How Green Is My Plug-In?

By **John Voelcker**

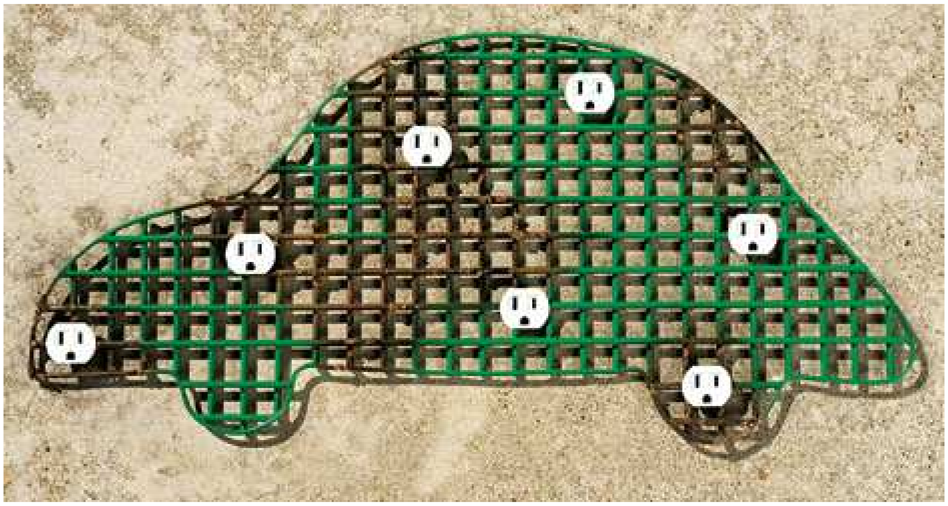


IMAGE: HOLLY LINDEM

"Our goal is to remove the car from the environmental debate," says Larry Burns, vice president for R&D and strategic planning at General Motors. His vision is that one day cars will emit no harmful pollutants from their tailpipes—or perhaps they'll have no tailpipes at all. And if the beleaguered automaker survives that long, GM may be able to achieve that goal.

But no company can ever remove cars from the environmental equation. Public impressions are fleeting and malleable, but the laws of physics and chemistry are immutable. Cars require energy to move, and that energy—even if it's stored in a battery pack rather than in fuel sloshing around in a tank—has to come from somewhere.

And therein lies the problem. Odds are those batteries won't be recharged with solar or wind energy. In most places, grid power is for many decades going to come from the burning of fossil fuels, which generate their own emissions. So the question becomes: If you power a vehicle with electricity from the grid rather than with fuel from the tank, is that better or worse for the environment, particularly with respect to greenhouse gases like carbon dioxide?

It's a question that dogs not just automakers but also policymakers all over the developed world. Companies and governments are already spending billions of dollars engineering the vehicles and infrastructures to kick off the transition from gasoline and diesel to electricity. Plug-in hybrids even became a mantra during the 2008 U.S. presidential election—with both candidates citing them as an environmental panacea.

A few analysts forecast that by 2020, plug-in vehicles, including plug-in hybrids and purely electric cars, will make up almost a third of new-car sales in the United States. And by 2050, plug-ins could account for most of China's burgeoning vehicular travel. But the environmental implications of such a massive shift are hardly straightforward.

The complexity stems from the multiplicity of vehicles, electricity-generating technologies, and assumptions behind future projections for both. Imagine that two years from now you're comparing a newly available hybrid model that can recharge from wall current with a conventional gasoline car that consumes, say, 9.4 liters per 100 kilometers (25 miles per gallon). In this case, using grid power to drive electrically emits fewer greenhouse gases per kilometer—under any circumstances.

But if you compare the plug-in with an ultraeconomical European diesel or a conventional hybrid-electric like Toyota Motor Corp.'s Prius—either of which burns just 4 to 5 L/100 km—the picture is more complicated: The plug-in emits fewer greenhouse gases in some circumstances, but more in others.

