CW COLLECTIONS

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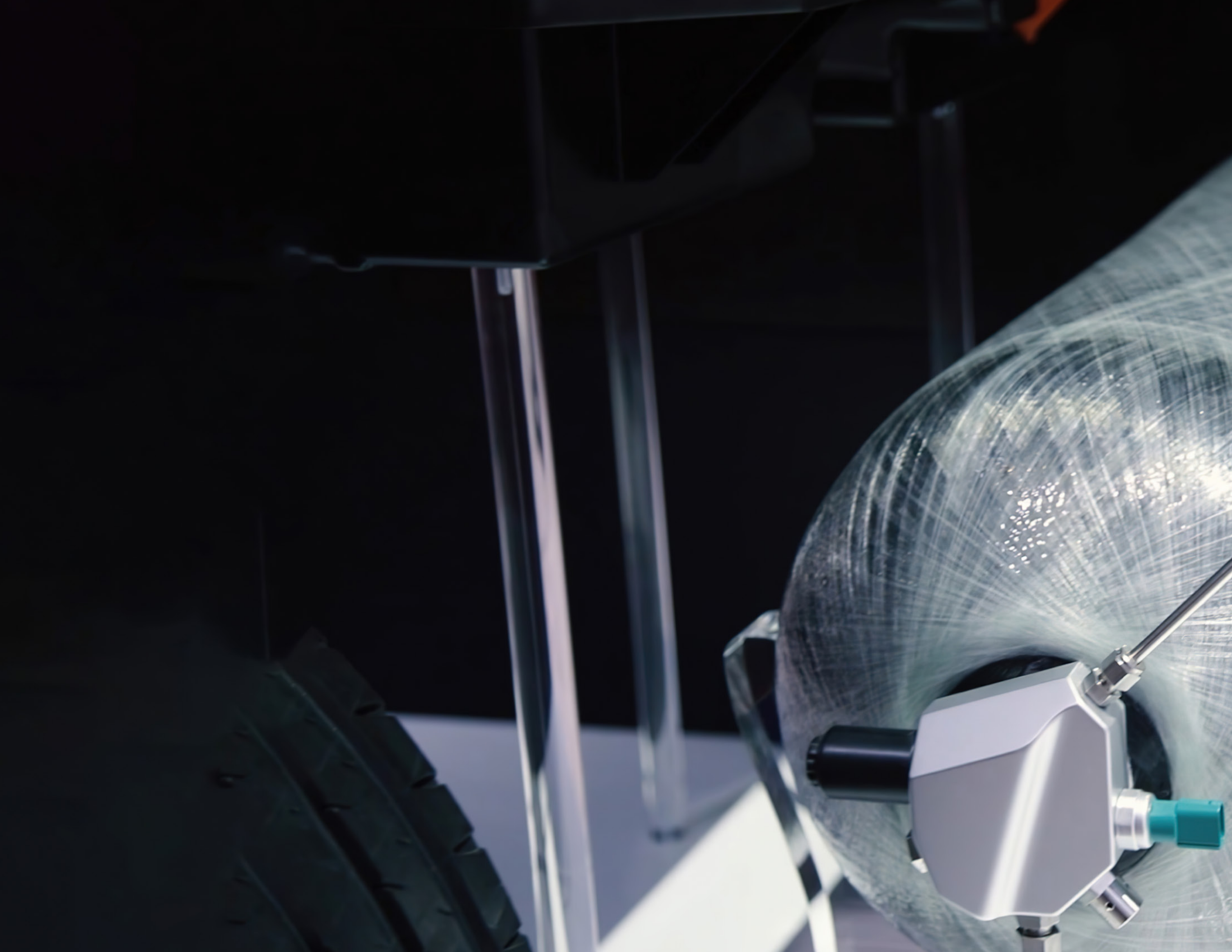
Composites in Hydrogen Storage



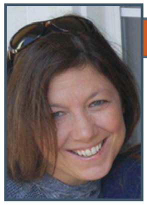
INTRO

As changes in climate have become scientifically linked to fossil fuels, hydrogen has been identified as a sustainable, realistic option for decarbonizing transport by powering cars, heavy-duty trucks, forklifts/logistic equipment, railcars, marine vessels and aircraft, as well as stationary power plants. These systems require storage and transport of the hydrogen fuel in a pressurized gaseous, cryogenic liquid or hybrid cryo-compressed state. Composite pressure vessels are a well-proven and mature solution for high-pressure hydrogen gas storage that could provide a doubling of the industrial market for carbon fiber. However, the low volumetric capacity of hydrogen gas is also pushing higher-density liquid and cryo-compressed solutions that could use more metal than composites. The price of carbon fiber composites is also an issue.

This content collection aggregates two recent reports from CompoositesWorld on the demand for hydrogen as an energy source and the role composites might play in the transport and storage of hydrogen. The first part of this collection is a story I wrote for CW's 2020 "Next-Generation Materials and Processes" supplement. Titled, "Carbon fiber in pressure vessels for hydrogen," it explores how the emerging hydrogen economy is driving tank development for aircraft, ships and gas transport.

The second part of this collection is a presentation developed by myself and composites consultant Mike Favaloro. Titled, "Carbon fiber opportunities in the hydrogen economy," it reviews how hydrogen is sourced, where and how it supplies energy, the tank technologies being developed for its storage and transport, and what the opportunities are for hydrogen in certain geographic regions.

The hydrogen economy is just emerging and has obvious potential for growth. The opportunities for composites here are important and substantial and I hope this collection provides a good introduction for continued discussion regarding the role our industry has to play. If you have questions or comments about composites in hydrogen storage, please don't hesitate to contact me directly at ginger@compositesworld.com



Ginger Gardiner
Senior Editor
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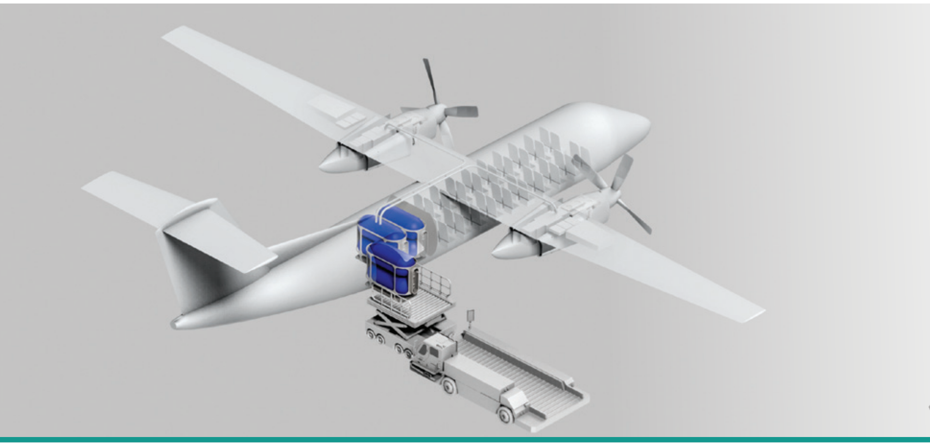
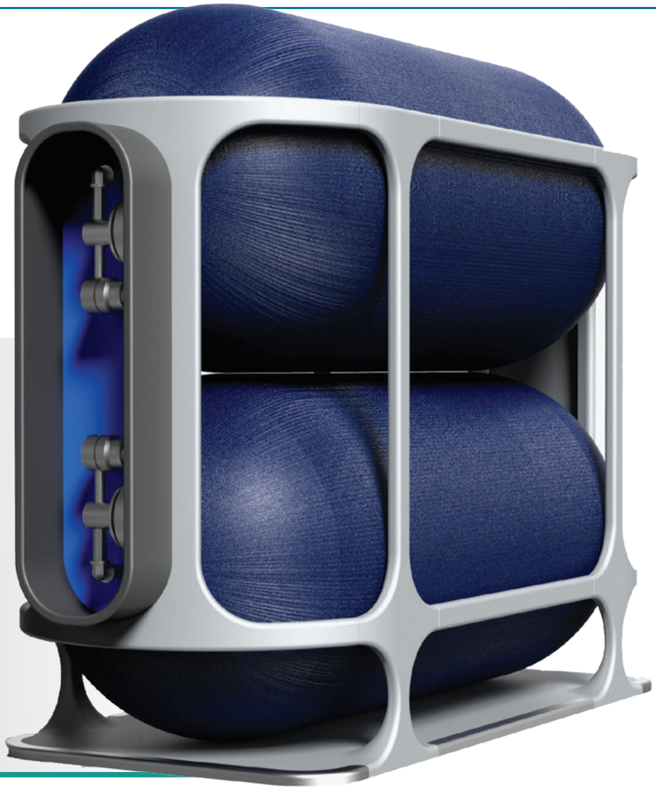
Carbon fiber in pressure vessels for hydrogen storage

The emerging H_2 economy drives tank development for aircraft, ships and gas transport.





Enabling hydrogen-powered aviation

Universal Hydrogen's twin-tank module uses carbon fiber-wrapped pressure vessels to store H_2 gas at 850 bar, enabling a 400-nm range for a *Dash 8* or *ATR* turboprop as well as easy transport and loading using existing infrastructure.

Source | Universal Hydrogen

By Ginger Gardiner / Senior Editor

»Hydrogen as a CO_2-free alternative to fossil fuels has been on the horizon for decades, and growth in carbon fiber-reinforced plastic (CFRP) pressure vessels for hydrogen storage has definitely been on the rise. But in 2020, hydrogen became a mandate, identified by the European Commission (EC) as a key priority to achieve the European Green Deal for a sustainable economy and climate-neutral EU by 2050. Key events for hydrogen in aviation include:

May 2020 — Clean Sky 2 and The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) published "Hydrogen-powered aviation," detailing how short-range (85-165 passenger) hydrogen-powered aircraft could achieve entry into service (EIS) by 2030-2035.

June 2020 — France's $17 billion pandemic relief program is tied to goals from the "Hydrogen-powered aviation" report; Air France says it will cut CO_2 emissions in half for domestic flights by 2024.

July 2020 — EC publishes "A hydrogen strategy for a climate-neutral Europe," calling for a €65 billion investment for hydrogen transport, distribution, storage and refueling stations, listing support policies and funding mechanisms including the Clean Hydrogen Partnership and ETS Innovation Fund (€10 billion during 2020-2030).

July 2020 — Airbus CEO Guillaume Faury, in an interview with *Aviation Week* editor Graham Warwick, commits to the first decarbonized aircraft, with EIS by 2035; he forecasts program launch by 2027-28 and maturation of necessary technologies by 2025.

July 2020 — ZeroAvia (Hollister, Calif., U.S.) completes test flight of single-engine, six-seat *Piper* aircraft modified to use compressed hydrogen (H_2) gas and unveils U.S.-based flight testing for similarly modified twin-turboprop, 19-seat *Dornier Do* 228 per its roadmap to certify a 20-seat, H_2-powered aircraft with 500-mile range by 2023.

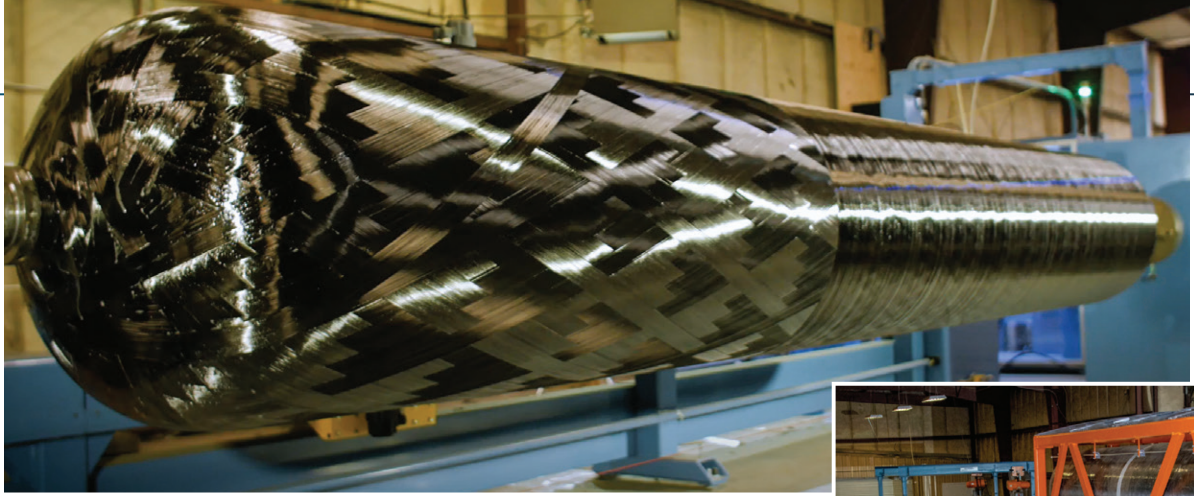
August 2020 — Universal Hydrogen (Los Angeles, Calif., U.S.) announces twin-tank modules for a 50-seat aircraft (see photo), plus refueling logistics and infrastructure for regional airlines/operators to be commercial by 2024.

