Hydrogen Fever!

From H_2-powered trams and railways to supersonic transport, the global carbon economy may soon get a lighter, cleaner competitor

By **Arielle Emmett**

SPEED—WILDLY SUPERSONIC, hydrogen-powered speed—might soon be available for passengers traveling across the American continent in giant tubes resembling PVC water pipes.

The tubes will contain multi-articulated vehicles—crosses between a plane and a train. Inside the tubes, the vehicles will breathe fuel, store oxidant, and increase in weight during operation.

This is Arnold Miller's vision. Miller, a Ph.D. chemist and inventor in 2002 of the first American hydrogen fuel cell-powered mining locomotive, dreamed up his prototype supersonic vehicle and published the first of seven journal articles detailing an aerodynamic analysis of it beginning in 2008.[1] If hydrogen atmosphere were contained within the tubes, he said, passenger vehicles could race along on a hydrogen aerostatic fluid film at Mach 3 relative to the air outside.

"You have a lower Mach number in hydrogen since it has a much higher speed of sound than air, so inside the tube you'd be experiencing the ride as subsonic—no shock waves," said Miller, a former professor at the Colorado School of Mines and now president of Vehicle Projects Inc. and the non-profit Supersonic Institute, a Colorado group advancing new concepts in high-performance transportation.

"Major Challenge"

"Taking hydrogen fuel from the tube solves the problem of vehicle hydrogen storage, a major challenge of contemporary hydrogen-powered vehicles," he explains (2008, p. 1995). Based on comparisons with the aerodynamic properties of a mid-size turboprop plane (the Bombardier Dash 8 Q400™), Miller estimated that his hydrogen-oxygen fuel cell powered vehicles would require 2330 liters of liquefied oxygen onboard which, combined with hydrogen, would generate 2.0 MW of power. This would run the vehicle at 1500 km/hour (932mph).That's supersonic speed with respect to air, propelling passengers from New York to Los Angeles in 2.64 hours, about half the time of a conventional jet.

Arnold Miller

Miller's startling proposal may be decades ahead of realization. However, lower-speed hydrogen-oxygen fuel cell powered vehicles including light rail, city trams, switching and mining locomotives, along with hydrogen-powered cars, trucks, even single-engine airplanes, are already in action, part of a fast-growing global hydrogen economy.

That economy is based on two factors: one is the impact of climate change and the exhaustion of natural resources, including dirty carbon fuels, creating new opportunities to link mass transportation with renewable sources. In addition, the hydrogen economy is based on a concept of hydrogen gas as an *energy vector*—a medium for conveniently transporting, storing, and converting energy into electricity to fuel sustainable growth.

Abundant hydrogen can generate power with little or no carbon emissions provided the source of energy to produce hydrogen is clean—for example, renewable wind power, hydroelectric, or solar. Hydrogen can either be burned to generate heat, or can combine with air in a fuel cell (usually in the presence of a platinum catalyst) to produce electricity to power a train, car, or even an apartment building, its only byproduct water.

However, since hydrogen gas (H_2) is too chemically active to be available in nature, it must be generated by applying energy to a source—most often natural gas (a process known as steam methane reforming, which also produces CO2 emissions), along with biomass, alcohols, or electrolysis of water. Electrolysis splits water molecules into hydrogen gas and oxygen, and can be utterly non-polluting if the electrolysis is driven by renewable energy.

Feuds over Efficiency

Hydrogen gas in turn can be compressed, liquefied, and stored. On board a train, for example, it can be run through a fuel cell where it recombines with 0_2 from the ambient air, producing free electrons that generate the current necessary to move the train or charge batteries that power the train. Fuel cells work best at constant output so on rail vehicles they are generally used in combination with batteries which absorb stopping energy and use it again for re-acceleration.

