BY LAWRENCE M. FISHER

**Remember how** Bullwinkle (the cartoon moose in the *Rocky & Bullwinkle Show*) used to offer to pull a rabbit out of his hat just before the commercial break? "But that trick never works," Rocky (his faithful squirrel companion) would scoff, to which Bullwinkle would gamely reply, "This time for sure."

Pardon the author and his nostalgia for a TV era in which irony was still a novelty. But that routine came to mind on first glimpsing the latest round of hype for hydrogen-powered fuel-cell vehicles.

There has always been an element of magic to the hydrogen-fueled automobile: here's a car that would run in near silence on the most common element in the universe, emitting only pure water vapor from its tailpipe. Hydrogen enthusiasm ran high during the administration of George W. Bush, who predicted in his 2003 State of the Union speech that "the first car driven by a child born today could be powered by hydrogen, and pollution-free."

But then Steven Chu, President Obama's first Secretary of Energy (and a Nobel Prize winner in physics), brought the dreamers back to earth. For the hydrogen car to be viable, Chu said, four miracles would be needed – better ways to produce, store and distribute hydrogen, along with sharp cuts in the cost of fuel cells. Chu deemed this combination unlikely, at least in the following two decades. Federal research funding was subsequently slashed in favor of technologies thought more promising, presumably putting the miracle quartet even farther out of reach.

DAVID MAREUIL/ANADOLU AGENCY/GETTY IMAGES

Yet automakers, fuel-cell manufacturers and hydrogen producers never stopped working on the technology. And at last fall's Los Angeles Motor Show, hydrogen fuel-cell vehicles were displayed by Honda, Toyota, Hyundai, Volkswagen/Audi and Daimler-Benz.

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Moreover, these were not the chimerical concepts that automakers unveil to test the marketing waters or just to show they're cool. Some of them are poised to appear in showrooms.

You can already lease a hydrogen fuel-cell-powered Hyundai Tucson compact SUV in Southern California for $2,999 down and $499 a month, including the hydrogen fuel and all maintenance. Toyota will offer its edgy Mirai hydrogen cars for $58,325 later this year, with Honda's as-yet-unnamed FCV sedan to follow in 2016.

In fact, the hydrogen trail has already been blazed, albeit lightly: Honda produced a handful of FCX Clarity sedans for public use from 2008-14. Analysts estimated each one cost at least $1 million to build, and only 43 of them were leased at $600 a month. Nevertheless, the BBC's *Top Gear* called it "the most important car for 100 years."

So what has changed? Perhaps nothing. Hydrogen skeptics still decry the technology as an expensive boondoggle, or even a cynical ploy by automakers to establish their green credentials and to meet state zero-emissions quotas as they continue to derive the bulk of their revenues from gas-chugging pickup trucks and SUVs.

Electric-car advocates have been among the harshest critics. Tesla's Elon Musk, himself once a prime target of skeptics, likes to talk about "fool cells," while echoing Chu's pessimism about the cost of manufacturing fuel cells, not to mention producing, storing and distributing sufficient fuel at a low enough cost to make hydrogen cars commercially viable. But while there have been no true breakthroughs, there has been a steady incremental progress on all the important fronts.

