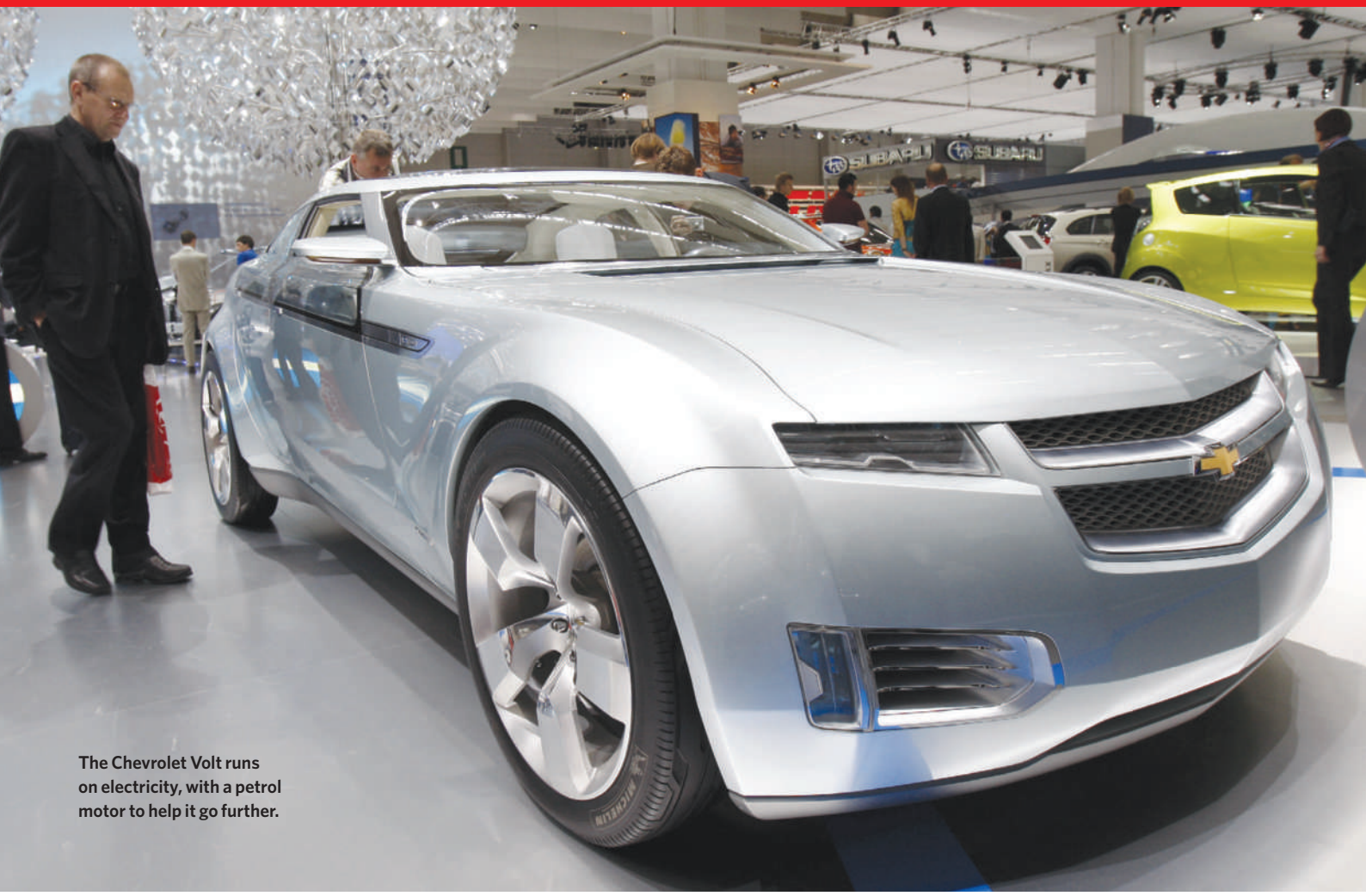

The Chevrolet Volt runs on electricity, with a petrol motor to help it go further.

