Plug-in Hybrid Vehicles for a Sustainable Future

Appropriately designed hybrid cars will help wean society off petroleum. The necessary technology is available now

Andrew A. Frank

The idea of a hybrid vehicle—one that propels itself using both a conventional engine and an electric motor—is not new. Indeed, some hybrid automobiles were produced more than a century ago, when the internal combustion engine was still in its infancy. These cars were designed to address the limited range of existing electric vehicles and the difficulty of starting the early engines, which had to be cranked by hand (a procedure that resulted in not a few broken arms). The early hybrid vehicles, and the purely electric cars that dominated the fledgling automobile industry early in the 20th century, eventually gave way to a proliferation of cars based on the now-ubiquitous internal combustion engine, a development made possible by the relatively low cost and widespread availability of gasoline.

As a result, the hybrid concept remained dormant until the 1970s, a decade during which the price of a gallon of gas tripled. The higher cost brought to light an inherent problem of using internal combustion engines in cars: inefficiency. For example, until recently it's been universal practice to keep the engine running at all times, even when the car comes to a stop, because having to restart the engine was viewed as problematical. So the engines in our cars are simply idled, which uses fuel to do essentially nothing. Even when the car is moving, much energy is wasted because the engine is usually throttled—the amount of air it is allowed to take in is restricted, which lowers power to an appropriate level but also acts to diminish efficiency. What's more, fuel is even consumed in *slowing* the car, because this is normally done by throttling back the engine after running at speed.

Such inefficiencies are not so worrisome for aircraft or ships, which seldom idle and infrequently run at anything other than an optimal speed. But automobiles typically operate at very low power levels. In the city, the average speed of a car is just 19 miles per hour, which requires around 9 kilowatts (equivalent to 12 horsepower). Yet the driving public demands rapid acceleration from its cars, which requires something like 150 kilowatts or 200 horsepower. Thus our cars usually operate with their engines throttled way back so as to use only a small fraction of their available power. With highway driving, which uses 12 kilowatts or about 16 horsepower (for a medium-sized sedan cruising at 65 miles per hour), somewhat better fuel economy can be realized. But even at highway speeds, the efficiency is far from what could be achieved were automobile engines not throttled so much.

Space-Age Quest

The inherent inefficiency of the engines used to power cars and trucks has long been recognized. So when the price and availability of gasoline became a concern three decades ago, automotive engineers began to search for better alternatives—and the hybrid-car concept looked quite interesting.

In the 1970s, I was a new professor at the University of Wisconsin, having come from more than a decade in industry where I worked on helicopters, missiles and spacecraft sent to the Moon. I was thus armed with knowledge of the latest aerospace technology, so it was natural for me to want to tackle the problem of greatly improving the fuel efficiency of the automobile. I set the personal goal of designing a car that could get 100 miles per gallon while providing performance equal to or better than the conventional car up to 65 miles per hour (somewhat faster than the 55-mile-per-hour national speed limit set in 1974). But I didn't announce my aims to the agencies funding me at the time for fear that I would be scoffed at.

I studied the possibility of reaching my targets using a hybrid that exploited the technology of the day. But I quickly discovered that the kinds of batteries then available (lead-acid, nickel-cadmium or iron-nickel Edison cells) were too heavy and could not produce the needed power or store the energy required to provide the desired power-leveling effect. In addition, although the concept of an automobile with two energy supplies on board remained conceptually sound, it was difficult to imagine the average American grandmother driving a vehicle with more controls than a steering wheel, accelerator and brake pedal. How then was the driver to manage the two separate power sources? Another thorny issue was the need to have enough power available to perform any maneuver desired by the driver—whether that be passing a truck on a grade or bringing the vehicle swiftly to highway speed on an uphill on-ramp.

One way to satisfy this requirement is to keep the engine at about the same

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Figure 1. "Yosemite," a Ford Explorer that was transformed into a plug-in hybrid, was tested at Ford's proving grounds in Yucca, Arizona. This and similar prototypes have demonstrated the technology needed for a vehicle that can travel for several tens of miles on electric power alone while still having a small internal combustion engine available for longer trips. (Photograph courtesy of Argonne National Laboratory.)

size as it is in a conventional car. Then a hybrid vehicle can always revert to its engine to provide the power needed. Another way is to have a large battery pack with enough energy for the longest anticipated maneuver—an approach that allows the designer to reduce the size of the engine and thus save weight. Beginning in 1972, my students and I began exploring these strategies by designing and constructing various prototype vehicles for contests run by the U.S. Department of Transportation and later by the Department of Energy (DOE). With our early work, the challenges of engineering hybrid vehicles became abundantly clear.

One of the missing pieces at the time was an efficient and lightweight energy-storage device that could instantaneously produce high levels of power. Another gap in technology was a computer that could manage multiple sources of energy efficiently and automatically. It would have to deliver high power to the wheels when required and also, when the car needed to be slowed, to transform the kinetic energy of motion into electricity for charging the battery so this energy could later be reused. Another element that was lacking was a transmission system that could efficiently handle more than one power plant.

