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# Plug-In Electric Vehicles



**COMMENTS OR QUESTIONS**

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# Plug-In Electric Vehicles

By Dan Greenberg, Bryan Jungers

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## FAST FACTS

- Plug-in electric vehicles (PEVs) are now available for purchase worldwide and more new vehicle models are being released each year.
- Current automotive-grade lithium-ion batteries cost between $400 and $800 per kilowatt-hour (kWh) of storage capacity.
- Battery cost is the primary reason PEVs are priced at a substantial premium relative to comparable gasoline-only vehicle models. Technology development, mass production, tax credits, and competition are expected to drive this cost down to perhaps $100 to $200 per kWh, but it will probably take a decade or more to reach that price range.
- Existing grid infrastructure could support a PEV fleet about 73 percent larger than the existing US light duty fleet (which includes non-commercial cars, small trucks, and SUVs) with no additional generating plants needed—as long as these vehicles are recharged during off-peak hours. The grid as a whole can handle the added PEV capacity, and so far, even localized grid impacts appear to be ofonly minor concern to utilities.
- Vehicle-to-grid (V2G)—the concept of dispatching the energy stored in PEV batteries to provide grid-support services—has been demonstrated on a small scale but is unlikely to reach mass markets within the next decade or two.
- Smart charging—modulating the rate at which a battery charges depending on grid conditions—can provide many of the same benefits as V2G at lower cost and with little impact on battery life span, if implemented carefully.
- Electric motors can convert electricity into mechanical power with efficiencies exceeding 90 percent. That compares quite favorably to the internal combustion engine (ICE), which typically operates at an efficiency of only about 18 to 25 percent.
- PEVs could reduce carbon dioxide ($CO_2$) emissions by one-fourth to one-third compared to conventional vehicles, and that's assuming that the PEVs are recharged with electricity from a coal-fired power plant.

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## OVERVIEW

PEVs are vehicles that can operate on electric energy stored in an onboard battery that's charged via the electric grid. One type of PEV is the all-electric vehicle (also called a battery electric vehicle), which operates exclusively on electricity from an onboard battery with no additional power plant (such as a gasoline engine) for backup. Another is a plug-in hybrid vehicle (PHEV), which can operate using electricity provided from an onboard battery or fuel stored in an onboard storage tank, or some combination of the two. Hybrid electric vehicles (HEVs), by contrast, do not charge via the grid; instead, they use their ICEs to generate their own electrical power, recharging their batteries as they drive (**Table 1**).

**TABLE 1: Differentiating vehicle types**

The category of "plug-in electric vehicles" (PEVs) includes all vehicles that plug into an electricity source and store the electricity on board. PEVs come in two basic types: all-electric vehicles and plug-in hybrid electric vehicles (PHEVs, which have a secondary power plant of some kind). Hybrid electric vehicles are similar to PHEVs, but they have smaller batteries and can't plug in. Each type of vehicle shown accesses multiple energy sources, at various usage levels, while it's in motion.

| | Energy-source usage | | |
|---|---|---|---|
| Vehicle type | Engine | Electric motor | Battery |
| Plug-in electric | | | |
| All-electric | — | High | High |
| Plug-in hybrid electric | Moderate | Moderate | Moderate |
| Hybrid electric | Moderate | Low | Moderate to low |
| Conventional (with ICE) | High | — | Low |

Note: ICE = internal combustion engine.



Initially promoted by a small, dedicated group of tinkerers and enthusiasts, PEVs have enjoyed rapidly escalating attention in recent years as a growing coalition of stakeholders has come to understand and promote the technology's numerous advantages over conventional vehicles. Among those advantages are dramatically increased fuel efficiency, resulting in reduced or eliminated gas consumption and enhanced energy security; lower greenhouse gas emissions; and lower operating and maintenance costs. But along with their many benefits, PEVs present a challenge to electric utilities because on-peak charging could create or exacerbate capacity constraints throughout the utility system.

Like HEVs such as the popular Toyota Prius, PEVs boost vehicle fuel economy by using electricity to provide drive energy. The difference between HEVs—which have been available on the US market for well over a decade now—and PEVs is that PEVs have larger battery capacity, allowing them to operate on electricity for a distance determined by the vehicle design and battery size. The larger battery capacity also gives the PEV greater ability than the HEV to capture and reuse the vehicle's kinetic energy through regenerative braking (which uses the PEV's motor as a generator, charging the vehicle's batteries as it slows down).

All PEV batteries operate within a specific state-of-charge (SOC) window that typically accounts for between 50 and 90 percent of the battery's total energy-storage capacity. For example, an HEV battery might be designed to stop charging when the battery reaches 95 percent of its nominal storage capacity; when traveling, the vehicle might run largely on electric power until the battery has drained to a 35 percent SOC, after which the vehicle would run chiefly on the backup ICE. In this case, the usable SOC of the vehicle is about 60 percent of total nominal battery capacity. Operating the battery within this limited window—which automotive and battery researchers are continuously trying to pry wider—maximizes battery life span. Before the battery hits the lower limit of its operating window, the vehicle is said to be operating in charge-depleting mode because battery energy is being depleted. Once it hits that lower SOC limit, the vehicle is said to be operating in charge-sustaining mode because the ICE will, at least intermittently, be providing some power either to the vehicle's wheels or to generate electricity to recharge its battery.

"All-electric range" is a term historically used in the research literature to describe how far a PHEV can travel in charge-depleting mode. Some researchers in this field have adopted the nomenclature "PHEV-x" to designate a PHEV with a designed all-electric range of x miles, indicating that the vehicle can travel that many miles on electricity before the engine kicks in. In reality, not all PHEVs will be designed to travel completely on electricity because, absent significant energy-storage advances, it's often too expensive to build PHEVs with batteries that can satisfy the vehicle's peak power needs. More commonly, vehicles are being designed to combine battery and ICE power whenever necessary—for example, when accelerating up to highway speeds on an on-ramp. So even over a short distance, if the driver stomps on the accelerator, a PHEV's engine may fire up. Although the PHEV-x nomenclature isn't entirely accurate—actual charge-depleting range will vary by driver, temperature, and trip topology—it's a useful way of indicating the distance a given vehicle is designed to travel primarily on electricity.

Unlike HEVs, a PEV can be recharged by plugging the vehicle into an electrical outlet—and it's this feature that provides both its benefits and its challenges to the electric utility industry. Electric motors can convert electricity into mechanical power with efficiencies exceeding 90 percent. That compares quite favorably with ICEs, which typically operate at an efficiency of only about 18 to 25 percent. It also takes quite a lot of energy and effort to extract and refine crude oil and deliver a gallon of gas to a vehicle's tank, further amplifying the PEV's emissions benefits. Of course, there are considerable losses in generating and distributing electricity, but the overall energy and emissions balance has been repeatedly shown to be decisively in the PEV's favor. In addition, plugging into the grid not only reduces our vulnerability to oil price spikes and supply disruptions on a national level, it also transfers a portion of our transportation needs to a diverse, stable, and increasingly low-carbon set of energy resources.

There are, of course, downsides to PEVs. For one thing, they're very expensive. The price premium for a PHEV sedan with a 20-mile all-electric range could easily exceed $10,000. Similarly, an all-electric PEV with 100 miles of driving range carries about the same price premium relative to a gas-only vehicle. This cost will undoubtedly decline over time with energy-storage technology advances, mass-production economies of scale, and increased competition. But for now, if you want to purchase a PEV, you're going to have to pay a significant premium for that privilege.

Another big headache PEVs could pose to utilities is their potential to exacerbate peak loads. Although there's plenty of spare generating capacity to serve even a relatively huge fleet of PEVs if charged during off-peak hours, several modeling studies indicate that PEVs would severely stress the grid if charged on-peak. If utilities work in advance to deploy the necessary infrastructure and establish consumer incentives properly (such as some form of time-of-use pricing structure that consumers will respond to), they can turn this potential problem into an opportunity to generate additional revenue from existing base load and cycling generators.

