HYDROGEN-ELECTRIC AIRPLANES:

A Disruptive Technological Path to Clean Up the Aviation Sector

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INTRODUCTION: Recently, the COVID-19 pandemic has been a painful reminder of the vulnerability of the aerospace industry. It is currently facing challenges with costs, expensive fuels, and carbon emissions. In recovering the industry, regaining its competitiveness, and addressing future climate goals, an unprecedented revolution is needed. The aviation sector is at a crossroads, and several international agencies have put forth radical goals for its future. Sectors that were hardest hit by COVID-19 require particular attention and must be prioritized. In June 2020, the European Union issued an urgent call for a green recovery of air travel due to the heavy impact on the sector. An aggressive timeline was put forth pushing hydrogen-powered aviation as a commercial product for the commuter-, regional- and short-range segments before 2035. It seems as if the pandemic that has disseminated the aerospace sector has accelerated to prospects of sustainable aviation. Investment decisions are on the rise, where the French government plans to invest 17 billion dollars in aviation over the coming years.

The radical shift in focus toward hydrogen-based aviation has also been observed from airplane manufacturers. Rolls Royce and Airbus recently canceled their joint E Fan-X project of a hybrid-electric demonstrator – one year before the planned virgin flight. The decision gives a hint of their disruptive shift in focus toward hydrogen-powered aircraft. Still, their preliminary results gave interesting insights into individual components technologies. One of them was the world's most powerful aircraft generator (Mark I) built by Rolls Royce Electrical Norway in Trondheim[1] (completed in August 2019). However, it is well understood that the E Fan-X

[1] "J. K. Nøland, et. al., "*High-Power Machines and Starter-Generator Topologies for More Electric Aircraft: A Technology Outlook*", IEEE Access, vol. 8, pp. 130104 - 130123, June 2020.

series hybrid-electric architecture did not put forth sufficient levels of improvements needed in the next years to recover the aviation sector. The complex partial solution of electric hybridization of conventional technology can only reduce gross emissions by at least 10 percent, with a potential of 50 percent. According to Airbus, they have recently attracted attention to fuel cells, either for electric propulsion or for their auxiliary electric systems. In addition, Airbus looks at the potential of hydrogen (H_2) combusted in modified gas turbines. Both of these concepts can be explored in hybrid- or turbo-electric variants with batteries merely as an energy buffer rather than as a large-scale energy storage. Figure 1 illustrates the future projection of electric aviation is toward higher levels of electrification, where hydrogen is the key enabler. The total propulsion power of today's aviation is far greater than the electric power currently installed (electrification for auxiliary services). In future all-electric aviation, the electrification would potentially increase by 50 to 100 times compared to today's levels.

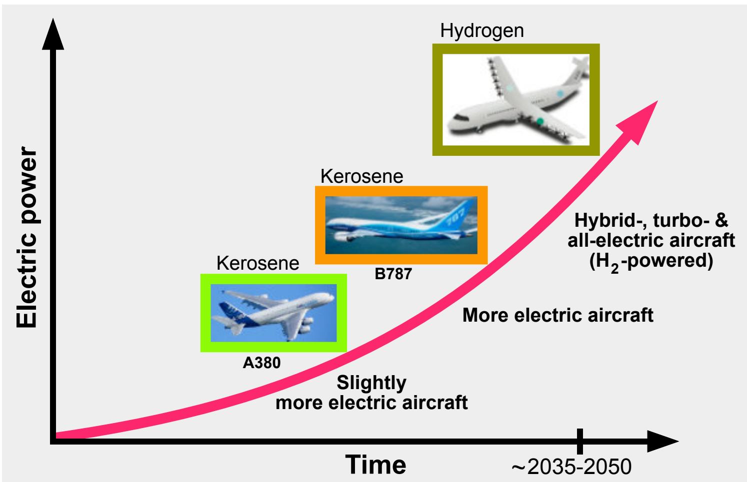

Figure 1 Progression toward the future electrification of aviation (approx. 2035-2050).

A report (ordered by EU) prepared by McKinsey published in May 2020 concludes that "*H_2 combustion could reduce climate impact by 50 to 75 percent, and fuel-cell propulsion by 75 to 90 percent*" [2] and argues to go for a radical shift to reduce the future climate impact of aviation.

[2] "*Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050*", https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf, May 2020.

It is shown that the use of hydrogen as a non-drop-in fuel is cheaper than synfuels for aircraft segments up to the medium range (250 PAX, 7000 km).
According to conventional aircraft development cycles, new platforms are usually introduced every 15 to 20 years. The next window of opportunity is expected to be in the time frame between 2030 and 2035. This is the needed time to go through the phases of conceptualization, development, certification, and aircraft handover. The McKinsey report conceptualizes a future 2050 scenario, where 40 percent of all aircraft could potentially be switched to liquefied hydrogen (LH_2), yielding an impressive decarbonization result. Already by 2035, the needed supply infrastructure for LH_2 could be available for H_2-aviation to be introduced large-scale.

Hydrogen (H_2) is currently 4 to 6 times more expensive to produce than conventional jet fuel (kerosene). Historically, the cost and availability of H_2 have always been a limiting factor. However, it is expected to decrease to a factor of 1.5 to 2 times the cost of kerosene in the long term as we are approaching 2050. This is illustrated in Figure 2, where different scenarios for the equivalent energy costs of LH_2 is compared against jet fuel. It is assumed a flat development of kerosene's energy-equivalent costs. However, according to the EIAs oil price reference, it is predicted that kerosene prices might as well increase. The cost projection highlights the fact that the cost will behave differently depending on the geographic region, as the production of hydrogen is ramping up. Due to the availability of solar renewable energy sources, H_2 will be produced cheaper in the Middle East rather than in Europe. Figure 2 highlights a study of the production of gaseous hydrogen in Texas in 2050, in which the costs will highly depend on the demand. If all the cheap sources of clean H_2 is already taken, the costs for further expansion in demand will increase the costs. In addition to the cost reductions needed and predicted, H_2-powered aircraft would also need ultra-efficient energy conversion solutions to sustain further and develop a cost-competitive fuel economy. It is worth noting that LH_2 can only play a role in aviation segments, where it is the most cost-efficient solution to reduce climate impacts. According to the recent EU report[1], H_2 could replace all aircraft segments up to the 10000 kilometer-range after 2028-2038. While synfuels and biofuels would handle the long-range segments, 40 percent of aviation could be fueled by LH_2 by 2050. Unfortunately, synfuel requires an additional processing step and will be structurally more expensive than H_2.

