Bjorn’s Corner: The challenges of Hydrogen. Part 1. Background.

leehamnews.com/2020/07/24/bjorns-corner-the-challenges-of-hydrogen-part-1-background/

July 24, 2020

July 24, 2020, ©. Leeham News: What a difference three months make!

By Bjorn Fehrm

When I wrapped the 20 piece Corner series about e in ePlane not standing for electric, on the first of May, I was virtually alone in saying hydrogen is the best long term alternative to our airliners’ jet fuel.

Today it’s all about hydrogen, especially if you ask industry and authorities in Europe. What happened?

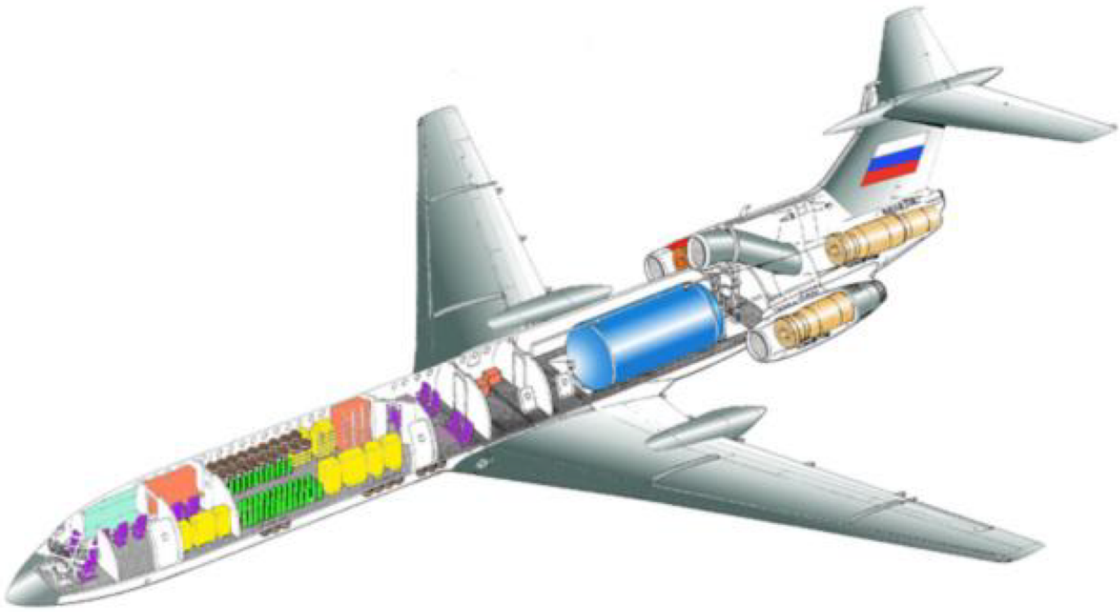


Figure 1. The Russian Tu-155 hydrogen fuel research aircraft that flew in 1988. Source: Tupolev.

Why hydrogen is now the focus for sustainable airliners

What happened? How can a World-wide conviction the next non-jet fuel airliner is electric turn to hydrogen in just three months? The actual turn has taken a bit longer but it happened fast. Let’s go through why.

It was all in our ePlane Corner series. There we concluded:

- We have a mounting environmental problem where global warming is the pressing one right now. The key action needed is to lower the CO_2 emissions from our burning of fossil fuels for heating, industrial production, and transport.
- Though air transport is 2% of the problem, it's part is growing and it's highly visible. Action is needed in all areas and this includes air transport.
- To lower our CO_2 emissions we must stop burning the stored energy in our fossil fuels. The dominant alternative energy store for vehicles is the battery.
- But there are problems with planes that use the battery as an energy store. Its energy density (the amount of kg battery for each kilowatt-hour stored) is way to low for airplanes. It makes our cars more efficient only because our normal cars are such energy hogs, with an energy efficiency below 10%. When over 90% of the stored energy in the fuel is not used, it's not difficult to find ways to improve. With such a low bar for improvement, battery-based solutions work.
- Airliner propulsion system efficiency passes 50% as we speak and the goal is to achieve 60% or more. This raises the bar for any competing propulsion technology to a level where batteries can not be part of the solution.

Why didn't the aeronautical community realize that batteries are not an option for airliners?

Other developments gave hope and the early movers didn't have the experience to see the challenges the airliner application presented.

What happened over the last decade was the electric and hybrid car went from a curiosity to the mainstream. The classic car makers were cornered by Tesla (100% battery) and Toyota (battery-based hybrids). Entrepreneurs wanting to be the new Elon Musk predicted the same change would happen for aircraft. After all, aircraft are driven by combustion engines, as are cars.

Those who set about cornering the aircraft industry and create the aircraft industry's Tesla or SpaceX didn't do their homework before presenting their Powerpoint projects. Promises of new battery-driven airliners taking over from the Boeing 737 MAX and Airbus A320 before 2030 and being 30% more efficient occupied the industry magazine pages over the last years.

Gradually, experienced airplane designer teams from the OEMs made the sums (as did I) and the impossibility of achieving anything usable with present battery technology became clear. Then investigations into progress in battery technology showed it would be a struggle, even for a short-range airliner. There’s a huge difference between the performance of a research lab battery and what can be certified as an airliner propulsion battery system.

The focus then turned to hybrids. While it was possible to make it work, the same seasoned people saw it would not bring any real gains as long as batteries were the complementary energy store to jet fuel. A very little gain for substantial technical complexity and risk.

The key realization over the last year was the battery as an energy store for airliners didn’t cut it. Not today, not tomorrow, and probably not in the foreseeable future.

The alternative energy store that was continuously looked at was Hydrogen, H2. It was the fuel the world’s first jet engine used (H. von Ohain’s He S-1 engine in 1937) and it was the fuel used in the Russian Tu-155 hydrogen research airliner in 1988, Figure 1.

It has some very attractive features like three times higher energy density than jet fuel (batteries have 70 times worse) but also challenges like four times worse volume density and a non-existent production ecosystem for air transport.

In the next Corners, we dig deeper into the challenges for H2 and the possible solutions to handle them.

PS. For anyone that wants to revisit the ePlane articles, go to our search box, top right, and enter “ePlane”. The series is then listed with all the parts. DS.

Bjorn's Corner: The challenges of Hydrogen. Part 2. Ecosystem.

leehamnews.com/2020/07/31/bjorns-corner-the-challenges-of-hydrogen-part-2-echosystem/

July 31, 2020

July 31, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliner use we begin by looking at the needed ecosystem that can produce and distribute Hydrogen.

By Bjorn Fehrm

When I was skeptical about hydrogen as a means to propel our airliners three years ago, the main problem was the lack of this ecosystem. That year, in 2017, 13 transport and energy companies formed the Hydrogen Council, to create this ecosystem. Today the council has 81 members, with 22 joining in the last year, Figure 1. The list reads as Who's Who in the transport and energy sector.

Figure 1. Members of the Hydrogen Council. Source: Hydrogen Council.

The hydrogen ecosystem is gaining momentum

Here the charter of the Hydrogen Council:

The Hydrogen Council is a CEO-led global initiative of leading energy, transport and industry companies with a united vision and long-term ambition for hydrogen to foster the energy transition. The coalition of 81 members including large multinationals, innovative SMEs and investors *collectively represent total revenues of over €18.7 trillion and close to 6 million jobs around the world. The coalition has more than quadrupled in size since its founding in 2017 by 13 members.*

This grouping has the necessary incentive, knowledge, and firepower to establish the production and distribution capacity for ramping of a Hydrogen energy ecosystem.

EU has through it’s Clean Sky initiative sponsored a study of a Hydrogen powered aviation that was published last month, Figure 2.

Figure 2. The EU sponsored study for Hydrogen-powered air transport. Source: Clean Sky and EU.

It had Airbus and Boeing as participants, and several members from the Hydrogen Council contributed to the report. It has the latest information on several topics around Hydrogen for air transport and we will quote from it as we go forward.

Our first extract is around the capability to support a change to Hydrogen for parts of the airline fleet until 2050 (the report sketches two scenarios for the Hydrogen ramp, an aggressive and an, in my opinion, more realistic ramp):

In the two scenarios, the global demand for hydrogen would reach approximately 10 or 40 million tons of LH2 by 2040 per annum, and approximately 40 or 130 million tons by 2050. This amount represents 5 or 20 percent of the total global demand for hydrogen projected by the Hydrogen Council by 2040, and 10 or 25 percent of global demand by 2050.

We see that the lower projection represents 5% of global Hydrogen production by 2040 and 10% by 2050, fully realistic quantities.

One of the contributors to the report is the French company Air Liquide, with experience around Hydrogen as fuel through among other sectors, the space launcher area. Here what it says about its aircraft Hydrogen research and experience:

Air Liquide has been working on introducing hydrogen in aviation since the early 2010s. A project supported by the European Union (EU), launched in 2013, demonstrated the feasibility of an airborne gaseous hydrogen tank to power fuel cells. It has clearly demonstrated gaseous hydrogen was not the solution for the propulsion of aircraft, given the large quantities required (several tons aboard) and that liquid hydrogen (LH2) is the only way forward.

We now believe that it is urgent to use flight demonstrators as the principal means of evaluating, maturing and validating the technology and the procedures required to use liquid hydrogen. This is the goal of the Heaven project, granted by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), where Air Liquide is in charge of the storage while the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) will modify its existing “HY4” R&D platform by switching from a gaseous to a liquid hydrogen storage. The first flight will occur in 2022 and it will be the world’s first passenger aircraft powered by fuel cells fed with liquid hydrogen.

The announcements from the French and German governments where they support the development of a Hydrogen ecosystem and the first Hydrogen fueled aircraft until 2035 shall be seen in the context of European participation in the Hydrogen Council and different EU research programs.

There has been a lot going on behind the scenes around Hydrogen in the last year. The announcement on the 10th of June by the French Government that they support their industry with €15bn investments for, among other items development of the first Hydrogen powered airliner, was carefully coordinated with industry partners and the EU.

Bjorn’s Corner: The challenges of Hydrogen. Part 3. Application space.

leehamnews.com/2020/08/07/bjorns-corner-the-challenges-of-hydrogen-part-3-application-space/

August 7, 2020

August 7, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we now look at the emission targets one is chasing and then discuss for what type of airliner does a hydrogen propulsion system make sense.

By Bjorn Fehrm

The CO2 emission target as expressed by Air Transport Target Group (ATAG) is shown in Figure 1. The graph is from the EU report on Hydrogen Powered Aviation.

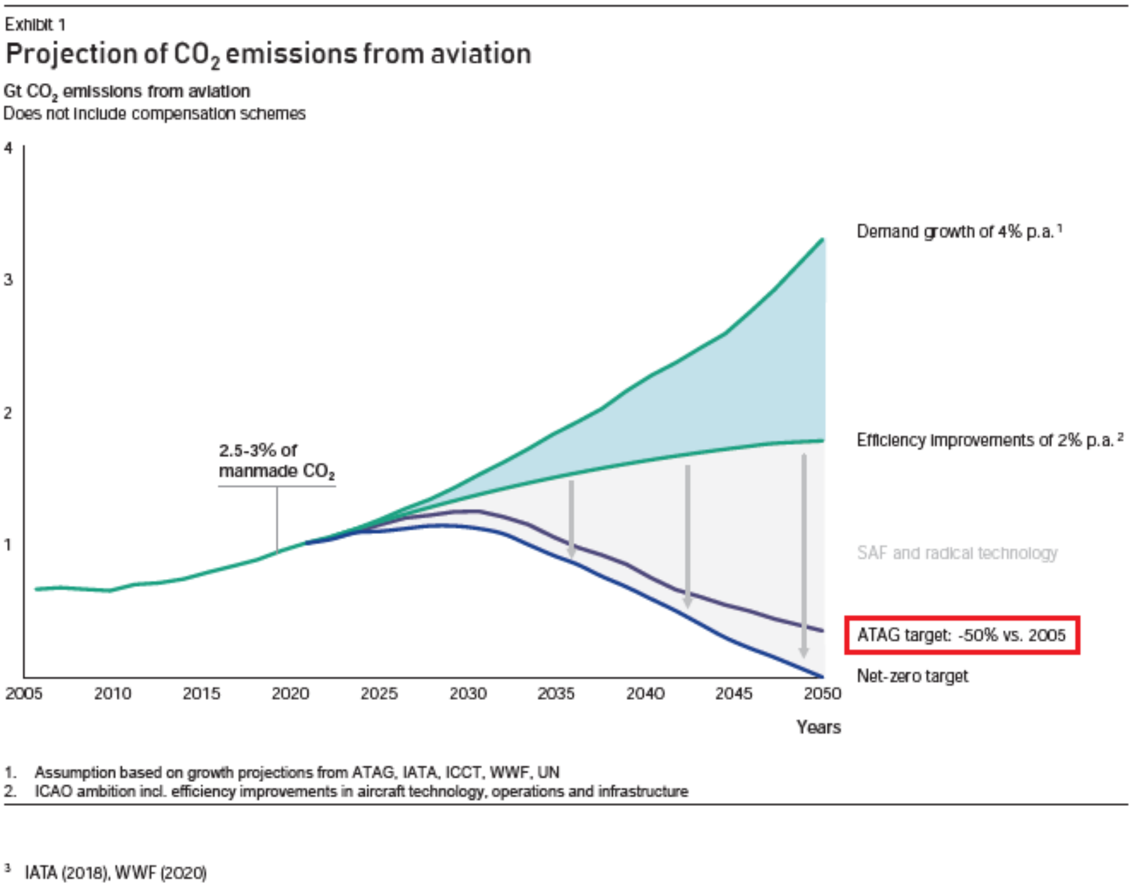


Figure 1. The development of CO2 from aviation and the ATAG 2050 target. Source: EU Hydrogen Powered Aviation report.

The emission target for Air Transport

Figure 1 shows we were on route to increase the air transport CO2 emissions to about double the 2018 value by 2050 if the traffic had developed without the COVID pandemic. This assumes a 2% improvement of airliner efficiency per year (the present trend is about 1.5%/year).