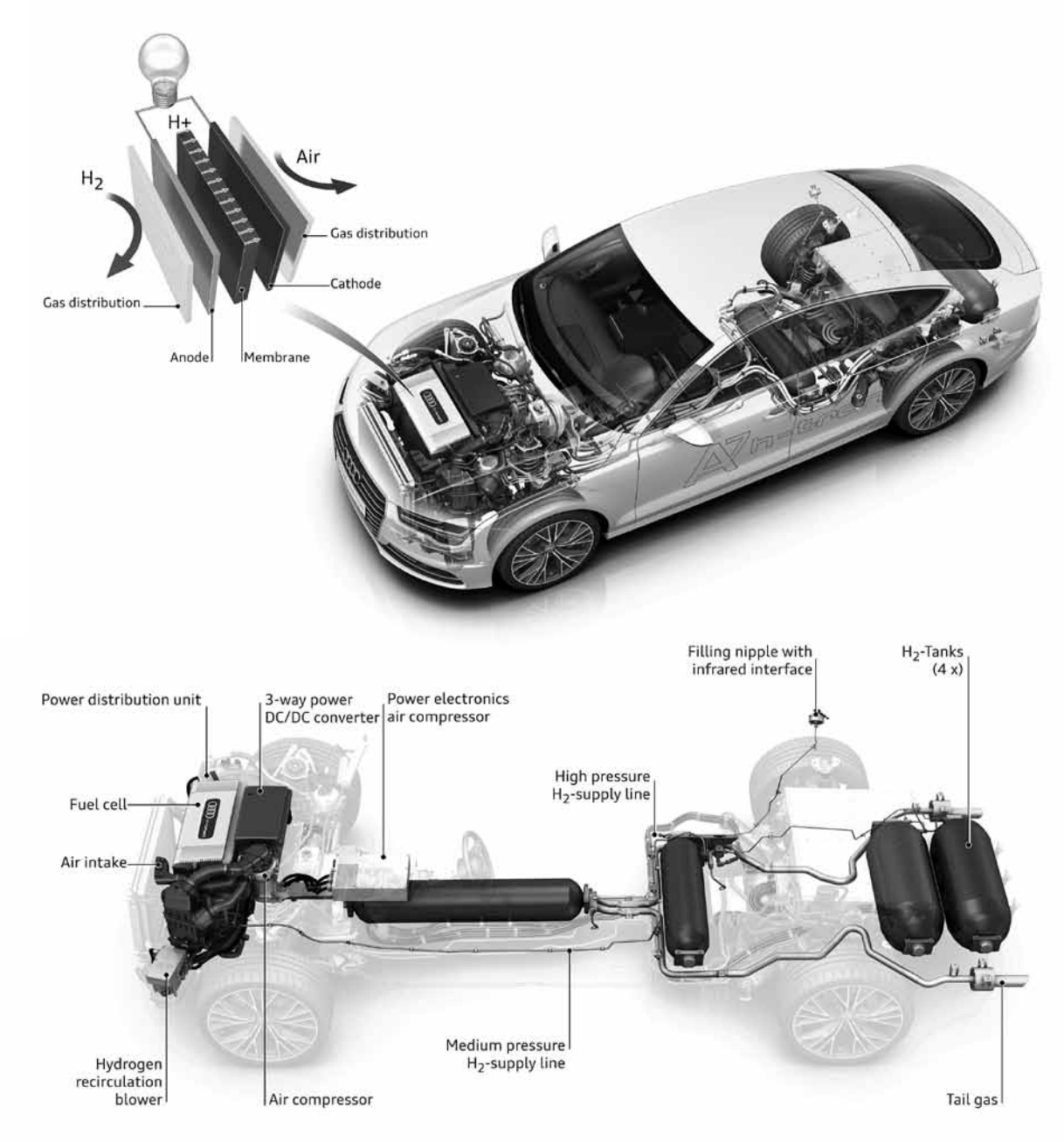
At the same time, the growing urgency of combating climate change and the corresponding changes in public policy, like the Zero Emission Vehicle requirement in California and seven other states, have created a less skeptical market climate. Moreover, the "better-than-expected" success of electric cars, like the Tesla Model S and Nissan Leaf, and the ever-greater market penetration of hybrids like the Toyota Prius, provide a model for public acceptance of alternative fuel vehicles. It's surely no coincidence that Toyota and Honda, which produced the first gasoline/electric hybrids, are among the first to market with hydrogen fuel-cell cars.

"I've been driving a fuel-cell vehicle for four years and it's great – a Honda Clarity," exclaims James J. Provenzano, president of Clean Air Now (an environmental nonprofit) and co-author, with Geoffrey B. Holland, of *The Hydrogen Age: Empowering a Clean-Energy Future*. "It's a beautiful car; it performs, and I'm coming from a Mercedes E-class. The biggest thing is the costs have come down … This technology is ready."

## WAIT 'TIL NEXT YEAR

It is the perverse nature of new technologies that they rarely if ever develop as rapidly as politicians, technology writers or financial backers expect. The idea of fuel cells, which convert fuel into electricity without the muss and fuss of combustion, can be traced back as far as 1838. But the first quasi-commercial application did not come for more than a century, when NASA used them to generate power for probes, satellites and space capsules. The hydrogen-oxygen fuel cell was designed and first demonstrated publicly in 1959, and was used as a primary source of electricity in the Apollo spacecraft, which carried 24 astronauts to the moon from 1969 to 1972.

Not bad for a proof of concept. But for more down-to-earth applications, cost remained a huge barrier. Hydrogen-oxygen fuel cells generate electricity by capturing the en-




COURTESY OF AUDI

ergy released when hydrogen combines with oxygen to form water. That sounds simple enough. But for it to happen in the right place at the right time, the two gases first have to be processed through a membrane electrode assembly, which includes a catalyst to separate the hydrogen atoms into protons and electrons. That catalyst has typically been made of platinum or other scarce metals, and early fuel cells captured only a modest portion of the energy released by the electrochemical reaction, limiting their efficiency.

