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Fuel cell vehicle

A **fuel cell vehicle** (**FCV**) or **fuel cell electric vehicle** (**FCEV**) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat. As compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of the hydrogen production, where hydrogen is typically derived from reformed natural gas. Transporting and storing hydrogen may also create pollutants.[1]

2015 Toyota Mirai

2017 Honda Clarity Fuel Cell

2018 Hyundai Nexo

Foton BJ6123FCEVCH-1 fuel cell bus in operation

Fuel cells have been used in various kinds of vehicles including forklifts, especially in indoor applications where their clean emissions are important to air quality, and in space applications. The first commercially produced hydrogen fuel cell automobile, the Hyundai Tucson FCEV, was introduced in 2013, Toyota Mirai followed in 2015 and then Honda entered the market.[2][3] Fuel cells are being developed and tested in trucks, buses, boats, motorcycles and bicycles, among other kinds of vehicles.

As of 2020, there was limited hydrogen infrastructure, with fewer than fifty hydrogen fueling stations for automobiles publicly available in the U.S.,[4] but more hydrogen stations are planned, particularly in California, where, as of 2019, according to *Hydrogen View*, there had been over 7,500 FCEVs sold or leased.[5] Critics doubt whether hydrogen will be efficient or cost-effective for automobiles, as compared with other zero emission technologies, and in 2019, *USA Today* stated "what is tough to dispute is that the hydrogen fuel cell dream is all but dead for the passenger vehicle market."[6]

Contents

Description and purpose of fuel cells in vehicles

All fuel cells are made up of three parts: an electrolyte, an anode and a cathode.[7] In principle, a hydrogen fuel cell functions like a battery, producing electricity, which can run an electric motor. Instead of requiring recharging, however, the fuel cell can be refilled with hydrogen.[8] Different types of fuel cells include polymer electrolyte membrane (PEM) Fuel Cells, direct methanol fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, reformed methanol fuel cell and Regenerative Fuel Cells.[9]

History

The concept of the fuel cell was first demonstrated by Humphry Davy in 1801, but the invention of the first working fuel cell is credited to William Grove, a chemist, lawyer, and physicist. Grove's experiments with what he called a "gas voltaic battery" proved in 1842 that an electric current could be produced by an electrochemical reaction between hydrogen and oxygen over a platinum catalyst.[11] English engineer Francis Thomas Bacon expanded on Grove's work, creating and demonstrating various Alkaline fuel cells from 1939 to 1959.[12]


1966 GM Electrovan[10]

The first modern fuel cell vehicle was a modified Allis-Chalmers farm tractor, fitted with a 15 kilowatt fuel cell, around 1959.[13] The Cold War Space Race drove further development of fuel cell technology. Project Gemini tested fuel cells to provide electrical power during manned space missions.[14][15] Fuel cell development continued with the Apollo Program. The electrical power systems in the Apollo capsules and lunar modules used alkali fuel cells.[14] In 1966, General Motors developed the first fuel cell road vehicle, the Chevrolet Electrovan.[16] It had a PEM fuel cell, a range of 120 miles and a top speed of 70 mph. There were only two seats, as the fuel cell stack and large tanks of hydrogen and oxygen took up the rear portion of the van. Only one was built, as the project was deemed cost-prohibitive.[17]

General Electric and others continued working on PEM fuel cells in the 1970s.[14] Fuel cell stacks were still limited principally to space applications in the 1980s, including the Space Shuttle.[14] However, the closure of the Apollo Program sent many industry experts to private companies. By the 1990s, automobile manufacturers were interested in fuel cell applications, and demonstration vehicles were readied. In 2001, the first 700 Bar (10000 PSI) hydrogen tanks were demonstrated, reducing the size of the fuel tanks that could be used in vehicles and extending the range.[18]

Applications

There are fuel cell vehicles for all modes of transport. The most prevalent fuel cell vehicles are cars, buses, forklifts and material handling vehicles.[19]

Automobiles

The Honda FCX Clarity concept car was introduced in 2008 for leasing by customers in Japan and Southern California and discontinued by 2015. From 2008 to 2014, Honda leased a total of 45 FCX units in the US.[20] Over 20 other FCEVs prototypes and demonstration cars were released in that time period,[21] including the GM HydroGen4,[16] and Mercedes-Benz F-Cell.