T. KIENZLE/AP

CHARGING UP THE FUTURE

A new generation of lithium-ion batteries, coupled with rising oil prices and the need to address climate change, has sparked a global race to electrify transportation. **Jeff Tollefson** investigates.

"We have had a massive shift in one of the biggest industries in the world," says Stephan Dolezalek, who leads the CleanTech group at the venture-capital firm VantagePoint Venture Partners in San Bruno, California. Dolezalek has been watching the global automobile sector embrace the idea of plug-in electric cars: "In three years we've gone from thinking 'it can't be done' to not only 'it can be done' but 'we are all going to do it.'"

The shift is partly a story of technological innovation, which has produced rechargeable batteries that pack enough power to propel some of the basic passenger vehicles currently being designed further than 200 kilometres. Billions of dollars have poured into start-up companies that promise new batteries, and billions more have poured into fledgling electric-car manufacturers eager to take on the global automotive giants — every one of which is also developing electric vehicles.

The shift is also a story of oil supplies, national security and global warming. Record-high oil prices have pushed consumers towards fuel-efficient vehicles and prompted many governments to consider electric transport as a way to escape their dependence on imported petroleum and to address climate change. Money currently spent abroad could instead be spent on domestic power generation from wind, solar and other low-carbon energy sources.

And the shift is a story of a shared vision: developing the technology that would entice all drivers to plug in rather than fill up. Millions of battery-powered cars plugged into an increasingly green electric grid would not only save drivers money and reduce greenhouse-gas emissions, it would also provide the grid with a distributed, high-capacity storage system for electricity. Such a system would help to accommodate the variable and unpredictable nature of renewable electricity sources. And further out, it could allow power companies to store energy generated during times of low demand, then draw it back again to meet peak demand. The end result could be more a stable and efficient grid that might even lower home electricity bills.

Getting there won't be easy. All these hopes hinge on battery technology that is only just emerging from the lab. A suite of technical challenges remains to be overcome, and it is not yet clear how much further the technology can be pushed. At the same time, the manufacturers who are arguably best able to bring about these changes — the global automotive giants — have been hammered by an energy crisis followed by an epic financial meltdown.

None of them has abandoned the effort yet, in large part because they all believe that, despite the current lull, oil prices have nowhere to go but up. Moreover, batteries have leapt ahead of expensive hydrogen fuel cells as the technology of choice for getting beyond oil, at least for now. But the field is wide open in terms

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of bringing them to market. Dolezalek believes that major car companies might well perish in the face of versatile young upstarts, and he isn't alone. The automobile industry secured a place in this autumn's first round of economic bailouts from the US government with US$25 billion in loan guarantees for retooling its plants, and it is already seeking more. That has people such as Andrew Grove, former chairman of Intel, who has become a leading proponent of electric transportation, talking about the 'valley of death' that often accompanies a massive technological transformation. Grove says that car manufacturers have already begun their march through the valley, knowing that many won't make it through to the other side.

"The only time people make these moves [through the valley] is when things are rough, but they can't afford to make them when times are rough," Grove says. And that means that governments might have to step in. "I just hope that it's going to be done in such a way that the government says, 'I'll give you some water and food to get through the valley of death, but don't turn back.'"

"Don't worry about charging electric cars from some perfect grid of the future — just get the cars out there."
— Mark Duvall

Building a better battery

Pioneers have turned back before, most notably General Motors. In 1996, the US company released the EV-1, the first all-electric car from a major manufacturer. The vehicle was expensive, rolled out in response to a California mandate, which was later rescinded, for 2% of all cars sold in the state to have zero-emissions by 1998. But its fate was ultimately sealed by one thing: its battery.

Building batteries has been an exercise in chemical compromise for more than two centuries. The idea is simple: chemical bonds can be used to trap ions in one electrode. When a battery is hooked up to a circuit, the ions flow through a separator to a second electrode; as the ions flow, they release electrons, generating an electric current. In rechargeable batteries, the chemical reaction can be reversed to store energy (see graphic, overleaf). But the reality is complex: although scientists have produced numerous potential battery chemistries (see *Nature* **451,** 652–657; 2008), none of them performs well on all the crucial factors of cost, safety, durability, power and sheer capacity.