Until recently, PEVs were essentially a laboratory curiosity. PHEVs, in particular, were developed by researchers operating in a small number of academic groups and only a handful of boutique commercial enterprises. But as of mid-2009, most large automobile manufacturers began openly conducting research into PHEV development. So far, only General Motors (GM), Toyota, Ford, and Fisker have brought plug-in hybrids to market, though other companies have announced their intentions to offer a PHEV model within the next few years. As for all-electric vehicles, which are distinctly less complex to design and manufacture, there are at least a dozen manufacturers that now have models for sale, including Nissan, Ford, Toyota, Mitsubishi, Renault, Honda, Think, BYD Auto, Citroen, Tesla, Electric Vehicles International, Bright Automotive, and Boulder Electric Vehicle. For a more detailed and up-to-date list, see Plug In America's Plug-in Vehicle Tracker.

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## APPLICATIONS AND LIMITATIONS

The largest market segment envisioned for PEVs is the one that probably got you to work this morning: the commuter/family car. It's the largest vehicle customer segment in the US, with over 250 million personal vehicles on the road today. Though there are few PEVs on the road currently, numerous manufacturers are developing production passenger PEVs in a variety of body types that are just starting to hit the market (see Market Outlook). But the family car is by no means the only segment being targeted by established automakers and the numerous start-ups angling to bring PEVs to market. Other market segments for which PEVs have been or are being developed include delivery vans, utility service trucks, dump trucks, military vehicles, freight trucks, heavy-duty off-road vehicles, and commuter and school buses.

PEVs are best suited to transportation applications that call for frequent trips covering relatively short distances (tens rather than hundreds of miles) and punctuated by frequent stops and starts; that is, trips consisting of mostly city driving. There are two reasons for this, one economic and the other technical.

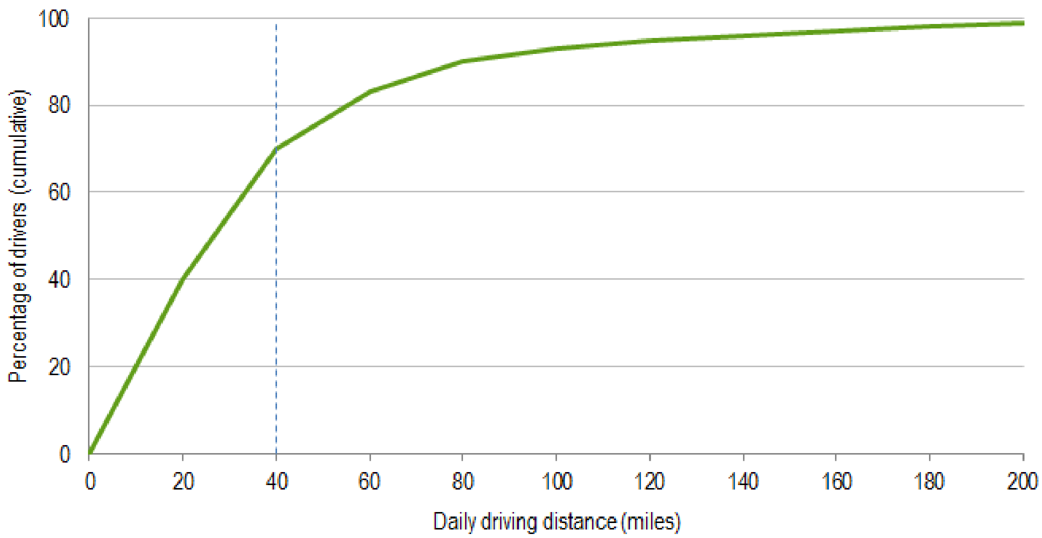
First, the economics: PEVs have a higher purchase price but lower operating costs (see Economics) than either conventional vehicles or HEVs. As a result, drivers will obtain the most value out of their PEV by selecting one with a battery capacity that's well matched to their daily driving needs and by maximizing the fraction of total miles driven on electric power (making maximum use of low-cost electricity to provide their transportation needs). A PEV that's only used on the weekend or one that's used daily for a single trip of only a few miles when its electric range is significantly larger is going to take a long time to repay its higher initial cost compared with a PEV with an all-electric range that's well matched to its driver's daily travel needs.

The technical reason PEVs are not well suited to driving patterns dominated by long highway trips is that such trips don't make optimal use of the expensive PEV capabilities the owner paid for. Depending on a PEV's design, it may be able to accelerate to highway speed and maintain that speed without any trouble or it may require that an ICE provide the additional power needed to get up to highway speed. In either case, once the battery's SOC has dropped to its lower limit, the vehicle will either need to be recharged or the power required for the remainder of the trip will need to come from an onboard ICE, assuming one exists. Using the ICE in this way reduces the fraction of miles driven on battery power. Long highway trips also provide little opportunity to use the PEV's regenerative braking capabilities.

For the average consumer, the best PEV applications will be for the most common types of driving: commuting to work; short trips around town; and perhaps the occasional trip to the beach, the mountains, or across the country to visit mom. Of course, a cross-country trip taken in an all-electric vehicle would be considered by most drivers to be logistically impossible; the long recharge times, in the absence of a dense "fast charger" network, would seem impractical to most motorists. But fortunately for the market potential of PEVs, data from the US Department of Transportation (DOT) demonstrate that the vast majority of our car trips consist of relatively short, regular travel to work and other local destinations (**Figure 1**)—70 percent of US drivers' daily travel is at distances of 40 miles or less.

**FIGURE 1: Cumulative distribution of daily driving distances in the US**

Data from the US Department of Transportation's 2009 National Household Travel Survey indicate that 70 percent of US drivers travel, on average, 40 or fewer miles per day.




© E Source; data from US Department of Transportation

When it comes to commercial vehicles that drive primarily in cities, short trips punctuated by frequent stops and starts make delivery vehicles and commuter and school buses excellent PEV applications. Delivery vehicles and buses that have already been converted to PEVs are already on the street, and Bright Automotive has developed a purpose-built (as opposed to a conversion) PHEV delivery vehicle.

In another application closer to home for electric utilities, the Electric Power Research Institute (EPRI) and Eaton Corp., in conjunction with several member utilities, have demonstrated a prototype PHEV bucket truck, or "trouble truck." This truck uses electric power for traveling both to and from work sites and to power the truck's boom and other ancillary systems at the work site. [1]

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## ECONOMICS

The relatively large electric-drive components of PEVs—electric motors and generators, batteries, control systems, and charging circuitry—tend to increase costs significantly relative to conventional vehicles and HEVs. Lower operating costs and projected savings in maintenance costs can help to offset these higher initial costs over time, but studies suggest that conventional vehicles and HEVs may offer consumers more attractive life-cycle economics than PEVs do in many scenarios. Any life-cycle cost assessment must make assumptions about many factors, including some that are highly speculative—such as the future price of gasoline and cost of advanced energy-storage systems. In addition, PEVs offer substantial reductions in oil consumption and $CO_2$ emissions compared with conventional vehicles and HEVs. And because these reductions advance vital societal goals in an increasingly energy- and carbon-constrained world, it's likely that public policies subsidizing the production or purchase of PEVs, such as those supported by the 2009 American Recovery and Reinvestment Act (ARRA), will influence consumer economics and improve the market for PEVs over time.

An additional factor that may someday play a role in PEV economics is the potential for tapping into the distributed energy-storage resource of a large PEV fleet to provide ancillary services to stabilize the electric grid. Provision of such services, which could take the form either of bidirectional power flow to and from a vehicle's battery or of a simple modulation of the rate of battery charging, may offer the PEV owner a revenue stream or a reduced electricity rate that would further offset the initial cost of the vehicle. So although PEVs cost substantially more than conventional and hybrid vehicles and probably will for the foreseeable future, factors that offset their higher price could help PEVs gain a more secure foothold in the market.

