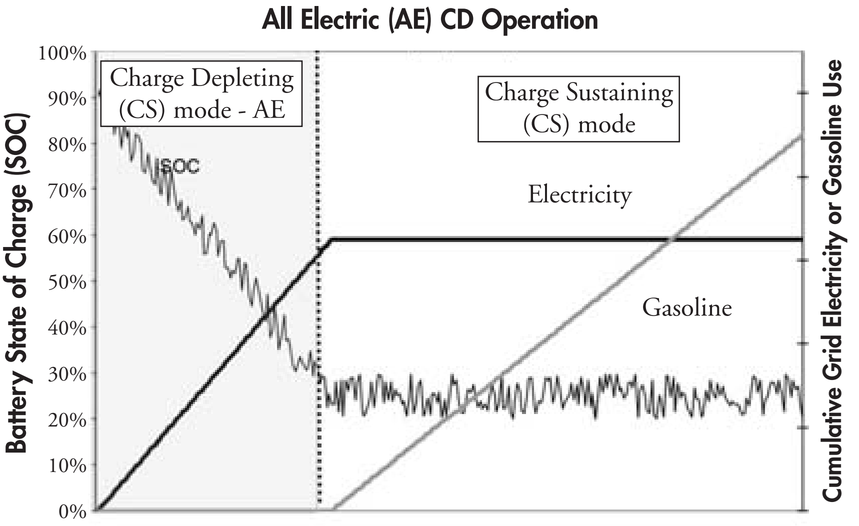
The commercial success of the PEV depends on the development of appropriate battery technologies. Much uncertainty exists about the battery parameters to best power a PEV and where different battery technologies stand in meeting such requirements. While electric-drive advocates claim that battery technology is sufficiently advanced to achieve commercial success, critics counter that substantial technological breakthroughs are required to realize mass market adoption. Further, there is disagreement on what a PEV is or should be.

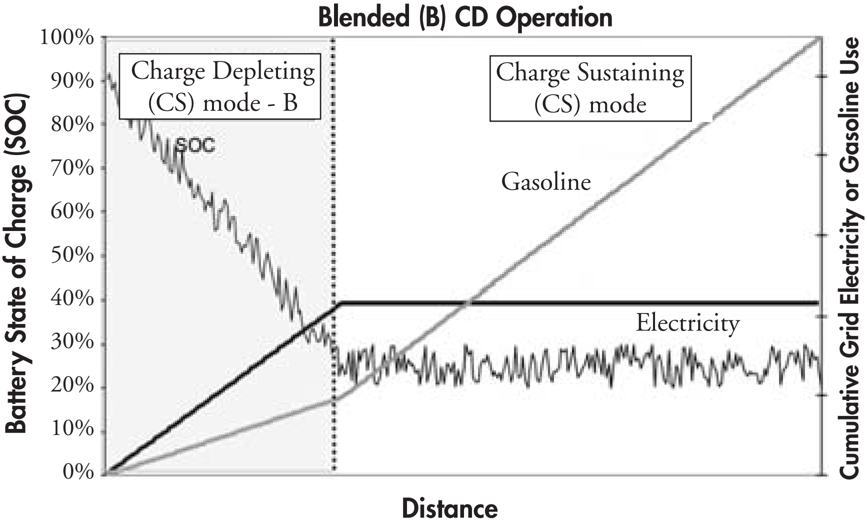
DIFFERENTIATING PEVS BASED ON THEIR BATTERY DISCHARGE PATTERNS

There are many different designs for PEVs based on their battery discharge pattern. Here's a breakdown of the differences:

- While a BEV is designed to operate only in charge-depleting (CD) mode, a PHEV can operate in CD *or* charge-sustaining (CS) mode. Driving the PEV in CD mode depletes the battery's state of charge (SOC), and CD range is the distance a fully charged PEV can be driven before depleting its battery. While a BEV would need to be recharged, a PHEV switches to CS mode, which then relies on gasoline energy as with a conventional HEV; the gasoline energy maintains the battery's SOC—but the vehicle does not use grid electricity until recharged.

- PHEVs can be further differentiated based on whether their CD mode is designed for all-electric (AE) operation (using only electricity from the battery) or for blended (B) operation (using both electricity and gasoline in almost any proportions). In this chapter, we denote CD range and operation for PHEVs as AE-X or B-X, where X is the CD range in miles. We use BEV-X to denote the range of electric vehicles.





This figure compares the battery discharge patterns of two different PHEVs, one with a CD mode designed for all-electric (AE) operation (top graph) and one with a CD mode designed for blended (B) operation (bottom graph), measured as state of charge (SOC) on the left axis. Holding CD range constant, an AE-X design requires more battery energy and power capacity and is thus costlier than a B-X design (for the same X). On the other hand, at any distance cumulative gasoline use will be higher in the B-X design for any vehicle trips that include a portion of CD driving. Source: Adapted from M. A. Kromer and J. B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, *LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007).*

The key requirements of PEV battery technology—power, energy capacity, durability, safety, and cost—depend on various assumptions about vehicle design. These factors include vehicle types (BEV versus PHEV), range in charge-depleting (CD) mode, and for PHEVs, type of CD operation (all-electric or blended), as well as use patterns.[4] The U.S. Advanced Battery Consortium (USABC) has set goals for batteries to be used in a PHEV with an all-electric range of 10 miles (AE-10) and one with an all-electric range of 40 miles (AE-40). Alternative targets have been suggested by the Sloan Automotive Laboratory at the Massachusetts Institute of Technology and the Electric Power Research Institute (EPRI). Here is a summary:[5]

Power: The rate of energy transfer is measured in kilowatts (kW) for automotive applications and typically portrayed as power density (W/kg) for batteries. Power goals range from 23 kW up to 99 kW, requiring densities between 380 and 830 W/kg.

Energy capacity: Battery storage capacity (kWh) relates to the size of the battery and its energy density (Wh/kg). (Note that there is an important distinction between available and total energy.

While a battery may have 10 kWh of battery storage capacity or total energy, only a portion of this capacity is available for vehicle operations. A battery with 10 kWh of total energy operating with a 65-percent depth of discharge would have only 6.5 kWh of available energy.) USABC goals range from 5.7 to 17 kWh of total energy, and from 100 to 140 Wh/kg.

Durability: With usage and time, battery performance—including power, energy capacity, and safety—can substantially degrade. Four measures are typically important: (1) calendar life, the ability to withstand degradation over time (15 years for USABC); (2) deep cycle life, the number of discharge-recharge cycles the battery can perform in CD mode (USABC's goal is 5000 cycles); (3) shallow cycles, state-of-charge variations of only a few percentage points, where the battery frequently takes in electric energy via a generator and from regenerative braking and passes energy to the electric motor as needed to power the vehicle (USABC targets 300,000 cycles); and (4) survival temperature range (USABC targets –46°C to +66°C).

Safety: Because batteries store energy and contain chemicals that can be dangerous if discharged in an uncontrolled manner, safety must be considered. Safety is typically measured through abuse tolerance tests, such as mechanical crushing, perforation, overcharging, and overheating.[6] USABC sets only the goal of "acceptability."

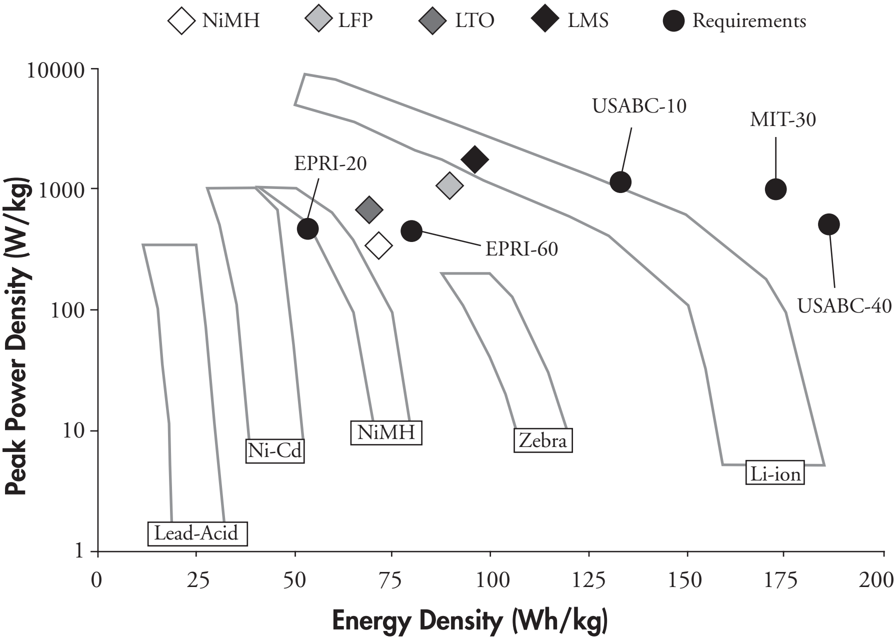
Cost: Although battery cost is thought to be one of the most critical factors in commercial PEV deployment, these costs are highly uncertain. USABC cost goals are $1,700 and $3,400 for AE-10 and AE-40 battery packs, respectively, under a scenario where battery production has reached 100,000 units per year, which equates to $200 to $300/kWh. The USABC estimates that in general, current advanced battery costs range from $800/kWh to $1000/kWh or higher. (See Chapter 4, Comparing Fuel Economies and Costs, for a look at how battery costs factor into the economic attractiveness of hybrid electric and plug-in hybrid electric vehicles in the future.)