The first-generation EV-1 deployed a lead-acid battery, still the technology of choice for conventional vehicles. Lead-acid batteries are safe, cheap, long-lived and reliable, but they are also big and heavy. They could push the car for about 150 kilometres per charge. A second-generation vehicle released in 1999 featured a nickel metal hydride battery, and travelled 50% farther on a charge, but General Motors cancelled them after the first year, saying that it could not sell enough to make them profitable.

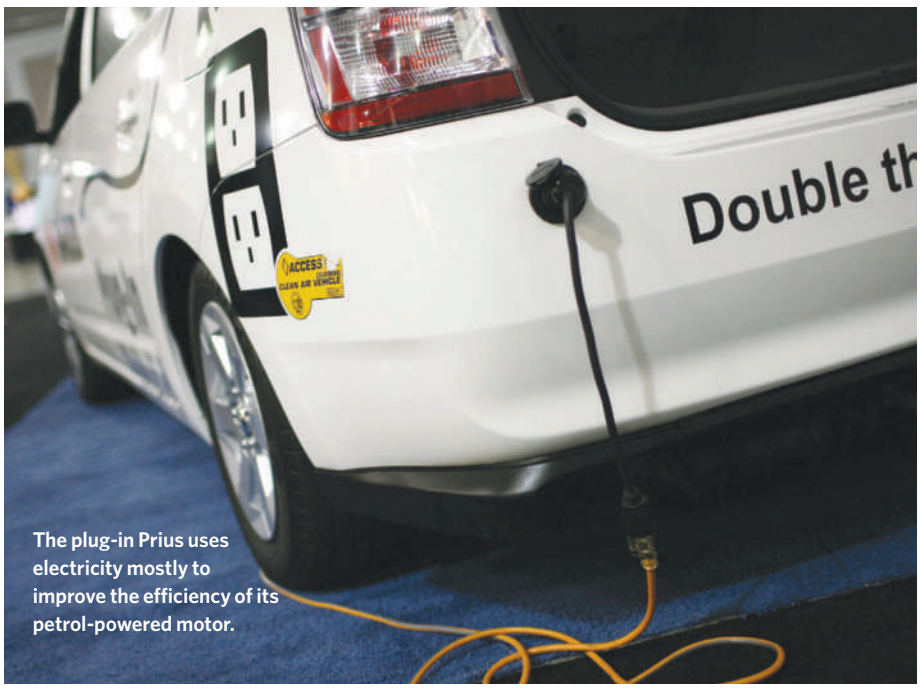
It was a decision that General Motors would come to regret. As it turned back to large and profitable vehicles such as the Hummer, its up-and-coming Japanese rival Toyota was digging into the new technology, using the same battery that General Motors had abandoned to produce hybrid cars that combined a standard combustion engine with an electric motor. Toyota has gone on to set the standard for hybrids: its third-generation Prius has been immensely popular, proving that consumers will adopt advanced battery technology in automobiles if it is done well. The Prius fortified Toyota's reputation, and helped it to surpass General Motors last year to become the largest automobile manufacturer in the world.

But nickel metal hydride batteries can be developed only so far. These batteries pack more power than standard lead-acid ones but can be permanently damaged if allowed to discharge too far. To maintain an adequate safety margin, Toyota limited the Prius to using about 20% of its battery charge during normal operation. But although not using 80% of the capacity is acceptable if the battery is simply supplementing a petrol engine, it is a luxury that fully electric cars can't afford. Electric cars need all the charge they can get, and that means new chemistries.

Lithium-ion batteries, which are compact and have a high capacity, are a natural place to start. Sony paved the way with the lithium cobalt oxide battery, which made its mass-market debut in a 1991 version of the firm's Handy-Cam video camera, and is now widely used in consumer electronics. Lithium is a light metal, and the lithium cobalt oxide lattice structure allows plenty of space for the give and take of ions. But scaling this chemistry up for vehicles is problematic. Cobalt is expensive and toxic, and the batteries have been known to show 'thermal runaway', battery lingo for fires or explosions. "It has affected a tiny, tiny fraction of all of the batteries sold, but nonetheless, it's pretty freaky to think about a big fire in one of the vehicles," says Jeff Dahn, who works on advanced battery technology at Dalhousie University in Halifax, Canada. "Safety really needs to be the focus for the research community."

