DRIVING THE SOLUTION
THE PLUG-IN HYBRID VEHICLE

by Lucy Sanna

The Story in Brief

As automakers gear up to satisfy a growing market for fuel-efficient hybrid electric vehicles, the next-generation hybrid is already cruising city streets, and it can literally run on empty. The plug-in hybrid charges directly from the electricity grid, but unlike its electric vehicle brethren, it sports a liquid fuel tank for unlimited driving range. The technology is here, the electricity infrastructure is in place, and the plug-in hybrid offers a key to replacing foreign oil with domestic resources for energy independence, reduced CO_2 emissions, and lower fuel costs.

In November 2005, the first few prototype plug-in hybrid electric vehicles (PHEVs) will roll onto the streets of New York City, Kansas City, and Los Angeles to demonstrate plug-in hybrid technology in varied environments. Like hybrid vehicles on the market today, the plug-in hybrid uses battery power to supplement the power of its internal combustion engine. But while the conventional hybrid derives all of its propulsion energy from gasoline, the PHEV gains much of its energy from the electricity grid.

What does this mean for the consumer? At current U.S. energy prices—that is, with the cost of gasoline at $3 per gallon and the national average cost of electricity at 8.5¢ per kilowatthour—a PHEV runs on an equivalent of 75¢ per gallon. And given that half the cars on U.S. roads are driven 25 miles a day or less, a plug-in with even a 20-mile-range battery could reduce petroleum fuel consumption by about 60%.

The PHEV combines the best of both electric vehicle and hybrid technologies. Like the electric vehicle, the PHEV is fueled by electricity generated from domestic resources: it reduces carbon dioxide (CO_2) and urban pollutants, provides utilities with a new, sustainable market for off-peak electricity, and offers consumers a clean, low-cost transportation fuel option. And like the hybrid, the PHEV can run on liquid fuel for unlimited driving range. This combination makes the PHEV more efficient in fuel and total energy use than any vehicle of comparable size and performance on the road today.

Dr. Fritz Kalhammer, who beginning in 1973 established and directed EPRI's programs for energy storage, fuel cells, and electric vehicles, has advocated a shift in focus to PHEVs for more than five years. "The PHEV is unique," he states. "It offers the optimal mix of power from the battery and the engine—of energy from the grid and the gas station—to consumers with varying transportation needs. Auto manufacturers can eventually provide a variety of battery options tailored to specific applications—vehicles that can run 20, 30, or even more electric miles."

Until recently, however, even those automakers engaged in conventional hybrid technology have been reluctant to embrace the PHEV, despite growing recognition of the vehicle's potential. A chief concern is the prospectively higher cost of the larger batteries required. Indeed, because the advanced batteries needed for PHEVs are currently produced on a limited scale, prototype PHEVs are costly, but once batteries go into mass production, costs are expected to come down.

According to Robert Graham, manager of EPRI's Electric Transportation Program, "We have the basic technology for the PHEV—the electric drive system and advanced batteries—and we have the infrastructure—home recharging. Our main challenge is to optimize the design of the batteries and the integrated battery-engine control systems that will allow us to take full advantage of the superior fuel savings and emissions reduction potential of this vehicle."

But is there a market? In a 2001 study, EPRI found that 30–50% of consumers surveyed would choose a PHEV even if it were priced up to 25% higher than a $19,000 conventionally powered vehicle. What's more, 63% of respondents preferred plugging in a vehicle at home to going to the gas station. At the time of that survey, the U.S. national average price of gasoline at the pump was projected to be $1.65. Since then, the price has nearly doubled. This ongoing trend makes all types of hybrids—and especially the PHEV—increasingly attractive. Today, in fact, the market for fuel-efficient vehicles has begun to escalate along with the price of oil.

Oil at a Boiling Point

Though the United States holds only 3% of global petroleum, Americans consume 25% of the world's oil supply. According to the U.S. Department of Energy, that was 20.5 million barrels of oil per day in 2004, more than half of which came from imports.

With growing global demand, particularly from China and India, the price of a barrel of oil is climbing at an unprecedented rate. The added cost and vulnerability of relying on a strategic energy resource from an unstable part of the world continues to threaten national security. Add to that the environmental concerns surrounding global warming: petroleum combustion accounts for about 40% of all U.S. CO_2 emissions. Taken together, these three significant issues—fuel cost, national security, and the environment—gained momentum in September 2004 when an unusual alliance of U.S. environmentalists and security hawks, the Set America Free coalition, called on the Bush administration to cut U.S. oil consumption in half over the next four years.

