FUEL OF THE FUTURE?

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Hydrogen fuel-cell vehicles, largely forgotten as attention turned to biofuels and batteries, are staging a comeback. Jeff Tollefson investigates.

"The first car driven by a child born today could be powered by hydrogen and pollution-free," declared former US president George W. Bush in 2003, as he announced a US$1.2-billion hydrogen-fuel initiative to develop commercial fuel-cell vehicles by 2020.

The idea was appealing. Ties to foreign oil fields would be severed, and nothing but water vapour would emerge from such a vehicle's exhaust pipe. Congress duly approved the money, and the Department of Energy and other research agencies got to work. But then the whole effort faded into obscurity, as attention shifted first to biofuels and then to battery-powered electric vehicles. Both seemed to offer much quicker and cheaper routes to low-carbon transportation.

The shift seemed complete when the US Secretary of Energy Steven Chu entered office last year. Chu outlined four primary pitfalls with the hydrogen initiative. Car manufacturers still needed a fuel cell that was sturdy, durable and cheap, as well as a way to store enough hydrogen on board to allow for long-distance travel. Hydrogen also required a new distribution infrastructure, and even then the greenhouse-gas benefits would be marginal until someone worked out a cost-effective way to make hydrogen from low-carbon energy sources rather than natural gas.

Last May, four months after being sworn in, Chu announced that the government would cut research into fuel-cell vehicles in his first Department of Energy budget. Biofuels and batteries, he said, are "a much better place to put our money". The move came as a relief to the many critics of hydrogen vehicles, including some environmentalists who had come to see Bush's hydrogen initiative as a cynical ploy to maintain the petrol-based status quo by focusing on an unattainable technology.

But the budget proposal served only to energize the supporters of hydrogen vehicles, and it became clear during subsequent months that the debate was far from over. The same car manufacturers who were investing so heavily in biofuels and batteries felt that hydrogen fuel cells had a long-term potential that they could not afford to ignore. The hydrogen lobby was so effective that Congress eventually voted to override Chu and restore the money.

Then on 9 September in Stuttgart, Germany, nine major car manufacturers — Daimler, Ford, General Motors, Honda, Hyundai, Kia, Renault, Nissan and Toyota — signed a joint statement suggesting that fuel-cell vehicles could hit dealerships by 2015. In a coordinated announcement the next day in Berlin, a group of energy companies including Shell and the Swedish firm Vattenfall joined Daimler in an agreement to begin setting up the necessary hydrogen infrastructure in Germany.

This push for rapid deployment has left many people shaking their heads. "I just don't see it," says Don Hillebrand, director of the Center for Transportation Research at the Argonne National Laboratory in Illinois. "It doesn't make sense."

Yet the proponents of hydrogen vehicles are brimming with confidence. "This memorandum of understanding marks the will of the industry to move forward," says Klaus Bonhoff, who heads the National Organisation for Hydrogen and Fuel Cell Technology (NOW), a Berlin-based organization created by the German government in 2008 to spearhead that country's hydrogen programme.

Here *Nature* assesses the four major challenges facing hydrogen fuel-cell vehicles, and finds that both sides have a point: some of the challenges are close to being met — but others have a long way to go.

Fuel cell

Conceptually, at least, a fuel cell is simply a device that takes in oxygen from the air and hydrogen from a tank, and reacts them in a controlled way to produce water vapour and electric power. In a vehicle, that power can then be directed through an ordinary electric motor to turn the wheels.

In practice, fuel cells are anything but simple: controlling the reaction and extracting the electric current requires a sophisticated assembly including nozzles, membranes and catalysts. And therein lies the challenge: how to pack all that complexity into a device that is light, cheap, robust and durable — as well as being powerful enough to provide rapid acceleration, plus drive all the lights, air conditioning, radio and other amenities that consumers have come to expect in a modern vehicle.

Ten years ago this goal seemed far off. Car manufacturers didn't even dare to expose their experimental fuel-cell vehicles to cold weather: they worried that when the cells shut down, residual water vapour could freeze and wreak havoc on the delicate insides. Instead, the companies would shuttle the vehicles around in heated trailers.