Many of the lithium batteries under development for vehicles replace cobalt oxides with manganese oxides and iron phosphates. Both are safer, but they do have their own problems, not least of which is a lower storage capacity for their size. Another challenge has been dealing

J. SULLIVAN/GETTY IMAGES



The plug-in Prius uses electricity mostly to improve the efficiency of its petrol-powered motor.

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with the physical expansion and contraction of the electrode material as the lithium ions flow back and forth during charge and discharge, which can lead to fractures. Researchers at multiple institutions have addressed the issue by adding carbon and other substances to the electrode material.

They are also probing other chemistries — often at the nanoscale — based on silicon, fluorides and oxygen, which have a greater capacity. Others are looking at equipping the battery pack with capacitors, which can rapidly store and discharge electricity.

> "Safety really needs to be the focus for the research community."
> — Jeff Dahn

Even in their current state, however, lithium-ion batteries are performing well enough to keep car manufacturers interested. Last year, General Motors inaugurated the race for mass-market electric vehicles when it announced plans to market its plug-in hybrid, the Chevrolet Volt.

A break with the past

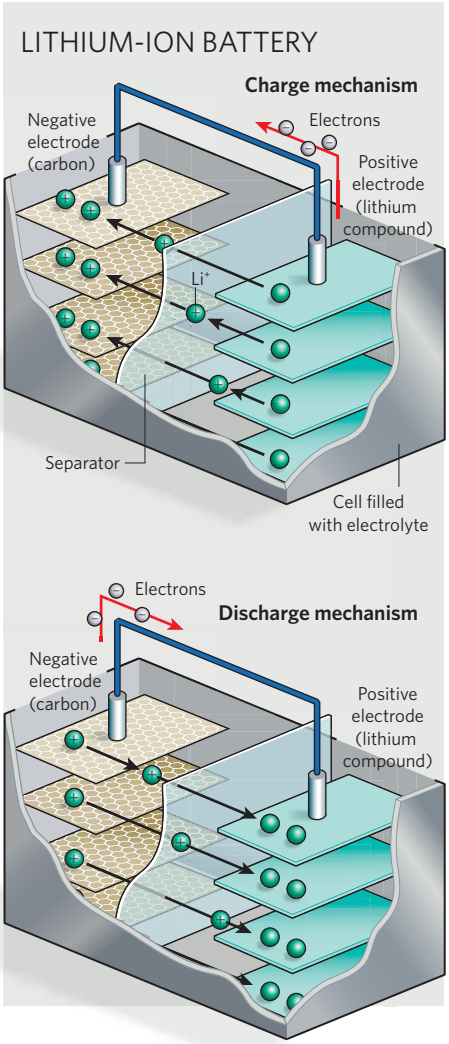
The Volt, now scheduled for a 2010 roll-out, is a radical shift in design. Hybrids such as the Prius are powered by petrol, and use a battery simply to improve fuel efficiency. The Volt hybrid will be the reverse: an electric car that uses petrol to extend its range. Only when the charge dies will a small petrol motor kick in to charge the battery, which then continues to power the vehicle. The goal is for Volt owners to plug in at night and then drive more than 60 kilometres a day on a single charge — before burning a single drop of petrol. Given that as many as 80% of US drivers commute less than that on an average day, such vehicles could eliminate a sizeable chunk of the nation's oil consumption.

The Volt initiative could open the door to a new kind of transportation system — if the company can pull it off, both on time and at a cost that will tempt consumers. Many observers have their doubts. "They are fundamentally redefining what a car is, but can they do it? I don't know," says Don Hillebrand, who heads the Center for Transportation Research at Argonne National Laboratory in Illinois. "When the first generation of anything comes out, to a certain extent car manufacturers are rolling the dice, and this is the biggest roll of the dice anybody has ever made."

Some say it is a long shot. With sales plummeting in the midst of a deepening recession, the company is facing possible bankruptcy, and has joined with the other major US car manufacturers in seeking an additional bailout from the government. But through it all, General Motors has continued to sink everything it can spare into the Volt, viewing it as a key technology that would allow the company to leapfrog its competitors.