### Incremental Up-front Costs

The higher up-front cost of PEVs is typically cited as the single largest barrier to widespread adoption. In response to sluggish sales, some manufacturers have lowered the purchase price of their PEV models, bringing them more in line with the pricing of conventional vehicles. An ongoing "plug-in price war," coupled with a US federal tax incentive of up to $7,500, has helped to narrow the price gap between PEVs and standard gasoline cars. Still, the incremental price premium for a PEV remains in the range of $6,000 to $15,000 relative to its plugless counterpart. **Table 2** shows pricing data (provided by the manufacturers) and incremental cost comparisons for five popular vehicle models.

**TABLE 2: Plug-in cars are more expensive than their plugless counterparts**

The purchase prices of these PEV models, when compared to those of comparable vehicles from the same manufacturers, illustrate the currently high price of fuel efficiency. The price premiums are estimated based on the reduced PEV price (after federal tax incentives). Note that, in every case, the base model PEV costs more than a comparable base model conventional vehicle—although, in fairness, some PEVs come "fully loaded" by default, which makes direct comparison difficult.

| Manufacturer (model names) | PEV price ($) | PEV tax credit ($) | Conventional vehicle price ($) | PEV price premium ($) |
|---|---|---|---|---|
| Ford (Focus) | 39,200 | 31,700 | 16,995 | 14,705 |
| GM (Volt versus Malibu) | 39,145 | 31,645 | 21,995 | 9,650 |
| Nissan (Leaf versus Versa) | 28,800 | 21,300 | 14,670 | 6,630 |
| Tesla (Model S) | 59,900 | 52,400 | NA | NA |
| Toyota (Prius)[a] | 32,000 | 29,500 | 23,215 | 6,285 |

Notes: NA = not applicable; PEV = plug-in electric vehicle.

a. For the Prius, we are comparing a plug-in hybrid to a plugless hybrid, rather than to a conventional gas car. Also note that the plug-in Prius is only eligible for one-third of the incentives of the other PEVs listed here, due to its smaller battery size.

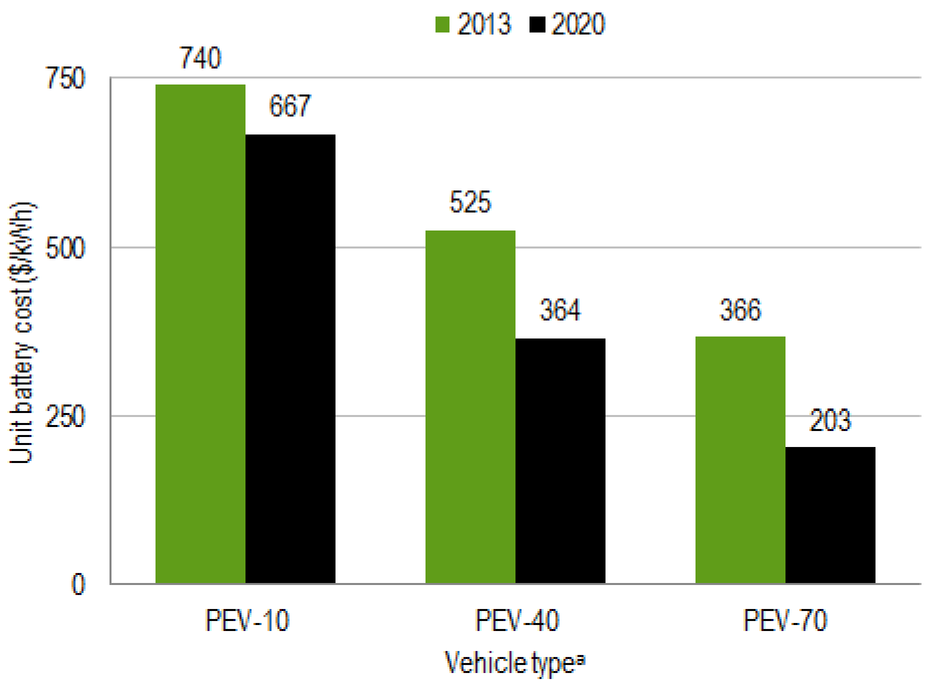


A direct apples-to-apples comparison of PEV and conventional vehicle up-front costs is complicated. The baseline MSRP (manufacturer's suggested retail price) for a conventional vehicle can be several thousand dollars lower than its "fully loaded" price. For PEVs, a single model is often all that's available and customized options are limited if they're available at all. Though we're seeing the beginnings of a shift toward more options in PEV purchasing—for example, the Nissan Leaf is available in three classes as of model year 2013—these options are fairly minimal when compared with those available for conventional vehicles. In some cases, PEV models are only available with all of the options included—features like leather interior, navigational systems, or parking assistance—even though these are not standard features in most vehicle models. In other cases, standard upgrade options aren't available at all. As PEVs continue to inch their way into the mainstream market, we're likely to see greater alignment with conventional vehicles in terms of option packages and tiered pricing.

Battery packs are by far the largest cost component of a PEV, but the cost of lithium-ion (Li-ion) batteries has been dropping steadily over the past several years. Battery costs are commonly referenced in terms of how many kWh of energy can be stored. By this measure, HEVs typically have the most expensive batteries, and all-electric vehicles have the least expensive batteries on a basis of cost per unit of energy stored ($/kWh). For high-power battery packs like those used in HEVs, the current unit cost for Li-ion batteries is between $800 and $1,000/kWh; for short-range PEVs (such as the plug-in Prius), the current cost is just under $800/kWh; and for larger PEVs it's about $300 to $500/kWh, depending on the size of the battery pack. EPRI recently published a report that compares current PEV battery unit costs (in 2012 dollars) with projected costs in 2020 (**Figure 2**). [2] EPRI's work to model battery costs has been significantly influenced by work taking place at Argonne National Laboratory, notably the research of Dr. Paul Nelson. Findings from Nelson's battery cost modeling work suggest that manufacturing process speed is perhaps the most significant factor in the cost of batteries for PEV applications. [3]

**FIGURE 2: Battery costs are expected to decline over the next decade**

The Electric Power Research Institute (EPRI) estimates that lithium-ion battery costs will be lower in 2020 relative to present-day costs. Although only minor incremental cost reductions are expected for small battery packs (less than 10 percent), the unit costs for large battery packs are expected to be considerably lower (up to 45 percent).




Notes: kWh = kilowatt-hours; PEV = plug-in electric vehicle.
a. In the PEV-x naming convention, x stands for the equivalent all-electric driving range in miles.

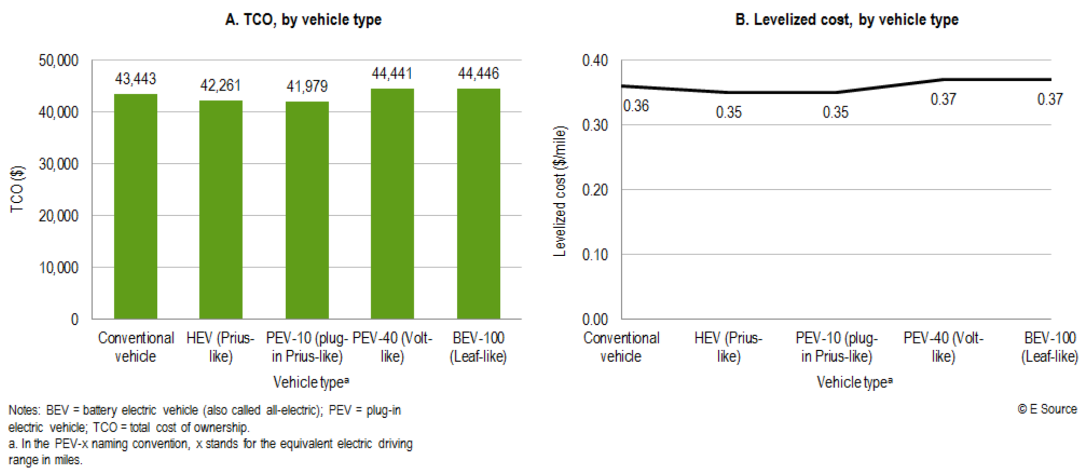
© E Source; data from EPRI

## Total Cost of Vehicle Ownership

Due to their lower operating and maintenance costs, PEVs have an operational cost advantage over conventional vehicles and, to a lesser extent, over HEVs. The degree of that advantage strongly depends on the assumptions made about regional and future gas and electricity costs. Assuming a significantly large number of vehicle miles traveled and relatively high gas prices, lower operating costs should help to reduce PEV life-cycle costs to below those of conventional vehicles and, eventually, HEVs. An EPRI study on the total cost of ownership (TCO) for PEVs relative to HEVs and conventional vehicles found that, at an assumed annual production volume of 100,000 vehicles per manufacturing facility (looking to about the 2020 time frame), the TCO for different vehicle types is very similar, ranging between $42,000 and $45,000 per vehicle over an assumed 10-year vehicle life. [4] **Figure 3** illustrates the projected lifetime and levelized cost estimates for conventional vehicles, HEVs, and PEVs as derived from EPRI's analysis.

