VEHICLE OF CHANGE

Hydrogen fuel-cell cars could be the catalyst for a cleaner tomorrow

BY LAWRENCE D. BURNS, J. BYRON McCORMICK AND CHRISTOPHER E. BORRONI-BIRD

RUNNING BOARD: General Motors's Hy-wire prototype hydrogen fuel-cell vehicle sits up on a lift, stripped down to its operational essentials—a "skateboard" chassis filled with a fuel-cell stack, electric motor and programmable electronic controls.

When Karl Benz rolled his Patent Motorcar out of the barn in 1886, he literally set the wheels of change in motion. The advent of the automobile led to dramatic alterations in people's way of life as well as the global economy—transformations that no one expected at the time. The ever increasing availability of economical personal transportation remade the world into a more accessible place while spawning a complex industrial infrastructure that shaped modern society.

Now another revolution could be sparked by automotive technology: one fueled by hydrogen rather than petroleum. Fuel cells—which cleave hydrogen atoms into protons and electrons that drive electric motors while emitting nothing worse than water vapor—could make the automobile much more environmentally friendly. Not only could cars become cleaner, they could also become safer, more comfortable, more personalized—and even perhaps less expensive. Further, these fuel-cell vehicles could be instrumental in motivating a shift toward a "greener" energy economy based on hydrogen. As that occurs, energy use and production could change significantly. Thus, hydrogen fuel-cell cars and trucks could help ensure a future in which personal mobility—the freedom to travel independently—could be sustained indefinitely, without compromising the environment or depleting the earth's natural resources.

A confluence of factors makes the big change seem increasingly likely. For one, the petroleum-fueled internal-combustion engine (ICE), as highly refined, reliable and economical as it is, is finally reaching its limits. Despite steady improvements, today's ICE vehicles are only 20 to 25 percent efficient in converting the energy content of fuels into drive-wheel power. And although the U.S. auto industry has cut exhaust emissions substantially since the unregulated 1960s—hydrocarbons dropped by 99 percent, carbon monoxide by 96 percent and nitrogen oxides by 95 percent—the continued production of carbon dioxide causes concern because of its potential to change the planet's climate.

Even with the application of new technologies, the efficiency of the petroleum-fueled ICE is expected to plateau around 30 percent—and whatever happens, it will still discharge carbon dioxide. In comparison, the hydrogen fuel-cell vehicle is nearly twice as efficient, so it will require just half the fuel energy. Of even more significance, fuel cells emit only water and heat as byproducts. Finally, hydrogen gas can be extracted from various fuels and energy sources, such as natural gas, ethanol, water (via electrolysis using electricity) and, eventually, renewable energy systems. Realizing this potential, an impressive roster of automotive companies are making a sustained effort to develop fuel-cell vehicles, including DaimlerChrysler, Ford, General Motors, Honda, PSA Peugeot-Citroën, Renault-Nissan and Toyota.

Overview/*Hydrogen Fuel Cells*

- Fuel cells convert hydrogen gas into electricity cleanly, making possible nonpolluting vehicles powered by electric drive motors. When combined with compact drive-by-wire electronic steering, brakes and throttle controls, fuel-cell technology allows engineers to split a vehicle into a rolling chassis and a (potentially interchangeable) body with an expansive interior.
- The prospect of clean hydrogen fuel-cell vehicles could also augur an altered energy economy and a sustainable environment without compromising personal mobility.
- The chicken-and-egg problem: large numbers of fuel-cell vehicles require adequate fuel availability to support them, but the required infrastructure is hard to build unless there are significant numbers of fuel-cell vehicles on the roadways.

It's an Automotive World

IT IS IMPORTANT to find a better solution to the problems posed by personal transportation because the environmental impact of vehicles is apt to wax as use booms. In 1960 fewer than 4 percent of the world's population possessed vehicles. Twenty years later 9 percent were owners, and currently the share has reached 12 percent. Based on present growth rates, as many as 15 percent of the people living on the planet could have a vehicle by 2020. And because the world's population may climb from six billion today to nearly 7.5 billion two decades hence, the total number of vehicles could increase from about 700 million to more than 1.1 billion. This projected expansion will be spurred by the burgeoning of the middle class in the developing world, which translates into rising per capita income. Higher income correlates almost directly with automobile ownership.