Hydrogen's viability as a fuel source — regardless of industry — depends on rapid development of a variety of transport, delivery and storage technologies that are young but fast-evolving. Commercialization will not be simple, but is being addressed. Below is a summary of some work being done.

H_2 gas transport by road, rail or sea

Neptune high-pressure (517 bar) CFRP tanks enable transporting 600 kg of H_2 gas in a standard 20-ft container.

Source | Cimarron Composites



Universal Hydrogen

Co-founded in 2020 by Paul Eremenko, ex-CTO for Airbus SE (Leiden, Netherlands) and United Technologies Corp. (Farmington, Conn., U.S.), Universal Hydrogen's goal is to help transition to hydrogen-powered aviation by providing a hydrogen fueling infrastructure. One key component is its fuel module comprising twin H_2 storage tanks in a carbon fiber-reinforced polymer (CFRP) frame. "We will supply the modules to site as needed, so there's no need for hydrogen storage infrastructure," explains Universal Hydrogen CTO J.P. Clarke. "The modules are simply loaded into the plane like a battery or galley supplies."

Modules have been developed first for the 50-seat *Dash* 8 and *ATR* turboprop regional aircraft. These modules will feature 7-foot long by 3-foot-diameter tanks, using either carbon fiber to hold H_2 gas at 850 bar achieving a density of 50 kg/m^3, or insulated metal tanks to hold liquid H₂ (LH_2) at standard pressure and temperature achieving a density of 71 kg/m^3. Though the LH_2 tanks offer higher volumetric efficiency, the insulated but uncooled tanks must be used within 42 hours because LH_2 vaporizes if not kept at -253°C. "Both type tanks will sit within a lightweight, structurally-optimized composite frame that also lends impact resistance and some load-bearing capabilities," says Clarke.

The H_2 gas tanks will include an impermeable polymer liner wrapped with layers of *dry* carbon fiber braid and a Kevlar aramid fiber protective outer layer. "There is no need for resin," Clarke explains. "The liner addresses permeability, while the carbon handles the hoop and axial loads and the outer layer plus frame prevents damage; thus weight and thickness are reduced. This integrated tank and frame design, when combined with the mapping of functions to each of the tank layers, has allowed us to get some significant improvements in the mass fraction."

Maximizing mass fraction — ratio of stored H_2 mass to whole system mass — is key. "We did a very extensive trade study looking at the mass fraction and volumetric efficiency in the context of the *Dash* 8 and *ATR* aircraft," Clarke notes. "So, you're looking at volume and weight of fuel versus what can fit in these aircraft, achievable range and maximum takeoff weight, weight distribution, etc. With H_2 gas at 850 bar, we can fly about 400 nautical miles with a 45-minute reserve and about 550 nautical miles with the LH_2 tanks. However, the average stage length for a turboprop mission is around 300 nautical miles, so the *vast* majority of these flights can be done with a gaseous H_2 system using carbon fiber wound tanks."

Will Universal Hydrogen partner with a composite tank manufacturer? "Our strategy is to partner where it makes sense and stick to our core business," says Clarke. "We want to be the provider of the fuel and the infrastructure. We'll provide the modules, and we'll get them to where they're needed so that our partners can focus on the rest of the aircraft design and operation."

SpaceTech4Sea

Like aviation, shipping is also coming under regulations designed to reduce CO_2 and other greenhouse gas (GHG) emissions. From January 2018, ships of more than 5,000 gross tons loading or unloading cargo or passengers at ports in the European Economic Area (EEA) must monitor and report their CO_2 emissions. Further, as part of its MARPOL convention to reduce pollution from ships, the International Maritime Organization (IMO) has mandated from January 2020 that sulfur in fuel oil must be reduced from 3.50% m/m (mass by mass) to 0.50%.

The IMO has also committed to an initial GHG strategy to pursue a 50% reduction by 2050 compared to 2008 levels.

"The best possibility to be in compliance is to initially shift to liquid natural gas (LNG)," says Dr. Panayotis Zacharioudakis, managing director of Ocean Finance (Athens, Greece), an advisory firm advancing maritime sustainability and coordinator of the EC projects SuperGreen and SpaceTech4Sea. SuperGreen will create a sustainable and green transport system in Greece comprising electric commuter vessels and two hybrid LNG/electric catamarans that will connect the port of Piraeus with other ports in the eastern Mediterranean network. "For this project, we are building a high-speed ferry in CFRP," explains Zacharioudakis. "If we used a state-of-the-art metal LNG tank, it would weigh seven metric tons, which equates to a little more than 70 passengers [100 kilograms per person with baggage]. So, we'd have to decrease the passenger capacity by 70."

Why the extra weight? "Compared to diesel, LNG must be stored at a cryogenic -163°C and the metal tanks must use materials, construction, insulation and operating systems that meet the IMO's requirements for gaseous fuels, or IGF code," says Zacharioudakis. For Ocean Finance, the extra weight was not acceptable, so it began researching possible solutions and found a report about cryotanks Cimarron Composites (Huntsville, Ala., U.S.) developed with NASA.

"This is when we began the EASME (European Agency for SMEs) SpaceTech4Sea project," says Zacharioudakis. "The idea is to modify aerospace technology for maritime applications." The third project partner is classification society American Bureau of Shipping (ABS, Houston, Tex., U.S.), which will validate and qualify the technology. In September 2019, ABS granted approval in principle (AIP) for Cimarron's conceptual design of an ultralight, cryo-capable composite LNG tank. Since then, it has built and tested sub- and full-scale tanks for certification. "They just finished the last testing," says Zacharioudakis. "In a little more than two months, we will have a full certification for composite LNG tanks for the marine market. This tank will provide weight savings of more than 85% versus a conventional metal tank."

Though most of the tank's specifics are proprietary, Cimarron Composites founder and president Tom DeLay says it is made with carbon fiber and an advanced thermoset resin using some resin infusion and wet filament winding. "We have tested 25- and 40-inch-diameter tanks and are talking to the CFRP ferry builder for SuperGreen about tanks with a capacity of five cubic meters [5,000 liters], which could be achieved with a tank 2 meters in diameter and 2.5 meters long." Ocean Finance sees a market for more than a thousand such tanks and will work with Cimarron to establish automated production, possibly in Greece.

And what about hydrogen? "Even while we finish these LNG projects, we have started to look at hydrogen," notes Zacharioudakis. "There is so much interest, activity and now funding available in Europe. One issue, however, is that maritime regulations specify tanks must provide a holding time of up to 15 days for LNG. This will be the same for LH_2." DeLay concedes that developing a cryo-capable tank for LH_2 (-253°C) is much more difficult than developing a tank for LNG (-196°C); among the challenges is to find materials that can resist embrittlement and cracking. He is working now with Ocean Finance to help complete a trade study, looking at the technical and economic factors of using liquid versus gaseous H_2 for marine vessels.

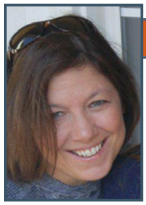
Neptune tanks for H_2 gas

Notably, Cimarron Composites has already developed a Type IV CFRP tank for high-pressure storage of hydrogen and other gases. "Our Jupiter tank was developed for the transport of most industrial gases, including hydrogen, at a pressure of 4,350 psi [300 bar]," says DeLay. "Hydrogen, however, is transported more effectively at higher pressures, which is why we developed the 7,500-psi [517 bar] Neptune tank."

Both Jupiter and Neptune tanks have passed the myriad tests per UN ISO 11515 requirements and are available in a range of diameters and lengths up to 26 feet. "These tanks were developed for shipping in standard modules by truck, rail or ship," notes DeLay. "We have found that a 30-inch diameter has an ideal packing efficiency, allowing us to haul more hydrogen than with larger-diameter cylinders. With a 19-foot length, we can fit nine tanks into a standard 20-foot container. At 67 kilograms of hydrogen gas per tank, we can move 600 kilograms in a 20-foot container and 1,200 kilograms in a standard 40-foot container."

"We buy carbon fiber from all of the main suppliers, including Toray [Tokyo, Japan], Mitsubishi Rayon [Tokyo], Teijin [Rockwood, Tenn., U.S.] and Hyosung [Seoul, South Korea]," adds DeLay, "but for Neptune we have qualified with three different suppliers simultaneously. We formulate the resin ourselves using commercially available products and very tightly control the fiber and resin content as well as the tension during filament winding and oven cure cycle to prevent thermal stress. All of this adds to the mechanical performance of the tanks."

DeLay sees H_2 opportunities growing for both cryogenic liquid and high-pressure gas storage. "It has taken us years to develop our expertise," he says, "starting from fuel tanks for rockets to the large transport and storage tanks we're producing now. A year ago, I was skeptical about hydrogen, thinking it was just a push by the government. But now we are getting very large orders and all kinds of requests. We can see that, globally, a wide range of industries are investing seriously in hydrogen. It looks like we're ready with the right products at the right time." CW



ABOUT THE AUTHOR

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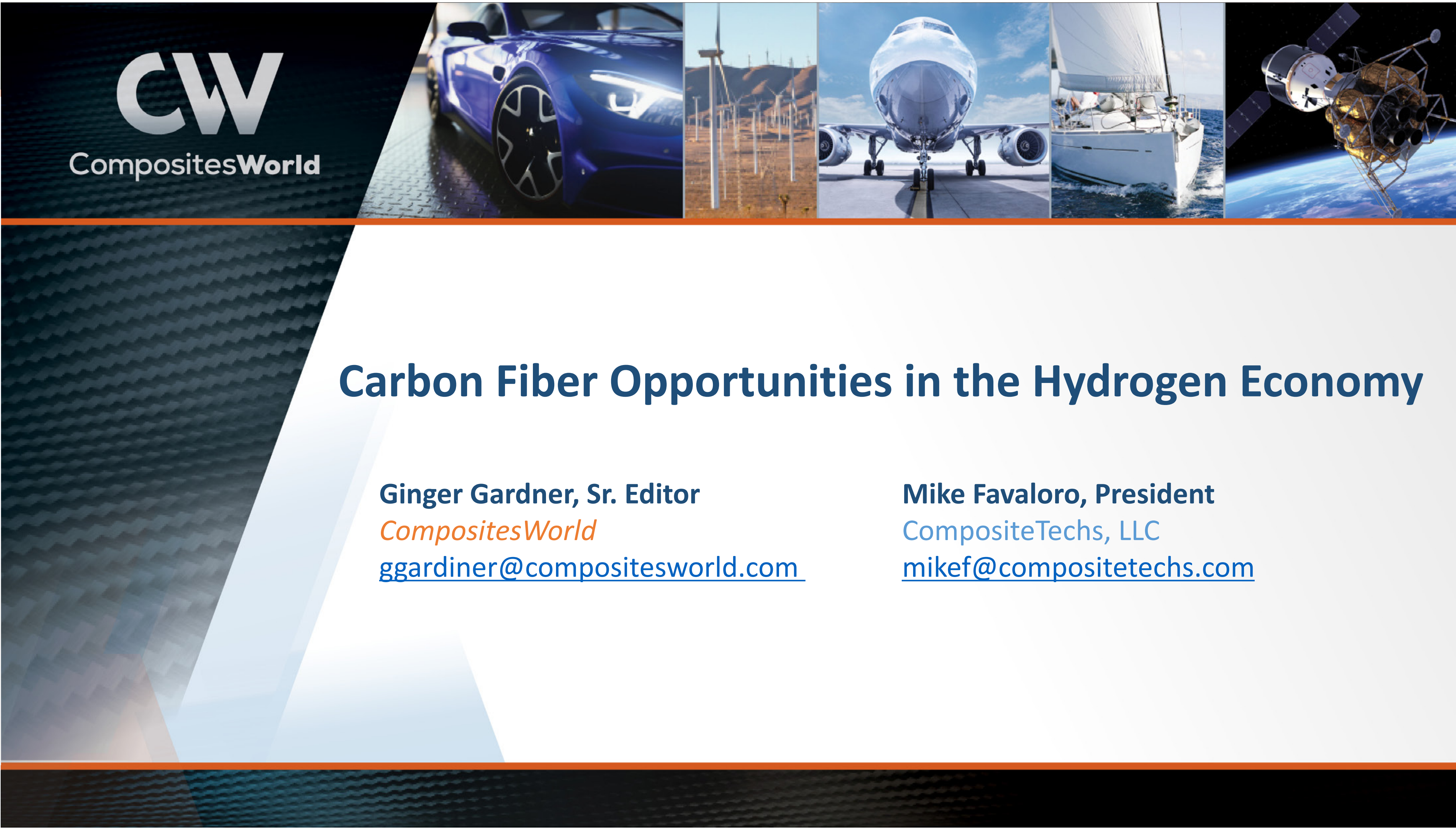