Toyota is taking a more measured approach with its plug-in hybrid, which is expected to roll out with a lithium-ion battery in 2009. John Hanson, a spokesman based at Toyota's US headquarters in Torrance, California, talks about managing customer expectations: the company is promising only that the vehicle will go "at least" 16 kilometres on an electric charge. After that, it will blend petrol and electric power in much the same way as the current Prius.

That would leave General Motors in pole position, at least in terms of the electric range it is promising. But will the Volt succeed? The answer to that question depends on consumers. What will they want several years from now? And how much will they be willing to pay? General Motors expects to lose money in the beginning and has not yet announced a price for the vehicle, but the continued viability of the firm could depend on how fast it can sell the new cars and at what price. The company is banking on tax credits, enacted this year by Congress, to encourage people to buy plug-in hybrids, and high petrol prices would help as well.



But the firm's chief economist Mustafa Mohatarem says that he can't help but wonder whether consumer demand for electric vehicles has been exaggerated. "It is critically dependent on the battery," he says. "Until you have a much better handle on the cost of this technology, to talk about demand is in a sense ridiculous."

Have we forgotten something?

Others look at the market and see a different problem: a lack of batteries. Charles Gassenheimer, chief executive of Ener1 Group, a company in New York that produces lithium batteries, says that car manufacturers have collectively announced some 75 types of electric cars that are supposed to hit the road by 2013. But they have been slow to commit to orders, he says. And without orders, battery manufacturers can't invest the time and money necessary to ramp up production, a bottleneck that could delay the roll-out of new vehicles.

Governments seeking to spur the electric-car market must look at battery manufacturing in addition to consumers and car manufacturers, Gassenheimer says. "There needs to be some government intervention at this phase in the game. Otherwise it's going to be a chicken-and-egg problem that doesn't get solved."

Gassenheimer also raises concerns that countries such as the United States will simply trade their dependence on Middle Eastern oil for a reliance on Asian batteries. He has a sizeable stake in the outcome, of course, but the issue has political resonance as governments look to spur new green jobs. Experts say that Ener1 and other Western companies have the technology, but Asian companies have a leg-up on the manufacturing side simply because Asia has such a lead in producing lithium-ion batteries for electronics.

"The United States is certainly not being blindsided at this time, but whether or not we really have the resources and critical mass to compete in the long term in automotive batteries is still very much an open question," says Yet-Ming Chiang, a materials scientist at the Massachusetts Institute of Technology in Cambridge, and founder of lithium-battery manufacturer A123Systems in Watertown, Massachusetts. "The same thing goes for Europe."

Others dismiss concerns about where the batteries are going to be made, citing a crucial difference between electronics and vehicles:

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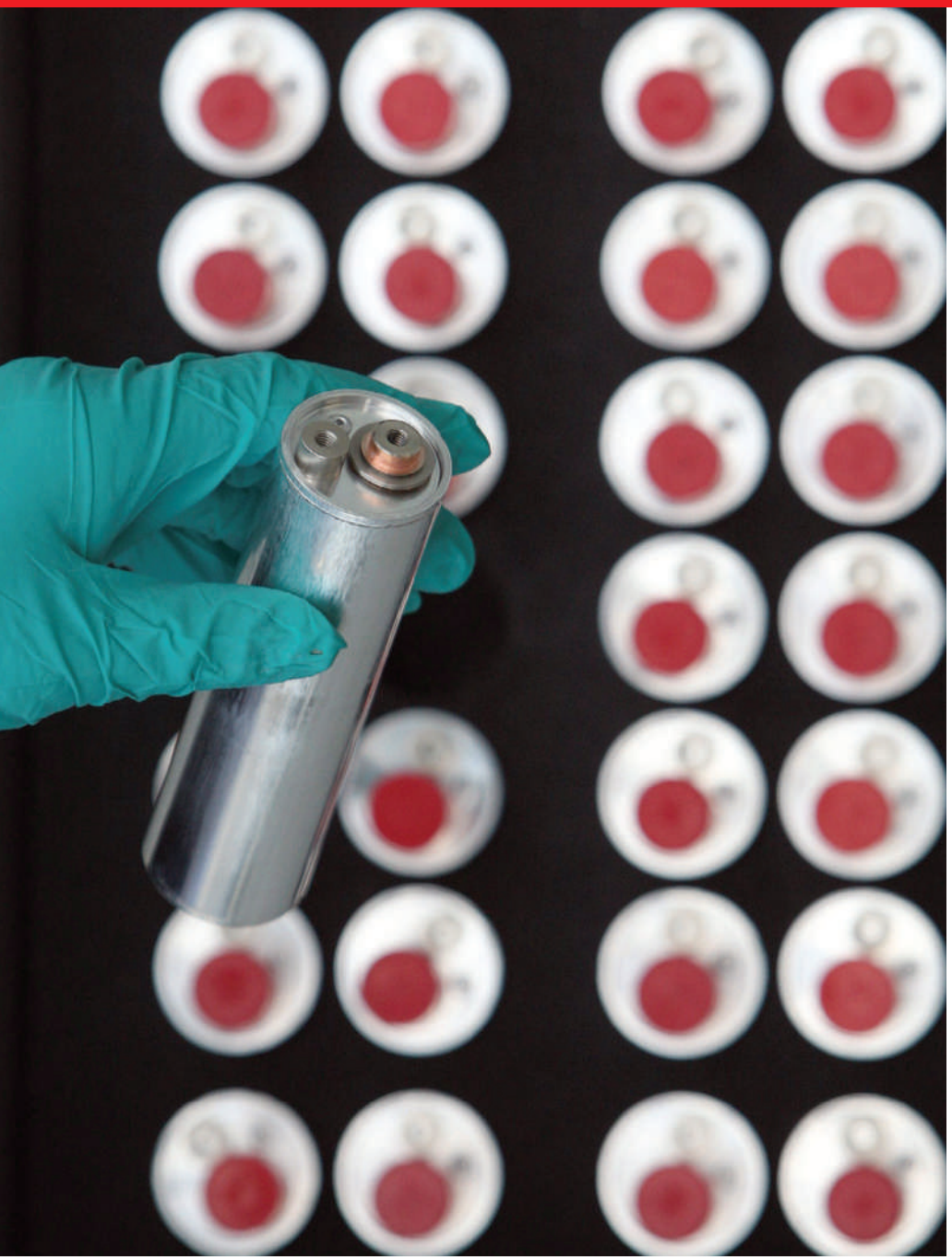

R. DUVIGNAU/REUTERS

New-generation lithium-ion batteries can power a car for up to 200 kilometres.

electronics are by and large made in Asia, but cars are made in the West, too. Building batteries near automobile plants would not only save money, it would also get around complex international shipping regulations that put lithium-ion batteries in the 'dangerous goods' category. The market "is driven by where the end product is", says Khalil Amine, a battery researcher and one of Hillebrand's colleagues at Argonne. "For electronics, we buy everything from Asia. For transportation, there is plenty of production here."

General Motors tested lithium batteries from every manufacturer it could find and narrowed the decision down to two companies: A123Systems and LG Chem, a Korean giant that made its name in electronics. Only in late October did the contract reportedly go to LG Chem, which has a stronger base and a longer history on the manufacturing side. LG Chem has already partnered with the Korean car manufacturer Hyundai to supply 7,000–10,000 lithium-battery packs for a pair of hybrid vehicles that will begin rolling off the line in 2009.

Soonho Ahn, LG Chem's vice-president for battery research and development, says that his company isn't expecting to make money on its automotive batteries for some time but wants to be ready when the market takes off. He notes that the battery market in Asia is in "equilibrium" after several years of stiff competition in the electronics sector. "We have some time to look at the next mega-application, and the next mega-application is the automotive industry," he says. "We're pretty sure that the market is coming."

Making connections

So what will the market be like when it does come? Plug-in hybrids such as the Volt represent a leap beyond battery-augmented cars that merely make better use of petrol. They also give drivers the freedom to run on electricity for short trips while still making long trips, albeit guzzling gas on the way. But some car manufacturers say that the best path forward would be an all-electric vehicle, which could one day all but eliminate oil consumption in the transportation sector.