Much credit for bringing fuel-cell cost down and efficiency up is due to Ballard Power Systems, a British Columbia-based company that has been quietly plugging away at the technology since 1983. Although the automotive market remained a bridge too far,

Ballard did produce fuel cells for other purposes, including backup power for wireless telecom networks, onsite power generation for remote places, materials-handling systems like forklifts and even a fleet of city buses. The company also supplied fuel-cell know-how to Daimler-Benz and Ford, and more recently has entered a strategic alliance with Volkswagen. The shapely Audi A7 H-tron, the fuel-cell-powered version of Audi's sports sedan that was displayed at the Los Angeles show, employed Ballard's technology.

"Performance of the automotive fuel-cell system has improved significantly, to where it really is competitive with the internal-combustion engine, in terms of acceleration, smoothness, cold starts and efficiency," explains Guy McAree, Ballard's director of investor relations. "There's still some cost reduction that has to happen, though that's come a long way, too. We are still talking about limited deployments – hundreds of cars, not tens of thousands. But it's exciting because two or three years ago, you didn't see anything like this."

Honda, Toyota and Hyundai have also improved the efficiency and reduced the cost of their fuel cells. "We've been working on the technology for 15 years," says Derek Joyce, a Hyundai spokesman. "We did almost exclusively our own development. We want to be a leader in the technology."

Toyota has been working on fuel cells for 22 years; indeed, it leased 104 hydrogen Highlander SUVs to the public in the 2000s. "There were steady improvements along the way," notes Craig Scott, Toyota's national advanced technology vehicle manager. "The good news for fuel cells compared with batteries is we weren't looking for a fundamental breakthrough in physics."

Recently, fuel-cell technology has seen some developments that do verge on breakthroughs. A new class of catalysts developed by researchers at the Department of Energy's Lawrence Berkeley and Argonne National Labs could make fuel cells cost-competitive with other power generators. Employing nanotechnology, the researchers created a catalyst that uses roughly one-sixth as much platinum and offers more than 30 times the catalytic activity, making it both cheaper and more efficient than the conventional technology.

## UBIQUITOUS BUT ELUSIVE

Hydrogen is the most abundant element in the universe, but there's a problem. It binds so promiscuously with other elements that it is virtually never found on its own. It is most often bound to carbon, as in fossil fuels, and, of course, with oxygen to form water. While hydrogen gas was first synthesized in the 16th century by mixing metals with acid, production of the gas remains costly today. Industrial production is mainly done by exposing the methane in natural gas to superheated steam, and less often, by the electrolysis of water. Most industrial hydrogen, which is highly flammable and expensive to compress for transport, is employed near its production site.

There have been no real breakthroughs in steam reformation, which accounts for about 95 percent of U.S. hydrogen production, but there have been serendipitous developments in the source of the raw material. Fracking, while nobody's idea of a green technology, has yielded an abundance of natural gas, driving down costs.

Producing hydrogen requires a lot of energy – the energy that heats the steam to at least seven times the boiling point of water – but so, for that matter, does generating electricity or refining gasoline with fossil fuels. In a study conducted by the Union of Concerned Scientists comparing well-to-pedal

emissions of the Hyundai Tucson hydrogen fuel-cell vehicle with a gasoline-powered Tucson showed a reduction of 34 to 60 percent in energy consumption, depending on the source of the hydrogen.

"At least in California, we have a renewable hydrogen standard – a minimum 33 percent must come from renewable sources, and we are estimating 46 percent by the end of the year," says David Reichmuth, a senior engineer in the UCS's Clean Vehicles Program. "That makes it a good bit cleaner. I think the promise of hydrogen – and this is similar to electric cars – is that there are a variety of ways to make it. There are cleaner ways, just like there are cleaner ways to make electricity."

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The cleanest way is through electrolysis, applying electricity to water to separate the $H_2$ from the O. And if that electricity comes from renewable sources like wind or solar, the cycle can be very clean, indeed. In most instances, electrolysis remains too expensive to be practical. But in areas with substantial wind and solar power that can only be produced episodically, it could be viable as a means of storing energy that would otherwise go to waste.