The target as defined by ATAG is to halve the emissions level from 2005 by 2050. This is a sporty target as we only have 30 years to achieve it.

We need to prioritize the first moves to focus our innovation and development resources where they bring maximum effect.

The sweet spot for lower emissions

We shall focus the first airliner development for a segment that suits the constraints of a hydrogen powered airliner (the energy will take more space) at the same time as we achieve a maximum effect on the emission curve in Figure 1.

Figure 2 shows the hot spot of emissions to be in the segment between 81-165 seaters and the next segment 166-250 seaters.

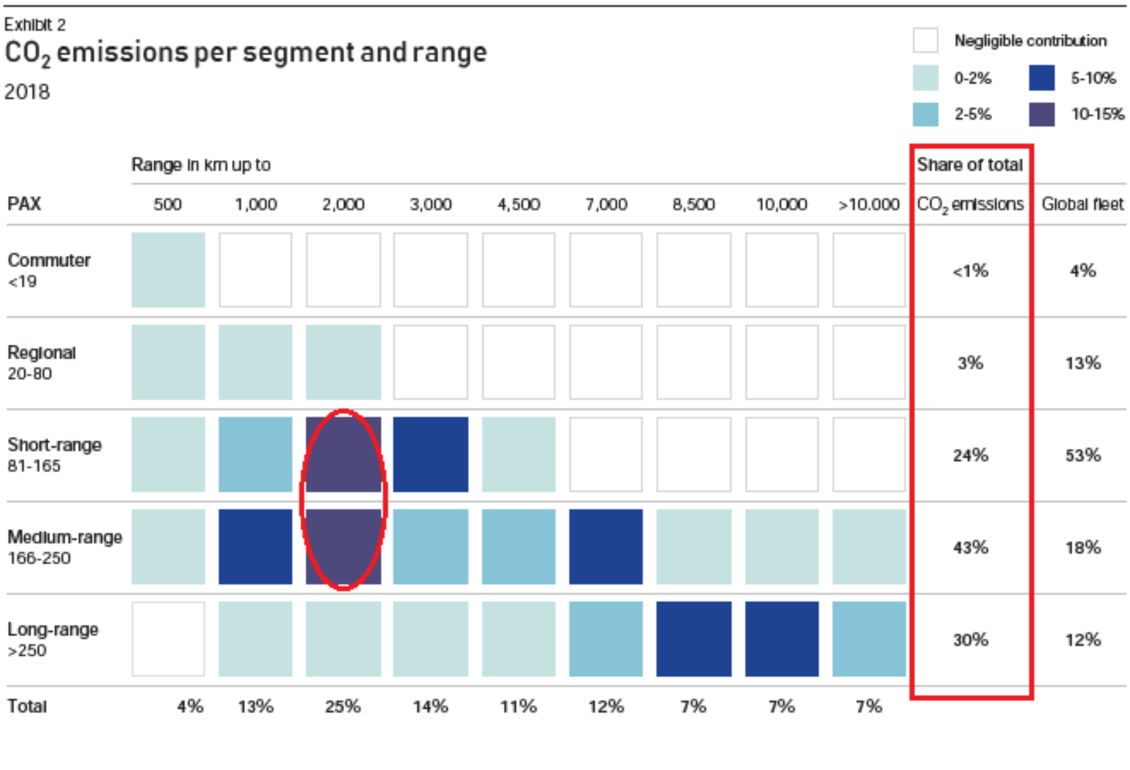


Figure 2. CO2 emissions per aircraft type and range flown. Source: EU Hydrogen Powered Aviation report.

The reality is easier than that. The Boeing 737-800/8 and Airbus A320ceo/neo dominates this segment, and these have 150 to 180 seats dependent on when a cabin update was made. They represent 11,000 of the

25,000 airliners that fly in our skies (in normal times). The other members of these airliner families represent a much smaller part of the segment.

So we should focus a hydrogen-powered airliner at the segment of 165 seats plus any increase in seating that follows from now and to 2035 when it shall be introduced. In fact, we shall size it for its first ten years in service, not the year of entry into service.

We can also see the range sweet spot is between 500nm and 1500nm. This is important as LH2 has three times higher energy content per kg (which is good) but it takes four times the volume of jet fuel (which is problematic).

It will help us if we let the over 2,000nm range segment be flown with the jet-fuel powered aircraft in the segment. This range segment is not the center of emission and it will skew our aircraft to an inefficiently large LH2 storage tank if we try to cover these routes.

Conclusion, aircraft size and range

For the development of a hydrogen airliner that shall start bending the CO2 curve down by 2035, we shall focus the seating segment that represents the 165 seat aircraft of today. Would it be 180 seats (one seat up per year)? Perhaps, with the damping effect of the pandemic, we might land there.

We see from Figure 2, there is no point in going for the easier to achieve regional hydrogen airliner. We burn our powder without bending the emission curve appreciably.

As for range, we shall go for the sweet spot there as well. A practical 1,500nm range which equals a maximum trip length of three and a half hours, means we need a nominal range of around 2,000nm (for in-service deterioration and ATC/weather margins).

By avoiding going after the routes over 1,500nm we make the sizing of the hydrogen propulsion system easier and we wouldn't gain much in emission suppression by sizing for longer range for the first project.

Bjorn's Corner: The challenges of Hydrogen. Part 4. Hydrogen safety.

leehamnews.com/2020/08/14/bjorns-corner-the-challenges-of-hydrogen-part-4-hydrogen-safety/

August 14, 2020

August 14, 2020, ©. Leeham News: In our series on hydrogen as an energy store for airliners we are closing in on the design problems for a hydrogen-fueled airliner.

By Bjorn Fehrm

One of the aspects we must understand before discussion aircraft solutions are the safety aspects of hydrogen as a fuel in aircraft. Another is the requirements for the storage of liquid hydrogen, LH2.

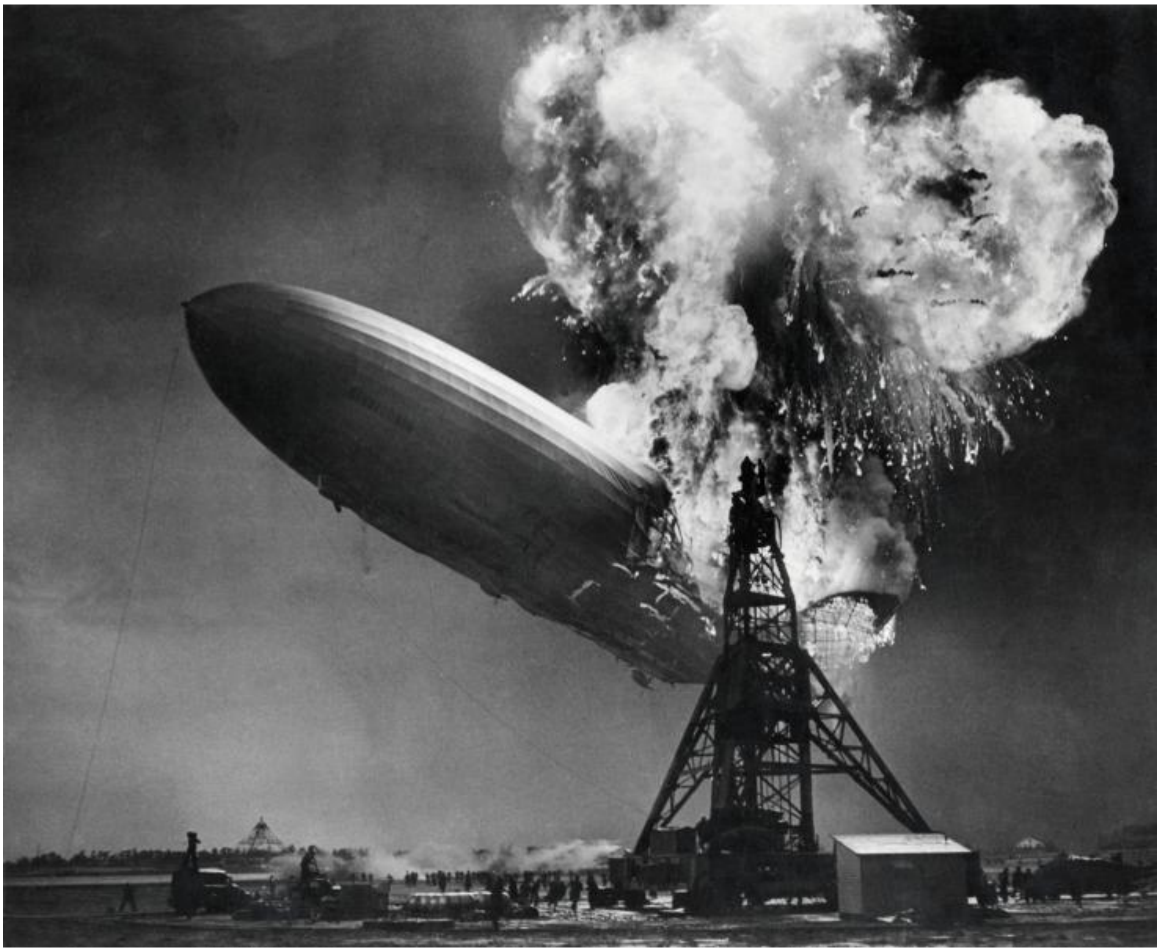


Figure 1. The Hindenburg disaster at Lakehurst in May 1937. Source: Wikipedia.

The safety of hydrogen as a fuel for aircraft

When one thinks about hydrogen-fueled aircraft, the airship Hindenburg catching fire when landing at the Lakehurst Naval Station, NJ, comes to mind, Figure 1. The immediate reaction is: it seems dangerous, which is the wrong impression.

Hydrogen as a fuel has been used over the last 100 years for many vehicle types. One example is the space launcher industry. Others, where its use is growing, are cars, buses, trucks, forklifts, etc. For each area, there were extensive safety studies and tests before its use.

The elevator version of the results is**:**

It’s not more dangerous than hydrocarbon fuels like car gasoline or Jet-A1.

Figure 2 is from a good 2009 graduate research project by Adam D. Reiman at the US Air Force Institute Of Technology. He’s studied LH2 as an alternative to the US Air Force’s JP8 fuel (Jet-A1 with corrosion and anti-ice additives) for it’s Air Mobility Command.

His literature study examined all relevant work around hydrogen-fueled vehicles up to the reporting year of 2009. The report contains several tables comparing the fuels’ different aspects, where Figure 2 is the one comparing the safety aspects of JP8 to hydrogen.

Hydrogen vs JP-8		
Safety		
Item	**Information**	**Advantage**
Detonation	Gun shot tests into liquid hydrogen tanks failed to result in detonation. Heavy impact tests of liquid hydrogen tanks failed to result in detonation. Detonation of a perfect mixture of hydrogen and air only takes place with a strong detonator, but it is improbable that a perfect mixture of hydrogen and air will occur at the time of a strong detonation. JP-8 has a lower detonability limit in air as a percentage of volume than hydrogen. (Brewer, 1991)	Hydrogen
Emissivity	Hydrogen has a lower emissivity than JP-8 making the thermal radiation during a fire less. If a large hydrogen spill occurs outside an aircraft, remain inside for the heat will not be likely to enter the fuselage due to the low emissivity. (Brewer, 1991)	Hydrogen
Frost Bite	Contact with minute amounts of liquid hydrogen can lead to severe frost bite, while JP-8 poses no frostbite hazard. (Praxair, 2007)	JP-8
Fuel Spills	Hydrogen evaporates much more rapidly than JP-8 and if ignited burns quicker than JP-8. A 12,600 kg hydrogen fuel spill will dissipate in 32 seconds, while a similar volume of JP-8 would take closer to 13 minutes. (Brewer, 1990)	Hydrogen
Ignition Temperature	Hydrogen has a higher autoignition temperature than JP-8, but a lower temperature in an air mixture. A lit cigarette will not ignite in pure hydrogen although it could light a hydrogen-air mixture. A lit cigarette could ignite JP-8. (Brewer, 1991)	JP-8
Invisible Flame	Hydrogen can be a burn hazard due to invisible flame, while JP-8 has a visible flame. (Praxair, 2007)	JP-8
Suffocation	The high diffusion rate of hydrogen can rapidly replace the oxygen in an unventilated room leading to possible suffocation, while JP-8 poses a lesser suffocation hazard. (Praxair, 2007)	JP-8
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic. (Dfdl, 2001).	Hydrogen

Figure 2. US Air Force University Graduate Research Project. Source: D. Reiman US Air Force.

Airbus' Cryoplane study from 2001 comes to the same conclusions, Figure 3.

- **Psychological problem primarily.**
- **In free atmosphere, hydrogen rises quickly, hence small danger zone if hydrogen leaks out/ is spilled.**
- **Hydrogen will burn at concentrations significantly below the limit for detonation.**
- **No detonation in free atmosphere.**
- **Will not form a fire carpet.**
- **Fast burning, very low heat radiation.**
- **Not toxic. Combustion products not toxic.**

Figure 3. Safety of hydrogen as a fuel for airliners. Source: Airbus' Cryoplane report.

The bad image of hydrogen safety comes from the Hindenburg crash. The reality is that it's in several aspects better than today's jet fuels. It has characteristics that must be considered, but this applies to all fuels.

A leak will quickly evaporate, hence any leakage when fueling will benefit from the fast evaporation in free air, where H2 is a non-toxic substance. Leakage in closed compartments like tank and fuel system areas need detectors and ventilation safeguards.

The detonation risk is lower than with Jet-A1 and a fire burns quickly, with less heat than for Jet fuel. The fire is invisible, however, which is a problem.

Cryogenic tanks

We have learned we need LH2 (liquid hydrogen) to keep the storage volume down for airliners. This requires cryogenic tanks, where the LH2 is held at -253°C. This means double wall tanks, spherical or cylindrical, with isolation between the walls. We only need about one-third of the Jet-A1 fuel weight but it will take four times as much volume as this weight of Jet-A1 would take.

Jet kerosene as fuel has the advantage to use the wing structure as tanks (carefully sealed), which means it's placed close to the center of lift and gravity, and the structure holding it is almost for free. For hydrogen, this will be difficult as it requires cylindrical tanks, and these will have a too large diameter to store in the wings (dividing the hydrogen over many tanks is not efficient).