Getting rid of the petrol motor greatly lessens costs and complexity and opens up space for more battery power. "In terms of a solution, both from a carbon dioxide point of view and from a technical point of view, the hybrid and the plug-in hybrid do not provide the technical breakthrough that the electric vehicle could provide," says Serge Yoccoz, who is in charge of electric vehicles at Renault. "And from what we've seen, the plug-in hybrid is definitely more expensive [than an electric car would be], even if you take into account the need to develop a charging infrastructure."

So while researchers search for the technical breakthrough, entrepreneurs are trying to get around the high costs by rethinking the way we market cars, batteries and ultimately energy.

One such innovator, Better Place of Palo Alto, California, is aiming for nothing short of a wholesale conversion of the transportation sector. The company likens itself to a cellphone network for all-electric cars: you buy the car from a Better Place partner and then sign up for one of its various user plans. Better Place then provides a network of charging spots — at home, work and retail outlets — as well as stations at which used battery packs could be swapped for recharged ones by a robotic arm in a matter of minutes (see graphic, overleaf).

But to accomplish all this, Better Place needs a computer system that can track electricity charges wherever they are incurred. It also needs to partner with governments and industry, including the automotive, battery and utility sectors. So far, Better Place has lined up partnerships with an alliance between Nissan and Renault to pursue electric cars, and the company plans to roll out its system in Israel, Denmark, Australia and California, with the first deployments scheduled for 2010.

The scheme is ambitious, but Sidney Goodman, head of automotive alliances at Better Place, says that's the only way to do it. "We don't believe we can do this on a small scale. It's one of these projects where either you do it big or you don't do it".

Better Place is aiming to provide family sedans that have a 160-kilometre range in an effort to attract all drivers, not just city commuters with

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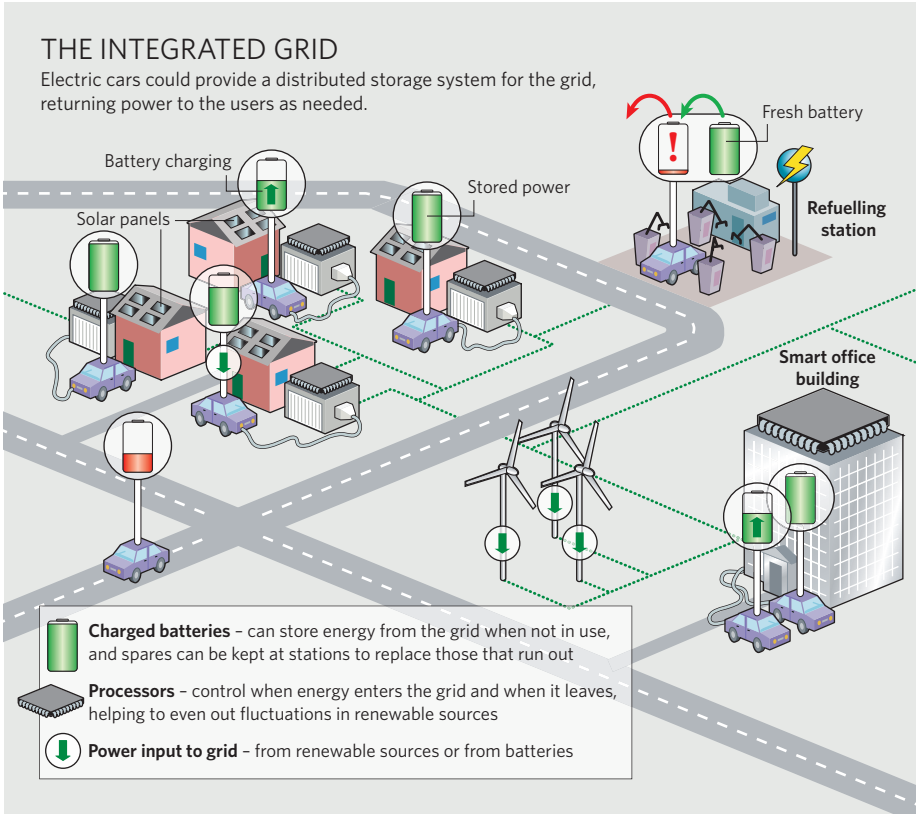

an environmental bent. Goodman runs through some rough numbers — assuming that a battery costs US$15,000 (which is likely to be on the high end of the scale, he stresses), an electric vehicle would cost about 6 cents per kilometre to power. That compares with just under 12 cents per kilometre for conventional cars in the United States, and twice that in Europe.