There are inherent trade-offs among these attributes. Some existing battery technologies can achieve some of these goals, but meeting all goals simultaneously is far more challenging. For example, higher power can be achieved through the use of thinner electrodes, but these designs tend to reduce cycle life and safety while increasing material and manufacturing costs. In contrast, high-energy batteries use thicker electrodes that increase safety and life but reduce power density. Thus, it can be very difficult to meet ambitious targets for both power and energy density in the same battery, let alone also meet goals for longevity, safety, and cost. Understanding these trade-offs is key to understanding the requirements and challenges facing battery chemistries.

Currently, there are two main categories of battery chemistry that have been developed for electric drivetrains: nickel-metal hydride (NiMH) and lithium-ion (Li-ion). NiMH batteries are used for most HEVs currently sold in the United States, though some automatkers are starting to use Li-ion. The primary advantage of this chemistry is its proven longevity in calendar and cycle life, and overall history of safety, while drawbacks include limitations in energy and power density, and low likelihood of future cost reductions.[7] In contrast, Li-ion technology has the potential to meet the requirements of a broader variety of PEVs. Lithium is very attractive for high-energy batteries due to its light weight and potential for high voltage (while still falling short of the ambitious power targets of the USABC). Li-ion battery costs are predicted to fall as low as

$250–400/kWh with 100,000 units of production.[8] However, the high chemical reactivity of Li-ion provides a greater threat to calendar life, cycle life, and safety compared to NiMH batteries—thus, Li-ion batteries require a greater degree of control over cell voltage and temperature than do NiMH batteries.

POWER- AND ENERGY-DENSITY TRADE-OFFS FOR DIFFERENT BATTERY CHEMISTRIES



A Ragone plot represents the trade-offs between power density and energy density for a given battery chemistry. Power density (W/kg) is plotted on the vertical axis on a logarithmic scale. Energy density (Wh/kg) is presented on the horizontal axis for a specified discharge rate, say C/1 (complete discharge over 1 hour). Here the light gray bands represent the current power and energy capabilities of an individual battery cell of each of five different chemistries: lead-acid, nickel-cadmium, NiMH, ZEBRA, and Li-ion. The USABC, MIT, and EPRI battery requirements are plotted as black circles. The diamonds represent the performance of four PHEV batteries tested at UC Davis: one NiMH, and three Li-Ion.

Battery specifications assume a motor efficiency of 85 percent, a packaging factor of 0.75, and an 80-percent battery depth of discharge (DOD). The battery pack (or system) designed for a particular PHEV consists of many individual battery cells, plus a cooling system, inter-cell connectors, cell monitoring devices, and safety circuits. The added weight and volume of the additional components reduce the energy and power density of the pack relative to the cell. In addition, the inter-cell connectors and safety circuits of a battery pack can significantly increase resistance, decreasing the power rating from that achievable by a single cell. When applying cell-based ratings to a battery pack, and vice *versa, a packaging factor conversion must be applied. There is typically a larger reduction for power density—and thus a smaller packaging factor—than energy density due to added resistance, in addition to the added weight. We assume an optimistic packaging factor of 0.75 for each conversion. Source: Ragone plots from Kromer and Heywood,* Electric Powertrains. *Figure adapted from J. Axsen, K. S. Kurani, and A. F. Burke, "Are Batteries Ready for Plug-in Hybrid Buyers?"* Transport Policy *17 (2010): 173–82.*

More important than this current snapshot are the long-term prospects for improvements to Li-ion batteries. Li-ion batteries can be constructed from a wide variety of materials and vary by electrolyte, packaging, structure, and shape. The main Li-ion cathode material used for consumer applications (such as laptop computers and cell phones) is lithium cobalt oxide (LCO). But there are safety concerns about using this chemistry for automotive applications, so several alternative chemistries are being piloted, developed, or researched for PEVs, including lithium nickel, cobalt, and aluminum (NCA); lithium iron phosphate (LFP); lithium nickel, cobalt, and manganese (NCM); lithium manganese spinel (LMS); lithium titanium (LTO); and manganese titanium (MNS). The attributes of any one of these chemistries may not represent Li-ion technology in general, and no single chemistry excels in all five requirement categories.

COMPARISON OF ALTERNATIVE CHEMISTRIES FOR PEV BATTERIES

A comparison of alternative chemistries for PEV batteries shows that no single chemistry excels in all five requirement categories. Trade-offs are necessary.

Name	**Description**	**Automotive Status**	**Power**	**Energy**	**Safety**	**Life**	**Cost**
NiMH	Nickel-metal hydride	Commercial production	Low	Low	High	High	Mid
LCO	Lithium cobalt oxide	Limited production	High	High	Low	Low	High
NCA	Lithium nickel, cobalt, and aluminum	Limited production	High	High	Low	Mid	Low
LFP	Lithium iron phosphate	Pilot	Mid- High	Mid	Mid-High	High	Low
NCM	Lithium nickel, cobalt,	Pilot	Mid	Mid-High	Mid	Low	High
LMS	Lithium manganese spinel	Development	Mid	Mid-High	Mid	Mid	Low-Mid
LTO	Lithium titanium	Development	High	Low	High	High	Mid
MNS	Manganese titanium	Research	High	Mid	High	?	Mid

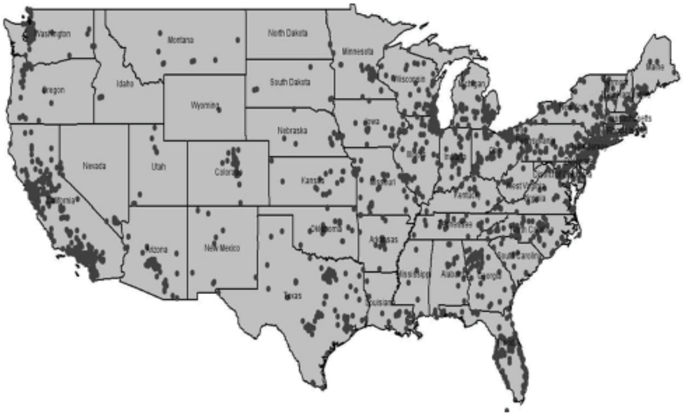
Qualitative assessment by A. Burke at UC Davis, July 2010. Source: J. Axsen, A. Burke, and K. Kurani, "Batteries for PHEVs: Comparing Goals and the State of Technology," in Electric and Hybrid Vehicles: Power Sources, Models, Sustainability, Infrastructure and the Market, *ed. G. Pistoia (New York: Elsevier, 2010).*

Consumer-informed goals and the "battery problem"