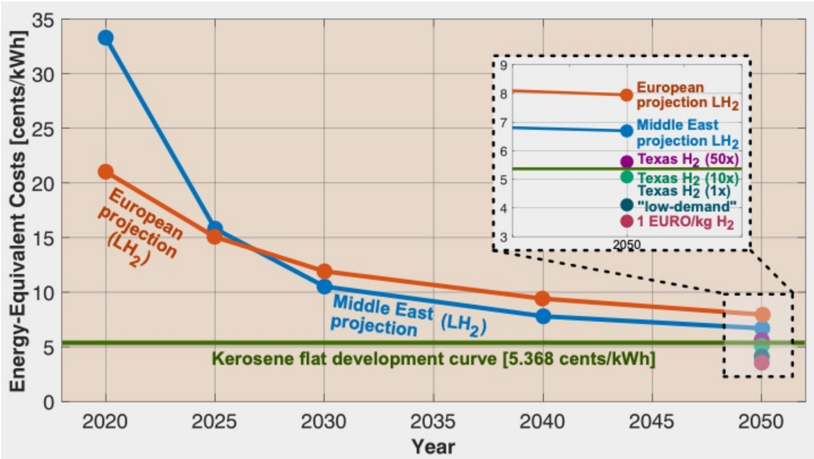

Figure 2 The future projection of the equivalent energy costs of liquefied H_2 toward 2050. The data are based on the methodology employed in "*Hydrogen-powered aviation – A fact-based study of hydrogen technology, economics and climate impact by 2050*" [1]. The scenarios for H_2 costs in Texas in 2050 is conducted by the Electricity Markets and Energy System Planning (EMESP) at the Norwegian University of Science and Technology (NTNU) based on available data from the United States Environmental Protection Agency, Documentation for National Electric Energy Data System (NEEDS) v.5.13 (2019), https://www.epa.gov/airmarkets/documentation-national-electric-energy-data-system-needs-v513.

It must be stressed that the exciting opportunity given by H_2-aviation may be one of the last chances left to address climate change in the aviation sector. By considering the "business as usual" projection, the industry will grow by 3 to 4 percent annually with an efficiency improvement of 2 percent per year. Air travel is currently the fastest-growing mode of passenger transport. As a result, the climate impact would be twice as high by 2050, contributing to 24 percent of global CO_2 emissions in contrast to 3 percent of today. Moreover, it is important to recognize that the total emissions would go beyond pollutants like CO_2 and NO_X. They also include soot and water vapor, which can cause contrails and cirrus clouds. The only "true-zero" alternatives are fuel-cell electric and battery-electric concepts[3].

[3] A. Schafer, et. al., "*Technical, economic & environmental prospects of all-electric aircraft*", Nature Energy, vol. 4, no. 2, 2019.

HYDROGEN AS A KEY DISRUPTOR

Hydrogen (H_2) is the most abundant element in the universe and a great energy carrier but must be pressurized or liquified to be effectively stored. It can be burnt cleanly, but is flammable and can be ignited by a small amount of energy. As shown in Figure 3, H_2 has significantly higher gravimetric power density than battery-electric and traditional kerosene-based solutions, which has the potential to reduce the overall weight of the fuel onboard.

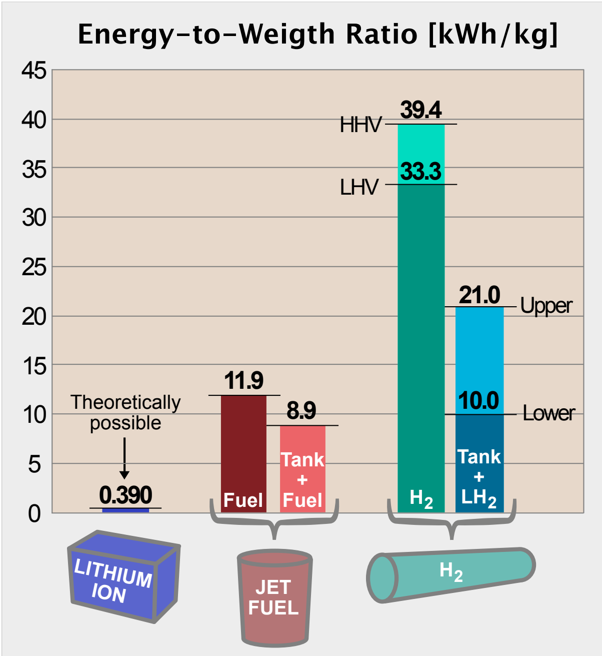

Figure 3 The specific energy density with respect to weight of different aviation fuels. The lower heating value (LHV) of H_2 is about 3 times higher than traditional kerosene (jet fuel) and about 85 times higher than the theoretical maximum of lithium-ion-based batteries. The power density taking the weight of the storage into account is based on the information given in the Roland Berger report, "*Hydrogen – A future fuel for aviation*".

However, the volume needed to store H_2 is a major issue that makes the aircraft bulkier. A potential increase in the size of the airframe affects the drag that must be compensated with more thrust. In fact, bulky shapes are not a dream scenario for aircraft designers. In order to reduce the space required to store the fuel, liquid storage is the preferred solution. It is highlighted in Figure 4 that liquefied H_2 is one-half of the volume of compressed H_2. It is also up to 3 times more size-efficient than today's batteries. However, it requires at least 4 times more space than kerosene, but the weight of the storage medium is approximately 3 times lower. Moreover, the tanks needed to store LH_2 can be made significantly lighter than storing gaseous H_2. Still, LH_2 would require a slightly adapted fuselage and airframe. There is currently ongoing progress toward the tube-and-wing design for future H_2-aviation.

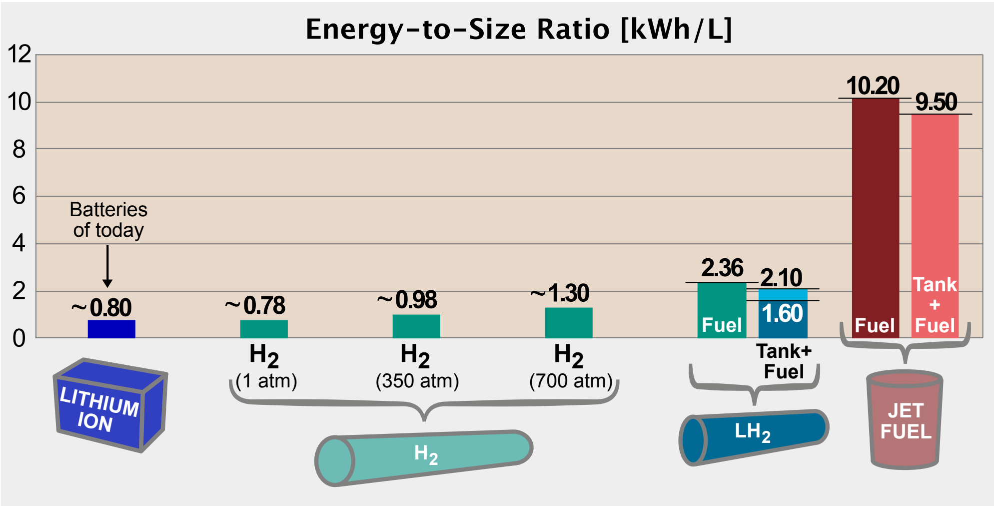

Figure 4 The specific energy density with respect to volume of different aviation fuels. The lower heating value (LHV) is used for H_2 and LH_2. Different pressures of H_2 is compared with cryogenically cooled LH_2.