That largely explains why Chu, the critic who put the kibosh on federal R&D subsidies, is inching toward acceptance of hydrogen's role as an alternative fuel. Hydrogen, Chu explained to the *MIT Technology Review*, "could effectively be a battery of sorts. You take a certain form of energy and convert it to hydrogen, and then convert it back [into electricity]."

In 2013, the UK turned down a million megawatt-hours of renewable power because it was surplus to its needs at the time it was generated. ITM Power, a Sheffield, England-based company, proposes to turn that surplus electricity into hydrogen for use in fuel cells. It has a pilot electrolyzer project in Frankfurt, Germany, and will build three hydrogen refueling stations in London at a cost of £2.8 million ($4.2 million). It also has two refueling projects in the works in California and, overall, has some $15 million worth of projects "under contract or in the final stages of negotiation" around the world.

Hydrogen can also be produced from biomass, which a recent study by the University of California at Davis concluded could begin to make a significant contribution in about 2020. Provenzano of Clean Air Now says he often fuels his Honda Clarity from a hydrogen station attached to a sewage treatment plant in Orange County that produces enough hydrogen to fill 50 cars a day. Now there's a renewable resource.

### BOUNCING BULLETS

Hydrogen has long suffered from bad word association because it brings to mind either a really big bomb or the *Hindenburg* disaster. Both are a bit unfair in the context of fuel cells.

The hydrogen weapon of the early 1950s was a uranium or plutonium fission bomb that heated a reservoir of hydrogen to temperatures found at the center of stars, fusing the atoms into helium and releasing humongous quantities of energy. And while the *Hindenburg* was filled with lighter-than-air hydrogen,

**The Toyota Mirai.**

the proximate cause of the deadly fire was probably a lightning strike or the flammable paint on the dirigible's fabric covering.

Nevertheless, safe storage of hydrogen has obviously been a concern for the automobile industry. In order to store enough hydrogen to provide a range comparable to internal-combustion-engine cars, it must be compressed, raising the question of what happens if a tank is punctured and the fuel rapidly escapes. Those who have seen the *Hindenburg* film clip (which is practically everybody) envision cars engulfed in flames when they are rear-ended.

Automakers are understandably at pains to allay such fears. The Toyota Mirai employs carbon-fiber-wrapped resin composite tanks, which were the first in Japan to meet the international standard for compressed hydrogen storage containers for vehicle fuel systems. In a dramatic video (since removed from the Internet), Toyota engineers fired bullets of increasing sizes at the pressurized tanks; they bounced off. Not until they fired a large-caliber explosive shell was a tank punctured – and then the hydrogen just hissed into the atmosphere without spectacle.

"Storage is always an issue when you're comparing it against a liquid fuel like gasoline" that does not require high pressure, acknowledges Toyota's Craig Scott. "We are still researching new technology, but this is sufficient to bring it to market today."

Remember the BMW Hydrogen 7, produced from 2005 to 2007? These were not fuel-cell vehicles, but conventional BMW 7-series sedans with internal-combustion engines that had been modified to run on either gasoline or liquid hydrogen. Liquid hydrogen, now the fuel of choice for NASA rockets, has high energy density and is relatively easy to transport.

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But hydrogen must be cooled to within shouting distance of absolute zero in order to turn into a liquid. And liquefying one kilogram of hydrogen using electricity from the U.S. grid would by itself release some 18 to 21 pounds of $CO_2$ into the atmosphere, roughly equal to the $CO_2$ emitted by burning one gallon of gasoline. Moreover, the safety issues escalate with gas under these sorts of pressures. As Scott puts it, "Handling liquid hydrogen is not for the faint of heart."

### CHICKEN AND EGG

There's still the nagging issue of hydrogen distribution infrastructure. While electric cars can be recharged at home – or anywhere else recharging equipment can be attached to the electricity grid – hydrogen fuel-cell vehicles need "gas" stations, just like their internal-combustion counterparts. This creates a commercial Catch 22: without the convenience of broadly deployed hydrogen fuel stations, consumers won't buy fuel-cell cars. But without a critical mass of hydrogen vehicles on the road, business won't have the financial incentive to build the fueling stations. The solution (if there is one) turns on the willingness of governments and hydrogen vehicle manufacturers to jumpstart the construction of the fueling network.

A year ago, the California Energy Commission announced that it would invest some $47 million to accelerate the development of public hydrogen refueling stations as part of its agenda to create a market for zero-emission fuel-cell vehicles. The Commission awarded funds for six fueling stations that will deliver only hydrogen derived from renewable sources. Still to come: another 13 stations in Northern California and 15 in Southern California, strategically placed to make it practical to use fuel-cell vehicles in regional centers

and along major transit corridors. California has earmarked an additional $150 million, with a goal of building yet another 100 new stations throughout the state.