Carbon Fiber Opportunities in the Hydrogen Economy

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Carbon Fiber Opportunities in the Hydrogen Economy

The Hydrogen Economy

- What is the hydrogen economy? Why hydrogen?
- Path to green hydrogen
- Fuel cells and combustion require storage

Hydrogen Storage

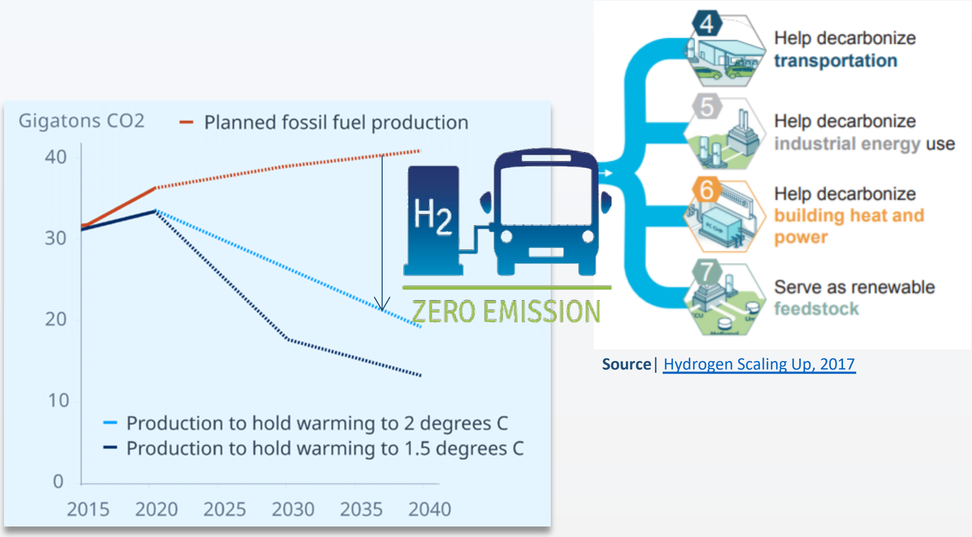
- Tank types and use of carbon fiber (CF) composites
- Issues and development

Opportunity for Carbon Fiber

- Assumptions
- Projections
- Conclusion

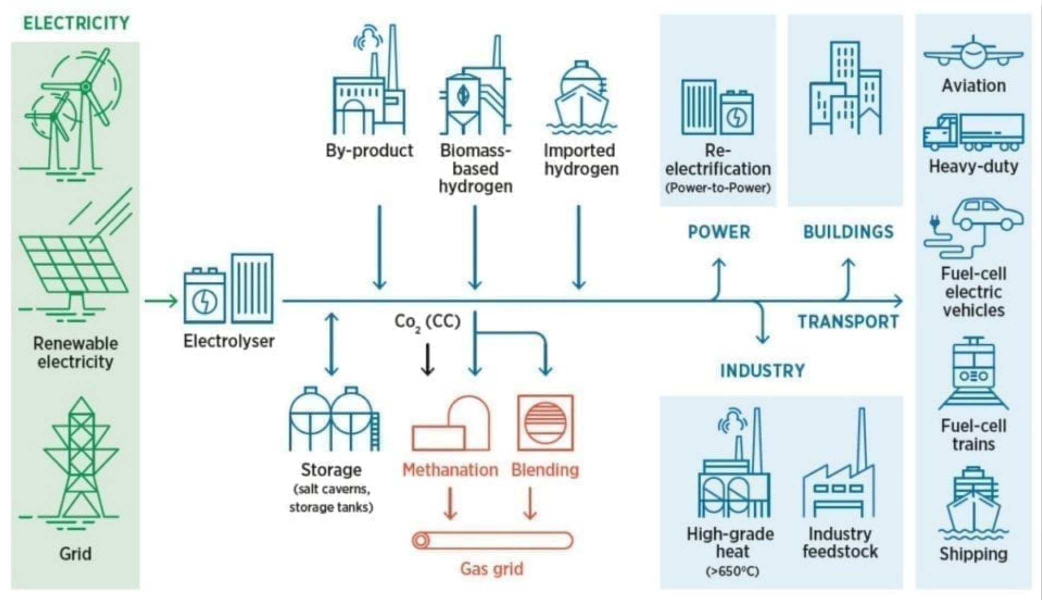
What is the Hydrogen Economy?

- To limit global warming to 2°C vs. 2010 levels, world CO_2 emissions must drop > 60%/yr until 2050.
- H_2 offers sustainable decarbonization



Source | The Production Gap Report 2019

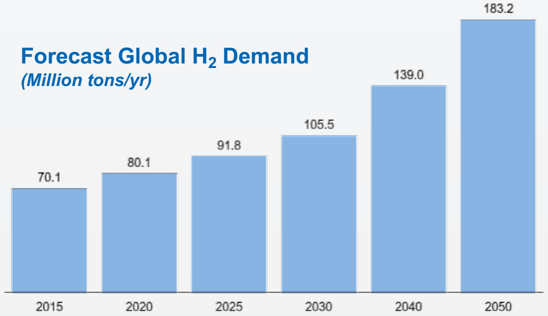
Source | Hydrogen Scaling Up, 2017



Source | Powermag.com, International Renewable Energy Agency (IRENA)

Forecast Global H_2 Demand

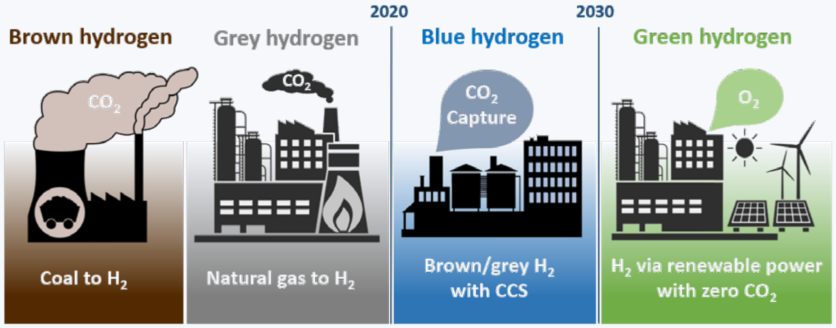
(Million tons/yr)

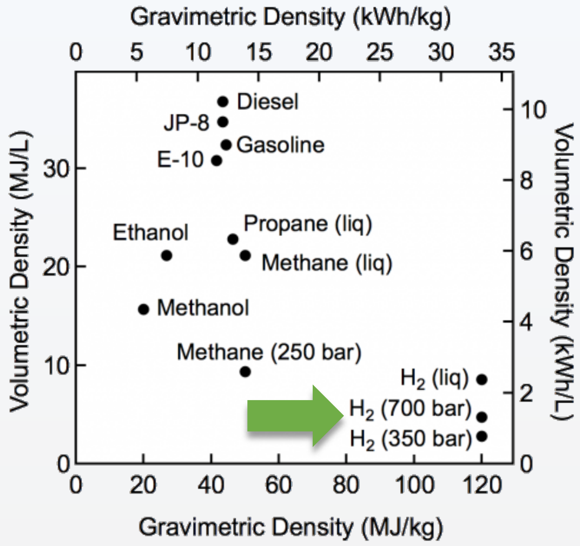


Source | ADI Analytics

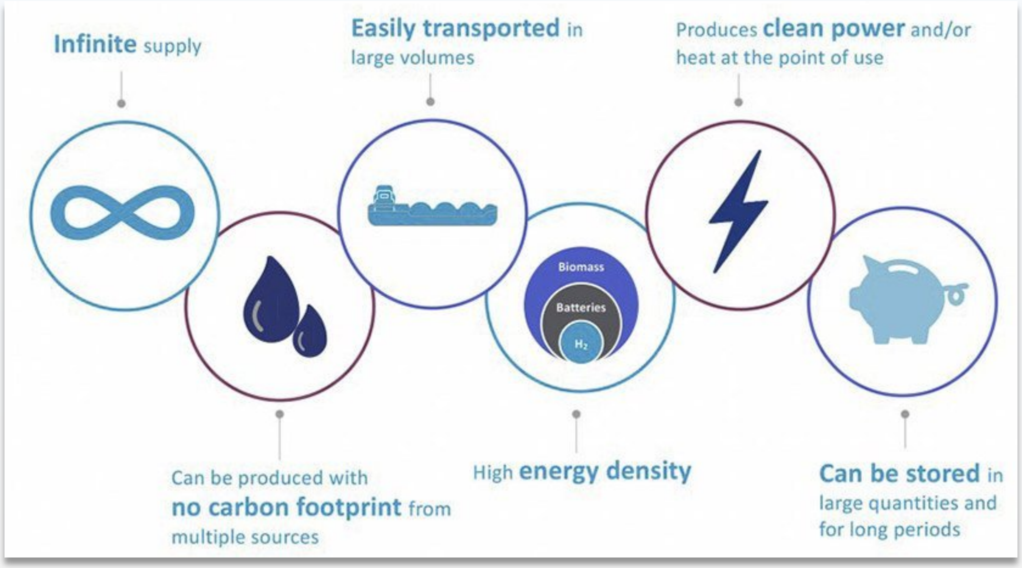
Why Hydrogen?

- Highest energy density, zero emissions possible
- Produced from coal, methane, biomass or water
- Readily stored and converted





Source | www.energy.gov/eere/fuelcells/hydrogen-storage



Source | https://www.egsa.org.za/general-news/green-hydrogen-for-buses/

Path to Green H_2

- Hydrogen is produced from natural gas now and the industry will help scale blue hydrogen

“We will ultimately move to a green hydrogen economy. But we are convinced that you can only make the step towards green hydrogen via blue hydrogen first.” — *Hans Coenen, VP corporate strategy/business development at Dutch gas network company, Gasunie*

Oil & gas execs who said their companies will invest in H_2

2019 – 20%
2020 – 42%
108% increase

Source| 2020 oil and gas industry’s outlook for hydrogen by DNV-GL, p. 5

Source| 2020 Mobile Fuel Cell Application Market Trends by IEA

today
- 25,212 Vehicles, 470 HRS (end of 2019)

2020
- China 5,000 FCV 100 HRS
- Germany 100 HRS
- Hydrogen Mobility Europe project: 1,400 FCEV, >45 HRS
- Japan 40,000 FCEV, 100 FCB 160 HRS
- Spain 500 FCEV 20 HRS
- Switzerland 50 heavy duty trucks

2022
- Korea 81,000 FCEV, 310 HRS
- California 26,900 FCEV

2023
- Europe 291 buses (JIVE projects)
- France 5,000 FCEV, 100 HRS, 200 heavy duty vehicles
- Germany minimum 41 passenger trains

2025
- California 48,000 FCEV, 200 HRS
- China 50,000 FCV, 300 HRS
- Europe minimum 747 HRS
- Germany 400 HRS
- Japan 200,000 FCEV, 320 HRS
- Switzerland 1,600 heavy duty trucks

2028
- France 20,000 – 50,000 FCEV, 400 - 1000 HRS, 800 – 2,000 heavy duty vehicles

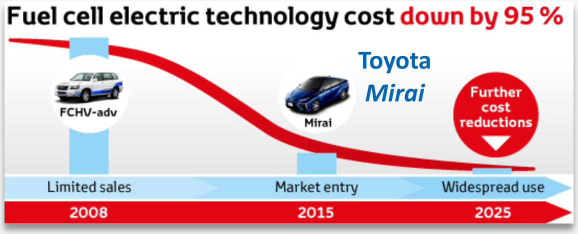
2030
- CAFP vision / California 1,000,000 FCEV 1,000 HRS
- China 1,000,000 FCV 1,000 HRS
- Hydrogen Council vision Globally 10-15 million cars and 500,000 trucks
- Japan 800,000 FCEV, 1,200 FCB, 900 HRS
- Hydrogen Europe vision / Europe 5 million cars, 15,000 buses, 95,000 trucks, 4,500 HRS

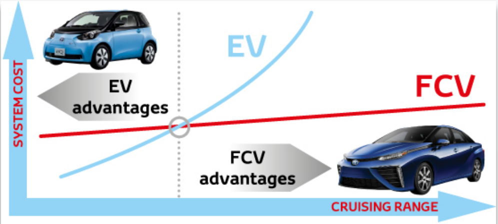
2040
- Korea 6,200,000 FCEV (5,900,000 passenger cars, 120,000 taxis, 60,000 buses, 120,000 trucks), 1200 HRS

