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Hydrogen-powered ultralight training aircraft – a systems engineering approach

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Abstract

Aviation as a sector is responsible for an ever-increasing amount of emissions harmful to environment, including oxides and dioxides of carbon, nitrogen and sulfur, as well as water vapor. With current industry approach of slow creep into slightly higher inter-turbine temperatures and bypass ratios, improvements in turbine engines specific fuel consumption are stagnating with every new generation. To decisively close the pollution gap between reality and sustainability the aviation industry must shift to where automotive giants went decades ago – electrification of propulsion, and in particular, by introducing hydrogen as a fuel.

Application of hydrogen in aviation is nothing new – as early as in the 1970s serious resources have been put to use [1] into determining viability of using hydrogen as primary fuel for passenger airplanes. This idea seems to be reappearing in aviation experts minds like an unfortunate comet, with new wave of papers and research emerging every few decades [2], but no commercial projects have been introduced up to date. This is surprising considering wide use of hydrogen in electric cars and forklifts, and begs the question – why?

There are multiple possible answers to this question, but one seems to be dominating over the others – hydrogen in aviation has always been seen as a research project, and never as viable product. Technical barriers are both well-known and well-researched - hydrogen storage is problematic both as a gas [3] and liquid [4], and magnitude of infrastructure investment needed scares any serious attempts of commercialization. With lack of regulation for aircrafts and airports [5] most hydrogen-related projects were planned as research-only.

As serious as aforementioned barriers are, they can be broken using systems engineering approach [6] and Minimum-Viable Product development methodology.

Firstly, most important obstacles to commercialization are laid down, and abatements for all are proposed. The most viable Minimum Viable Product is determined to be a training airplane, developed in the ultralight category, propelled with electric motor, powered by a PEM fuel-cell stack, with hydrogen stored as a high-pressure gas in a composite tank onboard. This architecture allows for minimized impact of the aforementioned technical obstacles and gives a real chance of creating a competitive and economically viable product.

In conclusion, a conceptual framework is laid down, in which, with already existing technology, a hydrogen airplane can be worthwhile investment, and not only a dead-end research project.

Keywords: electric flight, hydrogen airplane, ultralight, training airplane, systems engineering

1. Problem statement – increasing aviation pollution

In 2018, aviation traffic broke an important barrier of emitting worldwide over **1 billion tonnes** of CO2. Although aviation was responsible for only 2.5% of global CO2 emissions (and all modes of transport constituting 15% [7]), its share is steadily increasing for as long as data has been gathered. This is especially concerning because of how many restrictions are put on how the industry operates and how the products look like. We cannot simply make airplanes lighter overnight in order to burn less fuel. Despite a big reduction in airplanes engines specific fuel consumption after World War II, recently it is getting harder and harder to push it even lower:

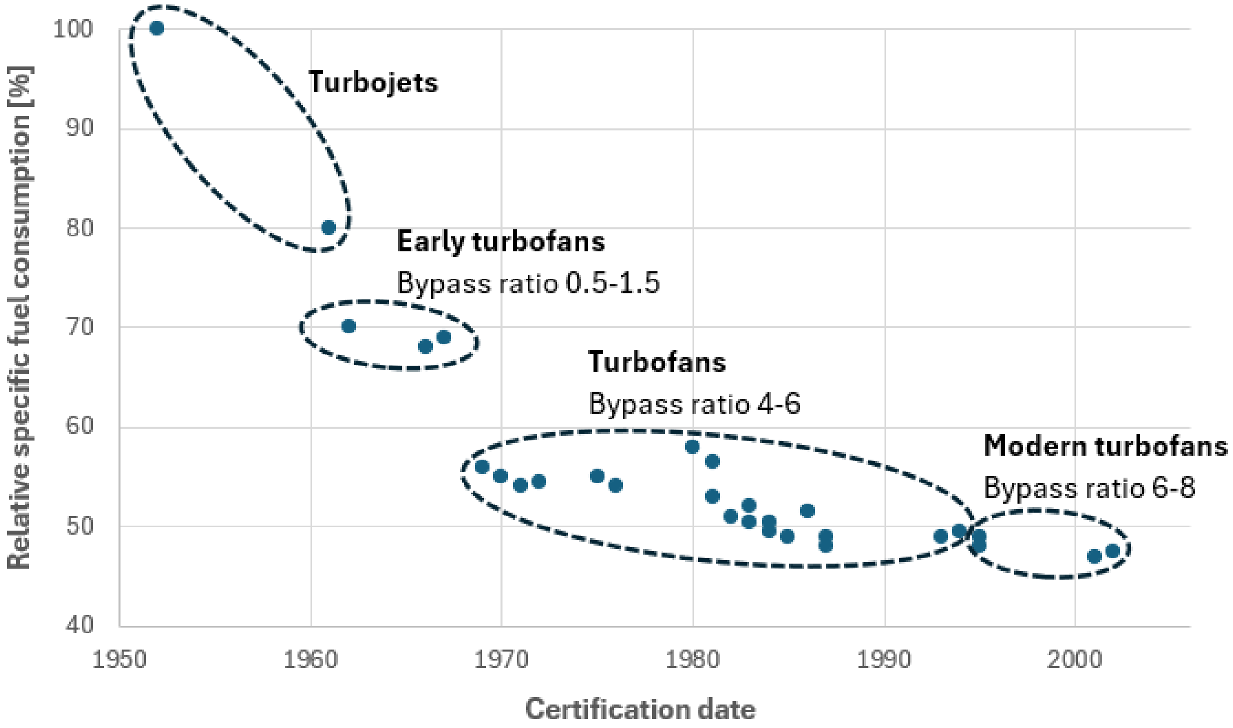

Figure 1 Relative specific fuel consumption for aircraft engines vs certification year [8]

With a tactic of creepingly increasing bypass ratios, implemented in last few decades, further significant cuts in fuel consumption are not imaginable with the existing technology. Aviation may not be the most carbonogenic industry in the world – but may just be one of the hardest to de-carbonize [9].

As the total number of passenger-kilometers was growing steadily post-World War II, so were the emissions. Even since 2008 total CO2 emissions increased yearly by about 4% [10][11] vs 5% increase in air traffic (still counted by passenger-kilometers). Note and important fact here - if the world stopped developing in 2008, and we used only the existing technology to cover the increase in air traffic, the emission increase would be roughly 5% too. Instead, with all the technological advancement, operational improvements, increased use of Sustainable Aviation Fuels [12] and other means, we managed to get it down to only 4%. This is by no means low – after all, 20% reduction in per-passenger-kilometer-emission is nothing to be ashamed of – but it just means it is not enough.

So – we have on our hands an industry with an immense and increasing pressure to reduce emissions, and technology that seems to be reaching its limitations. One possible solution, which will be further analyzed within this paper, is wide application of hydrogen in aviation.

1.1 Hydrogen in aviation

Hydrogen has the highest energy density by weight among all chemical fuels. As such, it was one of the primary energy sources considered in aerospace industry, where weight matters above all else. When considering weight taken on board, no other means of transportation eliminate waste in this area as ruthlessly as aviation, maybe with the exception of space exploration vehicles, which use hydrogen extensively.

Hydrogen, as every fuel, is only a storage for energy, and to access this energy must be put through a chemical reaction, most often with oxygen. There are two main ways to do it – either burning it in a combustion engine or using fuel cells to generate electricity. Properties of hydrogen as an element generate widely different set of issues for both of these technologies, so it is appropriate to approach them separately.