The Hyundai ix35 FCEV Fuel Cell vehicle has been available for lease since 2014,[22] when 54 units were leased.[23]

Sales of the Toyota Mirai to government and corporate customers began in Japan in December 2014.[24] Pricing started at ¥6,700,000 (~US$57,400) before taxes and a government incentive of ¥2,000,000 (~US$19,600).[25] Former European Parliament President Pat Cox estimated that Toyota initially would lose about $100,000 on each Mirai sold.[26] As of December 2017, global sales totaled 5,300 Mirais. The top selling markets were the U.S. with 2,900 units, Japan with 2,100 and Europe with 200.[27]

2015 Toyota Mirai

Retail deliveries of the 2017 Honda Clarity Fuel Cell began in California in December 2016.[28] The 2017 Clarity has the highest combined and city fuel economy ratings among all hydrogen fuel cell cars rated by the EPA, with a combined city/highway rating of 67 miles per gallon gasoline equivalent (MPGe), and 68 MPGe in city driving.[29] In 2019, Katsushi Inoue, the president of Honda Europe, stated, "Our focus is on hybrid and electric vehicles now. Maybe hydrogen fuel cell cars will come, but that’s a technology for the next era."[30]

By 2017, Daimler phased out its FCEV development, citing declining battery costs and increasing range of EVs,[31] and most of the automobile companies developing hydrogen cars had switched their focus to battery electric vehicles.[32]

Fuel economy

The following table compares EPA's fuel economy expressed in miles per gallon gasoline equivalent (MPGe) for the hydrogen fuel cell vehicles rated by the EPA as of December 2016, and available only in California.[29]

Comparison of fuel economy expressed in MPGe for hydrogen fuel cell vehicles available for leasing in California and rated by the U.S. Environmental Protection Agency as of October 2016[29][33]

Vehicle	Model year	Combined fuel economy	City fuel economy	Highway fuel economy	Range	Annual fuel cost
Hyundai Tucson Fuel Cell	2017	49 mpg-e	48 mpg-e	50 mpg-e	265 mi (426 km)	US$1,700
Toyota Mirai	2016	66 mpg-e	66 mpg-e	66 mpg-e	312 mi (502 km)	US$1,250
Honda Clarity Fuel Cell	2017	67 mpg-e	68 mpg-e	66 mpg-e	366 mi (589 km)	-

Notes: One kg of hydrogen has roughly the same energy content as one U.S. gallon of gasoline.[34]

List of models produced

List of modern fuel cell automobiles, pickups, vans and SUVs commercially produced (1990–present)

Model	Production	Original MRSP(2) /Lease per month (current $)	Range	Comments
Models out of production				
 Honda FCX-V4	2002-2007	Leasing only US$11,500[35]	160 mi (260 km)[36] to 190 mi (310 km)[37]	First fuel-cell vehicle to be approved for American roads by the Environmental Protection Agency and the California Air Resources Board, with subsequent leasing in California. Also approved for Japanese roads by Japan's Ministry of Land, Infrastructure and Transport.[38] Approximately 30 leased in the Los Angeles area and Tokyo.[39] Leasing later expanded to 50 states.[37]
 Ford Focus FCV	2003-2006	Leasing only unknown	200 mi (320 km)[40]	Initially planned to be leased across 50 states,[36] it was eventually only leased in California, Florida and Canada.[37]
 Nissan X-Trail FCV 04	2003-2013	Leasing only ¥1,000,000[41] (US$8,850)	350 km (220 mi)[41]	Leased to businesses and government entities in Japan and California.[42][43]
 Mercedes-Benz F-Cell (A-Class based)	2005-2007	Leasing only unknown	100 mi (160 km)[40] to 110 mi (180 km)[44]	100 leased around the world.[45]
 Chevrolet Equinox FC	2007-2009	Leasing only	190 mi (310 km)[46]	Leased in California and New York.
 Honda FCX Clarity	2008-2015	Leasing only US$600	280 mi (450 km)[47] later 240 mi (390 km)[48] and 231 mi (372 km)[49]	Leased in the United States, Europe and Japan.