2050
- Hydrogen Council vision 400 million cars, 15-20 million trucks, 5 million buses
- Europe / FCH 2 JU vision 45 million cars, 6.5 million LCVs, 1,7 million trucks, 250,000 buses

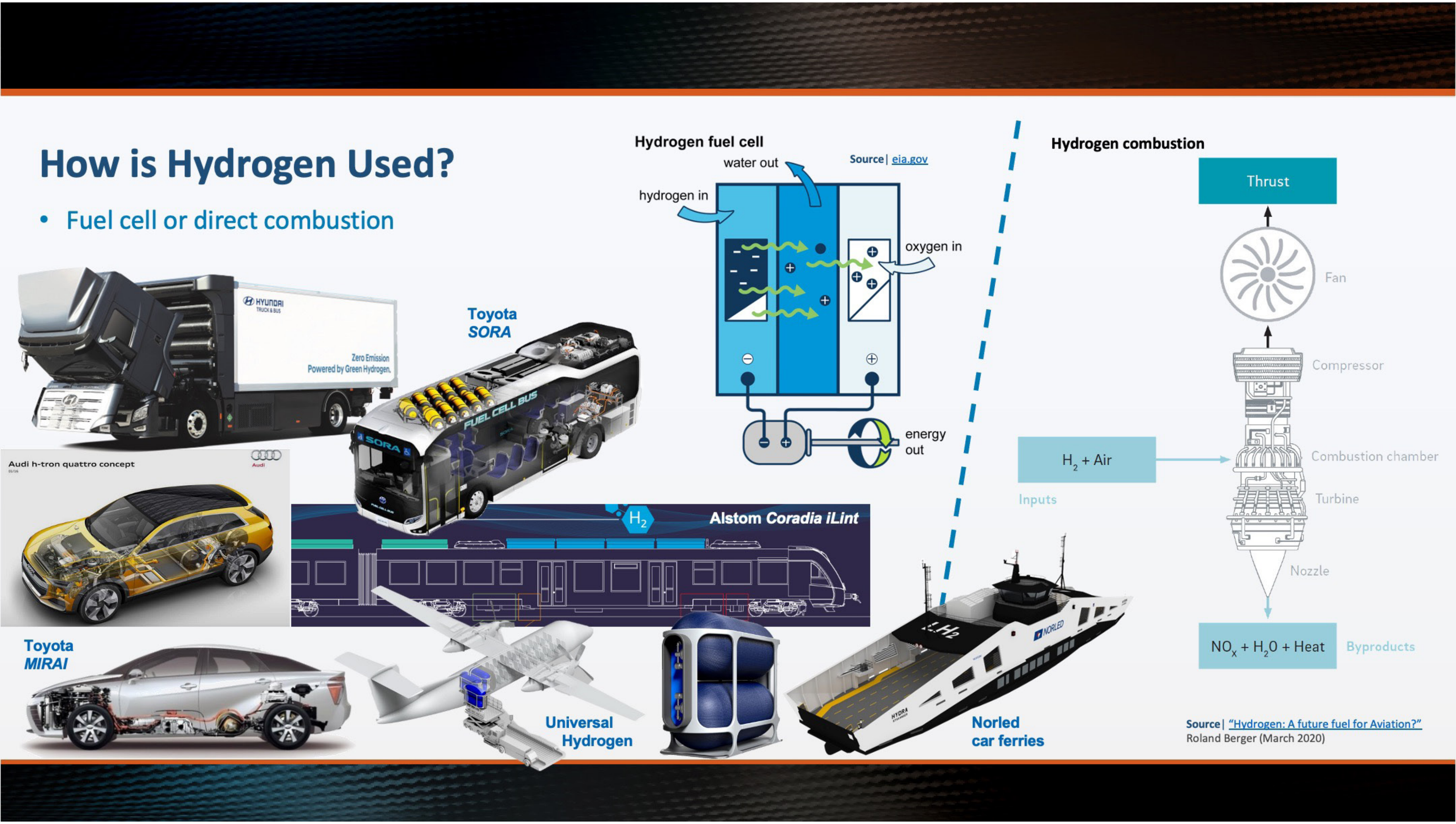
FCEV: Fuel cell electric vehicles (passenger cars)
FCV: Fuel cell vehicle (all categories)
FCB: Fuel cell bus
HRS: Hydrogen refueling station
LCV: Light commercial vehicle

- FCEV technology is ready with vehicles in production





Source| Toyota



How is Hydrogen Used?

- Fuel cell or direct combustion

Hydrogen fuel cell

water out

hydrogen in

oxygen in

energy out

Source | eia.gov

Hydrogen combustion

Thrust

Fan

Compressor

Combustion chamber

Turbine

Nozzle

H_2 + Air

Inputs

$NO_x + H_2O$ + Heat

Byproducts

Source | "Hydrogen: A future fuel for Aviation?" Roland Berger (March 2020)

HYUNDAI TRUCK & BUS

Zero Emission Powered by Green Hydrogen.

Toyota *SORA*

FUEL CELL BUS

SORA

Audi h-tron quattro concept

Audi

H_2 **Alstom *Coradia iLint***

Toyota *MIRAI*

Universal Hydrogen

Norled car ferries

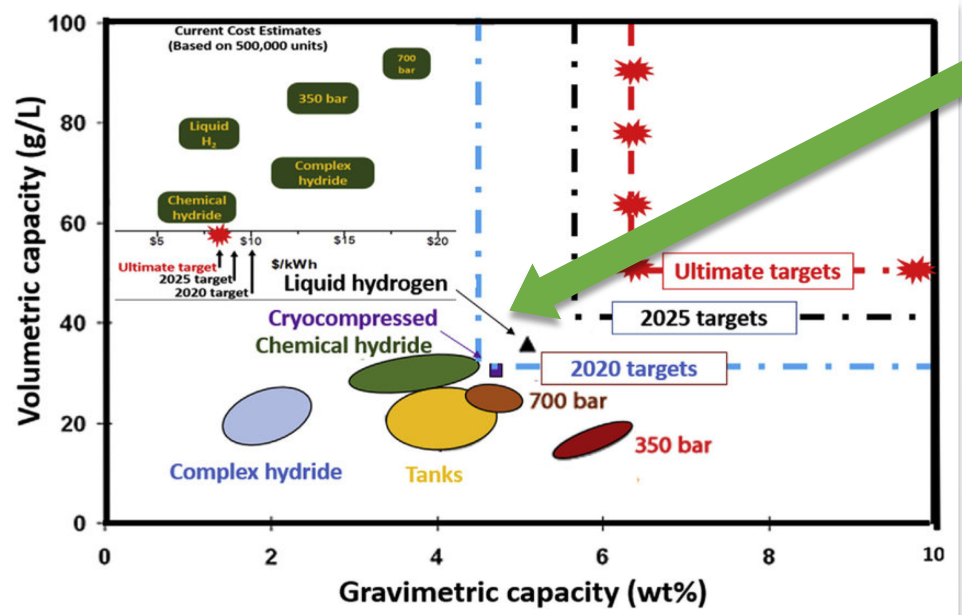
LH2

NORLED

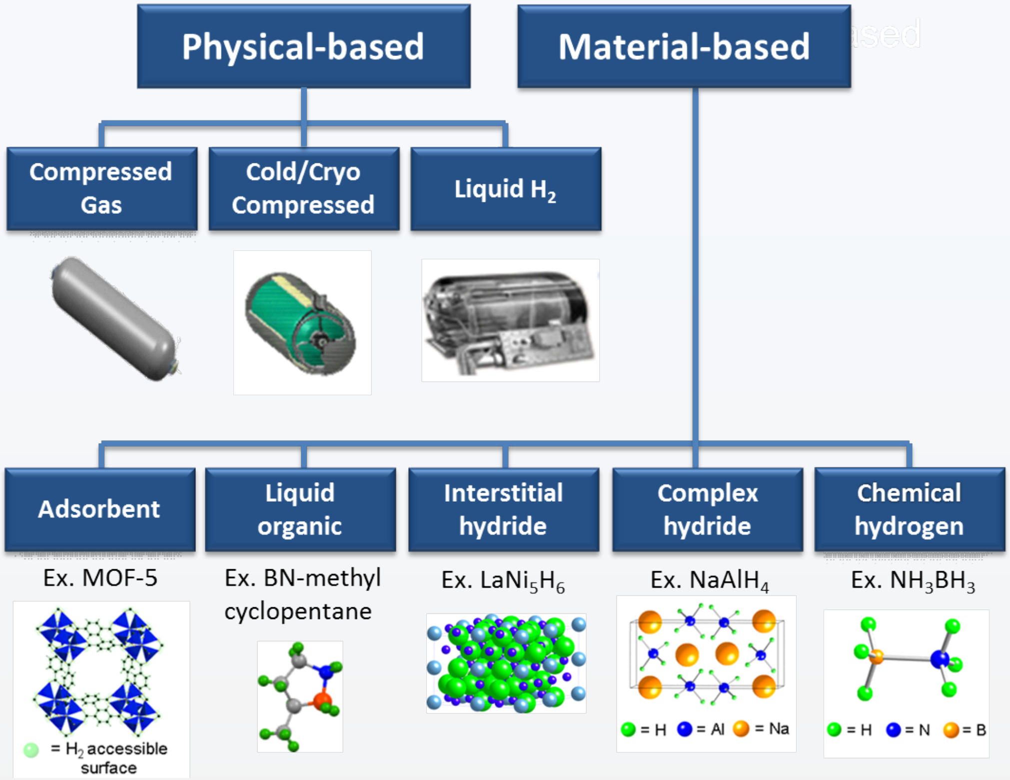
HYDRA

Hydrogen Fuel Storage

- Fuel cell or combustion requires fuel storage
- H_2 has high energy per mass but ***low energy per volume***



Source| "Boateng, Chen, "Recent advances in nanomaterial-based solid-state hydrogen storage" , June 2020.



Physical-based

- **Compressed Gas**
- **Cold/Cryo Compressed**
- **Liquid H_2**

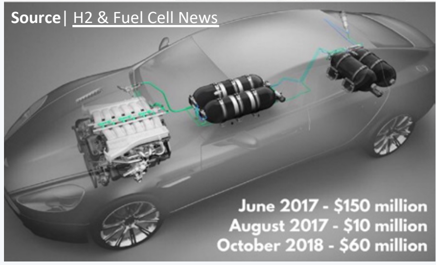
Material-based

- **Adsorbent** Ex. MOF-5
- **Liquid organic** Ex. BN-methyl cyclopentane
- **Interstitial hydride** Ex. $LaNi_5H_6$
- **Complex hydride** Ex. $NaAlH_4$
- **Chemical hydrogen** Ex. NH_3BH_3

Source| www.energy.gov/eere/fuelcells/hydrogen-storage

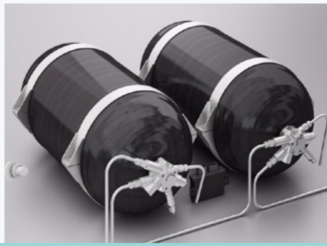
Hydrogen Storage Tanks

- Primary market for carbon fiber
- Applications
  - **Transportation** (car, rail, aero, etc.)
  - **Distribution** (mobile pipeline)
  - **Hydrogen Refueling Stations (HRS)**

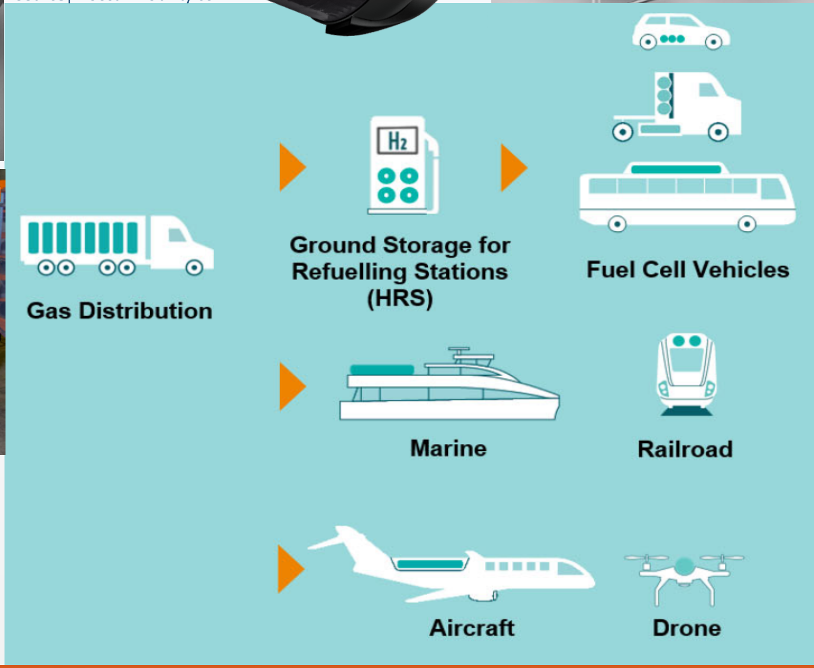

Source | H2 & Fuel Cell News

June 2017 - $150 million
August 2017 - $10 million
October 2018 - $60 million


UAV tank
Source | DoosanMobility.com


Bus tanks
Source | Plastic Omnium


Source | Cimarron Composites

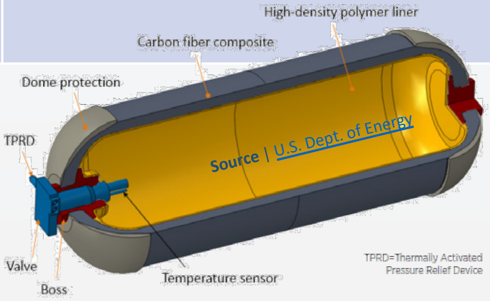


Hexagon Composites supplies tanks for first full-size Dutch refueling station
Source | fuelcellworks.com

