Plug In, Charge Up, Drive Off

by Douglas L. Smith

This zippy two-seater goes from zero to 60 in 3.6 seconds, and has a top speed of 100 miles per hour. It's an electric car that, even more remarkably, can drive from Los Angeles to Las Vegas without needing recharging. Designed by Alan Cocconi (BS '80) with some styling tips from Art Center College of Design student Scott Sorbet, who now works for Ford, the t_{ZERO} runs on the same high-energy-density batteries that power your laptop.

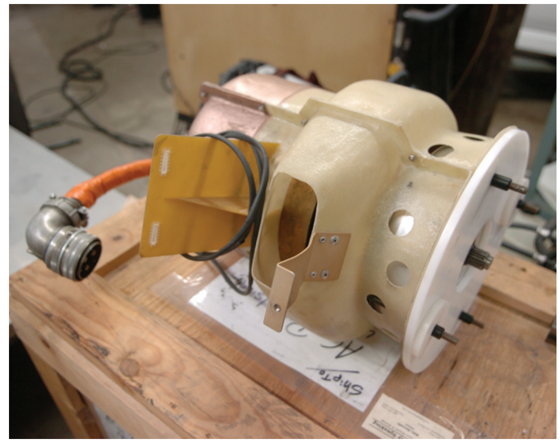
Well, here we are 30-odd years after the Great Energy Crisis. We're importing more oil than ever, gasoline prices are once again going through the roof, and there's still turmoil in the Middle East. So what's different this time around? Two things: This time, there really *is* an energy crisis. In *Out of Gas: The End of the Age of Oil* (W. W. Norton, 2004), Caltech vice provost David Goodstein argues that the so-called Hubbert Curve, which tracks global oil production, will peak in the next decade or so and then inexorably decline. After that, he writes, "increasing demand will meet decreasing supply . . . the shortage will not be artificial and it will not be temporary." Since America consumes one-quarter of that production to drive our SUVs (our 5 percent of the planet's population burns 45 percent of the world's gasoline), heat our houses, and manufacture everything from fertilizer to pharmaceuticals to plastic trash cans, the consequences will be profound.

There's one simple, obvious way to help minimize them, says a group of Caltech alums: battery power. Electric cars flopped in the '70s, as the lead-acid batteries that cranked the starters on our station wagons just weren't up to the job. They were (and are) big and heavy, and didn't hold that much juice; much of what they did store was turned into heat by inefficient power controllers. Consequently, electric cars ran like they were powered by tired hamsters. They didn't go very far, and they took an eternity to recharge.

That was then. You can curse all you want at those pinheads whose cell phones ring in theaters, but the explosion in laptops, PDAs, cell phones, pocket GPSes, iPods, and other techno-toys has sparked a revolution in battery technology. In the last couple of years, the lithium batteries that power all your favorite techno-toys have become incredibly small and remarkably powerful, to the point where such batteries would make electric cars practical.

Just a few kilowatt-hours east of Pasadena, a company called AC Propulsion is converting vehicles to run on laptop power. In case you've never disemboweled your Dell, its batteries are roughly the size of rolls of dimes. Six to eight of them let you cruise the information superhighway; driving the L.A. freeways takes 7,000. In 2003, AC Propulsion hand-built a sporty two-seater dubbed the t_{ZERO} that has a 300-mile range. Says

Electric cars never have to shift gears. The t_{ZERO}'s motor puts out up to 240 horsepower in one smooth, continuous whine reminiscent of the sound of the Batmobile.



founder Alan Cocconi (BS '80), who sold the company to a group of investors last December, this "really means you have 250 when you drive without paying any attention to your driving style at all. And we always quote 300 as 'being careful at 65 miles an hour.'" There are no sleep-deprived rodents under this hood—the t_{ZERO} can do zero to 60 in 3.6 seconds and has a top speed of 100 miles per hour. (He knows this from actual experience.) It will out-accelerate a Lamborghini.

"Some of the Lamborghini road tests report that you can do zero to 60 in 3.6 seconds," Cocconi remarks, "but no owner can. We've cost a couple of them some pretty expensive clutches, too. But with electric cars, no big deal. Just jam the pedal and it goes." The t_{ZERO} has a three-phase induction motor that revs to 13,000 rpm at 100 mph. Explains Cocconi, "That's one thing about electric motors. You can push them for extremely high peak power without making the motor much bigger than you need for continuous power. So you can get this fantastic performance with almost no penalty in energy efficiency, size, or weight."

You won't see a t_{ZERO} at Le Mans any time soon, however, as the motor and batteries would overheat in a few laps at full throttle. But for realistic use, or abuse, around town, it's got all the punch you'll ever need. And for people who fantasize about driving in one of those BMW commercials, if "you go on a mountain road, and have fun speeding around the turns, you still use less energy than doing 75 on the freeway," Cocconi says. "You can really hammer it, but your energy per mile is low because at the end of each turn you get it back."