My research, and that of many of my contemporaries in automotive engineering, immediately moved to finding technical solutions for these challenges. Our first efforts were directed at developing a way to store energy other than in an electrochemical battery. About this time the DOE learned of research on energy-storage flywheels and started a program to develop mobile flywheels that could store enough energy to drive 100 or more miles. Rough calculations published in an article in *Scientific American* showed that it was possible to design a flywheel to do this. There were, however, a few technical issues not mentioned in the article. In particular, it glossed over the difficulty of making a device for vehicular use that could safely carry an enormous amount of kinetic energy in a spinning mass.

The idea that had sold everyone on this approach was that a flywheel made of composite material would be inherently safe, because if it failed it would suddenly become a group of randomly arranged fibers, and all the energy would be dissipated as heat. The problem is that the law of conservation of momentum makes other, more dangerous failure modes more likely, and safety precautions were needed to protect from them. The best researchers in industry and government labs missed this simple fact. After a few disastrous accidents and a lot of money spent, the DOE program was canceled at the end of the '70s. In the meantime, I had constructed two flywheel-powered cars and demonstrated that such a vehicle could achieve 50 percent better fuel economy than was then typical. The flywheel hybrid could get about 35 miles per gallon, but that would be about the limit—a long way from my original 100-mile-per-gallon goal.

One reason that these flywheels didn't work out better was that they stored very little energy for their weight and bulk. To give a modern perspective on the problem, the flywheel systems my colleagues and I built into these hybrid cars weighed about 500 pounds,

Figure 2. Only two plug-in hybrids are now commercially available: a special version of the Mercedes Sprinter delivery van *(left)* and an electric version of the Renault Kangoo *(right)* that carries a small internal combustion engine to charge its batteries, thus extending the car's range. (Photographs courtesy of DaimlerChrysler, left, and Renault, right.)

but the same amount of mass today in advanced electrochemical batteries can hold 20 to 30 times more energy. Because the flywheels could not store enough energy for long maneuvers, the engines in these hybrid cars could not be made any smaller than normal. Thus the considerable added weight of the flywheel could not be balanced by adopting a lighter engine.

In the 1990s, the California Air Resources Board, the authority charged with cleaning up the state's smoggy skies, realized that it would be possible to build zero-emission cars powered only with electricity from the power grid. Use of such vehicles would shift emissions from tailpipes to central power plants, where pollutants could be more easily controlled. The key was a good electrochemical battery. Research by Ovonic Battery Company and a consortium of other battery makers showed that the metal-hydride battery could store enough energy to make an electric vehicle practical, and many companies around the world began research in this area.

Further thrust came from a government-industry effort (spearheaded by Al Gore, then the vice president) called the Partnership for a New Generation of Vehicles. The managers of that program decided that California's electric-car initiatives were too ambitious, so they set the goal of constructing a gasoline-burning vehicle that could get three times the fuel economy of a conventional automobile. The only way to achieve that kind of mileage was with a hybrid, which would require electrochemical cells of one sort or another. The prospect that auto makers might build such cars in larger numbers further spurred research on electrochemical cells.

By about 1995, battery technology had advanced to a point where it was sufficient for hybrid cars. The next task facing designers was to bring the overall cost down to a level that would be competitive. In the late 1990s, Toyota and Honda introduced hybrid vehicles into the marketplace, demonstrating that considerably improved fuel economy can be achieved at a reasonable price. Today every other car company is suddenly realizing that many people are willing to pay more for better gas mileage, which should create enough sales volume to drive the costs down even further. Thus the hybrid power train is being established as a modern automotive standard.

The hybrid cars being sold today are showing improvements of 20 to 30 percent in fuel economy, but they still fall far short of the goalposts I set for myself in 1970: 100 miles per gallon, along with better performance. I and many others are convinced that the solution is to design hybrid cars in a way that many car makers are resisting—so that they can be recharged by plugging them into an ordinary electrical outlet and can travel a considerable distance on electric power alone. Only two plug-in hybrids are now on the market, and both are being sold only in Europe: a version of the Mercedes Sprinter delivery van and the "elect'road" variant of the Renault Kangoo, which is really an electric car with a gasoline-powered "extender" option. General Motors has just recently announced plans to offer a plug-in hybrid in the United States, a version of its Saturn Vue sport-utility vehicle, which is expected to be able to travel something like 10 miles on battery power alone. And in January GM unveiled a concept car dubbed the Volt, a plug-in hybrid with 40 miles of all-electric range. However, it remains unclear when these new GM vehicles might go into production.

Going the Last Mile

The more-typical hybrids one finds on American roads today, those being sold by Toyota, Honda and Ford, for example, follow a design philosophy that puts most of the burden of powering the vehicle on the engine. Were these cars to offer an all-electric mode (which they don't), the batteries would hold only enough energy to drive a very short distance.

My colleagues and I like to characterize hybrids according to the ratio of electric power to total power, a number we call the degree of hybridization. This statistic would be 0 for a conventional car and 1 for a purely electric vehicle (although one wouldn't, of course, calculate the degree of hybridization in either of these two extreme cases). Another useful way to gauge the degree of hybridization is simply by noting the all-electric range. A hybrid electric vehicle that can travel, say, 60 miles on battery power alone would be termed an HEV 60.