Faurecia to supply tanks for 1,600 Hyundai trucks

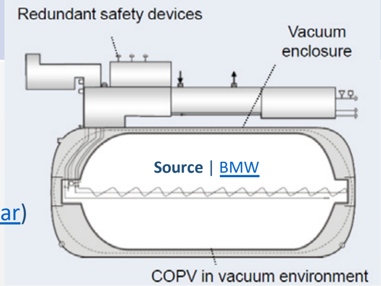
Hydrogen Storage Tank Types

	Compressed Gas H2	Cryo-compressed H2	Liquid H2
Pressure	350 - 1,000 bar	up to 350 bar	Atmospheric pressure
Temperature	Room temp	64 K/-203°C	20.4 K/-253°C
Common tank	**Type IV plastic/CF overwrap** composite pressure vessel	**Type III metal/CF overwrap** super-insulated cryogenic pressure vessel	**Metal tank w/ perlite insulation** super-insulated, low-pressure cryotank
Advantages	• Most mature • Proven safety record	• Higher density/less space required • No boil off vs. LH2 • More safety/redundancy vs. LH2	• Higher density/less space required
Disadvantages	• More space required due to low density • Most carbon fiber required	• Not mature • More complex, heavy and expensive	• 40% loss to compress H2 liquid • High insulation + cryo temp issues • Hard to scale down for small vehicles • Liquid boil off + safety issues



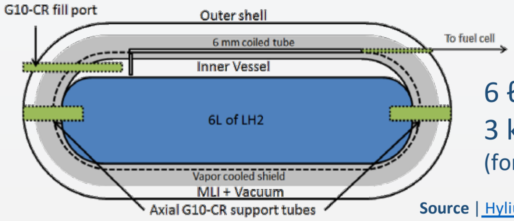
Source | U.S. Dept. of Energy

69 ℓ
37.5 kg
(Faurecia 700 bar)



Source | BMW

235 ℓ
145 kg



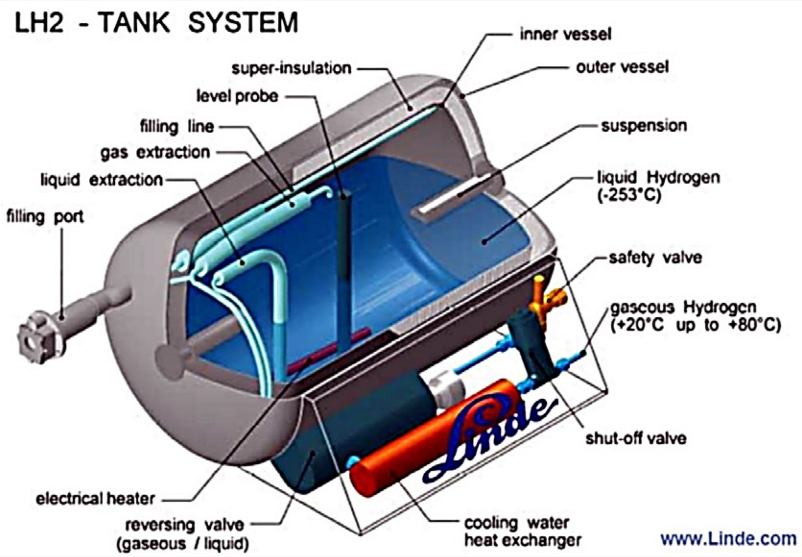
6 ℓ
3 kg
(for UAV)

Source | Hylium

Liquid Hydrogen Tanks

- Tankers, ground tanks, spacecraft
- Ground-based LH2 tanks
  - Insulation = perlite + vacuum layer
  - Boil-off rates = 1-5% per day
- Magna Steyr tank for FCEV auto (2004):
  - Stainless steel inner, outer tanks
  - Multilayer insulation (MLI)
    (40 layers aluminum + glass fiber spacers)
  - CFRP support structure withstands
    crash load: 20G fwd, 8G side
  - Boil-off 4%/day (leaves as water)[1]
- Boil-off <.05%/day w/ MLI and cooling.[2]

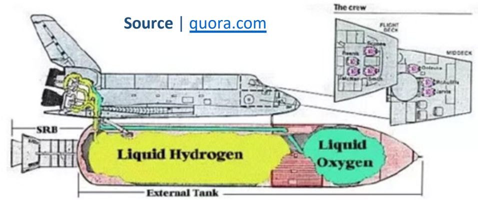
Source | 1 "Safety demands for automotive hydrogen storage system" by Magna Steyr, 2004?
2"Liquid HydrogenStorage: Status and Future Perspectives" by Hendrie Derking, Cryoworld BV for Cryogenic Heat and Mass Transfer, Nov 2019




Source | Linde


Picture: Kawasaki

JAXA (Kawasaki), 540 m^3, 38 t


Source | quora.com

Liquid Hydrogen Tanks

- Possible higher density, lower cost vs. compressed gas (GH_2) at 350 or 700 bar
- Does not have to be active cryo
- Tanks primarily metal

Cryoshelter

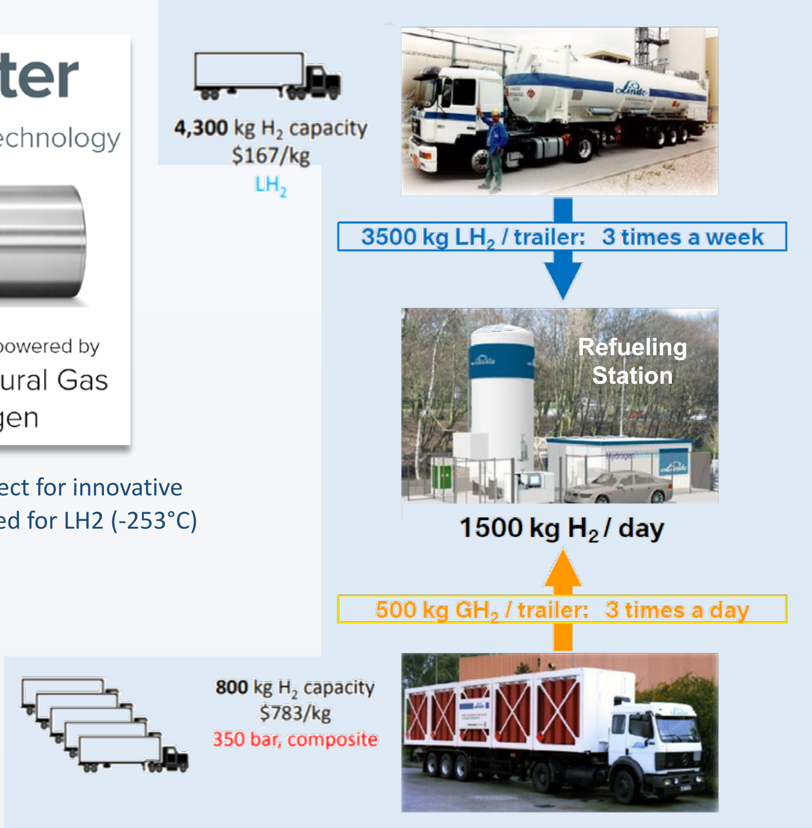
cryogenic vehicle tank technology

for heavy duty trucks powered by

- ▪ LNG – Liquefied Natural Gas
- ▪ LH2 – Liquid Hydrogen

2015-2017 Horizon 2020 project for innovative LNG (-162°C) tank now adapted for LH2 (-253°C)

Source | European Commission



4,300 kg H_2 capacity
\$167/kg
LH_2

3500 kg LH_2 / trailer: 3 times a week

Refueling Station

1500 kg H_2 / day

500 kg GH_2 / trailer: 3 times a day

800 kg H_2 capacity
\$783/kg
350 bar, composite

Source | "LH2 Installation Description", by PRESLHY , Nov 2018 and Krishna Reddi, et. al., 2015.

Source | Kircher, BMW 2012

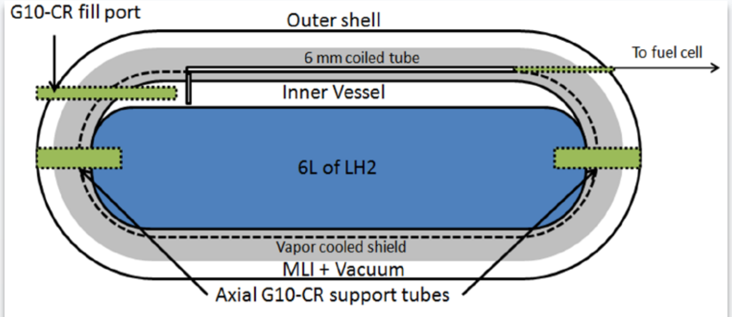


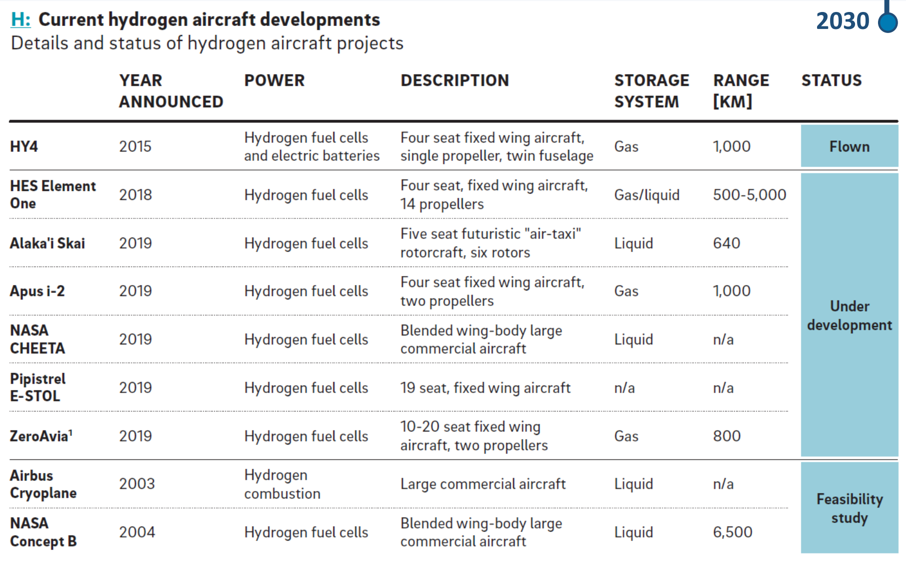
Figure 1. Simple schematic diagram of 6 L UAV LH_2 tank.

Source | "Performance test of a 6 L liquid hydrogen fuel tank for unmanned aerial vehicles" by Hylium Industries 2015

Liquid H_2 for Aviation?