This is the electric car's secret weapon: regenerative braking. Take your foot off the t_{ZERO}'s gas—excuse me, accelerator—pedal and the electric motor gets turned by the wheels instead of turning them. The motor becomes a generator, recharging the battery for free, and the resistance slows the car down. You only need the brake pedal for panic stops caused by sudden red lights or a deer in the road. In general, regenerative braking gives you about a 30 percent increase in driving range in stop-and-go traffic, as opposed to conventional cars where the mpg plunges. And the worse the traffic, the better you do. Says Cocconi, "That's the beauty of electric drive—every time you slow down, you fill your tank a bit." As a bonus, you don't waste fuel idling at stoplights, because the motor only turns when the car is moving.

Speaking of city driving, AC Propulsion is starting to convert Toyota Scion *x*Bs—those squared-off minivans that look like what happened when you sat your G.I. Joe down in a shoebox and called it a Jeep—into electric vehicles for utility-company fleets. "There are none on the market right now," Cocconi says, "and the electric companies really don't like to buy natural-gas vehicles to meet their alternative-fuel-vehicle requirements." The first of five prototypes is rolling out of the garage as *E&S* goes to press, and the company plans to do 100 conversions a year.

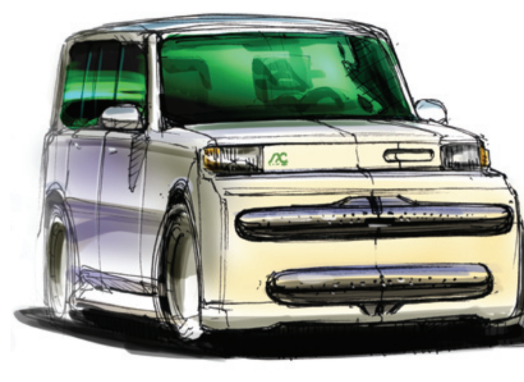


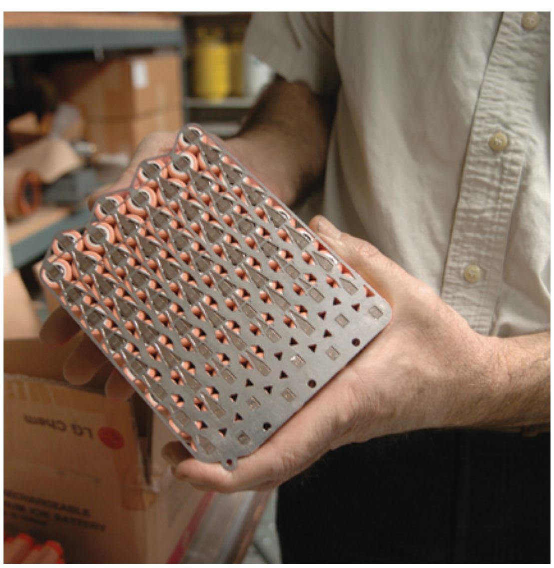
Illustration by Julius Bernardo, Art Center College of Design.

AC Propulsion's electric Scion. Streamlining isn't a big issue in city driving, but minimizing the drag from the frontal area is, so the Scion was chosen for its narrow wheelbase.

"I spend 15 seconds a day recharging my electric car: 10 seconds to plug it in when I get to work, and five seconds to unplug it when I leave."

This first prototype has a 580-pound battery pack and a range of some 180 miles, but an economy version with a smaller battery pack and about half the range is also under development. "It's a tradeoff between cost and range," says Dave Sivertsen (BS '80, PhD '89), AC Propulsion's vice president for research and development. When people first started trying to build electric cars as a commercial venture, one question asked of potential customers was, "How far do you want to go on a full charge?" And people, being used to gasoline, would say, "As far as possible," or "As far as my car does now." But, says Sivertsen, "the question you really want to ask is, 'Here is a car that, as built, will go 100 miles between charges—how much more are you willing to pay to go 200 miles?' Now it becomes a pocketbook issue. Some people would say, 'It's really not worth that much to me. I'll only pay $500.' And others might say, 'Wow! That's great! I'll pay $5,000!' And you can make that economic decision accordingly."

AC Propulsion's lithium-ion battery bricks are especially designed to maximize the air circulation between the individual cells. Charging and discharging the brick produces a good deal of heat, which, without proper ventilation, would lead to unhappy batteries.



Which brings us to the biggest impediment to going electric—laptop batteries aren't cheap. AC Propulsion buys them in bulk from the factories in China and Korea, but not on the same scale that Compaq or even Apple does, and not at the same deep discounts. The company then repackages the batteries into five-and-a-half-pound bricks, 53 in a brick, all hand-assembled and hand-welded by expensively educated people. ("We really want to sell the drive system, motor, and electronics technology," Cocconi says. "We're not in the battery-assembly business, but we do it ourselves because our volume's too low.") When all is said and done, a Scion's worth of battery packs winds up costing him about $25,000. This would fall to under $12,000 or so if the battery packs were made to order at the factory. Says Cocconi, "Right now unless you're building 50,000 cars a year, you don't come *close* to laptops. There are probably four or five major manufacturers in the world, and when we talk to them, they're not very enthusiastic about a new market because they can't meet the present one. It isn't the best situation for us, but on the other hand, it does drive the R&D and the prices. And they're all building new plants. So I hope in two years or so they'll have excess capacity and be looking for more markets."