The balance hangs on just what sort of power plants are being used to generate the electricity. So before you decide what to buy, you will need to answer a second question: How green is your grid?

Electric vehicles have been around for decades, although their limited ranges have made them impractical for most people. But now, with automakers preparing to introduce the first vehicles with automotive-quality lithium-ion batteries, the situation is about to change dramatically. Lithium-ion cells can store roughly four times as much energy as lead-acid cells and twice as much as nickel-metal hydride, the kind used in the Toyota Prius and most other currently available hybrid cars.

In the near term, lithium-ion offers the promise of plug-in hybrids that can achieve about 15 to 65 km (10 to 40 miles) of all-electric range, along with purely electric vehicles that can go about 160 km (100 miles) or more before recharging. And as battery costs diminish, the maximum ranges may improve considerably.

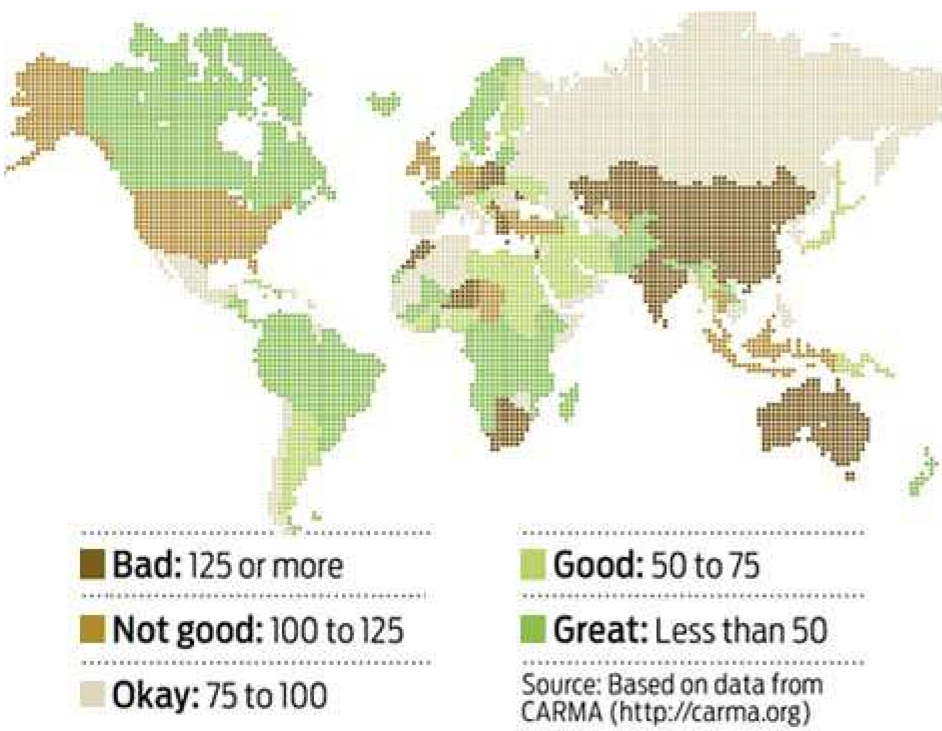
The advances in electric drive are unfolding in stages. The Prius, launched in Japan in 1997, was the first mass-production car since the 1930s with an electric traction motor. It has a 1.5-L combustion engine, supplemented by two electric motors and a battery pack, which can provide only short bursts of pure electric travel—1 to 2 km at most. But the Prius can't use grid power to charge its battery: It generates all its own electricity using both engine power and regenerative braking. Having a combination of electric motors and a combustion engine working in parallel is valuable, though, because it allows the Prius (and similar parallel hybrids) to use its fuel much more efficiently.