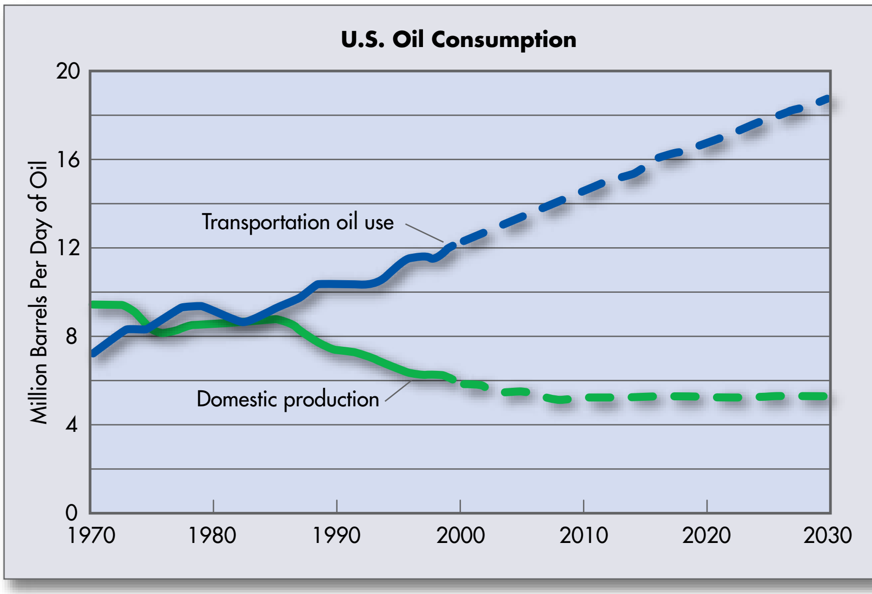
The concern is not new. Anyone over the age of 35 today will remember the so-called Arab Oil Embargo of 1973, which created a worldwide oil shortage. Six years later, the Iranian revolution underscored global energy vulnerability. Before the decade was out, world leaders and energy experts alike sought ways to reduce oil consumption. Energy conservation became the watchword, and efficiency played a major role in reducing overall energy use. Auto manufacturers developed smaller, more-efficient vehicles, appliance manufacturers developed energy-efficient products, and utilities reduced the use of oil for generating electricity; in the United States alone, oil used for electricity decreased from nearly 17% in 1973 to less than 3% today.

In recent years, however, auto manufacturers have increased the power and size of cars and sports utility vehicles, thereby increasing oil dependence. Today because two-thirds of all U.S. oil consumed goes into cars, trucks, and buses, the focus in energy conservation is on transportation.

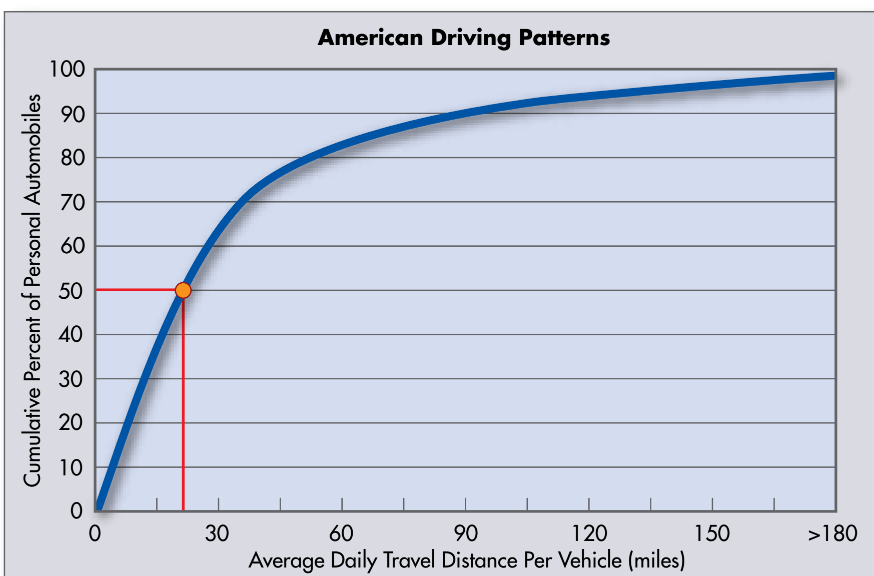
What's Driving the Market?

The internal combustion engine (ICE) is designed to start quickly and provide power as soon as the driver demands it. But until the engine warms up, it runs quite inefficiently. It also idles at every stop, and according to Mark Duvall, manager of technology development for EPRI's Electric Transportation Program, "in urban driving, that idling translates to about 10–15% of total vehicle carbon emissions."

One clean solution is the electric vehicle. In 1996, GM boldly entered the electric vehicle marketplace with its EV1. The EV1 served as a benchmark for electric vehicle technology development, but because of its limited utility and driving range, it met with limited acceptance. Early adopters—mostly environmentalists ready to trade urban pollutants for a clean and quiet if limited ride—were generally enthusiastic about their EV1 experience, but they didn't constitute a large enough consumer base to make the vehicle profitable within the few years that it was available.



While U.S. domestic production of oil has decreased 44% since the 1970s, the use of oil for transportation has increased 83%, and the gap is widening. Given a continuation of this pattern, U.S. oil consumption is expected to grow 60% over the next 25 years, with consequential increases in transportation fuel costs, carbon emissions, and security vulnerability. (Source: Energy Information Administration)



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This being said, hundreds of electric vehicles such as the Toyota RAV4, manufactured for several years under California's zero-emission mandate, continue to operate in communities such as Los Angeles; and a variety of electric vehicles of limited range and performance are now successfully serving such niche markets as airports, retirement communities, city governments, and golf courses. These limited applications, however, cannot solve the problems of strategic vulnerability and trade imbalance caused by dependence on imported oil.