The hybrid cars being sold in the United States today have degrees of hybridization close to 0.1. And they all operate so as never to let their batteries become appreciably depleted, thus making them all in essence of the HEV 0 class. What is needed are hybrid cars built with larger electric motors, smaller engines, greater amounts of battery storage and energy-management schemes that allow the batteries to become drawn down to a small fraction of their capacity. Such vehicles could go for several tens of miles without using gasoline at all.

The advantage of that approach becomes obvious when one considers how most passenger cars and trucks are used by private citizens. The typical driver travels less than 40 miles a day. Thus having a car with at least a 40-mile range on battery power alone would allow most people to use no gasoline at all on a daily basis if they could recharge their car's batteries at night by plugging them into an electric outlet. This practice would not only save consumers money at the pump, it would at the same time reduce their tailpipe emissions to zero. Those who drive farther than 40 miles a day would, of course, have to use some gasoline in their cars, but much less than they now do.

What are the impediments to building such plug-in hybrid vehicles? The first is cost. The "power-split" propulsion system Toyota currently uses for its immensely popular Prius (an approach that General Motors, DaimlerChrysler and BMW have also chosen) contains two electric motor-generators and a complex arrangement of gears in the transmission. The problem is that these power trains must compete with conventional engines and transmissions, which cost comparatively little, meaning that such hybrid cars would be expensive even if they required no batteries at all.

A simpler propulsion system is needed to be competitive with conventional cars. One possible strategy is to use what is called a series configuration, whereby the engine is employed only to generate electricity, which is then used to charge the battery and to power one or more electric motors coupled to the wheels. That arrangement has the advantage of being mechanically simple, perhaps requiring no transmission at all. It also allows the engine to run always at maximum efficiency. But a series hybrid also has some important drawbacks. For one, it needs to include a separate electric generator distinct from the motor (or motors) driving the wheels. More important, it suffers from the inherent inefficiency of having to convert the mechanical power produced by the engine into electrical power and then back to mechanical power.

The best strategy, in my view, is to use a single electric motor coupled with a simple transmission that links both it and the car's internal combustion engine directly to the wheels, which is termed a parallel hybrid configuration. In particular, I believe that the key is using a continuously variable transmission, which does away with the usual fixed gears and instead allows the ratio between rotation of the engine and the rotation of the wheels to take on whatever value will allow most efficient operation.

Although engineers have been doing research on continuously variable transmissions since the advent of the automobile, the first truly practical and simple design emerged only in the 1980s with work done in the Netherlands by Van Doorne's Transmissie (which is now owned by Bosch). An alternative design, which came from work done

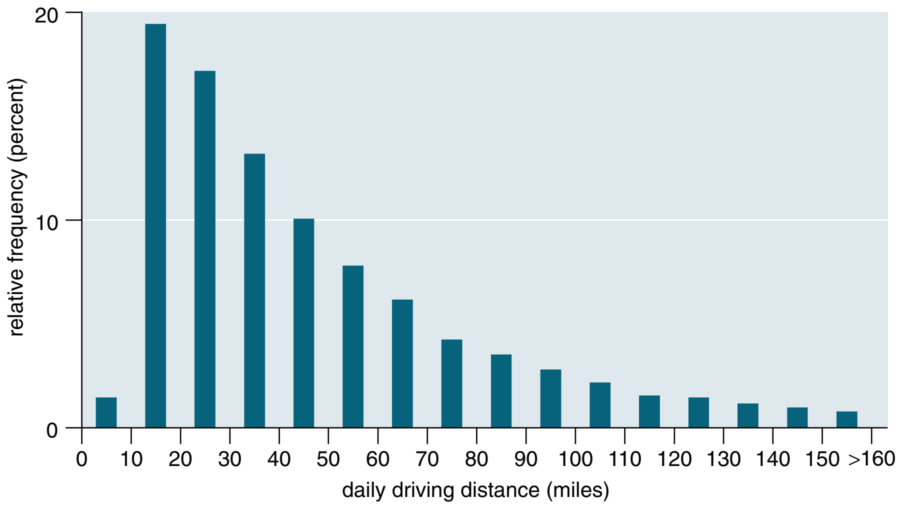

Figure 3. Daily driving distances usually measure less than 40 miles. A plug-in hybrid that could travel that far on electric power alone would thus satisfy most people's requirements while freeing them from their reliance on petroleum-based fuel. (Daily driving distances are based on the results of the 1995 National Personal Transportation Survey.)

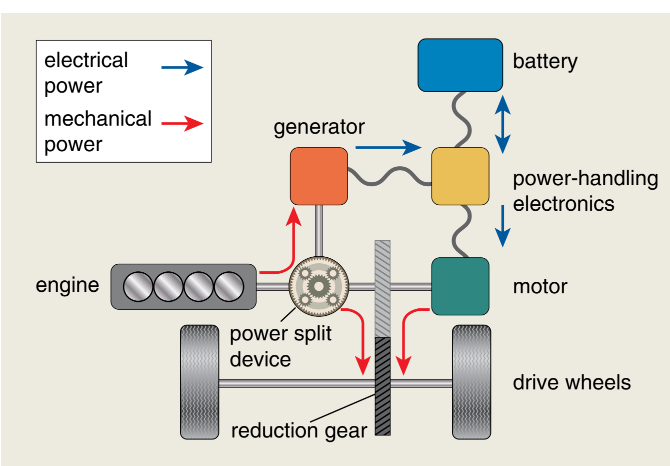

Figure 4. Power-split hybrids channel a fraction of the power from their internal combustion engine to the wheels; the rest is used to turn a generator, which charges the vehicle's modestly sized battery *(left)*. Stored energy in the battery is used to operate an electric motor, which in conjunction with the engine drives the wheels. The Toyota Prius uses this general configuration, as do many of today's other hybrid vehicles. Some Prius owners have equipped their cars with larger battery packs and chargers that plug into the electric grid, a combination that provides impressive fuel economy *(right)*. (Photograph courtesy of CalCars.org.)