A Norwegian company called Th!nk is taking a similar route with its all-electric commuter car, which is due to hit roads in Norway, Denmark and Sweden in coming months. With an initial price tag of about 200,000 Norwegian krone ($30,000), the car will cost about 20% more than the same-sized petrol-powered car and will drive some 180 kilometres on a charge. Customers then pay a monthly lease to cover the cost of electricity and the battery. "We'll get the costs of our car down to somewhat similar to the cost of a petrol-powered car, and then we'll have a very strong proposition going forwards," says Richard Canny, Th!nk's chief executive.

Tapping the matrix

Utility firms are eager to cooperate. Although making electric vehicles a reality will require unprecedented cooperation between two industries that have until now had little in common, utilities actually see many more benefits than headaches. The fundamental fact is that most of the charging would take place at night, which creates a new source of revenue at a time when utilities typically have excess capacity.

In the end, this should translate into substantial reductions in greenhouse-gas emissions, even in countries such as the United States that get much of their electricity from coal. A plug-in hybrid running on electricity generated entirely from coal is roughly equivalent to a conventional hybrid in terms of emissions, but utilities say that in the early years, electric vehicles will frequently draw power from spare generating capacity that uses cleaner-burning natural gas. Scaled up, millions of batteries — either in cars or in a future after-market for used batteries — could provide utilities with a flexible storage system that could soak up renewable power, particularly from wind turbines at night.

Assuming that plug-in hybrids will make up 60% of the US automobile market in 2050, electric transport would consume as little as 8% of the nation's electricity, according to a joint modelling study conducted in 2007 by the Electric Power Research Institute — a non-profit research organization in Palo Alto — and the Natural Resources Defense Council, an environmental advocacy group based in New York. The resulting report, *The Power to Reduce CO_2 Emissions*, predicts that the nation would use 15–20% less oil and reduce its greenhouse-gas emissions by 450 million tonnes, which is akin to pulling 82.5 million internal-combustion vehicles off the road.

"Our fundamental conclusion from this study is that the number one driver of benefits is really the number of vehicles," says Mark Duvall, programme manager of electric transportation at the Electric Power Research Institute. "Don't worry about charging them from some perfect grid of the future — just get the cars out there. They don't have to be perfect."

Utilities such as Southern California Edison in Rosemead are already thinking about how to integrate cars into the electricity system, allowing them to charge up at work or park in 'smart garages' that coordinate activities between the car and the grid. In the early days, advanced charging equipment would communicate with the utility to time the charging so that everybody's vehicle is fully juiced when it needs to be — but not necessarily before. That would help ensure that millions of vehicles don't create a sudden surge on the electricity system when people return from work, when they also tend to turn on lights and crank up their appliances. Further out, this process could be reversed, allowing batteries to provide power to the grid when it is needed most — so long as they are fully charged when it comes to time to drive.

Levelling out the daily demand cycles would allow utilities to manage the grid more efficiently, potentially lowering costs to consumers. "The more cars that come onto the energy system, the better off it is for the energy system," says Ed Kjaer, director of electric transportation for Southern California Edison. And Kjaer says that the vehicles will become cleaner over time as utilities expand their renewable electricity offerings.

> **"We have some time to look at the next mega-application, and the next mega-application is the automotive industry."**
> — Soonho Ahn

That kind of logic has convinced many researchers that electric cars are a must if the planet is to deal with global warming, even if they ultimately raise the stakes on efforts to produce carbon-free electricity. "We've got to electrify the transportation system and then clean up the grid," says Timothy Lipman, research director at the University of California's Transportation Sustainability Research Center in Berkeley. "It's the easiest path." ■

Jeff Tollefson covers climate, energy and the environment for *Nature*.

See Editorial, page 421.

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