The hybrid electric vehicle is a move in the right direction. Its battery/electric motor combination provides the quick starts, so when the vehicle is standing still, the gas engine can be shut off automatically to prevent idling and conserve fuel. In fact, the hybrid can achieve an increase in fuel efficiency of roughly 30%. The battery also boosts the performance of the ICE at takeoff and for passing.

The hybrid's ICE uses fuel available from any gas station, and the battery charges whenever the ICE is running. The battery also charges when the driver brakes to stop; in a process called regenerative braking, the electric motor becomes a generator and converts otherwise wasted kinetic energy into electricity. Hybrids are not designed to operate on electricity alone, but if they run out of gas, most can go a short distance with extremely limited performance.

In 1997, Toyota introduced the world's first mass-produced hybrid to the Japanese market, and two years later Honda brought its own hybrid design to the United States. Since that time, improvements in battery and system control technologies have increased hybrid power and drivability, and today designs by U.S. and European manufacturers have also emerged on the marketplace.

Because hybrids can cut carbon emissions up to 30% and also reduce urban particulates, early adopters purchased them primarily for the sake of the environment. More recently, however, hybrids have attracted consumers concerned with the price of gas at the pump. In 2003, the Public Policy Institute of California found that 47% of those surveyed would consider buying a hybrid in spite of the higher sticker price. In fact, hybrid sales rose 81% in the United States last year and are expected to double in 2005.

Electricity in the Driver's Seat

Although such hybrid electric vehicles offer substantial fuel efficiencies, they depend entirely on petroleum to charge their electric batteries. If electricity is the end game, why not design a vehicle that will plug directly into the electricity grid—a vehicle that offers high performance and fuel efficiency in both electric and hybrid mode, with a battery pack that would draw a charge directly through a standard home outlet?

"When we saw the results of the 2001 plug-in hybrid design and comparison study," states Graham, "we were encouraged about the potential benefits and market. If these vehicles look so attractive on paper, we reasoned, we ought to build some of them to see if they behave as predicted, and get customer responses."

Aa a result, EPRI has been collaborating with DaimlerChrysler AG of Stuttgart, Germany, to design and build the PHEV prototypes that are now rolling into demonstration in U.S. cities. Based on the DaimlerChrysler Sprinter van, the PHEV Sprinter uses a parallel hybrid configuration with five-speed automatic transmission. The prototypes are testing two different advanced battery chemistries: nickel–metal hydride (NiMH) and lithium ion (Li-Ion). They're also testing hybrid performance for two different liquid fuels: diesel and gasoline. Lessons learned in the demonstration of these initial PHEV commercial vehicles can be applied to mass consumer vehicles in the near future.

"DaimlerChrysler recognizes the potential market for zero-emission PHEVs in sensitive environmental areas, including cities that are becoming closed to polluting vehicles," says Graham. "Once we have results from this demonstration phase, we'll work with DaimlerChrysler to refine the technology, with a drive toward mass production."

How is a PHEV battery charged? "A PHEV sedan could be charged through a 120-V outlet in three to four hours," says Graham, "and a commercial delivery van charges in about four to five hours on the 240-V connection typically found in commercial garages." The PHEV will either have an onboard charger that plugs into an electric outlet, or it will plug into a charger installed in a service garage. "In the future," Graham notes, "auto manufacturers could make PHEVs even more convenient by offering a docking station: when the vehicle arrives in the garage, it rides onto the docking station and charges automatically, without a plug."

Regarding the cost of this electricity to the consumer, Duvall states, "If a van like the Sprinter PHEVs now being demonstrated is driven about 20 miles on batteries five days a week for 50 weeks a year, it will use about 2000–2500 kWh to cover its 5000 annual all-electric miles. In the United States, this electricity will cost about $170–$215 annually. Compare this with the annual fuel cost of about $750–$825 for a gasoline van driving the same 5000 miles at an average fuel efficiency of 18 miles per gallon and today's gasoline prices."