The next step in modern automotive electrification will be to add grid charging to hybrid-electric vehicles, turning them into plug-in hybrids. Toyota, for example, plans to offer a plug-in version of its Prius in 2010, but it will probably have a limited range in pure-electric mode—up to 20 km (12 miles). Other production vehicles of this sort may go somewhat farther on battery power. (Their quoted electric ranges, however, are not necessarily continuous—at highway speeds or under heavy loads, the engine may switch itself on.)

A further move toward full electrification is the series hybrid. Assuming General Motors is still with us in late 2010, it will begin selling such a car: the Chevrolet Volt, which GM calls an "extended-range electric vehicle." The Volt supplements a 16-kilowatt-hour battery that provides 65 km (40 miles) of pure-electric range with a 1.4-L combustion engine. But as with all series hybrids, the engine isn't mechanically connected to the wheels. Instead, the Volt's engine spins a generator that provides enough current to the battery to sustain its charge and run the car for another 480 km (300 miles) or more on a tank. Even without the engine, the Volt would still function as a limited-range electric car.

Finally, there are models built as purely electric cars, also known as battery-electric vehicles, whose main drawback at present is the high cost of the battery pack. Analysts expect mass-produced electric cars with reasonably affordable lithium-ion batteries—and consequently with ranges of 160 km or less—to enter the market by 2012. Nissan Motor Co. and its partner Renault have already announced one such compact sedan.

Calculating the green credentials of these different drivetrains is not at all a straightforward exercise. But let's start with the simplest, and for many the most pertinent, yardstick: how much climate-warming carbon dioxide is generated for each kilometer driven—whether it's delivered by gasoline or electricity.



HOW GREEN IS YOUR GRID?: Electric driving's carbon dioxide output (grams per kilometer)

To figure out the amount of CO_2 that might result from running on grid power, the first thing you need to know is how much electricity a plug-in car uses. That, of course, depends on the vehicle in question. Tesla Motors has claimed that its sporty Roadster consumes just 110 watt-hours per kilometer, although some real-world measurements show its usage can be more than twice that—for reasons that may be unique to this specific high-performance car. For something like a plug-in version of a Toyota Prius, a more reasonable number to use might be 150 Wh/km, although more data are needed to know for certain.

The next key factor is how much carbon dioxide is released while the electricity is generated. For that, the U.S. electric grid provides a convenient benchmark. According to the U.S. Department of Energy, roughly 600 grams of CO_2 were emitted for each kilowatt-hour of electricity generated in the United States in 2006. The transmission and distribution of electricity is thought to incur losses of about 9 percent, and charging a car's battery pack is about 90 percent efficient. So the actual amount of carbon dioxide emitted is probably closer to 700 grams—or 0.7 gram for each watt-hour in an electric vehicle's battery pack.

The plug-in's 150 Wh/km therefore translates to 105 grams of CO_2 per kilometer, assuming the car is charged on the U.S. power grid, averaged across all its many different generating sources. Remarkably enough, the standard Prius available today emits almost exactly the same amount of CO_2: 104 g/km. And it's possible to go even lower: a few small, ultraefficient European diesels emit less than 100 g/km.

But don't jump to conclusions: The full analysis needs to be done on a "well to wheels" basis. That's because the fuel for the car must be pumped from the ground, transported, refined, and transported again to the filling station—steps that add about a third more CO_2. And you also need to consider how much carbon dioxide would come from plugging a car into your *local* grid, with its particular mix of generating technologies.

The impact of electric-drive cars on the grid has been most thoroughly analyzed for the United States, whose citizens buy the most hybrid vehicles. In 2007, the Electric Power Research Institute (EPRI) and an unlikely partner, the Natural Resources Defense Council (NRDC), released the results of an 18-month, two-volume study, aptly titled *Environmental Assessment of Plug-In Hybrid Vehicles*, the first part of which considers greenhouse gases.