 Mercedes-Benz F-Cell (B-Class based)	2010-2014	Leasing only US$850	190 mi (310 km)[48]	Leased in southern California.[48]
 Hyundai Tucson FCEV (ix35)	2014–2018	Leasing only US$599[50]	265 mi (426 km)[51]	Leased in South Korea, California, Europe and Vancouver.
Models in production				
 Toyota Mirai	2015–present	Sales and leasing US$58,500[52]	312 mi (502 km)[51]	Sold and leased in Japan, California, Europe, Québec and United Arab Emirates. As of 15 February 2017, global sales totaled 2,840 units since inception.[53]
 Honda Clarity	2016–present	Leasing only US$369[54]	300 mi (480 km)[54]	Leased in Japan, Southern California, Europe.[54][55]
 Hyundai Nexo	2018–present	Sales and leasing US$58,300[56]	370 mi (600 km)[57]	Sold in South Korea, California, and Europe.

Fuel cells powered by an ethanol reformer

In June 2016, Nissan announced plans to develop fuel cell vehicles powered by ethanol rather than hydrogen. Nissan claims this technical approach would be cheaper, and that it would be easier to deploy the fueling infrastructure than a hydrogen infrastructure.[58] The vehicle would include a tank holding a blend of water and ethanol, which is fed into an onboard reformer that splits it into hydrogen and carbon dioxide. The hydrogen is then fed into a solid oxide fuel cell. According to Nissan, the liquid fuel could be an ethanol-water blend at a 55:45 ratio. Nissan expects to commercialize its technology by 2020.[58]

Buses

There are also demonstration models of buses,[59] and in 2011 there were over 100 fuel cell buses deployed around the world. Most of these buses were produced by UTC Power, Toyota, Ballard, Hydrogenics, and Proton Motor. UTC buses had accumulated over 970,000 km (600,000 mi) of driving.[60] Fuel cell buses have a 30-141% higher fuel economy than diesel buses and natural gas buses.[61] Fuel cell buses have been deployed in Whistler Canada, San Francisco US, Hamburg Germany, Shanghai China, London England, São Paulo Brazil and several other cities.[62] The Whistler project was discontinued in 2015.[63] The Fuel Cell Bus Club is a global cooperative effort in trial fuel cell buses. Notable projects include:

Mercedes-Benz fuel cell bus.

- 12 Fuel cell buses were deployed in the Oakland and San Francisco Bay area of California.[62]
- Daimler AG, with thirty-six experimental buses powered by Ballard Power Systems fuel cells, completed a successful three-year trial, in eleven cities, in 2007.[64][65]
- A fleet of Thor buses with UTC Power fuel cells was deployed in California, operated by SunLine Transit Agency.[66]
- The first hydrogen fuel cell bus prototype in Brazil was deployed in São Paulo. The bus was manufactured in Caxias do Sul, and the hydrogen fuel was to be produced in São Bernardo do Campo from water through electrolysis. The program, called "*Ônibus Brasileiro a Hidrogênio*" (Brazilian Hydrogen Autobus), included three buses.[67][68]

Forklifts

A fuel cell forklift (also called a fuel cell lift truck or a fuel cell forklift) is a fuel cell-powered industrial forklift truck used to lift and transport materials. Most fuel cells used in forklifts are powered by PEM fuel cells.[69]