In the past, though, the process of producing, compressing, and transporting hydrogen to a user for conversion into electrical energy was believed to be inefficient; some engineers claimed only 20 to 25% of the total

Alstom's Coradia iLint, a hydrail running up to 140km/hr (87mph), is tested and ready to roll in Germany by late 2017.

processing energy could be recovered for fuel cell use. In 2006, for example, Ulf Bossel, an energy consultant with the European Fuel Cell Forum, called the hydrogen economy a "wasteful economy," arguing that electricity obtained from hydrogen fuel cells appeared to be four times as expensive as electricity drawn from the conventional transmission grid.

"Because of the high energy losses within a hydrogen economy the synthetic energy carrier cannot compete with electricity," Bossel claimed.[2] But hydrogen proponents today say the economics have transformed.

"Conversion efficiencies have improved and going all the way to liquefying hydrogen isn't seen as necessary (and adds inefficiency)," observed Alistair Miller, an energy consultant and research emeritus at Canadian Nuclear Laboratories (CNL) in Chalk River, Ontario. "What Bossel didn't acknowledge—and perhaps in 2006 couldn't see—was the extreme swings in the value of electricity on grids from substantially negative to very expensive, in large part caused by the deployment of wind and solar renewables," Miller explained.

The New Bitcoin

Today, in fact, renewables and fuel cell advances have turned the economic "bitcoin" of hydrogen into a winner, especially in rail applications. With high–efficiency wind turbines and solar cells that now produce excess power in countries like Canada and Germany, it's now possible to use peak production excess to split water electrochemically and produce hydrogen gas without emissions, and at comparatively low cost.

Further, claims Stan Thompson, a former BellSouth environmental and transportation futurist and inventor of the term "hydrail" (a term designating hydrogen fuel cell railway technology in 2003), "there is very roughly a 65% efficiency in the two-way, electricity to hydrogen to electricity transition," he says, citing technical discussions of efficiency among fuel cell experts whose opinions vary depending on application.

"In return for the 35% loss, hydrail avoids the need for [multiple millions] per kilometer of overhead track electrification infrastructure. Overall, the cost of the hydrogen is trivial in proportion to the avoided cost of external power. And, as renewables supplant extracted fossil carbon, prices will only get cheaper."

The past decade has shown significant momentum for zero-emission mass transportation vehicles in Europe, China, Japan, and Canada. In Japan, for example, the first ever hybrid fuel cell-battery railcar was tested in 2006; Japan began building hydrogen-powered vehicle and residential fuel cell prototypes as early as 2000, according to Thompson. With North Carolina transpor-

Stan Thompson

Andreas Hoffrichter

tation specialists Bill Thunberg and Jason Hoyle, he started the International Hydrail Conferences, beginning in 2005, an annual event drawing hydrogen railway experts worldwide.

In China, hydrogen-powered light rail and tram applications will soon become widespread throughout the country's crowded urban centers. Research leaders include Southwest Jiaotong University, Tangshan Railway Vehicle Company (China's oldest railway, based in Tangshan, Hebei), and CRRC Sifang Co. Ltd. (Qingdao), a subsidiary of China South Rail Corporation. Development of the first fuel cell architecture for passenger trams began in 2009 in the laboratory of Southwest Jiaotong University's Weirong Chen, an engineer who develops power systems for hydrail with a big staff of scientists and students (China also has hydrogen research projects at leading universities in Beijing, Shanghai, and Wuhan).

Fully Operational

A demonstration fuel cell-powered locomotive known as "Blue Sky" bowed in 2013, which was equipped with Ballard 150 KW HD-6 fuel cell stacks. Separately, in 2015, China's Sifang Co., Ltd. debuted a fully operational hydrogen-powered tram accommodating 380 passengers in Qingdao.

With government permission, the first regular hydrail tram service could begin in Foshan, a relatively small city 28 kilometers east of Guangzhou and north of Hong Kong, according to Southwest Jiaotong sources. Foshan is part of the giant megalopolis that Southern Chinese cities are rapidly becoming.