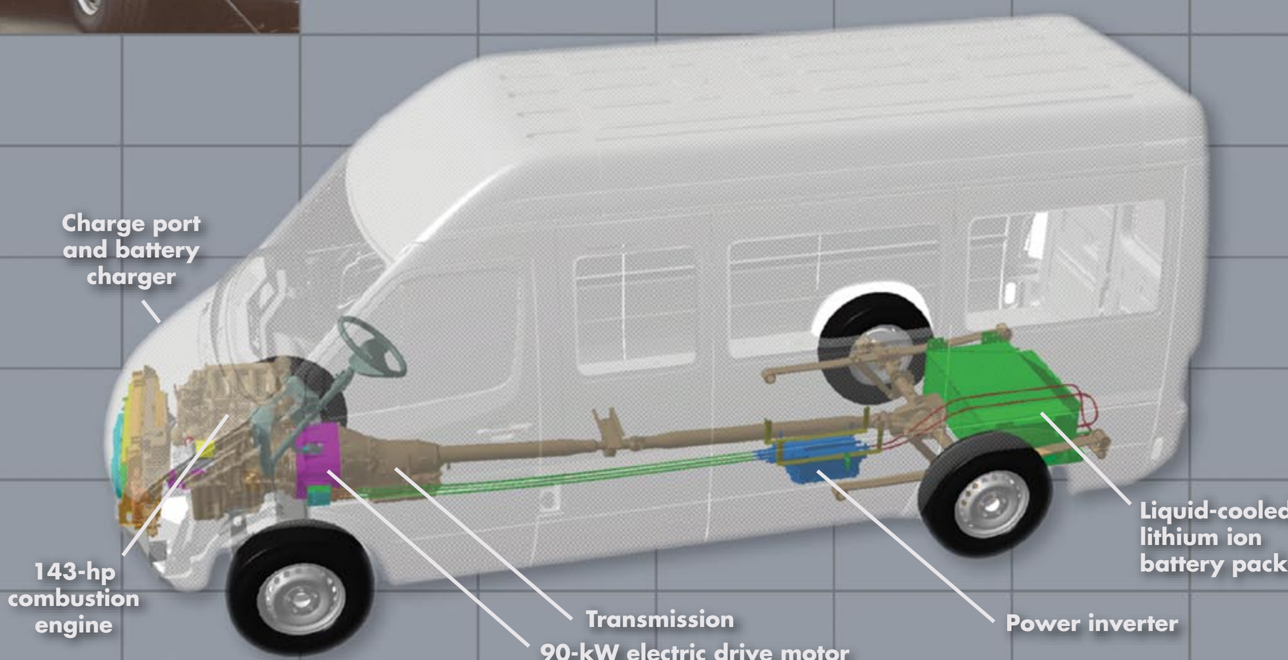
Where will the electricity come from to charge PHEV batteries? Consumer demand for electricity peaks during the day, but more than 40% of the generating capacity in the United States sits idle or operates at reduced load overnight. It is during these off-peak hours that most PHEVs would be recharged. According to Roger Duncan, deputy general manager, Austin Energy, "Our national power system could charge tens of millions of PHEVs without requiring new plants. What's more, we produce a lot of wind-generated electricity, mostly at night, which provides a perfect fit for environmentally friendly PHEVs."

Putting PHEVs on the Road

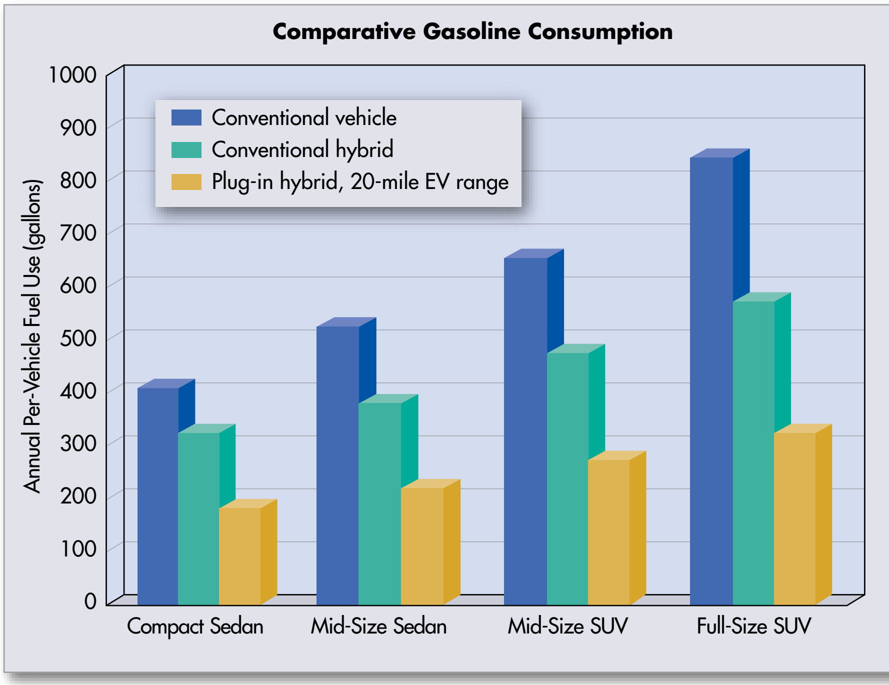
"EPRI is leading the charge on the technology side of this issue," says Duncan, "and political groups such as Set America Free are working on the regulatory and policy side. What's needed now is a market for PHEVs, and we're starting at the grassroots level." With that goal, Austin Energy has taken the lead in forming a national coalition of local and state governments, electric utilities, nonprofits, and the business community to initiate grassroots campaigns in 50 to 75 cities to demonstrate that a market exists today for the mass production of PHEVs.

