LIQUID HYDROGEN AS AIRCRAFT FUEL: IS IT A GOOD WAY TO REDUCE CO2 EMISSIONS?

March 2023

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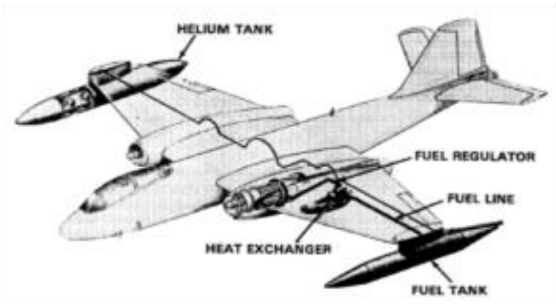
The members of the Energy and Environment Commission (C2E) of the Air and Space Academy (AAE) whose names follow: Dominique Bajeux, Xavier Bouis, Alain Cassier, Éric Dautriat, Michel Desaulty, Michel Eymard, Jean-Marc Garot, Nicolas Jeuland, Alain Joselzon, Thierry Prunier, Bruno Stoufflet and Gérard Théron spent a year analysing numerous documents on the use of liquid hydrogen as fuel for commercial transport aircraft. Their opinion is the purpose of this report.

Hydrogen has been used for many years in industry and space transport. Much scientific and technical knowledge has been accumulated on its characteristics and its use. Due to climate change, there is renewed interest in hydrogen as an energy vector and for direct use in transport.

Going back in history, one of the first uses of hydrogen for air transport was for airships, the adventure of which ended in 1937.

Some aircraft demonstrators were successfully flight tested (B-57 in 1956 - Tupolev 155 in 1988), but without further development, in particular because of the higher cost of hydrogen compared to kerosene. In the 2000s, the subject was again discussed in Europe, then abandoned.



For aviation, hydrogen has two advantages. On the one hand, its combustion offers the possibility, at least theoretically, of essentially producing only water vapor and no CO_2. On the other hand, it has a high calorific value, three times greater than that of kerosene (a LHV[1] of 120 MJ/kg instead of 43 MJ/kg) and in the cryogenic form of liquid hydrogen (LH2), the mass of fuel to be transported is reduced by a factor of 2.8 compared to kerosene but occupies a volume 4 times larger.

Hydrogen gas (GH2) can also be used, but being of lower density, it occupies a volume almost twice as large as LH2. It can be stored in high pressure tanks (up to 700 bar). The two forms GH2 and LH2 can be used as a source of energy supplying fuel cells, the latter

[1] LHV: Lower Heating Value i.e. total amount of heat released by combustion

providing electrical energy for propulsion or additional power in hybrid engines. **But this is not the subject of this document, devoted to liquid hydrogen as a fuel.**

For industrial and land transport applications, there are solutions that address the problems posed by the specificities of hydrogen. However, accidents have occurred, which encourages specific risk prevention for air transport.

For several decades, hydrogen has been used for space launchers in liquid form (LH2 at -253°C). But, will it be possible to transpose the experience of space (a dozen launches per year, sites closed to the public, with drastic precautions and frequent postponements, to the air transport sector (in 2021, 32,600 aircraft performed 25.7 million flights worldwide with only 7 catastrophic accidents) The use of hydrogen as a replacement for kerosene in daily airline operations would be, by far, more than just a fuel switch: it would be a new air transport, with its various actors, having to cohabit with the existing one.

A fundamental point is the following: liquid hydrogen has a very low density, 70kg/m3 at -253°C. This is a disadvantage for the size and weight of the tanks, but also, as soon as the liquid turns into gas, the smallness of its molecule creates a very significant risk of leakage, which can cause a fire or an explosion, in a confined enclosure. The requirement for tightness levels for all fittings and equipment will be imperative, disproportionate to those existing for kerosene. This is a challenge not only for aircraft, but also for airports and their infrastructure (refuelling and storage facilities, even liquefaction).

Safety, on the ground and on board, is a subject for which there can be no regression, and which will require a certification process that is out of all proportion to what has been done so far, both for the ground and for the board. This certification process must be defined in parallel and from the beginning of the design of the systems. And it will be necessary to convince passengers to fly in hydrogen planes. This is certainly one of the most important challenges to overcome.

This change in fuel, if it occurs, will induce a change in technology for many systems with technical challenges that will take time to master. Different concepts and projects for aircraft of different sizes and different ranges are offered by Airbus, by start-ups such as ZeroAvia or by European research centres and universities. Some of these projects are supported by R&T work and tests are planned to bring to maturity the solutions responding to the issues to be dealt with. However, these projects must have a sufficient level of maturity to evaluate their **overall feasibility** before deciding to invest several billion euros for the development of such aircraft.

When we examine the various concepts and industrial or research projects in progress, we see that the prospects for the date of commissioning are moving away. It will probably take years to demonstrate whether the key technologies can be mastered. The first types of aircraft, if they materialize, will undoubtedly be limited to short haul (less than 1,000 NM) with limited capacity (less than 100 seats, or even an even lower limit).

Manufacturing, supplying, storing and refuelling airports with LH2 will pose challenges of the same magnitude. The global deployment of a new mode of air transport will raise the question of the interoperability of airport facilities, maintenance and repair of aircraft and propulsion systems, because airports will have to keep refuelling in parallel with kerosene and Sustainable Aviation Fuels (SAF). If only part of the airports is equipped with liquid hydrogen, the diversion of a hydrogen plane to an airport not equipped to supply liquid hydrogen will lead to its immobilization for several days, or even longer. When will airport managers be ready to invest, if such hydrogen is available?

For the same aircraft performance expressed in PKT (passengers transported per km), it takes as much electrical energy to supply SAF e-fuels as LH2, hence equivalent fuel expenditure. On the other hand, the manufacturing and distribution processes being different, producing, transporting, liquefying and refueling LH2 would require a duplication of investments, already considered very important for the SAFs which are a priority.

The objective of reducing CO2 emissions should primarily target medium and long-haul flights, which represent 2/3 of traffic and emissions, while the aircraft projects envisaged with hydrogen fuel only seem to target short ranges aircraft.

For air transport, the impact of hydrogen-powered aircraft in terms of reducing CO2 emissions will therefore remain modest at least until 2050/2060.

Three quotes can be noted, the first from ICAO's Long-Term Ambitious Goals (LTAG) report:

"*On-board hydrogen is not expected to have a significant impact by 2050 (with only **1.9%** of the energy share in 2050), but this proportion could increase in the 2050s and 2060s if this solution is technically feasible and commercially viable*".

A second by Boeing CEO David Calhoun at the American Chamber of Commerce Aerospace Summit in Washington, DC on October 23, 2022: "*Green hydrogen will only be able to offset 2% of emissions at best. of CO2 from aviation in 2050. That's not to say we don't believe in it, but the contribution of H2 is in the second half of the century, not the first*," he said.

And the last by the CEO of Safran Olivier Andries: "*Hydrogen is an attractive solution because its combustion does not generate CO2, but it represents considerable technical and ecosystem challenges. We are talking about several hundred billion euros for the installation of cryogenic infrastructures in airports around the world. […] The carbon neutrality targeted by global air transport in 2050 will go through SAF*".

Conclusion:

he ability to refuel aircraft with liquid hydrogen in many airports around the world will be a key decision-making factor, in particular because of the large investments required and the strategic orientations that the various state, industrial and commercial players will take. Within the same airline, the mix of fleets between hydrogen planes and planes using fossil kerosene or drop-in SAF will limit interoperability and complicate operations.

Air transport will find itself confronted with many other users of hydrogen (industry, ground, and even maritime transport, as well as the SAFs which will have been developed by then and will have taken their place on the market).

Nevertheless, at this stage, with this political, media and technical enthusiasm, it is understandable to see the initiation of technological developments and ground and flight tests of key elements of a "hydrogen system" which could provide answers to the many issues to consider. These will be useful in clarifying the long-term potential of LH2 fuel, as long as their scale remains measured and they do not divert attention, or funding, from stronger, faster-to-implement decarbonization solutions.

Even in roadmaps that include liquid hydrogen as aircraft fuel, the contribution of hydrogen to reducing CO2 emissions will remain modest compared to technical and operational improvements and the use of Sustainable Air Fuels (SAF): biofuels and e-fuels, which are “drop in” compatible.

Ultimately, faced with the many challenges to overcome, the prospect of hydrogen as a fuel for aircraft engines appears very weak by 2050 and uncertain beyond.

Table of contents

1. Technical, operational, and regulatory challenges on an unprecedented scale

This document is mainly devoted to liquid hydrogen used as fuel (H2-Burn) and not to solutions using fuel cells (H2-FC).

Opinion: Among the points to be studied and to which solutions will have to be provided before the launch of an aircraft project using liquid hydrogen as fuel for engines:

1. The availability of non-polluted LH2 liquid hydrogen in sufficient quantity in many airports;
2. Safety conditions when refuelling aircraft without the use of helium, dictating where and for how long;
3. On-board storage of hydrogen in tanks at -253°C, 24 hours a day, 7 days a week, minimizing evaporation (unfortunately unavoidable);
4. The behaviour of liquid hydrogen during aircraft movements, attitudes, turbulence…;
5. The structural integrity of the tanks, resistance to sloshing and load factors, thermal bridges, etc.;
6. The transfer of hydrogen stored in the tanks (-253°C, a few bars) to the combustion chamber of the engine (~50°C, 50 to 100bars);.
7. Adaptation of the engine and heat exchangers, cryogenic pumps, materials, etc.
8. Leak management, and temperature management (materials) during the life of the aircraft, i.e. 50,000 to 70,000 flight hours.
9. …

Point 1 is covered in Chapter 2
Point 2 is mentioned in #Appendix 1: Lessons learned from H2 fueling/defueling in space activities.
Points 3 to 8 are the subject of #Appendix 2: Cryogenic LH2 on board aircraft
and - #Appendix 3: What types of Hydrogen engines .

<u>Opinion</u>: If we manage to overcome all the technical obstacles linked to the development of a hydrogen-powered aircraft for a series application, very significant investments in R&T will in any case be necessary over a long period. to deal with all the technological and certification locks. Before developing and putting into service new aircraft operating with hydrogen, it will be necessary to have answers to several questions and to satisfy several fundamental requirements, including these:

- According to the International Energy Agency, the current investments in the means of production of carbon-free H2, although already considerable, risk being used as a priority to meet industrial needs and to produce SAF and could be insufficient to cover the need for a quantity of LH2 for aviation that would make a substantial contribution to carbon neutrality in 2050.

- It will be necessary to demonstrate that the aspects relating to operational safety are mastered and therefore to establish, with the European Union Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) authorities, the certification framework for an airplane operating with hydrogen, including its propulsion system and its ground environment

- An aircraft running on liquid hydrogen must be certified with a level of safety at least equivalent to that of current aircraft.

- The cryogenic part of the aircraft tanks and its equipment up to the outlet of the engine HP pump must be treated as a single system. This is a logic that stems from the experience of space launchers, but which requires reviewing the division of certification regulations between the aircraft, its subsystems, and the engine.

- Given the means to be implemented to ensure safety at the level of an aircraft, including redundancies and associated controls, the availability of the aircraft will represent a major potential issue for airlines with possibilities of delays or reduction of rotations which are to be evaluated. This is also feedback from space launchers, many of whose launches have been postponed following incidents on hydrogen processes. In addition, a mix of LH2 and SAF aircraft within the same airline will limit interoperability and complicate operations.

Notice: Does the use of H2 due to the production of water vapor generate induced cirrus clouds? How do these contribute to the greenhouse effect? Can a massive use of H2 in air transport be envisaged without an increase in its atmospheric concentration, and what would be its contribution to the greenhouse effect? The evaluation of hydrogen losses in operation will have to be the subject of preliminary studies to deduce the potential impact on the environment (degassing, transients, cold maintenance, etc., degraded operating cases such as draining tank in flight, maintenance operations, …)

Opinion: University studies, as well as reports from consulting companies (McKinsey, Roland Berger) or others (ICCT, The Shift Project, Institut Montaigne, etc.) have identified the hard points of the technologies to be developed and integrated into a system. hydrogen aviation. But what these studies and reports do not say:

• What is the height of the step to go from TRL 2/3 to TRL 6/7?

• What are the action plans and the "proof of concepts" to obtain sufficient maturity and by what timeframe?

• How much will it cost and how long will it take?

The answer to these questions will have to be provided as soon as possible based on detailed studies and substantiated justifications before the launch of development programs.