But a decade has brought fuel-cell technology a remarkably long way. "Nobody woke up one morning and said, 'Ah-ha! Here's the salient breakthrough!'" says Byron McCormick, who headed the fuel-cell programme of General Motors until January 2009. "It has really been a whole lot of small steps."

For example, General Motors' fuel-cell vehicles eliminate the cold-weather problem in part by continuing to run the cell's exhaust system for a minute or two after the car is shut down, using the cell's residual heat to drive the water out of the system. Toyota says that its experimental, fuel-cell-equipped Highlander sports-utility vehicle will start up at −37 °C.

Engineers are also cutting back on the use of expensive catalysts. General Motors' fuel-cell assembly uses roughly 80 grams of platinum to split electrons and protons from hydrogen atoms. At the current platinum price of about US$60 per gram, this totals some $4,800. But General Motors officials say that their next fuel cell will use less than 30 grams of platinum, thanks to using ever thinner coats of the metal. And the company's scientists are continuing to experiment with measures such as increasing the surface area of the catalyst by introducing more texture at the nanoscale. Within a decade, they expect to get platinum use to below 10 grams, which would make the fuel cells competitive with today's catalytic converters in terms of precious-metal use.

These and other advances translate into price reductions. The Department of Energy estimates that fuel-cell costs per kilowatt of power dropped by nearly 75% between 2002 and 2008, based on cost projections for high-volume manufacturing. Companies won't discuss retail prices except to say that the vehicles slated to appear by the middle of the decade will be priced competitively. "I've been doing this for 10 years, and the numbers even surprise and shock me," says Craig Scott, manager of Toyota's advanced technologies group in Torrance, California. "It is definitely going to be a car that is in reach of a lot of people."

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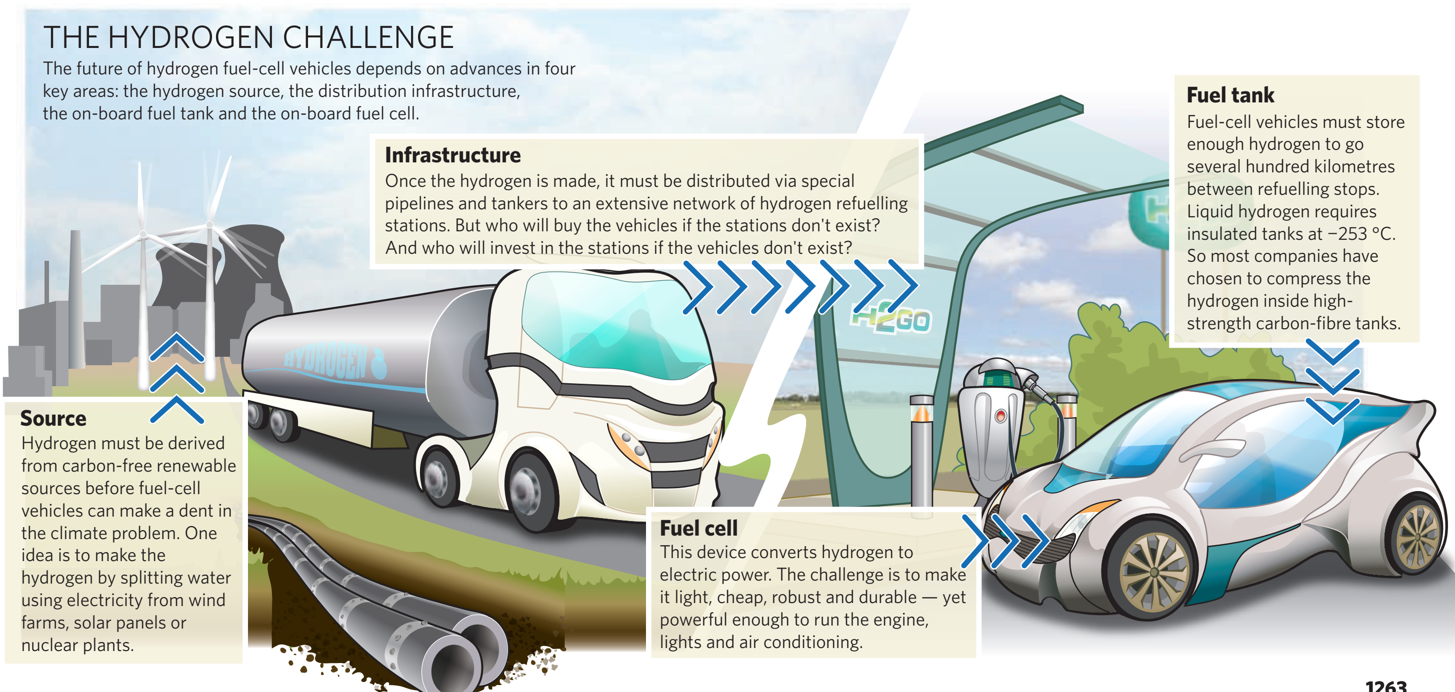
On-board storage