According to Will Wynn, mayor of Austin, "We believe that the 50 largest cities in this country, united in purpose, can build a groundswell of demand sufficient to entice carmakers to mass produce what is the logical near-term step toward the critical goal of energy independence. And we intend to set the example right here."

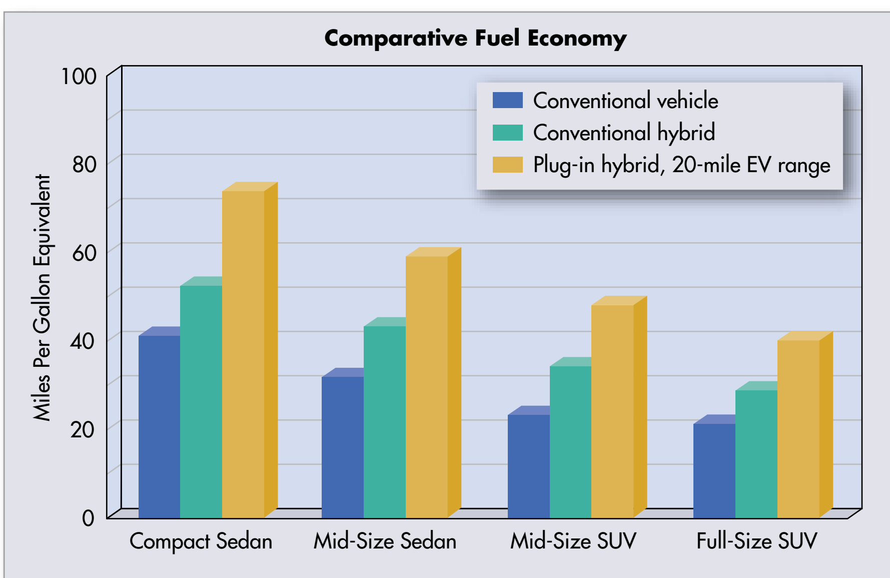
For starters, the city of Austin will set aside a million dollars for rebates to help local governments, businesses, and citizens acquire PHEVs once they become available for purchase. The campaign is also asking local governments and businesses to make "soft" commitments to add PHEVs to their fleets. In addition, Austin will be one of some 10 cities that will sponsor testing of a plug-in hybrid DaimlerChrysler Sprinter van. The city is circulating petitions whereby signees can express to automakers their desire to purchase PHEVs. The national coalition's plan is to replicate this package of rebates, fleet orders, and consumer



Designed and built in a collaboration between EPRI and DaimlerChrysler AG of Stuttgart, Germany, the PHEV Sprinter van incorporates a parallel hybrid configuration with five-speed automatic transmission and an electric energy battery that can be charged from a 240-V AC outlet in four to five hours. The vehicle is designed to use either a nickel–metal hydride (NiMH) or a lithium ion (Li-Ion) battery pack, and is available with the option of either a gasoline or a diesel engine. Sprinters are likely to find their first uses as fleet vehicles, such as delivery vans and shuttle buses, that can run cleanly and noiselessly in stop-and-go driving on city streets throughout the day and then plug into the electricity grid at night to take advantage of off-peak power.



Nearly 70% of all oil consumed in the United States fuels cars, trucks, and buses, and as auto manufacturers increase the power and size of passenger vehicles, the amount of petroleum needed for personal transportation increases as well. The hybrid was a step forward in reducing petroleum consumption, and now the PHEV takes the next step, doubling that improvement—the PHEV is to the hybrid as the hybrid is to the conventional vehicle. (Source: Energy Information Administration)



The equivalent fuel economy of the plug-in hybrid vehicle with a 20-mile-range battery is more than double that of a conventional vehicle and 30–50% higher than that of a conventional hybrid. Because of the amount of petroleum it displaces, for example, the PHEV version of the full-size SUV has a fuel economy equivalent to that of a mid-size hybrid. (Source: Bureau of Transportation Statistics)

endorsements in municipal governments across the country.

While a plug-in hybrid can be a vehicle of any size, the earliest market targets are fleet vehicles—delivery vans, shuttle buses, and maintenance vehicles, for example. For many local service and government organizations, fleet vehicles can run cleanly and noiselessly on city streets throughout the day and then plug in at night to take advantage of off-peak power. Some of these vehicles may almost never need to visit a gas station because of their short routes. But in cases where the vehicle drives beyond that range and depletes the battery charge to a preset minimum level, the PHEV will automatically switch to its ICE/battery combination and operate as a typical hybrid. In that mode, the electric motor supplements the PHEV's ICE for highly efficient acceleration and passing performance with minimal emissions.

The Environmental Equation

Cutting back on imported oil may be good for the U.S. economy and national security, but what about the environment? After all, 55% of the nation's electricity is generated by coal. If we transition from gasoline to electricity, aren't we just trading one set of pollutants for another?