Any improvement in weight helps to reduce the required lift of the aircraft. In addition, a less bulky and compact body will reduce the energy consumption associated with the aerodynamic drag. This issue is illustrated in Figure 5, where the different forces acting on the aircraft body is depicted in a free body diagram. According to conventional designs, classical H_2-powered aircraft bodies tend to be heavier and bulkier, which requires more energy to propel. However, there are different radical design approaches that are proposed to mitigate some of the major propulsive issues. Revolutionary concepts introduce new designs from scratch, including 1) blended-wing-body designs, 2) lift-optimized distributed propulsion, 3) drag-optimized boundary-layer-ingestion, and other techniques to achieve highly efficient aerodynamics. However, the drawback of this more radical path is the long and unpredictable process toward commercialization. A more pragmatic evolutionary approach yields a faster entry-into-service H_2 solution. Still, higher costs of H_2-powered aircraft is due to the integrated LH_2 tank structure, which increases the complexity of the fuel distribution system and the overall size of the aircraft. The main drawback of LH_2 is the fact that the heat transfer from the tank must be minimized to avoid vaporization and to make the fuel remain cold. The tanks are strategically designed with spherical and cylindrical shapes to keep losses at a minimum. In achieving an optimal integration of the tanks in the fuselage (e.g., 10% volume extension)., the frame of the aircraft must be extended, which makes the empty operating weight (EOW) larger.

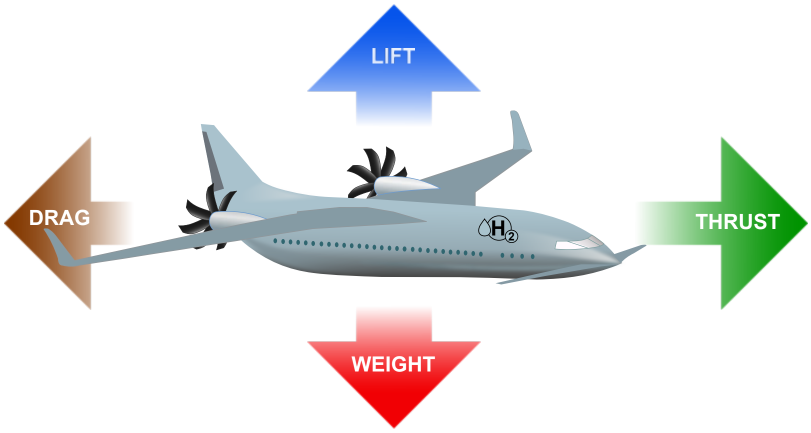

Figure 5 Free-body diagram of an envisioned H2-powered aircraft showing the impact of weight on the required lift and the bulkiness on the drag that the airplane must overcome.

Current challenges, targets and opportunities

A big challenge with battery-electric solutions is their inherently slow fueling rates when considering their feasible charging power capabilities. This would demerit them to be used as the main energy storage and the sole power source in future large aircraft beyond the commuter segment (19 PAX, 500 km). On the contrary, H_2 as a non-drop-in fuel (i.e., not compatible with conventional fuels) has this potential as it allows fast refueling times and massive storage of energy, and it can be harvested from non-carbon sources. The turnaround times of H_2-aircraft is slightly longer, which only causes 5 to 10 percent fewer flights per year with the same airplane, compared to kerosene aircraft. However, improving the competitiveness of the refueling time will be an important challenge in the future. Even though battery-electric solutions are favorable for smaller airplanes[4], batteries will still play together with H_2 in advancing future large-scale aviation technologies. They can be effectively used as an energy buffer for peak-shaving and to achieve higher power capabilities during take-off.

[4] P. J. Ansell & K. S. Haran, "*Electrified Airplanes – A path to zero-emission travel*", IEEE Electrific. Mag., vol. 2, no. 2, June 2020.

The best imaginable way to utilize future air transport in a radical fuel-saving way is to go for fully electric propulsion. H_2-power solutions have been targeted to be best suited for the commuter, regional, short-range, and medium-range aircraft. For example, the fuel-cell-based electric propulsion can reduce the climate impact by 75 to 90 percent, and it has been proposed as the best solution for commuter and regional aircraft. In addition to the potential to reduce emissions, they can also improve the overall efficiency during different phases of the flight by taking advantage of the benefits of electric propulsion. The EU program targets for fuel improvements and emission reduction in different segments[5], as outlined in Table 1 below.

Table 1 The EU program Clean Aviation targets on future developments[5]. Future goals highlighted in yellow.

Aircraft Class	PAX	Range	Global fleet	CO_2 share	Emission reduction	Fuel reduction	Target year
Commuter	<19	<500 km	4%	<1%	-87 to -100%	n/a	2030+
Regional	20-80	<2000 km	13%	3%	-90%	-50%	2035
Short Range	81-165	<4500 km	53%	24%	-86%	-30%	2035
Medium Range	166-250	<10000km	18%	43%	-86%	-30%	2035
Long Range	>250	<18000 km	12%	30%	-86%	-30%	2040

For commuter aircraft, full-electric concepts, including fuel-cell and battery-based concepts, will be key solutions to address the goals. Moreover, for the regional segment, the focus will be placed on highly efficient configurations, including distributed propulsion, fuel cell electric solutions and hybrid-electric arrangements. For short- and medium-range aviation, advanced ultra-efficient and radical approaches will be needed to address the goals. Finally, for the long-range segment, drop-in sustainable aviation fuels (SAF) will be needed.

Table 2 below showcases a summary of three hydrogen-electric aircraft designs for commuter, regional and short-range segments, respectively. All three cases are based on fuel cells as the main source for electric propulsion during cruise mode. The superior efficiency of the fuel cells

[5] "*Strategic research and innovation agenda - The proposed European Partnership on Clean Aviation*", May 2020 http://clean-aviation.eu/files/Clean_Aviation_SRIA_R1_for_public__consultation.pdf

causes the energy demand to be reduced by 10, 8, and 4 percent, respectively. In addition, all concepts radically reduce the climate impact, with complete elimination of CO_2 emissions. In order to reach beyond the smaller segments, revolutionary aircraft designs would be needed to make H_2 competitive for medium- and long-range categories beyond 10000 kilometers. For other segments, there are no limitations on the range. Battery-electric is limited to ranges up to 500-1000 kilometers due to lower battery energy density. Moreover, they have limited life cycles and still suffer from low gravimetric power density of 0.2 to 0.5 kWh/kg, which reduces their potential for larger airplanes. However, they have the best achievable climate impact since they cause no emissions or emission-related effects.

Table 2 Summary of the EU) case studies of different H_2-powered revolutionary electric aircrafts for different segments[1]. CASK: Cost per available seat kilometre. MTOW: Maximum take-off mass. PMAD: Power management and distribution. FCS: Fuel cell system.