In 2013, there were over 4,000 fuel cell forklifts used in material handling in the US[70] from which only 500 received funding from DOE (2012).[71][72] Fuel cell fleets are operated by a large number of companies, including Sysco Foods, FedEx Freight, GENCO (at Wegmans, Coca-Cola, Kimberly Clark, and Whole Foods), and H-E-B Grocers.[73] Europe demonstrated 30 fuel cell forklifts with Hylift and extended it with HyLIFT-EUROPE to 200 units,[74] with other projects in France[75][76] and Austria.[77] Pike Research stated in 2011 that fuel-cell-powered forklifts will be the largest driver of hydrogen fuel demand by 2020.[78]

PEM fuel-cell-powered forklifts provide significant benefits over petroleum powered forklifts as they produce no local emissions. Fuel-cell forklifts can work for a full 8-hour shift on a single tank of hydrogen, can be refueled in 3 minutes and have a lifetime of 8–10 years. Fuel cell-powered forklifts are often used in refrigerated warehouses as their performance is not degraded by lower temperatures.[79] In design the FC units are often made as drop-in replacements.[80][81]

Motorcycles and bicycles

In 2005, the British firm Intelligent Energy produced the first ever working hydrogen run motorcycle called the ENV (Emission Neutral Vehicle). The motorcycle holds enough fuel to run for four hours, and to travel 160 km (100 mi) in an urban area, at a top speed of 80 km/h (50 mph).[82] In 2004, Honda developed a fuel-cell motorcycle which utilized the Honda FC Stack.[83][84] There are other examples of bikes[85] and bicycles[86] with a hydrogen fuel cell engine. The Suzuki Burgman received "whole vehicle type" approval in the EU.[87] The Taiwanese company APFCT conducts a live street test with 80 fuel cell scooters[88] for Taiwans Bureau of Energy using the fueling system from Italy's Acta SpA.[89]

Yamaha FC-me motorcycle.

Airplanes

Boeing researchers and industry partners throughout Europe conducted experimental flight tests in February 2008 of a manned airplane powered only by a fuel cell and lightweight batteries. The Fuel Cell Demonstrator Airplane, as it was called, used a Proton Exchange Membrane (PEM) fuel cell/lithium-ion battery hybrid system to power an electric motor, which was coupled to a conventional propeller.[90] In 2003, the world's first propeller driven airplane to be powered entirely by a fuel cell was flown. The fuel cell was a unique FlatStack stack design which allowed the fuel cell to be integrated with the aerodynamic surfaces of the plane.[91]

The Boeing Fuel Cell Demonstrator powered by a hydrogen fuel cell.

There have been several fuel cell powered unmanned aerial vehicles (UAV). A Horizon fuel cell UAV set the record distance flown by a small UAV in 2007.[92] The military is especially interested in this application because of the low noise, low thermal signature and ability to attain high altitude. In 2009, the Naval Research Laboratory's (NRL's) Ion Tiger utilized a hydrogen-powered fuel cell and flew for 23 hours and 17 minutes.[93] Boeing is completing tests on the Phantom Eye, a high-altitude, long endurance (HALE) to be used to conduct research and surveillance flying at 20,000 m (65,000 ft) for up to four days at a time.[94] Fuel cells are also being used to provide auxiliary power for aircraft, replacing fossil fuel generators that were previously used to start the engines and power on board electrical needs.[94] Fuel cells can help airplanes reduce CO_2 and other pollutant emissions and noise.

Boats

The world's first Fuel Cell Boat HYDRA used an AFC system with 6.5 kW net output. For each liter of fuel consumed, the average outboard motor produces 140 times less the hydrocarbons produced by the average modern car. Fuel cell engines have higher energy efficiencies than combustion engines, and therefore offer better range and significantly reduced emissions.[95] Iceland has committed to converting its vast fishing fleet to use fuel cells to provide auxiliary power by 2015 and, eventually, to provide primary power in its boats. Amsterdam recently introduced its first fuel cell powered boat that ferries people around the city's canals.[96]

The Hydra fuel cell boat.