The EPRI-NRDC study accounted for many factors, including losses throughout the cycle of fuel production, generation, transmission, and distribution. It also evaluated the consequences of drivers recharging their vehicles at different times of the day. In general, power companies want consumers to charge at night or at other off-peak times to take advantage of unused capacity when demand is lowest, and the companies will be willing to provide strong incentives to make that happen. (Electric carmakers anticipate as much: The Volt, for instance, will allow delayed charging, so a driver can plug in the car when she returns home from work but instruct it not to charge until after cheaper nighttime rates kick in—at 11 p.m., say.)

Finally, the EPRI-NRDC study assumes a gradual rollout of electric-drive vehicles, which only makes sense. It took hybrid cars eight years to surpass 2 percent of the U.S. market, reaching 347 000 vehicles out of 16.2 million sold in 2007. While plug-in hybrids may be adopted slightly faster than conventional hybrids—especially if spurred by tax incentives—the United States has roughly 300 million vehicles on the road, so change to the overall composition of the fleet will be slow.

In practice, this means that in the near future electric cars will impose a very small load on the grid. If projections by GM's Bob Lutz are accurate, some 60 000 new Chevy Volts will hit the road in 2012. In the most optimistic scenario, other makers will add perhaps three times that number. The load of one car being recharged overnight (about 2 kilowatts) is roughly that of four or five plasma TVs. Adding the load of a million plasma TVs to the entire U.S. grid—at 2 a.m.—won't lose utility executives any sleep. Far from it—the prospect of additional demand at precisely the time when they can most easily meet it would make them very happy.

Not surprisingly, the EPRI-NRDC analysis found that plug-in vehicles won't strain the grid. Earlier, less-nuanced studies from Oak Ridge National Laboratory and the Pacific Northwest National Laboratory came to essentially the same conclusions.

As for greenhouse gases, the EPRI-NRDC study determined that total emissions of plug-in hybrids, including the power plants used to charge them, are considerably lower than those of regular gasoline-powered cars—under all scenarios. The comparison between plug-in hybrids and conventional hybrids, however, depends on the sources used to generate the electricity.

Consider a plug-in hybrid that runs half its distance on gasoline and half on electricity derived from an advanced combined-cycle power plant fired by natural gas, for example. Such a car would reduce greenhouse-gas emissions by about 25 percent with respect to the well-to-wheels emissions of a conventional hybrid. Charging that same plug-in using electricity from nuclear power or renewables cuts CO_2 emissions almost in half, because the carbon dioxide emissions involved with nuclear energy (mostly from mining) are minimal and are essentially undetectable for hydroelectric power. But if you run that plug-in with electricity from a typical coal-fired power plant, it now releases from 4 to 11 percent *more* greenhouse gases than a conventional hybrid would.

So how green is your grid—or, more accurately, how carbon intensive is your supply of electricity? In the United States, the three cleanest states—at well below 200 grams of CO_2 per kWh—are Idaho, Washington, and Oregon, due to their extremely high percentage of hydroelectric generation. The worst—at just over 1000 g/kWh—are North Dakota and Wyoming, which use large amounts of coal. California, the state that buys the most Priuses, comes in at roughly 450 g/kWh, about 25 percent better than the U.S. average. Be aware, though, that much electricity crosses state lines.

Variation among countries is even more extreme. On the low-carbon end are Norway and Brazil, which get most of their power from hydroelectric stations, or France, where generation is 80 percent nuclear. On the other side of the spectrum is China, where four-fifths of the electricity comes from burning coal—and not at particularly clean plants, either.

The moral of the story: If you're concerned about the carbon footprint of your vehicle travel, definitely buy a plug-in— *if* you live in Norway, Brazil, France, or other areas with largely carbon-free electricity. Otherwise, have a look at your local grid—and think twice if you live in a place with lots of old coal-fired power plants. For you, a conventional hybrid may be kinder to the planet.