**FIGURE 3: EPRI's projected 10-year lifetime vehicle costs show little differentiation by vehicle type**

The Electric Power Research Institute (EPRI) had to make many simplifying assumptions in order to estimate lifetime vehicle costs, especially when projecting out into the future. For this total cost of ownership (TCO) comparison (A) and levelized cost analysis (B), gasoline is assumed to cost $3.00 per gallon, electricity is $0.10 per kilowatt-hour, vehicles are assumed to travel 12,000 miles annually (9,000 for all-electrics). Note that, although the PEV-10 (similar to the Plug-in Prius) has the lowest TCO and the PEV-40 (similar to a Volt) has the highest, there's relatively little difference between these values, so changes made in the input assumptions would likely result in a different outcome.




Some important insights on PEV lifetime ownership costs can be drawn from EPRI's TCO study. As far as first costs are concerned, it seems likely that PEVs will continue to be more expensive than conventional gas vehicles for the foreseeable future. This suggests that additional economic incentives may be necessary to tip the scale in favor of PEVs, such as payments made to PEV owners in return for utilizing their vehicles' batteries as a distributed storage resource (see Vehicle-to-Grid and Smart Charging). Another conclusion that can be drawn from this work is that production volume may be the last remaining hurdle that PEV manufacturers must overcome to reach lifetime cost parity with conventional vehicles. Last, considering how small the TCO margins are from one vehicle type to the next, any significant variation in the economic conditions assumed in this analysis will likely lead to a different outcome. For a good general overview on the state of PEV technology development, see the EPRI report Transportation Electrification: A Technology Overview. [5]

## Federal Incentives

Given the many potential benefits PEVs offer, it's not surprising that the US federal government included several provisions in ARRA designed to promote the production and sale of PEVs. The most relevant ARRA provisions include: [6]

- *Consumer tax credits:* A credit of $2,500 toward the purchase of a PEV, plus $417 for each kWh of battery storage capacity above 4 kWh, up to a maximum of $7,500
- *Federal fleet purchases:* A budget of $300 million for purchase of PEVs by federal agencies and $3 billion for the acquisition of more fuel-efficient vehicles (of any type) for the federal fleet by September 30, 2011
- *Battery manufacturing:* $2 billion in grants for the manufacture of batteries and related components, targeting Li-ion batteries, hybrid electrical systems, and related software (the US Department of Energy announced the recipients of these grants on August 5, 2009) [7]

- *Demonstration projects:* A $400 million budget for integrating PEVs into the US transportation sector through test demonstrations (awards were announced on August 5, 2009) [8]
- *Clean Cities program:* A budgeted $300 million in competitive grants to state and local governments and metropolitan transportation authorities for alternative fuels and advanced vehicle projects

Several US states offer tax incentives for HEVs that would also be applicable to PEVs, and it's likely that additional state and local incentives will be issued.

### Vehicle-to-Grid and Smart Charging

Another factor that may eventually affect PEV economics is the potential to tap the distributed energy-storage capacity of large numbers of PEVs to provide ancillary (grid-support) services such as frequency regulation and spinning reserve. These services account for about 10 percent of the cost of electricity, or about $12 billion per year in the US. [9] Although it may be many years before the most sophisticated approaches to tapping these capabilities are commercially viable, simpler approaches appear to face fewer obstacles, and companies are already gearing up to provide the necessary infrastructure.

On average, vehicles are parked well over 90 percent of their useful lives. [10] If these vehicles are plugged in whenever they are parked, their storage capacity could conceivably be used to absorb excess power from the grid and even to source power to the grid. Vehicle-to-grid capability could be used to assist utilities in maintaining constant frequency, reacting quickly to generator or transmission-line failures (providing a service identical or perhaps even superior to spinning reserve), providing power on peak-load days, and moderating the dynamics of intermittent resources like wind and solar power. Many of these capabilities have already been demonstrated by Pacific Gas and Electric Co. (PG&E), Pepco, and Xcel Energy, [11] among others.

Using vehicle battery capacity to provide ancillary services has been most effectively advocated by Willet Kempton, a professor at the University of Delaware. Kempton developed analytical techniques to estimate how much of that value a PEV might be able to capture. [12] His analyses suggest that the value of grid-support payments for each vehicle could amount to several thousand dollars annually. If he's correct, such payments could go a long way toward offsetting PEV incremental costs and hastening a thriving market for PEVs.

Unfortunately, Kempton's analyses may not be completely correct. One issue with his valuation technique is that it assumes constant rates for ancillary services, even though the emergence of a large new resource for providing these services would likely depress the market price for them. So the likely annual value to the vehicle owner would probably be significantly less than Kempton's estimates. Another issue is that some party, either a utility or an aggregator, would have to gather performance data and facilitate large numbers of small transactions to create a market for the ancillary services provided by PEVs, and the resulting transaction costs would reduce the value accessible by vehicle owners.

Nonetheless, the technical capability already exists for PEVs to provide ancillary services, to source power during peak hours, and to act as a counterbalance to the ebbs and flows of renewable power. Therefore, it's certainly possible that this capability could one day improve the life-cycle economics of PEVs and enable renewable resources to constitute a much larger fraction of a utility's generating capacity.

But that day may not occur for many years following the commercial introduction of PEVs. There are many obstacles to the emergence of a thriving market for the grid-support services PEVs could provide, but probably the most salient short-term issue is legal rather than technical. At least in the early years of PEV deployment, auto manufacturers will lack robust real-world experience with their battery packs and will almost certainly enforce warranty exclusions for batteries used for V2G. Harnessing the energy contained in a PEV battery on even an intermittent basis could reduce a battery's lifetime. This is particularly true when tapping PEV batteries to provide power during peak-load hours or when a calm descends on a wind farm and output suddenly plummets. Such operation would likely cause the battery state of charge to drop to the lower limit of its operating window, which would hasten its demise. And even the very shallow cycles needed for frequency regulation could degrade battery lifetimes because these cycles would be numerous.

Until vehicle manufacturers gain confidence that their battery packs can provide grid-support services and still meet consumer demands for reliability and durability, they will be unwilling to guarantee the performance of batteries used for grid support. And few consumers will be willing to risk a $10,000 battery investment in order to access the $2,000 per year such services might yield. To provide sufficient grid-support services without accelerating the degradation of any individual PEV's battery pack requires that a very large number of PEVs have been aggregated to provide this service, thereby limiting the maximum power draw per vehicle. And that, of course, can't happen without widespread PEV adoption.

Although V2G appears to be many years off (if it ever becomes a reality), there's a much simpler approach that could provide many of the same benefits much sooner. Collectively, such approaches are now being referred to as "V2x," where x can be anything that connects to a PEV for power exchange. Rather than installing the power electronics hardware necessary to convert the battery's direct-current (DC) power into alternating-current (AC) power that's compatible with the grid, intelligence can be built into the battery chargers that allow them to receive and respond to utility signals, effectively integrating the PEV into a smart grid system. So-called "smart chargers" would modulate the power being sent into the battery in reaction to grid conditions. If supply is tight, chargers could be requested to curtail or cease charging. If there's excess supply (perhaps a surge in wind or solar power), chargers could be signaled to begin or ramp up charging to soak up the extra supply. By modulating the rate at which PEVs are charged, smart charging could provide considerable stability benefits to the grid and even enable a higher percentage of generation capacity to come from variable renewable resources.