2. Manufacturing, supplying, storing, and refuelling hydrogen

To provide sufficient range, commercial hydrogen aviation will have to use liquid hydrogen (LH2). Gaseous hydrogen (GH2 pressurized to 700 bars usually) is not suitable, leading to a totally prohibitive mass of reservoir structures (from 12 to 15 times the mass of hydrogen carried away) and to volumes almost twice as large as the liquid hydrogen (LH2). On small aircraft with a very short range, the GH2 can however be used to power fuel cells which either provide power to electric turbines or are coupled to heat engines to provide them with additional power. power (hybrid engines**). This aspect of hydrogen aviation (H2-FC) is not covered in this document.**

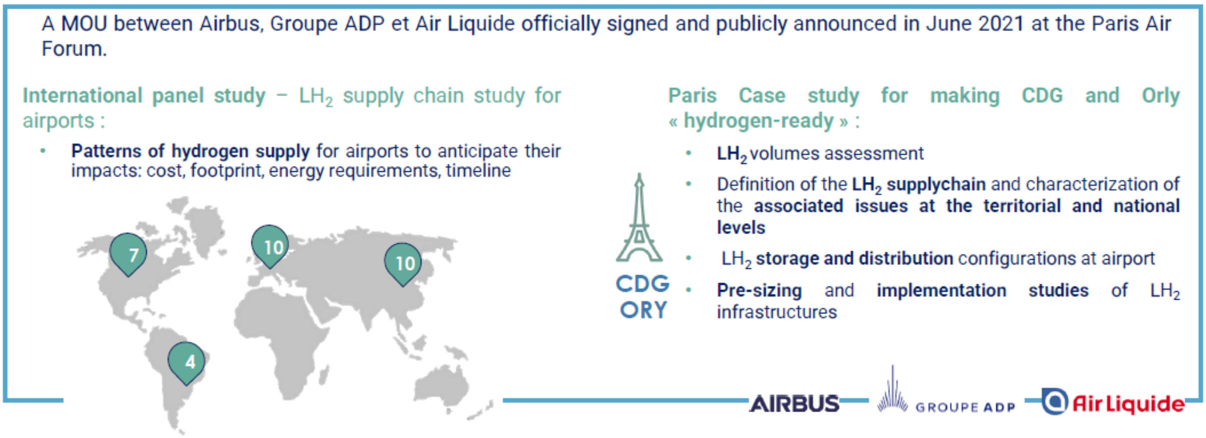
However, liquid hydrogen LH2 is an uncommon product: its main "industrial" application is for space launchers given the excellent specific impulse provided by the "cryogenic couple" H2/O2. Europe, with the Ariane sector, has very good experience with this propellant. However, the transposition from a launcher to a commercial aircraft is difficult. For aviation, everything is different: safety issues (probability of catastrophic failure less than one per billion flight hours), aircraft lifespan (60 to 100,000 hours), liquid hydrogen storage time (24/24, 7/7), environment, architecture, operational and logistics coverage; and it does not go in the direction, never, to conclude that an aircraft use is "easier" than on a space launcher. At least the experience of the latter allows you to know in advance what are the hardest points to consider. This is a completely new aviation ecosystem.

Once 'manufactured', this hydrogen must be transported. Perhaps in liquid form by tank truck initially, then in gaseous form by pipeline to supply all H2 consumers, including major airports and, in this case, equip the airports themselves with liquefaction means requiring a large input of electrical energy.

There is yet another variant: decentralize in the airports, not only the liquefaction, but the electrolysis itself and do not forget the storage (at 20 K!). Will airport managers be convinced of the commercial superiority and the future of this concept? In fact, only massive investment by States could break this vicious circle. This subject shows, if it were needed, that a 'French' aeronautical hydrogen initiative only makes sense if it is accompanied by (or if it knows how to arouse) international support, even beyond Europe.

Before flying planes with LH2, sufficient hydrogen must be available. If we want to achieve zero-emission aviation, it is not a question of flying a few planes here and there, but of converting as much of the world's fleet as possible.

In June 2021, Airbus, Groupe Aéroport de Paris (ADP) and Air Liquide signed and announced their partnership agreement to characterize the challenges of defining a hydrogen supply chain and integrating hydrogen infrastructure / equipment at airports (supply, liquefaction, storage, distribution) in order to refuel aircraft using LH2.



In particular, ADP has carried out a study on the transformation of thirty airports around the world that could be able to accommodate and refuel aircraft with LH2.

According to German academic studies, the refuelling of planes could be done near the terminals and near other planes and in a time equivalent (15 min) to that of current operations. See on this point #Appendix Lessons learned on hydrogen fueling/defueling gained from space activities. Nevertheless, the proximity of passenger flows will require a serious risk analysis.

Based on kerosene consumptions data from Roissy-CDG and Orly Parisian airports, experts have estimated the quantity of hydrogen needed to refuel 30% of medium range flights: 700 to 900 t/day of LH2 for CDG and half of it for Orly. Eventually the hydrogen would be manufactured outside the airport and then liquefied at the airport. An objective close to 1500-1600t/day would therefore be expected in France (including a 3rd international airport), 3000t/day in Europe to ensure returns. That is an annual need of 1 million tonnes of LH2 per year for hydrogen aviation using French airports. By extrapolating to about thirty international airports, the need would be about 10 million tons of LH2 per year.

Opinion: *we can already anticipate that governments will favour the conversion to hydrogen of activities that not only have a global impact on global warming, but also locally on air pollution. We can already see that the demand for carbon-free hydrogen will grow faster than production capacities, creating strong competition between many users who are closer to a concrete application (energy, industry, land and even maritime transport) and also for production of SAF e-fuels, such that the additional need that hydrogen-powered aviation would create would not be "sustainable" for a long time. Quoting the newspaper Le Monde: "The lack of capacity and competition between sectors could reduce the take-off of hydrogen in the air sector".*

During the Airbus summit at the end of November 2022, Guillaume Faury declared: "*Green hydrogen must be available in large quantities, in the right place and at the right price [….] When we must decide on the launch of the plane hydrogen at Airbus in 2027 or 2028, if we are faced with a situation where there is no certainty that there will be enough hydrogen under the right conditions available for entry into service in 2035, this could be a reason to delay the launch of the program. Even if the technologies on the plane itself are mature*".

The newspaper La Tribune of November 30, 2022, comments on these remarks: "*With these words, the executive chairman of the European manufacturer placed the energy dimension at the heart of the development of the use of hydrogen in aeronautics and largely insisted on the need to build an ecosystem capable of supporting its use. Enough to put pressure on energy companies and regulators rather than on its engineers committed to the zero-emission aircraft (ZEROe)*".

No doubt aware of this constraint, the representatives of the 184 member states (out of 192) present in Montreal at the last ICAO general assembly in October 2022, did not retain the motion supported by France and the Netherlands. encouraging the development of hydrogen aviation.

An alternative solution that can be quickly applied in the short and medium term is to use SAF (drop-in fuels). What distinguishes SAFs from liquid hydrogen for medium and long-distance air transport is that SAFs (especially e-fuels) will be complicated to produce but very simple to implement, while Liquid hydrogen, relatively simple to produce, will be tricky to implement. Between the two solutions, the difference in fuel cost seems small.

Waiting for an answer to all the SAF and LH2 questions should not delay the 'take-off'... at least of the SAF.

3. For safety: a certification to be invented.

The history of aeronautics and space, including very recent ones, shows that even minor modifications can lead to unforeseen consequences. What then can be said of "hydrogen aviation", which will lead to significant changes in the design of the aircraft and its ground infrastructure.

#Appendix 4: Potential issues linked with the use of H2.

For an aircraft fuelled with hydrogen, with substantially new subsystems, equipment and components and their installation, failure assumptions that were based on acquired knowledge and previous estimates based on experience, may no longer be valid for most of them and must be reviewed and adapted.

As with current aircraft, the upper bound of the average probability per flight hour for each catastrophic failure condition should be at least 1 × 10-9, which establishes an approximate probability value for the term "extremely unlikely".

#Appendix 5: Background on Risks into probabilistic terms (FAA and EASA)

All the experience of space and other applications must obviously be taken advantage of, by transposing the data, "from one real context to another", each having its own criteria, constraints, and requirements.

#Appendix 6: Lessons learned from space launch.

Some experience could also be gathered from reports and statistics related to hydrogen in industrial installations.

#Appendix 7: H2 Accident statistics in industrial facilities

In this context, work related to the regulatory certification process must be initiated very early on with the support of EASA and the FAA, including the ground and on-board aspects. This work will be implemented simultaneously with the design of the systems preferably in integrated teams.

#Appendix 8: Need of a system architect team.

The criticality of the safety and certification aspects is such in aviation that they must receive very close attention right from the research projects, which should involve the competent authorities if necessary.

Opinion: Safety represents one of the major challenges of the introduction of new technologies such as those of a hydrogen plane. The objectives that the certification authorities will set will be based on the need to have, from the start of operation, a level of security at least equal to that of the existing systems, this considering all the feared events and degraded cases of functioning inherent in the new technology and all the systems interacting with it.

Even if the feasibility of hydrogen planes is demonstrated on each of the critical points mentioned in chapter 1, taken separately, the feasibility at the level of global integration will still have to be demonstrated, and the various actors will have to carry out a preliminary complete and detailed full-scale project covering all aspects on board and on the ground using integrated, agile, co-located teams, and relying on highly qualified and experienced high-level experts..

4. Aircraft concepts and projects

<u>Reminder</u>: This document is mainly devoted to liquid hydrogen used as fuel (H2-Burn) and not to solutions using fuel cells (H2-FC).

Opinion: The concepts and projects of aircraft using liquid hydrogen as fuel for the engines known to date have for the most part a low level of maturity. The critical aspects and potential difficulties raised now can only be addressed through demonstrations of key technologies, subsystems and systems including proof of concepts through extensive representative testings. At the level of global integration, it will be necessary to carry out a complete and detailed full-scale preliminary project covering all on-board and ground aspects and fed by the results of ground and flight tests on various components. It is only at the end of these demonstration phases that the horizon of commercial deployment of these new generation aircraft and their potential market can be considered and consolidated.

4.1. What types of aircraft

In its final report published in September 2022 "Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050 Final Study", the TRAN Committee of the European Parliament declares:

*"A number of companies are already working on electric and/or hydrogen-fuel aircraft (e.g., Aviation, Wright Electric, Zunum, GKN Aerospace, Cranfield Aerospace Solutions, ZeroAvia). Some have quite ambitious targets for entry into service (e.g., 2026 for the GKN Aerospace H2GEAR project). However, all aircraft currently being developed **are small** (the current ZeroAvia development aircraft has 19 seats, although they are projecting 100-seat aircraft for the future) and will have short ranges. The timing for the extension of the technology to larger aircraft (e.g., 150-seat single-aisle aircraft or 300-seat twin-aisle aircraft) with longer ranges remains uncertain. The dates should be considered the earliest that such aircraft may enter service. It is prudent to allow for this uncertainty in the availability dates in analyses of the impacts of such technologies.*

*The other key propulsion system technologies in development are those associated with the use of non-drop-in, zero-carbon fuels (electricity and hydrogen). These may appear within the next 10 years, but will initially be restricted to **small, short-range aircraft**, because of energy density issues. Their use on larger, longer-range aircraft is likely to take significant extra development and is **unlikely before 2040**."*

The following paragraphs present certain concepts and projects under study and development as well as the planned tests, with the comments and opinions of the writers.

4.2. *Airbus*

In June 2022, the French government announced a 15-billion-euro aeronautics support plan, accompanied by one requirement: the launch of a "green" hydrogen-powered aircraft by 2035. A few months later, Airbus already presented three concepts of hydrogen aircraft, "exceptionally promising as a clean aviation fuel".

The first two hydrogen aircraft concepts presented by Airbus are of a classic configuration with a cylindrical fuselage. One is a regional short-haul turboprop and propeller, the other a medium-haul twin-engine. With its flying wing shape, the third sketch is more disruptive.

4.2.1. Regional short-haul concept

The complexity of the development of hydrogen aircraft, as well as the necessary concomitant development of the associated logistics mean that the first commercial development could concern a concept of regional or even “super regional” aircraft with a capacity of 100 passengers and a radius of action of around 1000 NM for an entry into service around 2035.