Meanwhile, the batteries keep improving with no end in sight. "We bought 2.0 amp-hour cells when we built the t_{ZERO}," Cocconi says. "The ones we're working with now are 2.2 amp-hour. We have some 2.4s and 2.6s in stock. We went from 2.0 to 2.6 in two years, so it's more than 10 percent a year. And the cost per cell remains about constant." As has the cell size—18 millimeters in diameter by 65 millimeters long.

But, says AC Propulsion president Tom Gage, the Scion conversions will use 2.0s and 2.2s. "The 2.4s and 2.6s aren't as long-lived," he says. "For cars, low cost and long life are the most important features, but with laptops, it's high energy density. People trade in their laptops every couple of years."

Which brings us to the other problem with lithium-ion batteries: They wear out. The end of their useful life is considered to be 80 percent of their original range, which is about three years at the moment. Cocconi would really like to see batteries with a life of six or seven years, which are probably several years off. It's not just a question of the cell electrochemistry, but of the battery-management electronics and software. Fortunately, Sivertsen's specialty is software design. "With a gas tank, all

AeroVironment's Gossamer Penguin, a three-quarter-scale, solar-powered version of the Gossamer Albatross, takes wing over Rogers Dry Lake bed in the summer of 1980. The Penguin was the prototype for AeroVironment's Solar Challenger and Helios—the latter holding the world altitude record for any steady-flying (as opposed to ballistically climbing) airplane. It soared to 96,863 feet, two miles higher than the SR-71 "Blackbird" it beat.

you need is a fuel gauge," he explains. "But we need to monitor the batteries' temperature, voltage, and current." So the t_{ZERO} has 125 "popcorn" microprocessors, so called because they're very cheap and not too bright, distributed throughout the battery pack. The power-electronics unit, in turn, talks to two slightly more expensive microprocessors in the vehicle-management unit that controls the charge/discharge rates and overall temperature of the system. And that's where the software comes in—being clever in how you shuffle the electrons in and out of your batteries can have a big effect on how long they last. But Sivertsen's job should get easier when battery makers actually begin to cater to the electric-car market. "If the manufacturers just spent another 10 percent up front on better materials, we'd get much better life."

Electric-car buyers pay a stiff premium for the batteries, but get some of it back in lower fuel costs. Says Cocconi, "With gas at $3.75 a gallon, a $12,000 battery pack that lasts 120,000 miles will give about the same operating costs as a conventional car that gets 27 miles to the gallon." Another number to look at is miles per hour of charging: The t_{ZERO} takes three hours to charge fully. This translates to six dollars' worth of electricity for 300 miles' travel at the standard residential rate of 11 cents per kilowatt-hour, compared to $45 for 300 miles' worth of gasoline at 25 miles per gallon and $3.75 a gallon. So as gas prices spiral upward, electricity will look better and better. And an electric car refuels itself overnight—no more waiting in line at the pump!

Says Bart Hibbs (BS '77), "I spend 15 seconds a day recharging my electric car: 10 seconds to plug it in when I get to work, and five seconds to unplug it when I leave." Hibbs is a senior engineer for technology initiatives at AeroVironment in Monrovia, California. Founded in 1971 by Paul MacCready (MS '48, PhD '52), who is probably best known for the Gossamer Albatross, a pedal-powered aircraft that flew across the English Channel in 1979, the company builds tens of millions of dollars' worth annually of lithium-battery-powered drones that weigh 10 pounds or less and can stay in the air for up to four hours. (More prosaically, AeroVironment also makes fast-charging systems for electric forklifts and airport service vehicles.) As the company's name implies, MacCready has an abiding interest in the environment as well as aviation, and along with aerodynamicists he employs a formidable collection of experts on fuel cells, battery packs, solar arrays, and windmills, as well as the control electronics that go with them. Back in 1987, AeroVironment's solar-powered car, the GM Sunraycer, designed and built by a team led by Alec Brooks (MS '77, PhD '81),

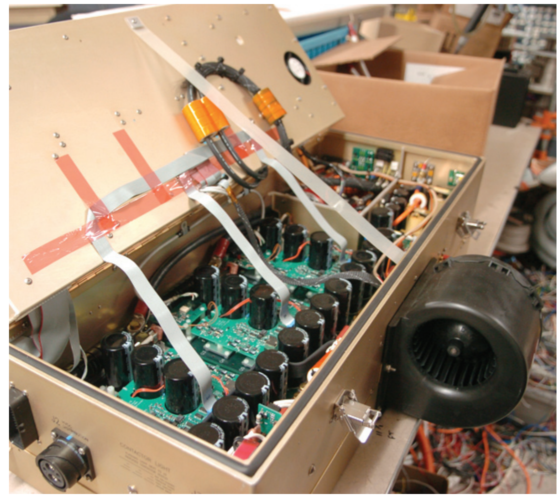
Who Killed the Electric Car?