Smart charging has been demonstrated by researchers at the Pacific Northwest National Laboratory (PNNL), who coined the term "V2G-half" to refer to their technique. (For a brief description of PNNL's efforts, see our 2010 report Vehicle-to-Grid Implementation: Halfway There?) AeroVironment—a company with an impressive history of PEV technology development that is now a manufacturer of charging equipment—has licensed PNNL's technology to integrate into its PEV charging stations. [13] On the utility side, PG&E has teamed up with Honda and IBM to demonstrate PEV smart-charging capabilities, [14] and Austin Energy has included automated demand response for PEV charging as part of its Pecan Street Project. [15]

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## PERFORMANCE

PEVs promise numerous benefits over conventional vehicles and HEVs, including higher fuel economy, substantially lower oil consumption (supporting reduced oil imports and enhanced energy security), and reduced greenhouse gas emissions. Although these benefits may come at a significant price premium (see Economics), they should be achievable without sacrificing vehicle performance in terms of handling and acceleration. In fact, PEVs are often considered to have better drivability than conventional vehicles for the same vehicle class, contributing to satisfied drivers and what is colloquially referred to as the "PEV smile." The primary caveat for utilities is the potential to create a peak-load burden or to put stress on the components of the distribution system if charging rates and times aren't carefully managed.

### Fuel Economy

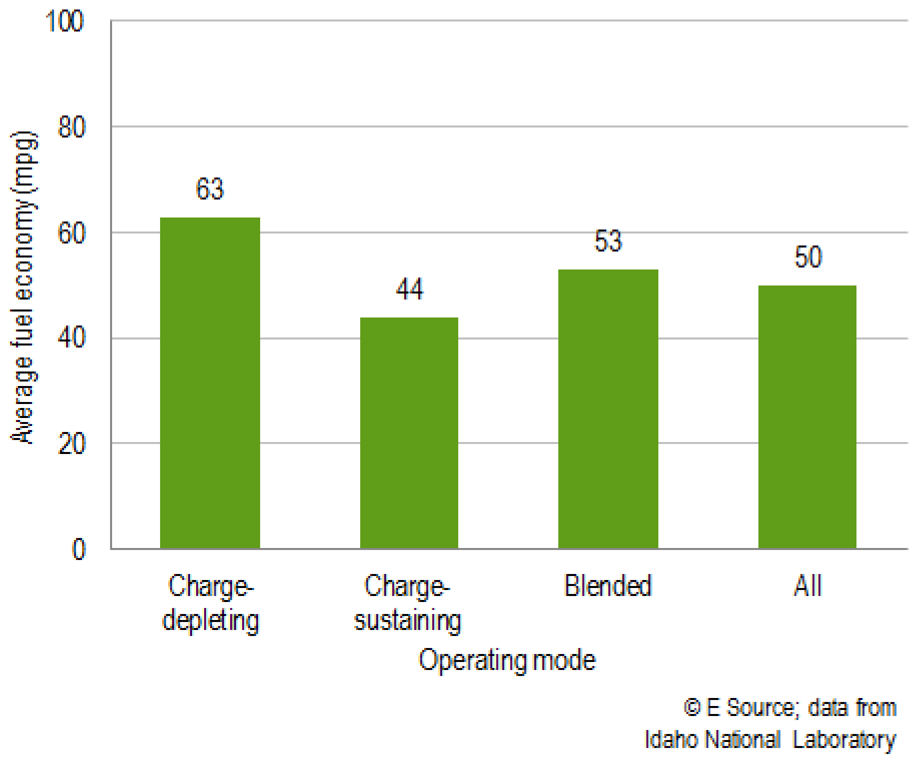
PEVs promise fuel economy well in excess of that of comparable HEVs. Although it's possible to operate a PEV so that its efficiency is worse than that of an HEV, some PEV drivers have reported fuel economies in excess of 100 mpg, though this is difficult to maintain over long periods or for long-distance trips. In August 2009, GM announced that the Chevy Volt would achieve a fuel economy of 230 mpg. [16] In reality, the US Environmental Protection

Agency's rated fuel economy for the Volt is 98 mpg, just shy of the often-touted 100 mpg target for PEVs.

As you might expect, PEVs achieve their best fuel economy when operating primarily on electricity in charge-depleting mode. But even for a specific PEV design driven over a specific route, fuel economy can vary to a surprisingly large degree. A July 2009 report from Idaho National Laboratory (INL) demonstrates this clearly. As part of the US Department of Energy's Advanced Vehicle Testing Activity, INL researchers analyzed the performance of 141 Toyota Prius HEVs that were converted to PHEVs. [17] These vehicles, operating in 21 US states and Canada, logged more than 575,000 miles over the course of the yearlong study. The research team evaluated individual vehicles' fuel economy for each trip taken and categorized whether the trips were driven entirely in charge-depleting mode, in charge-sustaining mode, or in a blended charge-depleting/charge-sustaining mode. The trips completed entirely in charge-depleting mode averaged 63 mpg, trips completed entirely in charge-sustaining mode averaged 44 mpg, and blended-mode trips were intermediate, averaging 53 mpg (**Figure 4**).

**FIGURE 4: Prius PHEV fuel economy**

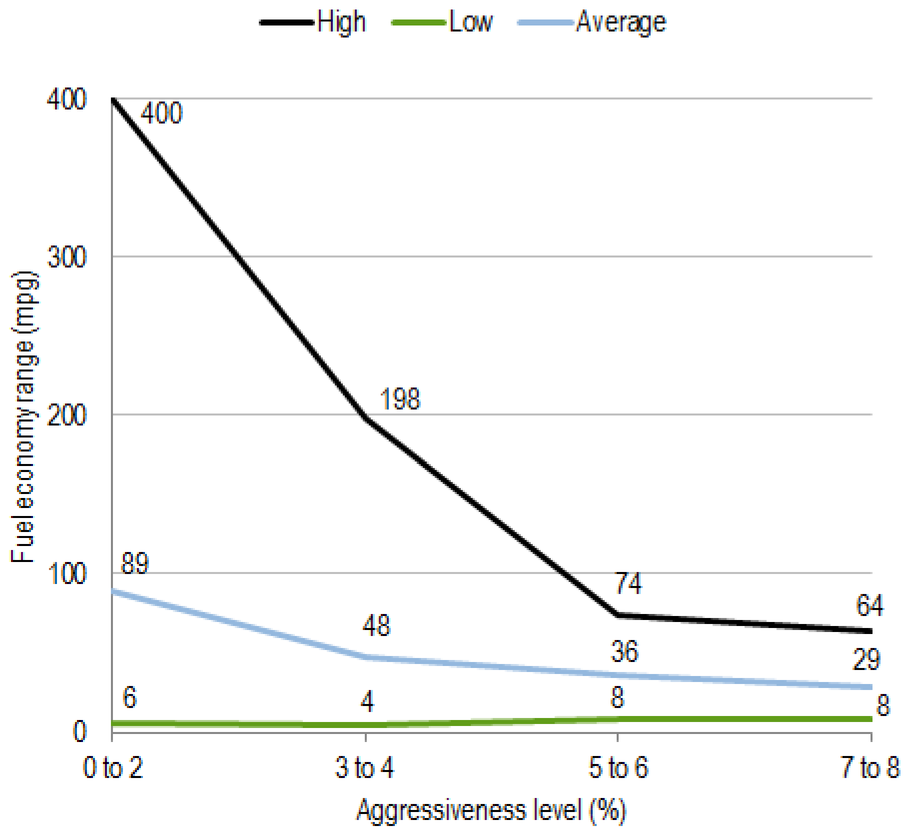
Idaho National Laboratory analyzed the fuel economy of 141 Toyota Priuses that had been converted to plug-in hybrid electric vehicles (PHEVs), monitoring a total of more than 44,000 trips and a cumulative 575,000 miles over the course of a year. Fuel economy varied depending on whether the vehicle was operating in charge-depleting, charge-sustaining, or blended (charge-depleting/charge-sustaining) mode.