#10.1 Appendix 10.1 Regional short-haul concept

Hydrogen as a Fuel

H_2 aircraft basis

H_2 Properties and storage

	Kerosene	H2		
	1b, 273K	1b, 273K	700b	20K
	Liquid	Gas	Gas	Liquid
Specific Energy (MJ/kg)	42,8	120	120	120
Density (kg/m^3)	800	0.09	42	71

3x more specific energy

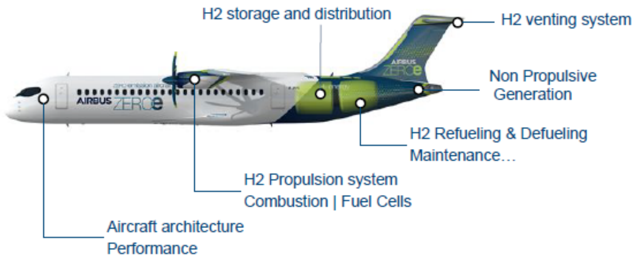
4x more space required to store LH_2 @ (iso energy)

What' needed for making an H_2 aircraft?

- Technologies satisfying aeronautic standard for H_2 storage, Distribution and Thrust generation
- Safety level at least equivalent to legacy aircraft
  Specific certification rules & means of compliance
- New overall aircraft architecture
- Infrastructures and operations adapted to H_2 aircraft

The changes driven by the use of H2 as a fuel impose to review aircraft architecture & ops

H_2 Aircraft specificities



H_2 flight vehicles heritage

Operational LOx/LH2 Space Launchers & techno, since ~40 years in UE (but: limited lifetime, lower safety standard…)

12

AIRBUS

__Avis:__ *A condition que les études et les démonstrations à effectuer au cours des prochaines années confirment la faisabilité et permettent de certifier de tels 'super-régionaux' aussi bien pour leur opération que pour leur maintenance, la réduction de CO_2 associée serait d'environ* ***4 à 5%*** *des émissions totales du Transport Aérien, en supposant qu'environ 20% d'avions de ce type puissent être utilisés sur tout le réseau de moins de 1000 NM* ***avec des aéroports compatibles de l'avitaillement de LH_2*** *et au prix d'une complication notable des opérations pour les compagnies aériennes. Ces avions pourraient s'avérer trop petits (avec seulement 100 passagers) pour être rentables sur des lignes à fort trafic, trop complexes pour les petites lignes vraiment régionales, inutiles sur les lignes déjà doublées par des TGV efficaces (Paris-Bordeaux, etc). Alors qu'une très forte priorité est mise sur les SAF afin qu'ils soient disponibles et comme ils sont très simples à utiliser par leur capacité 'drop-in', ils répondront assez bien au besoin de décarbonation. Alors pourquoi est-ce qu'on en "priverait" ce segment du marché pour le mettre au régime hydrogène ? Qu'est-ce que l'économie générale du système y gagnerait ?*

4.2.2. Medium range concept

Opinion: Provided that the studies and demonstrations to be carried out over the next few years confirm the feasibility and make it possible to certify such 'super-regionals' both for their operation and for their maintenance, the associated CO2 reduction would be approximately ***4 to 5%*** *of total Air Transport emissions, assuming that about 20% of aircraft of this type can be used on the entire network of less than 1 000 NM* ***with airports compatible with LH2 refuelling*** *and at the cost of a notable operational complication for airlines. These planes could prove to be too small (with only 100 passengers) to be profitable on high traffic lines, too complex for small, truly regional lines, useless on lines already doubled by efficient TGVs (Paris-Bordeaux, etc.) . While a very high priority is placed on SAFs so that they are available and as they are very simple to use due to their 'drop-in' capacity, they will respond quite well to the need for decarbonization. So why would we "deprive" this segment of the market to put it on a hydrogen diet? What would the general economy of the system gain from this?*

4.2.3. Medium range concept

Opinion: The entry into service of a **hydrogen-powered medium-haul Airbus twin-engine** (200 pax / 2000 NM) seems postponed beyond the years 2035 previously announced, given the difficulties of all kinds it poses. The renewal of the medium-haul fleets from 2030 should go through the adoption of measures to significantly reduce consumption compared to the most recent aircraft, by acting primarily on the engines but also by continuing to optimize the cells (mass, aerodynamics, etc.). For example, the engine manufacturer CFM announces a reduction in consumption of around 20% with its Open Rotor RISE (Revolutionary Innovation for Sustainable Engines) project which, combined with aircraft improvements, could bring this gain to 30%.

https://www.journal-aviation.com/actualites/cfm-rise-le-futur-demonstrateur-de-ge-et-safran-s-affranchira-des-soufflantes-contrarotatives~53191.html

According to Airbus, if environmental regulations tighten and the price of carbon taxes increases, a possible future will see hydrogen aviation and in order to achieve this, it must start tackling it now.

Nevertheless, it will remain to certify these planes and produce many of them for decades to gradually replace the fleets of companies, before seeing a beneficial effect on global warming

This is also what the ICAO's Long Term Aspirational Goal (LTAG) report states: 'On-board hydrogen should not have a significant impact by 2050 (with only 1.9% of the energy share in 2050), but it could increase in the 2050s and 2060s if this solution is technically feasible and commercially viable

https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf (Para 2.1.c page 8).

Among the three hydrogen aircraft concepts presented by Airbus, this medium-haul aircraft uses liquid hydrogen to power two conventional turbojet engines.

Assuming all definition and safety points resolved, a group of AAE/C2E engineers attempted to carry out a pre-project study of such a medium-haul H2 based on an A321- neo capable of stages of around 2000 NM with around 180 passengers (A321 neo-H2).

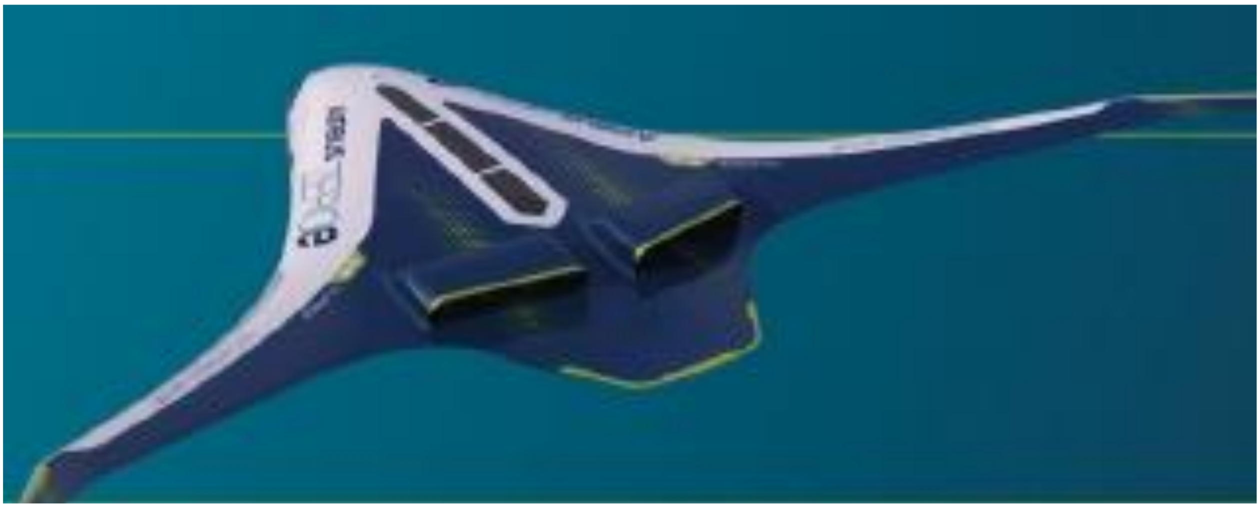
What are the difficulties of this type of project? How can they be resolved? How long ? What would be the hydrogen production needs to refuel these planes? With what energy to manufacture this hydrogen? What would be the costs of use compared to using SAF?

#10.2 Appendix 10.2 Questions about a potential hydrogen medium-haul preliminary project

Opinion: *To carry out missions of approximately 2,000 NM, it is necessary to obtain a gravimetric index of 0.35 for the tanks and associated systems (ratio: LH2 mass/total tank mass + LH2). What proofs of concept are planned and when, to demonstrate that this index of 0.35 could be achieved while controlling thermal evaporation, sloshing in flight, gauging, safety with detection of hydrogen leaks?*

At the end of 2022, some developments are at TRL2. A Clean Aviation project is targeting TRL 4/5 for 2026 with initially only €10 million in funding to be distributed among 14 partners…. Other funding exists in Europe (Clean Hydrogen) or in France, Germany, Spain…. Airbus, with other financing, maintains the objective of reaching TRL6 in 2026 for all technologies and systems and is positioning itself as a tank designer within the framework of the ZEDC (Zero Emission Development Centre) located in Nantes and Bremen.

4.2.4. Long-range concept



Opinion: Review: This artist's view of a flying wing depicts what a future LH2-powered long-haul aircraft could look like. No comment since no information is available on this concept. With such a revolutionary architecture, the development of such a project will take a long time with a distant commissioning (estimated beyond 2050 based on the Concorde experience).

4.3. Boeing

Boeing is focusing on using SAFs to reduce CO2 emissions. Without losing interest in hydrogen, Boeing emphasizes the potential difficulties and associated challenges.

Boeing has established a four-pillar strategy for meeting the aerospace industry's commitment to achieve net zero carbon emissions by 2050, including fleet renewal, improved operational efficiencies, energy transition, and advanced technologies. While Boeing continues to make progress against every pillar, Sustainable Aviation Fuels (SAF) and their scale-up offer the largest potential to decarbonize aviation over the next 20-30 years.

By 2030, all commercial airplanes Boeing delivers will be capable to fly on 100% SAF, that was the commitment made in January 2021.

Boeing CEO David Calhoun reported at US Chamber of Commerce Aerospace Summit in Washington (DC) on 23 Oct. 2022: '' What you must do to get to net zero by 2050 green hydrogen in its best day it's going to move that about 2%. On its best day. On its best effort. That doesn't mean we don't believe in it, but H2 contribution is in the second half of the century, not the first half," he said..

Opinion: If Boeing does not embark in the medium term on the development of hydrogen-powered aircraft, how will Airbus succeed in establishing itself in the United States and on the world market and in triggering the significant investments corresponding to the equipping a large number of airports capable of storing and refuelling planes with hydrogen?

The choice of a hydrogen aviation sector will be decisive for the competitive positioning of global players in the aeronautical field. This choice should therefore be argued, consolidated, and challenged by world-renowned experts before irreversible decisions are taken. This is what Guillaume Faury said at the Airbus Summit at the end of November 2022.

4.4. Engine tests

Several engine manufacturers have planned to test on the ground and in flight a propulsion system using hydrogen.

4.4.1. Airbus and CFM

In February 2022 Airbus signed a partnership with CFM International, an equal joint venture between General Electric and Safran Aircraft Engines, to demonstrate the in-flight feasibility of a hydrogen propulsion system towards the middle of the decade.

The objective of this program is to test on the ground and in flight a hydrogen-powered direct combustion engine with a view to the entry into service of a zero-emission aircraft by 2035. The demonstration will be carried out on an aircraft A380 test cells equipped with liquid hydrogen tanks prepared by Airbus sites in France and Germany. Airbus will also define the specifications of the hydrogen propulsion system, supervise the flight tests, and provide the A380 test bed which will allow the hydrogen engine to be tested in the cruise phase.

https://www.lesechos.fr/thema/articles/bientot-un-demonstrateur-pour-lavion-a-hydrogene-dairbus-1406135

CFM International will focus on modifying the combustion chamber, fuel system and control system of a GE Passport turbojet engine to run on hydrogen. The engine, assembled in the United States, was selected because of its dimensions, advanced turbomachinery and fuel flow. It will be installed on the side of the aft fuselage of the flight test bed so that engine emissions, including contrails, can be monitored separately from those of the engines propelling the aircraft. CFM will carry out an extensive ground test program prior to the A380 flight tests.

4.4.2. Rolls-Royce (RR)

EasyJet and Rolls-Royce announced in July 2022 a ground-breaking new partnership that will pioneer the development of hydrogen combustion engine technology capable of powering a range of aircraft, including those in the narrow-body market segment.

Both companies have committed to working together on a series of engine tests on the ground, starting end 2022 and have a shared ambition to take the technology into the air. The objective of the partnership is to demonstrate that hydrogen has the potential to power a range of aircraft from the mid-2030s onwards.