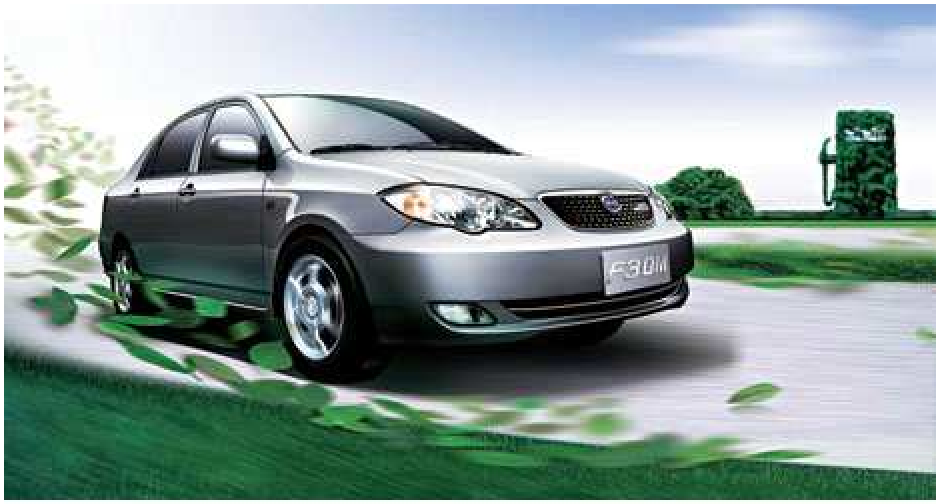


PHOTO: TOP: BYD; BOTTOM: FORD

GREEN CHOICES: Countless environmentally conscious car buyers in Europe and North America are looking forward to the day when they can purchase a practical plug-in. The introduction of BYD's newly developed F3DM plug-in hybrid [top] in China suggests that their wait may soon end. But even in its all-electric mode, this car can cause appreciable carbon dioxide emissions at the generating station that supplies its electricity. So driving an ultraeconomical gas or diesel car, such as the Ford Fiesta Econetic [bottom], may be the better choice in some places.

And be prepared to reevaluate that situation each time you trade in, because the grid is bound to change with time—probably for the better. Indeed, the authors of the EPRI-NRDC study excluded a future with large numbers of new coal-fired power plants, viewing that as an unlikely scenario for the United States. Instead, they modeled a gradual shift toward lower-carbon sources of generation.

Declining carbon intensity in the grid, however, will be chased by more and more efficient cars. Fuel economy laws in the United States and China, and carbon penalties in Europe, will make the new vehicles emit less carbon—a trend that is modeled in the EPRI-NRDC study, which supposes that the consumption of gasoline by vehicles of all sizes, including conventional hybrids, will drop by roughly 25 percent by 2050.

And that's only reasonable. Already, U.S. and European carmakers are turning to gasoline direct injection, often paired with a turbocharger, to maintain power while reducing engine size. More exotic combustion technologies may be on the horizon, including homogenous charge-compression ignition engines, under development by Mercedes-Benz, General Motors, and others. Eventually, designers may put such advanced combustion engines into hybrid-electric cars, further improving efficiency. Whether these gains could rival the advantages of plug-in vehicles is hard to say. Clearly plug-ins will continue to make environmental sense in nuclear-powered France, but will they ever do so in coal-heavy China?

It's a question worth pondering now, in light of China's determination to nurture its own electric- and hybrid-vehicle industries. The country already manufactures a huge portion of the world's batteries for consumer electronic goods, including the latest lithium-ion cells. And Chinese automaker BYD shocked the industry last November when it introduced the world's first production plug-in hybrid electric vehicle, the F3DM, with a claimed electric range of about 110 km (68 miles). It is being sold only in China and likely wouldn't pass U.S. safety and emissions standards. But it may point the way for Chinese automakers—combining the country's strength in battery production with the desire to use vehicle manufacturing as a lever for industrialization, as South Korea and Japan have.