Not so, according to the California Air Resources Board. A CARB study looked at the so-called well-to-wheel emissions of electric vehicles—that is, emissions along the entire supply chain, from extraction of the fuel source all the way to the tailpipe and the wheel. Using today's national grid, a battery-powered electric vehicle generates only a third of the greenhouse gases produced by an equivalent gasoline vehicle. The differential will only improve as old plants are modified with pollution controls or retired and as new generation comes to rely increasingly on clean coal technology, renewable energy, and in the longer term, advanced nuclear power. What's more, pollution is easier to manage at a large, central electric generating plant than at the tailpipes of millions of gas-guzzling vehicles.

Advanced Battery Technology

The battery is the heart of any electrically powered vehicle. The performance and practicality of the vehicle depend on the weight of the battery in relation to the amount of energy it can store and the power it can produce. The lighter and more compact the battery, the more efficient and practical the vehicle; and the more energy the battery stores, the longer the vehicle's driving range.

Electric vehicles of the past used mostly lead-acid batteries and had very limited range. The considerable battery weight compromised vehicle performance and efficiency. And lead-acid batteries had a relatively short life, which meant several replacements over the life of a vehicle.

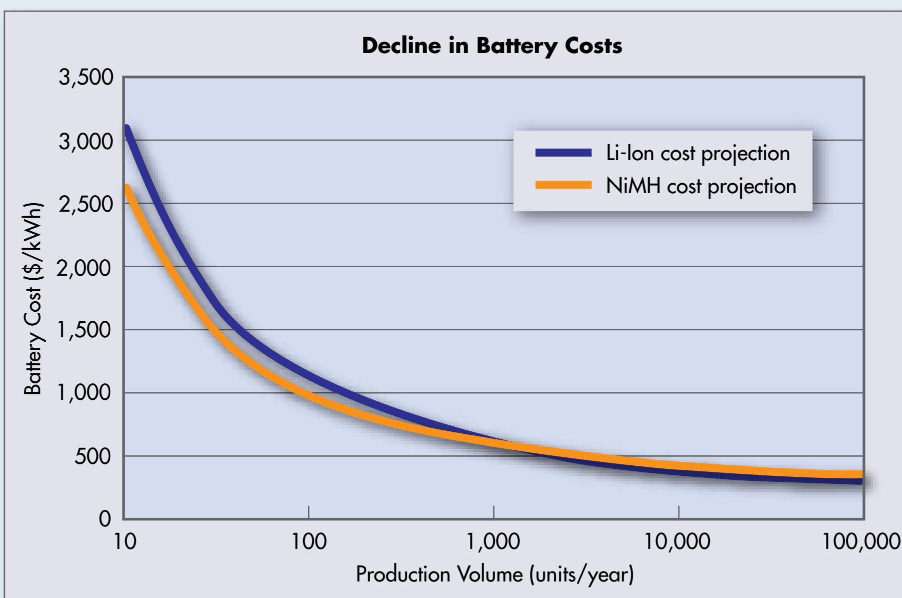
Today's advanced batteries, principally the nickel–metal hydride (NiMH) and the lithium ion (Li-Ion), have demonstrated not only much-higher energy storage and power delivery capabilities but also far longer life in the deep-discharge cycling required for electric vehicle and PHEV propulsion. Specifically, for a given amount of energy storage, the NiMH battery weighs half as much as a lead-acid battery and produces two to four times the power. The Li-Ion battery weighs half as much as a NiMH battery and provides up to 100% more power than NiMH. Being the lightest and most powerful, the Li-Ion battery has a fundamental advantage. For example, a state-of-the-art NiMH battery that weighs around 250 kg can give a Sprinter a range of 20 to 30 miles on electricity alone, which is perfectly adequate for PHEVs that can perform a substantial fraction of their daily operations within that range. The lighter Li-Ion battery, on the other hand, would be the choice for PHEVs that need a greater electric range—say, 40 to 60 miles—and for purely electric vehicles.

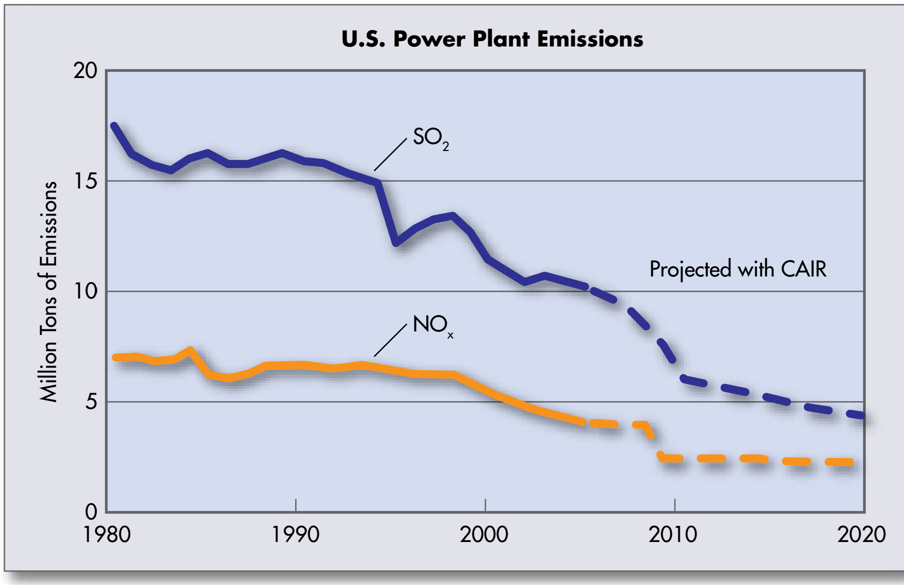
Unlike the lead-acid battery, both NiMH and Li-Ion batteries have the potential for very long life. The NiMH battery has demonstrated more than 2000 deep-discharge cycles—that is, cycles that nearly deplete the battery of its stored energy. The Li-Ion battery has shown more than 3000 deep-discharge cycles. These numbers correspond with the number of cycles a PHEV battery is expected to deliver over the vehicle's 10- to 15-year life. In the lab, a lead-acid battery can live through just 1000 such cycles at best, and in practice, not more than 300 or 400. What's more, NiMH and Li-Ion batteries can be recycled to recover and reuse their valuable metal content, and unlike lead-acid batteries, they don't use any toxic materials.