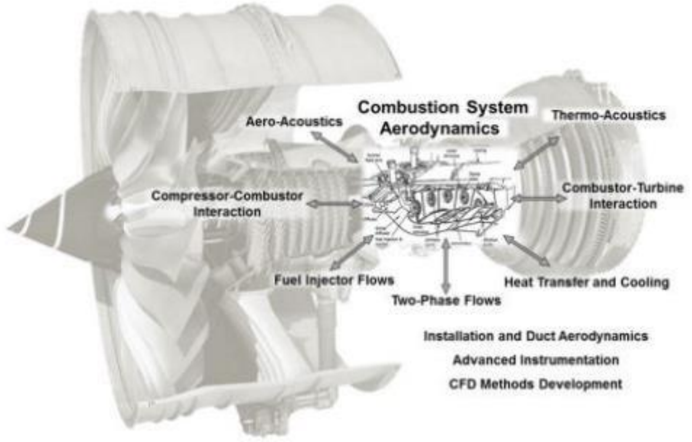
Over the last few years Rolls-Royce have been and still are deeply involved in the ATI FlyZero activity, providing many staff including the Chief Technology Officer from RR so the studies and responses were shaped by RR views.

Rolls-Royce are doing testing on H_2 initially ground based to establish technical credibility. This is both at combustor subsystem level at the National centre for Combustion & Aerothermal Research at Loughborough and whole engine level. One of the first tests took place in November 2022 with an AE2100 engine running on liquid hydrogen.

This is an engine used to power a range of aircraft, including the Lockheed C130 Hercules. Some of the key things that are tested by organizers are typical:

- How liquid hydrogen burns,
- The emissions generated by burning hydrogen,
- How hydrogen is fed to an engine,
- How temperatures are handled in an engine (hydrogen combusts at higher temperatures),

Which materials work or don’t work in a hydrogen engine.



The Loughborough UTC studies all areas relating to the aerothermal processes occurring within gas turbine combustion systems. This is a significant challenge as the combustion system consists of many highly complex components and contains a wide range of complex flow physics.

After having analysed these first tests and with a slightly longer timeline, Rolls-Royce intends, to run a Pearl 15 engine on hydrogen. This engine powers the Bombardier Global 5500 and Global 6500 private jets. The Pearl 15 test will take place on the ground in Stennis, Mississippi. Exact timeline not yet public.

The programme will build on initial hydrogen combustion and fuel system rig tests that Rolls-Royce is undertaking with both Cranfield and Loughborough universities.

On terrestrial and maritime applications, Rolls-Royce will market new MTU Series 500 (500kW) and Series 4000 gas engines (700 to 2500kW) for use with up to 100% hydrogen in 2023.

4.4.3. Pratt & Whitney (P&W)

In February 2022, Pratt & Whitney was selected by the U.S. Department of Energy to develop novel, high-efficiency hydrogen-fueled propulsion technology for commercial aviation, as part of DoE’s Advanced Research Projects Agency-Energy (ARPA-E).

P&W call this HySIITE – Hydrogen Steam Injected, InterCooled Turbine Engine. P&W claims its HySIITE engine with steam injection will “dramatically reduce” nitrogen oxide emissions. Steam engines and aircraft go back a long way, in aviation terms. As a reminder, that company developed and delivered two hydrogen-powered engines to the Skunk Works several decades ago, during the Cold War.

5. Des développements technologiques

Opinion: Academic and university studies mainly highlight recommendations on requirements and procedures. Some researchers are involved in technology roadmaps including proof of concepts through trials to achieve sufficient maturity (TRL up to 6) on critical key topics for direct propulsion by liquid hydrogen, including, among others: :

- *Safety conditions when refuelling aircraft*
- *Storage of LH2 on board in tanks at -253°C, 24 hours a day, 7 days a week, minimizing evaporation*
- *The behaviour of liquid hydrogen during aircraft movements, attitudes, turbulence*
- *The structural integrity of the tanks, resistance to sloshing and load factors, thermal bridges*
- *The transfer of hydrogen stored in the tanks (-253°C, a few bars) to the engine combustion chamber (~50°C, 50 to 100bars)*
- *Adaptation of the engine and exchangers, cryogenic pumps, materials (in particular for hydrogen-related embrittlement).*
- *Leak management, and temperature management (materials) during the life of the aircraft, i.e. 50,000 to 70,000 flight hours*

5.1. Clean Aviation JU

#Appendix 11: Summary of Clean Aviation JU activities (as of October 2022)

Clean Aviation Joint Undertaking has approved over EUR 700 million in funding for 20 projects researching innovative solutions to power the next generation of sustainable aircraft and support EU Green Deal ambitions for a climate-neutral future.

The 20 successful projects cover 14 topics elaborated from the "Clean Aviation Strategic Research and Innovation Agenda (SRIA)" built around 3 thrusts:

- Hydrogen-powered aircraft
- Hybrid Electric Regional aircraft
- Ultra-Efficient Short and Medium Range aircraft

Swift adoption of these technologies from 2035 will enable the biggest step-change reduction in aviation's climate impact by 2050, together with the accelerated adoption of low or zero-carbon energy sources and fuels e.g. clean hydrogen and/or sustainable aviation uels.The official launch of projects started in 4Q2022.

CLEAN AVIATION Co-funded by the European Union

Starting in 2022 Clean Aviation's daring new projects

	PROJECT TITLE	PROJECT COORDINATOR	PROJECT TOPIC*
HYBRID ELECTRIC POWERED AIRCRAFT	HE-ART	ROLLS-ROYCE DEUTSCHLAND LTD & CO KG	Multi-MW Hybrid-Electric Propulsion System
	AMBER	GE AVIO SRL	
	TheMa4HERA	HONEYWELL INTERNATIONAL SRO	Thermal Management Solutions
	HECATE	COLLINS AEROSPACE IRELAND, LIMITED	Electrical Distribution Solutions
	HERWINGT	AIRBUS DEFENCE AND SPACE SA	Innovative Wing Design
HYDROGEN POWERED AIRCRAFT	CAVENDISH	ROLLS-ROYCE PLC	Direct Combustion of Hydrogen in Aero-engines
	HYDEA	GE AVIO SRL	
	NEWBORN	HONEYWELL INTERNATIONAL SRO	Multi-MW Fuel Cell Propulsion System
	H2ELIOS	ACITURRI ENGINEERING SL	Large Scale Lightweight Liquid Hydrogen Integral Storage Solutions
	fLHYing tank	PIPISTREL VERTICAL SOLUTIONS DOO PODJETJE ZA NAPREDNE LETALSKE RESITVE	Near Term Disruptive Technologies
	HyPoTraDe	PIPISTREL VERTICAL SOLUTIONS DOO PODJETJE ZA NAPREDNE LETALSKE RESITVE	
ULTRA EFFICIENT SHORT & MEDIUM RANGE AIRCRAFT	OFELIA	SAFRAN AIRCRAFT ENGINES	Ultra Efficient Propulsion Systems
	SWITCH	MTU AERO ENGINES AG	
	HEAVEN	ROLLS-ROYCE PLC	
	UP Wing	AIRBUS OPERATIONS GMBH	Ultra Performance Wing
	FASTER-H2	AIRBUS OPERATIONS GMBH	Advanced Low Weight Integrated Fuselage and Empennage
TRANSVERSAL AREAS	HERA	LEONARDO - SOCIETA PER AZIONI	Aircraft concepts enabling 30 to 50% reduction in emissions
	SMR ACAP	AIRBUS OPERATIONS GMBH	
	CONCERTO	DASSAULT AVIATION	Novel Certification Methods and Means of Compliance for Disruptive Technologies
	ECARE	AEROSPACE VALLEY	Developing a European Clean Aviation Regional Ecosystem (ECARE)

* Official launch of projects is still subject to legal redress and to successful completion of grant preparation

https ://clean-aviation.eu/our-daring-new-projects-clean-aviation-awards-over-eur-700-million

https ://clean-aviation.eu/our-daring-new-projects-clean-aviation-awards-over-eur-700-million

The hydrogen power aircraft projects received a 1st batch of ~180 M€ fundings and includes:

- **Cavendish** project by **Rolls-Royce plc** for direct combustion of hydrogen in aero-engines: 50/60 M€ - TRL 4/5 targeted after 48 months – 20 partners.
- **Hydeaby** project by **GE Avio** Srl for direct combustion of hydrogen in aero-engines: 50/60 M€ - TRL 4/5 targeted after 42 months – 35 partners.
- **Newborn** project by **Honeywell** International Sro for multi-MW fuel cell propulsion system: 50 M€ - TRL 4/5 targeted after 42 months – 18 partners.
- **H2Elios** project by **Aciturri** Engineering SL for large-scale lightweight liquid hydrogen integral storage solutions: 10 M€ - TRL 4/5 targeted after 36 months – 14 partners.
- **fLHYing tank** project and **HyPoTraDe** project by **Pipistrel** Vertical
- Solutions for near-term disruptive technologies : 7 M€

See details in #Appendix: Summary of Clean Aviation JU activities (as of October 2022)

The H2Elios project, awarded to Aciturri (Spanish), is dedicated to the development and ground test of Large Scale Ultra lightweight LH2 Integral Tanks of ~150kg LH2 capacity with a gravimetric index of 35% @TRL4 or higher by end of Phase 1, aiming at large integral tanks (600kg H2, gravimetric index >45%) for Regional and SMR applications.

Opinion: Clean Aviation JU's European R/D funding is allocated to multi-partner teams and distributed throughout Europe: €50/60 million is allocated to two aeronautical teams of 20 to 35 partners. After 3 to 4 years of effort, the objective is to achieve only TRL 4/5: a modest ambition. Another example is the development of cryogenic LH2 reservoirs. This project is awarded by Clean Aviation to a Spanish company with funding of €10 million. It brings together 14 partners with the aim of reaching TRL4/5 by the end of 2025. Funding and efficiency seem very low.

5.2. UK Studies

Led by the Aerospace Technology Institute (Cranfield University) and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements, and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel, with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions, and recommendations of the project.

See https://www.ati.org.uk/flyzero/

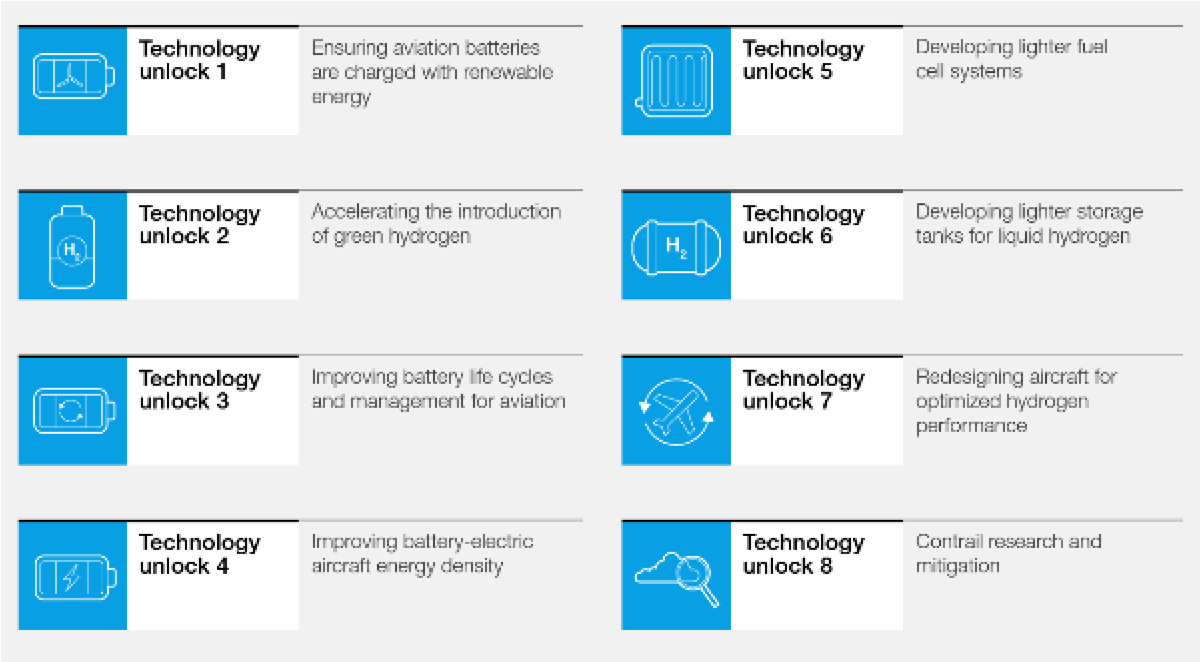
A new report by the World Economic Forum and University of Cambridge's Aviation Impact Accelerator explores how aviation can achieve a true zero climate impact. The report finds that by 2035 three promising types of alternative propulsion aircraft could offer viable alternatives to conventional carbon emitting aircraft.