In the long run, the electrification of China's vehicle fleet should be a good thing. But today, plug-in cars in many parts of China may end up releasing more CO_2 than would conventional hybrids—or even the best combustion-powered vehicles. And stiff new taxes on vehicles with low fuel economy will raise the efficiency of all new cars there. Given that, environmental organizations concerned over global warming may want to encourage China to hold off on promoting electric vehicles until the country improves its generating mix.

What does it all mean for planet Earth? Researchers are just now starting to answer that question. Geoffrey Blanford, a senior project manager and global climate policy analyst at EPRI, has taken a first look at what electric-drive vehicles might mean for the world's future.

"Electrification is a big deal," Blanford says. His initial assessment, in the form of an unpublished working paper, suggests that replacing liquid fuels with electricity reduces greenhouse-gas emissions from vehicles and that plug-in hybrid vehicles will become a cost-efficient way to meet carbon constraints.

Blanford came to those conclusions after working with a computer simulation known as MERGE, for Model for Evaluating Regulatory and Global Effects, which calculates the high-level costs and benefits of different energy policies. The late Alan Manne, of Stanford, worked with EPRI's Richard Richels to create the original model to assess policy decisions for different mixes of generating capacity.

Blanford added more detail about passenger vehicles to the model so that he could gauge the global impact of plug-ins specifically. For that he made various assumptions in his working paper about the rate of market penetration for plug-ins from now until 2050, based on projected decreases in the cost premiums for such new technologies as large battery packs and increases in electric-motor efficiency.

The impact of plug-ins was most striking in China, which analysts expect to become the world's largest single automobile market around 2020 and thus a major source of the growth in CO_2 emissions. Blanford showed that electricity could come to power 30 percent of the annual 12 trillion km of passenger-vehicle travel predicted for China by 2050. "It's the scale factor," he says, explaining that because China is starting from such a low number of vehicles, new technology can have a disproportionate impact. "The growth in demand is tremendous," he observes.

Blanford considers the rest of the world, too, and the effect that plug-in hybrids will have on electric-power generation and greenhouse gases. The impact on the grid should be minimal: If one-third of the world's vehicles in 2050 are plug-in hybrids and run half their distance on grid power, the total electricity consumed would be just 3.6 percent of the world's total generating capacity. Even if 80 percent of all plug-in travel is powered by grid electricity, that load would consume only 5.6 percent of capacity by 2050.

"The question of CO_2 impact is subtler," Blanford notes. Even when incremental generation is fired largely by coal, plug-in hybrids produce a modest reduction in overall CO_2 compared with liquid-fueled power, a category that in his study *includes* conventional hybrids. For China, Blanford figures, roughly 4 percent of that country's CO_2 emissions will be prevented in 2050 by the introduction of plug-in hybrids. For the world as a whole, plug-in hybrids would cut annual CO_2 emissions from the use of energy by 3 percent in 2050. If carbon taxes or caps are enacted, plug-ins only get more valuable.

Still, not everybody sees plug-ins as the best bet. Toyota's Jaycie Chitwood and John German, formerly of American Honda Motor Co., among other analysts, suggest that conventional hybrids—with their smaller, less expensive battery packs—will be a lower-cost way to reduce emissions than plug-in hybrids or full-electric vehicles for at least a decade and perhaps much longer. And indeed, the EPRI-NRDC study results suggest that this approach might be just as effective in reducing CO_2 emissions in places with typical coal-fired electrical power generation. In the real world, it's not going to be an either-or choice. Automakers will offer both alternatives, and the market, driven by fuel costs and government incentives, will pick the winners.

Of course, carbon dioxide is hardly the only pollutant to worry about. As with cars, power plants have their own suite of regulated emissions, including some—sulfur and mercury, for example—that aren't an issue for vehicles. So pursuing a policy that reduces one pollutant may end up increasing another. In vehicle travel as in life, there's no free lunch.