Most studies have the tanks in the fuselage, above or aft of the passenger compartment.

Figure 4. Airbus Cryoplane study with tanks above the cabin for the A310 and on the wing for Do 328. Source: Airbus.

In Figure 4 an Airbus A310 has the tanks above the cabin (from the 2001 Cryoplane study). The study also looked at a regional Do 328 where the tanks were placed on the wings.

Bjorn's Corner: The challenges of Hydrogen. Part 5. The Hydrogen tank.

leehamnews.com/2020/08/21/bjorns-corner-the-challenges-of-hydrogen-part-5-the-hydrogen-tank/

August 21, 2020

August 21, 2020, ©. Leeham News: In our series on hydrogen as an energy store for airliners we start the design discussion of a hydrogen-fueled airliner by understanding the onboard storage of hydrogen better.

By Bjorn Fehrm

While there is present knowledge from for instance the space launcher industry, the storage demands for launchers are hours rather than days. Several implementations of longer storage aeronautical tanks have been done, among others by NASA/Boeing for high flying UAVs.

Airbus and the Russian aircraft industry were also active with research during the 1990s and Tupolev built a test aircraft that included a complete hydrogen fuel system (Figure 1).

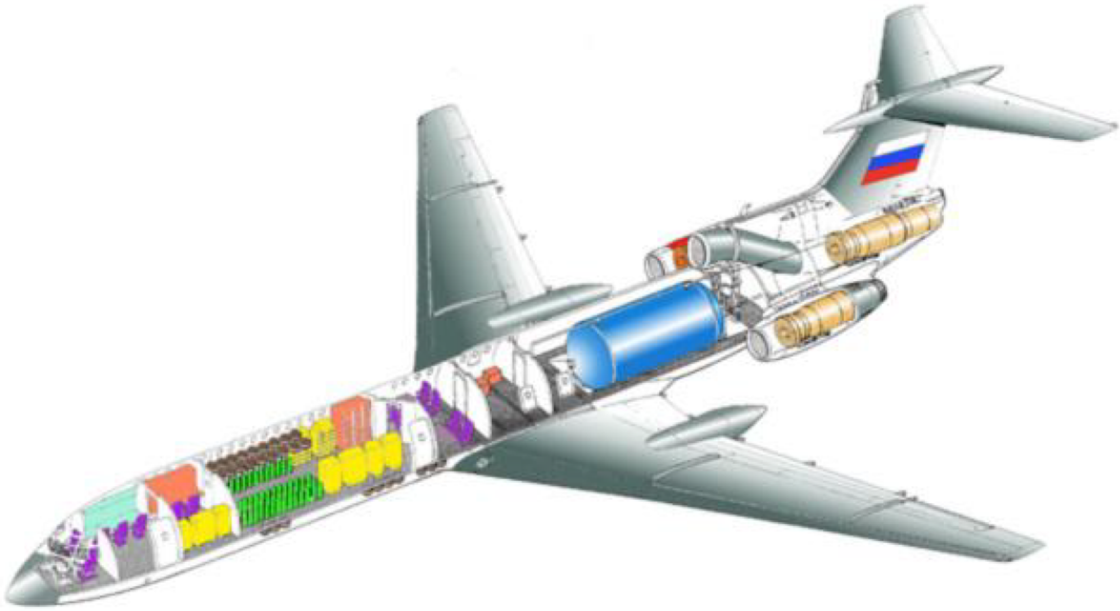


Figure 1. The Tu-155 Hydrogen research aircraft. Source: Tupolev.

How to store hydrogen efficiently on airliners?

We will discuss the tank design for liquid hydrogen (LH2) in this Corner. It's the area that forces a major change compared to the airliners as we make them today, and the subject has enough variables that we focus the aircraft fuel system in the next Corners.

Hydrogen is the most common chemical substance in the universe. It melts from solid material to liquid at 14K (-259°C) and boils to gas at 20K (-253°C). It means, unless we want to store it under extreme pressure (which is not weight efficient for an aircraft), we need to store the LH2 between 14K and 20K in our tanks.

For cars, buses, trucks, and forklifts it's commonly stored in gas form at ambient temperature in pressure tanks of 350 or 700 bars (35 or 70 MPa, 5 kpsi or 10 kpsi).

As discussed, this is too volume inefficient for airliners and we, therefore, store hydrogen in its liquid phase as LH2. This means we need to figure out how we keep hydrogen below 20K in the tanks. You do it by insulating the tanks extremely well.

The common designs are an inner liner that can sustain the characteristics of LH2 (among others no permeable leakage and no embrittlement), followed by an insulation layer to keep the fluid at the below 20K it has when filled from the fueling truck.

This is not possible for all parts of the tank over a longer period. At parts where the temperature exceeds 20K, hydrogen will boil off and there will be a top layer in the tank of hydrogen gas, Figure 2.

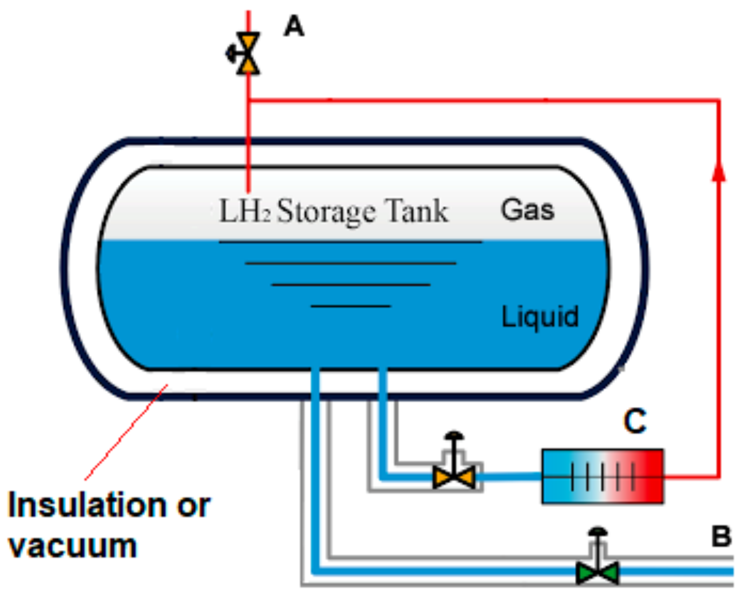


Figure 2. Typical liquid hydrogen tank. Source: Fullcryo.

A certain loss of hydrogen is accepted, the boil-off factor, which is less than a percent per day for well-insulated tanks. The boil-off gas also replaces any LH2 that has been consumed from the tank through B.

The gas is not allowed to build high pressure in the tank, above a fraction of a bar a pressure relief valve will vent the hydrogen to the surroundings or to for instance a hydrogen fuel cell system that replaces the APU in the aircraft (A in Figure 2).

To keep the fuel cell feed when the boil-off is not sufficient, a path from the liquid side with a liquid-to-gas heat exchanger is included at C.

The inner tank (the liner) is typically aluminum, with a foam style insulation or a vacuum chamber on the outside. Designs that use a vacuum layer have an insulation layer on top. The vacuum functions according to the Dewar or thermos principle to reduce heat transfer to the LH2 area. The additional insulation is a safety measure in case the vacuum is lost. Without the insulation layer, the boil-off in the tank would be strong, creating a potentially dangerous outflow of gas.

As hydrogen gas is a non-toxic gas it can be vented to the atmosphere for any excess or leaked gas. Schemes where the boil-off gas is re-liquified by cooling, such as the storage tanks for missile launcher sites, are appearing for stationary longer-term storage, Figure 2.

(We use the word Cryogenic a lot in this series, it also appears in Figure 2. Here its meaning from Wikipedia: *In physics, cryogenics is the production and behavior of materials at very low temperatures.)*

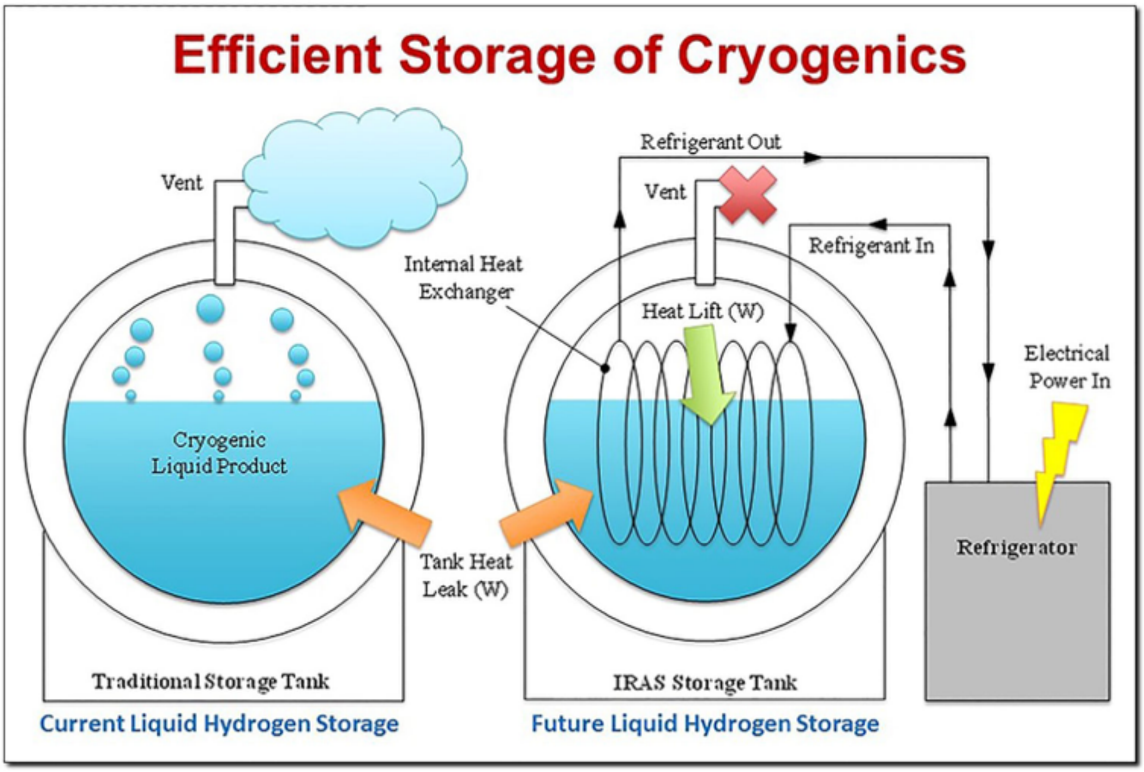


Figure 2. Traditional and future LH2 storage at launcher sites. Source: NASA.

It has not found its way to airborne tanks yet, the system complexity and weight doesn’t pay off for missions of up to 15 hours.

There are several reasons why efficient tanks have spherical or cylindrical or near-spherical/cylindrical shape:

- The key characteristic of a tank is its low heat leakage, which depends on the external surface area to contained volume. This ratio is minimal for a sphere. The next practical and efficient shape is a cylinder.
- The tank shall endure pressure variations from internal hydrogen gas and the external atmosphere as the tanks are normally placed outside the pressurized area of the aircraft. An aircraft cycles from 1 bar to 0.2 bar (14.5 to 2.9 psi) external pressure and 20-30°C to -65°C several times a day, creating a material fatigue problem. Round shapes handle such pressure variations best.

The insulation of the tank is designed to give the desired heat transfer for the storage of a day or so. For longer parking of the aircraft, the LH2 is returned to the airport tanks via the tanking trucks.

In the next Corner, we look at tank placement and compromises in tank shape.

Bjorn’s Corner: The challenges of Hydrogen. Part 6. Tank placement.

leehamnews.com/2020/08/28/bjorns-corner-the-challenges-of-hydrogen-part-6-tank-placement/

August 28, 2020

August 28, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we look at the challenge of placing the hydrogen tanks efficiently.

Different from carbon fuels, liquid hydrogen needs specially shaped and bulky tanks. It can’t be stored in the wingbox as today’s Jet-A1.

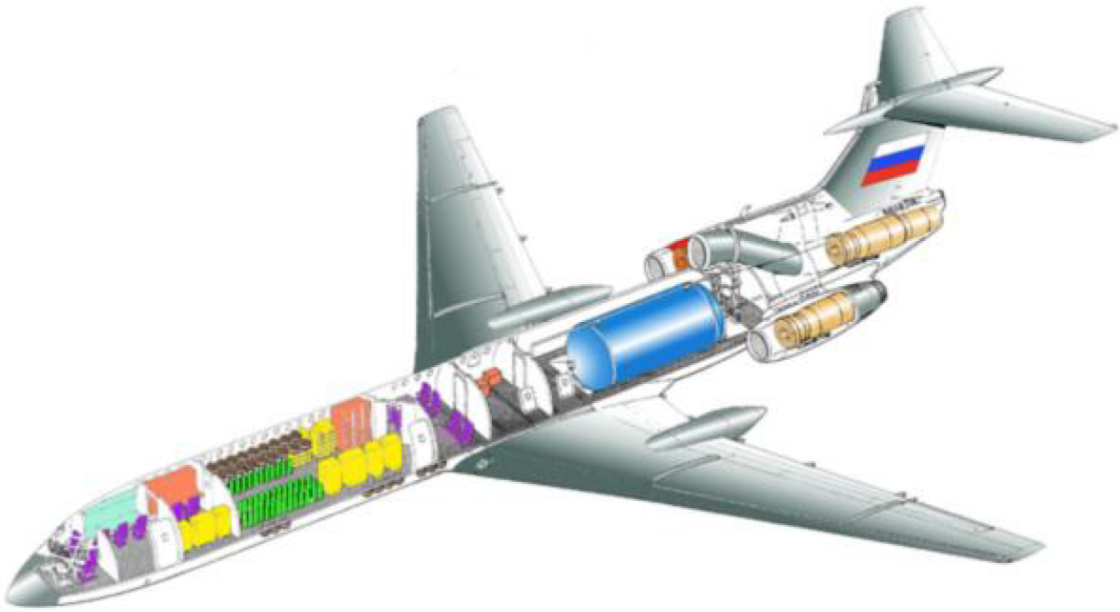


Figure 1. The Tu-155 Hydrogen research aircraft with its aft fuselage tank. Source: Tupolev.