1.2 Hydrogen in turbine engines

When it comes to turbine engines using hydrogen, especially for aviation, general principles of the engine are not changing – take air from outside the airplane, put it through a compressor, burn in a combustion chamber and use power turbine to extract energy, powering a propeller or a fan. There are some differences however that prevent us from using the same engines for kerosene-based fuels and hydrogen:

- Hydrogen is burning at a higher temperature than kerosene-based fuels – ergo requires redesigning most of the main flowpath hardware and cooling systems to withstand higher working temperatures

- Hydrogen has a higher flame speed than kerosene-based fuels - this has implications for fuel system elements, especially valves and nozzles, and means an additional increase of working temperature for the flowpath hardware, as the flame is literally closer to the surface of the parts and coatings. This also means that hydrogen is flammable and prone to explosions in lower concentration than most other gases

One additional note is that hydrogen has a different mix of exhaust gases – obviously no carbon oxides are present, but its higher temperature of burning it increases the amount of nitrogen oxides generated. Vast amounts of water vapor generated also shouldn't be forgotten, as it can act as a greenhouse gas. Nonetheless, the basic goal of eliminating carbon emissions is met completely.

1.3 Hydrogen in electric engines

In general, electric propulsion has a much higher efficiency than combustion engines. When deciding to use hydrogen for an airplane it is logical to at least try applying electric motor before switching to a combustion engine, as the same issues with hydrogen storage and infrastructure must be resolved.

Hydrogen-electric architecture for aviation receives great interest since early 2000s, especially after successful adoption within the automotive industry. With much research already done, overall architecture and characteristics of the system as it is usually proposed are provided below.

There are several different kinds of fuel cells, but when considering temperature, weight and volume limitations, the only one practical one to use on airplanes are Proton Exchange Membrane Fuel Cells (or PEMFC). These fuel cells, working in temperature up to 120 degC, are the lightest per unit of generated power out of all existing fuel cell technologies.

Putting this into an airplane propulsion schematic, the following is its simplest form:

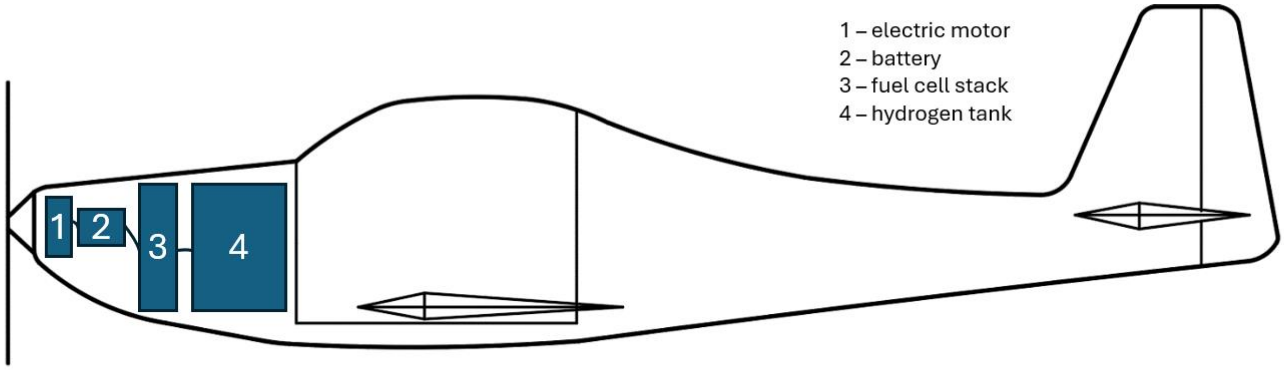

Figure 2 Hydrogen-electric airplane propulsion system

Hydrogen must be stored onboard, either as a liquid or gas, and then delivered to fuel cells stack, together with air from outside. Generated electricity powers an electric motor, which in turn powers a propeller or a fan, and excessive heat and water are dumped back to the atmosphere.