- Airbus ZEROe aircraft will use LH_2
- Universal Hydrogen developing LH_2 (metal) and GH_2 (carbon fiber)

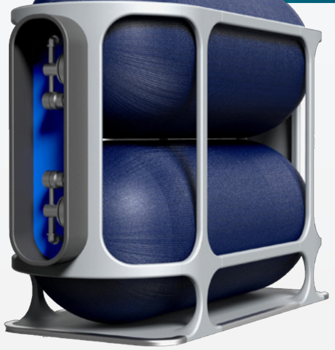
2021	**Ground demonstrator**
2023	**Flight demonstrator**
2024	**Finalize technology**
2025	**1st flight**
2030	**Entry into service**



H: Current hydrogen aircraft developments

Details and status of hydrogen aircraft projects

	YEAR ANNOUNCED	POWER	DESCRIPTION	STORAGE SYSTEM	RANGE [KM]	STATUS
HY4	2015	Hydrogen fuel cells and electric batteries	Four seat fixed wing aircraft, single propeller, twin fuselage	Gas	1,000	**Flown**
HES Element One	2018	Hydrogen fuel cells	Four seat, fixed wing aircraft, 14 propellers	Gas/liquid	500-5,000	**Under development**
Alaka'i Skai	2019	Hydrogen fuel cells	Five seat futuristic "air-taxi" rotorcraft, six rotors	Liquid	640	
Apus i-2	2019	Hydrogen fuel cells	Four seat fixed wing aircraft, two propellers	Gas	1,000	
NASA CHEETA	2019	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	n/a	
Pipistrel E-STOL	2019	Hydrogen fuel cells	19 seat, fixed wing aircraft	n/a	n/a	
ZeroAvia[1]	2019	Hydrogen fuel cells	10-20 seat fixed wing aircraft, two propellers	Gas	800	
Airbus Cryoplane	2003	Hydrogen combustion	Large commercial aircraft	Liquid	n/a	**Feasibility study**
NASA Concept B	2004	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	6,500	



Universal Hydrogen 850-bar GH_2 tanks

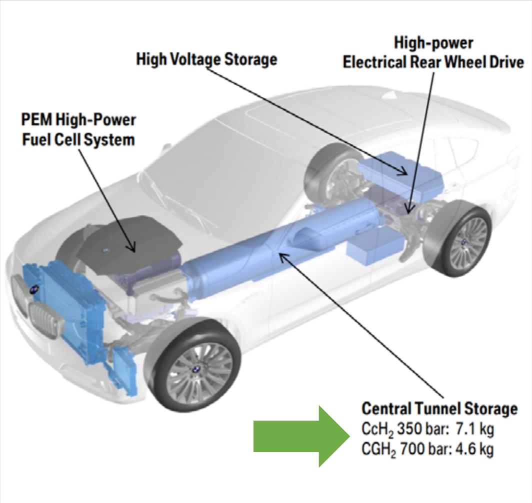
- 3-ft diameter, 7-ft length for 20-pax commuter AC
- Plastic liner with dry carbon fiber braid, no resin
- Protective outer coating
- CFRP load-bearing frame for twin tanks

Source | "Carbon fiber in pressure vessels for hydrogen", ***CW*** 2020

Cryo-Compressed Tanks

- BMW development 2007-2015

BMW TECHNOLOGY DEMONSTRATOR VEHICLES 2015 WITH COMPRESSED AND CRYO-COMPRESSED HYDROGEN STORAGE.



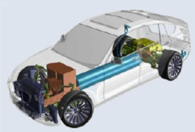
700 bar CGH_2 (Compressed Gas)	**350 bar CcH_2** (Cryo-compressed Gas)
> 350 (500*) km Range	> 500 (700*) km Range
Refueling time < 5 min for 350 km	Refueling time < 5 min for 500 km
-	Boost cooling mode for additional performance
High bonfire and crash safety	Highest bonfire and crash safety
Non-compromised compartment space	Non-compromised compartment space

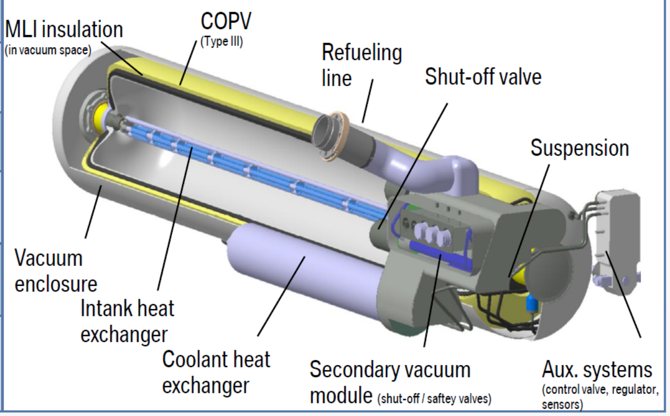
Source| "Hydrogen Fuel Cell Technology", Tobias Brunner, BMW Group, 2013

Modular Super-insulated Pressure Vessel (Type III)

Max. usable capacity	CcH_2: 7.8 kg (260 kWh) CGH_2: 2.5 kg (83 kWh)
Operating pressure	≤ 350 bar
Vent pressure	≥ 350 bar
Refueling pressure	CcH_2: 300 bar CGH_2: 320 bar
Refueling time	< 5 min
System volume	~ 235 L
System weight (incl. H_2)	~ 145 kg
H_2-Loss (Leakage| max. loss rate | infr. driver)	<< 3 g/day | 3 – 7 g/h (CcH_2) | < 1% / year

+ Active tank pressure control
+ Load carrying vehicle body integration
+ Engine/fuel cell waste heat recovery

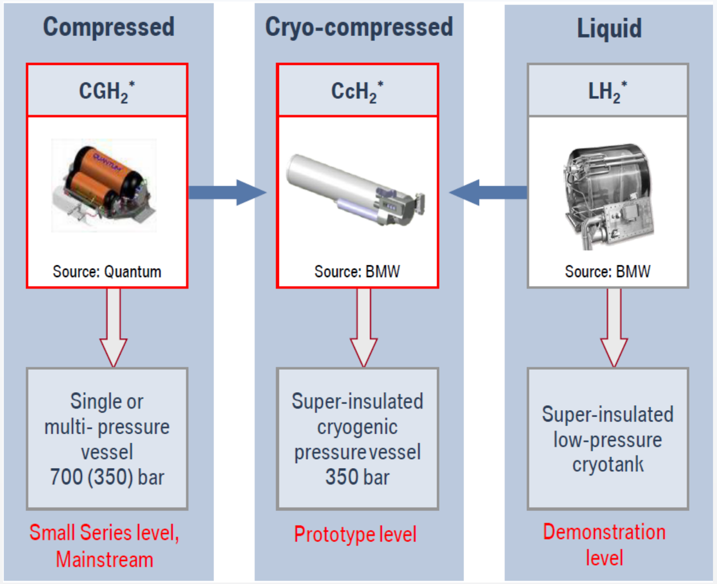




Source| "Cryo-compressed hydrogen storage", BMW Group, 2012

Cryo-Compressed Tanks

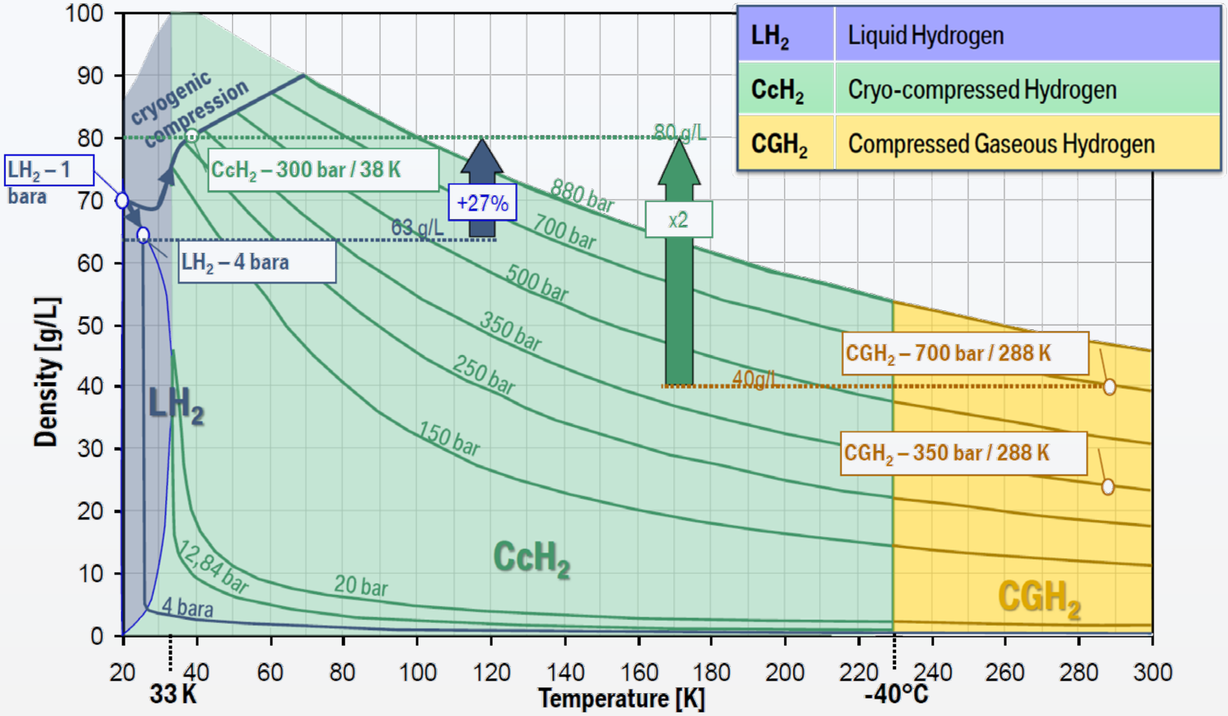
- BMW strategy: pursue CGH_2 and CcH_2



Compressed	Cryo-compressed	Liquid
$CGH_2{}^*$	$CcH_2{}^*$	$LH_2{}^*$
Source: Quantum	Source: BMW	Source: BMW
Single or multi- pressure vessel 700 (350) bar	Super-insulated cryogenic pressure vessel 350 bar	Super-insulated low-pressure cryotank
Small Series level, Mainstream	Prototype level	Demonstration level

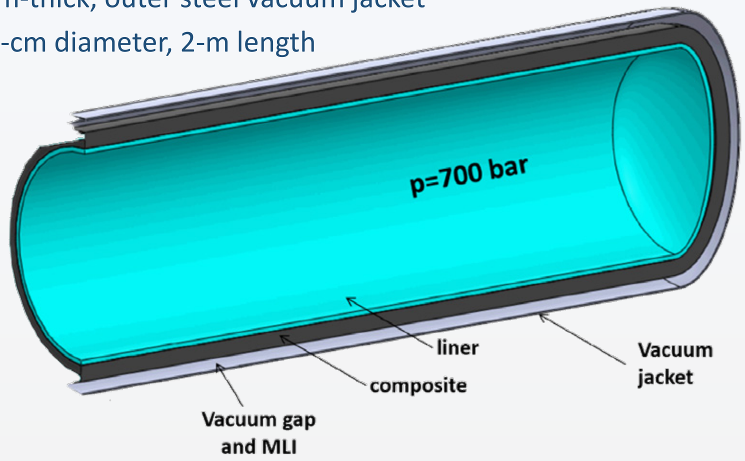
Source| "Cryo-compressed hydrogen storage", BMW Group, 2012

BMW HYDROGEN STORAGE . CCH_2 – CRYOGENIC GAS DENSER THAN LH_2.



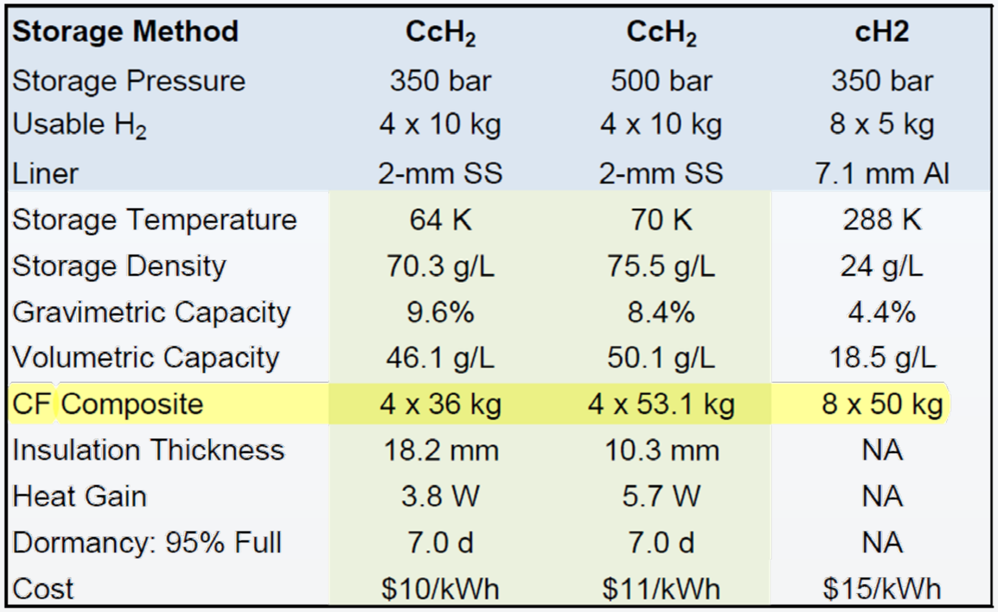
Cryo-Compressed Tanks

- Potential to use significantly less carbon fiber
  - **Table 1** – 8 compressed gas tanks vs. 4 cryo-compressed tanks
- Lawrence Livermore National Lab CcH_2 tank for buses
  - CF-wrapped alum. liner = inner vessel
  - 1.5-cm-thick vacuum gap + plastic MLI
  - 2-mm-thick, outer steel vacuum jacket
  - 31.5-cm diameter, 2-m length