Fully battery electric aircraft could enable completely emission free flight over the shortest distances.

Hydrogen, meanwhile, could be used to electrify aircraft with fuel cells over mid-range distances, or through direct combustion.

The latter could be applied to any aircraft operating any distances flown today.

Eight key technological unlocks have been identified which will enable the technology to be adopted in aviation:



Technological unlocks that will contribute to reaching true zero flight in aviation.

See: https://www.weforum.org/agenda/2022/07/how-to-achieve-net-zero-in-aviation/

5.3. German Studies

Several research members belonging to German universities (Stuttgart – Braunschweig – Hannover – Munich) investigated the potential use of H2 to power transport aircraft. To be developed in an updated version of this document.

5.4. Japanese Studies

On April 2021, Kawasaki Heavy Industries (KHI) and Airbus signed a Memorandum of Understanding to work together on a hydrogen ecosystem and supply chain. The MoU focuses on the development of airport hydrogen hubs that include the production of hydrogen, its delivery to airports, and getting the liquid, super cold fuel onboard aircraft.

Kawasaki is developing hydrogen technology under the government-backed Green Innovation Fund from the New Energy and Industrial Technology Development Organization (NEDO). KHI plans to spend the next ten years developing technology in:

- hydrogen aircraft engine combustor and systems
- storage tanks of liquid hydrogen
- hydrogen-aircraft architecture concept research

KHI plans to carry out verification-purpose ground tests in 2030.

Mitsubishi Heavy Industries RJ Aviation Group (MHIRJ) and ZeroAvia announced in October 2021 that they are developing a hydrogen-electric propulsion system with fuel cell technology for the Mitsubishi CRJ family for availability in 2027. The hydrogen kit will be available on new and converted aircraft. https ://airinsight.com/japans-kawasaki-invests-further-in-hydrogen-research/

https ://airinsight.com/japans-kawasaki-invests-further-in-hydrogen-research/

5.5. Chinese Studies

http://www.ecns.cn/news/cns-wire/2019-03-20/detail-ifzfsfwt8635949.shtml

No comment.

6. A modest impact on the reduction of CO2 emissions

6.1. *Which legs, for which traffic, with which aircraft?*

In 2019, the world commercial passenger air traffic expressed in RPK – number of paying passengers multiplied by number of km (pax*km), was distributed between:

- Short distance flights from 0 to 1000 km. 78% of traffic is provided by single-aisle short/medium-haul (typically A320/B737) / 15% by regional aircraft either turboprop (typically ATR/Dash 8) or jet (typically CRJ/E170), and the remaining 7% by twin-aisle jumbo jets (typically B777/A350). [ATR/Dash8 ~70 pax; CRJ/E170 ~100pax; A320/B737 ~180 pax; A350/B777 ~350 pax]
- Medium distance flights from 1000 km to 2000 km. 85% of traffic is handled by single-aisle short/medium-haul / 10% by twin-aisle jumbo jets and the remaining 5% by regional aircraft
- Medium distance flights from 2000 km to 4000 km. 77% of traffic is provided by single-aisle short/medium-haul / 22% by twin-aisle jumbo jets and the remaining 1% by regional aircraft
- Long distance flights from 4000 km to 15000 km. 95% of traffic is handled by twin-aisle jumbo jets and the remaining 5% by single-aisle short/medium-haul aircraft.

<u>Opinion</u>: Having to share fleets equipped on the one hand with super-regional H2 turboprops capable of ranges of less than 1 000 NM (1850 km) and on the other hand with medium-haul SAF then H2 capable of stages up to 2 000NM (3700 km), does not seem to offer the interoperability and flexibility offered today by medium-haul aircraft, which handle around 80% of traffic on stages of up to 4000km+..

08 **Passenger flights volume (RPK) by flight distance (2019)**

Flight distance (km)	0-1,000	1,001-2,000	2,001-4,000	4,001-8,000	8,001-15,000	Total
Route example	London - Berlin	London - Rome	London - Beirut	London - New York	London - Jakarta	
RPK (billion)	1,097	2,222	2,063	1,790	1,508	**Passenger volume** = 8,680 billion RPK
Emissions (Mt CO_2)	163	210	176	170	150	**Passenger emissions** = 869 Mt CO_2
Emission intensity (g CO_2 / kRPK[1])	149	95	85	95	99	

Source: ICCT (2020); IEA (2021); Deloitte analysis
Notes: 1) g CO_2/kRPK stands for grams of CO_2 per thousand revenue passenger kilometres

6.2. *Traffic and CO2 emissions*

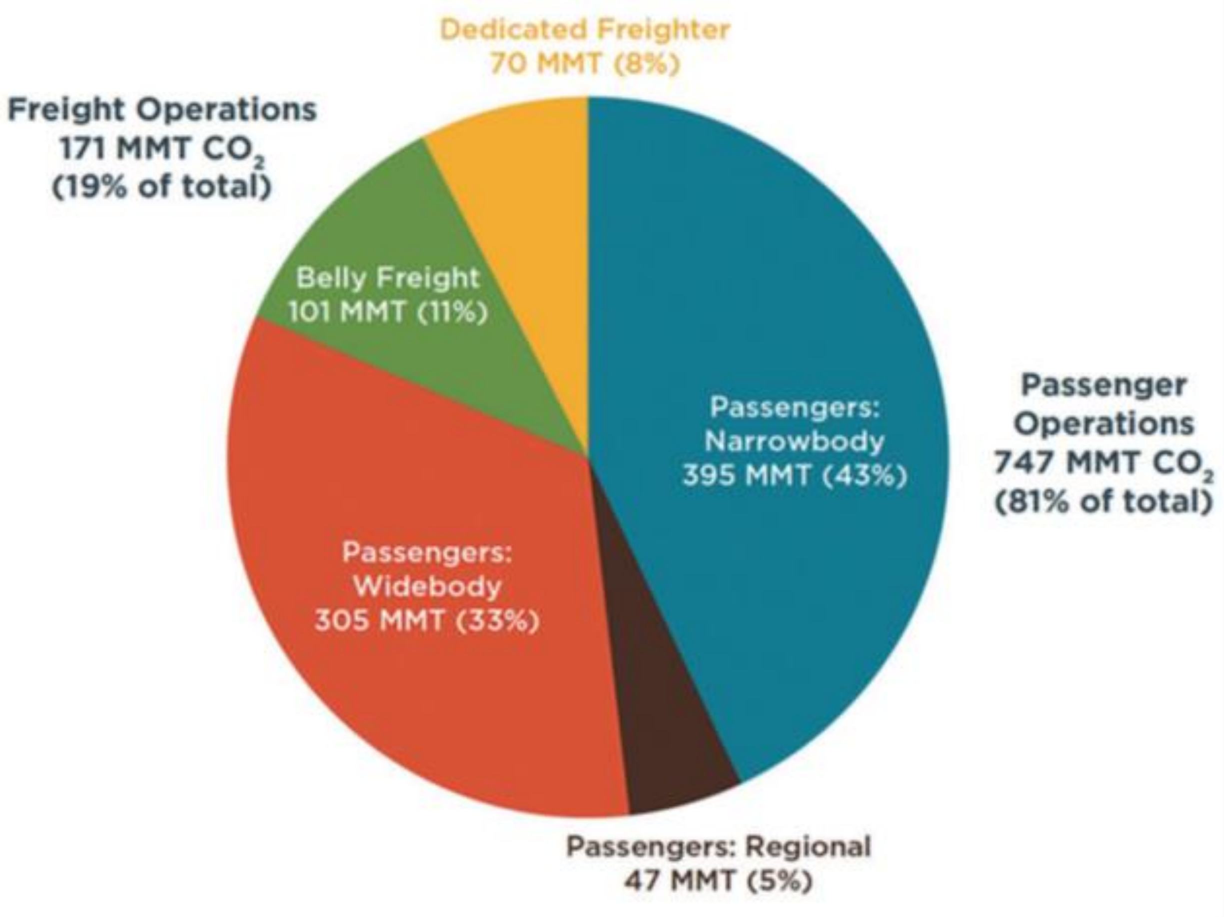
Air transport carried out an average of 39 million annual flights with an overall consumption of kerosene of around 300 Mt/year (corresponding to 3,600 TWh). As a result, it is responsible for 915 Mt/year of CO2 emissions globally. In Europe, consumption was nearly 150 Mt/year and French consumption (national flights and international flights departing from France) is estimated at 7 Mt/year. The breakdown of emissions by type of flight is as follows (source ICCT):

CO2 emissions

- **1/3 are produced on short-haul flights (< 1,500 km).**
- **1/3 are produced on medium-haul flights (from 1,500 to 4,000 km).**
- **1/3 are produced on long-haul flights (> 4,000 km)**

Opinion: The reduction of CO2 emissions must focus as a priority and as urgently as possible on medium and long-haul, which represent 2/3 of traffic and emissions. With the risk that the short-haul plane will be replaced by the train if the journey can be made in an acceptable time.

CO_2 emissions in 2018 by operation and aircraft class.



7. Four levers to reduce the environmental footprint of air transport

These 4 levers are technological advances, improved operations, the use of sustainable aviation fuels (synthetic kerosenes and other fuels, such as hydrogen) and offsets.

Beyond these levers and depending on their real potential, the question of a certain sobriety may arise for developed countries. Progress in aircraft consumption has been almost continuous for more than 50 years and the longevity of aircraft is increasing. As a result, the world fleet in service always has performances that correspond to its average age, quite far from those of the latest born. It therefore displays today (figures for the year 2019) an average of 3.4 liters per passenger per 100 kilometers (pk*t) over real distances covered in operational conditions. However, the latest generation of Airbus (since 2017) is given for just over 2 liters pk*t. under ideal conditions (new aircraft, high density and direct distance).

By 2050, all fleets will be at this level and the next generation of lighter aircraft, innovative in various fields and above all equipped with engines with a very high bypass rate, the development of which is already well advanced, should lead us from the years 2035-2040 towards 1.5 liters pk*t. The optimization of traffic, in flight and on the ground, promises us an additional gain of more than 5%. So in the years 2050-2060, counting on average unit consumption around half of today's is a reasonable bet. A latest-generation aircraft at the current average filling rate therefore consumes a little more than 2 liters pk*t and emits less CO_2 per passenger and per kilometer (60 g) than a car occupied by one or two people.

Although it is difficult to predict what will be the progress within the fleet of 2050 because of the unknowns of its quantitative evolution, its composition in types of planes as well as the nature of the fuels used, the projections of the Most credible air transport growth scenarios lead to consumption in the order of 500 to 600 Mt/year (= 6,000 TWh) by 2050.

All of the scenarios identify that the primary energy needs (primarily electricity) that will be required (21 ExaJ/year in 2050) will represent a significant share of world production (around 1,000 ExaJ/year in 2050). It should be remembered that air transport is a global system for which the regulations are based on ICAO standards and that technical solutions must therefore be thought out at global level, and the question of adapting infrastructures, in particular of "all" airports of the world, taken into account. It should also be noted that airlines have always sought to rationalize their fleets, by homogenizing them, and will most certainly continue to favour this approach.

Appendix 1: Lessons learned from H2 fuelling/defueling in space activities.

An Ariane mission lasts only 30 minutes. With long ballistic phases (up to five hours) and multiple re-ignitions, the issue of cryogenic propellants has already been widely explored. For example, for the launch of the James Webb Space Telescope a year ago, it was necessary to demonstrate to NASA that the residual propellants in the stage after orbit insertion were not likely to cause a collision with the satellite during its transfer to the Lagrange point (several weeks of coexistence between a part of launcher and the $10 billion satellite, the only source of energy being the vaporization of liquid hydrogen, natural leaks more or less controlled, etc.). The required probability was 10^{-9}.

The Ariane 5 Operational Safety construction approach applies to all complex systems, including civil aviation. The difference in design and then manufacturing results from the safety requirements. If we evacuate the launch area, it is because it makes it easier to demonstrate that the risk of killing a person in this phase is less than 10^{-7}. We can set the goal at 10^{-9}, it does not change the approach; it only complicates a possible solution (e.g., a larger evacuation area, or particularly tight connections beyond the current state of the art).