GENERAL MOTORS (*preceding pages*)

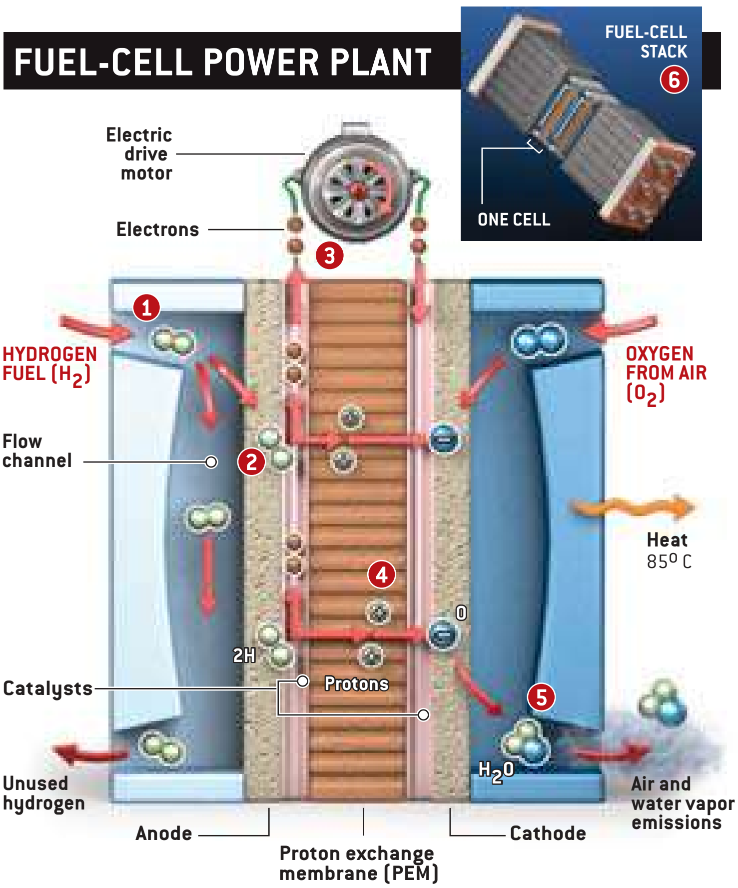
Three quarters of all automobiles are now concentrated in the U.S., Europe and Japan. We expect, however, that more than 60 percent of the increase in new vehicle sales during the next 10 years will occur in eight emerging markets: China, Brazil, India, Korea, Russia, Mexico, Poland and Thailand. The challenge will be to create compelling, affordable and profitable vehicles that are safe, effective and environmentally sustainable.

Rethinking Automotive Propulsion

TO UNDERSTAND WHY this technology could be so revolutionary, consider the operation of a fuel-cell vehicle, which at base is a vehicle with an electric traction drive. Instead of an electrochemical battery, though, the motor gets power from a fuel-cell unit [*see illustration below*]. Electricity is produced when electrons are stripped from hydrogen fuel traveling through a membrane in the cell. The resulting current runs the electric motor, which turns the wheels. The hydrogen protons then combine with oxygen and electrons to form water. When using pure hydrogen, a fuel-cell car is a zero-emission vehicle.

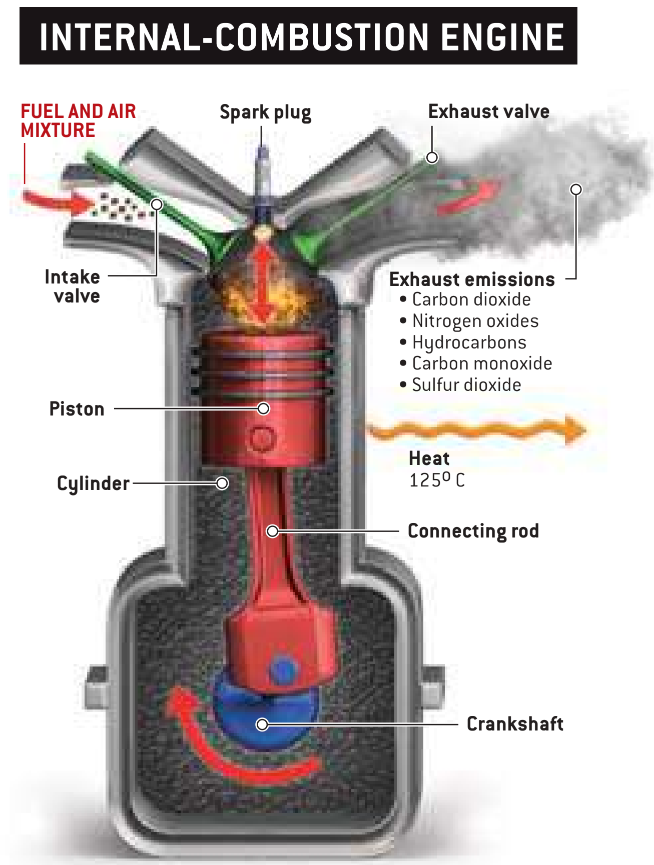
Although it takes energy to extract hydrogen from substances, by either reforming hydrocarbon molecules with catalysts or splitting water with electricity, the fuel cell's high efficiency more than compensates for the energy required to accomplish these processes, as we will show later. Of course, this energy has to come from somewhere. Some generation sources, such as natural gas-, oil- and coal-burning power facilities, produce carbon dioxide and other greenhouse gases. Others, including nuclear plants, do not. An optimal goal would be to produce electricity from renewable sources such as biomass, hydroelectric, solar, wind or geothermal energy.