Where to put the liquid hydrogen tanks on an airliner?

After discussing the need for a cryogenic (a very low temperature, -253°C), low pressure, tank-type in last week’s Corner we now look at the placement in the aircraft.

Our present hydrocarbon fuel, Jet-A1, is stored in the void space formed by the wing’s central structural element, the wingbox, Figure 2.

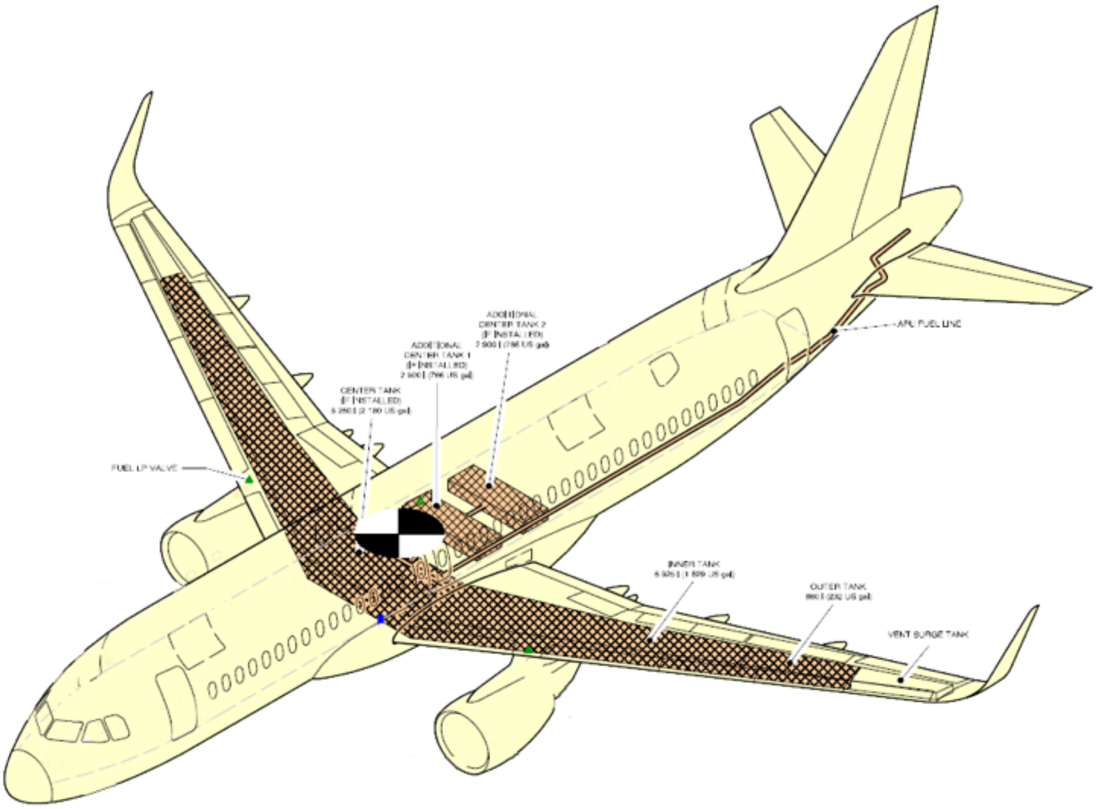


Figure 2. The placement for the fuel tanks on an A320. Source: Airbus.

I've added the approximate placement of the Center of Gravity (CG) of an A320 (approximate as it varies between ~15% and ~40% of the mean aerodynamic chord) as a circle with black and white sectors.

Observe how the fuel is positioned around the CG, with the center tank slightly ahead and the outer tanks slightly behind the CG. Extra center tanks are also placed as close as possible to the CG.

It's all to minimize the change in CG during flight as the tanks go from filled to empty. With fuel management among these tanks, where the center tank is emptied first, the CG variations during a flight are kept small.

A typical two-hour mission for these aircraft (an 800nm trip for A320/737-8), consumes four tonnes of fuel whereas a four-hour mission takes 7.5 tonnes (a 1,500nm air distance trip).

If we assume that a hydrogen version of such an aircraft consumes 35% weight wise of what a hydrocarbon fueled aircraft consumes, we have a consumption of 1.4 tonnes LH2 for the short trip and 2.6 tonnes for the long trip.

We don't want this variation to take place too long from the center of gravity of the aircraft.

The tanks are heavy, typically two to three times the LH2 weight, but this can be outbalanced statically by moving the wing forward-aft on the aircraft.

For short-haul aircraft, where the fuel weight variation is small in relation to total aircraft weight, an aft tank can be accepted, Figure 3.

Figure 3. For short-haul aircraft an aft tank placement is acceptable. Source: Airbus.

As we progress to larger aircraft where the variation of LH2 weight is a larger portion of the total weight of the aircraft, we start to place the tanks so LH2 can be pumped around to keep CG variations within limits, Figure 4.

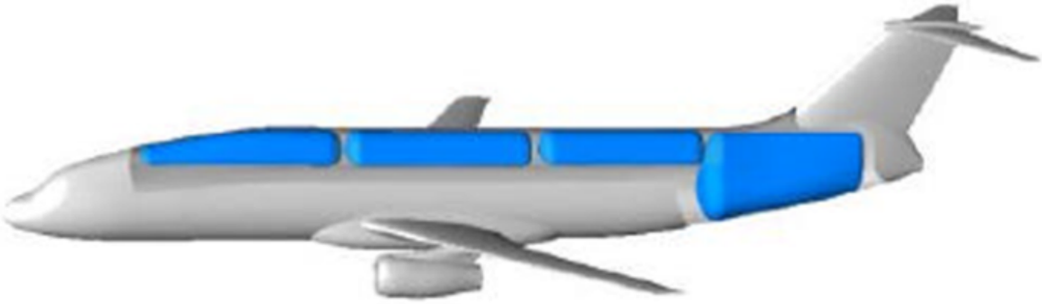


Figure 4. LH2 tank placements for a short/medium range airliner. Source: Airbus.

The ideal placement of tanks is fore and aft in the aircraft fuselage. Figure 5 describes tank placement in a large long-range aircraft.

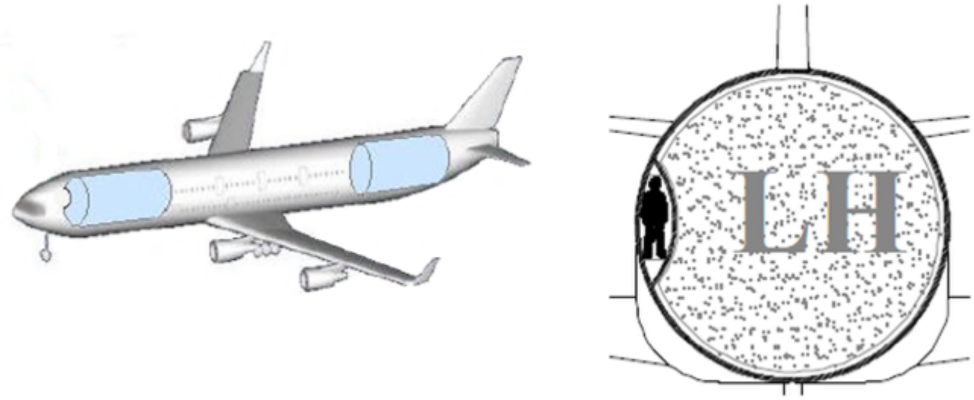


Figure 5. LH2 tank placement when the LH2 weight variations are large. Source: Airbus.

The problem to solve is access to the cockpit during flight. With the last year's closed cockpit doors, one can question if a catwalk to the cockpit beside the forward tank is needed. It's a phycological question if passengers feel safe with pilots in a compartment that is hermetically separated from the passenger cabin or not.

As we can see from these sketches from the Airbus Cryoplane project, the tanks are not perfectly cylindrical. As the tanks are low-pressure designs it's the heat leakage that must be optimized. Slight variations from a cylindrical shape are then possible.

The solution for tank placement of the first hydrogen test aircraft can be an aft placed tank as in the Tu-155, Figure 1.

If the maximum range is kept within limits, an aft placed cylindrical tank is an acceptable solution. Once the appetite for more range increases, more balanced designs are necessary.

Bjorn's Corner: The challenges of Hydrogen. Part 7. The fuel system.

September 4, 2020

September 4, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we look at the rest of the fuel system after we looked at the hydrogen tanks over the last weeks.

The cryogenic state of the liquid hydrogen (cryogenic=very low temperatures, -253°C) creates some new challenges when designing the fuel system.

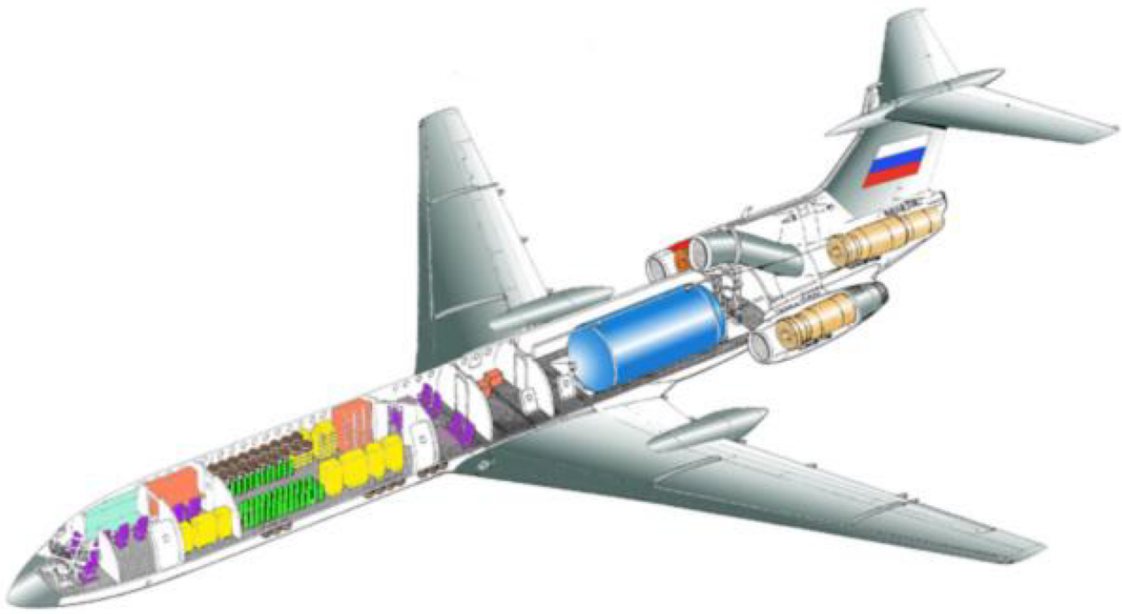


Figure 1. The Tu-155 Hydrogen research aircraft with its aft fuselage tank and fuel system. Source: Tupolev.

How to design the fuel system of a liquid hydrogen airliner?

The low temperature of LH2 forces some special solutions around the fuel system of an LH2 based airliner.

Tanks layouts with engine collector tanks and feeder storage tanks like today's airliners have been analyzed in Airbus' Cryoplane studies. It works if special care is given to tank form and its insulation to avoid heat leaks and the material choices and insulation of pipes, valves, pumps, and sensors are done carefully.

Special hydrogen leak detectors with appropriate ventilation are required for all areas where the fuel system is present.

The tanks are isolated low-pressure tanks as in Figure 2, with both LH2 (B) and H2 (A) insulated fuel pipes and a dedicated insulated LH2 filling line (D) to each feeder tank. The tank feeds the collector tank via the tank pump at E.

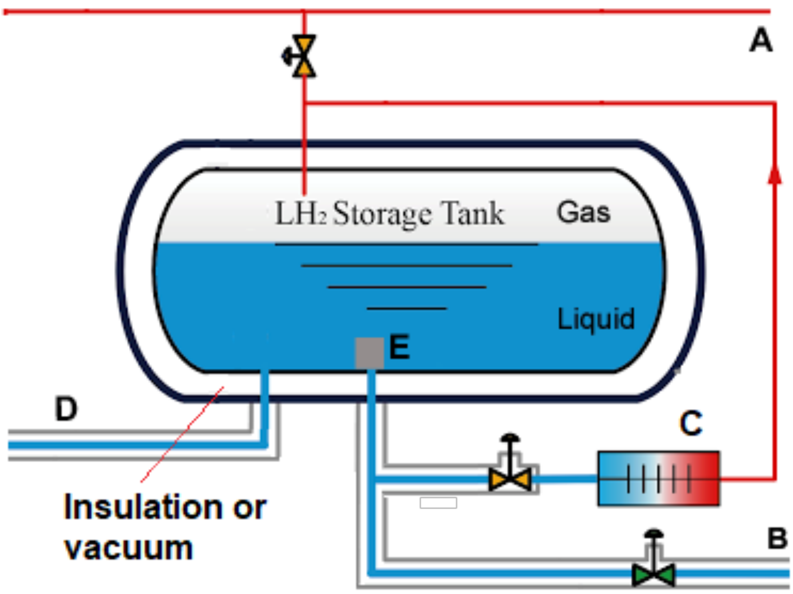


Figure 2. LH2 feeder tank. Source: Leeham Co.

There is no specific problem having a central filling receptacle for the LH2, with LH2 flowing concurrently to each feeder tank.

There is long-time experience of cryogenic tanks, pipes, valves, pumps, and sensors from the Technical and Space industry. The Space experiences must be further developed to suit the longer storage times of the airliner application (typically a 12-hour case without excessive boil-off due to heat leakage).

The leakage gas at A, when needed to be supplemented with gas from the heat exchanger at C, can be routed to a hydrogen fuel cell providing the aircraft with electrical power, both when stationary and during flight, thus replacing the APU and the engine-driven electrical generators. With the appropriate development of the efficiency of such fuel cells, they can provide sufficient electrical power to feed a more electric aircraft architecture.