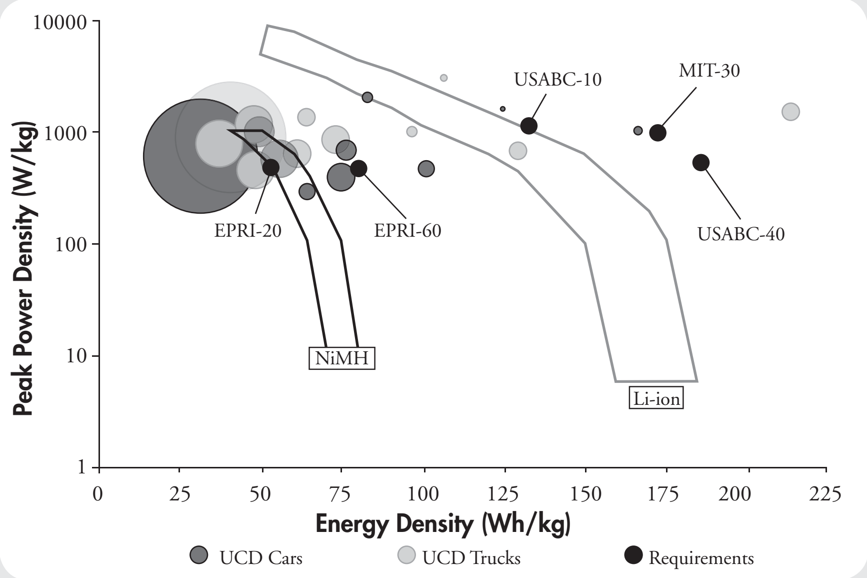
Our summary of USABC goals and the capabilities of battery chemistries suggests there is a battery problem—that the inadequate performance and high cost of available battery technologies are the main barriers to the commercialization of electric passenger vehicles with plug-in capabilities. But how does the state of battery technology compare to what consumers actually want from PHEVs? STEPS researchers investigated this question in a web-based survey of a representative sample of new-vehicle-buying households in the United States in which consumers could create their own PHEV designs and thus set their own PHEV goals.[9]

ANTICIPATING THE PHEV MARKET WITH A CONSUMER SURVEY

To arrive at consumer-informed PHEV design goals and estimates of use behavior, STEPS researchers conducted a web-based survey in 2007 with a representative sample of 2,373 new-vehicle-buying households in the United States. The survey was implemented in three separate pieces, requiring multiple days for households to answer questions, conduct a review of their own driving and parking patterns, and then complete a sequence of PHEV design exercises.



The sample was deemed representative of U.S. new car buyers according to geographic distribution, as well as income, age, education, and other sociodemographic variables. Source: J. Axsen and K. S. Kurani, "Early U.S. Market for Plug-in Hybrid Electric Vehicles: Anticipating Consumer Recharge Potential and Design Priorities," Transportation Research Record *2139 (2009): 64–72. Design choices presented to survey respondents included charge-depleting (CD) operation—all-electric or three levels of blended operation—and CD ranges of 10, 20, or 40 miles. The design space also offered respondents a choice of recharge times (8 hours, 4 hours, 2 hours, or 1 hour) and charge-sustaining fuel economy (+10, +20, or +30 MPG over a conventional vehicle). This offered respondents a choice of 144 possible combinations for cars and again for trucks. We focus here on results from the 33 percent of respondents we identify as "plausible early market respondents": those who currently have 110V recharge potential at home and who demonstrated interest in purchasing a PHEV even at a relatively high price.*



This Ragone plot summarizes the PHEV designs selected by our potential early-market PHEV buyers. The region bounded in black represents a range of NiMH capabilities and the region bounded in gray represents Li-ion chemistries. For comparison, we also plotted the battery cell requirements derived by USABC, MIT, and EPRI. The centers of the gray circles mark the location of the peak power density and energy density requirements derived from the respondents' designs; the sizes of the gray circles are proportional to the number of respondents who chose or designed the PHEV corresponding to those battery requirements. In contrast, the black circles marking the location of the USABC, MIT, and EPRI requirements have been sized solely to make them perceptible in the figure. What we see is that potential buyers have different requirements from those specified by USABC and MIT; they are closer to the EPRI goals, and especially the EPRI-20 goal. Source: Axsen et al., "Are Batteries Ready for Plug-in Hybrid Buyers?"

A substantial number of new-vehicle-buying households reported that they would like to buy vehicles with plug-in capabilities. The majority of these potential early market respondents selected the most basic PHEV design option: a B-10, requiring the lowest power and energy densities. Even including respondents who designed more demanding PHEVs, about 85 percent of the potential early buyers designed PHEVs that required peak power density and energy density within the current capabilities of NiMH batteries. In contrast, experts' projected PHEV designs all result in much higher peak power and energy density requirements, most of them seemingly beyond the present capabilities of Li-ion batteries.

The bottom line is that given consumers' preferred PHEV designs, the experts' aggressive battery technology goals may be unnecessary for near-term PHEV commercialization. To put it another way, the real battery problem may be better summarized as the challenge of aligning technological development with distribution of consumer interests in the near and long terms.

Other PEV components

The drivetrain configuration of a battery electric vehicle is relatively simple in that it consists of only a few components: electric motors, power electronics (a DC/AC inverter), a motor controller, and a battery pack. PHEVs are more complex in that they integrate an internal combustion engine and potentially a transmission into the drivetrain as well as the EV components. There is a great deal of design freedom for PHEVs in terms of the size and configuration of the various components (hardware) and the operation and control of these components during different types of driving (software).

While the individual component technologies beyond the batteries are relatively mature, the vehicle design, integration, and controls are the major areas for innovation and value added by the automakers. There will be a great deal of innovation in this arena over the next decade as we move from prototype vehicles in labs to commercial, mass-market vehicles that will attempt to appeal to regular drivers rather than just early adopters.

Infrastructure for PEVs

While the success of PEVs largely hinges on the development of robust, low-cost batteries that match consumer needs, the fueling and infrastructure side of the equation is also important. A key consideration is the present state and future prospects of recharge infrastructure to allow PEV recharging at home, work, and other locations. We must also consider the ability of the electrical grid to handle additional demand and anticipate the temporal and spatial distribution of charging behavior. This section discusses electricity demands for PEV charging and their potential interaction with the electricity grid and how costs and emissions depend on the quantity, location, and timing of vehicle electricity demands.

Charger technology

Electric vehicles need to be plugged in to recharge the vehicles' batteries. While current PEVs can plug into a conventional home 110V outlet, recharging this way takes a long time for BEVs and longer-range PHEVs (for many PHEVs, this will be sufficient). To recharge more quickly, it is necessary to use higher voltage (220V or higher) coupled with a PEV charger (also known as electric vehicle supply equipment or EVSE).

There are several categories of charging (Levels 1 through 3), depending on the voltage and power supplied to the vehicle. The EVSE designs that will allow for faster, higher-power charging will have higher costs, not only for the equipment but also for the electrical connection and installation. And batteries are charged with DC power, requiring conversion of AC to DC either onboard the vehicle or in the EVSE.

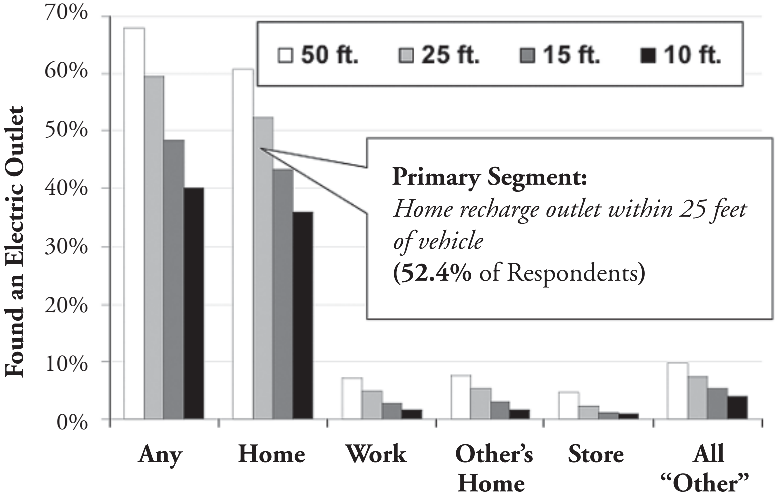
Public charging stations are expected to be relatively high power (Level 2) in order to allow for reasonable charging times for drivers. Very high power chargers (Level 3) will allow for significant recharging (perhaps 80 percent of battery capacity) in under half an hour.

The demand side: Anticipating recharge potential, timing, and location

To better understand the present state of charging infrastructure for PEVs, the 2007 PHEV survey also assessed respondent access to 110V electrical outlets over the course of one day of driving their conventional vehicle. As noted earlier, 110V outlets may be appropriate for PHEV recharging, while higher voltage will likely be necessary for most users of BEVs. However, 110V access may serve as a stand-in for proximity of access to circuits that may be upgraded to house 220V infrastructure or higher.