By adopting hydrogen as an automotive fuel, the transportation industry could begin the transition from near-total reliance on petroleum to a mix of fuel sources. Today 98 percent of the energy used to power automobiles is derived from



UP TO 55% EFFICIENCY

ELECTROCHEMISTRY VS. COMBUSTION: A proton exchange membrane (PEM) fuel cell comprises two thin, porous electrodes, an anode and a cathode, separated by a polymer membrane electrolyte that passes only protons. Catalysts coat one side of each electrode. After hydrogen enters (*1*), the anode catalyst splits it into electrons and protons (*2*). The electrons travel off to power a drive motor (*3*), while the protons migrate through the membrane (*4*) to the cathode. Its catalyst combines the protons with returning electrons and oxygen from the air to form water (*5*). Cells can be stacked to provide higher voltages (*6*).



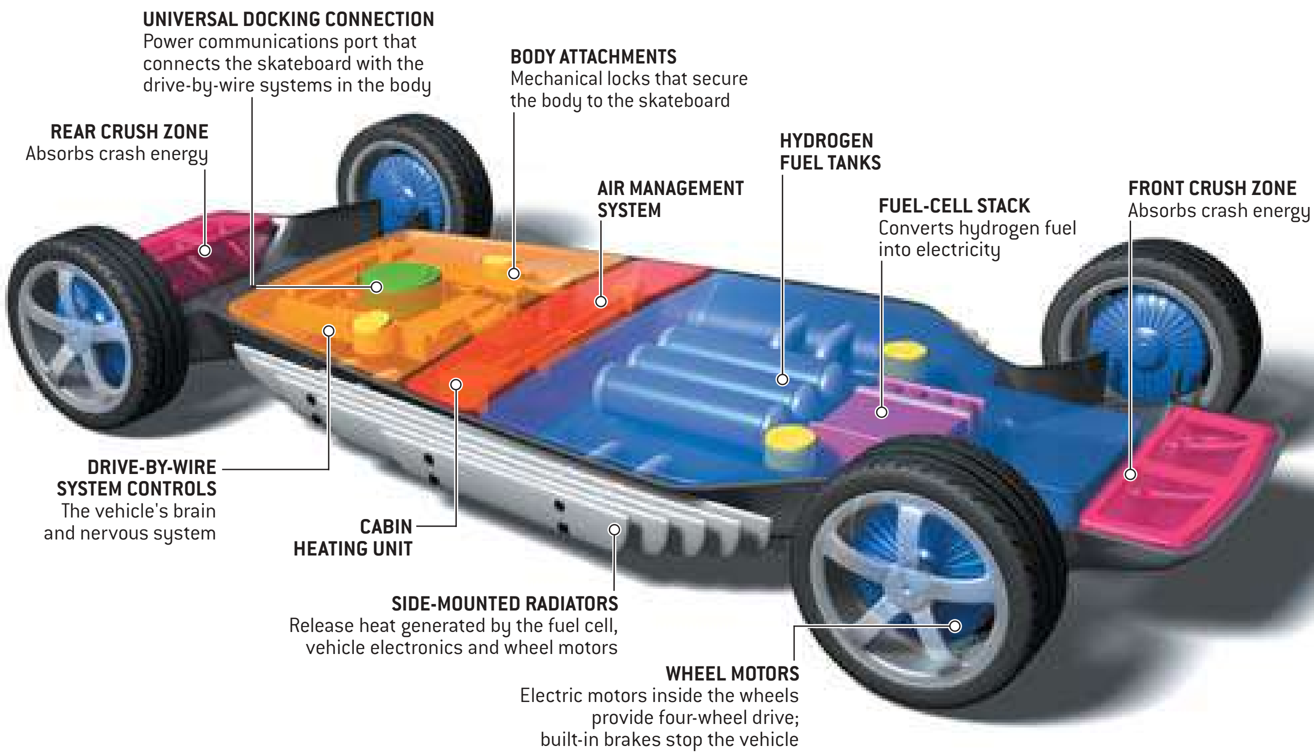
UP TO 30% EFFICIENCY

MOST U.S. CARS use four-stroke internal-combustion engines. The piston, which travels up and down when the crankshaft rotates, starts at the top of the cylinder. The intake valve opens and the piston drops, allowing the fuel/air mixture to enter the cylinder. The piston moves back up, compressing the gasoline and air. The spark plug fires, igniting the fuel droplets. The compressed charge explodes, driving the piston down. The exhaust valve opens, allowing the combustion products to exit the cylinder.

JOE ZEFF

AUTONOMY'S "SKATEBOARD" CHASSIS

SHOEHORNING functional automotive systems into the flat, skateboard-like chassis is the key to General Motors's AUTOnomy concept for a future hydrogen fuel-cell vehicle. That and the use of compact electronic drive-by-wire technology for steering, braking and throttling permits designers much greater freedom in configuring the upper bodies. It means no more bulky engine compartment, awkward center cabin hump or conventional steering wheel to work around. The novel approach also allows bodies to be interchangeable. Owners could have new, personalized bodies "plugged in" to their used chassis at the dealership, or do it themselves—turning, say, a family sedan into a minivan or a luxury car.



petroleum. As a result, roughly two thirds of the oil imported into the U.S. is devoted to transportation. By supplementing fossil fuels, the U.S. can reduce dependence on foreign oil and foster development of local, more environmentally friendly energy sources. This effort will also introduce competition into energy pricing—which could lower and stabilize fuel and energy costs in the long term.