With electrically driven De-Icing, Environmental Control System (ECS=Air Condition System), hydraulic pumps, and engine starters, the aircraft can gain efficiency by not tapping this power from the Turbofan engines or an APU.

The Turbofans can be optimized for delivering propulsive power, where the LH2 is supplied to the combustor injectors at the appropriate temperature via a heat exchanger in the engine pylon.

In the next Corner, we will explain why we use LH2 based Turbofans as propulsors for an A320/737 class of aircraft, instead of fuel cell-driven electrical propulsors as outlined in the EU study.

Bjorn's Corner: The challenges of Hydrogen. Part 8. Fuel cell electric or Turbofan propulsion?

leehamnews.com/2020/09/11/bjorns-corner-the-challenges-of-hydrogen-part-7-fuel-cell-electric-or-turbofan-propulsion/

September 11, 2020

September 11, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we look at whether we use an LH2 burning Turbofan as propulsion or as the EU study proposed, a Parallel Hybrid feed by a fuel cell, Figure 1.

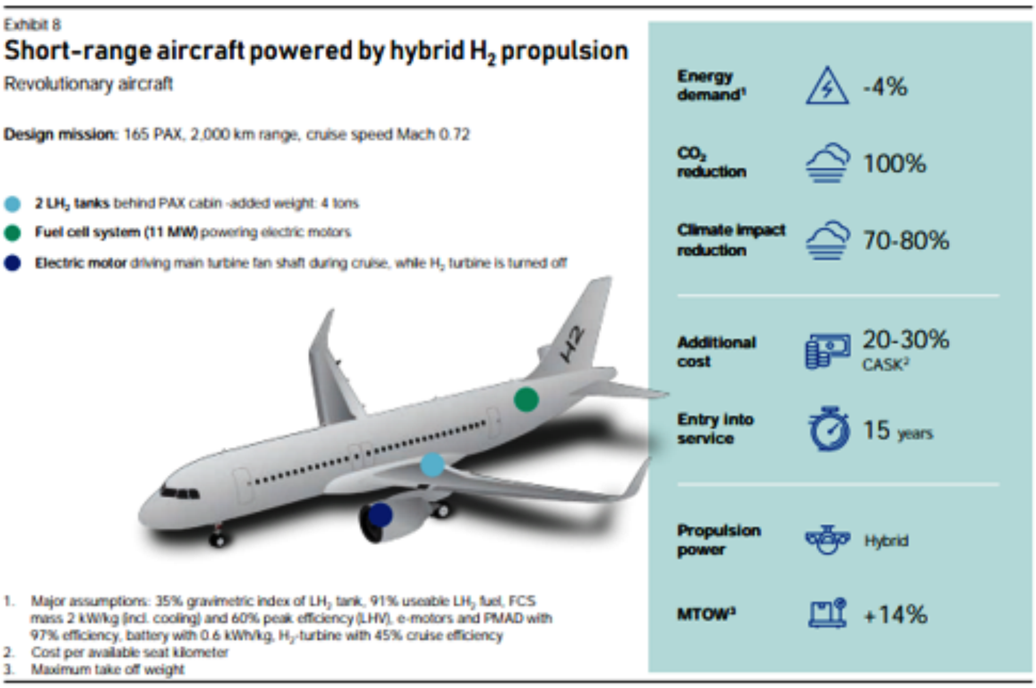


Figure 1. The Parallel Hybrid 165 seat aircraft from the EU Hydrogen study. Source: EU.

Fuel cell electric hybrid or Turbofan propulsion?

The EU study presented a Fuel cell parallel electric hybrid aircraft at 165 seats for introduction in 2035 as the alternative to today's Airbus A320 and Boeing 737 aircraft. Let's call this the LH2 Hybrid. Key data and assumptions are shown in Figure 1. Let's examine these a bit closer.

The size and configuration is a modern variant of an A320/737. This is the size class we dissect in our series. The configuration of the propulsion should be the bottom alternative in Figure 2.

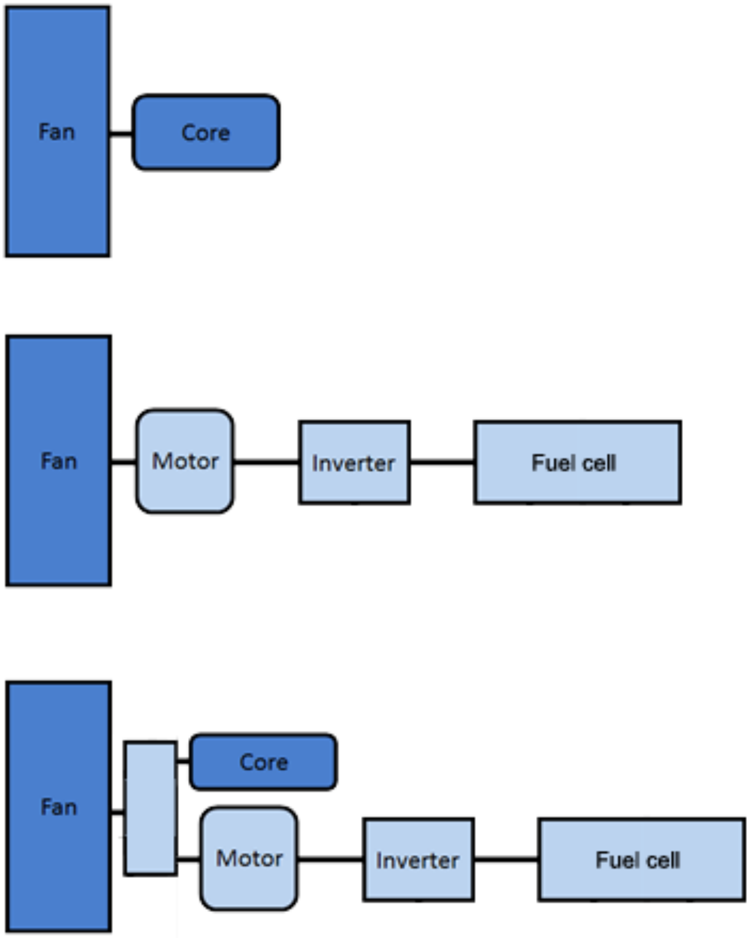


Figure 2. The different hydrogen propulsion concepts we study. Turbofan, Serial fuel cell, and Parallel Hybrid fuel cell. Source: Leeham Co.

The study assumes the cruise power needed to propel the aircraft is 10MW, taken from an 11MW fuel cell, through the inverter, and driving a motor that drives the fan on each side (1MW disappears in chain losses). During takeoff and climb an LH2 gas turbine core is assisting.

The picture assumes 11MW fuel cell output is enough to propel the cruise for the aircraft at 0.72M cruise speed. After losses through the Inverter, the Distribution network, and Motor we are at 10MW fan power for the LH2 Hybrid case.

Takeoff power to the fans for today's A320 is 40MW, with cruise power of 14MW at the average weight on the average sector. Cruise speed is then 0.76M.

Let's first calculate the weight of the components for the LH2 Hybrid and then discuss how realistic this configuration is for a 2035 realization.

The fuel cell weighs 5.5t with the assumption of 2kW/kg. The inverters weigh 0.6t and the motors 0.9t (kg/MW values from the Electric Corner series).

To understand the weight of the parallel helper core we need to assume an additional power need on top of 10MW. With today's A320neo it would be 30MW.

The EU LH2 Hybrid assumes to be more efficient than today's A320neo, so it should need less takeoff power. It's easy to think it should be (let's disregard the battery in the concept, in order to give the LH2 Hybrid it's best shot. We know by now batteries kill any configuration).

But we know the empty weight and wetted are of any LH2 aircraft will increase because of the tanks as a carbon fueled aircraft gets the tanks for free (in the wingboxes) and the isolated LH2 tanks weighs a lot and take considerable space in the fuselage. So before we look at the LH2 Hybrid propulsion system we have a heavier aircraft with a larger wetted area.

The fuel weight fraction will be lower (LH2 has three times the energy per kg of Jet-A1) but on the short-range flights we look at it can't fully compensate. We fly a larger and on average heavier aircraft on the sector we fly. This is consistent with the conclusions of the Airbus Cryoplane study (we talk of around 10% higher drag = energy consumption for an LH2 aircraft compared to carbon fueled variant according to the Cryoplane study, everything else being equal).

The fix for this is a wing with a higher aspect ratio, to reduce the wetted area of the wing and offer a higher effective span, by it, reducing induced drag. But we are span limited to 36m, otherwise, the aircraft doesn't fit the airports. In reality, we are lucky if we can improve the power need from today's A320neo.

Let's give the LH2 Hybrid its best shot

To not be to negative, let's assume we can by some magical means keep takeoff power at 30MW and cruise power to the fans at 10MW, a 25% or more improvement from today.

We then need a core of 10MW to complete the hybrid. Today's PW1100/LEAP engines weigh 3t. Let's assume 1.5t is the fan and the structure that we need in both cases. The 20MW turbofan cores are then 1.5t each (we need 2*20=40MW to get an A320/737 in the air). Our helper cores then weigh 0.75t each (we assume a linear scaling).

To summarize our Carbon fueled propulsive power to the fans weighs 2*1.5t=**3t** and the LH2 Hybrid’s power 5.5+0.6+0.9+2*0.75=**8,5t** (we don’t count the tanks or additional structure in either case, we just analyze the power section right now).

So we have LH2 Hybrid power that weighs 8.5t with a 60%*97%*97%=56% cruise energy efficiency compared with a PW1100/LEAP core of 3t that has a 53% cruise efficiency as of today (I don’t know where they got the 45% efficiency from, it’s not a present core).

As we can see it’s break-neck developments for a Hybrid power that 2035 is not more efficient than today’s PW1100/LEAP cores. And this assumes we can develop all the components for the Hybrid at the assumed weights and efficiencies. We are today at 1MW motors/inverters and aircraft fuel cells of below 1MW.

In the next Corner, we examine LH2 fueled Turbofans as alternative propulsion.

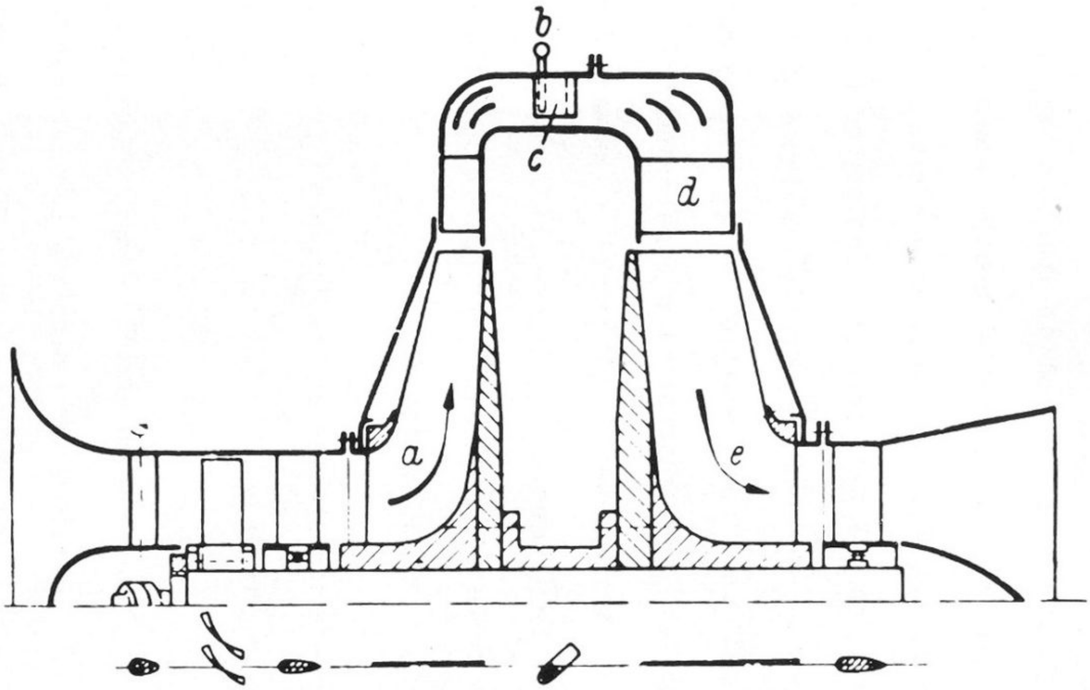
Bjorn’s Corner: The challenges of Hydrogen. Part 9. Hydrogen Gas Turbines

leehamnews.com/2020/09/18/bjorns-corner-the-challenges-of-hydrogen-part-9-hydrogen-gas-turbines/

September 18, 2020

September 18, 2020, ©. Leeham News: In our series on hydrogen as an energy store for airliners we analyze the conversion of the present Turbofan and Turboprop airliner engines to hydrogen as fuel instead of carbon-based fuels.

We know it’s possible as the world’s first jet engine from 1937 ran on hydrogen, Figure 1. But what are the problems and how good are the hydrogen-fueled engines in efficiency and emissions?



RADIAL TURBOJET (He S-1)
WITH HYDROGEN
(Built in 1936; tested in April 1937)

Radius of rotor - 1'
Thrust - 250#

Figure 1. The world’s first jet engine, Hans von Ohain’s He S-1. The engine’s aerodynamics is pictured below the cut-through. Note the skewed hydrogen injector at c. Source: Wikipedia.

Hydrogen based Turbofans and Turboprops

There are no big changes needed to convert a gas turbine to run on hydrogen instead of carbon-based Jet fuel.

It has been analyzed in detail in several studies and converted research engines have confirmed the research findings.

The major changes are in the combustor. It needs a different design to burn the gaseous hydrogen which enters at about 200K (-73°C). To take the LH_2 from 20K liquid to 200K gas just before entering the engine a heat exchanger is used.

The exchanger can be placed around the exhaust of the gas turbine, but more sophisticated approaches can be used that also enhances the efficiency of the engine.

A straight converted engine with a simple heat exchanger has the same efficiency as the carbon fueled engine. As hydrogen has three times the energy content the fuel consumption will be one third.

The hydrogen burns a bit differently which means the turbine will run about 40K cooler for the same performance level. This will increase the turbine life for the engine.