Survey results indicate that more new vehicle buyers may be pre-adapted for vehicle recharging than estimated in previous constraints analyses. Our study was different because it elicited reports of vehicle parking proximity to electrical outlets (not circuits), directly from respondents instead of via proxy data. About half of our U.S. new-vehicle-buying respondents have at least one viable 110V recharge location within 25 feet of their vehicle when parked at home. But this also means that approximately half do not have access to charging, perhaps because they park in an apartment parking lot or on the street, which is an important barrier to achieving high levels of PEV adoption. Only 4 percent of respondents found 110V outlets at work, and 9 percent found 110V outlets at other nonhome locations—for example, at a friend's home, school, and commercial sites. When we aggregated recharge potential across this sample, we found that total recharge potential ranges from more than 90 percent of respondents from 10:00 p.m. to 5:30 a.m., to less than 30 percent from 11:30 a.m. to 1:30 p.m. Throughout the day, home is by far the most frequent location of recharge opportunities for respondents.

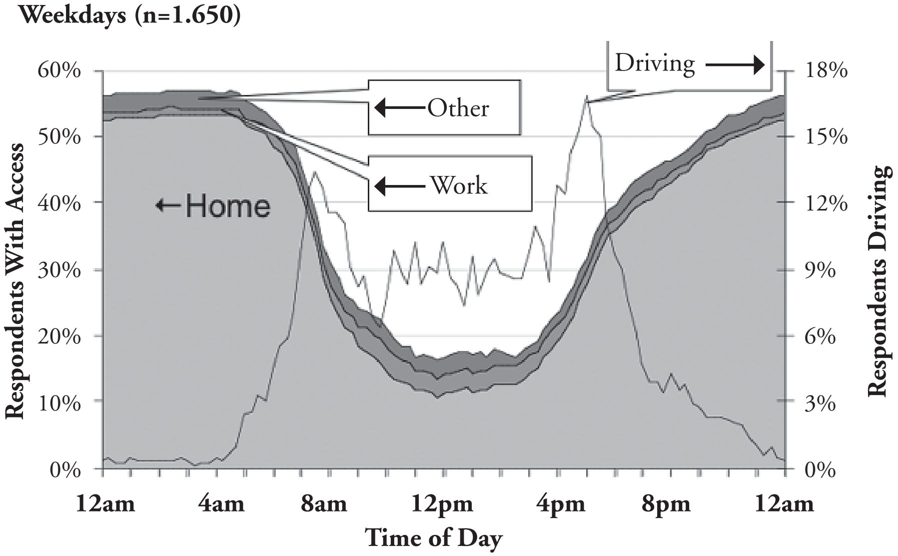
ACCESS TO 110V RECHARGE SPOTS BY LOCATION AND OUTLET DISTANCE



Primary Segment:
Home recharge outlet within 25 feet of vehicle
(52.4% of Respondents)

About half of our 2,373 U.S. new-vehicle-buying survey respondents have at least one viable 110V recharge location within 25 feet of their vehicle when parked at home. Only 4 percent of respondents found 110V outlets at work, and 9 percent found 110V outlets at other nonhome locations. Source: J. Axsen and K. S. Kurani, "Early U.S. Market for Plug-in Hybrid Electric Vehicles: Anticipating Consumer Recharge Potential and Design Priorities," Transportation Research Record *2139 (2009): 64–72.*

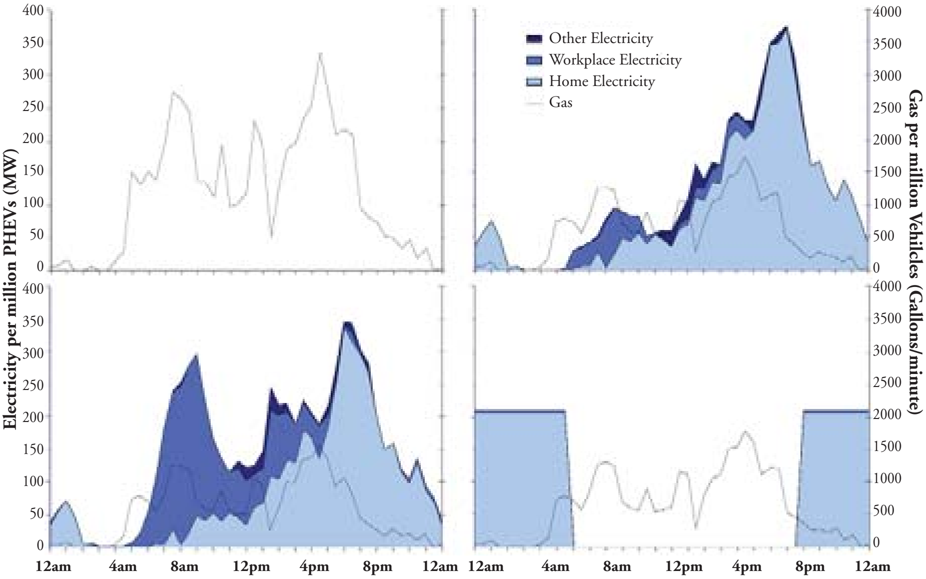
DRIVING AND RECHARGE POTENTIAL BY TIME OF DAY



When we aggregated recharge potential across the 2,373 U.S. respondents, we found that total recharge potential ranges from more than 50 percent of respondents from 9:00 p.m. to 7:00 a.m., to fewer than 20 percent from 10:00 a.m. to 3:00 p.m. (weekdays only). Source: J. Axsen and K. S. Kurani, The Early U.S. Market for PHEVs: Anticipating Consumer Awareness, Recharge Potential, Design Priorities and Energy Impacts*, UCD-ITS-RR-08-22 (Institute of Transportation Studies, University of California, Davis, 2008).*

STEPS researchers integrated this consumer data to construct consumer-informed profiles representing the potential electrical demand of PEVs in California. Results suggest that the use of PHEV vehicles could halve gasoline use relative to conventional vehicles. Using three scenarios to represent plausible recharge patterns (immediate and unconstrained recharging, universal workplace access, and off-peak only), we assessed trade-offs between the magnitude and timing of PHEV electricity use. In the unconstrained recharge scenario, recharging peaks at 7:00 p.m., following a pattern throughout the day that is far more dispersed than anticipated by previous research. PHEV electricity use could be increased through policies that expand nonhome recharge opportunities (for example, the universal workplace access scenario), but most of this increase occurs during daytime hours and could contribute to peak electricity demand. Deferring all recharging to only off-peak hours (8:00 p.m. to 6:00 a.m.) could eliminate all additions to daytime electricity demand from PHEVs, although less electricity would be used and less gasoline displaced in this scenario.

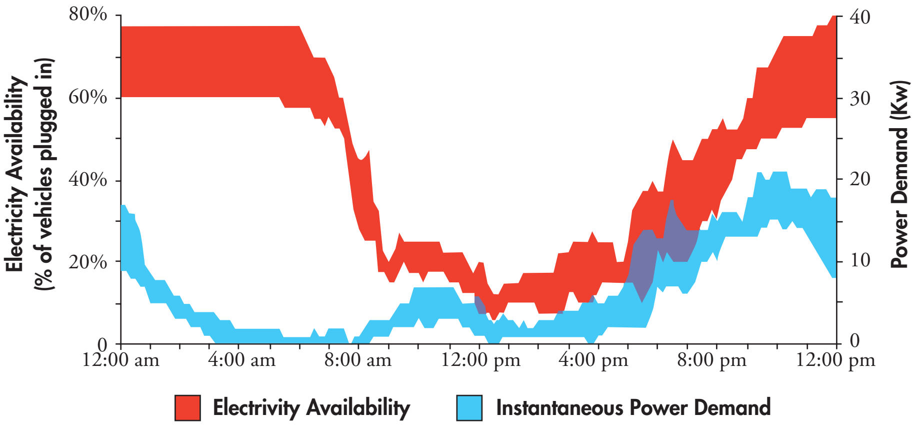
CONSUMER-INFORMED PROFILES OF GASOLINE USE AND GRID ELECTRICITY RECHARGE



Based on the responses of 231 "early-market respondents" in California (consisting of those who identified an electrical outlet within 25 feet of where they park their vehicle at home and demonstrated interest in purchasing a PHEV in the survey described earlier in this chapter), STEPS researchers constructed four scenarios for weekday gasoline use and grid electricity recharging. A is "no PHEVs," B is "plug and play," C is "enhanced workplace access," and D is "off-peak only." Source: J. Axsen and K. S. Kurani, "Anticipating Plug-in Hybrid Vehicle Energy Impacts in California: Constructing Consumer-Informed Recharge Profiles," Transportation Research Part D *15 (2010): 212–19.*

STEPS researchers also investigated PHEV recharge behavior by observing participants in a PHEV demonstration project in northern California. A total of 40 households took part in the project. Each household used a Toyota Prius converted to a PHEV (B-30) in place of one of their vehicles for a four-to-six-week trial. The resulting distribution of recharge potential and actual electricity use showed a broad weekday peak between 6:00 p.m. and midnight—during which period behavior varied substantially across respondents. The range of behaviors supports the contention that the success of PEVs in meeting energy and emission goals depends on PEV users' recharging and driving behavior as much as or more than on vehicle design.