The United Kingdom's first hydrogen-powered passenger train completed a pilot trip in 2012, but research activities and experiments go on all the time at University of Birmingham Center for Railway Research and Education. Engineer and teaching/research fellow Stephen Kent and Andreas Hoffrichter, Ph.D. (who is now the Burkhardt Professor of Railway Management at Michigan State University) undertook some risky railway experiments back in 2009.

"Andreas' Ph.D. was on hydrogen as an energy carrier for rail applications," Kent said. "While he was doing that with us, we took part in the Institution of Mechanical Engineers Railway Challenge in 2012, which was to design and build a narrow gauge train" using high performance characteristics for acceleration, regenerative braking and ride quality. With Hoffrichter's input, the Birmingham team built a hydrogen fuel-cell prototype at 1/5th scale; fuel cell power was 1.1 kW supplemented by batteries resulting in a total of 4.4 kW, sufficient for the vehicle to compete. Though the prototype didn't win the competition in that year (the vehicle that won was a more "traditional combustion engine with a petrol generator," Kent said), "the next year we went whole hog with a hydrogen powered fuel cell with a battery pack hybridized. It had a solid state hydrogen storage (metal hydride) instead of storing hydrogen as a gas, and we used a high-end industrial computer and controlled the train with a touch screen tablet computer."

This past year, the group produced another hydrogen-powered locomotive that came in second in the annual challenge. Although he knows of no definite plans for hydrail deployment right now, "people are talking about it," Kent said. "The UK government is introducing clean air zone cities by 2020, and since we're increasingly using renewable energy, hydrogen could potentially help with energy storage and transportation." Britain's regional rail may want to modernize its diesel fleet with hydrail since the cost of overhead wires had gone through the roof—as much as $20 million per kilometer (0.62 miles).

The cost of conventional rail electrification is also forcing Canada to look at hydrail alternatives. In June 2017, Ontario announced a feasibility study to evaluate hydrogen-powered passenger trains as part of its $13.5 billion GO Transit network electrification program. Ontario Transportation Minister Steven Del Duca told the *Toronto Star* that the feasibility study will evaluate whether hydrogen trains might be a better option than traditional electrical vehicles requiring catenary (wires). The economics are complex—much of the presumed advantage of hydrogen power depends on how hydrogen gas is generated in the first place (whether from renewable electricity like hydro or wind, or traditional sources such as steam methane reforming). Therefore, Del Duca says, "It could be traditional electrification, it could be electrification by hydrogen fuel cell. It could be a combination of both."[3]

Germany's First Hydrail Passenger Train

No doubt the most exciting news this year comes from Germany. In 2014, the French multinational company Alstom issued an RFP to five major fuel cell companies for a planned single level, self-propelled, emissionless passenger train known as the Alstom Coradia iLint. Alstom enlisted the interest of four German States—Lower Saxony, North Rhine-Westphalia, Baden-Württemberg, and Hesse—to test and deploy the hydrogen-powered train. By 2015, a Canadian company, Hydrogenics, of Mississauga, Ontario, won the $50 million Alstom fuel cell contract to support development of as many as 100 hydrogen-oxygen fuel cell stacks for train cars. "We had a hard time getting a hearing [for several years]," said Hydrogenics CEO Daryl Wilson. "We had tried eight different railway companies and couldn't find one that would use our fuel cells. But Alstom was the exception."

Still, it took the French company five years of study

Alstom's iLint 200kW fuel cell will power hydrogen rail in Germany. Hydrogenics, of Mississauga, Ontario, developed the cell.

before it decided to take the plunge. By September 2016, Alstom's 80 km/hour, emission-free hydrogen fuel cell passenger train was tested successfully in Saxony, followed by a test of the train at 140 km/hour (87 mph) in Velim, Czech Republic. Emitting nothing but steam and water, the Coradia iLint operates silently, and will begin regular commercial service in Saxony by the end of this year. Schleswig-Holstein, Germany's northernmost state, will come afterward; it operates a 1,100-kilometer (684-mile) rail network, most of whose trains are now diesel fueled.