Revamping Vehicle Design

ANOTHER KEY to producing a truly revolutionary vehicle is the integration of the fuel cell with drive-by-wire technology, replacing previous, predominantly mechanical systems for steering, braking, throttling and other functions with electronically controlled units. This frees up space because electronic systems tend to be less bulky than mechanical ones. By-wire system performance can be programmed using software. In addition, with no conventional drivetrain to limit structural and styling choices, automakers will be free to create dramatically different designs to satisfy customer needs.

Replacing conventional ICEs with fuel cells enables the use of a flat chassis, which gives designers great freedom to create unique body styles. Drive-by-wire technology similarly liberates the interior design because the driving controls can be radically altered and can be operated from different seating positions. Recognizing this design opportunity, General Motors came up with a concept called AUTOnomy, which the company introduced early this year. A drivable prototype, Hy-wire (for *hy*drogen by-*wire*), debuted at the Paris Motor Show in late September.

The AUTOnomy concept and the Hy-wire prototype were created, literally, from the wheels up. The foundation for both is a thin, skateboard-like chassis containing the fuel cell, electric drive motor, hydrogen storage tanks, electronic controls and heat exchangers, as well as braking and steering systems [*see illustration above*]. There is no internal-combustion engine, transmission, drivetrain, axles or mechanical linkages.

In a fully developed AUTOnomy-type vehicle, drive-by-wire technology would require only one simple electrical connection and a set of mechanical links to unite chassis and body. The body could plug into the chassis much like a laptop connects to a docking station. The single-electrical-port concept creates a quick and easy way to link all the body systems—controls, power and heating—to the skateboard. This simple separation of body and chassis can help keep the vehicle body lightweight and uncomplicated. It also makes the body easily replaceable.

JOE ZEFF

The hydrogen fuel-cell vehicle is nearly twice as efficient as an internal-combustion engine, so it will require only half the fuel energy.

In principle, simply by having the dealer or car owner "pop on" an interchangeable body module, the vehicle could be a luxury car today, a family sedan next week or a minivan next year.

Much like a computer, vehicle systems would be upgradable through software. As a result, service personnel could download programs as desired to improve vehicle performance or to tailor particular ride and handling characteristics to suit a particular vehicle brand, body style or customer preference.

With drive-by-wire electronic controls, the driver needs no steering wheel, gear shifter or foot pedals. GM's Hy-wire prototype is equipped with a steering guide control called X-Drive that easily moves from side to side across the width of the car to accommodate left- and right-hand driving positions. The X-Drive operates something like a motorcycle's handgrips: the driver accelerates by twisting the handgrips and brakes by squeezing them. Steering involves a turning action similar to today's steering wheel. The driver also has the option to brake and accelerate with either the right or left hand, with braking taking priority in the case of mixed signals. Motorists start the vehicle by pushing a single power button and then select one of three settings: neutral, drive or reverse.

X-Drive also eliminates the conventional instrument panel and steering column, which frees up the vehicle interior and allows novel placement of seats and storage areas. For example, because there is no engine compartment, the driver and all passengers have more visibility and much greater legroom than in a conventional vehicle of the same length.

By lowering the vehicle's center of gravity and eliminating the rigid engine block in front of the passengers, an AUTOnomy-like skateboard chassis can improve ride, handling and stability characteristics beyond what is possible with conventional vehicle architecture.

Reorganizing the Automobile Business

THE SIMPLIFIED DESIGN of an advanced fuel-cell vehicle, as suggested by the AUTOnomy concept and the Hy-wire prototype, could have a profound effect on vehicle manufacturing, perhaps setting the stage for a reinvention of the automobile business. Today's auto industry is capital-intensive, with modest profit margins. Even as car companies are aggressively managing the costs of vehicle development and manufacturing, excess production capacity in the global industry is driving down vehicle prices. At the same time, the regulatory standards–driven content of cars and trucks continues to grow, pushing up costs. Taken together, lower prices and higher costs are threatening profit margins.

A concept such as that of AUTOnomy, however, could significantly change the current business model. It could conceivably lower vehicle development costs because, with modules able to be produced independently, design changes to the body and chassis modules could be made more easily and cheaply. As with today's truck platform derivatives, it will be possible to design the chassis only once to accommodate various body styles. These derivatives could easily have different front ends, interior layouts and chassis tuning. With perhaps only three chassis needed—compact, midsize and large—production volumes could be much larger than those now, bringing greater economies of scale.