It's notoriously hard to predict the energy market. An oil-price decline from US $147 a barrel to $35 in six months would have been thought impossible—until it occurred last year. But assuming the cost of advanced batteries falls over time, electric vehicles seem poised to offer reasons to plug in beyond lower carbon emissions, including smog reduction and energy security for oil-importing nations.

And that's even before the auto marketers get to work. Imagine ads that compare the 10 cents or so it takes to run a car one kilometer on gasoline with the cost of electric cruising—in some markets, 2 cents a kilometer. Then there's the driving experience, a steady, smooth, silent surge of electric acceleration.

Within a decade, no matter what kind of car you're looking for, you'll have the option of an electric or partially electric vehicle. Will you take it?

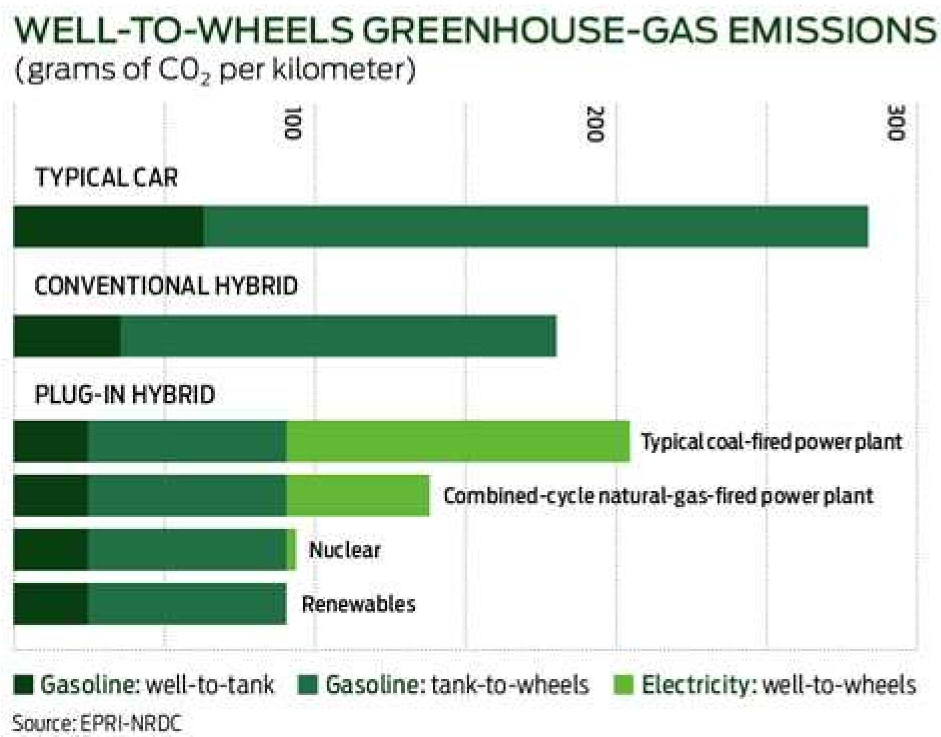
About the Author

JOHN VOELCKER didn't expect to delve into energy policy when he became *IEEE Spectrum*'s automotive editor, but it may have been inevitable. The push for electric vehicles addresses global warming and energy security, so designing future cars requires more knowledge of the energy sector than before. For Voelcker, the best part of writing "How Green Is My Plug-In?" was learning that he was asking questions at the same time researchers were. "That made me confident that my coverage was headed in the right direction," he says.

Sidebar 1

An Electric Car's Carbon Footprint

Even an electric car (or a plug-in hybrid on electric power) can cause CO_2 to be released from the power station that supplies its electricity. The results shown above indicate how much, based on each country's average generation mix. In actuality, emissions would vary at a finer scale. The chart below compares overall CO_2 emissions caused by different types of vehicles, assuming that the plug-in travels half its distance on gasoline.



SOURCE: EPRI-NRDC