This simplified description is not including many other aspects of fuel cell operation, such as:

- Fuel cells have to be periodically cleaned to remove pollution from air or hydrogen and excessive humidity – this requires a precise FC stack management system
- Temperature and pressure of incoming air and hydrogen should be controlled if efficiency is to be maximized
- Fuel cells have inertia of about 1-2 seconds in reaction to power management system, which is too slow for any fast airplane power adjustment, ex. in emergency situations. Most often additional battery is implemented in the system between fuel cell and electric motor to cover short-time peaks in power demands
- Fuel cell stack efficiency is decaying with accumulated time of operation, but not far from degradation process of combustion engines

There are well-researched and documented examples of recently developed UAVs [13][14], moto-gliders [15] and airplanes [16][17] using hydrogen-supplied PEM fuel-cells in-flight (although again, no commercially available aircrafts up to date), the concept seems to be definitely viable from technical perspective then. In comparison to other possible ways to decrease emissions in aviation, it offers much faster and more complete advances towards carbon neutrality of air transport. However, the more we dig into hydrogen propulsion (either with a combustion engine or electrical motor), the more of the same issues are quoted as showstoppers for this technology – hydrogen storage problems, problematic airplane integration, lack of hydrogen production and distribution infrastructure and residual emissions of water vapor.

It is time to thoroughly review these obstacles and propose abatements for all of them.

2. Technical challenges for hydrogen propulsion in aviation

Hydrogen architecture in aviation seems to have an equal number of advantages and obstacles in front of it. After familiarizing ourselves with a concept of hydrogen propulsion in aviation next logical step is to review what is preventing it from on-mass implementation.

2.1 Hydrogen storage

Because of its molecular construction, hydrogen is highly problematic to store. In 1 atm pressure hydrogen remains a gas of very low density (0.0899 kg/m^3 vs ex. 0.717kg/m^3 of LNG). Cooling it all the way down to 20K temperature turns it into a liquid, but the density problem persists – liquid hydrogen is still at least 10 times less dense than kerosene (71 kg/m^3 vs 800 kg/m^3). Solid state is possible under the immense pressure of 400 GPa and further cooling down to only 14K, and density increases to only 86 kg/m3, making it one of the least dense solids as well.

This density problem means that despite hydrogen's high energy density per-weight, when recalculated into volume – numbers look drastically different:

Table 1 Energy density comparison of different fuels

Fuel	**Energy Density [MJ/kg]**	**Energy Volumetric Density [MJ/litre]**
Hydrogen (Gas at 1 bar)	*120*	*0.1*
Hydrogen (Gas at 300 bar)	*120*	*3.03*
Hydrogen (Gas at 600 bar)	*120*	*6.06*
Hydrogen (Liquid)	*120*	*8.49*
Jet-A Fuel	*45*	*34*
Gasoline	*44*	*31.5*
Diesel	*46*	*35*
Ethanol	*28.8*	*20*

Now it becomes apparent why in the two big studies from Lockhead Marting [1] and Airbus [2] hydrogen was stored in liquid form in a cryogenic tank. With high power required for these applications only cryogenic storage made technical sense.

Summarizing the challenges then:

- Hydrogen as a gas required very high pressure storage, which the increases mass of fuel tanks, at least partially denying weight advantages coming from hydrogen properties
- Hydrogen as a liquid requires cryogenic tanks and consumes energy to maintain about 20K temperature. Additional energy is then required to boil it off before passing to either a combustion chamber or fuel cell stack

As unimpressive as this comparison looks at the moment, it should be kept in mind that conventional storage of electric energy in batteries is even less effective than gaseous hydrogen (about twice higher volume and four times higher weight for the same amount of energy stored [18]).

It is also worth to remember one peculiar property of hydrogen – how small its particles are. Thanks to being number #1 on periodic table atoms of hydrogen are small and very penetrative. Even with the best possible sealing technologies it is just hard to keep them in any container – another consideration for safety of hydrogen on-board.

Outside of storing hydrogen as liquid and gas, there are multiple alternative ways of storing it by bending to a metal surface (adsorption) or to the metal itself (absorption). Such storage is called metallic-hydrogen storage. However, so far all properties of this solution point to a far lower energy density than high-pressure gas or liquid storage, and for aviation purposes using them is excluded from further consideration within this paper.