The advantage of Ariane (for liquid hydrogen) is to have a set of events for which the technique, technology and industrial environment that led to proven risks have been addressed to demonstrate 10^{-7}. It is up to aeronautics to take over and not to reinvent these risks (by discovering them by chance) but to demonstrate 10^{-9}, at least in these cases.

Appendix 2: Cryogenic LH2 on board aircraft

Storage: An A320 carries up to 23 tons of kerosene. 9 tons of liquid hydrogen (LH_2) are enough to provide the same energy, but LH_2 occupies a volume four times larger than kerosene and because of its low density requires a volume of tanks of about 150 m3 (integrating the necessary "dead volumes") It is also necessary to maintain the temperature of LH_2 at -253 ° C to avoid boiling with extremely well insulated tanks and anti-sloshing partitions.

The storage of LH_2 on board cannot be located in the wings: one logic is to install the tanks at the rear of the fuselage, which leads to a considerable increase of its length (by several meters). What additional weight results from this configuration? This depends, among other things, on the thermal insulation. The thermal protection of Ariane type tanks (polyurethane cell) is not suitable. Unlike the launcher, it is necessary to have tanks with very low evaporation rates given the duration of the flights (several hours on aircraft compared to 9 minutes of operation for the main stage of Ariane 5).

It seems more logical to move towards a vacuum multilayer insulation, such as the liquid helium tank of Ariane 5, or that of the Herschel infrared satellite... but in much larger dimensions!

Is it economically feasible, knowing that these tanks are known to be expensive? As for the weight, it is not relevant to attempt a transposition to the scale of the aircraft, given all the differences.

Will it also be necessary to put the engines at the rear of the fuselage to minimize heat loss from the engine fuel supply systems?

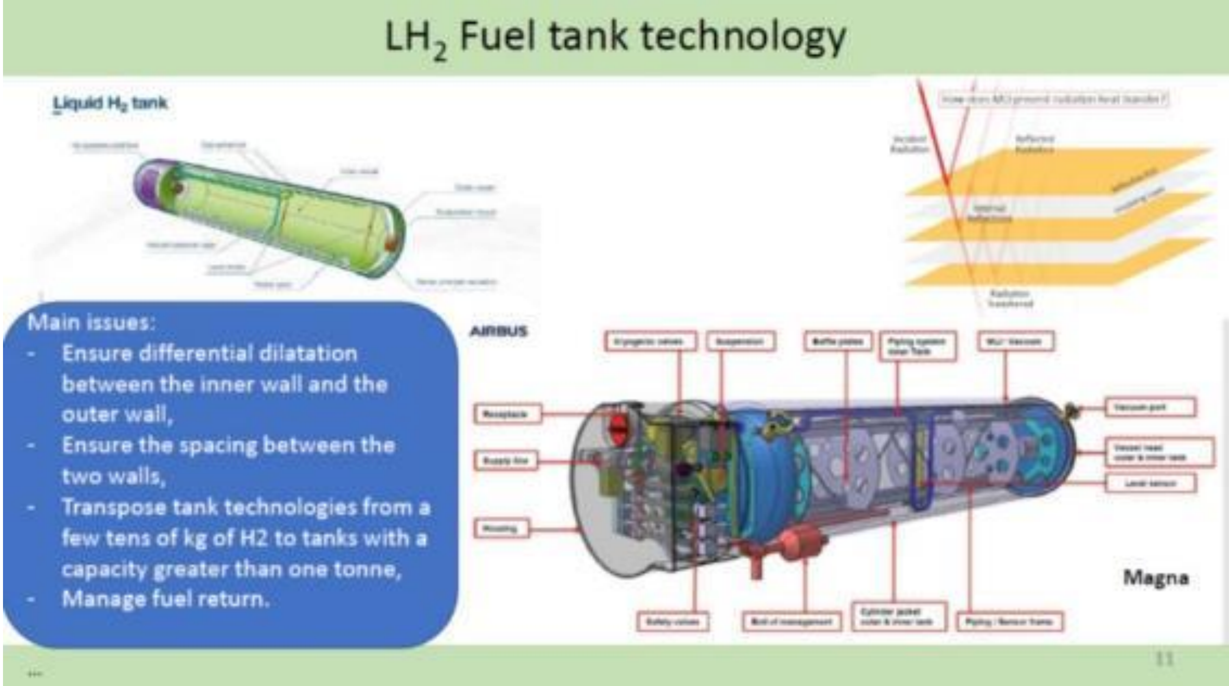
Another solution: an integrated fuselage, close to a flying wing, could free up more interior space and facilitate the voluminous storage of hydrogen, but this is a breakthrough project, where many elements are to be invented, tested, developed, and certified, which will take a lot of time.

Some attempts were made, then abandoned, to install liquid hydrogen tanks in the automotive field, in order to feed fuel cells or even combustion engines (BMW).

The ratio of hydrogen weight / total weight (equipped tank + hydrogen) called gravimetric index (GI) is an important factor in the design of an hydrogen aircraft and must take into account a high performance thermal insulation (probably with double walls) because LH_2 is stored at -253°C.

Air Liquide says it has know-how to achieve a GI of 16 to 20%. Airbus is aiming for 35%, a sine qua non condition for the feasibility of a medium-haul 200 pax / 2000 NM project.

https://www.airbus.com/en/newsroom/news/2021-12-how-to-store-liquid-hydrogen-for-zero-emission-flight



Hypoint and GTL (US industrial) announce a GI of 70%. GTL and Hypoint have obviously forgotten several hundred kilos for insulation, valves, internal pipes to tanks, multiple sensors and other attachment fittings to the aircraft. Note: this article was published on April 1st!

https://www.compositesworld.com/news/hypoint-partners-with-gtl-to-extend-zero-emission-flight-with-ultralight-liquid-hydrogen-tanks

Significant progress is therefore to be made on the tanks weight... How?

LH_2 sloshing due to changes in attitude and load factors may lead to centering variations and additional evaporations. However, these changes in attitude for an aircraft are much greater (50 degrees) than the modest turning of the nozzles of a launcher. It will be necessary to provide anti-sloshing partitions, so additional weight.

The supply of fuel to the engines requires a high pressure, up to around 100/150 bar, this time in gaseous form at the inlet of the combustor. It is necessary to provide cryogenic pumps (variable flow in a high range: 1 to 25 from idle to full throttle), and heat exchangers. A series of equipment and cryogenic lines will have to avoid icing (such as thermal insulation of the tank).

Filling hydrogen tanks (refuelling) is another difficulty. Since hydrogen is obtained by electrolysis of water with renewable electricity, it must still be transported to airports (probably in gaseous form by pipelines or liquefied by trucks), and liquefied on site, in the vicinity of the airport. Then fill the tanks: will this refuelling be done in the vicinity of the public avoiding any leak that represents a major risk, hydrogen being likely to cause fires or even explode at low concentrations.

Once the aircraft is ready, it must be filled from hydrogen storage on the ground. You don't fill an LH_2 tank like a gas tank. Filling should be done slowly enough, maintaining its pressure slightly above atmospheric pressure and incredibly low temperature, while avoiding boiling. And probably away from the public. This refuelling may take one or two hours for a medium-haul aircraft. Hardly compatible with the daily utilization rates of current fleets!

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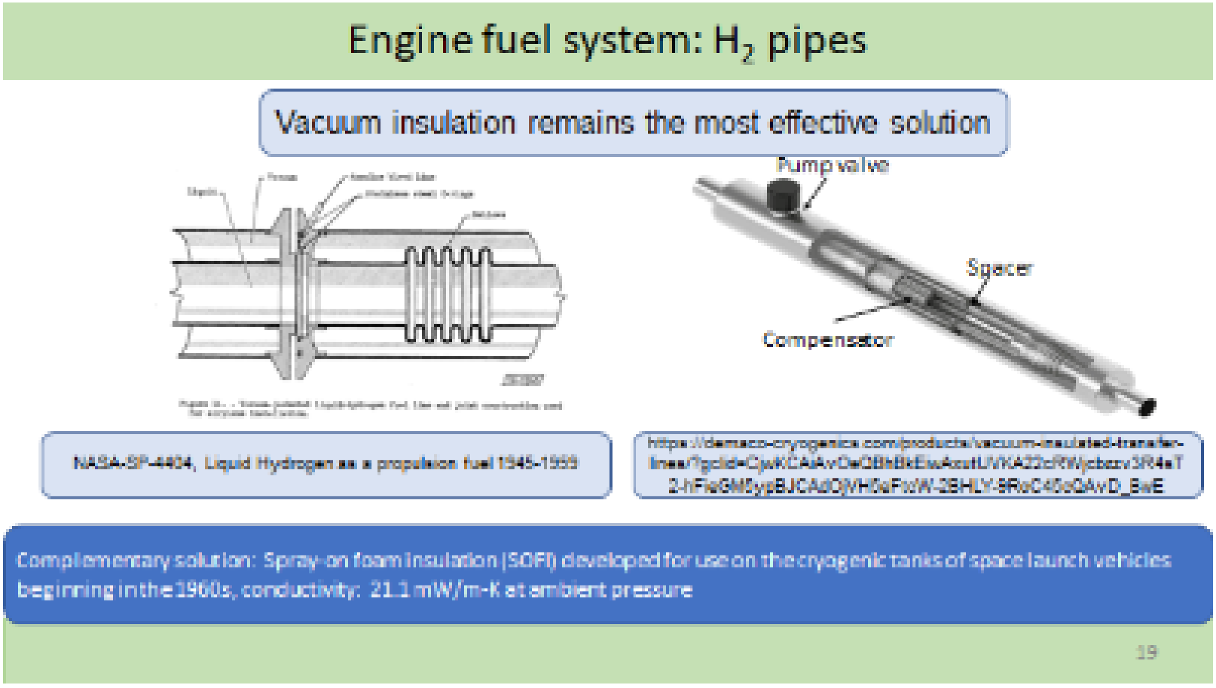


For the same energy, the volume flow of hydrogen being four times higher than that of kerosene, the weight of these pipes is impacted by the increase in diameter (multiplied by 2 in first approximation) and by thermal insulation (double-skin system and / or use of insulating foam). Gains are to be sought by optimizing the relative position of tanks-engines.

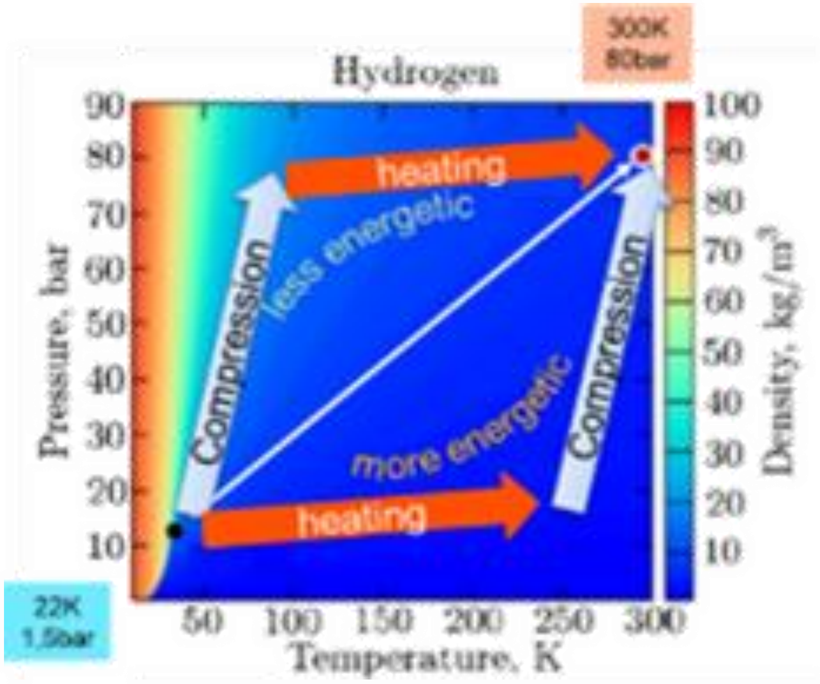
With hydrogen, cryogenic temperatures on certain portions of the circuit impose constraints on insulation and material compatibility, both for material and human environment. The quality of hydrogen in tanks will depend on the quality of its manufacturing and the mastery of intrinsic sealing and use. Indeed, cryogenic temperatures induce a risk of having a presence of air or nitrogen in solid form that could require suitable filtering devices. The very low density of hydrogen and its high heat capacity require unprecedented energy expenditure to pressurize and heat it. Finally, the high flammability of hydrogen requires avoiding any contact with air outside the chamber, which leads to drastic constraints in terms of sealing, prevention and protection measures or even particular operating modes such as purging and sanitizing the system.