Description	**Commuter**	**Regional**	**Short-Range**
Passengers	19 PAX	80 PAX	165 PAX
Range	500-kilometer 270 nautical miles	1000-kilometer 540 nautical miles	2000-kilometer 1080 nautical miles
Cruise speed	500 km/h Mach 0.419	543 km/h Mach 0.440	889 km/h Mach 0.720
Propulsion	Fuel-cell (FC) electric distributed motors	Fuel-cell (FC) electric distributed motors	Hybrid fuel-cell (FC) electric and H_2 turbine
Efficiency	FCS: 58% peak e-motors & PMAD: 97%	FCS: 59% peak e-motors & PMAD: 97%	FCS: 60% peak e-motors & PMAD: 97%
Power density	FCS: 1.50 kW/kg e-motors: 5 kW/kg	FCS: 1.75 kW/kg e-motors: 5 kW/kg	FCS: 2.00 kW/kg e-motors: 5 kW/kg
Energy density	Battery: 0.60 kWh/kg LH_2: 2.36 kWh/L	Battery: 0.60 kWh/kg LH_2: 2.36 kWh/L	Battery: 0.60 kWh/kg LH_2: 2.36 kWh/L
Climate impact reduction	80-90% overall 100% in CO_2	80-90% overall 100% in CO_2	70-80% overall 100% in CO_2
Energy demand	-10%	-8%	-4%
Added weight	2x LH_2 tanks: 0.5 tons +15% MTOW	2x LH_2 tanks: 2 tons +10% MTOW	2x LH_2 tanks: 4 tons +14% MTOW
Additional cost	0-5% CASK (10-15% less expensive than synfuel)	5-15% CASK (10% less expensive than synfuel)	20-30% CASK (5-10% less expensive than synfuel)
Entry-into-service	< 10 years	10-15 years	15 years

Examples of commercial H_2 aviation

Hydrogen-powered aviation has until recently been limited to demonstration projects and feasibility studies. Table 3 presents a list of several hydrogen-based aviation projects that have been recently initiated. They all use fuel cells as the main energy source, but it varies whether gaseous or liquefied hydrogen is employed. The concepts are mostly made for a few passengers (PAX), but the range can be relatively high.

Table 3 Examples of H_2 aviation projects. GH_2: Gaseous hydrogen. LH_2: Liquid hydrogen.

Project	PAX	Range	Propellers	Storage	Initiated
HY4	4	800-1500 km	1	GH_2	2015
HES Element One	4	500-5000 km	14	GH_2/ LH_2	2018
Alaka'i Skai	4	640 km	6	LH_2	2019
Apus i-2	4	1000 km	2	GH_2	2019
NASA CHEETA	n/a	n/a		LH_2	2019
Pipistrel E-STOL	19	n/a		n/a	2019
ZeroAvia	10-20	6500 km	2	GH_2	2019

One of the projects is highlighted in more detail in Table 4, which shows the key performances of a smaller airplane. In this example, the energy storage density of gaseous hydrogen is about 13 times higher than the internal battery storage buffer onboard. Moreover, the airplane is composed of a conventional permanent magnet motor as the electric propulsor.

Table 4 Key performance metrics of the HY4 hydrogen-electric aircraft development with gaseous hydrogen (GH_2) at 437 bar (http://hy4.org/hy4-technology). 1500 kg MTOW, 145 km/h cruise speed.

Subsystem	Design specification		
Propulsor	80 kW permanent magnet machine		
Battery	21 kWh	130 kg	161.5 Wh/kg
Fuel cell	45 kW	100 kg	450.0 W/kg
GH_2 storage	355 kWh	170 kg	2088 Wh/kg

HYDROGEN-ELECTRIC SOLUTIONS

In an H_2-power aircraft, there will always be a need for a variety of electric solutions. Even though it could be decided that the hydrogen should be burnt directly to produce propulsion (i.e., as a modified gas turbine), there will always be a need for auxiliary electric power installations. In this sense, electric power generated from fuel cells will be the most efficient solution. There are also concepts that introduce a combination of combustion propulsion and electric propulsion in future aviation.

Before going into the specialized propulsion technologies, the two main hydrogen conversion concepts are highlighted in Figure 6, i.e., the hydrogen combustor and the fuel cell. Their inputs, outputs, and by-products are indicated. The combustor produces parasitic NO_X emissions and heat, yielding higher climate impacts, and lower efficiencies. From the main H_2 concepts, there are four architectures that will be treated below, including 1) all-electric fuel cell propulsion, 2) a combination of fuel cell propulsion and direct-driven hydrogen turbines, 3) pure combustion propulsion, and 4) hydrogen-fueled turbo-electric propulsion.

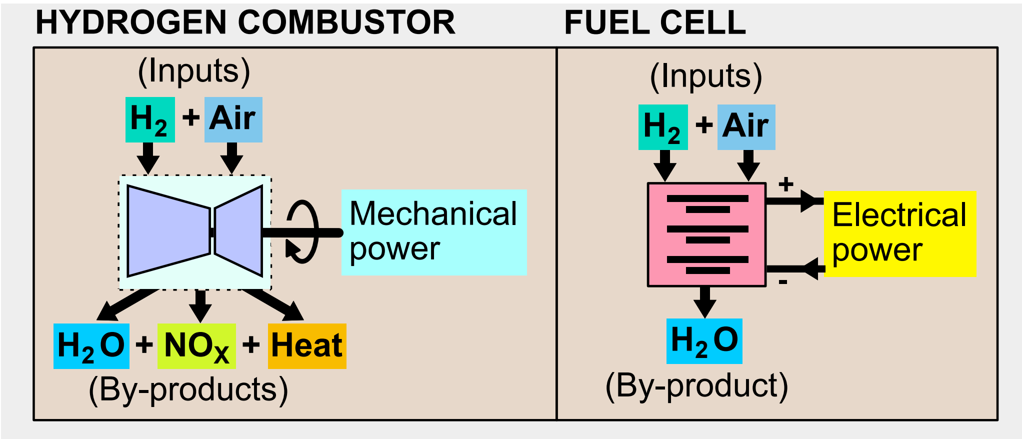

Figure 6 Overall flowchart of the hydrogen combustor and the fuel cell conversion system, indicating inputs and outputs.

Fuel cell propulsion system (FCPS) – an all-electric configuration

One way to achieve 100 percent electric propulsion is to go for the fuel cell propulsion system (FCPS). The electricity is generated and drives one or multiple electric propulsors, which consists of an electric motor and a propeller. A battery can be added inside the system to ensure faster load following and to optimize the peak shaving of the propulsor. Figure 6 depicts a generic example of the FCPS, including an internal battery buffer for transients, which are one of the simples arrangements of a generic system with only one propulsor.

In the commuter segment (19 PAX, 500 km), contrail formation is unlikely, and consequently, the climate impact will be near a "true zero" scenario using the FCPS. However, commuter aircraft is just a minor stepping stone to the overall climate reduction in the aviation sector.

The next step is the regional segment (80 PAX, 1000 km), where the FCPS is also a good candidate. Here, the climate impact is also low since no contrails are formed, and the overall system efficiency is high. Figure 7 assumes liquid H_2 storage, which needs to be cryogenically chilled at 20 degrees Kelvin. The fuel needs to be evaporated before it can be used. In this context, there is a synergy where the boiling of the fuel can be utilized in a cryogenic cooling circuit to achieve superconducting power conversion of one or multiple of the components in the electric propulsion system. A promising future target is to show that the evaporated LH_2, to be injected into the fuel cell, will provide enough refrigeration power to chill the power components onboard effectively. There is also an opportunity to operate the fuel cell at low temperatures since this type of operation will reduce its own degradation when it is in use.