A major disadvantage of advanced batteries is their high cost. Both NiMH and Li-Ion are more expensive to produce today than lead-acid batteries: the materials themselves are more expensive, and the manufacturing methods are substantially more sophisticated. But just as the cost of the small NiMH and Li-Ion batteries used in cell phones and other hand-held devices has dropped dramatically, the cost of PHEV batteries is expected to drop as they go into mass production and as worldwide competition for that market develops.

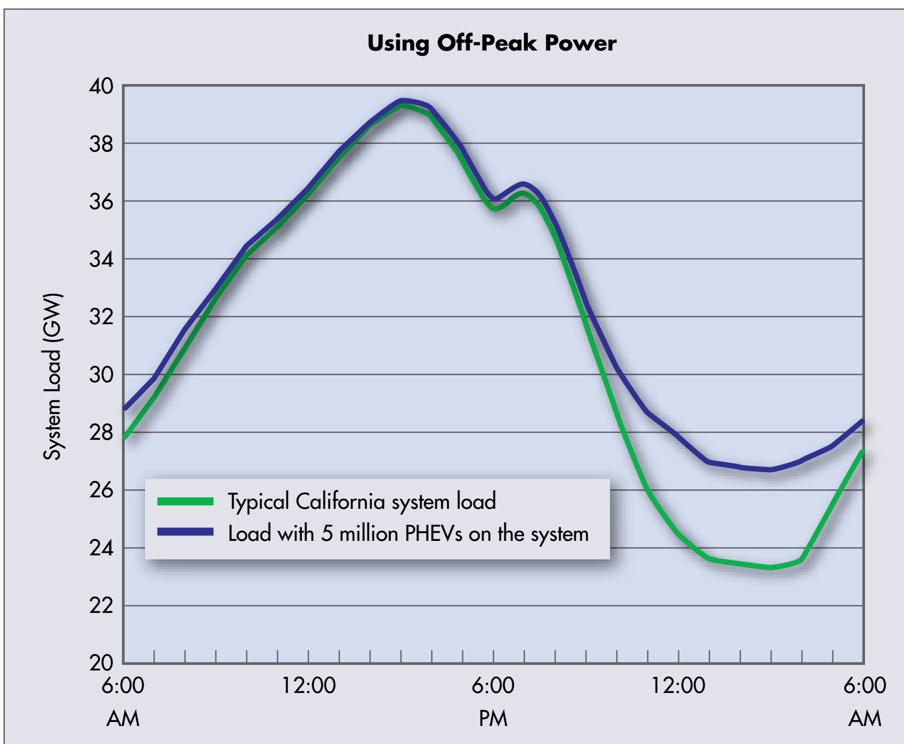
The ultimately achievable cost is likely to determine which applications develop first and to what degree PHEVs of extended electric range will penetrate markets. The PHEV DaimlerChrysler Sprinters in demonstration today are testing both NiMH and Li-Ion batteries to establish optimal weight, range, performance, and operation in a variety of climates and real-life applications.

The production cost of NiMH and Li-Ion batteries presents a key challenge to the marketability of PHEVs. As production volume increases, however, costs will come down with the introduction of automated manufacturing lines and economies of scale. The cost-effective tipping point is at about 100,000 battery packs annually. With roughly 16 million new cars sold in the United States every year, once auto manufacturers commit to the PHEV, that tipping point should be easily reached.





Over the past 25 years, electric utilities have reduced power plant emissions by retiring older plants and incorporating advanced, clean generation technologies. Since 1980, power plant emissions of SO_2 have decreased by 40%, and of NO_x by 36%. Projections based on the new Clean Air Interstate Rule (CAIR) show continued emissions reductions into the future, which means that the PHEV—which draws electricity directly from the grid—will actually get cleaner with age. (Source: U.S. Environmental Protection Agency)



Because PHEVs would be charged mainly at night—when electricity is readily available—generating plants would run much closer to steady load. Electric utilities could capitalize on expensive assets that now sit idle during off-peak hours, allowing for more-efficient operation. The PHEV also provides utilities with a new major electricity market without the need to build additional power plants.