In June 2009, Toyota engineers and US government monitors hopped into a pair of fuel-cell Highlanders at the company's US headquarters in Torrance and took a 533-kilometre round trip through real-world traffic — without refuelling. Calculations suggest that the vehicles' performances corresponded to a range of 693 kilometres on a single tank of hydrogen, which is on a par with the range of current petrol vehicles.

Ten years ago, this feat also would have seemed daunting. Gaseous hydrogen is easy enough to store in a tank. But getting enough of it on board would require either a ridiculously large tank that would eliminate space for people, groceries and camping gear, or an exceptionally strong tank that could safely store compressed hydrogen gas at hundreds of times atmospheric pressure. Liquid hydrogen is much denser, but it would have to be maintained in an insulated tank at −253 °C, which would add to a vehicle's weight, complexity and expense.

In the end, the comparative simplicity of compressed hydrogen won out. Most companies have chosen to use modern carbon-fibre tanks, which can store hydrogen at up to 680 atmospheres, while still being relatively lightweight. To improve range further, many companies are also equipping their vehicles with the same 'regenerative braking' technology that allows hybrid petrol and electric cars and all-electric cars to capture energy during braking, store it in auxiliary batteries, and reuse it for later acceleration.

Indeed, because hydrogen and battery-powered vehicles both use electric motors, they share many technologies. The only real difference is the power source: fuel cells versus batteries. Scott says that electric vehicles based on the lithium-ion battery chemistry are unlikely to get beyond a range of 150–250 kilometres on a single charge. And although that may be enough to cover urban driving, consumers like having the option to drive cross-country. So in the shift away from petrol, the hydrogen vehicle's greater range could give it an edge in the long term.



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Scott says that hydrogen and electric vehicles have a space to occupy. "I just think that fuel cells will occupy a bigger space," he says.

Distribution infrastructure

Regardless of range, every vehicle needs fuel at some point. And here lies hydrogen's chicken-and-egg problem: fuel-cell vehicles will never sell in a big way until there is a viable network of service stations to fuel them. But no one is going to invest the capital required to create such a network until there is a fleet of thirsty hydrogen vehicles to provide a market.

Hydrogen pumps can and have been added to existing petrol stations, where at first glance they look much the same as conventional pumps. Because the hydrogen used is a compressed gas, filling the tank is not just a matter of placing a nozzle in the petrol-tank opening and letting gravity take care of the rest. Instead, a tight seal has to be established between the nozzle and car, and high-powered pumps have to force hydrogen through the nozzle until the desired pressure is reached. In practice, the current-generation hydrogen pumps are already easy and safe enough for an average consumer to use. But they do have to work perfectly if tanks are to be filled to full pressure; at present their performance is solid but variable.

A larger question facing car manufacturers is how rapidly the network of hydrogen-filling stations will spread. In the United States, for example, the number of hydrogen pumps is at present measured in dozens, and there seems to be little coordinated effort to change the situation. And until recently, things seemed much the same elsewhere.

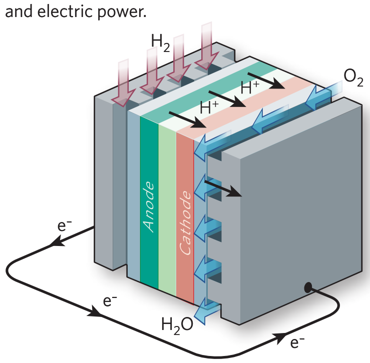
That's why hydrogen proponents see so much significance in last year's agreements in Germany, which promise to break the chicken-and-egg deadlock. The car manufacturers have promised the cars, and NOW is pushing for a network of several hundred pumps throughout Germany within a few years, and as many as 1,000 by the end of the decade. That should be enough to provide broad coverage within the metropolitan areas and regular access along the highways. Bonhoff says that the consortium expects the price to be within the range of what energy companies would normally spend to maintain, upgrade and expand their petrol infrastructure over the same interval.