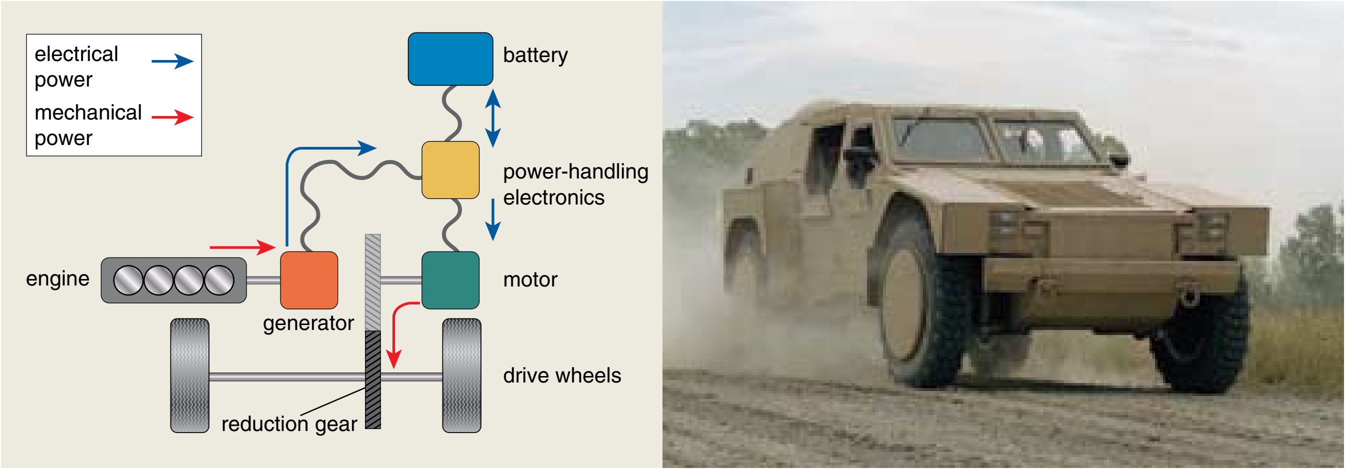

Figure 5. Series hybrids use their internal combustion engines only to generate electricity; traction power comes entirely from one or more electric motors *(left)*. One hybrid built in this way is the U.S. military's Shadow RST-V (Reconnaissance, Survey and Targeting Vehicle), which takes advantage of the series-hybrid configuration to have separate electric motors powering each wheel. Thus the vehicle can still propel itself even if one motor is damaged, offering a degree of redundancy that is particularly desirable on the battlefield. (Photograph courtesy of the Office of Naval Research.)

at another Dutch firm, Gear Chain Industries, in collaboration with two other companies, DAF and Volvo, soon showed improvements over the Bosch unit. Since that time, further efforts have yielded continuously variable transmissions that can now boast overall efficiencies above 95 percent and that are every bit as durable as gears while producing much less noise. What is more, because these transmissions require only about 25 parts (rather than the several hundred to more than 1,000 pieces found in conventional transmissions), their cost should be considerably lower once manufacturers begin producing them in large numbers. (I should note that the Prius transmission is also continuously variable, but the means used to attain this feature require two motor-generators, making the system more expensive than it needs to be.)

In addition to appropriate transmissions, plug-in hybrids also need high-power electric motors and controllers. Advances in the fabrication of the permanent magnets used in motors has allowed them to shrink considerably over the past three decades. These motors can be used with today's microcomputer controllers and with special semiconductor switches that are capable of handling many amps of current at high voltage levels, both to transfer power to the wheels and to recapture it when the car slows. The total package—including a down-sized internal combustion engine, a continuously variable transmission, modern batteries, an electric motor and control electronics—need weigh no more than a conventional engine and transmission yet can provide up to 60 miles of all-electric range while driving at up to 60 miles per hour using the electric motor alone (and much faster in hybrid mode with the engine running too).

The technology for plug-in hybrids is now advanced enough to allow all classes of vehicles to be manufactured, from the smallest to the largest. In an effort to help demonstrate that fact, my students and I have put together nine plug-in hybrids in the past 15 years, everything from two-seat sports cars to full-size sport-utility vehicles—all of which have 60 miles of all-electric range using ordinary metal-hydride batteries.