The hydrogen must be injected into the engine at a temperature compatible with the needs of the chamber (neither too cold nor too hot) and must therefore be fully vaporized and warmed. Multiple hot sources are identifiable, and the engine is one of the primary sources via its cooling needs (engine oil, cooling air, aircraft electric generators) or via ejection gases for example.

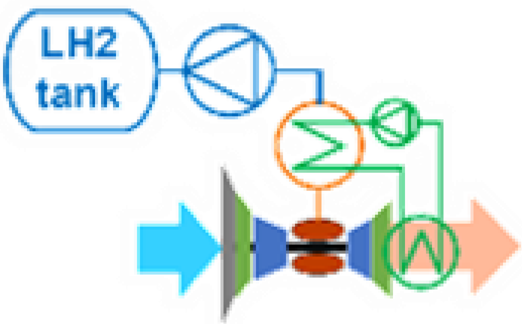
Similar to a kerosene system, the fuel pressure must be raised to the level specified by the combustion chamber. The flow rate must also be finely controlled to meet the precision and responsiveness requirements of modern gas turbines. A new main function must be introduced: liquid hydrogen must be heated and vaporized to reach the operating temperature. For efficiency reasons, it is preferable to pump liquid hydrogen rather than gaseous which determines the arrangement of the pressurization function upstream of the heating function.

Elever la pression → Réchauffer → Maîtriser le débit

The objective of the heating function is to increase hydrogen temperature from 20 K to a temperature level compatible with the fuel injection and combustion throughout the operating range. This represents powers of up to 2MW per engine for a medium-haul aircraft: significant sources of heat are therefore to be found.



This new function adds a new degree of complexity: a hot source must be introduced, or an existing source must be used. The most obvious solution is to retrieve the heat directly from the hot air circulating in the engine and advantageously via the exhaust gases. Air cooling during compression also presents an opportunity to optimize the thermodynamic efficiency of gas turbines, and many cycles are proposed by industry players.



In addition to these main functions, new secondary functions must be introduced to master the unstable nature of hydrogen. It includes functions of control of the pressurization of the tank, purge, cooling, ventilation, vacuum control of the insulation...

Cryogenic hydrogen has special characteristics to consider in the design of the architecture. The first, essential, is that all other fluids (except helium) freeze on contact with it. This property implies operational constraints: all circuits exposed to liquid hydrogen will have to be purged. The formation of nitrogen, oxygen or water ice can cause many failure modes, the main ones being the degradation of safety valves seal and the blockage of fuel nozzles. Helium use, widely developed in space, is not possible in aeronautics for economic reasons and because this gas is not renewable. Thus, these purge phases will have to be carried out from nitrogen (to remove oxygen and water) and hydrogen gas (to remove other gases).

In addition, hydrogen is usually stored in a state close to saturation. By circulating in hotter pipes or components, it undergoes a phase change. The rapid increase in the volume of gas leads to blockages and significant instabilities, or even reverse flows. Thus, it is necessary to cool down the entire system before starting. This operation also allows the various components to reach their nominal clearances to avoid leaks during pressurization, or contacts for moving parts.

These two new operations (purge and cooling down) are to be integrated into the aircraft availability studies.

The transition to hydrogen does not radically change the architecture of a turbomachinery but involves many technological breakthroughs that will have to be the subject of large-scale maturation plans with the implementation of new testing, qualification and certification facilities.

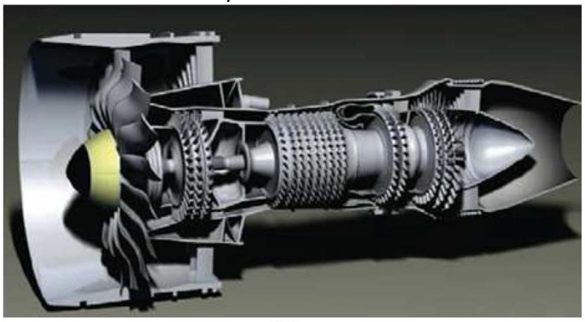
The hydrogen system therefore brings many novelties, and an adaptation of the current kerosene system will not be enough to achieve the level of performance and reliability obtained after 80 years of experience. Many functions need to be rethought starting from the base, i.e. the thermodynamics specific to hydrogen.

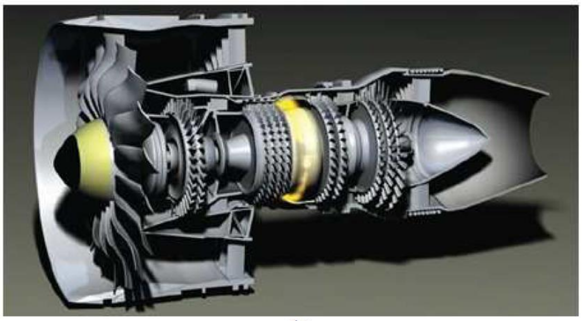
Bringing together specialists from the aeronautics and space sectors as well as other industrial players can only be encouraged.

Appendix 3: What types of Hydrogen engines

Different propulsion system configurations using hydrogen are possible::

- Use of classical turbomachinery based on the Brayton cycle (large bypass ratio engines, open rotors or turboprops).
- Combination of a turbomachinery and a SO-FC fuel cell operating at high temperatures. This type of configuration should make it possible to achieve thermal efficiencies of the order of 0.7.
- Exploitation of hydrogen detonation capabilities in the CDE (Continuous Detonation) or RDE (Rotary Detonation Engines) thermodynamic cycles, which reduces the number of HP compressor stages and improves thermodynamic efficiency.





(a) (b)

). (a) Schematic of the classical two-circuit turbofan engine (b) Scheme of the turbofan engine that uses detonation combustion

Use of a fuel cell driving an electric motor. In this case, PEM-type technologies operating at low temperatures are considered. These technologies are already widely used in the fields of electric vehicle and power generators. Synergy is therefore possible.

<u>Brayton Cycle</u>

The differences between kerosene and hydrogen turbomachinery are mainly in the fuel system, the control system, and the combustion chamber. The main challenges are the achievement of the operational safety requirements required by the certification and the limitation the weight increase compared to a kerosene engine.

- The engine « fuel system » shall be designed to perform fuel pressurization, heating and metering functions:
    - The engine pumps must raise the hydrogen pressure up to 100-150 bars at full throttle (OPR value of 35 to 50+ pressure drop of the fuel system and the injection system). The power required is proportional to the volume flow. It is therefore 4 times higher than with kerosene. The use of centrifugal pumps is envisaged but the lubrication of the bearings to ensure a sufficient lifespan is a sticking point. Electrical actuation of these pumps is contemplated;
    - Hydrogen must be heated before being introduced into the combustion chamber. The main source of heat is an exchanger, with a power of the order of one MW for an SMR engine, placed at the outlet of the primary flow;
    - The fuel pipes will be more numerous, more complex to guarantee tightness, with double skins and a large diameter (especially for the gaseous part).

- The actuation of the variable geometries must be carried out electrically, which requires power electronics. Hydrogen could be used to ensure its thermal management.
- Given the flammability range of hydrogen, a monitoring and ventilation system for the engine sumps and nacelle compartments must be put in place.

All of these elements will contribute to significantly increase the weight of the engine in a range of between 5 and 10% (150 to 300 kg for an SMR propulsion system).

With regard to the combustion chamber, the technologies under development should make it possible to control the production of nitrogen oxide. On the other hand, controlling the phenomena of self-ignition, flashback and combustion instability remains a major issue.

The use of LH2 as a heat sink will allow the implementation of new technologies, in order to improve performance, but these will introduce new risks and cases of failure to be taken into account:

- Pre-cooler and intercooler at the compression system level (with risks of icing),
- Cooled cooling at HP turbine cooling air level,
- Motor/ generator and their power electronics cooling,
- High temperature superconducting material for motors/generator.

Finally, the coupling of the gas generator to a SO-FC fuel cell offers prospects for improving the thermal efficiency. But this requires very significant improvements to be made in order to obtain fuel cells with sufficient specific power.

CDE or RDE type cycles

The use of detonation combustion simplifies the turbomachinery by reducing the number of HP compressor stages and/or increasing thermal efficiency. But because of its TRL level of around 3, the use of this technology in the SMR segment does not seem feasible by 2050. Scale 1 demonstrators would be necessary to abate integration risks (operability, impact of the structure of the flow at the outlet of the combustion chamber on the efficiency of HP turbine, emissions, noise, etc.) and to ensure fuel burn benefits.

Electric propulsion powered by a fuel cell

The use of PEM fuel cell to drive electric motors has the potential to improve thermopropulsion efficiency compared to a conventional turboprop. In addition, they operate at low pressure (less than 2 bar), do not produce NOx and the produced water can be captured at least partially.

High-temperature superconductivity provides access to very high values of specific power for wiring and motors. In addition, PEMs that are used for land vehicles operating with H_2 are expected to undergo significant developments in the coming years.

Appendix 4: Potential issues linked with the use of H2.

As an initial list of the main issues which need to be considered, the following can be identified.

Issues inherent to the hydrogen physical and chemical characteristic

- Broad flammability range: 4% to 75% concentration in air (very reactive reaction with oxygen), 4% to 94% based on volume percent of hydrogen in oxygen.
- Low minimum energy ignition (~0.02 mJ, vs ~0.3mJ for methane, i.e. ~1/15 effort to ignite; static electricity sparks ~1mJ); wide-range of combustible air-fuel mixtures.
- Higher flame velocity (~3m/s, vs 0.45 m/s for methane), resulting in detonation with shockwave.
- Low visibility of flames in case of fire.
- Buoyancy, low density, high permeability, low viscosity, extremely diffusive = vulnerability to leaking and accidental release.

These characteristics, considered in combination, making fire and explosion the most critical associated risks, imply the implementation of appropriate inerting, purging and venting systems, together with associated procedures, special precautions in handling (including hydrogen tank filling) and the implementation of specific protection features in design (including for instance fault-preventing devices, keying system connectors, fail-safe connector tightening adjustment, proper structural dimensioning at overall aircraft level and for hydrogen tanks, with proper leak proofing and insulation of tanks and systems). The corresponding precautions need to be applied all along the chain of design, from overall architecture down to elementary components. Well-thought design including failsafe features may bring the targeted reliability level of systems more efficiently than applying rules very strictly with blinders on.

In addition, there are important effects to be considered, caused by the vulnerability to liquid hydrogen sloshing under varying aircraft accelerations and bank angles attitude, possibly including significant turbulence events, when rapid thermodynamic phenomena are involved (sequence of LH_2 in contact with hot tank walls, sudden overpressure, cooling), necessitating the control of resulting LH_2 pressure variations. In connection with these phenomena, the accuracy of LH_2 gauging in tanks is challenging; it should be possible to overcome the corresponding potential safety issue, but with a potential impact on margins and overall performance.

a. Ability to embrittle metals, including carbon steel and weld metals: this makes tank manufacturing very challenging, constrains the choice of metals and alloys being used in the manufacturing of parts in contact with liquid hydrogen (including tanks, pipes, valves, pumps, on aircraft and engines), and is very likely to require specific maintenance and overhaul procedures (e.g., in relation to thermal protection defect detection, to crack detection of metallic parts, to repair, validation).

b. Low temperature, liquefaction/solidification of inert gas and constituents of air (oxygen enriched atmosphere), with multiple system implications, in combination with the risks of leaks and icing of parts.

c. High reactivity in presence of chlore, water and other substances.

Other situations, for instance in relation to aborted take-off, emergency landing and crash landing should also be considered for their specific potential consequences, associated with strong decelerations, structural damages, hydrogen leaks, etc.

The proper sizing and operation of systems and equipment needs to be supported by fault and failure analyses, verified, and validated by adequate simulations and tests at appropriate level, covering the whole flight envelope and all potential circumstances.

Many safety protocols need to be considered, in the activities linked with producing, storing, transferring, and using hydrogen.

It will be noted that it is difficult to categorize these issues in terms of their criticality or difficulty of handling/solving, of impact on products or of other repercussions. This depends on many factors which remain to be explored in depth, on the vehicle considered and on its individual design features.