Having far fewer components and part types will further reduce costs. The fuel-cell stack, for example, is created from a series of identical individual cells, each comprising a flat cathode sheet and similar anode component separated by a polymer-electrolyte membrane. Depending on the power requirements of a particular vehicle (or other device, such as a stationary electricity generator), the number of cells in the stack can be scaled up or down.

Although automotive fuel-cell technology is far from economical at present (thousands of dollars per kilowatt for a handbuilt prototype), costs have begun to decline dramatically. For instance, the 10-fold increase in the power density of fuel-cell stacks achieved over the past five years has been accompanied by a 10-fold decrease in their cost. And whereas fuel cells currently require precious metals for catalysts and expensive polymer membranes, scientists are making progress in finding ways to minimize the use of catalysts and make membrane materials cheaper.

The AUTOnomy concept also makes it possible to decouple body and chassis manufacture. A global manufacturer could

THE AUTHORS

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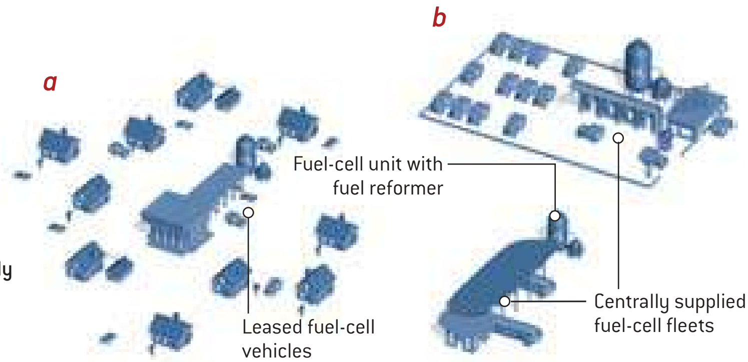
GENERAL MOTORS

STEPS TOWARD A HYDROGEN SOCIETY

WITHIN A FEW YEARS

a Small numbers of prototype vehicles are tested by leasing them to residents living near a hydrogen fueling station.

b Transit and business fleets that return to the garage each day, such as buses, mail trucks and delivery vans, start to be supplied by centrally located hydrogen stations.

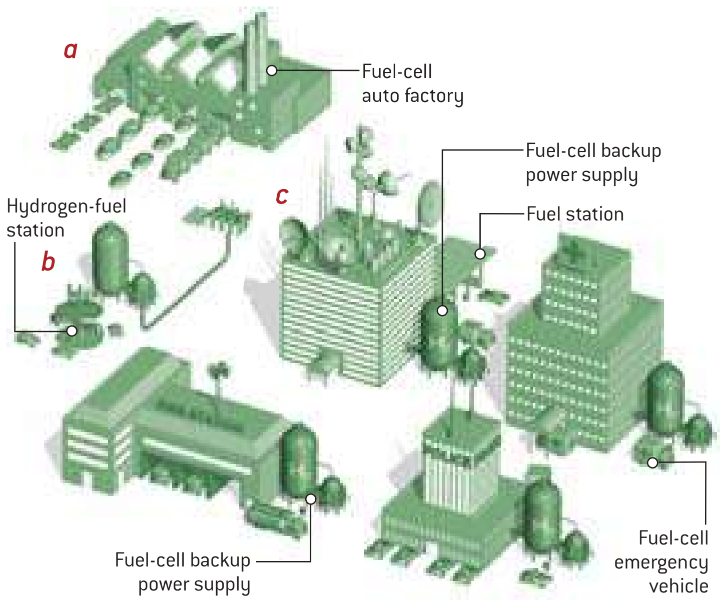


WITHIN A DECADE

a Car plants manufacture fuel-cell-powered "skateboards" and a few different "snap-on" body types.

b Hydrogen fueling stations with on-site natural gas reformers (chemical cracking units) are installed to provide hydrogen to early production vehicles.

c Stationary power generators, which reform natural gas into hydrogen and feed into the fuel cell, are installed in enterprises that require high-reliability "premium" power for data communications, continuous manufacturing, or emergency medicine. For example, ambulances and emergency vehicles refuel at the hospital fuel-cell unit.