Emissions

An important difference is the emission level. As no carbon is burned the emissions are H_2O and NO_x. So the CO_2 emission problem is solved.

The increased level of water in the exhaust has to be managed by flying slightly different flight levels. With these precautions, the level of contrails in the sky can be kept at the same levels as today. The NO_x level can be lowered to about 20% of today’s engines by careful design of the combustor and its processes.

The heat needed to convert 20K LH_2 to 200K gas can be used to increase the engine’s efficiency. Different alternatives have been looked at.

More efficient engines

One is an intercooled compressor. The principle is the same as for an intercooled turbo engine for a car.

Another idea is the use the hydrogen to cool the cooling air for the turbines. The first turbine stages are cooled by air from the last compressor stages to tap air at a pressure that is above the turbine pressure. This air is hot, around 500-600°C. If the hydrogen heat exchanger cools this air, the turbine runs cooler and can develop more power for the same size turbine.

These smarter use of the heat exchanger can save up to 5% in fuel consumption compared with a straight converted engine.

In addition to a redesigned combustor with injectors, the fuel system needs adaptations. But in all, the conversion of today's engines is straight forward and they are gamer changers in emissions.

The CO2 problem is gone and NOx emission levels are improved. The contrails need work but there are clear schemes on how this shall not be a new problem.

With further developments, the hydrogen gas turbine can surpass carbon fueled engines in efficiency.

With the performance and reliability we have achieved with today's gas turbine-based propulsion systems, I see little cause for focusing the first steps to hydrogen on fuel cell hybrids.

Focus for fuel cells

Fuel cell research shall be focused on replacing the APU and that the fuel cell energy source can be powerful and reliable enough to replace today's engine-driven generators.

This energy is then used in a more electric aircraft for de-icing, environmental control systems, and electricity consumers in the aircraft (non-active generators are kept on the engines as backup).

This requires efficient and reliable fuel cells of several MW and is a big enough challenge. We can also use these fuel cells to start work on small (20 to 50 seat) electrical hybrid turboprops to learn this trade in steps.

With well-converted hydrogen engines and a more electric aircraft driven by a fuel cell replacing the APU, we not only solve the emission problems but can also drive further efficiency into air transport.

Bjorn's Corner: The challenges of Hydrogen. Part 10. Airbus' Hydrogen ZEROe concepts

leehamnews.com/2020/09/25/bjorns-corner-the-challenges-of-hydrogen-part-10-airbus-hydrogen-zeroe-concepts/

September 25, 2020

September 25, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners, we look at the three hydrogen-based concept aircraft Airbus presented this week.

They are called ZEROe and are concepts and not products, but their design tells us a lot about where Airbus is with its studies and how the hydrogen demonstrator aircraft might look like come 2026-2028.

How to understand Airbus' Hydrogen concepts

Are the pictures of Airbus' hydrogen-based ZEROe aircraft from Monday's presentation also a hint of how future products will look like? Airbus EVP development Jean-Brice Dumont pointed out that concepts are not products.

The concepts are created to give Airbus and suppliers concrete example aircraft to work around when they look at configurations, aerodynamics, system solutions, and needed avionics to build efficient hydrogen-fueled airliners.

If we discard the Blended Wing-Body (BWB) variant, which I judge is there to spawn ideas and excitement more than show a realistic concept for the next move, the concepts still say a lot about what might come. Let's look at what we can conclude from the Airbus presentation.

Hints for the 2027 demonstrator and 2035 first product

A demonstrator aircraft is scheduled for 2026-2028, but the program has a main supporter in the French government and the Paris Air Show is 2027. So let's use June 2027 as the likely presentation date for a hydrogen-fueled demonstrator.

Will this be singular or plural? Airbus owns 50% of ATR and the turboprop concept looks very much like a more exciting ATR72, Figure 1.

Figure 1. Airbus hydrogen turboprop concept. Source: Airbus.

At the same token, the Turbofan concept has several similarities with the Airbus A220, Figure 2. It would not be difficult to put the chain saw in the rear fuselages of former prototypes of an A220 and an ATR72, install the hydrogen tanks in modified rear tail cones as shown, and put the aircraft together again, now a bit shorter in the back (we come to why).

Figure 2. A hydrogen turbofan for the heart of the market. Source: Airbus.

As we have seen, the challenge with hydrogen aircraft is the hydrogen tanks. The change of the rest of the fuel system components and the conversion of the Jet fuel-based engines to hydrogen is less of a challenge.

Airbus confirmed that all three concepts are hydrogen fueled gas turbine aircraft (also the BWB, I wasn't sure directly after the presentation). It has come to the same conclusion as I, the step to a fuel cell-based hybrid with electric propulsion is risking a lot with no gains at the moment.

At the announcement Grazia Vittadini, the Airbus CTO said the gas turbine-based engines will have electric motors built-in. This is the electric starter generators I talked about in this Corner.

By moving the air starter and generators from the engine auxiliary gearbox to one of the shafts of the core, the acceleration of the engine can be faster and the core can be optimized with smaller margins to compressor stall. This leads to a more efficient engine compared with today's engines with air starters and generators on the auxiliary gearbox.

I could talk to Vittadini in connection with the presentation and she confirmed that changing the APU to a hydrogen fuel cell that produces electrical energy is attractive, now that the main fuel is LH2. There was no confirmation or denying that this would find its way to the demonstrators or ultimately a product. We just have to wait and see.

Converting the APU of an A220 based demonstrator to hydrogen is straight forward, should the APU remain to reduce the risk budget. The ATR72 doesn't have an APU so no problem there (but a hydrogen variant might, the concept turboprop has an APU).

How much do the concepts say about a 2035 Airbus product?

Probably a few things:

- It will have hydrogen-fueled gas turbine Turbofan propulsion.
- The likely seating will be at the heart of the single-aisle market. I would guess around 180 seats.
- The general configuration of the aircraft will likely be like the Turbofan concept, with the tank in the rear of the aircraft. The heavy LH2 tank placed in the tail cone behind the cabin will move the wing back to balance the aircraft.
- The wing can be made more slender as there is no volume requirement on the wing's wingbox to house fuel. Many would say thinner but the profile of the wing and by it the thickness is dictated by super-critical transonic considerations and wing thickness is important for low wing weight. The wing cord (the width) will be shorter however to gain a high aspect ratio when paired with a large span. Folding wingtips might be used to get into the 36m gates of narrowbodies.
- There will be Fly-By-Wire and aerodynamic adaptations to cater to the change in the Center of Gravity (CG) for the aircraft when the 1.5t hydrogen sitting behind the CG gets consumed during a typical 800nm to 1,000nm sector. We can view the large swept-back winglets as such an adaptation. We will probably see more innovations to cater to this CG shift.
- These concepts have a hydrogen-based APU. Will the 2035 product? This will depend on the developments for the fuel cells. Will these be small, light, and reliable enough by 2035 to take over this role?
- Materials for the LH2 tank and all fuel related components will be intensively researched and tested. A major task for the demonstrators will be to test materials under realistic operational conditions over a longer time.
- Major aspects that are not shown in the concept pictures are the ground handling and airport infrastructure needed for hydrogen airliners. Once again, an important task for a demonstrator aircraft to test out.

As can be seen, we can deduce a number of hints from these concepts. We shall just avoid thinking these concepts define a 2035 product. Dumont said, one of the reasons is the market for a hydrogen airliner is not clear.

The demonstrator will be vital for airlines to understand all the aspects of operating a hydrogen airliner compared with today's carbon-based types. When this becomes clearer, including the cost picture of hydrogen contra carbon-based airliners and state subsidies/taxes, products can be defined.

Will there be a hydrogen turboprop demonstrator and then a product from ATR? Probably. The French €15bn program announced in June contained program components for the regional industry, and in France this means ATR. We can expect a Turboprop demonstrator, based on a converted ATR72 and this can be followed by a product should the market reaction be positive.

Bjorn’s Corner: The challenges of Hydrogen. Part 11. Emissions

leehamnews.com/2020/10/02/34733/

October 2, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we look deeper at the emissions from a hydrogen airliner and compare it to the emissions from today’s carbon fueled aircraft.

Figure 1. The three Hydrogen concepts from Airbus. Source: Airbus.

Emissions of a Hydrogen aircraft

In Part 9 of the series, we wrote the emission from a hydrogen-fueled Turbofan or Turboprop take care of the CO_2 problem (no CO_2 emissions), it lowers NO_x emissions and increases the emission of water, H_2O, into the atmosphere.

Figure 2 gives a more detailed view of the emissions from a carbon fueled and hydrogen-fueled airliner.

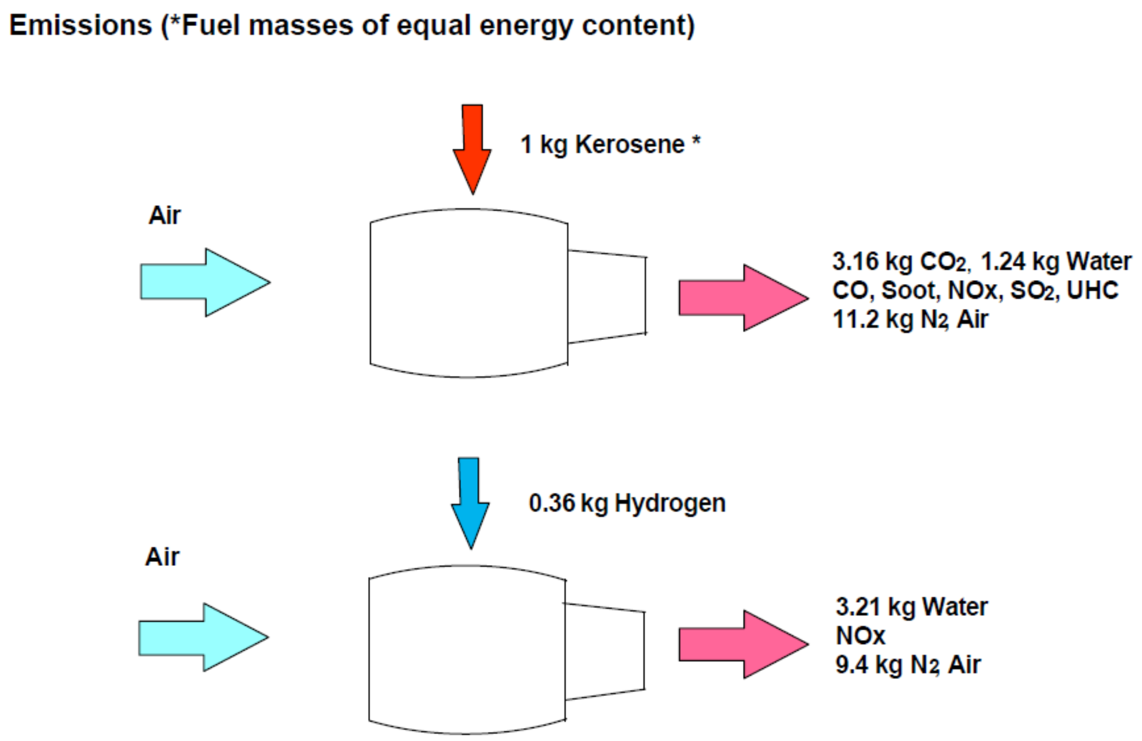


Figure 2. Emissions from a kerosene-fueled turbofan and hydrogen turbofan. Source: Airbus Cryoplane study.

Today’s airliner that burns 1 kg of jet fuel emits 3.16kg of CO2, 1.24kg H20, Carbon Monoxide, Soot, Sulphuric Acid, 11.2kg of Nitrogen and air. This compares with no CO2, 2.6 times more water, one fifth the amount of NOx, and 9.4kg Nitrogen and air from a hydrogen-fueled engine (both burn the same amount of energy, producing the same thrust). A hydrogen-based airliner is a clear improvement in terms of emissions.

The only caveat is the increased amount of water vapor in the exhaust. Water vapor has a greenhouse effect in the atmosphere but it disappears 200 times faster than CO2, and studies show that water vapor in the atmosphere is not the key problem from the increase in water emissions.

It’s rather contrails (ice crystals that form from water vapor condensation on nuclei in the turbofan exhaust) that are contributing to an increase in the greenhouse effect. Though hydrogen-fueled engines put out more water vapor, the ice crystals formed when the conditions create contrails are larger. This changes the effects of the contrails so they are thinner and contribute less to the greenhouse effect than the same amount of water vapor from a carbon fueled engine.

The combined effect of the increase in water vapor and the formation of contrails, considering the different types of ice crystals formed, is a reduction in the greenhouse effect from hydrogen-fueled airliners by around

20%.

I have taken these results from both the Airbus Cryoplane study (from 2000) and the EU’s study, released in May 2020. Both documents say these results are according to the best knowledge but this subject needs more research.

Summary

To summarize these and other studies, hydrogen-fueled airliners, as Airbus’ ZEROe concepts in Figure 2, would:

- Reduce CO2 emissions by 100%
- Reduce NOx emission by 80%
- Reduce the greenhouse effects from emitted water vapor by 20%

The above assumes the same efficiency aircraft and engines, transporting the same amount of passengers the same distance, fueled by Jet A1 kerosene alternatively hydrogen.

This assumes both aircraft fly the same trajectory, meaning the hydrogen airliner is not adapting it’s mission profile to avoid contrail creation (for instance, change flight level to one that does not produce contrails in areas where conditions predict contrail creation).

Bjorn’s Corner: The challenges of Hydrogen. Part 12. Safety

leehamnews.com/2020/10/23/bjorns-corner-the-challenges-of-hydrogen-part-12-safety/

October 23, 2020

October 23, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we look deeper at the safety of a hydrogen airliner.

Do the safety rules for the aircraft or the airport need to be written new or can the existing ones be used with changes?

By Bjorn Fehrm

How do you certify hydrogen aircraft and its infrastructure?

We have discussed different technical challenges that confront Airbus and others that embark on hydrogen-fueled aircraft projects.

But technical solutions are only part of the areas that require work. An equally important area is the safety aspects and what rules shall a new hydrogen airliner be designed and certified to?

What are the rules needed for the storage of hydrogen at the airport and the refueling of the aircraft?