The saga of the protracted gestation and untimely demise of GM's EV-1, the first production electric car in the United States in nearly a century, has been widely reported. For an inside view of the former, read *The Car that Could: The Inside Story of GM's Revolutionary Electric Vehicle*, by Michael Shnayerson, Random House, 1996. Premiering on June 28 in Los Angeles and New York, the Sony Pictures Classics documentary *Who Killed the Electric Car?* finds plenty of blame to go around for the latter. Like the assassination of Julius Caesar, many hands wielded the daggers, but the fatal blow was struck in April 2003, when the California Air Resources Board, in response to enormous pressure from the automotive and oil industries, essentially rescinded the Zero Emission Vehicle (ZEV) mandate it had passed in September 1990 at least partially in response to the debut of the Impact as a concept car at the Los Angeles Auto Show that January. Intended to combat the Los Angeles basin's worsening smog—41 stage-one alerts in 1990—the ZEV had required that 10 percent of all new cars and light trucks sold in California in 2003 be emissions-free.

Among the on-screen interviewees are Brooks, Cocconi, and Thomas Everhart, General Motors board member from 1989 to 2002 and Caltech president from 1987 to 1997, who had this to say: "I made the case at the General Motors board that the reason for the EV-1 was to give General Motors a very big head start in how you transform electricity into the drive power for the car. . . . But my frustration was they did not capitalize on the lead. And the reason, which was discussed with the board, was that there was not a profit seen to be coming out of either electric cars or hybrids. They could not understand how Toyota could possibly make a profit out of the Prius, for example. They were going to lose their shirt, and as the evidence has shown, I don't think Toyota is losing its shirt. . . . General Motors made a commitment to the Hummer, because they could see the Hummer would make them money. . . . It looks very schizophrenic, but I think when it started, it was, 'we could show the people in California we can meet the zero emission requirements,' and later on, it was, 'do we want to show them that we can?'"

But perhaps the most telling comment came from Wally Rippel (BS '68), a senior design engineer at AeroVironment. As an undergrad, Rippel electrified his '58 VW bus and challenged MIT to a cross-country electric-car race. Caltech won—see *E&S* October '68. At the time of the Impact project he was working for JPL, but he consulted on the design of the motor, electronics, and battery pack. "What the oil companies feared is that the electric vehicle would become successful six years from now. What the automobile companies feared was that they'd be losing money on electric vehicles in the next six months."

For further information, see http://www.sonyclassics.com/whokilledtheelectriccar/



Laptop batteries are DC; three-phase motors are AC. Ordinary inverters work in one direction only, changing DC to AC or vice versa; electric-car inverters have to be reversible in order to harvest the electricity generated when the brakes are applied. Cocconi built his first inverter in his garage; the production model shown here is one-third the size and produces 50 percent more power. About 100 of them have been sold around the world.

now a chief engineer at AeroVironment, trounced the competition in a race across Australia (see *E&S*, Winter '88). On the strength of this, Brooks and MacCready persuaded General Motors to fund the design and construction of the Impact, which became the prototype for General Motors' EV-1. In fact, Cocconi designed the Impact's power electronics as an AeroVironment consultant before leaving to found AC Propulsion in 1991.

While not in the automobile business itself, the company is something of a think tank on transportation and alternative-fuel issues. Some, including Hibbs, see the pure electric vehicle as the way to go, while others feel the so-called plug-in hybrid is the best bet. Like the wildly popular Toyota Prius, a plug-in hybrid has both an electric motor and a conventional gasoline engine. But the Prius's battery can only be charged from its engine, whereas the plug-in, as the name implies, can be recharged from the closest wall outlet.

No car company has announced any plans to start making plug-ins, but in 2004 Ron Gremban (BS '69), the technical lead for the California Cars Initiative (CalCars), converted his own Prius to a plug-in prototype with a lead-acid battery pack. Unlike AC Propulsion's bottom-up approach, integrating the plug-in charger and additional batteries into an existing hybrid called for some reverse engineering. Gremban and CalCars volunteers used a proprietary dashboard-mounted controller from EnergyCS, a builder of battery management systems, to override Toyota's controller, and the

Photo courtesy of CalCars and Set America Free.