IN MORE THAN A DECADE

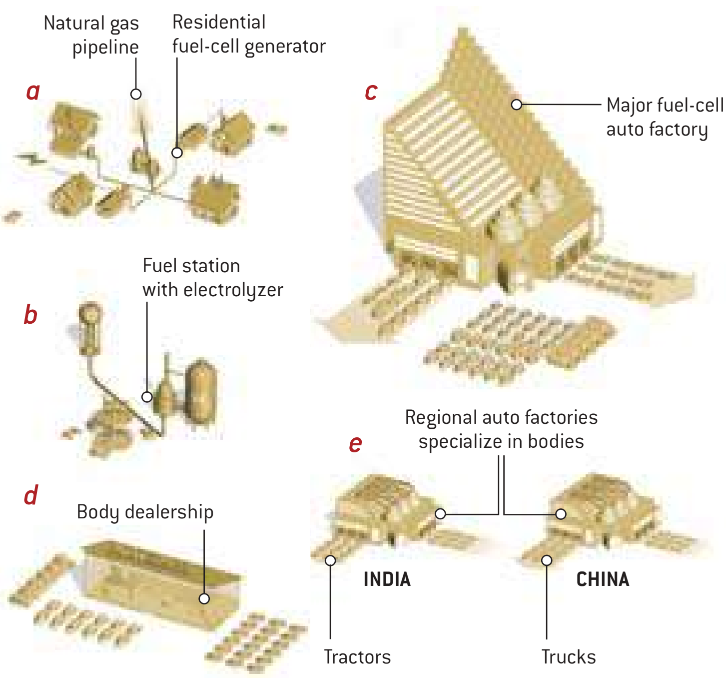
a Stationary reformer/fuel-cell units sited at more types of businesses and, eventually, homes sell extra power to the electricity grid in what's called a distributed generation system. These installations begin to provide hydrogen locally to employees.

b More hydrogen stations that use electrolyzers come online.

c Huge assembly plants put out three sizes of fuel-cell skateboard chassis (compact, midsize, large).

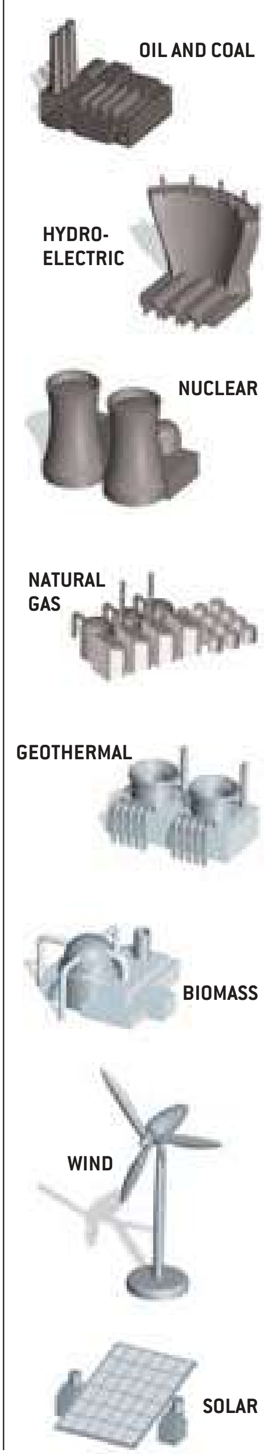
d Dealers sell new bodies in various styles for drivers' used skateboards.

e Other plants in different regions build diverse bodies for their local markets (for example, in India and China, tractors and trucks).



ENERGY SOURCES

Current fossil-fuel, nuclear and hydroelectric generation will be increasingly augmented by cleaner and renewable technologies.



SLIM FILMS

Hydrogen fuel-cell cars and trucks could help ensure a future in which personal mobility could be sustained indefinitely.

build and ship the chassis (an ideal scenario, given its thin profile), and local firms could build the bodies and assemble the complete vehicles. The chassis could be very economical because it would be mass-produced.

In high-end markets, this kind of arrangement might mean that new chassis might debut every three or four years—when software upgrades could no longer match performance desires—but that customers could purchase a new body module annually or lease one even more frequently. In addition, if chassis hardware is developed appropriately, then new hardware and software upgrades could become practical. Alternatively, consumers who wish to keep their vehicle body but want a higher-performance chassis could buy one. In less affluent markets, the chassis would comprise durable hardware and could be financed for much longer periods, perhaps decades.

Storing Hydrogen

THIS IS NOT TO SAY that all the technical barriers to engineering practical fuel-cell vehicles have been surmounted. Many obstacles have yet to be overcome before they will achieve the convenience and performance that customers have come to expect from their ICE automobiles. One of the biggest hurdles is the development of safe and effective onboard hydrogen storage technology that would provide sufficient driving range—about 300 miles. Any acceptable storage technology must be durable enough to run for at least 150,000 miles. It must function in temperatures from –40 to 113 degrees Fahrenheit (–40 to 45 degrees Celsius). And the refueling process must be simple and take less than five minutes to complete. There are various approaches to storing hydrogen, including liquid, compressed gas and solid-state methods. All are promising, yet all present challenges.

Compressed-gas tanks are the most likely to be used early on, but high compression remains a perceived safety issue. Currently these systems carry about 5,000 pounds per square inch (psi) of hydrogen (350 bars), but the goal is 10,000 psi (700 bars) to extend vehicle range. For safety purposes, the tank must have an impact burst strength of at least twice the pressure of the fuel. Vessels are currently made from materials that are either very expensive, such as carbon fiber, or very heavy. They are also relatively large, making it difficult to fit them in a vehicle.

Hydrogen can also be stored in liquid form, but a substantial amount of energy is needed to chill it to the extremely low temperatures required (–423 degrees F or –253 degrees C). Further, as much as 3 to 4 percent of the hydrogen will still "boil off" every day. Although most of this boil-off will be used by the vehicle, it would be a concern for cars parked for several days between trips.