Summarizing the storage problem – from both previously cited research and more recently published analyses [19][20][21][22][23] comparing storage means for electrical energy for aviation and analyzing aviation-specific problems of hydrogen storage (both as gas [24][25] and as liquid [26][27]), the following conclusions can be made:

- Comparing to currently used kerosene-based fuels, hydrogen systems have a lower energy density and energy volumetric density. However, when compared to batteries, their capacity for storage is much higher, therefore should be a preferred choice for powering electric airplanes (at least from the technical standpoint)
- When using hydrogen in aviation, two ways of storing are available – high pressure gas tanks or cryogenic liquid tanks
- Cryogenic liquid storage is more weight- and volume-efficient, but requires a number of supporting systems to maintain cryogenic temperatures. These cooling systems are not scaling well into small applications, but do comparatively better in larger airplanes
- Based on that, it is generally accepted that gas storage should be used for light and ultralight aviation applications, while liquid storage is applicable to all larger constructions

Drawing a precise line between gas- and liquid-based hydrogen propulsion systems depends on multiple assumptions regarding efficiency of all system components, energy and power density, mission-specific requirements for the airplane (such as range and duration of flight) and many others. Sometimes even non-technical arguments must be taken into account, such as available airport infrastructure (gas hydrogen requires more storage volume on the airport) or weather parameters (cryogenic temperatures are easier to maintain in colder climate).

2.2 Airplane integration challenges

Integration of hydrogen propulsion into an aircraft comes with a set of technical challenges. Some of them are a feature of hydrogen propulsion system itself, other come from its interfaces with and integration into an airplane structure.

The main challenges posed by the integration of hydrogen propulsion in aviation are:

2.2.1 Weight and volume characteristics of hydrogen propulsion system components

As described above, hydrogen propulsion system components can have a considerable weight when compared to other aircraft elements or even the whole structure. Additionally, some of them cannot be shaped freely, but instead are limited to only slightly modifiable shapes.

Pressurized tanks come with severe limitations to their shape. Generally, in order to maximize fuel/tank weight ratio, tank shape should be as close as possible to spherical, which minimizes tank surface (and hence its weight). This is true for both gas and cryogenic liquid tanks, although for different reasons. For gas tanks structural integrity of the tank, keeping high pressure inside, favors tank surface to be minimized as it allows more material to work against elongating force, and not bending force. For cryogenic liquid tanks, the surface must be minimized in order to limit heat exchange with the outside, which is much warmer, hence reducing energy spent on keeping the tank in a cryogenic state.

In practice, the most common are cylindrical tanks, since a spherical share is difficult to manufacture and hard to integrate with other elements. Cylindrical tanks, especially with low L/D ratio, are usually placed inside the fuselage, since putting them outside would significantly increase the drag of the aircraft. However, filling the fuselage with large hydrogen tanks comes at a price too – after all something must be removed for something else to be put in, and this something is most often space for passengers, making this solution less economically viable. This is a big disadvantage of hydrogen solutions in comparison to kerosene-based fuel, which is often placed in variable-geometry tanks inside different elements of wings and fuselage, literally filling the space that would remain empty otherwise.

For hydrogen combustion solutions, this is the end of limitations, since after leaving the tank, hydrogen passes through fuel lines to the engine, both of which are fairly similar to currently utilized solutions.

For hydrogen-electric propulsion, next element in the system is a fuel cell stack with all supporting infrastructure. The shape of the stack is rectangular, which is helpful in terms of integration with other elements, but its size is strictly defined by current/voltage requirements and cannot be changed without altering those. Air must be provided to it, and excessive heat and water vapor removed, which limits its placement within the aircraft infrastructure. Finally, powerful electric cables must connect it with an electric motor, so nearby placement is preferred, as it reduces overall weight of propulsion system (this same may be said about hydrogen tank, although to lesser extent, as fuel lines are usually lighter and allow for more shape modifications than high-voltage electric cables).