Source| “The Storage Performance of Cryo-Compressed Hydrogen Vessels”, Lawrence Livermore National Lab, June 2018

Table 1. Supercritical CcH_2 Storage for Fuel Cell Buses

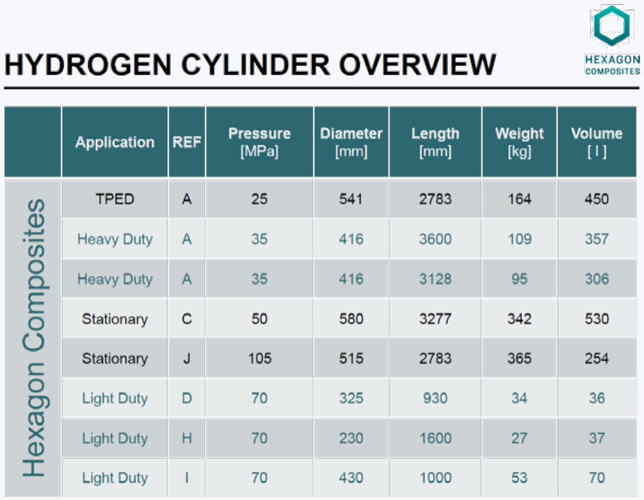


Storage Method	CcH_2	CcH_2	cH2
Storage Pressure	350 bar	500 bar	350 bar
Usable H_2	4 x 10 kg	4 x 10 kg	8 x 5 kg
Liner	2-mm SS	2-mm SS	7.1 mm Al
Storage Temperature	64 K	70 K	288 K
Storage Density	70.3 g/L	75.5 g/L	24 g/L
Gravimetric Capacity	9.6%	8.4%	4.4%
Volumetric Capacity	46.1 g/L	50.1 g/L	18.5 g/L
CF Composite	4 x 36 kg	4 x 53.1 kg	8 x 50 kg
Insulation Thickness	18.2 mm	10.3 mm	NA
Heat Gain	3.8 W	5.7 W	NA
Dormancy: 95% Full	7.0 d	7.0 d	NA
Cost	\$10/kWh	\$11/kWh	\$15/kWh

Source| “2018 Annual Progress Report, DOE Hydrogen and Fuel Cells Program,” pp. 200-203, Rajesh K. Ahluwalia, Argonne Nataional Lab

Compressed Gas Tanks

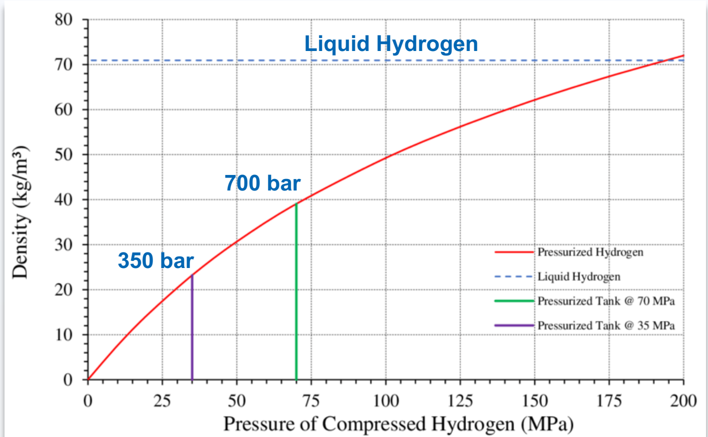
- 350 and 700 bar are standard, but there are others:
  - Universal Hydrogen 850 bar
  - NPROXX 300, 500 (TPED), 900 bar (PED)
  - MAHYTEC 60 bar (PED)
- Trade-off between H_2 mass/system mass, tank size, cost



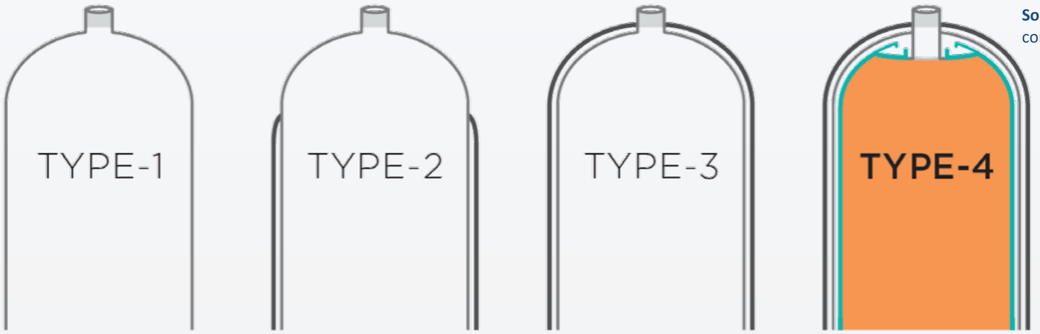
HYDROGEN CYLINDER OVERVIEW

	Application	REF	Pressure [MPa]	Diameter [mm]	Length [mm]	Weight [kg]	Volume [l]
Hexagon Composites	TPED	A	25	541	2783	164	450
	Heavy Duty	A	35	416	3600	109	357
	Heavy Duty	A	35	416	3128	95	306
	Stationary	C	50	580	3277	342	530
	Stationary	J	105	515	2783	365	254
	Light Duty	D	70	325	930	34	36
	Light Duty	H	70	230	1600	27	37
	Light Duty	I	70	430	1000	53	70

Source | Hexagon Composites company presentation, Feb 2019



Source | researchgate.net, Marshall Lee Crenshaw



TYPE-1	TYPE-2	TYPE-3	TYPE-4
All steel	Fiberglass hoop wrap steel liner	All carbon full wrap metallic liner	Fiberglass/carbon full wrap, plastic liner
(1.2-1.5kg/liter)	(0.7-1.4kg/liter)	(0.3-0.4kg/liter)	(0.25-0.35kg/liter)

"Hydrogen, however, is transported more effectively at higher pressures, which is why we developed the 7,500 psi (517 bar) Neptune tank." —Cimarron Composites

"500-bar pressure vessels deliver a good combination of volume-to-cost for the market." —NPROXX

NOTES: Transportable Pressure Equipment Directive (**TPED**) and **PED** (used for stationary tanks) are EU standards for tank requirements.

For Hexagon table, 35 Mpa = 350 bar and 70 Mpa = 700 bar

Compressed H2 Gas Tanks

- Issues: low volume, high cost
- 2017 DOE targets: -50% cost, 2X energy density

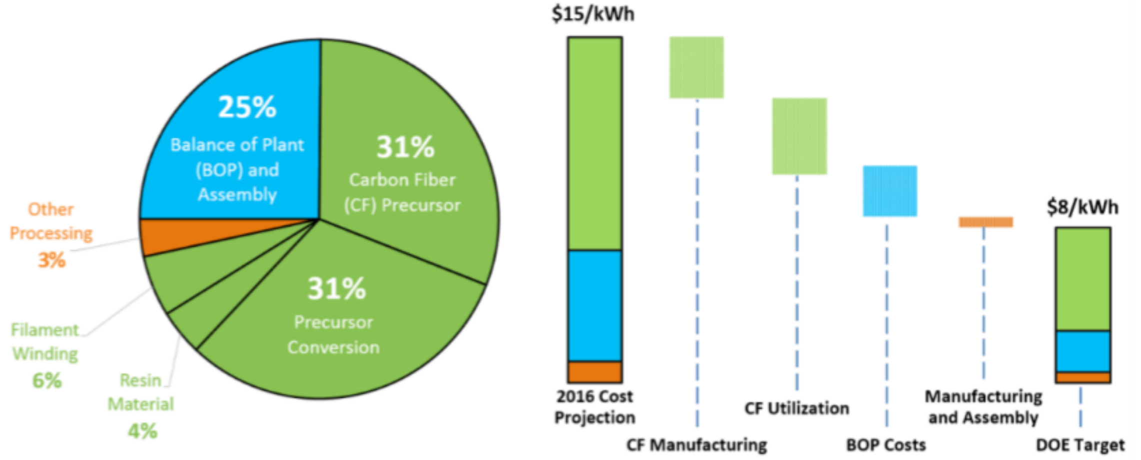


Figure 3: Potential strategy to meet cost target (700 bar cH2). To meet the ultimate cost target for 700 bar systems, the bulk of cost reductions must come from reducing the amount and costs of carbon fiber composite materials and Balance-of-Plant (BOP)

Source| DOE hydrogen storage fact sheet, 2017

2017 Targets – U.S. Dept. of Energy, Fuel Cell Technologies Office (FCTO)

Storage Targets	**Gravimetric kWh/kg (kg H_2/kg system)**	**Volumetric kWh/L (kg H_2/L system)**	**Costs [1] \$/kWh (\$/kg H_2)**
2020	1.5 (0.045)	1.0 (0.030)	\$10 (\$333)
2025	1.8 (0.055)	1.3 (0.040)	\$9 (300)
Ultimate	2.2 (0.065)	1.7 (0.050)	\$8 (\$266)
Current Status [2]			
700 bar compressed (5.6 kg H_2, Type IV, Single Tank)	1.4 (0.042)	0.8 (0.024)	\$15 (\$500)

[1] Projected at 500,000 units/year

[2] FCTO Data Record #15013, 11/25/2015:
https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

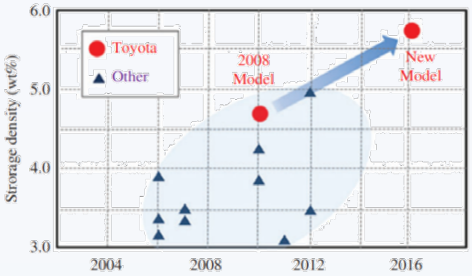
The full set of H2 storage targets can be found on FCTO's websites:
https://energy.gov/eere/fuelcells/downloads/doe-targets-onboard-hydrogen-storage-systems-light-duty-vehicles
https://energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles

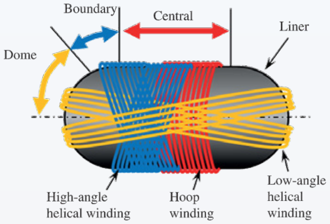
Source| Carbon Fiber Composite Material Cost Challenges, U.S. DOE, 2017

Reducing the cost of CGH_2 Tanks

- DOE/ORNL programs to reduce cost of PAN precursor and CF oxidation/carbonization
- Replace CF with glass or aramid fibers
- Toyota reduced CFRP by 20% for 5.7 wt% storage
  - ✓ Replaced aero-grade to new industrial grade fiber
  - ✓ Eliminated high-angle helical winding (≈25% of laminate)
  - ✓ Concentrated hoop winding at inner layers = highest stress
- Structural optimization
  - CIKONI claims 8.0 wt% storage possible
  - Cevotec cuts CFRP, time and cost 20% via FPP on domes
  - Universal Hydrogen cut resin via dry CF braid, aramid overwrap
- Alternative tank designs, processes
  - Conformable, chained tanks (e.g., BRYSON project)
  - HP-RTM of overbraided metal liner (BBG GmbH)
  - Faurecia aims to cut cost, weight and develop recyclable tank

Source | Cevotec





Source | Development of the Fuel Cell Vehicle Mirai, 2016

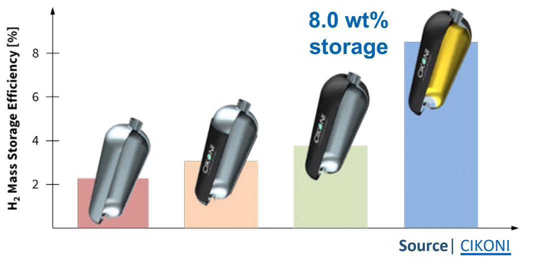
Source | TU Dresden, BRYSON project

Conformable 700 bar H_2 Storage Systems [CTE/HECR/UT/Stan Sanders]

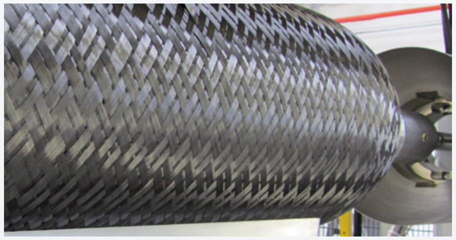
- Developing conformable 700 bar pressure vessels without use of carbon fiber composites
- Demonstrated vessel with a 34,000 psi burst (2345 bar), exceeding the 2.25 safety margin for 700 bar systems

Kevlar Over-Braided Coiled Vessels

Source | Carbon Fiber Composite Material Cost Challenges, U.S. DOE, 2017



Source | CIKONI



Up to 15 tanks with 50-mm-diameter can be molded simultaneously. Source | BBG GmbH & Co. KG