The hybrids we have fabricated weigh roughly the same as standard

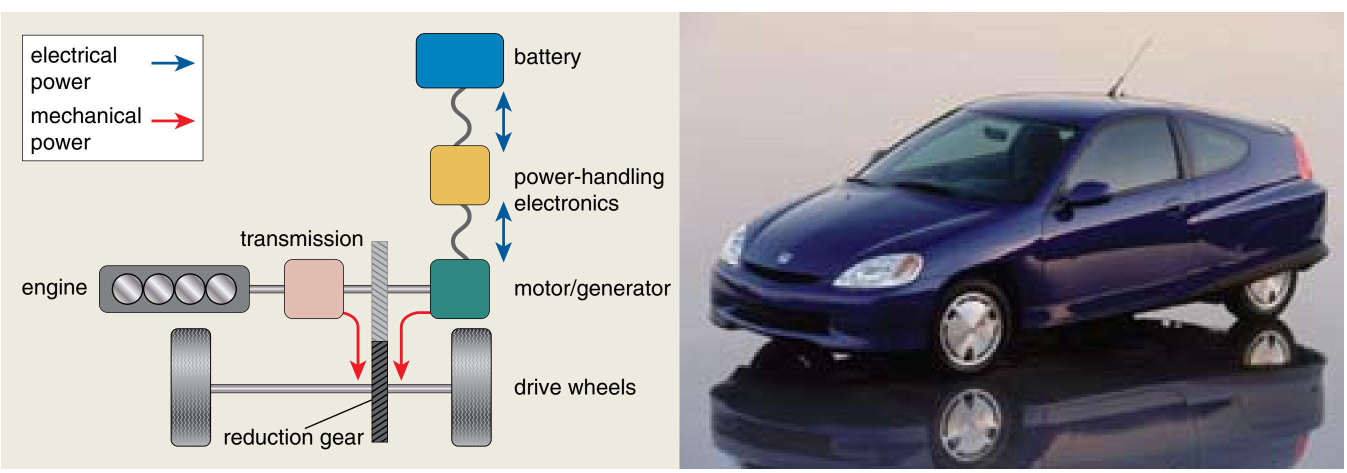

Figure 6. Parallel hybrids use both an internal combustion engine and an electric motor to drive the wheels *(left)*. The motor serves double duty, also acting as a generator to charge the batteries during braking or when the pack is depleted beyond a predetermined amount. A prime example of such a parallel hybrid is the Honda Insight *(right)*, the first mass-produced hybrid sold in the United States. (Photograph courtesy of Honda.)

vehicles because the internal combustion engines employed are less than one-third the size of those found in typical cars and because their continuously variable transmissions are much lighter and simpler than conventional multi-speed geared transmissions. The pounds we were able to save in this way could then be put into good-sized electric motors and batteries.

For example, a hybrid car we constructed in 1997 named "Coulomb" (a converted Mercury Sable sedan) has an engine with a displacement of only 660 cubic centimeters, something one finds more typically powering a modest-size motorcycle. Yet that diminutive engine can produce 36 kilowatts, which is more than sufficient for sustained hill climbing. Coulomb also contains an electric motor capable of putting out 75 kilowatts peak power, which allows the car to accelerate from a standstill to 60 miles per hour in only 9 seconds when used in conjunction with its gasoline engine. With the car's 18-kilowatt-hour pack of metal-hydride batteries, the motor can carry the car for 60 miles in all-electric mode.

Advanced lithium-ion batteries now becoming available for automotive use are smaller and lighter than the metal-hydride cells we have so far employed, which will allow for lighter vehicles with the same electric range or ones that can go even farther before they begin to use gasoline. At the moment, the main roadblocks to lithium-ion cells are higher cost, reduced longevity and concerns about safety, but some battery makers claim to have solved these issues with their newest designs. I look forward to testing some of the latest lithium-ion batteries in one of the plug-in hybrids that I am now building with my students. I fully expect that lithium-ion cells of one variety or another will eventually replace metal-hydride batteries in hybrid cars, offering a two- to threefold increase in energy storage for a pack of a given weight, along with a greater ability to absorb energy quickly during regenerative braking and, perhaps, with adequate durability to last for 15 years and 150,000 miles.

Charging time for the batteries in a plug-in hybrid is not nearly as much of an issue as it is for a purely electric car, because the engine can always provide propulsion. Thus the batteries can be charged relatively slowly, which can be done quite efficiently from nothing more elaborate than an ordinary household outlet. What is more, because the power requirements for slow charging are quite modest, the electricity doesn't necessarily have to come from the electric grid—it can also be derived from rooftop photovoltaic panels or from a small wind turbine.