Last but not least, an electric motor is roughly cylindrical, but its weight and volume are much less than these of an combustion engine of comparable power. It also generates much less heat and vibrations, doesn't require supplying air from the outside or exhaust to remove combustion products. In this aspect, hydrogen-electric propulsion has big advantage over conventional airplanes propulsion, where engine placement and integration to abate for its imperfections are of primary importance during design process.

2.2.2 Hydrogen leaks

The next feature to be addressed are hydrogen leaks. As mentioned before, due to its chemical properties, hydrogen is prone to leaking from tanks and valves. This may mean either unwanted circulation of hydrogen within the propulsion system when it is supposed to be shutdown or even accumulation in undesired spaces, posing a risk of fire or suffocation to crew or passengers.

Hydrogen circulation in a propulsion system is mainly a concern of losing fuel in an uncontrollable way, which is never optimal. Self-ignition in combustion engine or generating current in fuel cell are not likely, since both require delivering air from outside to support the reaction. Hydrogen accumulation in turn is equally unlikely precisely because it has the aforementioned properties – when leaking from a fuel system it has strong tendency to leak outside of the aircraft too, instead of accumulating inside.

As for the risk for humans onboard, hydrogen is not directly toxic, and excluding the risk of open flame or explosion, both of which are not likely for concentrations below 4%, the only real risk of suffocation occurs only if hydrogen concentration in air is high enough to decrease oxygen concentration below breathable levels. In this regard, it is no different than any other gas.

2.2.3 Temperature requirements

To summarize the earlier discussion, the only element generating a significant amount of heat is in hydrogen propulsion (other than combustion engine of course) is fuel cell stack. However, PEM fuel cell stacks have been re in use for a long time, including wide range of space and automotive industry applications, and current cooling systems are tackling the problem well.

A hydrogen combustion engine is assumed to have heat rejection close enough to currently utilized turbofans and as such does not require a separate analysis here.

The last part to consider is a cryogenic liquid tank, which should be separated from any big sources of heat, in order to reduce boil-off of hydrogen and energy consumed to maintain the cryogenic state.

2.2.4 Pressure requirements

When hydrogen is stored as a gas, only tanks with the highest possible pressure should be considered. As shown before, hydrogen is losing a lot of its advantages when stored at low volumetric density. However, this is increasing the risk for crew and passengers during flight, as well as for ground crew and operators, since any damage resulting in breaking the tank integrity can have the worst consequences. This balance must be carefully considered when designing the system and all possible precautions against overpressurizing the tank (limiting heat rejection to it, redundant safety valves, structural supports and protections) should be applied when needed.

For cryogenic liquid tanks, risk of overpressurizing is lower and easier to manage with controlled boil-off and low gas pressure in the system. Nonetheless, it should not be neglected, as high temperature gradients within the system are more likely to generate defects and damage over time.

2.2.5 Airport infrastructure

The high cost of world-wide implementation of hydrogen airport infrastructure remained the most often cited roadblock to hydrogenization of air transport. Even assuming a slow and gradual implementation, the minimum steps are still very extensive:

1) Introducing policies and regulations allowing for an actual implementation of hydrogen as an aviation fuel [28]. This includes the certification of propulsion systems, engines and airplanes, handling and maintenance requirements as well as the airport infrastructure itself (relevant ISO regulation 15594 was withdrawn in 2004 [29]), finally policies and incentives from major governments and international organizations, making the early implementation cheaper and more accessible for early technology adopters