Submarines

The first submersible application of fuel cells is the German Type 212 submarine.[97] Each Type 212 contains nine PEM fuel cells, spread throughout the ship, providing between 30 kW and 50 kW each of electrical power.[98] This allows the Type 212 to remain submerged longer and makes them more difficult to detect. Fuel cell powered submarines are also easier to design, manufacture, and maintain than nuclear-powered submarines.[99]

Trains

In March 2015, China South Rail Corporation (CSR) demonstrated the world's first hydrogen fuel cell-powered tramcar at an assembly facility in Qingdao.[100] 83 miles of tracks for the new vehicle were built in seven Chinese cities. China had plans to spend 200 billion yuan ($32 billion) over the next five years to increase tram tracks to more than 1,200 miles.[101]

Debut of the Alstom Coradia iLint at InnoTrans 2016

In 2016, Alstom debuted the Coradia iLint, a regional train powered by hydrogen fuel cells. It was designed to reach 140 kilometres per hour (87 mph) and travel 600–800 kilometres (370–500 mi) on a full tank of hydrogen.[102] The train entered service in Germany in 2018 and is expected to be tested in the Netherlands beginning in 2019.[103]

Swiss manufacturer Stadler Rail signed a contract in California to supply a hydrogen fuel cell train in the US, the FLIRT H2 train, in 2024 as part of the Arrow rail project.[104]

Trucks

In 2020, Hyundai started to manufacture hydrogen powered 34-ton cargo trucks under the model name XCIENT, making an initial shipment of 10 of the vehicles to Switzerland. They are able to travel 400 kilometres (250 mi) on a full tank and they take 8 to 20 minutes to fill up.[105]

In 2020, Daimler announced the Mercedes-Benz GenH2 liquid hydrogen concept expected to be produced beginning in 2023.[106]

Hydrogen infrastructure

Eberle and Rittmar von Helmolt stated in 2010 that challenges remain before fuel cell cars can become competitive with other technologies and cite the lack of an extensive hydrogen infrastructure in the U.S.:[107] As of July 2020, there were 43 publicly accessible hydrogen refueling stations in the US, 41 of which were located in California.[4] In 2013, Governor Jerry Brown signed AB 8, a bill to fund $20 million a year for 10 years to build up to 100 stations.[108] In 2014, the California Energy Commission funded $46.6 million to build 28 stations.[109]

Japan got its first commercial hydrogen fueling station in 2014.[110] By March 2016, Japan had 80 hydrogen fueling stations, and the Japanese government aims to double this number to 160 by 2020.[111] In May 2017, there were 91 hydrogen fueling stations in Japan.[112] Germany had 18 public hydrogen fueling stations in July 2015. The German government hoped to increase this number to 50 by end of 2016,[113] but only 30 were open in June 2017.[114]

Codes and standards

Fuel cell vehicle is a classification in fuel cell codes and standards.[115]

US programs

In 2003, US President George Bush proposed the Hydrogen Fuel Initiative (HFI). The HFI aimed to further develop hydrogen fuel cells and infrastructure technologies to accelerate the commercial introduction of fuel cell vehicles. By 2008, the U.S. had contributed 1 billion dollars to this project.[116] In 2009, Steven Chu, then the US Secretary of Energy, asserted that hydrogen vehicles "will not be practical over the next 10 to 20 years".[117][118] In 2012, however, Chu stated that he saw fuel cell cars as more economically feasible as natural gas prices had fallen and hydrogen reforming technologies had improved.[119][120] In June 2013, the California Energy Commission granted $18.7M for hydrogen fueling stations.[121] In 2013, Governor Brown signed AB 8, a bill to fund $20 million a year for 10 years for up to 100 stations.[108] In 2013, the US DOE announced up to $4 million planned for "continued development of advanced hydrogen storage systems".[122] On May 13, 2013, the Energy Department launched H2USA, which is focused on advancing hydrogen infrastructure in the US.[123]