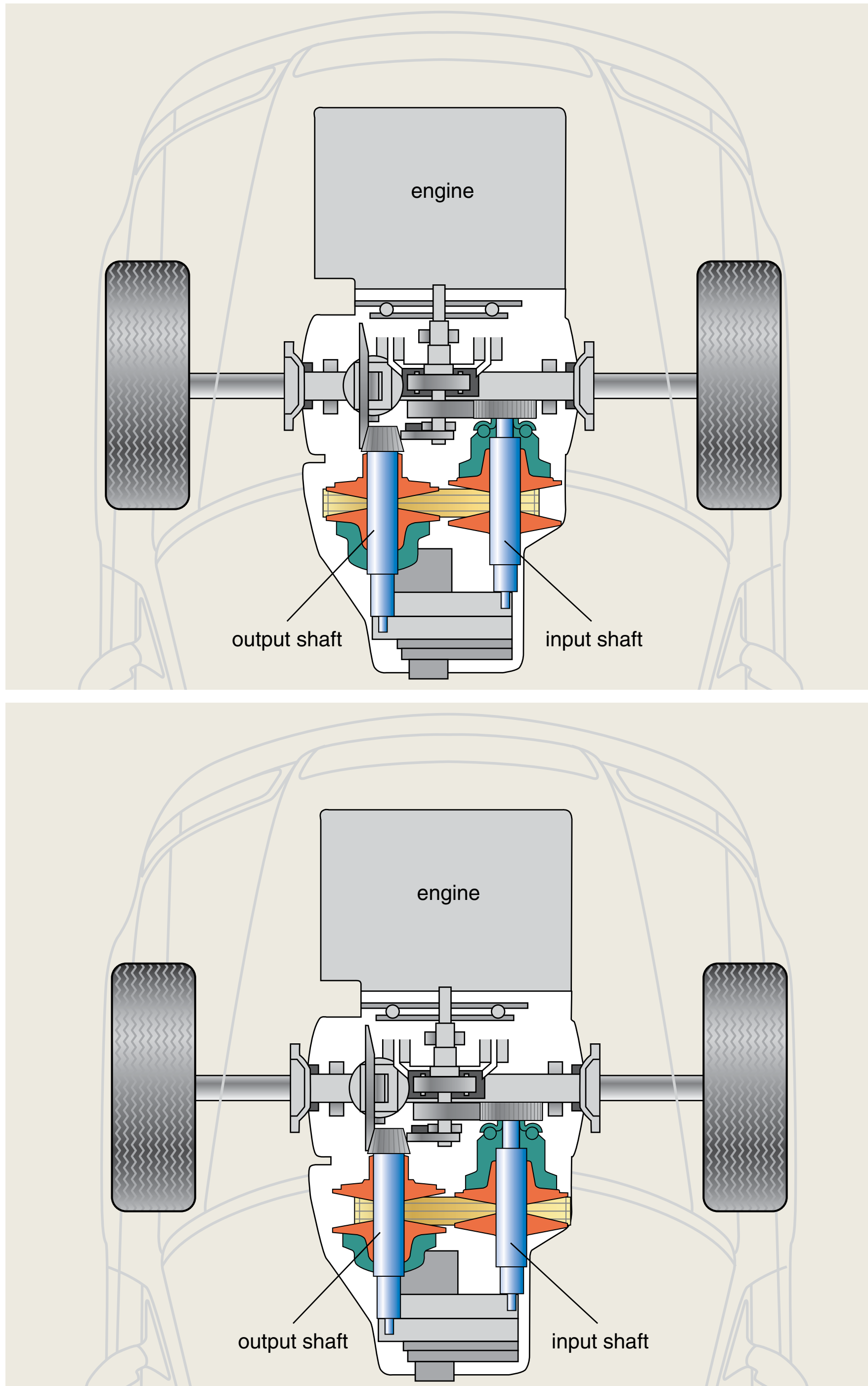

Figure 7. Plug-in hybrids built by the author and his students all employ continuously variable transmissions. Though unconventional, this equipment is well known to the automobile industry. Audi, for example, has used it on some of its vehicles, as depicted above. These transmissions use a metal belt *(yellow)* to connect two adjustable pulleys *(red)*. At one extreme, they are arranged so that the belt rides close to the input shaft and far from the output shaft *(top)*. The engine thus turns a large number of times for each rotation of the wheels, which is equivalent to the low gear on a conventional transmission. At the other extreme, the pulleys are shifted so that the belt rides far from the input shaft and close to the output shaft *(bottom)*. This configuration makes for fewer revolutions of the engine for each turn for of the wheels, equivalent to high gear. But unlike a typical manual or automatic transmission, a continuously variable transmission is not limited to fixed gear ratios as it moves between these operating points.