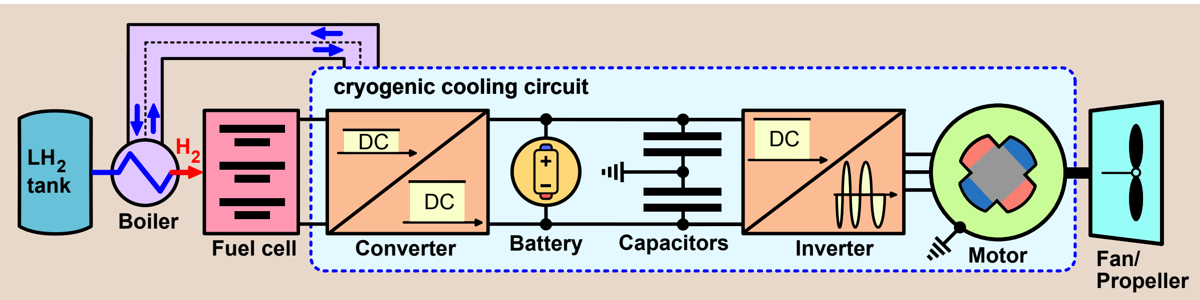

Figure 7 Generic fuel cell based drive system for a single propeller with cryogenically cooled power conversion.

Fuel cell hybrid-electric propulsion system (FC-HEPS)

One of the main drawbacks of the fuel cell all-electric propulsion is the lack of significant power density. In this regard, the hybrid-electric fuel cell propulsion system can take advantage of the higher power densities of the H_2 turbines with the climate-neutrality of fuel cells. Figure 8 illustrates how this type of system could be arranged. In its configuration, the fuel cell is the major power source in cruise mode, where low emissions are critical. In addition, the H_2 turbine is strategically sized to deliver the required thrust for take-off and climbing. As a result, the major parts of the flight do not emit NO_X, and it could also lead to fewer contrails. The system is feasible and interesting for the short-range aircraft segment (165 PAX, 2000 km). For this particular application, the fuel cell system will have a power rating greater than 10 megawatts, and thus, it will be crucial that the cryogenic cooling opportunities from the liquid hydrogen are sufficiently utilized. Another important issue is the fact that the parallel-hybrid configuration adds complexity to the certification process. The seamless and optimal interaction with the electric propulsor and the H_2 combustor is an important challenge.

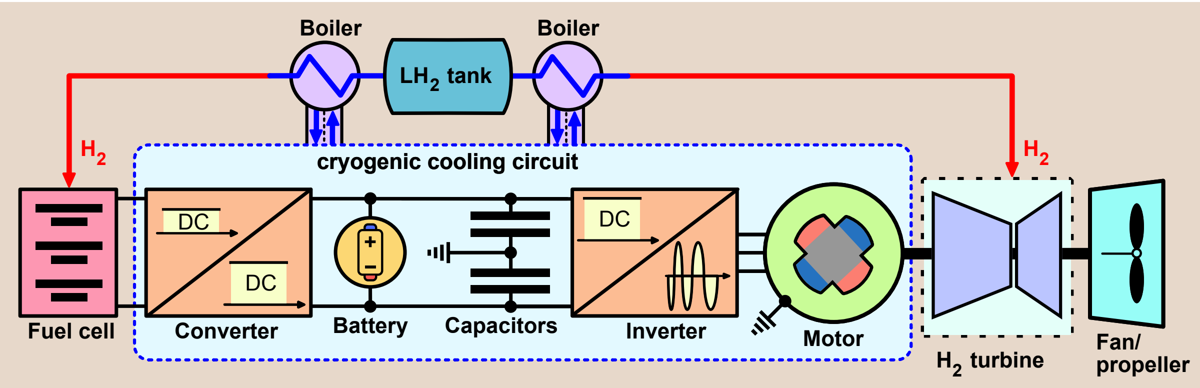

Figure 8 Parallel-hybrid fuel cell based drive system for a single propeller with cryogenically cooled power conversion.

Hydrogen combustion propulsion (HCP) - with auxiliary electric system

The aircraft propulsion can originate completely from the direct combustion of H_2 fuel, just like kerosene, to create thrust. Figure 9 depicts how the system would look like with a single fan, with few components. This is a system that is employed in cases where the weight of the fuel cell system (FCS) will be too high for propulsion. However, the FCS could be utilized to produce auxiliary electrical power in this kind of aircraft. The system is technically feasible for medium-range aircraft (250 PAX, 7000 km), but it will have significantly higher costs than conventional aviation. As shown in Figure 8, the system needs heat to boil the liquid hydrogen before it is burnt. However, there is less of a need to cryogenically chill power components, so a synergy is less likely due to lower levels of electrification.

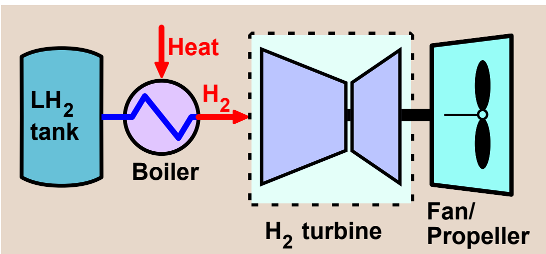

Figure 9 Hydrogen direct-burning propulsion for a single propeller.

Hydrogen turbo-electric propulsion system (TEPS)

As an alternative to the direct burning of hydrogen, a turbo-electric solution can be utilized. It allows turbo-electric distributed propulsion (TeDP), which has the potential to be the next disruptive technological breakthrough. It has a drawback of slightly lower energy conversion efficiency during cruise mode than direct burning, but the propulsive efficiency can be improved, and it has more flexibility in terms of new ultra-efficient aerodynamic designs and can optimize efficiency during take-off and climbing. The excellence of the propulsive efficiency is determined by the bypass ratio of the fan/propeller, which can be carefully controlled electrically. However, there are added weight penalties from electrical power conversion components. It would, therefore, require superconducting power conversion to save the added weight and minimize electrical losses. Superconducting solutions could make the conversion efficiency nearly as a high during cruise mode, and further improve the propulsive efficiency. The turbo-electric solution can reduce the overall power consumption by letting the H_2 turbine operate at its optimum point during the whole flight (improved gas turbine cycle). Moreover, it can take better advantage of the high level of synergy of the liquid hydrogen as a fuel and as a cryogenic cooling medium for superconducting power conversion.

Figure 10 and 11 depict two different turbo-electric architectures with batteries as an energy buffer. The first one (Figure 10) is composed of modular series-connected propulsors. This concept can be proposed to achieve high-voltage transmission, and thus, to save overall weight. The series-connected propulsors also have a benefit of floating ground for each propulsor, yielding low voltage across the insulation to achieve better reliability. Alternatively, the propulsors could have connected in parallel instead, as in Figure 11.