Cost

By 2010, advancements in fuel cell technology had reduced the size, weight and cost of fuel cell electric vehicles.[124] In 2010, the U.S. Department of Energy (DOE) estimated that the cost of automobile fuel cells had fallen 80% since 2002 and that such fuel cells could potentially be manufactured for $51/kW, assuming high-volume manufacturing cost savings.[125] Fuel cell electric vehicles have been produced with "a driving range of more than 250 miles between refueling".[125] They can be refueled in less than 5 minutes.[126] Deployed fuel cell buses have a 40% higher fuel economy than diesel buses.[124] EERE's Fuel Cell Technologies Program claims that, as of 2011, fuel cells achieved a 42 to 53% fuel cell electric vehicle efficiency at full power,[124] and a durability of over 75,000 miles with less than 10% voltage degradation, double that achieved in 2006.[125] In 2012, Lux Research, Inc. issued a report that concluded that "Capital cost ... will limit adoption to a mere 5.9 GW" by 2030, providing "a nearly insurmountable barrier to adoption, except in niche applications". Lux's analysis concluded that by 2030, PEM stationary fuel cell applications will reach $1 billion, while the vehicle market, including fuel cell forklifts, will reach a total of $2 billion.[127]

Environmental impact

The environmental impact of fuel cell vehicles depends on the primary energy with which the hydrogen was produced. Fuel cell vehicles are only environmentally benign when the hydrogen was produced with renewable energy.[128] If this is the case fuel cell cars are cleaner and more efficient than fossil fuel cars. However, they are not as efficient as battery electric vehicles which consume much less energy.[129] Usually a fuel cell car consumes 2.4 times more energy than a battery electric car, because electrolysis and storage of hydrogen is much less efficient than using electricity to directly load a battery.[128]

As of 2009, motor vehicles used most of the petroleum consumed in the U.S. and produced over 60% of the carbon monoxide emissions and about 20% of greenhouse gas emissions in the United States, however production of hydrogen for hydro cracking used in gasoline production chief amongst its industrial uses was responsible for approximately 10% of fleet wide greenhouse gas emissions.[130] In contrast, a vehicle fueled with pure hydrogen emits few pollutants, producing mainly water and heat, although the production of the hydrogen would create pollutants unless the hydrogen used in the fuel cell were produced using only renewable energy.[131]

In a 2005 Well-to-Wheels analysis, the DOE estimated that fuel cell electric vehicles using hydrogen produced from natural gas would result in emissions of approximately 55% of the CO_2 per mile of internal combustion engine vehicles and have approximately 25% less emissions than hybrid vehicles.[132] In 2006, Ulf Bossel stated that the large amount of energy required to isolate hydrogen from natural compounds (water, natural gas, biomass), package the light gas by compression or liquefaction, transfer the energy carrier to the user, plus the energy lost when it is converted to useful electricity with fuel cells, leaves around 25% for practical use."[133] Richard Gilbert, co-author of *Transport Revolutions: Moving People and Freight without Oil* (2010), comments similarly, that producing hydrogen gas ends up using some of the energy it creates. Then, energy is taken up by converting the hydrogen back into electricity within fuel cells. "'This means that only a quarter of the initially available energy reaches the electric motor' ... Such losses in conversion don't stack up well against, for instance, recharging an electric vehicle (EV) like the Nissan Leaf or Chevy Volt from a wall socket".[134][135] A 2010 Well-to-wheels analysis of hydrogen fuel cell vehicles report from Argonne National Laboratory states that renewable H2 pathways offer much larger green house gas benefits.[136] This result has recently been confirmed.[128] In 2010, a US DOE Well-to-Wheels publication assumed that the efficiency of the single step of compressing hydrogen to 6,250 psi (43.1 MPa) at the refueling station is 94%.[137] A 2016 study in the November issue of the journal *Energy* by scientists at Stanford University and the Technical University of Munich concluded that, even assuming local hydrogen production,"investing in all-electric battery vehicles is a more economical choice for reducing carbon dioxide emissions, primarily due to their lower cost and significantly higher energy efficiency."[138]