A longer-term solution is to transport hydrogen using a solid-state approach. One promising alternative is metal-hydride storage. In this method, the hydrogen is held in the interstices of pressed metallic alloy powder, much like a sponge absorbs water. This technique has many encouraging aspects, including straightforward construction, a high degree of safety and promising storage capacities. But temperatures in the range of 150 to 300 degrees C are needed to extract the hydrogen from the metal hydride. To avoid an energy penalty, the hydrogen must be released at a temperature nearer to 80 degrees C. Although research is still in the early stages, solid-state storage is tantalizing.

Reworking the Infrastructure

MOMENTOUS AS THE CHANGES to the automotive business might be, they could be overshadowed by the potential influence of AUTOnomy-type vehicles on the world's energy supply system. Viewed from where we are today, fuel cells and a hydrogen fueling infrastructure are a chicken-and-egg problem. We cannot have large numbers of fuel-cell vehicles without adequate fuel availability to support them, but we will not be able to create the required infrastructure unless there are significant numbers of fuel-cell vehicles on the roadways. Given that the creation of a potentially costly hydrogen generation/distribution network in the U.S. is a prerequisite to commercializing fuel-cell cars and trucks, strong advocacy from local and national leaders in the public and private sectors is crucial. Key issues that must be addressed include subsidy funding, incentives for developing refueling stations, creation of uniform standards, and general education about the topic. The FreedomCAR initiative announced by the U.S. Department of Energy earlier this year, a public-private partnership to promote the development of fuel-cell power and hydrogen as a primary fuel for cars and trucks, is a step in the right direction. Government

Major Automotive Fuel-Cell Developers

DaimlerChrysler AG	Stuttgart-Mohringen, Germany
Ford Motor Co.	Dearborn, Mich.
General Motors Corp.	Detroit, Mich.
Honda Motor Company Ltd.	Tokyo
PSA Peugeot Citroën	Paris
Renault-Nissan Alliance	Paris/Tokyo
Toyota Motor Corp.	Toyota City, Japan

support for the research and pilot demonstrations required to prove the feasibility of the infrastructure will be needed.

To be sure, industry also must do its part to enable the difficult transition to the hydrogen economy. GM is now developing a bridge strategy that should move things along. We are working on bringing to market interim hydrogen-based fuel-cell products that will earn revenues to help offset the hundreds of millions of dollars that the company is investing on fuel-cell technology, while providing real-world operating experience.

It is likely that fuel-cell generators will be marketed for use in businesses and, eventually, homes, before fuel-cell vehicles are widely available. These applications are much less complex than automobiles, which have very demanding performance requirements. GM has developed prototype stationary fuel-cell generators that run on hydrogen extracted from fossil fuels.

Within the next few years, GM plans to unveil a range of stationary fuel-cell generators that are aimed at the "premium power," or high-reliability "guaranteed power," energy market segment. This $10-billion-a-year business encompasses energy consumers that cannot afford to be without electricity, including digital-data centers, hospitals, factories using continuous industrial processes, and telecommunications companies. These generators would enable cost reduction through the ability to cut power usage during peak periods as well as provide revenue through net metering (selling power back to the grid). One of our initial products will be a 75-kilowatt unit incorporating a reformer that extracts hydrogen for the fuel-cell stack from natural gas, methane or gasoline. No breakthrough technical developments are needed to build these stationary power products. When operational, these decentralized power systems can also be used to refuel vehicles with hydrogen.

Once safe and reliable hydrogen storage methods are available, off-board fuel processing at the filling station becomes a viable avenue for generating the hydrogen needed for transportation. An advantage of fuel processing, of course, is that most of the infrastructure required to implement it already exists. The current petroleum-based fuel distribution network could be retrofitted by installing fuel reformers or electrolyzers right at the corner gas station, allowing local operators to generate hydrogen on the spot and pump it for their customers. With this approach, there would be no need to build new long-distance pipelines or dismantle the present automotive servicing infrastructure. As we begin the transition from petroleum to hydrogen, this might well be the optimal way to proceed.

An even more radical scheme would be to refuel at home or at work using the distribution network that currently provides natural gas to individual homes and businesses. Natural gas pipelines are as common in many areas as gasoline stations, making this infrastructure an ideal conduit for hydrogen. The natural gas could be reformed into hydrogen and then stored onboard the vehicle. Alternatively, electricity from the utility grid could produce the hydrogen. Electricity purchased during off-peak hours, such as when your car is housed overnight in a garage, might eventually be an affordable way to refuel in some locales.