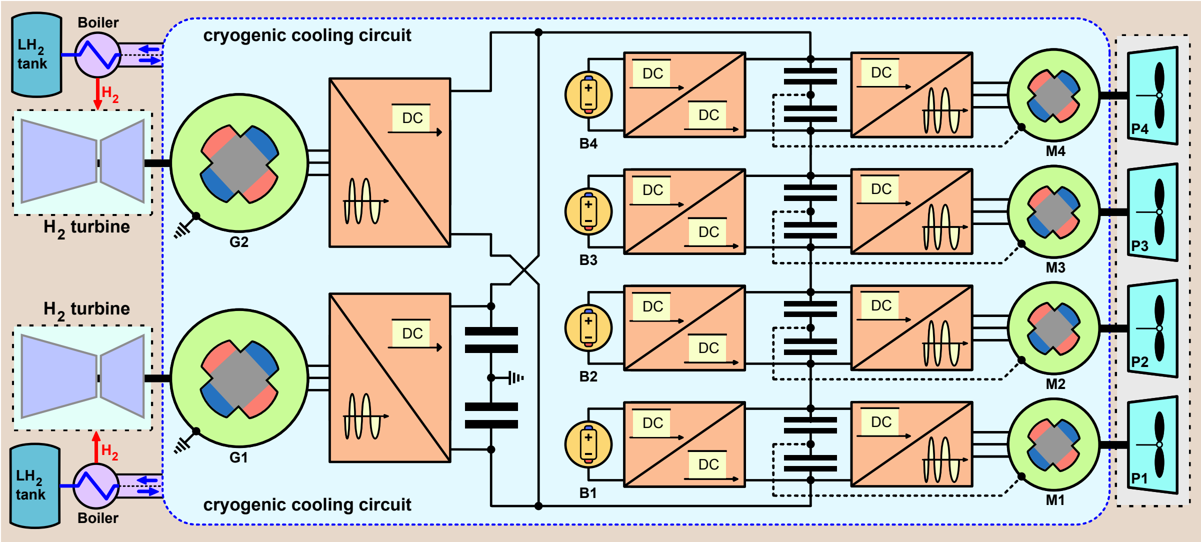

Figure 10 Hydrogen turbo-electric propulsion for four propellers in series configuration assisted with batteries as a buffer.

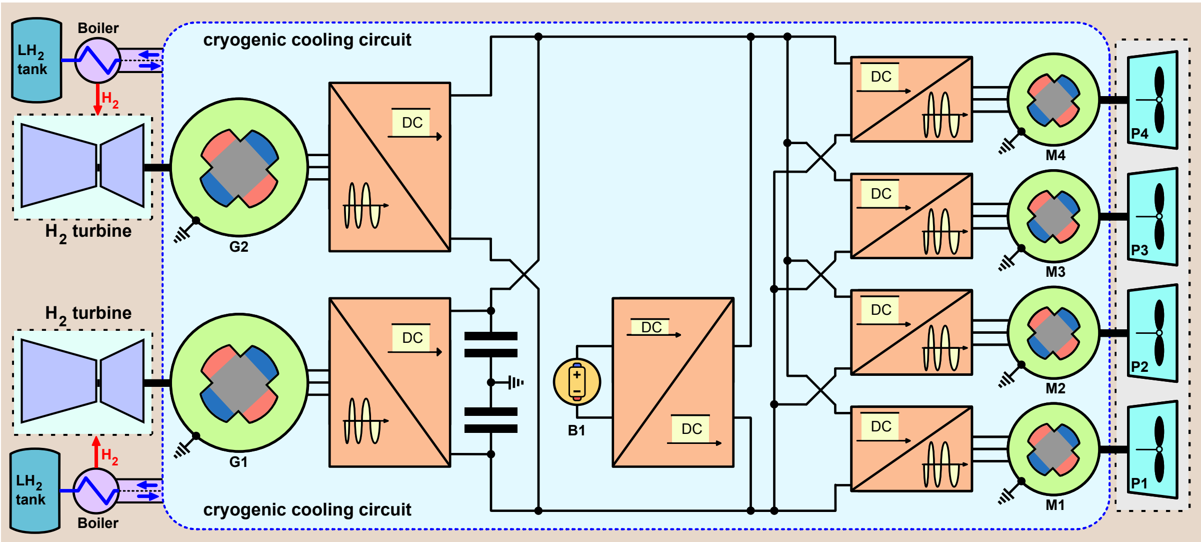

Figure 11 Hydrogen turbo-electric propulsion for four propellers in parallel configuration assisted with batteries as a buffer.

LH_2 as a key enabler for lightweight electric propulsion

All-electric aviation will always be technically possible by replacing the conventional propulsors with classical electric motors. However, they have an intrinsically high weight and size, which is a major technological barrier. In fact, today's electric machinery in the multi-megawatt range is roughly 50 to 100 times too heavy to be used in future electric propulsion systems in large aircraft segments[6]. By means of intensive cooling and lightweight design

[6] M. Filipenko, et. al., "*Concept design of a high power superconducting generator for future hybrid-electric aircraft*", Superconductor Science and Technology, vol. 33, no. 5, March 2020.

efforts, the weight could be reduced by a factor of 10 when compared to conventional designs. This is not sufficient in the large segments of aviation, where ultra-efficient lightweight solutions are needed. As an example, a power-to-weight (PTW) ratio of 16 kW/kg is required for a 100-seater aircraft with electric propulsion to make it weight-compatible with conventional designs. However, there is a synergy where liquefied H_2 can be used as both the fuel source and the coolant. LH_2 has been recognized as a highly efficient cryogenic cooling medium. In fact, the LH_2 must be evaporated before it is burnt in either an H_2 combustor or in a fuel cell (FC). The amount of heat needed to achieve gaseous H_2 from LH_2 can be much higher than the refrigeration power needed to cool the power conversion equipment onboard cryogenically[7]. Figure 12 depicts the strategy of using liquid hydrogen as a fuel and a coolant to cut emissions. This is a side-benefit of LH_2 in addition to its space-saving ability for fuel storage onboard. Moreover, the use of gaseous H_2 at lower temperatures can also reduce the degradation of the fuel cells.

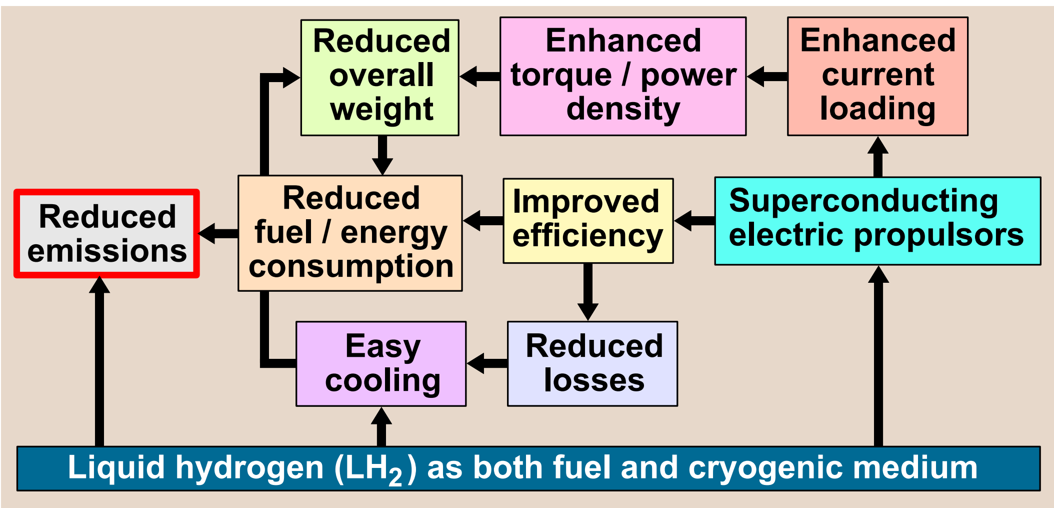

Figure 12 Overall philosophy when reducing emissions using liquid hydrogen as a fuel and a crycooler.