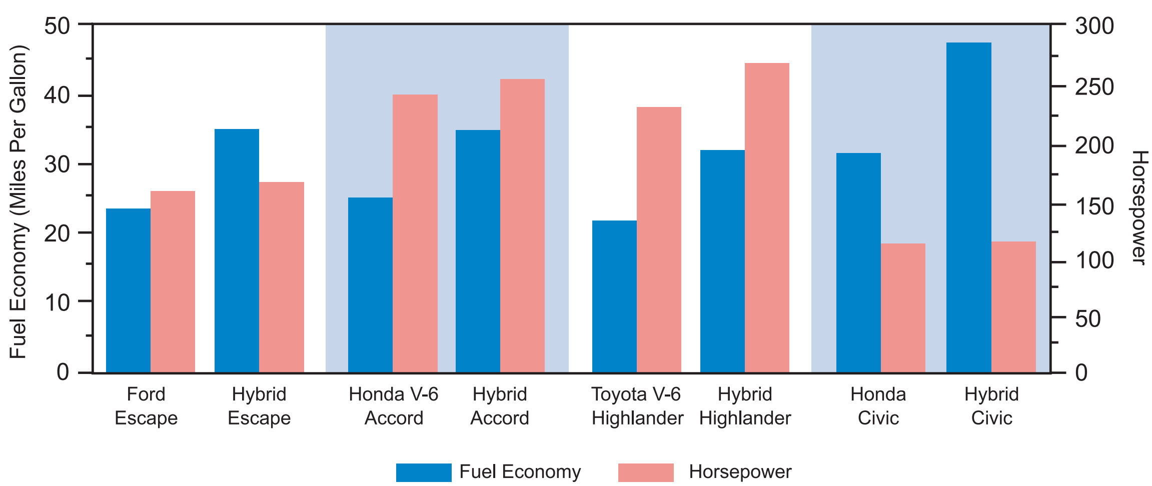
CalCars and the Set America Free coalition, an energy-security advocacy group, hosted a plug-in hybrid "Ride and Drive" for senators and congresspersons in May to coincide with President Bush's meeting with the heads of the Big Three automakers. From left: Gremban; John Davi of CalCars; Andy Frank, inventor of the modern plug-in hybrid; Anne Klein of Set America Free; Kramer; and Set America Free's Gal Luft. The silver Prius was modified by Electro Energy, a Connecticut-based battery manufacturer, for Set America Free.

success of this project has since inspired EnergyCS to form a company called EDrive Systems that plans to sell lithium-battery plug-in Prius conversions. Gremban has since learned how to "spoof" Toyota's system, a tactic he tested on the Prius belonging to CalCars' founder, Felix Kramer. It went so well that Gremban is now working it up into a public-domain conversion procedure.

Gremban recently did the electrical engineering for a Prius plug-in conversion at *Make* magazine's Maker Faire in San Mateo on April 22 and 23. *Make* is the *Popular Mechanics* of the high-tech do-it-yourselfers, and the conversion was done live, in public, from Saturday morning to Sunday afternoon. Well, mostly done, says Gremban. "The circuit boards arrived just barely in advance, and I wound up having to test them at the show, around in the back, while other people were doing the assembly up front. And then we had to finish it in my garage on Monday so that the owner could drive it back up to Seattle, where he lives. It was definitely the skin of our teeth."

A plug-in hybrid gives you the best of both worlds, its advocates argue—you can liberally dilute your gasoline with electricity while tooling around town, but still drive from Pasadena to Las Vegas without trailing a bright orange, 300-mile heavy-duty extension cord after you. Both the gasoline engine and the battery pack can be smaller, as neither has to go it alone. So if you've run the battery flat on the way in to work and your kid's school calls at 10:00 a.m. to say little Sasha is throwing up in the nurse's office and you'd better get over here *now*, no problem. You can afford to burn a few dinosaurs once in a while. A Prius-type hybrid, says Gremban, uses about two-thirds as much gasoline as an ordinary car, while a plug-in or "gas-optional" hybrid can use one-third as much. Says MacCready, "In the short term, let's say the next five years, it seems logical to think of hybrid cars that maybe go 40 to 45 miles" on a battery pack one-sixth the size of the t_{ZERO}'s, "but then when you have to go to San Diego and back in a day, you use the gasoline engine to supplement it. But the battery power would suffice for 80 to 90 percent of the total mileage for typical users." According to the National Household Transportation Survey in the 2000 census, the aver-

The commercially available hybrid versions of existing models not only get better fuel economy, but, surprisingly, increased horsepower, as shown in figure 1-7 of the National Commission on Energy Policy's (NCEP's) 2004 report, *Ending the Energy Stalemate*. This bipartisan commission of heavy hitters from the business world, environmental groups, government, and academia was founded in 2002 to provide real-world solutions to the thorny economic, national security, and environmental issues that entangle debates on energy policy.



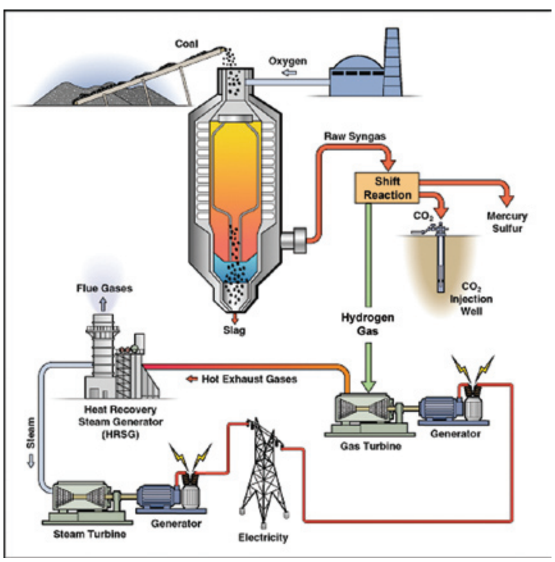
age American round-trip commute in private cars and light trucks was 22 miles in urban areas and, surprisingly, only 28 miles in rural ones. “What we would like to see happen is you go your 40 to 45 miles on battery power and then switch on the engine—gasoline, bioethanol, whatever. The battery and the electric drivetrain would still do all the maneuvering, the accelerations and decelerations, and the engine would just run at a constant output of 20 horsepower to generate electricity for the battery. The battery does everything, and the hybrid system just provides you the energy to go as far as you want. At the moment, that’s not the way hybrids are designed, but we hope they will move in that direction.”