As vehicle power-generation systems become more sophisticated, we see the role of the automobile within the global power grid changing. Vehicles could at some point become a new power-generation source, supplying electricity to homes and work sites. Most vehicles sit idle about 90 percent of the time, so imagine the exponential growth in power availability if the electrical grid could be supplemented by the generating capacity of cars and trucks in every driveway or parking garage. Consider, for example, that if only one out of every 25 vehicles in

HY-WIRE OPENS UP THE INTERIOR

FLEXIBILITY IN DESIGN and consumer choice is the key to GM's strategy of stuffing all the car's operational systems into the skateboard chassis. Body designers are now free to explore passenger compartment configurations unhindered by traditional limits such as the dashboard and central hump. The body designs could also be interchangeable, allowing a single chassis to feature a wardrobe of alternative tops.

GENERAL MOTORS

Hydrogen can be generated from natural gas at a cost that is comparable with conventional fuel costs.

California today were a fuel-cell vehicle, their combined generating capacity would exceed that of the state's utility grid.

Obviously there are multiple options to choose from in creating a hydrogen distribution network. Although the scenarios we have painted are plausible, one of the most important factors in determining what the infrastructure will eventually look like is cost. Energy companies around the world are studying the economics of hydrogen. In recent testimony before the U.S. House of Representatives Committee on Science's Energy Subcommittee, James P. Uihlein of BP stated that hydrogen can be generated from natural gas at a cost that is comparable with conventional fuel costs. In fact, he went on to note, at the refinery gate, hydrogen's cost-per-mile-driven is actually substantially less than conventional fuel because of the outstanding efficiency of the fuel-cell engine. Hydrogen's current high cost, Uihlein said, can be attributed to the expense of transporting and dispensing it.

Hydrogen Matters

DEPENDING ON THE FEEDSTOCK and the production and distribution methods used, the cost of a kilogram of hydrogen can be four to six times as high as the cost of a gallon of gasoline or diesel fuel. (A kilogram of hydrogen is the energy equivalent of a gallon of petroleum-based fuel.) Yet because an optimized fuel-cell vehicle is likely to be at least twice as efficient as an ICE vehicle, it will go twice as far on that kilogram of fuel. Therefore, hydrogen should become commercially viable if its retail price per kilogram is double that of a gallon of gasoline. As improvements in hydrogen storage, fuel processing and electrolysis technologies are achieved and as demand for hydrogen increases, the cost of hydrogen should move nearer to the required price range. In fact, recent studies indicate that with today's technology we are within a factor of 1.3 of where we would like to be in terms of price.

Even though we are in the early stages of exploring solutions, we believe that when the infrastructure is required, it could develop rapidly, despite the enormous challenges involved. That was the case a century ago, when the gasoline automobile was proving its usefulness to customers, and the infrastructure to support it grew quickly. Entrepreneurs are always ready to seize new opportunities. The world is already beginning to develop the technologies needed for hydrogen production and distribution. Nevertheless, the size and scope of this particular infrastructure are huge, and there are significant technical obstacles ahead.

As discussions about how to create the required distribution network continue, it is interesting to note that hydrogen infrastructures are currently installed in several locations, most notably along the U.S. Gulf Coast and in Europe around Rotterdam, the Netherlands. Hydrogen is produced by the oil and chemical industries (it is used for sulfur removal in the petroleum-refining process), so it flows today through hundreds of miles of pipeline in a number of countries. The existing infrastructure annually produces approximately 540 billion cubic meters of hydrogen, primarily reformed from natural gas. On an energy-equivalent basis, this equates to roughly 140 million tons of petroleum a year, which is almost 10 percent of the present transportation demand. Even though the infrastructure is dedicated to other uses, the fact that it is already in place demonstrates that a great deal of expertise on generating and transporting hydrogen is available.

Like any advance that has the potential to change the dominant technology completely, the implementation of fuel cells and the transition to a hydrogen-based energy infrastructure will take time. Although a precise timetable is hard to predict, given our current technological momentum and business realities, we aim to have compelling and affordable fuel-cell vehicles on the road by the end of this decade. We then anticipate a significant increase in the penetration of fuel-cell vehicles between 2010 and 2020 as automakers begin to create the installed base necessary to support high-volume production. Many of these companies, including GM, have invested hundreds of millions of dollars in fuel-cell research and development, and the sooner they can anticipate a return on these investments, the better.

Because it takes about 20 years to turn over the entire vehicle fleet, it will take at least that long to reap the full extent of the environmental and energy benefits that hydrogen fuel-cell vehicles can provide. But the AUTOnomy concept brings that future nearer—and makes it clearer. Instead of the historical evolution of the automobile, we now see the development of revolutionary technologies that fundamentally reinvent the automobile and its role in our world. SA

A broadcast version of this article will air September 26 on *National Geographic Today,* a program on the National Geographic Channel. Please check your local listings.

GENERAL MOTORS

MORE TO EXPLORE

Prepared Statement of James P. Uihlein to the U.S. House of Representatives Committee on Science, Subcommittee on Energy. Field Hearing on Fuel Cells: The Key to Energy Independence? June 24, 2002.

Designing AUTOnomy. Christopher E. Borroni-Bird. Available at **www.sciam.com/explore_directory.cfm**