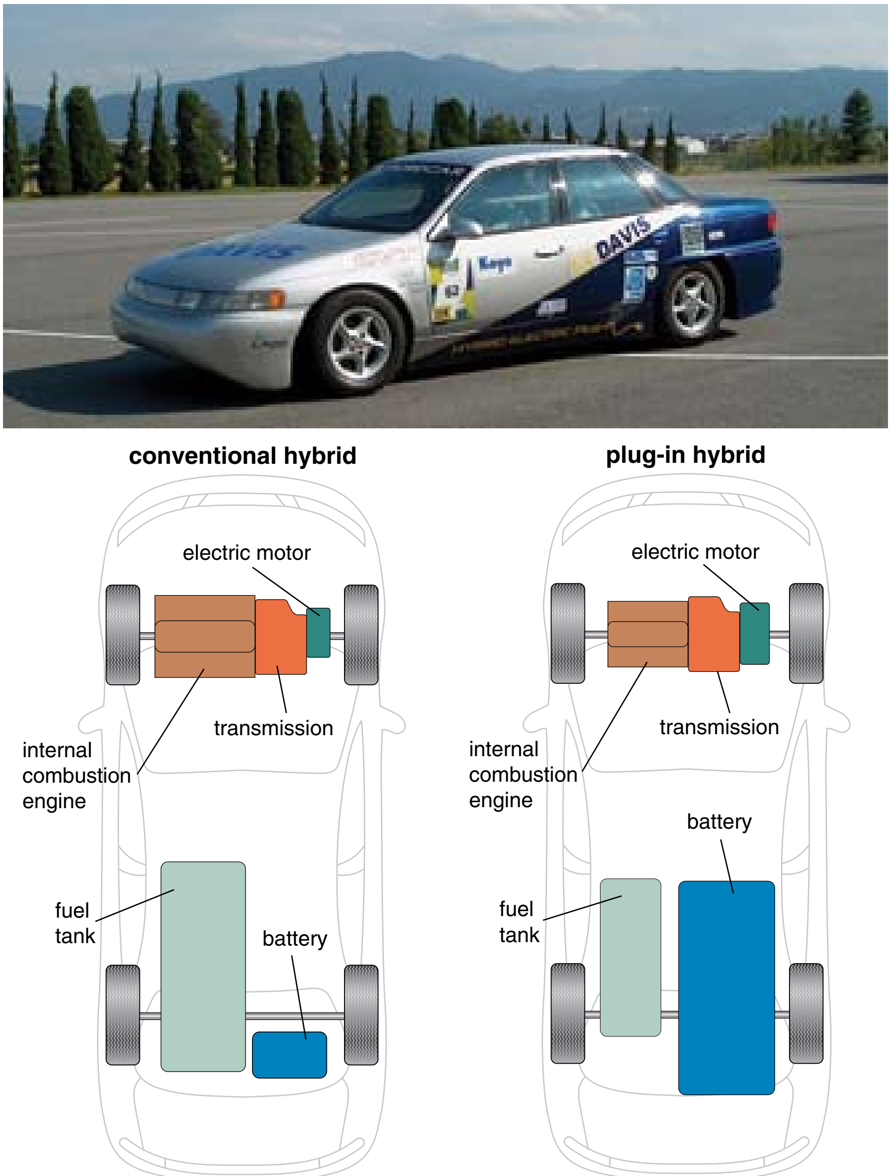

Figure 8. Unlike the hybrids one sees on the road today, plug-in hybrids use relatively small internal combustion engines and relatively large electric motors and battery packs *(diagram)*. As a result, they can have impressive all-electric ranges. For example, "Coulomb," a Mercury Sable that the author and his students converted to a plug-in hybrid *(photograph)*, can go 60 miles on electric power alone. (Photograph courtesy of the author.)

Why It Pays to Conserve

Although a plug-in hybrid will initially have a higher sticker price than what's found on a conventional car, the differential is bound to diminish with time. In any event, the cost of the automobile is only a part of the equation. Even if plug-in hybrids cost somewhat more, they can still end up providing a better value to the customer.

For example, plug-in hybrids can be charged from the grid late at night, at what in many places are lower nighttime rates, making the cost of transportation energy only a small fraction of what one pays now for gasoline or diesel fuel. Electric-power companies are sure to expand the availability of discounted nighttime rates in the future, to ease the burden on their systems during peak daytime hours. Right now, the demand for electricity during the day exceeds that at night by almost 50 percent. Hence about a third of electric-power plants have to be cut back or shut down at night, which leads to idled generating capacity (not unlike what happens with the engine of a conventional car). But even when they are doing nothing, these generating stations are expensive to maintain—and these costs must ultimately be passed on to consumers. Having a substantial number of people charging their plug-in hybrids at night would tend to even out demand, helping producers bring down the fees they charge everyone for electricity.

Might the widespread adoption of plug-ins overtax the power grid? Probably not. If these cars were recharged only at night, the electric grid as it currently stands could support more than half the transportation fleet being plugged in without the need for constructing any new plants or otherwise affecting the use of electricity. And because it would take at least a couple of decades for plug-in hybrids to become that common, the nation would have plenty of time to build new electric-generating facilities, be they powered by fossil fuels, with nuclear reactors or from renewable sources, such as wind or solar energy.

Indeed, one of the great advantages of plug-ins (and purely electric cars) is that they can directly use solar- and wind-generated electricity for transportation, a process that is three to four times more efficient than converting such renewable energy to hydrogen for vehicular use. Further, with solar panels or a small wind turbine generating a modest 1 to 2 kilowatts and with the appropriate power-handling electronics, the owner of a plug-in hybrid can have a reliable source of emergency power for his or her home, even when the sun is not shining and the wind is not blowing. In this way, a person can achieve a substantial degree of energy independence.

These features add value to owning a plug-in vehicle, making for an attractive product. The solar panels used to obviate the purchase of gasoline can be paid for with the money that is saved in about five to six years, whereas the panels themselves should last 30 years. This combination thus provides some 25 years of essentially free energy for transportation. Purchasing a plug-in hybrid and a renewable source of electrical energy to charge it thus buffers consumers from volatile energy prices. In addition, these cars could easily be made to burn biofuels (such as ethanol) when they need to run their engines. The widespread adoption of such vehicles would cut down on the net amount of carbon spewed into the air while providing considerable energy independence for the nation as a whole.