2) Increasing the production of hydrogen from renewable sources to cover the future demand – this is following the example of SAF, where too low of an output generated a loss of interest in technology and flatlined its advancement. Using currently available numbers for hydrogen production, the following conclusions can be made:
    - According to IATA predictions [30] global consumption of kerosene in 2024 will be roughly 100 billion US gallons, so about **300 billion kg** total
    - Assuming energy density of 43 MJ/kg, this gives a total number of **13 trillion MJ**
    - Hydrogen combustion systems have similar total efficiency as currently utilized turbofans. Hydrogen-electric propulsion systems have a much higher efficiency, but this gain may be reduced by overall challenges of handling and distributing hydrogen worldwide, especially in cryogenic state. For the sake of this simplified estimation, all efficiency impacts will be then neglected
    - Using hydrogen energy density of 120 kg/MJ, that leaves us with a total, worldwide demand of just about **109 million tonnes of H2** yearly if we wanted to replace all kerosene use with hydrogen propulsion
    - Current worldwide production of hydrogen is about **75 million tonnes** yearly, out of which only **1-3 million tonnes** can be considered “green”, depending on criteria applied [31]. Production-demand gap is therefore very significant and can be a potential showstopper
    - Additionally, it must be considered that for majority of this process of increasing production capabilities, “green” hydrogen will still be more expensive than conventionally produced

3) Developing a distribution network from hydrogen production facilities to at least the majority of big airports worldwide
4) Installing hydrogen storage and refueling infrastructure withing the airports

Even when assuming that some part of aviation, especially smaller airplanes, can still use fossil fuels for a long time after the adoption of hydrogen, hence limiting the airport infrastructure investment to only major passenger airports, this task is gigantic, and even without any detailed assessment available it is safe to assume that it would take billions of dollars and decades of time to implement.

2.2.6 Residual water vapor emission

While advantages of eliminating carbon oxide and dioxide emissions are undoubtful, it cannot be forgotten than using hydrogen either in a combustion or electric propulsion system results in significant emissions of water vapor. One must remember than when 1kg of hydrogen is burned, 9kg of water are produced, which (continuing the example from above) gives a total number of **1 trillion tonnes of water vapor** emissions yearly. While the overall impact on the climate and environment still seems to be undoubtfully positive [32], parallel research should be continued to mitigate the impact of increased water vapor concentration in the atmosphere, should a hydrogen solution be adopted widely.

The topic of increased contrails when using hydrogen is purposefully not discussed, as at the moment it still lacks proper research and decisive conclusions about environmental impact.

3. Hydrogen aviation Minimum Viable Product

So far, three main barriers have been identified that prevented the widespread implementation of hydrogen aviation – hydrogen storage problems, lack of hydrogen infrastructure and problematic airplane integration.

In this chapter, a Minimum Viable Product (MVP) approach will be used in order to determine the most suitable platform that would serve as the first step to commercial hydrogen aviation.

3.1 Hydrogen aviation Minimum Viable Product approach

First step to make hydrogen aviation a reality is to define a product which will be the easiest to introduce on the market. Following all great innovations, the initial shock of each is greatly lessened if potential clientbase can familiarize themselves with it piecemeal, starting with the smallest steps feasible. Therefore, the first introduction of hydrogen aviation shouldn't be a fast and wide-scale replacement of major airliners with hydrogen alternatives, but – just as with SAF – slow, step-by-step transition, and if the first step is too ambitious, it is unlikely to gather appropriate support. It is imperative to remember that it is a major modification of existing technology and every major stakeholder is likely to oppose it:

- Existing airplane production companies will fight to remain on the market
- Regulators will not prepare new regulations unless under immense pressure
- Public opinion – realistically speaking airlines customers – will not support an innovation which is too unfamiliar with or viewed as less safe to use

Another consideration is simply the cost – a hydrogen airliner is a program requiring hundreds of millions of dollars, while a smaller airplane will be much less expensive. It would be great to live in the world in which innovation is not limited by available funds, but this is simply not the case.

All these considerations – the cost of introduction, amount of regulation to be re-written, competition from already established aviation market giants – are favoring a small and light airplane over big airliners as the MVP for hydrogen aviation. Based on this, we can formulate a requirement that this product should be a Light or Ultralight category General Aviation (GA) airplane.

Requirement #1 – Light or Ultralight category GA airplane

3.2 Hydrogen storage

The second issue to address is - which hydrogen storage method and propulsion type should be used?