INL researchers found that driver aggressiveness was also a significant determinant of fuel economy. As a proxy for driver aggressiveness, the researchers calculated the percentage of time during each trip that the accelerator pedal was depressed by 40 percent or more, and then plotted trip fuel economy as a function of this variable (**Figure 5**). Among trips completed in charge-depleting mode, those with the lowest aggressiveness values achieved fuel economy numbers in excess of 200 mpg, while those with the most aggressive drivers had fuel economies as low as 5 mpg.

**FIGURE 5: Fuel economy as a function of driver aggressiveness**

To a much greater degree than for conventional vehicles, driving habits have a profound effect on the fuel economy of plug-in hybrid electric vehicles. Researchers measured driver aggressiveness as the percentage of time during a trip that the accelerator pedal was depressed at least 40 percent.

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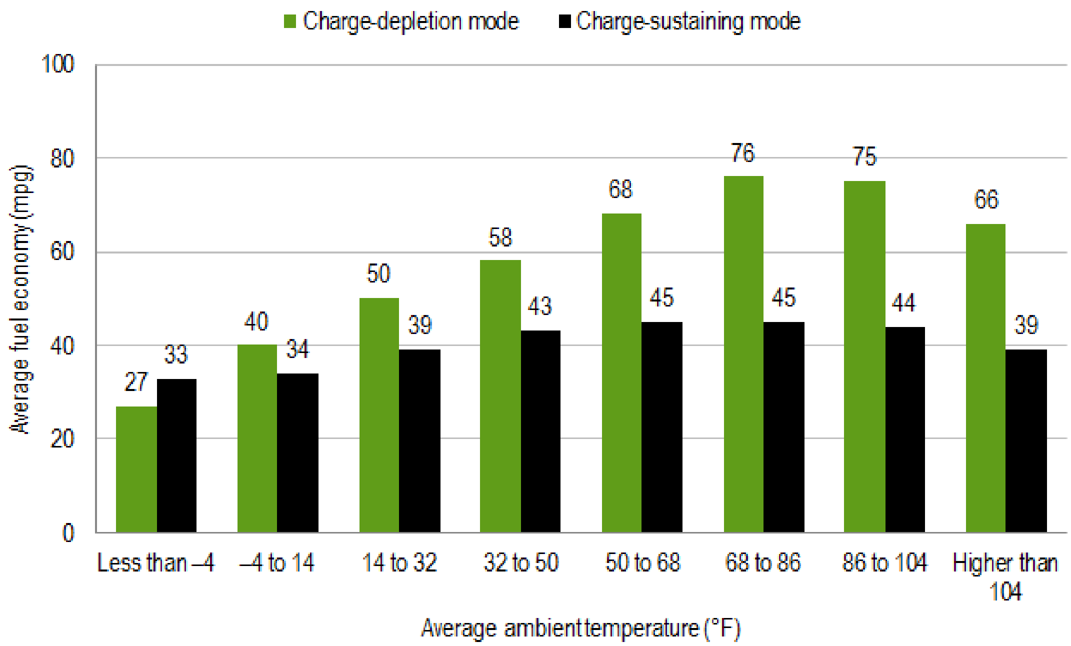
Ambient temperature can also profoundly affect PEV fuel economy. Engines operate inefficiently when they're cold; when the heat for the passenger compartment is provided by the engine, cold weather requires more-frequent engine starts. Similarly, if heat for the passenger compartment is provided by an electric resistive heater, it can quickly drain the battery and kill charge-depleting fuel economy. **Figure 6** shows how ambient temperature can affect fuel economy. [18]

**FIGURE 6: PHEV fuel economy is affected by temperature**

When the outside temperature gets cold, the engines of plug-in hybrid electric vehicles (PHEVs) operate inefficiently and fuel economy declines. Engine starts are also more common in cold weather because the engine is required for all passenger-compartment heating.




Notes: F = Fahrenheit.

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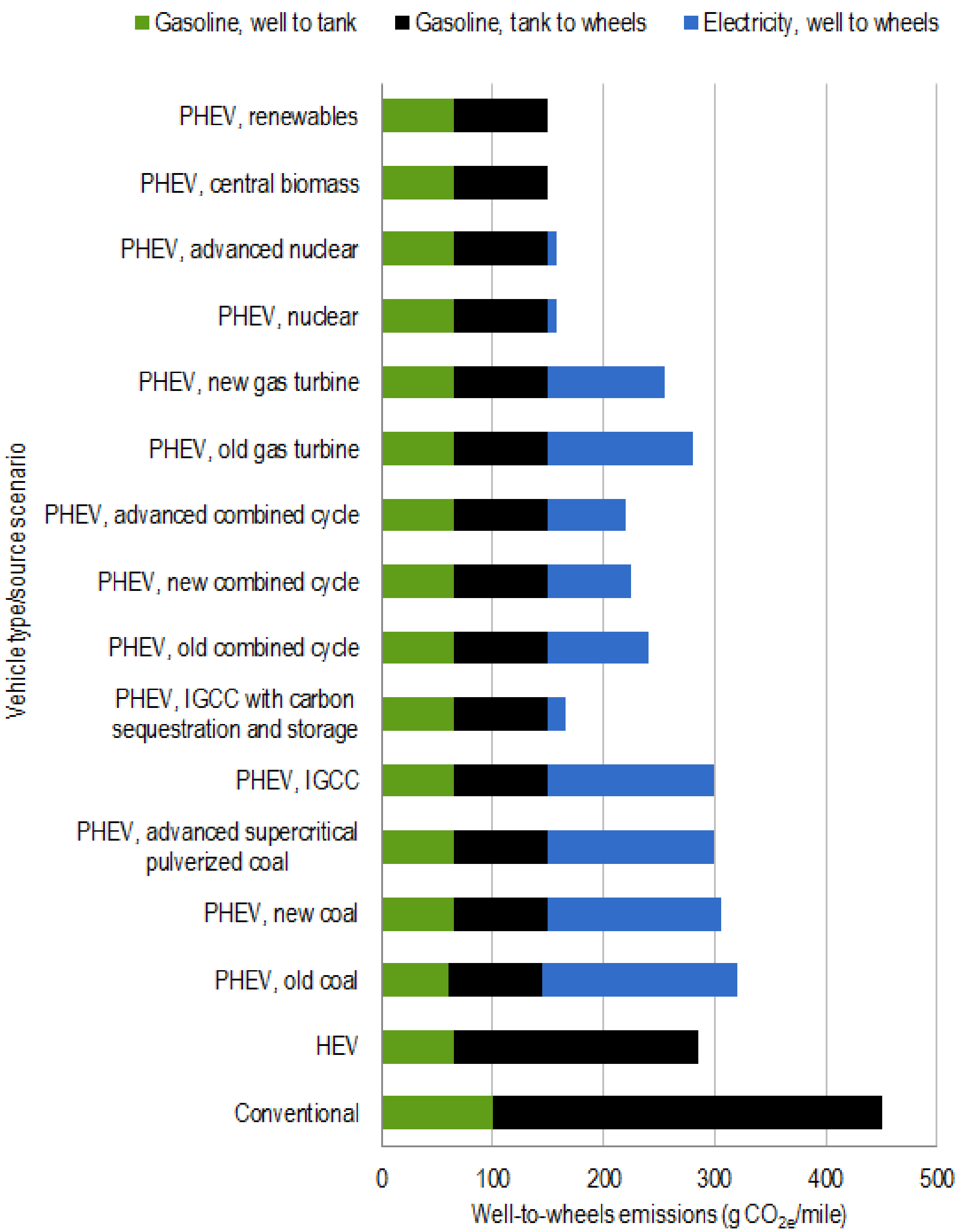
## $CO_2$ Emissions