Timed to the day of the Energy Commission's announcement, First Element Fuel, a California-based hydrogen fueling company, and Toyota announced an initial financial agreement that included a $7.2 million loan to assist First Element in the operation and maintenance of 19 new stations. Separately, Toyota said it will collaborate with Air Liquide, a big producer and supplier of industrial gases, to build and supply a network of 12 hydrogen stations in New York, New Jersey, Massachusetts, Connecticut and Rhode Island.

"We're trying to solve that last miracle by seeding infrastructure companies," said Toyota's Craig Scott. "We're building a hydrogen station right down the street from Tesla," he noted, in the expectation that Silicon Valley will be as receptive a market for the Mirai as it has been for electric vehicles.

### A DIVERSIFIED PORTFOLIO

One surprising, and ironic, aspect of the hydrogen car rollout has been the amount of vitriol flung in its face by the electric car lobby. Ironic, because fuel-cell vehicles are electric cars, too, and the experience of driving one is very similar. Put it down to sibling rivalry, because these two technologies are competing for public funds and market acceptance the way brothers and sisters compete for parental affection. While California continues to commit cash for EVs, the Obama administration is phasing out support for hydrogen. Electric-car advocates would like that trend to continue.

"Apart from the environmental benefits, what advantages do FCVs have over conventional [electric] vehicles?" asks Tom Saxton, chief science officer of Plug In America, a coalition of electric-car advocates that formed after General Motors, Toyota and other manufacturers withdrew their not-ready-for-prime-time EVs from the market in 2005. "Is there a single automaker committed to offering a mass-market FCV in every state in the U.S., or are they just selling compliance cars that take advantage of CARB's higher ZEV credits for FCVs?" he asks, referring to the California Air Resources Board, and to the state's $5,000 rebate to fuel-cell car buyers, which is double the rebate offered for battery-powered EVs.

Then there's the unknown of what hydrogen will run at the pump. "What does it cost to fuel an FCV?" Saxton asks. "So far the automakers seem to be hiding the cost of fuel by bundling it with their compliance cars, but this isn't a strategy that scales up."

Head-to-head, though, hydrogen may prove a match for battery-powered cars. Fuel-cell vehicles deliver the same instant torque, seamless power delivery and near silence that delight drivers of Teslas and Nissan Leafs alike, with the added advantage of 300 mile range and fueling that takes 5 minutes. Other than Tesla's $70,000 (and way up) Model S, most EVs can go only about 80 miles on a charge, and Tesla's refueling, even at on-the-road supercharger stations, takes about half an hour for an 80 percent charge.

Hyundai's spokesman said the company will sell its FCV in every state as fueling stations are built, though it is not offering to fund them. Toyota, too, plans nationwide distribution; the company is financing stations in multiple states as well as in Denmark, Germany and the UK. Honda and Volkswagen have not announced their distribution plans, but will likely respond to market signals.

Hydrogen fuel costs remain a question mark because there are so many variables, and the technology is still evolving. What is known is that the cost has already dropped


**Hydrogen-powered bus for California's Alameda-Contra-Costa Transit District.**

COURTESY OF AC TRANSIT

significantly and should continue to fall as the production technology evolves. Direct solar electrolysis, currently under development at the California Institute of Technology, would make low-cost renewable hydrogen abundant. "In quantity, the cost should be no more than natural gas," says Provenzano of Clean Air Now.

Lost in the hue and cry is the fact that none of the big automakers behind the FCV are putting all their eggs in the hydrogen basket the way Tesla has with electricity. Honda and Toyota have made a limited number of battery electric vehicles along with scads of gasoline hybrids and plug-in hybrids, while Volkswagen currently offers battery EVs, plug-in hybrids, gasoline hybrids and diesel hybrids. One area where the fuel cell is likely to dominate other fuel systems is in larger vehicles, like trucks and buses, where electric power simply requires more weight in batteries than is practical.

"I think the [Chu] miracle quote was headline catching, but a little off," says Reichmuth of the Union of Concerned Scientists. "Real drivers are going to be behind the wheel soon, and there are already some on the road in California. From our office, we see fuel-cell buses going by all the time."

So keep your eyes on that cartoon moose of TV legend. Maybe this time it really is for sure.