No More Nuclear Power

"In Germany we now have no more nuclear power and so much wind energy that is not immediately needed, [so] hydrail is becoming popular," said Holger Busche, Ph.D., the scientific advisor for economy, energy, traffic, and innovation for the Green Party of Schleswig-Holstein State Parliament. As a political organization, the Green Party helped jumpstart the call for hydrail. Busche collaborated with now retired Detlef Matthiessen, Speaker for Energy Policy and Technology Innovation for the Schlewsig-Holstein Landtag (Parliament), leading the commitment to convert 100% of the northern state's diesel-powered trains into hydrail by 2025.

"This is an economic thing," Busche explained. "Back in 1998 I was thinking about the whole system of electricity production and [calculating] times and locations where we would have too much renewable energy," he said. "You have to do something with the excess, and I asked myself how many wind turbines do I need to operate the trains in Northern Germany….that's how it started."

Today, "a hydrogen-powered train can easily travel 600-700 miles per day, and the costs are much better in terms of fuel per mile than [individual motor] cars," Busche explained. "For the [Coradia iLint] train, you need only two or three hydrogen gas filling stations because the trains always operate on the same lines as opposed to thousands of filling stations for cars. So the train is incredibly more economical than cars."

Busche, Arnold Miller, and perhaps a dozen others in Europe, the U.S., and Japan were working independently on hydrogen fuel cell projects and concepts more than twenty years ago, but the economics and, perhaps more important, the ideology of the energy and transportation industries militated against widespread support.

In the U.S., for example, Stan Thompson, the retired futurist at Bell South (later AT&T), co-founded the Mooresville Hydrail Initiative, a North Carolina organization intent on showcasing the first emissions-free hydrogen fuel cell commuter train running along a 28 mile north corridor from Charlotte to Mooresville —Thompson's suburban home on the shores of gigantic Lake Norman. The lake was created in 1960 by the damming of the Catawba River; it features hydroelectric, coal and nuclear power plants, ideal for supplying electricity for hydrogen generation. But even though Thompson believed fervently in a non-polluting transportation system—he championed hydrail to dozens of local, regional, and international business, government, and university research groups—his Mooresville transportation dream has never come about.

"At Bell South I had been studying the hydrogen economy and recognized it as a profound technology on the horizon—a game changer," Thompson said. "But propulsion innovations became moot when the local Iredell County Commission in North Carolina opposed funding the train connection altogether." That's when Thompson and Bill Thunberg, a former mayor of Mooresville and executive director of the Lake Norman Transportation Commission, decided to seek federal innovation funding and launched the international conferences to show that hydrail was more than just a local idea.

Was Hydrail Suppressed?

Thompson claims that both media and government also suppressed information about the hydrogen story for quite some time. "The Obama Administration declared hydrogen to be 'Bush science,'" Thompson said. Federal hydrogen project support was withdrawn in favor of funding other renewable technology. Even a promising joint project—a full size hydrogen fuel cell switching locomotive developed by Arnold Miller and funded by the U.S. Army Corps of Engineers jointly with Burlington Northern Sante Fe (BNSF)—eventually ground to a halt despite successful demonstrations.

"We got a big influx of money in fiscal year 2002 from the Department of Defense," Miller recalled. "The army was interested in this concept of moving munitions and supplies from points on the base to a main line railway where they could be transported for long distance," he said. "We also looked at the project as having high potential for emissions-free transit in urban rail. And the army thought of these fuel cell powered locomotives as mobile power sources, so if the base micro-grid was knocked out, you could use the locomotive to provide power to critical infrastructure like hospitals."

Miller and his team finalized two locomotives—each a 130-ton switching locomotive delivering maximum power of at least 1.5 MW from a fuel cell "prime mover" and an auxiliary traction battery. At the time, 2010, the first locomotive was the heaviest and most powerful fuel cell land vehicle invented, with an observed thermodynamic efficiency of 51%. The second locomotive had double the continuous fuel cell power (0.5 MW) and a high power-density auxiliary lithium battery enabling increased hydrogen storage (the locomotive was designed to be upgradeable to 175 kg of hydrogen). This vehicle was completely built, but its fuel cell failed during the final stage of testing.