A PEV's superior fuel economy, when combined with the fact that electricity can be converted into motion with far higher efficiency than the chemical energy in a gasoline can, gives PEVs a very large advantage relative to conventional vehicles when it comes to $CO_2$ emissions—regardless of where the charging electricity is generated. The picture is less clear when you compare $CO_2$ emissions of PEVs to those of HEVs. The winner of that comparison is usually the PEV, but computer simulations have demonstrated that when the charging electricity is generated by coal- or oil-fired power plants, HEVs will sometimes provide equal or better environmental performance relative to PEVs. [19]

There have been numerous modeling studies of the emissions impacts that PEVs might have if they were to penetrate the market in a meaningful way. [20] All of these studies conclude that the PEV is so much more efficient than an otherwise equivalent conventional vehicle that $CO_2$ emissions will decline even if the PEV is charged with electricity from an all coal-fired grid. Where the charging electricity is generated in a less carbon-intensive plant, $CO_2$ reductions can be substantial (**Figure 7**). In conducting such analyses, most (but not all) authors include emissions associated with each vehicle's direct consumption of gas ("tank-to-wheels" emissions) as well as those associated with transporting and refining oil and getting that fuel into the vehicle's tank ("well-to-tank" emissions).

**FIGURE 7: 2010 $CO_2$ emissions by charging generator type**

Even when the charging electricity for a plug-in electric vehicle comes from a coal-fired power plant, carbon dioxide ($CO_2$) emissions from plug-in hybrid electric vehicles (PHEVs) are substantially lower than those of conventional vehicles, albeit higher than the $CO_2$ emissions from hybrid electric vehicles (HEVs). This is based on "well-to-wheels" life-cycle accounting that quantifies the fuel-related emissions for each vehicle from source to end use. When the electricity comes from gas, nuclear, or renewable generators, PHEV emissions fall below those of conventional vehicles and HEVs.




Notes: g $CO_{2e}$ = grams carbon dioxide equivalent; IGCC = integrated gasification combined cycle.

© E Source; data from Electric Power Research Institute and Natural Resources Defense Council

In 2007, EPRI and the Natural Resources Defense Council (NRDC) published an assessment of the potential nationwide greenhouse gas emission impacts of PHEVs. [21] The study evaluated emissions under three potential carbon intensities for the grid in 2050 and three scenarios for PHEV market penetration. In each of the nine resulting scenarios, analysts found substantial $CO_2$ reductions resulting from PHEV adoption, ranging from 163 million tons (low PHEV penetration and high grid carbon intensity) to 612 million tons (high PHEV penetration and low grid carbon intensity) annually.

Oak Ridge National Laboratory (ORNL) evaluated the effects of a robust fleet of PHEV-20s in each of the 13 North American Electrical Reliability Council (NERC) regions and compared the results to scenarios in which the same transportation needs were met by HEVs. [22] Using EPRI's assumptions that the PHEV fleet would rise from 0 percent of the market in 2010 to 25 percent in 2020 and remain at that level, the study authors estimated a national fleet of 19.6 million PHEVs on the road in 2020 and 50.4 million in 2030.

The ORNL study results show considerable variability in $CO_2$ emissions from one NERC region to another, ranging from a 55 percent increase in 2020 emissions in the Mid-America Interconnected Network NERC region (Illinois and parts of Wisconsin, Iowa, and Missouri) where generation is dominated by coal-fired power plants, to a 28 percent decline in $CO_2$ emissions in the Electric Reliability Council of Texas NERC region, where all PHEV charging energy is generated by gas-fired power plants. On a national basis, the study concludes an increase in $CO_2$ emissions of 7 to 10 percent as of 2020, depending on the scenario. The simulation results for 2030 range from an increase of about 7 percent in national $CO_2$ emissions to a decrease of about 3 percent. It's important to note that this is a "tank-to-wheels" study; it doesn't account for emissions from the transporting and refining of crude oil, which is about 20 percent of total HEV emissions. And although this study does not quantify its criteria on pollutants associated with vehicle operation, EPRI and NRDC also produced a companion report that does assess them. [23]

## Energy and Load Impacts

PEVs present a double-edged sword to utilities. On the one hand, they promise a new and growing load and, potentially, an opportunity to garner $CO_2$ emissions credits. On the other hand, if not managed carefully, PEV charging threatens to overload feeders and substations and will require additional peak generation capacity. With some planning and foresight, utilities can reap the benefits that PEVs offer and avoid the peak-load headaches.

**PEV energy consumption.** PEV sedans can currently travel about 4 miles on 1 kWh of electricity. So if a vehicle travels 12,000 miles per year and electricity provides 80 percent of the motive power, that comes to about 2,400 kWh of electricity consumed per year per PEV. Assuming a battery charge-discharge efficiency of 85 percent, that brings the per-vehicle consumption to a little over 2,800 kWh. Multiplied by the millions of vehicles that some are projecting over the course of the next decade, [24] this load could amount to many millions of megawatt-hours. That may sound like a lot of energy, but it's a surprisingly small fraction of the existing electricity load given the proportion of transportation needs that the energy could provide.

In the ORNL study, researchers projected 19.7 million PHEVs on US roads in 2020 and 50.4 million in 2030; those projections are fairly consistent with EPRI's 2011 "high penetration" market projections of 65 million PEVs on the road by 2030. [25] ORNL researchers then distributed these vehicles across the NERC regions using data from the DOT's Bureau of Transportation Statistics. The charging energy required in 2020 for the anticipated regional PHEV fleets represented an increase of less than 2.0 percent in all but two of the regions: New England (a 2.0 percent increase) and California (a 2.7 percent increase). In the 2030 projection, the much larger PHEV fleet requires proportionately more electricity, but, with the same two exceptions, the increase is below 4.0 percent in all regions and is well below 3.0 percent in most.

**Peak load.** Although the energy requirement for PEV charging appears to be relatively modest and unlikely to pose much of a near-term problem for utilities, the location and timing of that consumption could well prove problematic. If drivers choose to charge their PEVs whenever they're parked to maximize battery state of charge, much of the load will occur during peak-load hours and new generating capacity will be needed to serve it. So far, it's unclear whether or not such "opportunistic charging" will play a major role in PEV charging overall because most charging occurs at home and (perhaps surprisingly) a large fraction of total charge events occur at standard, 120-volt outlets. [26]

If utilities actively engage consumers to educate them about potential peak loading problems and provide incentives for off-peak charging such as time-of-use pricing with a significant on/off peak price differential, then PEV power draw could prove to be of little or no concern. In fact, a PNNL study suggests that idle grid capacity could support the energy needs of as much as 73 percent of the existing fleet of light-duty vehicles (cars, pickups, vans, and SUVs) if they were converted to PEVs and charged during off-peak hours. [27]

Several studies have been completed to assess the potential magnitude of the peak load impact PEVs might have on the electric utility grid. The ORNL regional study evaluated peak load impacts of large PHEV fleets in 2020 and 2030 across six scenarios with three charging rates (1.4, 2.0, and 6.0 kilowatts [kW]) and two charge initiation times (5:00 p.m. and 10:00 p.m.). The analysis identified significant peak impacts in each region—as high as a 10.1 percent increase in peak load in 2020 and a 28.0 percent increase in 2030 for the scenarios in which PHEVs are charged at 6.0 kW beginning at 5:00 p.m. (**Table 3**). [28] The peak load impacts are of course lower in the lower-charge-rate scenarios—but none of the scenarios in which PHEVs are charged beginning at 10:00 p.m. suffered any increase in the annual peak load.