Criticism

In 2008, professor Jeremy P. Meyers, in the Electrochemical Society journal *Interface* wrote, "While fuel cells are efficient relative to combustion engines, they are not as efficient as batteries, due primarily to the inefficiency of the oxygen reduction reaction. ... [T]hey make the most sense for operation disconnected from the grid, or when fuel can be provided continuously. For applications that require frequent and relatively rapid start-ups ... where zero emissions are a requirement, as in enclosed spaces such as warehouses, and where hydrogen is considered an acceptable reactant, a [PEM fuel cell] is becoming an increasingly attractive choice [if exchanging batteries is inconvenient]". The practical cost of fuel cells for cars will remain high, however, until production volumes incorporate economies of scale and a well-developed supply chain. Until then, costs are roughly one order of magnitude higher than DOE targets.[139]

Also in 2008, *Wired News* reported that "experts say it will be 40 years or more before hydrogen has any meaningful impact on gasoline consumption or global warming, and we can't afford to wait that long. In the meantime, fuel cells are diverting resources from more immediate solutions."[140] *The Economist* magazine, in 2008, quoted Robert Zubrin, the author of *Energy Victory*, as saying: "Hydrogen is 'just about the worst possible vehicle fuel'".[141] The magazine noted that most hydrogen is produced through steam reformation, which creates at least as much emission of carbon per mile as some of today's gasoline cars. On the other hand, if the hydrogen could be produced using renewable energy, "it would surely be easier simply to use this energy to charge the batteries of all-electric or plug-in hybrid vehicles."[141] The *Los Angeles Times* wrote in 2009, "Any way you look at it, hydrogen is a lousy way to move cars."[142] *The Washington Post* asked in November 2009, "[W]hy would you want to store energy in the form of hydrogen and then use that hydrogen to produce electricity for a motor, when electrical energy is already waiting to be sucked out of sockets all over America and stored in auto batteries...?"[143]

The Motley Fool stated in 2013 that "there are still cost-prohibitive obstacles [for hydrogen cars] relating to transportation, storage, and, most importantly, production."[144] Volkswagen's Rudolf Krebs said in 2013 that "no matter how excellent you make the cars themselves, the laws of physics hinder their overall efficiency. The most efficient way to convert energy to mobility is electricity." He elaborated: "Hydrogen mobility only makes sense if you use green energy", but ... you need to convert it first into hydrogen "with low efficiencies" where "you lose about 40 percent of the initial energy". You then must compress the hydrogen and store it under high pressure in tanks, which uses more energy. "And then you have to convert the hydrogen back to electricity in a fuel cell with another efficiency loss". Krebs continued: "in the end, from your original 100 percent of electric energy, you end up with 30 to 40 percent."[145]