The bottom line is this: because electricity generation is getting cleaner over time, electric vehicles and PHEVs will actually get cleaner with age. The PHEV offers the most promising approach to reducing CO_2 emissions in transportation.

Sustainable Transportation

"We are currently in the PHEV feasibility phase, with the objective of testing and demonstrating the concept in multiple applications," says Graham. "Beginning in 2006, we plan to promote interest across the country in order to lower vehicle production costs and demonstrate a business case to additional auto manufacturers, particularly those who would like to partner with us in developing PHEVs for consumer markets. We expect PHEVs to be available for commercial van application by 2008 and to be in the mass consumer marketplace by 2010."

In the future, the PHEV can become a key part of the long-term transition to a carbon-free energy economy, where petroleum will be replaced by clean energy sources through the energy vector electricity. All renewable and carbon-free primary energy sources—hydropower, solar energy, wind energy, biofuels, and uranium materials—are readily and efficiently converted to electricity, and the PHEV offers the best prospects for widespread use of electricity as a transportation fuel.

What about hydrogen? Derived primarily from water, hydrogen is not a new idea as a fuel source. In 1874, in fact, Jules Verne saw water as "the coal of the future." While the current U.S. administration views the fuel cell hydrogen vehicle as the solution for reducing foreign oil imports and greenhouse gases, energy experts predict that the hydrogen economy may be at least fifty years in the future.

But if we do see that day, will there be a role for the PHEV? According to Graham, most definitely. "It would make enormous sense for a fuel cell vehicle to have a battery of sufficient storage capacity to provide battery-only range for the vehicle.

For one thing, the cost of a battery capable of delivering a given amount of power will very likely always be lower than that of a fuel cell with the same power rating. Batteries are inherently simpler to manufacture and operate than fuel cells. Just as important, electricity will be much less expensive as a transportation fuel than hydrogen, in part because we already have the required electricity production and distribution infrastructures, and in part because the well-to-wheel efficiency is much higher for electricity from the grid. So any fuel cell capacity and hydrogen fuel you can replace with a battery and grid electricity will lower both the first and the operating costs of transportation. Instead of being a competitor, the PHEV actually might help effect a long-term transition to fuel cell vehicles because of the PHEV's potential to lower the high capital and fuel cost barriers faced by fuel cell electric vehicles."

Today the plug-in hybrid is attracting the attention of U.S. municipalities concerned about reducing both fuel costs and urban pollutants. It's attracting the attention of political organizations on both the left and the right that are concerned with global warming on the one hand and energy security on the other. The future of the PHEV depends on the willingness of market leaders to grab hold of this solution and drive it to commercialization.

"Municipal governments benefit from lower urban emissions and lower-cost transportation," says Duncan. "And utilities gain a new market for off-peak power. EPRI is paving the road to sustainable transportation, but it can't achieve that goal alone. Electric utilities and municipalities must make it both attractive and convenient for consumers to plug in hybrid electric vehicles."

Background information for this article was provided by Robert Graham (rgraham@epri.com), Mark Duvall (mduvall@epri.com), Fritz Kalhammer, and Roger Duncan.

The Impact of Collaboration

EPRI's Electric Vehicle Program began as an effort to understand the benefits and challenges of introducing a new electricity-based technology to the U.S. marketplace. According to Dr. Fritz Kalhammer, who initiated the program in 1976, "We saw the potential of electric vehicles, but we knew that the utility industry alone couldn't design, test, and demonstrate them and take them to market. We needed the backing of major auto manufacturers." Over the ensuing years, EPRI collaborated with a number of partners that included government organizations, auto manufacturers, and electric utilities in the development, testing, and demonstration of electric vehicle technologies.

Because the success of the electric vehicle depends on the batteries that power it, EPRI collaborated with GM, Ford, Chrysler, and DOE in 1991 to found the U.S. Advanced Battery Consortium—the USABC. It has been largely responsible for bringing the NiMH and Li-Ion electric and hybrid vehicle battery technologies to where they are today.

Perceiving the potential of hybrid electric technology, EPRI in 1999 formed the Hybrid Electric Vehicle Working Group (HEVWG), which brings together representatives from the utility and automotive industries, government and regulatory agencies, and university research organizations. From its inception, the HEVWG has led the energy and auto industries in studies and analyses of PHEV technology and market acceptance.

In 2001, the HEVWG completed the first public domain multivariate study comparing benefits and impacts of conventional vehicles and PHEVs; the study provided evidence that grid-connected hybrid electric vehicles would be technologically feasible and could offer significant benefits. The report also presented results of a customer survey indicating that people preferred plugging in a vehicle to going to the gas station. With the encouraging results of that study as support, EPRI was able to develop its partnership with DaimlerChrysler to design, develop, test, and demonstrate the PHEV prototypes that are on the road today. Other funders and participants include Southern California Edison Company, New York Power Authority, the Federal Transit Administration, the Metropolitan Energy Center of Kansas, Long Island Power Authority, and the South Coast Air Quality Management District.

Further Reading

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