OBSERVED HIGH AND LOW WEEKDAY ELECTRICITY AVAILABILITY AND POWER DEMAND



The power demand of the 40 households participating in a PHEV demonstration project in northern California showed a broad weekday peak between 6:00 p.m. and midnight—during which period behavior varied substantially across respondents. Source: J. Davis and K. Kurani, "Recharging Behavior of Households' Plug-In Hybrid Electric Vehicles: Observed Variation in Use of Conversions of 5-kW-h Blended Plug-In Hybrid Electric," Transportation Research Record *2191 (2010): 75–83.*

Of course, recharge behavior concerning PEVs may differ substantially from that of actual and hypothetical PHEV drivers. As the market develops, utilities may offer incentives to motivate charging at off-peak, lower-cost rates as well as prevent charging that adds to peak demands and the need for additional power plants to be built. Recharging infrastructure availability will also play a role in where and when drivers charge their PEVs.

SPATIAL ANALYSIS OF EV ACTIVITY AND POTENTIAL FAST-CHARGE LOCATIONS

STEPS researchers conducted spatial research in an attempt to understand the limitations of electric vehicle range and potential for charging by comparing them to gasoline range and activity. This research explores questions such as: How important is range to the consumer? To what extent can an EV replace a gasoline vehicle? How would placement of fast chargers provide value to the customer?

The figure below represents the response of a single EV owner in San Diego to questions about where he drives his EV and where he drives his gasoline vehicle. The respondent never drove beyond the boundary of a small "activity space" near home in his EV. When asked which destinations he expected to be able to reach in his gasoline vehicle, he indicated a large area encompassing much of southern California as well as the

Lake Tahoe region and San Francisco. In response to the question of where he would like to place any number of fast chargers, he indicated only two locations, one to give him access to the Los Angeles area and one to help with range considerations within his existing EV activity space. It should be noted that this respondent had very limited access to charging away from home and had in fact never done it.

While conclusions cannot be drawn from a single response, this response highlights several themes surrounding electric vehicle range and charging. First, even though the EV activity space was significantly smaller than the gasoline activity space, the EV activity space represented a stated 90 percent of the respondent's driving. Further, meeting the need for this 90 percent of his driving resulted in the respondent being happy with the vehicle and satisfied with the range. The reason for not using the EV for the remainder of his driving could have been range limitations or cargo and passenger space.

The placement of fast chargers was also illustrative and highlights the concepts of intensification and extensification. In this context, *intensification* refers to the placement of chargers within a driver's EV activity space in order to recharge if the battery happens to be low. *Extensification* is the placement of chargers outside of the driver's primary EV activity space to enable travel outside of those boundaries. The respondent indicated that one of each type would be useful.

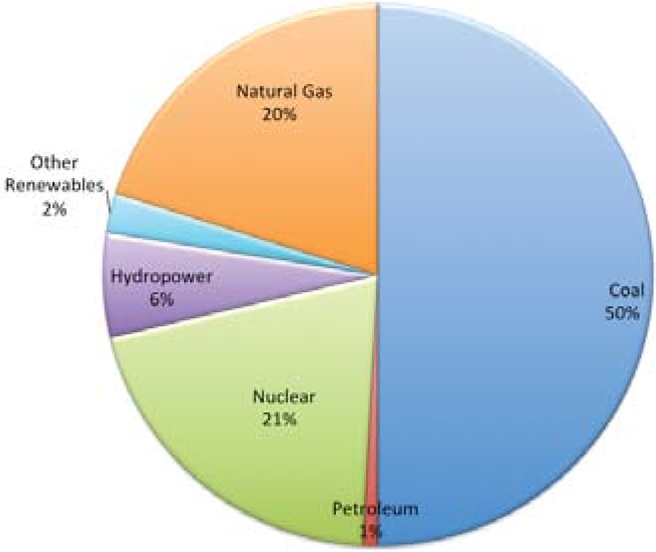
It is interesting to note that the respondent did not place fast chargers all along the highway to northern California. The implication is that an EV may not be seen as a viable substitute for a gasoline vehicle for long trips. The respondent only indicated that the immediately adjacent metropolitan area was a place he desired to go in his EV. Enabling travel along the corridor between adjacent metropolitan areas or metropolitan areas within 50 to 80 miles seems to be another oft-mentioned desire of EV owners.

The response of one EV owner in San Diego to questions about where he drives his EV and where he drives his gasoline vehicle highlight themes surrounding EV range and charging. The respondent never drove beyond the boundary of the small black "activity space" near home in his EV. When asked which destinations he expected to be able to reach in his gasoline vehicle, he indicated the large gray area encompassing much of southern California as well as the Lake Tahoe region and San Francisco.

The supply side: Generating and delivering electricity for PEVs

Charging a PEV requires the grid to respond by providing more electricity. STEPS researchers have worked to better understand the electricity grid—the collection of power plants and transmission and distribution facilities that produces and delivers electricity to end users. The grid has evolved to meet continually changing electricity demands by using a suite of power plants that fulfill various roles in the grid network. Each type of power plant operates differently: baseload facilities (often large coal or nuclear plants) are designed to operate continuously and at low cost, and peaking power plants (often fired with natural gas or oil) are operated only a handful of hours per year when demand is highest and are more costly to operate. The mix of power plants that make up the grid varies significantly from one region to another—based on local demand profiles, resource availability and cost, and energy policy.

U.S. ELECTRICITY GENERATION BY RESOURCE TYPE, 2008



In 2008, 70 percent of the electricity in the United States was generated from fossil fuels (coal and natural gas). Hydropower and other renewables represented only 8 percent, but this percentage is growing. Source: Energy Information Agency, U.S. Department of Energy, Annual Energy Outlook *2010.*

While fossil fuels (mainly coal and natural gas) account for 70 percent of U.S. electricity generation, the level of renewable generation is increasing. More than half of U.S. states and several European countries have a renewable portfolio standard (RPS), which mandates renewably based electricity generation. However, renewable resources are limited in quantity, temporal availability, and reliability. Intermittent renewables, such as solar and wind, can pose additional challenges to integration into the grid.

Vehicle recharging will impact the grid in both the immediate and long terms. In the near term, recharging vehicles will require additional electricity to be generated, although there is a large amount of excess capacity at night. A large number of PEVs will need to be driven in a region before power plants are operated differently or new ones are required. For example, adding 1 million PEVs in California (out of 26 million vehicles) increases total electricity consumption in the state by only about 1 percent.[12] Over time, as greater numbers of PEVs are introduced, their impact on the grid will increase. If each of the 240 million registered light-duty vehicles in the United States were charged at a rate of 5 to 10 kWh per day, an additional 12 to 23 percent of electricity generation would be required. However, if most PEVs were coordinated to charge overnight, additional capacity requirements could be much lower.

Typical U.S. households consumed approximately 11,000 kWh annually in 2001. If each household charged a PEV with 5 to 10 kWh of electricity once per day, this could add 21 to 43 percent (2200 to 4600 kWh) per year to the household electricity load, comparable to average central air conditioning and refrigeration loads.