As Miller explained it, each locomotive contained compressed hydrogen fuel stored in carbon-fiber composite tanks located on the roofline, and the price of the hydrogen fuel (in large quantities) was no more than diesel. Miller's first locomotive successfully completed a rigorous yard-switching demonstration at the BNSF rail yard in Los Angeles, producing enough power for an 11-hour operational shift. "It worked very well and did everything it was supposed to do. The train operators preferred the fuel cell because there is almost no vibration and the locomotive had more acceleration than a diesel," he said.

In another demonstration, Miller pulled the first hydrogen-powered locomotive up to a large maintenance shop at Hill Air Force Base, Utah, which was filled with big vehicles, lathes, and welding machines. "It worked like a charm, ran everything at 65 kW," he said.

But even though "the vehicle was a big leap forward," after 12 years of work, BNSF and the army shuttered the project. "BNSF decided not to pay for the repair of the fuel cell in the second-gen locomotive which had failed," Miller explained. "Instead the railway decided to pursue an alternative line of R&D, which they had already been pursuing. To my knowledge, hydrogen storage had nothing to do with the decision." BNSF had demonstrated "extraordinary support" for the dozen years (through 2014) that the project went on, he said.

Culture Derails Solutions

Nonetheless, Miller acknowledges how American culture has derailed many of the most inventive and green public transit solutions. "We don't have high-speed rail in this country even though the Japanese were doing it in the 1960s, and now the Europeans, Koreans, and Chinese are doing it big time," Miller observed. "Americans value rugged individualism; mass transit is for sissies in this view. We just don't put much value on it. We'd rather drive an SUV than hop a fast train."

Another factor is the sudden collapse of oil prices and other products related to petroleum, Miller explained. In the U.S., that itself has made fossil fuels continually attractive from an economic perspective. "It's very hard to compete against [the falling prices] of petroleum…for example, it would be expensive to buy a fuel-cell vehicle—I know based on our own results over the years, the price would be about twice."

There is evidence, however, that successful hydrogen projects worldwide, along with the falling prices of renewables, is producing the economics necessary to promote disruptive change. This will even happen in North America. In parts of Canada, for example, the abundance of both nuclear power and hydro has given the country new options to adopt clean fuel distribution and hydrogen-powered modes of transit.

"Hydrogen is the ultimate clean fuel as long as you don't use natural gas to produce it," said Alistair Miller, Ph.D., the research emeritus at Canadian Nuclear Laboratories (CNL). He looks to Toronto and the GO trains as a possible early demonstration of hydrogen power. Moreover, with the increasing abundance of wind and solar power "hydrogen is an obvious storage medium," he said. "In Canada you've got this network of commuter rail. But when [Ontario] went to electrify the Toronto to Barrie train line 100 km north, they discovered that installation of the overhead catenary and the cost of electrifying these lines would be horrendous. You can't justify it anywhere."

Quest for Zero Emissions

Trains, boats, spacecraft, localized hydrogen fuel cell production and energy distribution, even the actions of California legislators are all on the hydrogen radar these days. Some experts predict that fuel cells will disrupt the carbon economy in profound ways.

"Fuel cell [energy production] may soon have the same role as the microprocessor had for the computer," predicts Stefano Cordiner, a professor of energy conversion at the University of Rome Tor Vergata. "When the microcomputer came out, that was the breakthrough technology that [caused] the huge spread in personal computing," he said. "In a way the fuel cell represents a [similar] core technology component. Once you produce hydrogen as an energy vector, you can use it in many different devices and ways…even producing electric energy by yourself."

The whole idea of creating *distributed* generation of hydrogen may change the entire energy network worldwide. "If taken to the limit, it means that each user may be able to produce the energy required locally. In effect, the energy is located exactly at the point where it's needed, so that allows for the deployment of renewable energy anywhere," Cordiner said.