Now if you have all these cars charging in parking lots all day and garages all night, something really useful can happen. The load on the power grid is always in flux, tracking the aggregate behavior of all the air conditioners, elevator motors, and other devices drawing power from it. This makes the voltage fluctuate, which in turn makes sensitive electronic equipment, like computers—and what doesn’t have a computer chip in it these days?—unhappy. So, as Californians learned in the summer of 2000, the grid has a complex load-balancing system. Some power plants ramp their production up and down every few seconds to even things out, and get paid very handsomely for their flexibility. But a huge pool of plugged-in electric-car batteries could do the same job, in the simplest case by allowing the system to ramp up and down your charging rate to balance the load. It’s a win-win situation, says AeroVironment’s Brooks—you surrender some level of control to the grid operator, and the utility companies would need to induce car owners to participate by selling them discount electricity. Furthermore, most battery charging would happen at night, while drivers are sleeping, and demand (and hence electric rates) is low anyway, so the utilities would benefit by being able to operate their plants at a more even load around the clock. The whole thing could be run over the Internet, using wireless WiFi connections.

Eventually, two-way controllers could be used. “Drivers would specify how much their state of charge would be allowed to vary over the course of a day,” Brooks explains. “A lithium battery might have 200 miles’ range; allowing the top half to be cycled in and out would still provide 100 miles of available range, enough to get to your sick kid’s school.” If everyone allowed their batteries to be half drawn down, even such broad, multi-hour demand surges as midafternoon air-conditioning sprees could be handled.

But eventually, as we wean ourselves from gasoline, we’re going to need more electricity. And we don’t want to solve one problem by exacerbating another. California gets a fair amount of its electricity from “green” sources, but the nation as a whole relies on burning fossil fuels to turn the generators. Says MacCready, climatologists “are in 98 to two agreement that we are getting weather modification, mostly global warming, because of human activities, and CO_2 is a big part of that. But when you hear it discussed on television, they get one person from the two people who think it isn’t happening, and one from the 98 who think it is.”

In 2004, the last year for which Department of Energy statistics are available, 50 percent of the nation’s electricity came from coal, 15 percent from natural gas, and 3 percent from petroleum. That means that 68 percent of our juice came with a side order of CO_2. Coal is dirt cheap, and we’ve got a jillion tons of it—the largest reserves on the planet—so real-world economics says we’re not going to stop using it any time soon. But many of our coal-burning base-load plants, built 20 to 40 years ago, are reaching the ends of their useful lives. Fortunately, a decade-old technology called Integrated Gasification Combined Cycle (IGCC) generation is not only 15 percent more efficient than old-fashioned pulverized-coal power plants, it can reduce pollutants such as sulfur dioxide (acid rain), nitrogen oxides (ozone and haze), particulates, and mercury by over 90 percent. As currently practiced, the process converts coal to synthesis gas—a mixture of carbon monoxide and hydro-

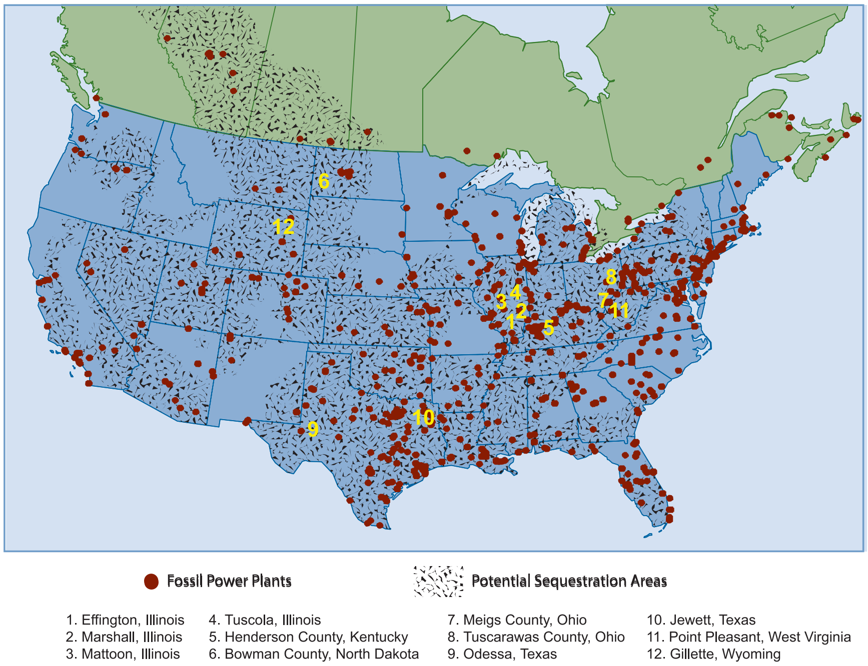


Courtesy of Jim Kopp, Kopp Illustration, Inc. Adapted from *OnEarth*, Fall 2005, p. 29, National Resources Defense Council.