Based on considerations in previous chapter and the first defined requirement above, it can be assumed that for a Light or Ultralight category airplane storing hydrogen as a gas in pressurized tanks is the most feasible solution. As for the propulsion type – combustion or electric – it can also be decided purely based on the size of the airplane. Light or Ultralight airplanes generally don't need much power in comparison to airliners, and tend to use propellers instead of turbine engines. These two characteristics strongly point to using electric propulsion with a propeller as main source of power to move the considered aircraft.

Requirement #2 – Hydrogen-electric propulsion system with high-pressure gas tanks

3.3 Hydrogen infrastructure

The cost of hydrogen infrastructure in case of the widespread implementation on the airports will be, to say the least, gigantic. A major limitation is that airplanes – in opposition to cars – are traveling to many different places during its utilization. With automobiles, it is much easier to put a number of gas stations around a certain area and *voilà* – everyone in this area can now drive hydrogen cars. With airplanes modifying only two airports is a significant investment and it still limits a number of itineraries to be served by hydrogen aviation to 1. Airplanes from the biggest manufacturers are sold worldwide, therefore nothing short of at least 50 biggest airplane hubs adaptation is likely to appeal to the industry as a sufficient incentive to work on hydrogen airliners seriously.

An alternative strategy could be adapting only one airport with hydrogen infrastructure and limiting airplanes to start and land on this one airport. This sounds ridiculous for most aircrafts, but accidentally it is exactly what most training airplanes do. Obtaining a touristic or commercial pilot license requires a high number of hours spent flying, and most of these hours can be spent on only one airplane, one airport. This allows to greatly limit the cost of infrastructure investment required for our MVP and seems to be the only sensible strategy to use without billions of dollars available at hand.

Additional note can be taken about the amount of fuel – training airplanes are almost exclusively 2-seaters certified in Light or Ultralight category, which use much less fuel than bigger passenger airplanes. This limits the amount of hydrogen needed and is unlikely to cause any supply-demand issues with regular deliveries of fuel.

Requirement #3 – Training airplane, 2 seater

3.4 Propulsion system integration

As with the integration of every two complicated systems, it is best to combine an airplane and its propulsion at the very beginning of the design process. This allows to create much leaner and more optimized design, where major faults can be detected and abated for early in the product development.

A major issue with hydrogen projects flying up to date was that most of them (Martin B-57B, Tu-155, ENFICA-FC) were adapting already existing constructions into hydrogen airplanes. This results in highly sub-optimal integration of the propulsion system into airplane infrastructure and elimination of a big portion of advantages coming from using hydrogen propulsion. The only exception – HY4 project – was purely research in nature and didn't have any commercial mission defined.

An airplane designed from the very beginning with a strong intention of adapting hydrogen propulsion is much more likely to fully show its advantages and to mitigate any shortcomings.

Requirement #4 – airplane designed from the start to integrate hydrogen propulsion system

3.5 Summary

In the world of ever-increasing care for the environment, there is no doubt that aviation emissions must be reduced. The most viable long-term alternative to currently utilized combustion engines seems to be hydrogen propulsion, involving either combustion engines or fuel cells and electric motors.

After reviewing all challenges and limitations of this technology - hydrogen storage problems, lack of hydrogen infrastructure and problematic airplane integration being the most significant – it appears that overcoming them is possible, but at significant cost, measured both in money and time. As a first step of implementation, a Minimum Viable Product is proposed for hydrogen aviation, with the following definition:

Light or Ultralight category training airplane powered with hydrogen-electric propulsion system (consisting of propeller, electric motor, PEM fuel cell stack and supplied with gas-hydrogen stored in *high-pressure tanks) designed from the beginning to optimize integration of hydrogen propulsion.*

This definition allows to abate for all challenges discussed within this paper and gives the best chances of success in commercialization attempts of hydrogen aviation. Further research work is needed to define detailed requirements for this airplane and regulatory conditions that would make it certifiable.

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