Still, car makers are understandably hesitant to bet on plug-in hybrids—or on any energy-conserving strategy for that matter—because a drop in fuel prices

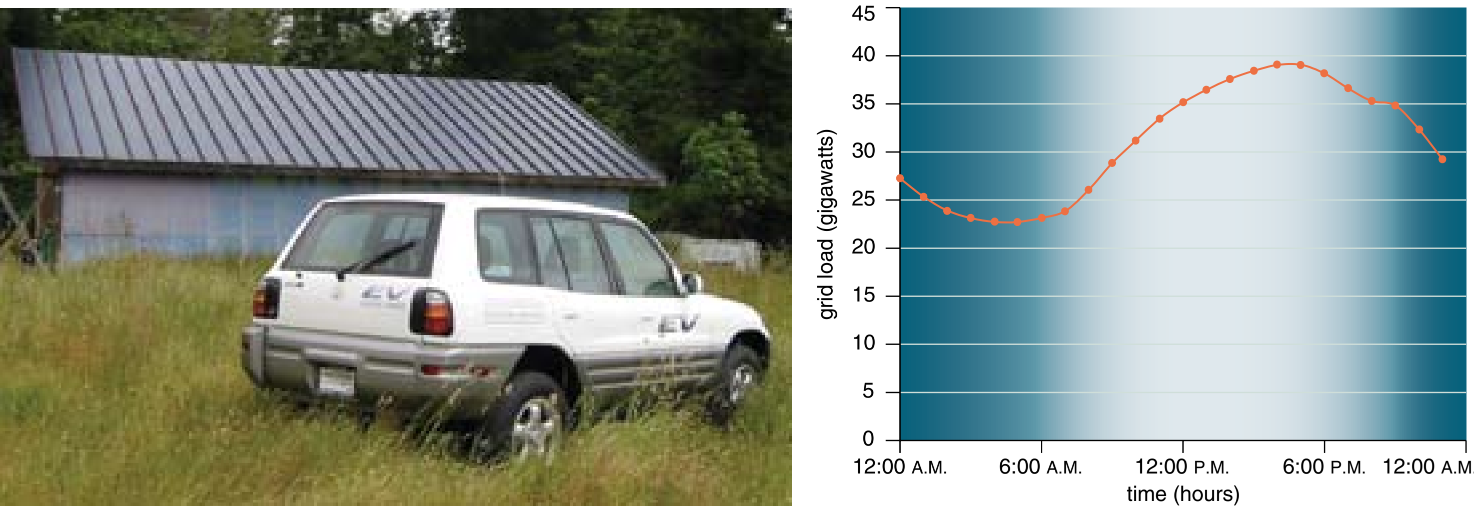

Figure 9. Plug-in hybrids can be charged from local renewable sources, such as roof-mounted photovoltaic panels during the day *(left)* and small-scale wind turbines whenever there is sufficient breeze—or from the electric grid. One day plug-in vehicles may even provide distributed storage for large-scale power producers, taking in energy from the grid at night, when surpluses are typically available, and feeding it back in late afternoon, which tends to be a time of peak demand, as can be seen from the varying load on the California grid during a typical August day *(right)*. (Photograph courtesy of Energy Conversion Devices-Ovonics.)

would cause demand for energy-thrifty cars to dry up. A national energy policy that ensured that fuel prices would undergo a steady, predictable increase would allow the automobile manufacturers to gauge the market with more certainty. But it seems unlikely that the United States would ever follow such a course. The politically likely alternative is to allow the price of energy to fluctuate drastically and to let the auto industry try to make the best guesses it can about what people will want to buy. Although this energy policy (or rather nonpolicy) can lead to poor business decisions, it should make plug-in hybrids attractive to some forward-looking consumers, who will seek energy independence wherever they can find it.

Getting From Here to There

Plug-in hybrid vehicles are clearly more than just devices for getting around. I view them as a realistic means by which society can significantly reduce its dependence on fossil fuels. When these cars hit the road in large numbers, which I fervently hope will not be more than a year or two away, some fraction of the energy used to recharge them will come from renewable sources feeding the grid. And some buyers will install solar panels or wind turbines specifically to recharge their plug-ins. As more and more people do so, society will gradually become less and less dependent on fossil-fuel energy.

Plug-in hybrids could thus diminish the amount of petroleum being used without requiring any new energy-delivery systems. That is, plug-ins don't face the Catch-22 of many other schemes, such as powering cars with hydrogen, which demands that a network of specialized filling stations be put in place before people can be expected to purchase cars that run on that oft-touted fuel—a development that is unlikely without enough hydrogen-powered cars around to justify the emergence of such an infrastructure.

With appropriate financial incentives, plug-in hybrids could one day serve to feed energy back into the grid on occasion, thus helping electric-power producers satisfy peaks in demand, which typically take place in the late afternoon. If, say, a kilowatt of power were transferred from a given car for an hour or two, its battery pack, which might hold 15 kilowatt-hours of energy, would not be drawn down significantly. The reduction in all-electric range would amount to less than 10 miles—indeed the effect could be minimized or entirely reversed if, after the peak in demand had passed, the same amount of energy were then returned from the grid back to the car before it was driven.

As plug-in hybrids are manufactured in increasing numbers, they will be paving the way to a society that bases its energy needs on renewable sources. The various impediments to designing such vehicles have been overcome one by one over the past three decades. The only element clearly needing further progress is energy storage in electrochemical batteries, and there is ample evidence that these devices can soon be made in a way that satisfies the needs of the automotive market. So I am confident that plug-in hybrids will allow all of us to retain and indeed improve our comfortable lifestyles at a lower cost and in a less disruptive manner than any transportation alternative envisioned today.

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