The Integrated Gasification Combined Cycle (IGCC) process, modified for carbon sequestration. Coal is partially oxidized into a mixture of CO and H_2 called synthesis gas, or “syngas,” in a common industrial process. An additional set of reactions continues the oxidation of CO to CO_2, which is easy to separate out at this stage—it’s about 40 percent of a high-pressure gas stream in a chemical plant, versus some 10 percent of a low-pressure flow up a smokestack. The hydrogen gas goes on to the generating station.

gen—before being burned. But adding a "shift reactor" to the gasification process converts all the carbon compounds to CO_2 that can be separated out and pumped deep underground into tapped-out natural-gas or oil wells. Only greenhouse-friendly hydrogen gets burned at the power plant, and only H_2O comes out the smokestack.

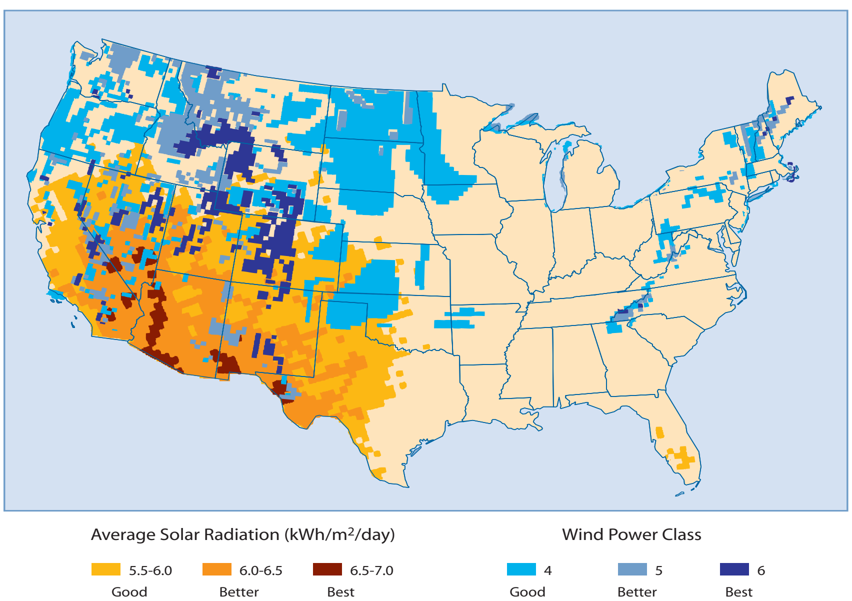
The logic to this method of carbon sequestration is that these rock formations have safely held hydrocarbons for hundreds of millions of years, so they can easily store CO_2 for a few million more. A pilot project under way since September 2000 at the Weyburn oil field in Saskatchewan is putting some 2,000,000 metric tons into the ground per year. And FutureGen, a 10-year, $1 billion Department of Energy project to build a 275-megawatt IGCC power plant—enough to charge some 700,000 electric cars, or nearly a million-and-a-half plug-in hybrids—with local CO_2 sequestration is now in the site-selection phase. Twelve sites in seven states are being considered, with the final selection to be made next summer. The plant is expected to sequester over 90 percent, and eventually close to 100 percent, of the coal's carbon content—1,000,000 metric tons of CO_2 per year. Current power-plant turbine designs need a feedstock containing less than about 70 percent hydrogen gas, so high-efficiency hydrogen turbines are among the technologies being demonstrated.



If IGCC catches on, it could be phased in at most of our coal-fired power plants as the aging ones get replaced. The "potential sequestration areas" include saline formations that are geologically similar to oil fields, but wound up containing salt water instead. The 12 sites being considered for the FutureGen plant are also shown. The map was adapted from figure 4-9 of the NCEP report. (The entire three-quarter-inch-thick report can be downloaded from http://www.energycommission.org/site/page.php?report=13.)

If the nation's entire fleet of 200,000,000 passenger cars and light trucks were all plug-in hybrids, it would take 145 FutureGens, built over several decades, to keep them all humming along. Whether more such plants will be built, however, depends on a number of factors, including the permitting and regulatory agencies—and, ultimately, the amount of pressure from the public they serve. And this would obviously be a *really* good time to start investing seriously in developing solar, wind, and other "green" electricity sources, but that's another article. Says MacCready, "California has more than enough wind-power potential to charge all of California's cars, were they plug-in hybrids. We should be building more wind farms."

You may have noticed that fuel-cell cars and the "hydrogen economy" have not



Above, left: Figure 4-14 of the NCEP report shows the parts of the country where solar and wind power is just sitting there for the taking on commercial scales, if people were so inclined to build facilities to capture it.