In California, as in Germany, energy production is transforming rapidly. The California legislature has passed new laws that support zero emission levels, and that will apply to trains in the ports of Los Angeles.

"There's a study that shows main line diesel trains originating in the ports of Los Angeles produce nitrous oxide (NOx) emissions equal to all the major industrial emissions from Southern California,"[4] said Herbert Wancura, the owner and principal of Synergesis, an Austrian engineering and energy consultancy. He says, railroads have evaded the toughest pollution standards because they can argue efficiency; that is, "their emissions per ton per passenger per mile or kilometer is very low, so they get away with technology that's not state of the art."

A technician works on the internal structure of the 200 kW fuel cell subsystem, designed to be roof-mounted on the Alstom Coradia ILint train. The fuel cell stack module building blocks can be seen, as well as the process (fluid and gas) manifolds which mechanically interconnect the modules.

But now, as in Austria, Germany, and soon other parts of Europe, California will be following the cleanest experimental standard known as Tier 5. "People will want to close the debate on emissions" Wancura predicts. He argues that the Alstom example of emission-less hydrail could also present the cheapest alternative for passenger rail in the U.S. (heavier freight rail is another matter; freight lines will take longer to adopt alternative emissions technologies like hydrail).

"Light rail systems with catenary are expensive and not well liked," Wancura continued. But with hydrogen-powered trains, especially trams, "the infrastructure is cheaper, about 1/5th of the cost of ordinary catenary type infrastructure. That type of commuter rail could work in the States."

Still, nothing will happen that quickly. Jason Hoyle, the research analyst at the Energy Center of Appalachian State University in Boone, NC, has been looking carefully at the economics of the fuel cell industry since 2004. He says that the fundamental orientation of governments in Europe and Japan versus the U.S. has spelled the difference between hydrail adoption and refusal to get on the bandwagon.

Willing to Invest

"European governments are willing to invest in things that have broader social benefits like transportation initiatives, and Germany is out front in this," he said. "In Japan, whose culture is technologically advanced, having no embedded interest in oil and gas, people are willing to sacrifice what in America we might see as personal liberties" which include transport by cars and trucks. In China, he adds, hydrail will become part of emerging "everything" transportation and energy culture, since virtually all green technologies there are brand new. But in the U.S., the political will to make disruptive change will come with hesitation, even arm twisting. For example, in cities that require mass transit, the choice either to foot the bill for overhead catenary or maintain scummy diesel may be so distasteful and impractical that hydrogen will finally emerge. Most likely, that will happen only when officials acknowledge that there is no other technology, especially for trams and light rail, as cheap, clean, or as good.

In January 2017, 13 major transport, mining, and energy companies signed an agreement at the Davos World Economic Forum to create The Hydrogen Council, a consortium planning to invest 10 billion Euros (US$10.7 billion) in products and technologies over the next five years. This is probably the biggest indicator that the hydrogen economy—and hydrail—are on their way.

In June, at the 12th Annual Hydrail Conference held in Graz, Austria, transportation specialist Bill Thunberg noticed a big change. "At the very beginning of these conferences, it was a bunch of academics getting together and discussing the barriers to hydrail and how to move forward," he said. "But at this meeting, instead of 95% academics, it was 95% commercial attendees. It was clear to me that these commercial interests will have to resolve competitive issues to move hydrogen forward," he continued. "Whether it's boats, trains, trams, switchers, or different kinds of vehicles required in intermodal ports, there's going to be a huge push to clean up diesel emissions without interrupting the business cycle."

"Hydrogen as an energy vector will be important," Thunberg predicts. "It's not going to be one size fits all. These days, when you have an intermodal yard, you'll have to find a way to do what you do to grow your business on a zero-emission basis. The idea of hydrogen as an energy vector will make a whole lot of sense in these zones. With no more diesel after a certain date, especially in Europe but also in the U.S., you're going to see a dramatic change in zero emissions technology. Whether it's hydrail or batteries or a combination of both, that's the big takeaway."

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