**TABLE 3: Projected increase in annual peak demand due to vehicle charging**

An Oak Ridge National Laboratory simulation demonstrates that if plug-in hybrid electric vehicles (PHEVs) are charged during peak load hours (starting at 5:00 p.m.), they will create significant additional peak load burdens for utilities, especially at the highest charging rate modeled (6 kilowatts). However, none of the modeled scenarios in which PHEV charging begins at 10:00 p.m. resulted in any additional contribution to peak load.

| | Increase by 2020 | | Increase by 2030 | |
|---|---|---|---|---|
| North American Electric Reliability Council region | Peak GW | Percentage | Peak GW | Percentage |
| East Central Area Reliability Coordination Agreement | 5.2 | 4.2 | 19.3 | 14.7 |
| Electric Reliability Council of Texas | 3.5 | 4.5 | 10.9 | 12.7 |
| Florida Reliability Coordinating Council | 3.3 | 5.3 | 10.2 | 13.7 |
| Mid-America Interconnected Network | 6.4 | 10.1 | 16.9 | 24.4 |
| Mid-Atlantic Area Council | 4.3 | 6.0 | 15.3 | 19.4 |
| Mid-Continent Area Power Pool | 2.5 | 7.4 | 6.9 | 18.5 |
| Northeast Power Coordinating Council (New England) | 1.6 | 4.9 | 7.4 | 21.7 |
| Northeast Power Coordinating Council (New York) | 2.4 | 6.9 | 7.9 | 21.8 |
| Southeastern Electric Reliability Council | 6.4 | 3.1 | 25.9 | 10.8 |
| Southwest Power Pool | 0.6 | 1.2 | 2.7 | 4.9 |
| Western Electric Coordinating Council (Rocky Mountain, Arizona, New Mexico, Southern Nevada) | 1.3 | 2.3 | 4.2 | 6.4 |
| Western Electricity Coordinating Council (California) | 5.6 | 9.0 | 20.7 | 27.9 |
| Western Electricity Coordinating Council (Northwest) | 3.2 | 6.9 | 9.4 | 17.9 |

Note: GW = gigawatts.

© E Source; data from Oak Ridge National Laboratory

National Renewable Energy Laboratory (NREL) published a study in which it analyzed the potential effects a fleet of 500,000 PHEVs (about 30 percent of vehicles currently on the road) would have in the Xcel Energy Colorado service territory, evaluating four charging scenarios: [29]

- *Uncontrolled:* Charging is initiated at home when commuters return from work
- *Continuous:* PHEVs charge whenever and wherever they're parked

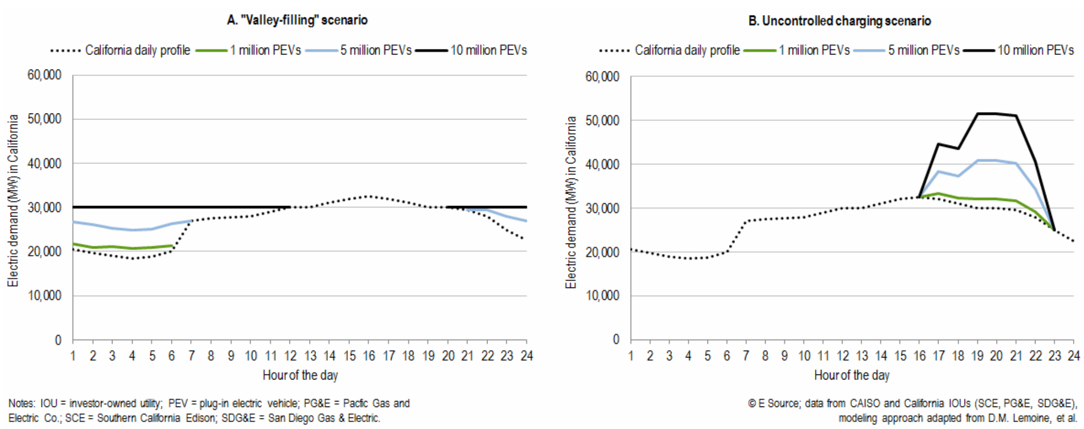
- *Delayed:* PHEV charging begins at 10:00 p.m.
- *Optimized:* The utility controls charging of each PHEV to minimize generation costs

As you might expect, the uncontrolled and continuous charging scenarios would add significantly to Xcel's peak capacity requirements, but neither the delayed nor optimized scenarios contribute to peak load. Clearly, unless utilities take action to motivate consumers to delay charging until off-peak hours, PEV owners will charge their vehicles whenever it's convenient, driving the need for expensive additional peaking capacity. Time-of-use rates can be effective where utilities have deployed meters capable of recording consumption in different time periods, where they have established communication networks capable of sending consumption data back to the utility with high enough frequency, and with a high enough on-peak/off-peak price differential.

Where utilities lack these capabilities, the options appear to be limited. One potential approach in these cases is to educate customers about the problems that on-peak charging can cause and appeal to them to delay charging until off-peak hours. Another possibility would be to distribute timers at low (or no) cost, or to subsidize the installation of PEV charging circuits that integrate timers at customer facilities. The success of these approaches, however, inevitably depends on the goodwill and behavior of consumers, and they would likely prove less reliable than time-of-use pricing. Though early time-of-use demonstrations for PEV charging in California suggest that drivers are cooperative and do not contribute to peak demand, [30] there's still reason to be concerned about the potential impacts on the grid of widespread and unconstrained PEV charging. **Figure 8** illustrates the difference between ideal and worst-case peak load impacts due to PEV charging for the three investor-owned utilities (IOUs) in California. [31]

**FIGURE 8: Demand-profile scenarios for PEV charging in California**

Controlled PEV charging could lead to an ideal "valley-filling" scenario for electric utilities, one with steady revenue and base load growth and little or no impact on peak demand (A). Conversely, uncontrolled charging—where PEV owners simply plug in when they arrive home each day—could drastically impact peak demand (B). These charging demand profiles are overlaid on top of the California Independent System Operator (CAISO) daily load curve.




Although nighttime charging would not contribute to system peak loads for most utilities, the added load posed by PEV charging could stress more-localized components of the transmission and distribution system, such as feeders or transformers, once PEV numbers become significant. PEV "clustering" around a single neighborhood transformer has long been a concern, and more recently the issue has been raised of reduced transformer cool-off time during off-peak hours, though so far, neither of these has presented problems in the field. As one example, grid-impact assessments done by DTE Energy suggest that the utility is unlikely to experience significant impacts to its distribution equipment for many more years. [32] Time-of-use pricing cannot in and of itself ameliorate this type of system constraint, so several groups are working to develop communication and control systems that will integrate PEVs into emerging smart grid systems. Such capabilities could eventually enable utilities to monitor loading on individual distribution components such as feeders and transformers and to control the charging rate of connected PEVs—keeping localized charging demand within acceptable limits. Such capability could also be used to modulate vehicle charging rates to provide grid stability benefits (see Vehicle-to-Grid and Smart Charging).

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## MARKET OUTLOOK

Despite the 2008 global economic downturn—and, in particular, the turmoil it has caused in the automotive industry—at a minimum, all of the major manufacturers are conducting research into PEVs and several have introduced commercial PEV models to the market over the past few years. They are joined by a handful of promising startup ventures and established foreign manufacturers hoping to gain a foothold in the American market with PEV offerings. For a relatively up-to-the-minute list of manufacturers entering the PEV market and the PEV models being made available, see Plug In America's Plug-in Vehicle Tracker.

It's very difficult to predict the uptake that these vehicles will enjoy in the market. So far, monthly PEV sales have fluctuated up and down considerably. A number of researchers have attempted to construct defensible projections of PEV market penetration—those referenced earlier in this report from ORNL and EPRI are among them—but such projections are inherently highly uncertain, given the rapidly shifting economic, technical, and policy environment that these vehicles are emerging into. Advancements in battery chemistry or the commercialization of alternative energy-storage devices could substantially alter the economic equation, as could the existing provisions of ARRA or future federal, state, and local policies. Given this uncertainty, we recommend that utility professionals and fleet managers watch the PEV space closely as it evolves so they can best take advantage of the benefits these vehicles offer and navigate around the potential pitfalls they pose for utility systems.

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