Above, right: General Electric Wind Energy built these 3.6-megawatt wind turbines for a wind farm 10 kilometers off the coast of Arklow, Ireland. The rotors sweep out circles 104 meters in diameter.

been mentioned. That's because it will cost a hundred billion dollars or so to build a cross-country network of hydrogen filling stations. (The entire state of California has 16 at the moment, with another 15 planned; Governor Schwarzenegger's California Hydrogen Highway Network's economic team estimates that it will cost $145,000,000 to build 250 of them. But there are some 180,000 or so gas stations nationwide.) And then there is the cluster of undeveloped technologies needed to store and distribute hydrogen safely on that scale. But finally—and this is a point overlooked in most discussions on the subject, says AeroVironment's Brooks—hydrogen is an energy *carrier*, like electricity, not an energy *source*, like a burning lump of coal, a splitting atom, or a turning windmill. Most hydrogen these days is manufactured from natural gas, which is by far the cheapest process. "Green" hydrogen is made by electrolytically splitting water molecules, and that electricity has to come from somewhere. And when the hydrogen recombines with oxygen in a fuel cell to make water and re-release that energy, guess what form it comes out in? Here's a hint: it's not mechanical—fuel-cell cars have no pistons and transmission, no spinning turbine geared to a drive shaft. The energy emerges as electricity; an electric motor turns the car's wheels. So there we are, back where we started . . . with an electric car. And we've already *got* electricity.

"Sometimes you see a sticker on a gas pump that says 'X percent of your cost per gallon goes to local, state, and federal taxes.' I'd like to see another one that says, 'Burning this gallon of gasoline puts more than 19 pounds of CO_2 into the air, where it will remain for hundreds of years, and over 40 cents of the purchase price goes to countries that hate us.' Then people could *really* make informed choices."

Worse, notes Brooks, the process of converting electricity into hydrogen and then back into electricity again is only about 25 percent efficient. Honda's prototype solar-powered electrolyzing station in Torrance, California, takes 32 kilowatt-hours a day to make half a kilogram of hydrogen, the energy equivalent of half a gallon of gasoline. Thus, says Brooks, only eight kilowatt-hours of that harvested sunshine are actually being used for transportation. With the wasted 24, he continues, you could heat the water (in a tankless electric heater) for four showers, use the dishwasher, wash and dry a load of laundry (with a natural-gas dryer), and run the fridge. You could also keep a three-ton central air conditioner, big enough for a 1,200-square-foot house, going for the five hottest hours of the day. That evening, you'd still have enough juice left to surf the net for four hours while the kids watched TV, while leaving 10 compact fluorescent lights burning all over the house for five hours, allowing ample time to get everyone tucked into bed. "So," says Brooks, "You can run your house *and* your car with electricity, or you can just run your car with hydrogen."

But wait a minute—the FutureGen plant will convert coal into "green" hydrogen, so why not siphon some off to run fuel-cell cars? Well, sure, you could do that, says Brooks, but you'd need to burn about one-quarter of that hydrogen right there at the plant to run the compressors needed to fill the cars' storage tanks. Add in the other losses inherent in the system, and the fuel-cell car's mpg equivalent compared to an electric car powered by a hydrogen-fired IGCC power plant plunges to about two-thirds. "Why bother trying to get the hydrogen to the vehicles?" Brooks asks. "It's a lot of trouble, will take much new invention, and you end up with a less efficient result."

In the end, "it all comes down to the personal economic decisions we all make every day," says MacCready. "Sometimes you see a sticker on a gas pump that says 'X percent of your cost per gallon goes to local, state, and federal taxes.' I'd like to see another one that says, 'Burning this gallon of gasoline puts more than 19 pounds of CO_2 into the air, where it will remain for hundreds of years, and over 40 cents of the purchase price goes to countries that hate us.' Then people could *really* make informed choices."

When it bet on the SUV instead of the EV-1, General Motors lost a golden opportunity to get a jump on building the cars of the new millennium. But, surprisingly, the long-term winner may not be Japan but China. The battery manufacturers are there already, and with an upwardly mobile urban population, few domestic oil reserves, and some of the worst smog on the planet, there's a huge untapped market for electric vehicles of all sorts. The Chinese government plans to have hundreds of electric buses on the streets of Beijing in time for the 2008 Olympics; Chinese-built electric scooters are as close as your local Wal-Mart.

But let's not bury the American automotive industry quite yet. CalCars is working with the R&D folks at Ford on a plug-in version of their hybrid SUV, the Escape. "We've been talking with higher-level executives for six months now to set up a 'qualified vehicle modifier company' to convert Escapes and eventually other cars," says Gremban. "We see a market for 10,000 to 100,000 vehicles, although we're going to start small. We'll build a few in California, let people try them out, get feedback from the field, and then go nationwide." Officially, the Ford Motor Company remains cagey on the subject, although board chairman and chief executive officer Bill Ford Jr. did say at the annual stockholder's meeting on May 11 that they were studying plug-ins. And since great-granddaddy Henry started the firm by building practical, economical vehicles that revolutionized transportation, maybe lightning will strike twice. □