"The question is whether we can afford not to have hydrogen infrastructure if we want to use renewables."

Charlie Freese, who heads the fuel-cell programme at General Motors, says that the hydrogen-infrastructure costs could be similarly manageable even in much larger countries such as the United States. In the early stages of a hydrogen-vehicle rollout, the Los Angeles basin could be well served with 50 hydrogen stations at a cost of roughly $200 million. Further down the line, some 11,000 stations might be needed to provide blanket coverage across the United States. "That's something you could do for roughly the cost of the Alaska pipeline," he says, referring to a proposed $35-billion project intended to carry natural gas from Alaska's North Slope to the North American market.

HOW THE FUEL CELL WORKS

The fuel cell combines hydrogen from the tank and oxygen from the air to form water vapour and electric power.



Hydrogen production

From a climate perspective, the main question facing hydrogen is where to get the gas in the first place. At present, the cheapest source is via a chemical reaction between steam and natural gas. But this process produces carbon dioxide, which means that the total greenhouse-gas production of a fuel-cell vehicle is not dramatically less than that of a conventional petrol vehicle. So the challenge is to derive hydrogen from carbon-free renewable sources.

Vattenfall, sees this as an opportunity and is building a facility in Hamburg that will use excess wind power to split water molecules and produce hydrogen for a fleet of 20 fuel-cell buses. Power companies tend to disperse extra wind turbines in various locations to compensate for the fact that wind is inherently unreliable. But those excess turbines will produce more electricity than the grid can handle if the wind blows in too many places at once. When that happens, turbines are shut down. Once the Hamburg facility comes on line, Vattenfall will instead fire up the electrolysis unit, tapping the excess power to make hydrogen and keeping the grid stable.

Cost is still an issue, says Oliver Weinmann, head of innovation management for Vattenfall in Germany. He says that the company will be able to produce hydrogen at €3–4 ($4–5.3) per kilogram, compared with €2 per kilogram for hydrogen produced from natural gas. But with Europe looking to expand its use of renewable energy over the coming decade, the growth potential is enormous, says Weinmann.

"It is not really a question of whether we can afford the hydrogen infrastructure," says Freese. "The question is whether we can afford not to have hydrogen infrastructure if we want to use renewables."

Adoption

Not everyone is persuaded by such arguments. Even if car manufacturers do get their fuel-cell vehicles to market by 2015, it will take years to establish a customer base, increase production and bring down costs. Few firms anticipate profitability on these vehicles until 2020 or even 2025. Meanwhile, they and the energy companies are also pushing biofuels and battery-powered electric cars, each of which would require its own distribution system. Building these transportation infrastructures simultaneously might not be possible.

These concerns are felt even within the car industry. Ford, for example, is confining its fuel-cell activities to long-term research, and has no current plans to market a commercial hydrogen vehicle. And BMW is hedging its bets with research into an otherwise conventional car whose internal combustion engine can burn petrol or hydrogen.

Some hydrogen advocates predict a multiple-niche scenario, in which battery vehicles are used in urban areas, whereas hydrogen pumps proliferate along the highways for long-distance travel. But perhaps the biggest mistake would be to assume that anybody in this game really knows what they are doing, says John Heywood, director of the Sloan Automotive Lab at the Massachusetts Institute of Technology in Cambridge.

Heywood says that the first round of vehicles will not be finished products so much as 'production prototypes' that allow companies to assess their performance — and the consumer response. Toyota followed this approach with its Prius hybrid car in 1997, and there's no reason to think that the process will be any faster for hydrogen or battery-powered vehicles. In either case, it could take three or more decades to revolutionize the global automobile fleet, says Heywood, and that's the kind of time frame that is guiding the car makers today.

"There are two paths, and they are going to invest in the electricity and the hydrogen pathway until it becomes clearer that one is significantly better than the other," he says. "Right now, we don't know the answer." ■

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