[7] M. Boll, et. al., "A holistic system approach for short range passenger aircraft with cryogenic propulsion system", Superconductor Science and Technology, vol. 33, March 2020.

The LH_2 is compact and its cooling abilities can be utilized to achieve a radical weight reduction of electric propulsors. In fact, the temperature in which LH_2 evaporates is compatible with the use of superconducting machines (SCMs) to achieve ultra-lightweight propulsors. As a consequence, the cryogenic cooling opportunities might be a low-hanging fruit and a small burden for the future H_2-powered aircraft. This is an important observation, since the penalty weight of the cryocooler is usually not taken into account in SCM performance evaluations, as they tend to diminish their benefits. In superconducting machines (SCMs), the conducting materials can handle massive amounts of currents (more than 100 times higher than regular copper) with no resistance. Moreover, they cause a minimum amount of dissipating heat, and as a result, they lead to ultra-high efficiency. In order to sustain the superconductivity, the superconductors have to be cryogenically cooled. Their performances are dependent temperature-dependent, as LH_2-cooling at 20 degrees Kelvin has a higher potential for reducing the weight of the SCMs when compared to LN_2-cooling at 63K.

Cryogenic hydrogen can also be used to achieve a high power density of power distribution and power electronics onboard[8]. There is a significant potential for improved power-to-weight ratio and efficiency gains compared to classical aircraft components. Figure 13 illustrates the drawback of fuel cells (FCs) with respect to hydrogen combustors when it comes to weight[9]. Therefore, it is important that FCs are combined with ultra-lightweight conversion components. Cryogenic PEC and SCMs have a potential of at least two to three times higher power-to-weight ratios compared to conventional components. Figure 14 shows that FCs can increase the energy efficiency compared to the combustion solution, even when it includes the electric power conversion components, which is an important benefit of FC systems.

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[8] K. Rajashekara & B. Akin, "*Cryogenic Power Conversion Systems*", IEEE Electrific. Mag., vol. 1, no. 2, December 2013.
[9] C. A. Snyder, et. al., «*Propulsion Investigation for Zero and Near-Zero Emissions Aircraft*», Technical report, NASA, 2009.

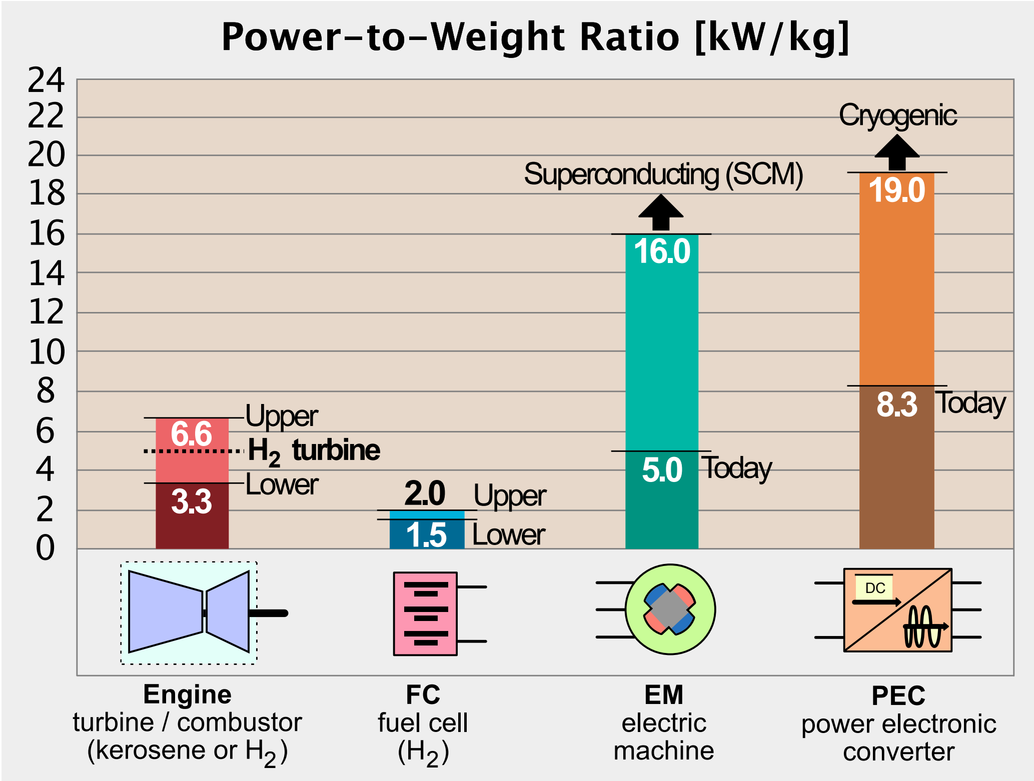

Figure 13 Comparison of power densities of different power conversion components in aviation. Based on estimated given in «*Turboelectric distributed propulsion system as a future replacement for turbofan engines*», Proc. ASME Turbo Expo, 2017.

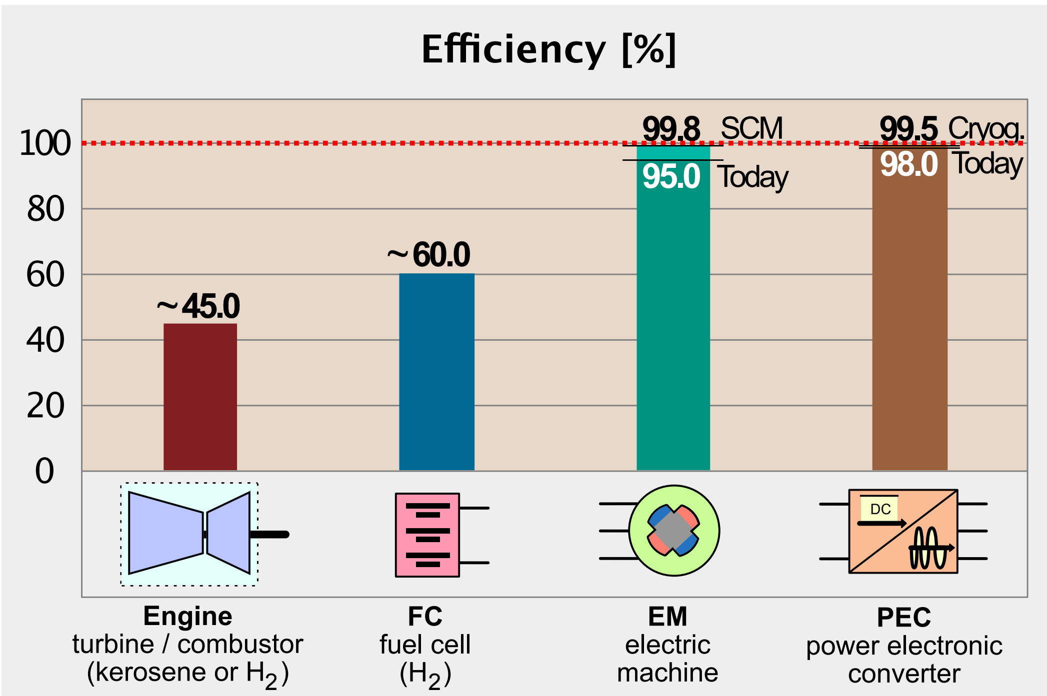

Figure 14 Comparison of energy efficiency of different power conversion components in aviation. Based on estimates given in the EU initiated report "*Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050*".