Several studies show that existing grid capacity (including generation, transmission, and distribution) can fuel a significant number of PEVs in the U.S. light-duty vehicle fleet.[12] But specific points along some distribution lines may face congestion if local patterns of electricity demand change significantly because of vehicle recharging. At the substation and feeder levels, where demands are less aggregated—and as a result more variable and sensitive to the patterns of a few customers—distribution impacts are important. If many consumers in a given circuit recharged their plug-in vehicles simultaneously (for example, in the early evening after work), it could increase peak demand locally and require utilities to upgrade the distribution infrastructure.

The mix of power plants supplying a region is largely a function of peak demand and the hourly demand profile. Peak demand determines the total installed power plant capacity needed to supply a region, while the hourly demand profile determines the best mix of plants. Charging off-peak will flatten the demand profile, improving the economics of baseload and intermediate power plants and lowering average electricity costs. Charging at peak demand times will increase capacity requirements, while lowering the utilization of existing plants and increasing electricity costs. If charging could be controlled to occur when it was most optimal, PEV demand could respond to grid conditions. Given that cars are parked approximately 95 percent of the time[13] and potentially plugged in for a large fraction of the time they are parked, this is a real possibility.

One framework for understanding how PEVs can impact the electricity grid is based on the concept of passive and active grid elements (for example, generators and loads). Passive elements are imposed on the system and do not readily respond to grid conditions. Active elements can be controlled and utilized when optimal (i.e. "demand response" utility programs). Baseload and intermittent generators are passive, since they cannot easily turn on or off, or up or down, in response to changes in demand. Active generators can be operated to follow or match demand. Most electricity demand is passive, as it is imposed instantaneously on the electric system by millions of individual customers and not easily controlled. But electricity demand for some loads, including plug-in vehicles, can be active. The timing of recharging demand is controllable, because energy is stored onboard the vehicle in batteries, and vehicle travel is temporally separate from the time when recharging occurs.

The grid manages active and passive elements in real time to match supply and demand. Traditionally, the grid has consisted of passive electric demands, which require precise matching by active generation, such as dispatchable natural gas power plants. But active loads, such as those from plug-in vehicles, may be used to match passive elements, potentially reducing the need for active generation. Additionally, plug-in vehicles can enable the deployment of intermittent renewable generators, such as wind or solar. Since these passive generators are highly variable, they must be matched by standby active generation, typically natural gas-fired generators that are utilized when the renewable resource is unavailable. But aggregated active loads from plug-in vehicles could also be used, potentially reducing the required number of standby power plants and decreasing the costs associated with integrating intermittent power on the grid.

The smart grid, incorporating intelligence and communication between the supply and demand sides of the electricity equation, is needed in order to realize the full benefits of this vehicle charging flexibility. Managing vehicle recharging requires a smart charging system that enables communication between the customer and utilities. Consumers may give the utility greater control in exchange for lower rates. This type of charging interface can also permit vehicle charging emissions to be appropriately tracked and allocated, which will become increasingly important as states and countries adopt low-carbon fuel standards and impose caps on GHG emissions in different sectors.

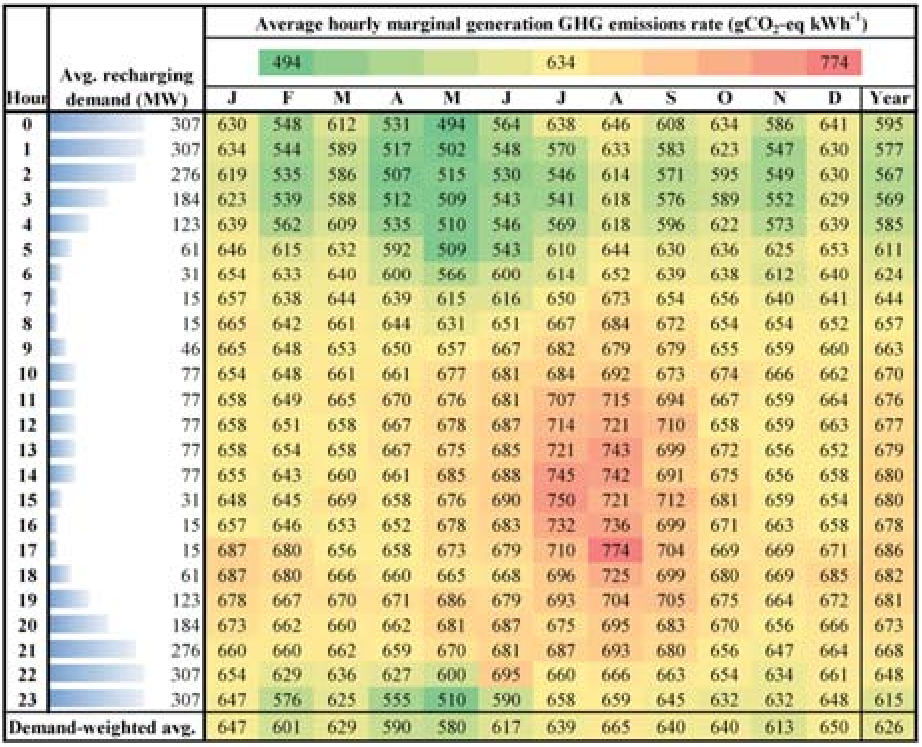
While recharging vehicles during off-peak hours is preferable from a grid operations and cost perspective, off-peak recharging may not always be preferable to all stakeholders. For example, a consumer may be able to avoid a trip to the gas station by recharging during the day, and though this may be more costly than charging off-peak (the cost of peak electricity can be three times or more higher than off-peak power), it may still be cheaper and less polluting than operating the vehicle on gasoline. Some companies may even incentivize daytime recharging by offering recharging stations at the workplace or other public locations around town.

Environmental Impacts of PEV Use

The environmental impacts of PEVs need to be analyzed on a well-to-wheels (fuel production and end usage) basis to fully account for their operational differences. The generation of electricity accounts for the bulk of emissions from PEV use. Thus, characterizing the emissions associated with electricity generation and distribution is important in quantifying the environmental impacts of operating these plug-in vehicles. This requires an understanding of which power plants are operating during vehicle recharging that would not be generating power otherwise, also known as the marginal generation. Emissions from marginal power plants often differ significantly from the average emissions of all plants operating at a given time. STEPS researchers have developed a model of electricity dispatch (which determines which power plants are operating at any given hour and demand level) for the state of California in order to assess the environmental impacts of different timing profiles of PEV recharging.

Emissions attributable to PEVs depend on the regional characteristics of the grid and the magnitude and timing of demand. A commonly held assumption (which contrasts with the consumer-informed recharge profiles shown earlier) is that vehicle recharging is likely to occur at night, during off-peak hours. If coal power plants (~1000 gCO_2/kWh) provide marginal generation for off-peak vehicle demands, GHG emissions from plug-in vehicles could be *higher* than emissions from conventional hybrid electric vehicles. However, if natural gas-fired power plants (~400–600 gCO_2/kWh) operate on the margin, which is often the case, well-to-wheels GHG emissions from plug-in vehicles will likely be lower than those from conventional HEVs, and considerably lower than those from conventional vehicles. The exact emissions comparison will depend on the vehicle design (BEV versus PHEV), the efficiency of the conventional vehicle, and how the vehicles are driven and recharged.