In 2014, electric automotive and energy futurist Julian Cox published an analysis that used US government NREL and EPA data that disproves widely held policy assumptions concerning claimed emissions benefits from the use of Hydrogen in transportation. Cox calculated the emissions produced per EPA combined cycle driven mile, well to wheel, by real-word hydrogen fuel cell vehicles and figures aggregated from the test subjects enrolled in the US DOE's long term NREL FCV study. The report presented official data that firmly refutes marketer's claims of any inherent benefits of hydrogen fuel cells over the drive trains of equivalent conventional gasoline hybrids and even ordinary small-engined cars of equivalent drive train performance due to the emissions intensity of hydrogen production from Natural Gas. The report went on to demonstrate the economic inevitability of continued methane use in hydrogen production due to the cost tripping effect of hydrogen fuel cells on renewable mileage due to conversion losses of electricity to and from hydrogen when compared to the direct use of electricity in an ordinary electric vehicle. The analysis contradicts the marketing claims of vehicle manufacturers involved in promoting hydrogen fuel cells and whose claims are frequently reflected in public policy statements. The analysis proved that public policy in relation to hydrogen fuel cells has been misled by false equivalences to very large, very old or very high powered gasoline vehicles that do not accurately reflect the choices of emissions reduction technologies readily available amongst lower cost and pre-existing new vehicles choices available to consumers, and also to the taxpayer that funded superfluous hydrogen Infrastructure on a premise that on scientific grounds is factually false. Instead the marketing and consequently public policy claims for hydrogen can be proven by the official US DOE figures to be highly misleading.[146] Cox wrote in 2014 that producing hydrogen from methane "is significantly more carbon intensive per unit of energy than coal. Mistaking fossil hydrogen from the hydraulic fracturing of shales for an environmentally sustainable energy pathway threatens to encourage energy policies that will dilute and potentially derail global efforts to head-off climate change due to the risk of diverting investment and focus from vehicle technologies that are economically compatible with renewable energy."[146] *The Business Insider* commented in 2013:

> Pure hydrogen can be industrially derived, but it takes energy. If that energy does not come from renewable sources, then fuel-cell cars are not as clean as they seem. ... Another challenge is the lack of infrastructure. Gas stations need to invest in the ability to refuel hydrogen tanks before FCEVs become practical, and it's unlikely many will do that while there are so few customers on the road today. ... Compounding the lack of infrastructure is

> the high cost of the technology. Fuel cells are "still very, very expensive".[147]

In 2014, climate blogger and former Dept. of Energy official Joseph Romm devoted three articles to critiques of hydrogen vehicles. He stated that FCVs still have not overcome the following issues: high cost of the vehicles, high fueling cost, and a lack of fuel-delivery infrastructure. "It would take several miracles to overcome all of those problems simultaneously in the coming decades."[148] Moreover, he said, "FCVs aren't green" because of escaping methane during natural gas extraction and when hydrogen is produced, as 95% of it is, using the steam reforming process. He concluded that renewable energy cannot economically be used to make hydrogen for an FCV fleet "either now or in the future."[149] GreenTech Media's analyst reached similar conclusions in 2014.[150] In 2015, *Clean Technica* listed some of the disadvantages of hydrogen fuel cell vehicles[151] as did *Car Throttle*.[152] Another *Clean Technica* writer concluded, "while hydrogen may have a part to play in the world of energy storage (especially seasonal storage), it looks like a dead end when it comes to mainstream vehicles."[153]

A 2017 analysis published in *Green Car Reports* found that the best hydrogen fuel cell vehicles consume "more than three times more electricity per mile than an electric vehicle ... generate more greenhouse-gas emissions than other powertrain technologies ... [and have] very high fuel costs. ... Considering all the obstacles and requirements for new infrastructure (estimated to cost as much as $400 billion), fuel-cell vehicles seem likely to be a niche technology at best, with little impact on U.S. oil consumption.[112] In 2017, Michael Barnard, writing in *Forbes*, listed the continuing disadvantages of hydrogen fuel cell cars and concluded that "by about 2008, it was very clear that hydrogen was and would be inferior to battery technology as a storage of energy for vehicles. [B]y 2025 the last hold outs should likely be retiring their fuel cell dreams."[154] A 2020 assessment concluded that hydrogen fuel cell vehicles are still only 38% efficient, while battery EVs are 80% efficient.[155]

See also

- Hydrogen vehicle
- Glossary of fuel cell terms
- Proton exchange membrane fuel cell
- Fuel cell auxiliary power unit
- Fuel Cell and Hydrogen Energy Association

Notes

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