A lot can be learned from the car and space launcher industry but it must all be adapted to the air transport situation and the safety level achieved there.

The Airbus Cryoplane study spent considerable effort and time to go through the safety aspects of the aircraft and the infrastructure around it. The goal was to identify any areas that could be showstoppers. Must the certification rules be written new?

After three years of work, where existing certification procedures and airworthiness regulations were assessed, it found the existing rules cover the needed areas.

No new rules need to be written, but the existing ones must be amended/changed as many safety aspects are specific to hydrogen as a fuel and its cryogenic (-253°C) storage state.

There are burn and explosion risks but also the inverse, where the low temperatures of the liquid fuel pose risks as does its heat absorption when it goes from liquid to gas, should a leak develop.

The tanks must be protected from engine disc bursts as a ruptured cryogenic tank can take in oxygen, creating an explosive mixture.

Also, all components of the aircraft that can come in contact with liquid hydrogen must be designed to withstand the low temperatures of the cryogenic fuel.

The rules for the airport storage and filling of fuel must be changed, adapted from the rules from the car and space launcher industry.

Not less safe than a carbon fueled aircraft

The aircraft safety assessment demonstrated that the existing paragraphs of the safety and airworthiness regulations cover the needed areas. Technical solutions and regulations can be adapted to meet at least the same level of safety as for carbon fuels.

Overall, the conclusion was:

Hydrogen poses its specific safety aspects to be considered in design and operation. However, the overall safety level will not be worse than for kerosene aircraft.

Bjorn’s Corner: The challenges of Hydrogen. Part 13. The supply of Hydrogen

leehamnews.com/2020/10/30/bjorns-corner-the-challenges-of-hydrogen-part-13-the-supply-of-hydrogen/

October 30, 2020

October 30, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we now address the problem of liquid hydrogen supply for air transport.

Before we go into the ecosystem and its costs, let’s start with a more principle discussion. Is continuing today’s consumption pattern a valid alternative?

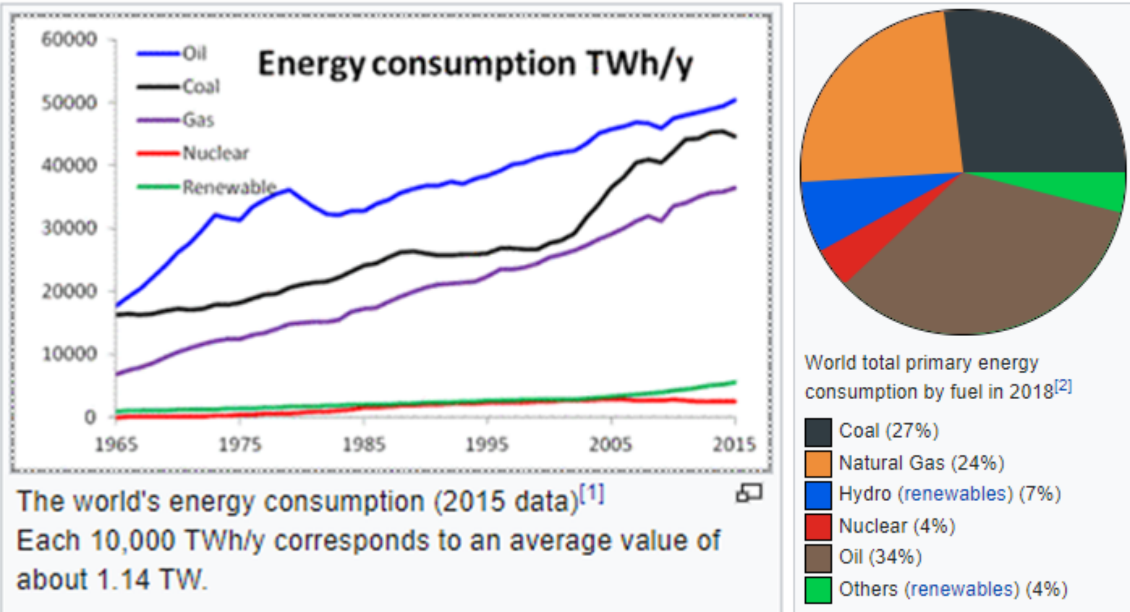


Figure 1. World energy consumption by type and development. Source: Wikipedia.

How do we structure a sustainable energy supply?

If we go directly into the hydrogen infrastructure needed and the cost of supply we shortcut the overall discussion on what options do we have for our energy supply in general and air transport in particular?

Figure 1 shows our energy consumption by energy type (right-hand pie chart) and the development of the types over time. If we group the energy types as Carbon-based, Nuclear based, and Renewable we get Figure 2.

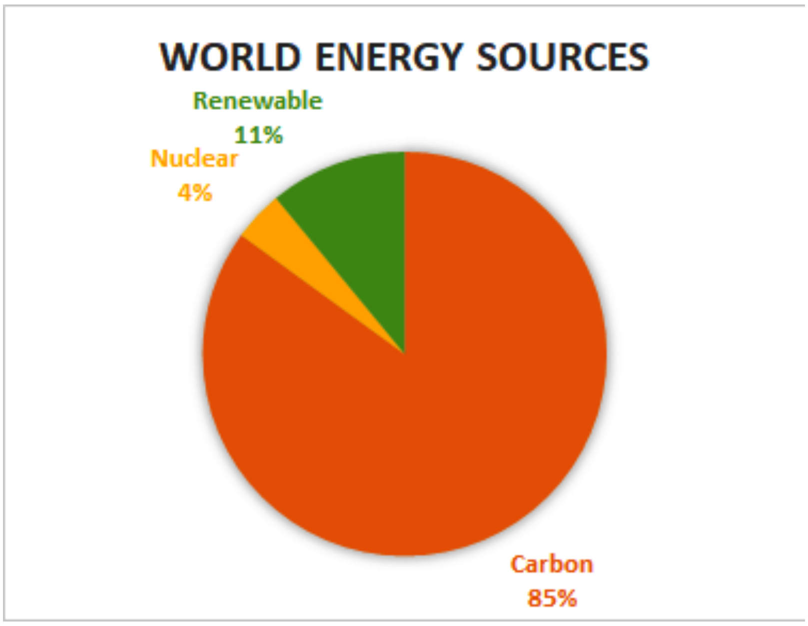


Figure 2. Words energy supply by type 2018. Source: Wikipedia.

Our energy mix by 2018 was 85% Carbon-based, 4% Nuclear, and 11% Renewable energy.

We know we live on borrowed time regarding our energy supply, as we to 85% (or more, data from 2018) burn Carbon-based fuels that were produced millions of years ago. The consumption of these fuels causes problems that are more manifest by the year.

Last year's fires in Australia and this year's on the US West coast tells us the development in Figure 1, where Carbon-based energy consumption increases and alternatives remain at around 15%, will create ever-larger problems for us.

There is no lack of renewable energy sources. The Sun creates enormous amounts of energy. It deposits a power of about 1kW/m2 on earth when in Zenith on a clear day (the solar constant). This energy goes to waste in the deserts and creates winds and rain over our land masses and waters.

Our problem with capturing this energy is that we don't have an efficient form of storing energy so that we then can use it at places where we have the need.

Presently we build power grids to connect hydropower, solar panels, and wind farms with our consumption networks. This means these capture areas must be close to where we use the energy.

Hydrogen, through electrolysis of water, can be the means to fix this problem. It’s the most energy-dense way of transporting captured energy (to my knowledge).

Is the problem the price of Hydrogen contra Jet fuel?

Given the above, we can question if the general problem is that produced hydrogen through electrolysis is xx% more expensive than if we consume the same energy from our carbon sources? Is this a valid comparison?

Given the effects of burning carbon fuels, I would say no.

In my view, the question is, what alternatives do we have to the present consumption pattern and how much extra must we pay to achieve a needed change?

Can it be that the present energy prices are so cheap because our generation is consuming energy in a way that our kids will pay for in the future?

I know this is dragging values into the discussion but I think it’s worth a thought and debate. The question is, are we energy squanderers today, leaving the problems we create with our consumption for others to fix?

If we are, then it’s a question of what a more sustainable path costs, not if it’s too costly compared to our today’s consumption.

Bjorn's Corner: The challenges of Hydrogen. Part 14. Supply of Hydrogen

leehamnews.com/2020/11/06/bjorns-corner-the-challenges-of-hydrogen-part-14-supply-of-hydrogen/

November 6, 2020

November 6, 2020, ©. Leeham News: In our series on Hydrogen as an energy store for airliners we now look at how to create a supply industry for hydrogen.

By Bjorn Fehrm

The problem of a sizable and competitive hydrogen supply industry is a chicken or egg problem. To achieve a competitive and functioning hydrogen transport system we need an adequate hydrogen infrastructure and to get an adequate hydrogen industry we need large-scale consumers.

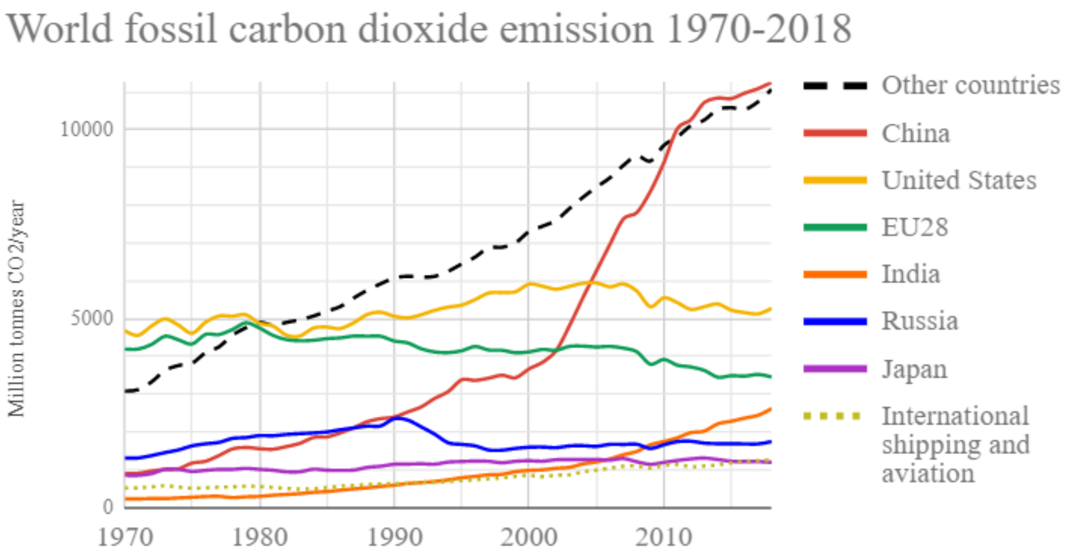


Figure 1. The CO2 problem and the main contributors. Source: Wikipedia.

How do we get a hydrogen industry going?

The problem of a sizeable and competitive hydrogen supply chain is a true chicken or egg problem. To get a hydrogen transport system that runs without massive subsidies, we need a competitive hydrogen infrastructure and to get a competitive hydrogen infrastructure we need consumers that consume substantial amounts of hydrogen.

This has been the hydrogen economy's problem for decades and it's only the unsustainability of the present solution, carbon-based energy, and its consequences (Figure 1), which results in the present urge to finally get the ball rolling. After analyzing other alternatives, like large scale electrification of the transport industry, hydrogen remains the best large-scale alternative to our carbon energy system.

To that end, the **Hydrogen Council** has formed three years ago as international cooperation between industry, research, and investors as described in our previous Corner. You read about it **here**.

The **Fuel Cells and Hydrogen Joint Undertaking**, **FCH JU,** was formed by EU 2004 to support research, technological development, and demonstration activities in fuel cell and hydrogen energy technologies in Europe.

Today, the three members of the FCH JU are the **European Commission**, fuel cell and hydrogen industries represented by **Hydrogen Europe**, and the research community represented by **Hydrogen Europe Research**.

Hydrogen Europe is a trade organization for 160 European companies. It cooperates with FCH JU, which with its €1.3bn budget promotes hydrogen research and demonstration projects, to create catalyst projects that can kick-start the development of a European hydrogen eco-system.

To build a hydrogen ecosystem, we need substantial projects that can gradually replace our present carbon-based energy system. An example of such a project, developed within the FHC JU partnership, that can achieve such a build-up is the proposal for a pan-European hydrogen pipeline system, where re-use of the existing NLG (Liquefied Natural Gas, cooled to -162°) pipelines is a central theme, Figure 2.