Even though the FC propulsion system can be configured with superconducting power conversion components, it cannot compete with the power density of directly burnt hydrogen. Figure 15 shows that the hydrogen-based turbo-electric propulsion system (TEPS) and fuel cell hybrid-electric propulsion system (FC-HEPS) have a higher potential in terms of power-to-weight ratio[10]. The equivalent power density (p_{eq}) in Figure 15 is calculated from the following expression

$$p_{eq} = \frac{1}{\frac{1}{p_1} + \frac{1}{p_2} + \frac{1}{p_3} + \cdots + \frac{1}{p_n}}$$

where p_1, p_2, p_3, and so on, are the individual power densities of the different power components in the system. The overall power density affects the weight of the aircraft, which again impacts the fuel consumption. However, a heavier aircraft can consume less fuel by being more efficient. Figure 16 shows that the turbo-electric TEPS has a high climate reduction by reducing the energy consumption by 20 to 40 percent, even though it is heavier than the classical HCP system.

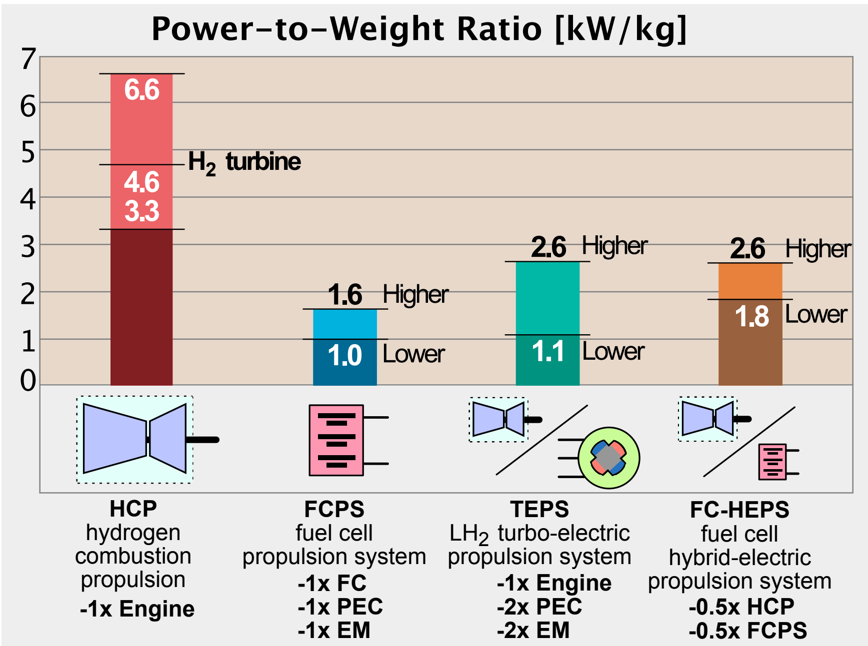

Figure 15 Equivalent power density of different propulsion systems when accounting for their key components. Calculations are based on the data presented in Figure 11.

[10] B. Lukasic, «Turboelectric distributed propulsion system as a future replacement for turbofan engines», Proc. ASME Turbo Expo, 2017.

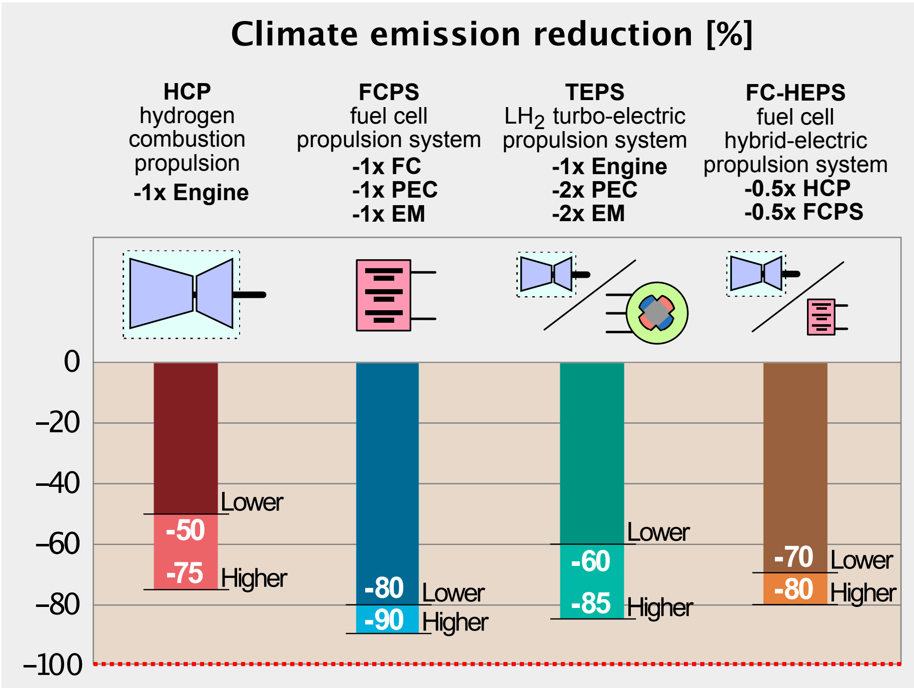

Figure 16 Total climate emission reduction of different propulsion systems. The TEPS assumes a reduced fuel consumption of 20 to 40 percent in comparison to HCP. FC-HEPS is assumed that its FCPS is designed for cruise. The estimates are based on the data given in the EU initiated report "*Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050*".

CONCLUSIONS

There is currently a paradigm shift occurring in aviation, moving away from evolutionary improvements of conventional solutions to more radical approaches. Several international agencies have recently restated their ambitions to bring the first-ever zero-emission passenger aircraft to the market already before 2035. In this era, hydrogen is now projected to play a significant role. However, shifting to hydrogen fuels is not without challenges, and they cannot be underestimated.

Small commuter aircraft segments can be designed battery-electric, whereas long-range aircraft are expected to go for sustainable aviation fuels (SAF). In all other segments in between, hydrogen-fuel and hydrogen-electric solutions are expected to be among the key disruptive solutions.

Currently, the main issues are the cost of hydrogen and the infrastructure to deliver it, as well as the technology on board the aircraft to utilize it efficiently. It is worth noticing that the achieved level of electrification will be essential, as it will be the key player to reduce non-carbon emissions (mainly from water, NOx, SOx, soot, contrails, and contrail cirrus), as well as reducing onboard fuel consumption and noise. The combination of hydrogen to reduce CO_2 emissions, and the development of electric propulsion to reduce the energy consumption, is expected to be key advancements needed to achieve a sustainable and cost-competitive future for aviation.

FOR FURTHER READING

[1] "*Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050*", May 2020. https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

[2] M. Boll, et. al., "*A holistic system approach for short range passenger aircraft with cryogenic propulsion system*", **Superconductor Science and Technology**, vol. 33, March 2020.

[3] C. A. Snyder, " *Propulsion Investigation for Zero and Near-Zero Emissions Aircraft*", **NASA – Technical report**, 2009.

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