MARGINAL GHG EMISSIONS BY TIME OF DAY AND MONTH OF YEAR FOR CALIFORNIA



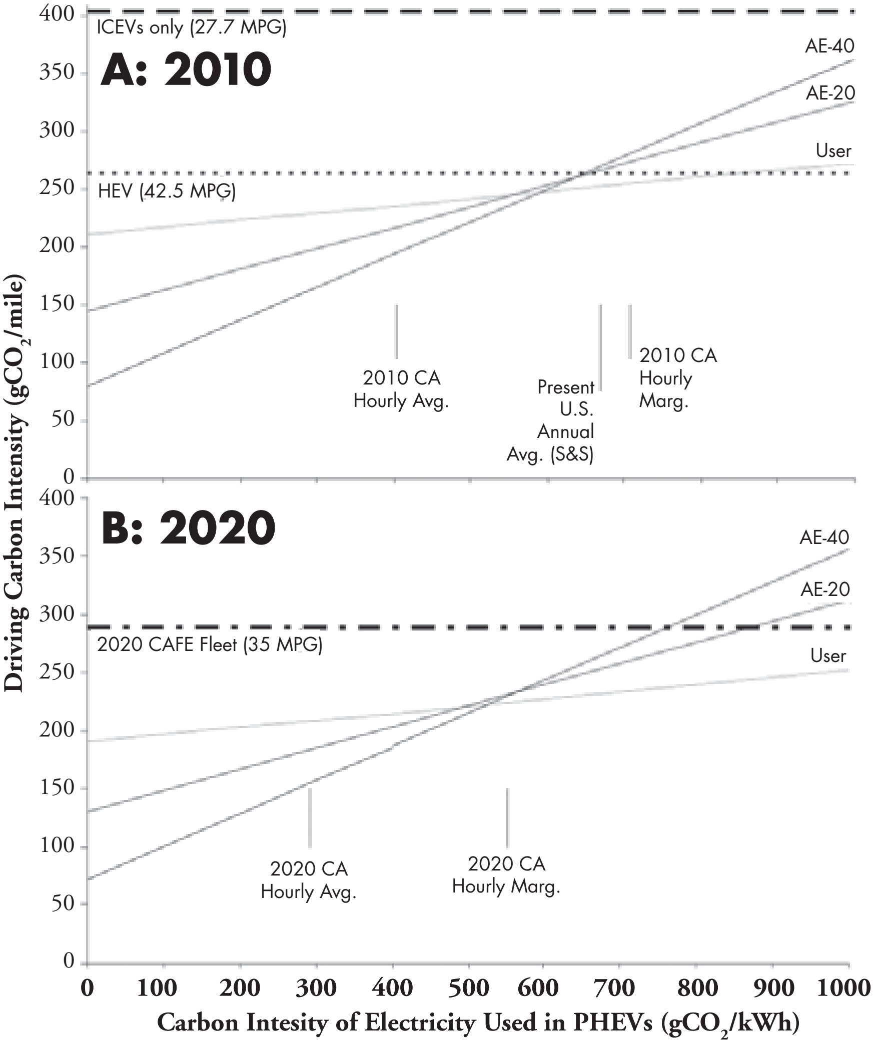
Hour	Avg. recharging demand (MW)	Average hourly marginal generation GHG emissions rate (gCO_2-eq kWh^{-1})												
			494					634					774	
		J	F	M	A	M	J	J	A	S	O	N	D	Year
0	307	630	548	612	531	494	564	638	646	608	634	586	641	595
1	307	634	544	589	517	502	548	570	633	583	623	547	630	577
2	276	619	535	586	507	515	530	546	614	571	595	549	630	567
3	184	623	539	588	512	509	543	541	618	576	589	552	629	569
4	123	639	562	609	535	510	546	569	618	596	622	573	639	585
5	61	646	615	632	592	509	543	610	644	630	636	625	653	611
6	31	654	633	640	600	566	600	614	652	639	638	612	640	624
7	15	657	638	644	639	615	616	650	673	654	656	640	641	644
8	15	665	642	661	644	631	651	667	684	672	654	654	652	657
9	46	665	648	653	650	657	667	682	679	679	655	659	660	663
10	77	654	648	661	661	677	681	684	692	673	674	666	662	670
11	77	658	649	665	670	676	681	707	715	694	667	659	664	676
12	77	658	651	658	667	678	687	714	721	710	658	659	663	677
13	77	658	654	658	667	675	685	721	743	699	672	656	652	679
14	77	655	643	660	661	685	688	745	742	691	675	656	658	680
15	31	648	645	669	658	676	690	750	721	712	681	659	654	680
16	15	657	646	653	652	678	683	732	736	699	671	663	658	678
17	15	687	680	656	658	673	679	710	774	704	669	669	671	686
18	61	687	680	666	660	665	668	696	725	699	680	669	685	682
19	123	678	667	670	671	686	679	693	704	705	675	664	672	681
20	184	673	662	660	662	681	687	675	695	683	670	656	666	673
21	276	660	660	662	659	670	681	687	693	680	656	647	664	668
22	307	654	629	636	627	600	695	660	666	663	654	634	661	648
23	307	647	576	625	555	510	590	658	659	645	632	632	648	615
Demand-weighted avg.		647	601	629	590	580	617	639	665	640	640	613	650	626

This table compares the carbon intensity of marginal electricity (in gCO_2eq/kWh) by hour of day and month in California for 2010 as calculated by the Electricity Dispatch Model for Greenhouse Gas Emissions in California (EDGE-CA). It shows that the highest marginal emissions occur in the afternoon on summer days (when demand is highest due to high air-conditioning loads and when all power plants, including inefficient peaking plants, must be utilized) and lowest during the middle of the night in the spring (when demand is low and there is abundant hydro power available). Statewide average emissions for the entire year are calculated to be approximately 400 gCO_2eq/kWh. Source: R. McCarthy and C. Yang, "Determining Marginal Electricity for Near-Term Plug-in and Fuel Cell Vehicle Demands in California: Impact on Vehicle Greenhouse Gas Emissions," Journal of Power Sources *195 (2010): 2099–2109.*

Studies of PEV environmental impacts rely on assumptions about vehicle designs, consumer values, driving and recharge behaviors, and the future electricity grid. Estimates of GHG reductions range from 32 percent to 65 percent relative to conventional vehicles.[14] But such analyses do not consider which designs PHEV buyers would want, or what design goals should be set. In short, most prior analyses of PHEV impacts assume a given PHEV design and that people will buy those PHEVs.

STEPS researchers sought to estimate potential PHEV GHG impacts in California by combining the consumer-informed recharge profiles described earlier with an electricity dispatch model representing the hourly GHG emissions associated with electricity demand across the year in California in 2010 and 2020. Results suggest that consumer-designed PHEVs can reduce well-to-wheels GHG emissions compared to conventional vehicles under all the recharge and energy conditions we simulated. Further, under present-day grid conditions, from a GHG perspective, these consumer-designed PHEVs may be more benign than the more ambitious AE-20 or AE-40 designs targeted by experts. However, as the carbon intensity of the California electricity grid falls in the future, more ambitious PEV designs will become increasingly advantageous.

POTENTIAL PHEV GHG IMPACTS IN CALIFORNIA, 2010 AND 2020



These graphs combine the consumer-informed recharge profiles described earlier with an electricity dispatch model representing the hourly GHG emissions associated with electricity demand across the year in California in 2010 and 2020. As the carbon intensity of the electricity used in PHEVs increases, so does the driving carbon intensity (the grams of CO_2 emitted per mile). Scenario A is for 2010; baselines include present conventional vehicles (CVs) and HEVs. Scenario B is for 2020; the baseline is the fuel economy stipulated by the 2016 CAFE standard. User is the distribution of respondent-designed PHEVs, while AE-20 *and* AE-40 *map those vehicle technologies onto observed consumer driving behavior and recharge potential. Consumer-designed PHEVs can reduce well-to-wheels GHG emissions compared to conventional vehicles under all the recharge and energy conditions we simulated. Source: J. Axsen, K. Kurani, R. McCarthy, and C. Yang, "Plug-in Hybrid Vehicle GHG Impacts in California: Integrating Consumer-Informed Recharge Profiles with an Electricity-Dispatch Model,"* Energy Policy *39 (2011): 1617–29.*

Over the longer term (out to 2050 and beyond), PEVs provide the potential for achieving the highest energy efficiencies of any technology for light-duty vehicles (LDVs). Also, given the move toward reducing the carbon intensity of electricity generation via the renewable portfolio standards (RPS) and other carbon policy measures, PEVs will have an increasingly clean source of low-carbon fuel to use. Further, PHEVs can use a combination of low-carbon biofuels and electricity, given their dual energy systems. However, the potential for GHG reduction that these vehicle technologies offer may be constrained by limitations such as high battery costs and the lack of universal home recharging. These limitations will need to be addressed with appropriate policies and business strategies if PEVs are to achieve their potential to reduce transportation GHG emissions.

Policies and Business Strategies Needed to Support the PEV Pathway

Perceptions of the "battery problem" hold important implications for policy and business strategy; it was the perceived gap between the capabilities of battery technology and the goals assumed by automakers for potential BEV buyers that convinced the California Air Resources Board to modify and reduce zero-emission vehicle sales requirements in the late 1990s. The commercialization potential for PEVs should be based on analysis of both the state of battery technology and the interests of consumers. As demonstrated in this chapter, there is a role for less ambitious PHEV designs with shorter CD ranges and blended CD operation in the near term. Such designs would meet the interests of many current vehicle buyers at relatively lower cost premiums while still significantly contributing to reductions in GHG emissions, air pollution, and petroleum use. Thus, it may not be necessary for battery technology to meet USABC's goals before PHEVs can be commercially viable, and business strategies should recognize this.