Opportunity for Carbon Fiber in Hydrogen Tanks

Assumptions and basis for calculations

- Carbon fiber in metric tonnes (MT) = (vehicle production) x (Gas H_2 tanks per vehicle) x (fiber weight)
  - No sales from liquid H_2 tanks assumed and projected vehicles assumed to use gas H_2 tanks
- T700 fiber or equivalent with epoxy resin
- Vehicle production data based on published government and industry figures
  - Smaller land vehicles will mostly use metallic tanks except in special cases
  - No aerospace activity in this timeframe is projected
- These projections are conservatively low
  - 2030 total H_2 vehicle projections are 1-7% of all current vehicle production
  - Excludes tanks for mobile pipeline/gas distribution, refueling stations and stationary power


Hexagon Composites Mobile Pipeline

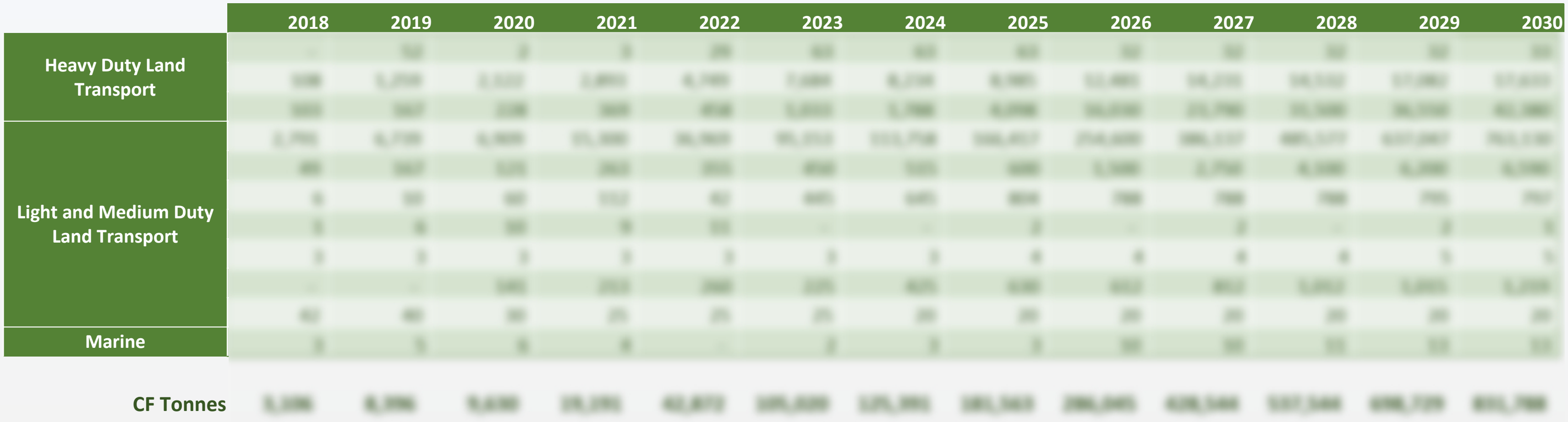
Source | pureenergycentre.com

Opportunity for Carbon Fiber in Hydrogen Tanks

- By 2023, carbon fiber in H_2 tanks **exceeds current 14,950 MT**[1] of carbon fiber into non-H_2 pressure vessels
- By 2028, carbon fiber in H_2 tanks **exceeds current 85,000 MT**[1] industrial carbon fiber market
- By 2030, carbon fiber in H_2 tanks **exceeds projected 142,350 MT**[1] industrial carbon fiber market for 2025

[1] *(AJR Consultancy forecast,* ***CW*** *2019 Carbon Fiber conference)*

Global Hydrogen Vehicles



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
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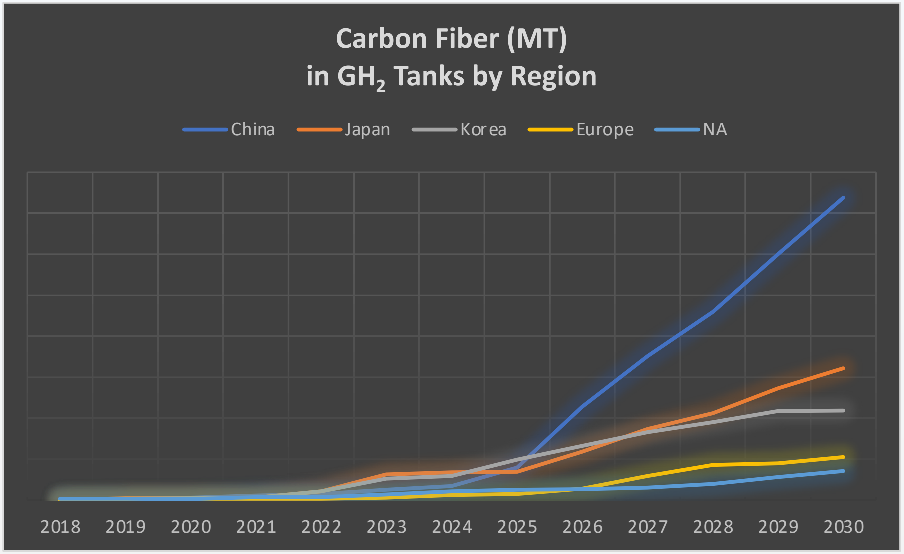
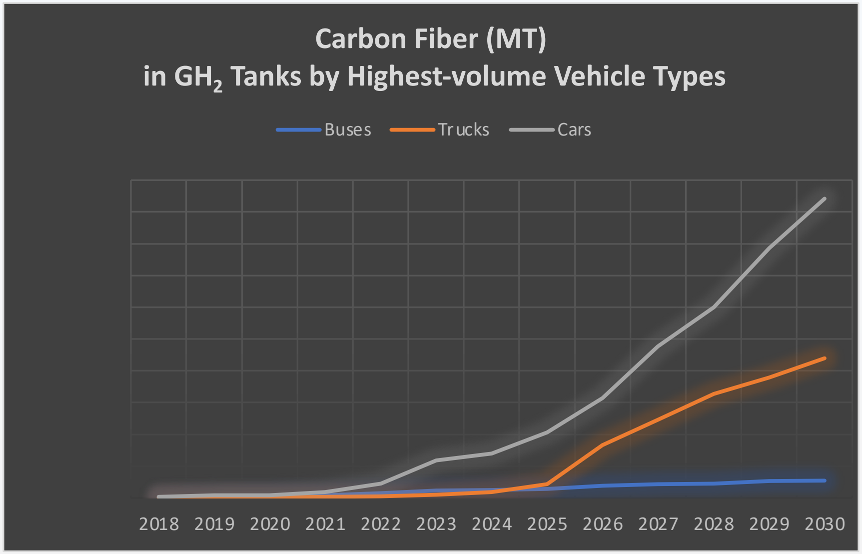
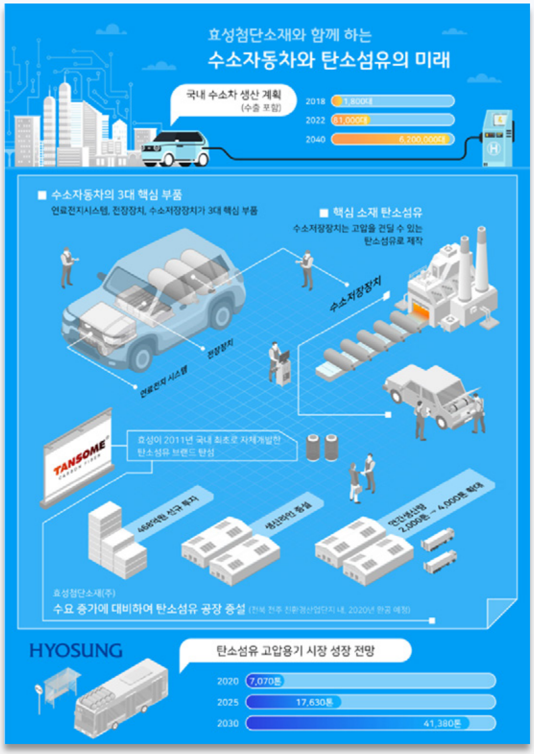
Carbon Fiber in GH_2 Tanks by Region and Vehicle

- Largest FCV production markets are in Asia and for cars
- U.S. is lagging due to lack of government strategy/investment with only market from California regulations





Carbon Fiber Manufacturers



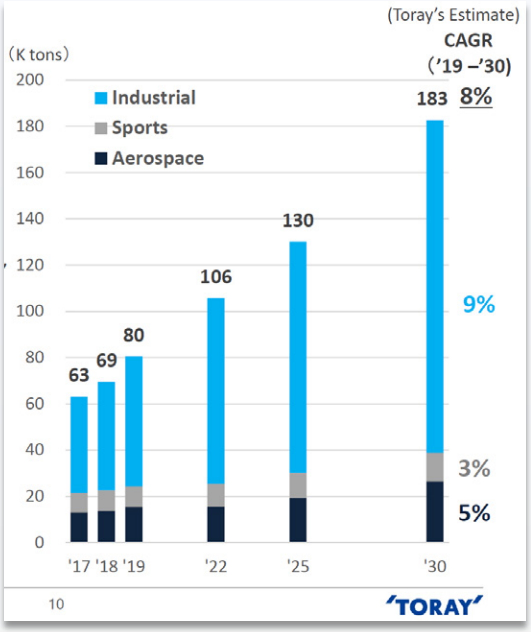
Source| Hyosung news Feb. 11, 2019

Toray

- "In addition to increased adoption of carbon fibers for wind turbine blade applications due to its size increase, hydrogen tanks and FC substrates have grown into major applications with the spread of FCVs."
- "Set **CHG tanks as the highest priority strategic application** and preferentially **allocate resources for development.** Add high-performance and reduce costs of carbon fibers, and add high-function to matrix resins"

Hyosung

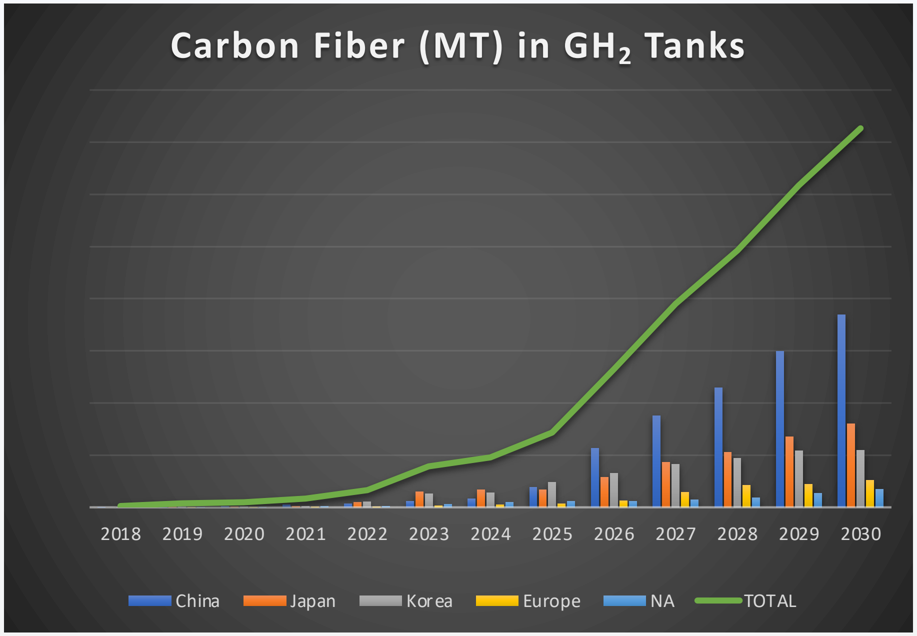
- Increase capacity from 1 line (2,000 tons) to 10 lines (24,000 tons) by 2028.
- "This expansion is part of efforts to prepare for increasing demand for carbon fiber, … a core material for hydrogen and CNG vehicles, …
By 2030, hydrogen fuel tanks and CNG high-pressure vessels are expected to grow 120 times and more than four times, respectively."



Source| Medium-term Management Program by Deputy General Manager, Torayca & Advanced Composites Division, June 2020

Conclusion

- The hydrogen tank market is promising but not assured
  - High cost of CFRP GH_2 tanks
  - Drive for increased H_2 mass and storage efficiency
  - Need for recyclability
  - R&D for metal LH_2 and cryo-compressed tanks as well as chemical/solid storage will continue and advance
  - TARGETS: cut tank cost by 75%, achieve storage system target cost of $8 kWh
  - Futher markets could be opened, including refueling stations, marine vessels and aviation



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