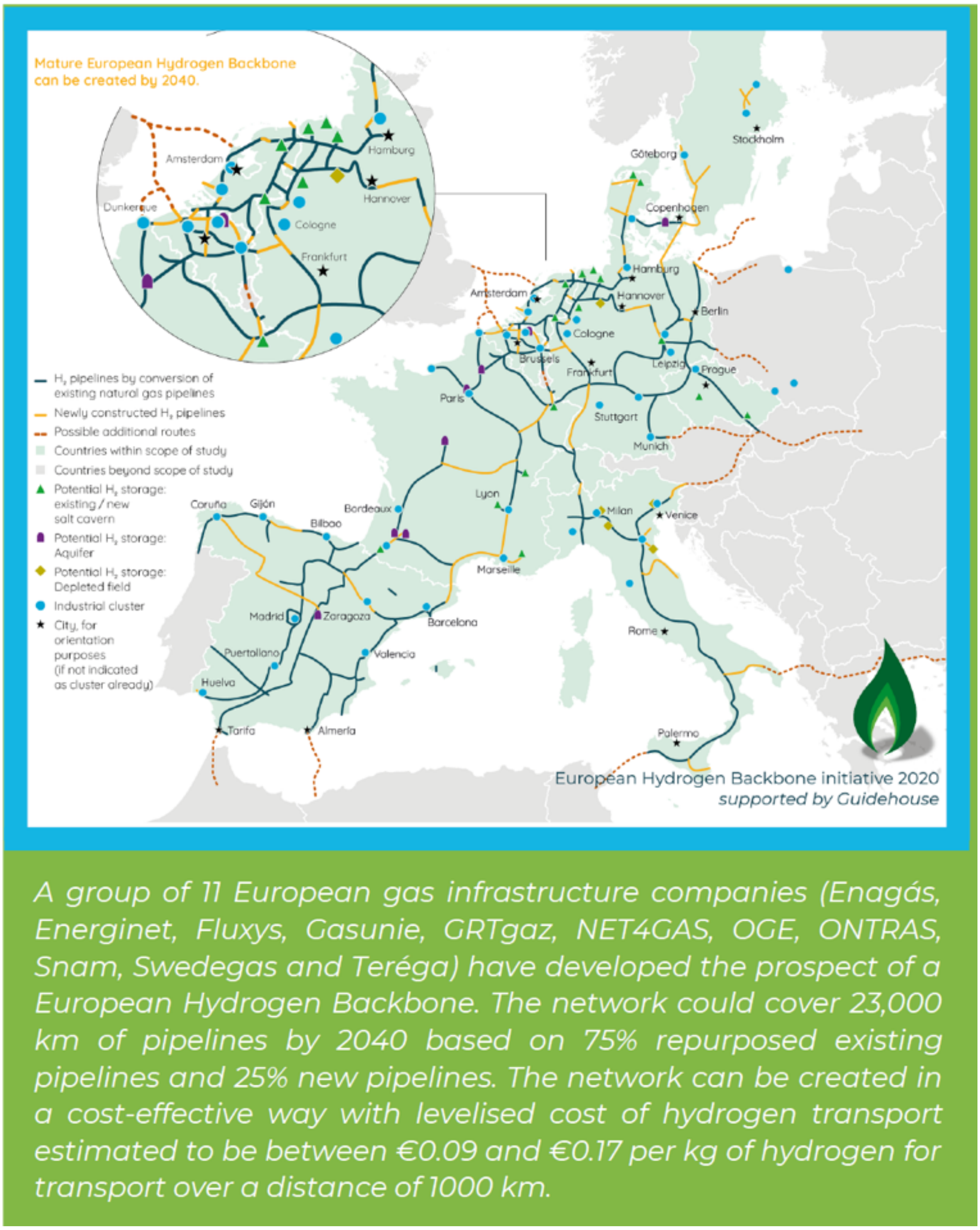


Figure 2. A proposal developed under the CFH JU for a European Hydrogen Backbone. Source: Hydrogen Europe.

With the gradual replacement of NLG with LH2, the necessary scale and ubiquity can be achieved for hydrogen. We will need projects like these, where not only pockets like air transport start the non-carbon journey but sizeable parts of the society converts as well. The conversion of a carbon-based NLG to LH2 is a good place to start. The troublesome distribution network is then mostly there.

Such changes will not come from market forces alone. The carbon energy prices do not include the cost of the negative effects of the industry and it’s over 100 years old with investments paid. It will be the role of the state to bootstrap the hydrogen industry so the Chicken or Egg hangup can gradually be untangled.

The investment in hydrogen airplane development by Airbus and its partners shall be seen in this context. It’s a very visible and high profile Lighthouse project. Airbus has repeatably said the many projects that it will start over the next years should be seen as a way to get a supply chain and industry going, both on the technical and energy side.

Airbus needs this industry and the industry needs Airbus. But air transport can’t be alone. It will not achieve critical mass for a hydrogen supply chain.

What other parts of society are candidates for change?

Figure 3 shows the energy consumption by sector in the EU 2018. Air Transport is a small part of Transport. With a conversion of public transport such as busses and rail, a part of the transport sector controlled by society can be converted. Also, with a gradually converted NLG network, either by mixing in LH2 or conversion of parts of the distribution network, large-scale energy consumers like households and industry can be supplied.

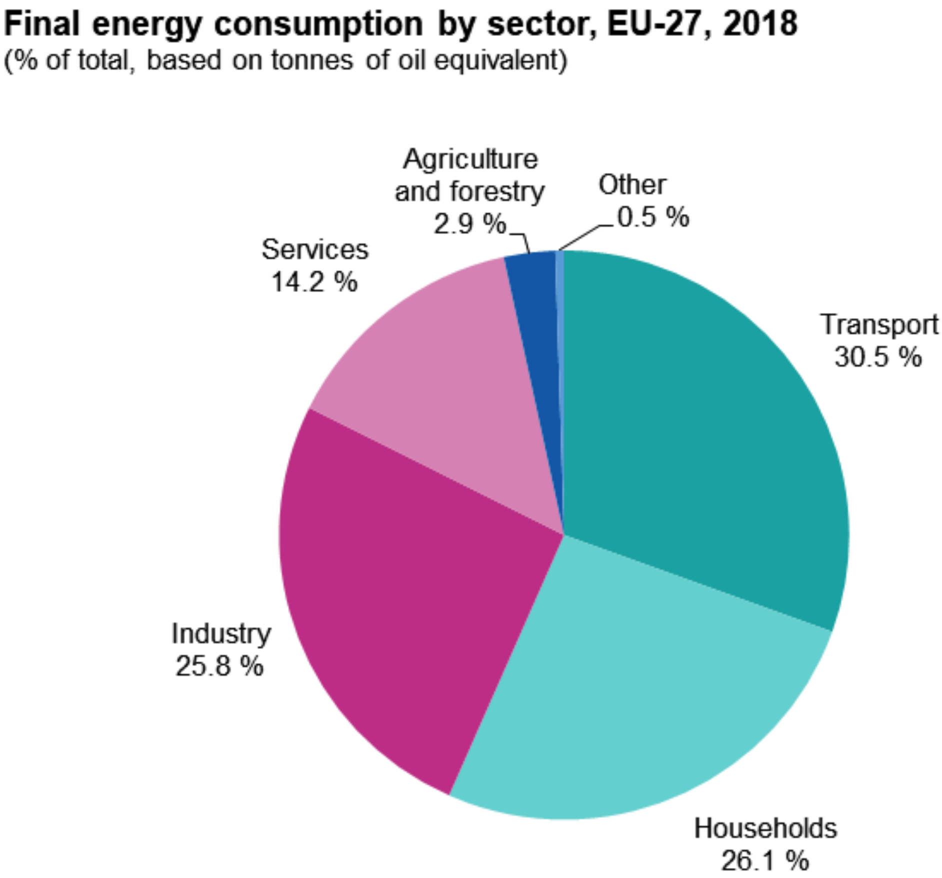


Figure 3. Energy consumption in the EU by sector 2018. Source: Eurostat.

Air Transport is too small a sector to drive a hydrogen industry. Other sectors must join to achieve the change. It will require state subsidies, but this shall be OK. It’s either this or taxes to be levied on the carbon industry to pay for its negative effects. Or perhaps both.

But it will require that the negative effects of the present carbon system are seriously felt, like the recent fires, to mobilize the political will for such steps.

Bjorn’s Corner: The challenges of Hydrogen. Part 15. Hydrogen cost

L leehamnews.com/2020/11/13/bjorns-corner-the-challenges-of-hydrogen-part-15-hydrogen-production/

November 13, 2020

November 13, 2020, ©. Leeham News: In our series on hydrogen as an energy store for airliners, we now look at the cost of hydrogen.

By Bjorn Fehrm

The current cost-efficient production is predominantly by reforming natural gas, meaning it’s a process that involves carbons. Hydrogen as an energy transporter then makes no sense as the point is to de-carbonize our energy supply.

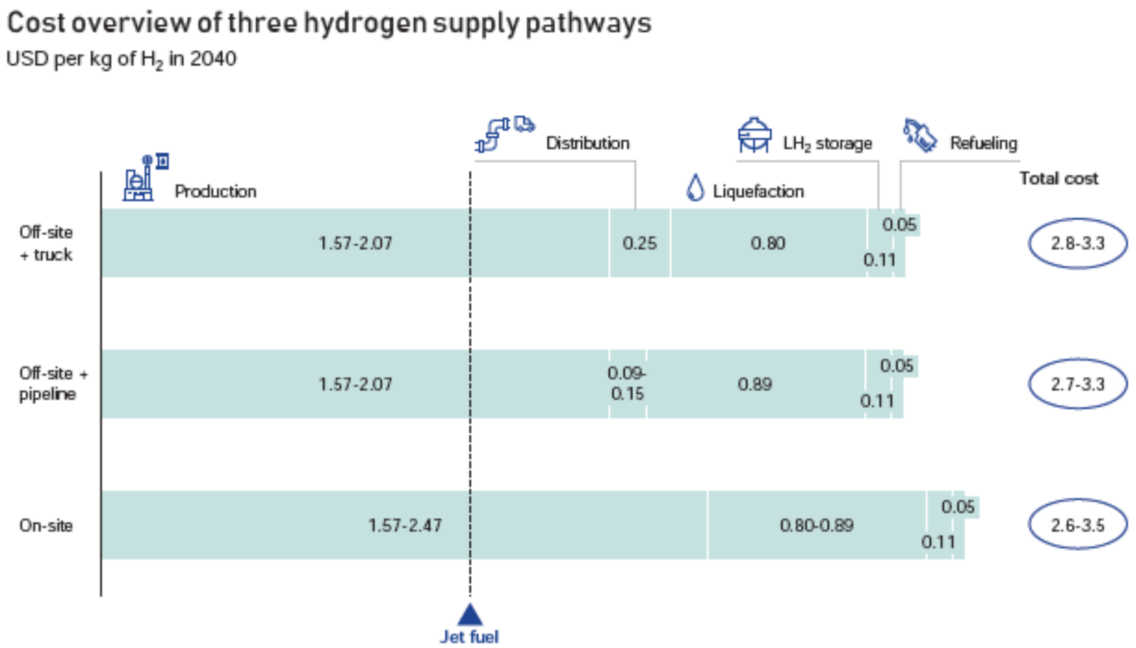


Figure 1. Cost of Hydrogen by 2040 as projected by the EU study. Source: EU.

Hydrogen production cost

When we talk about hydrogen production and its cost, we must separate the short-term and long-term goals.

Short term, we can accept that hydrogen comes from carbon fuels to build-up the eco-system. The whole system needs bootstrapping with adequate access to reasonably priced hydrogen.

The longer-term hydrogen production chain must transfer to non-carbon sources (or natural gas with carbon capture). Such investments are happening. The latest two weeks ago, when the Norwegian company Nel signed up to deliver 40-50MW of green hydrogen, produced through electrolysis from hydropower, to steel production in Norway. The present carbon-based energy for the steel plant emits 100,000 tonnes CO2 per year. The switch to green hydrogen energy will reduce this by 60%.

The most recent study on hydrogen production cost is the EU study; Hydrogen-powered aviation. Hydrogen produced in the quantities required for a green conversion of the transport industry, including aviation, would cost around $3 per kg by 2040, Figure 1.

The equivalent energy cost for Jet-A1 would be around $2 if the prices stay flat from today. Alternatives like synfuels would cost more than $4.

Figure 2 shows the long term evolution of fuel prices as projected by the EU study. Observe it’s per MWh, thus per unit of energy.

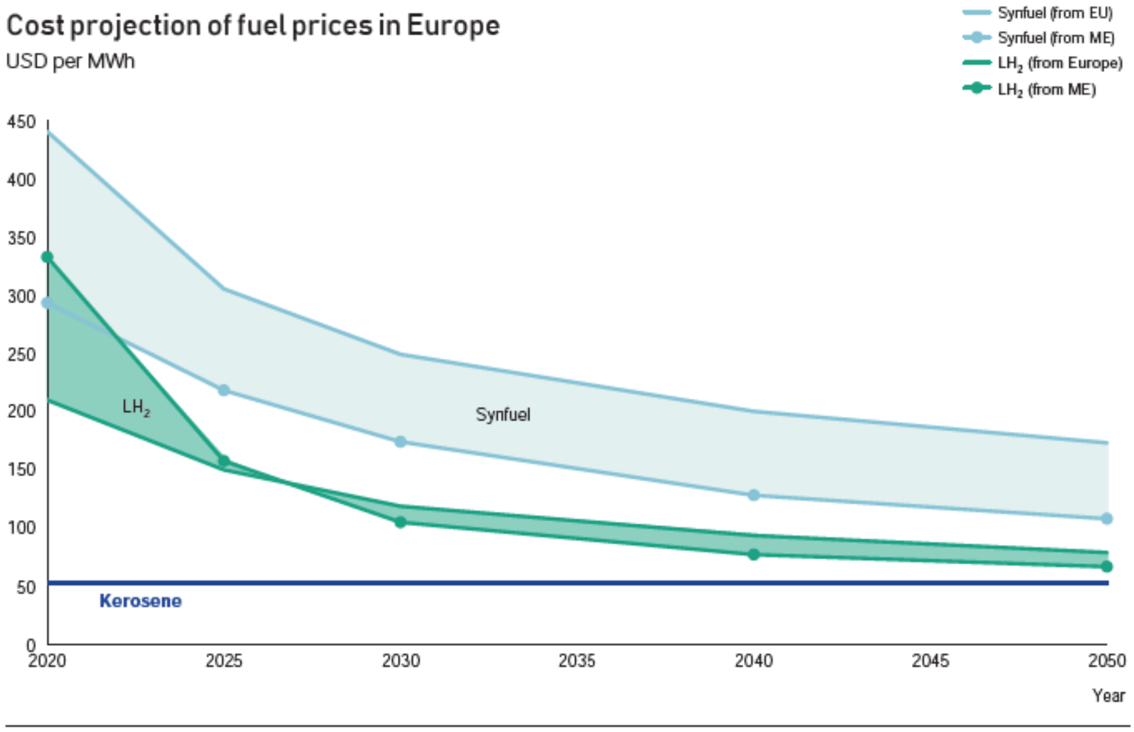


Figure 2. Long term development of fuel prices as projected by the EU study. Source: EU.

The projection builds on the continuation of today’s low fossil fuel prices. It’s then quite an achievement that sustainable energy production can come within 30-50% of the production costs of something that relies on Sun energy capture in nature over the last million years, now pumped up and burned off in a non-sustainable process.

The different production methods for green hydrogen needs development and built to scale to get to the above figures. But the change has started. The Nel electrolysis process referenced above will be more efficient than today's processes. And it uses renewable hydropower as the energy source.