The successful commercialization of ambitious PHEV designs in the short term would likely require more aggressive policy actions—such as high financial incentives, large-scale vehicle demonstrations, and pervasive information campaigns—to overcome not just the higher cost of such added performance but also the lack of inherent interest in all-electric (versus blended) driving observed among a sample of potential PHEV consumers. Thus, while the PHEV performance assumed by the USABC and others provides a possibly useful benchmark for future targets for PHEV battery technology, a near-term focus on less aggressive goals may offset more petroleum and emissions in the long run.

Assumptions regarding future strategies for developing PHEVs should be continually reevaluated from a consumer standpoint to assure alignment with a developing market. By making incentives preferential for more aggressive PHEV goals, we risk stalling the market for PHEVs. For example, 90 percent of potential early PHEV buyers designed vehicles requiring less than 4 kWh of batteries—which are not eligible for the federal tax credit. Incentives should be designed to help develop the market for these vehicles even before they reach the most ambitious performance goals.

And attention should be paid to the importance of well-to-wheels emissions metrics. Although PEVs can reduce or eliminate tailpipe emissions, the emissions associated with electricity generation can be substantial. Such emissions are not easy to calculate given the wide regional and temporal variations in electricity carbon intensity by energy sources and power plants.

Vehicle policy, such as fuel economy standards, will need somehow to account for these upstream emissions. Further, efforts to commercialize PEVs for the sake of societal benefits should also be coordinated with efforts to integrate renewable energy sources into the electrical grid. The use of electricity is incentivized by the low-carbon fuel standard (LCFS), a policy that targets GHG emissions reductions from transportation by calculating and regulating the carbon intensity of all fuels used.

Summary and Conclusions

- Interest in PEVs is currently running high in industry, government and among consumers. Nearly every automaker is announcing vehicles that can plug in and run on electricity. The benefits of these vehicles stem from their high efficiency and their use of electricity that can be generated from numerous domestic low-carbon resources. But while PEVs offer significant potential for environmental benefits, they also present a radical departure from conventional vehicles in terms of efficiency, range, utility, flexibility, and the refueling experience. STEPS research on PEVs has attempted to enable better understanding of different vehicle designs, and their resource utilization and emissions impacts, especially when in the hands of consumers.

- STEPS analysis of battery technologies reveals trade-offs among different battery chemistries on key requirements—power, energy capacity, longevity, safety, and cost. Some existing battery technologies can meet some of the goals set by the USABC, but meeting all goals simultaneously is far more challenging. Our consumer research indicates that PHEV designs preferred by consumers are within the current capabilities of NiMH batteries, and thus the experts' aggressive battery technology goals may be unnecessary for near-term PHEV commercialization. Battery cost is thought to be one of the most critical factors in PHEV deployment.

- Our study of vehicle recharging behavior showed that more new vehicle buyers may be pre-adapted for vehicle recharging than estimated in previous analyses (about half have access to charging when parked at home) and that the success of PEVs in meeting energy and emission goals depends on PEV users' recharging and driving behavior as much as or more than on vehicle design. In terms of vehicle recharging and electricity supply, a large number of PEVs will need to be driven in a region before power plants are operated differently or new ones are required. A smart grid that enables communication between customer and utility will be the key to realizing the full benefits of vehicle charging flexibility.

- The generation of electricity accounts for the bulk of emissions from PEV use. Emissions attributable to PEVs depend on the regional characteristics of the grid and the magnitude and timing of demand. Consumer-designed PEVs can reduce well-to-wheels GHG emissions compared to conventional vehicles under all the energy and recharge conditions we simulated. Given the trend toward reducing the carbon intensity of electricity generation, PEVs will have an increasingly clean source of low-carbon fuel to use.

- This research has highlighted important challenges to mass adoption of PEVs but also laid out a potentially significant path forward that relies on lower battery capacity and cheaper blended PHEV designs rather than all-electric PHEV designs. Blended designs can potentially help reduce GHG emissions in the medium-to-long term relative to conventional and hybrid vehicles. This starting point of cheaper blended designs could set the stage for future commercialization of all-electric designs by increasing consumer experience with, and exposure to, PHEV technology, increasing consumer valuation of all-electric capabilities, and reducing battery and drivetrain costs due to increased manufacturing experience. Over time, with improvements in vehicle and battery technology and decarbonization of the electricity sector, a fleet with more all-electric driving could lead to deep long-term GHG reductions.

Notes

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3. A. C. Revkin, "The Obama Energy Speech, Annotated," *New York Times*, August 5, 2008.
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5. A. Pesaran, T. Markel, H. S. Tataria, and D. Howell, "Battery Requirements for Plug-in Hybrid Electric Vehicles: Analysis and Rationale," presented at the 23rd International Electric Vehicle Symposium and Exposition (EVS-23), Anaheim, California, 2007; M. A. Kromer and J. B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007); R. Graham, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Report #1000349 (Electric Power Research Institute, 2001). These categories follow the California Air Resources Board's (CARB's) definition of PHEV-X, where X is the number of miles the vehicle can drive in all-electric mode during a particular drive cycle before the gasoline engine turns on. USABC goals are based on the Urban Dynamometer Driving Schedule (UDDS) to be consistent with CARB's testing methods. The USABC AE-10 goals are set for a "crossover utility vehicle" (an automobile-based SUV) weighing 1950 kg, and the AE-40 goals are set for a midsize sedan weighing 1600 kg.
6. D. Doughty and C. Crafts, *FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications*, 2005-3123 (Sandia National Laboratories, 2005).
7. M. Anderman, "PHEV: A Step Forward or a Detour?" presented at SAE Hybrid Vehicle Technologies Symposium, San Diego, California, 2008; F. Kalhammer, B. Kopf, D. Swan, V. Roan, and M. Walsh, *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007*, prepared for the State of California Air Resources Board, 2007, http://www.arb.ca.gov/msprog/zevprog/zevreview/zev_panel_report.pdf.
8. Kromer and Heywood, *Electric Powertrains*; Kalhammer et al., *Status and Prospects for Zero Emissions Vehicle Technology.*
9. Design games are summarized and portrayed in J. Axsen and K. S. Kurani, *The Early U.S. Market for PHEVs: Anticipating Consumer Awareness, Recharge Potential, Design Priorities and Energy Impacts*, UCD-ITS-RR-08-22 (Institute of Transportation Studies, University of California, Davis, 2008).
10. See, for example, B. D. Williams and K. S. Kurani, "Estimating the Early Household Market for Light-Duty Hydrogen-Fuel-Cell Vehicles and Other 'Mobile Energy' Innovations in California: A Constraints Analysis," *Journal of Power Sources* 160 (2006), 446–53; K. A. Nesbitt, K. S. Kurani, and M. A. Delucchi, "Home Recharging and Household Electric Vehicle Market: A Near-Term Constraints Analysis," *Transportation Research Record* 1366 (1992), 11–19.
11. One million PEVs each charging approximately 8 kWh/day (good for 25–35 all-electric miles) would require 2880 GWh/yr or 1 percent of 2010 California total electricity demand (288,000 GWh/yr).
12. See, for example, S. Hadley and A. Tsvetkova, *Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation* (Oak Ridge National Laboratory, 2008), and M. Duvall, E. Knipping, M. Alexander, L. Tonachel, and C. Clark, *Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions* (Electric Power Research Institute, Palo Alto, CA, 2007).

13. Cars and light trucks typically are driven about 12,000 miles per year. At an average speed of 30 miles per hour, this translates into a vehicle's being driven 400 hours per year, or about 5 percent of the time.
14. M. Duvall, E. Knipping, M. Alexander, L. Tonachel, and C. Clark, *Environmental Assessment of Plug-in Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions* (Electric Power Research Institute, Palo Alto, CA, 2007); C. Samaras and K. Meisterling, "Life-Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy," *Environmental Science and Technology* 42 (2008): 3170–76.
15. See H.R. 1 *American Recovery and Reinvestment Act of 2009*, Section 1141 (U.S. Government Printing Office, Washington, DC, 2009), http://purl.access.gpo.gov/GPO/LPS111758.