In addition, many risks need to be considered jointly: for instance, the risks associated with leaks, undetected cracks, of thermal insulation loss of integrity/efficiency, flames, flashback, fire, deflagration, detonation, or explosion, for obvious "cause and effect" reasons.

Some general issues (e.g., flammability range) need to be broken down into specific issues depending on the area and part affected (engine, structure, system, equipment, component), circumstances (ground or flight operation, maintenance, others).

Altogether, there are multiple, combined impacts to be addressed, which are connected and compounding with the potential safety risks and issues: these affect more or less directly aircraft and propulsion system design, manufacturing, operational procedures in all phases of activities on ground and in flight, maintenance procedures, airport infrastructures, turnaround times, spare parts, minimum equipment list, LH2 consumption, operating costs, aircraft productivity, personnel qualification and training, etc., finally the entire air system economic model.

There are additional safety issues specific to hydrogen use, concerning subjects outside of aircraft certification, and which need to be covered by other local (airport), national, regional (European) and international regulations, handled by relevant authorities. It is assumed that some interface situations already exist today between aircraft certification authorities and the other authorities involved, nevertheless, a thorough review of all potential interfaces will need to be conducted in the new context involving the use of hydrogen, to ensure a complete coverage of all potential issues, including the new ones, with all necessary new or revised requirements and procedures, documented as appropriate, to identify all interactions, and ensure that there is no point left uncovered.

At European level, in the Research domain, the CHJU, the Clean Hydrogen Joint Undertaking, has issued its work programme for 2022 which clearly considers safety aspects and has planned research topics dedicated to it: *"It will also support two topics with the objective of increasing the level of safety of hydrogen technologies and applications. One topic will look at the safety aspects of handling liquid hydrogen in public areas and another will look at the impact of injecting hydrogen on gas Transportation and Distribution (T&D) network components and on all end-users connected to the gas infrastructure."* (ref. xx p.37). The CHJU work programme mentions the contribution of the Joint Research Centre of the European Commission (JRC) to safety and to safety awareness, in conjunction with the work of the European Hydrogen Safety Panel (EHSP) launched in 2017.

Appendix 5: Background on Risks into probabilistic terms (FAA and EASA)

For several years, aeroplane systems were evaluated to specific requirements, to the "'single fault'" criterion, or to the fail-safe design concept. As later-generation aeroplanes developed, more safety-critical functions were required to be performed, which generally resulted in an increase in the complexity of the systems designed to perform these functions. The potential hazards to the aeroplane and its occupants which could arise in the event of loss of one or more functions provided by a system or that system's malfunction had to be considered, as also did the interaction between systems performing different functions. This has led to the general principle that an inverse relationship should exist between the probability of a failure condition and its effect on the aeroplane and/or its occupants. In assessing the acceptability of a design, it was recognised that rational probability values would have to be established.

Historical evidence indicated that the probability of a serious accident due to operational and airframe-related causes was approximately one per million hours of flight. Furthermore, about 10 % of the total were attributed to failure conditions caused by the aeroplane's systems. It seems reasonable that serious accidents caused by systems should not be allowed a higher probability than this in new aeroplane designs. It is reasonable to expect that the probability of a serious accident from all such failure conditions be not greater than one per ten million flight hours or 1×10^{-7} per flight hour for a newly designed aeroplane. The difficulty with this is that it is not possible to say whether the target has been met until all the systems on the aeroplane are collectively analysed numerically. For this reason, it was assumed, arbitrarily, that there are about one hundred potential failure conditions in an aeroplane, which could be catastrophic. The target allowable average probability per flight hour of 1×10^{-7} was thus apportioned equally among these failure conditions, resulting in an allocation of not greater than 1×10^{-9} to each. The upper limit for the average probability per flight hour for **catastrophic failure conditions would be 1×10^{-9}**, which establishes an approximate probability value for the term **extremely improbable**'. Failure conditions having less severe effects could be relatively more likely to occur.

Appendix 6: Lessons learned from space launch

An Ariane mission only lasts 30 minutes. With long ballistic phases (up to five hours) and multiple re-ignitions, the issue of cryogenic propellants has already been widely explored. For example, for the launch of the James Webb space telescope a year ago, it was necessary to demonstrate to NASA that the residual propellants in the stage after the injection were not likely to cause a collision with the satellite during its transfer to the Lagrange point (several weeks of coexistence between a piece of launcher and the $10 billion satellite, the only source of energy being vaporizing liquid hydrogen, more or less controlled natural leaks, etc.). Those demands were at 10-9.

The Ariane 5 Operational Safety construction approach is applicable to all complex systems, including civil aviation. The difference in the design, then the manufacturing results from the objectives that we set ourselves. If we evacuate the launch zone, it is because it makes it easier to demonstrate that the risk of killing a person in this phase is less than 10-7. We can set the objective at 10-9, it does not change the approach; it only makes a possible solution more complicated (for example a larger evacuation zone, or particularly tight connections outside the current state of the art).

The advantage of Ariane (for liquid hydrogen) is to have a set of events for which the technique, technology and industrial environment that led to proven risks have been resolved to demonstrate 10 -7, it is up to aeronautics to take over not to reinvent these risks (by discovering them by chance) but to demonstrate 10-9, at least in these cases.

Appendix 7: H_2 Accident statistics in industrial facilities

Unfortunately, we cannot claim that there will **never** be any accidents or serious incidents related to the use of hydrogen. All the more so for an aviation whose safety requires demonstrating probabilities of catastrophic risks (i.e., leading to fatalities) of less than 10-9 per hour, and this anywhere in the world, regardless of the personnel contributing to this safety.

Over a period of 12 years (1965-1977), there were 409 accidents related to the use of hydrogen, including 85 for liquid hydrogen (LH2).

In the document 'Handbook of hydrogen safety: Chapter on LH2 safety' the chapter 5 (pages 112 to 119) provides an exhaustive analysis of these accidents and their causes.

In summary:

- leaks or purges and insufficient degassing generally lead to fires
- the tanks must be extremely well thermally insulated
- thermal shocks due to too rapid refuelling/defueling lead to pipe ruptures; hence the rather lengthy procedures for cooling the circuits
- the tank filling rate cannot be 100%: be limited to 90%
- if air enters the circuits, it will freeze and cause clogging.
- All this information is well known to players in the space field where specific procedures have been adapted for several decades.
- For example, cooling Ariane before launch takes several hours and the launch area is completely evacuated during the filling of cryogenic propellants (LH2 and LOx).

Appendix 8: Need of a system architect team.

The development of applied science, especially in an industrial environment, most often leads to juxtaposing or adding specialists (experts) in the different technical disciplines to be implemented to optimize the "system", the object of the initial ambition of the project.

Each of the experts seeks optimization in his field of excellence at the (certain) risk of complicating the task of his colleague without both being always aware of it, especially if their vision, essentially local, is altered by a legitimate short-term obligation to reduce costs or planning.

It is in the final phases of activities (integration, certification, industrialization) that these malfunctions are observed, most often leading to significant delays, significant additional costs, sometimes to a halt of the project.

This observation is a consequence of the current complexity of certain industrial projects that are no longer controllable by a simple individual (or a small group of individuals) and require, in all circumstances, an ability to organize a confrontation between the local (that of technology, that of expertise, that of the subcontracted field) and the global (the project manager, the architect, the system) to make not the best decision, but the least bad one in the uncertain "local-global" context of when this decision must be made. The resulting system is not necessarily the perfect image of the initial ambition, but it certainly meets the fundamental objectives and above all it is "manufacturable" and immediately usable.

The use of liquid hydrogen to replace fossil fuels, and more generally the ecological challenge of adapting and changing the mechanisms of transformation of available energy sources, can only be overcome if engineers are trained in this multidisciplinary approach to better understand them, to identify local and global risks and to arbitrate in full knowledge of the facts.

Appendix 9: Certification aspects

A number of regulations/standards exist at international level (such as ISO/TR 15916:2915[2]), in Europe and in France (such as NF M58-003[3]), related to the use of hydrogen, including in liquefied form, in the industry and in the automotive sector. Some are still under development. The situation is less advanced today for the regulations concerning the use of LH2 in the aviation sector, but it is bound to progress rapidly, considering the fast-growing rate of related studies.

The regulatory aspects, those related to aviation, will be discussed under the regulatory and certification issues in the next section.

There are solutions already identified to address some of the issues, and it can be expected that further solutions will be developed to address others. The ultimate assessment will depend in any case on the type of product involved (design characteristics and size). The definition of solutions, their impact and the associated research and development time and costs involved are therefore difficult to predict, since they are multiple and will vary significantly.

Some experience could also be gathered from reports and statistics related to hydrogen in industrial facilities #Appendix H2 Accident statistics in industrial facilities

Many of the safety issues, as they may apply to the aviation sector, directly translate into regulatory and certification issues within that sector, since the aircraft (or engine) type certification aims by definition at ensuring a proper aircraft (or engine) safety level and calls for safety requirements and analyses. This one-to-one correspondence between safety issues and certification issues is true at aircraft (including propulsion system level) in all areas, including documentation. It is obvious for instance in terms of engine and aircraft certification, in relation to bird ingestion, fan blade-out and rotor burst.

There are additional safety issues specific to hydrogen use, concerning subjects outside of aircraft certification, and which need to be covered by other local (airport), national, regional (European) and international regulations, handled by relevant authorities. It is assumed that some interface situations already exist today between aircraft certification authorities and the other authorities involved, nevertheless, a thorough review of all potential interfaces will need to be conducted in the new context involving the use of hydrogen, to ensure a complete coverage of all potential issues, including the new ones, with all necessary new or revised requirements and procedures,

[2] ISO/TR 15916:2015: ISO/TR 15916:2015 provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate International Standards.

[3] AFNOR NF M58-003: covers the safety requirements relative to the installation of equipment for hydrogen production, equipment operating with hydrogen, hydrogen distribution systems, hydrogen storage containers, hydrogen pipes and their accessories.

documented as appropriate, to identify all interactions, and ensure that there is no point left uncovered.

At European level, in the Research domain, the CHJU, the Clean Hydrogen Joint Undertaking, has issued its work programme for 2022 which clearly considers safety aspects and has planned research topics dedicated to it: *"It will also support two topics with the objective of increasing the level of safety of hydrogen technologies and applications. One topic will look at the safety aspects of handling liquid hydrogen in public areas and another will look at the impact of injecting hydrogen on gas Transportation and Distribution (T&D) network components and on all end-users connected to the gas infrastructure."* (ref. xx p.37). The CHJU work programme mentions the contribution of the Joint Research Centre of the European Commission (JRC) to safety and to safety awareness, in conjunction with the work of the European Hydrogen Safety Panel (EHSP) launched in 2017.

In the regulatory domain relative to air transport, there is indeed a big open yard, which will have to integrate and/or develop the following:

- all relevant applicable / adapted inputs derived from all above general regulations and standards, themselves evolving; it can be noted however that the already quite significant steps achieved in knowledge and experience in other sectors, including the space domain, are valuable assets for making progress in technology and aircraft developments, as well as in the regulations, relative to the use of hydrogen in the air transport sector.
- specific standards for aviation (to complete existing ones and generate new ones as required to integrate fully all aspects concerning the use of hydrogen), related to components, equipment and systems, standards to which the regulations are referring to and relying upon (such as SAE ARP4754 and SAE ARP4761, which provide "*certification considerations for highly-integrated or complex aircraft systems*").
  These standards categorize failures as: no safety effect, minor, major (probability has to be $<10^{-5}$ per flight hour), hazardous ($P<10^{-7}$) or catastrophic ($P<10^{-9}$), which drive and frame the entire set of safety analyses.
- Thorough review of the whole set of current aviation regulations, including airworthiness requirements EASA CS2 (Large Aircraft), CS25-130 (System Design and Analysis), CS (Engines), to check whatever needs to be completed, adapted, corrected, added as new specific conditions, methodologies, means of compliance, equivalent processes.
- Overall check of consistency and completeness of processes and associated documents, identifying interfaces, interactions, gaps and proposing corrective actions.
- The set of policies, Plans (e.g., the Global Aviation Safety Plan: GASP), Standards and Recommended Practices (SARP), manuals, guidance and other documents and reports elaborated by ICAO will necessarily reflect the specific aspects linked to hydrogen in air transport activities.
- All certification reports, documents and manual, required in line with the regulations in relation to each aircraft type concerned, will obviously have to reflect the impact of hydrogen specific systems and presence on board on operational procedures.

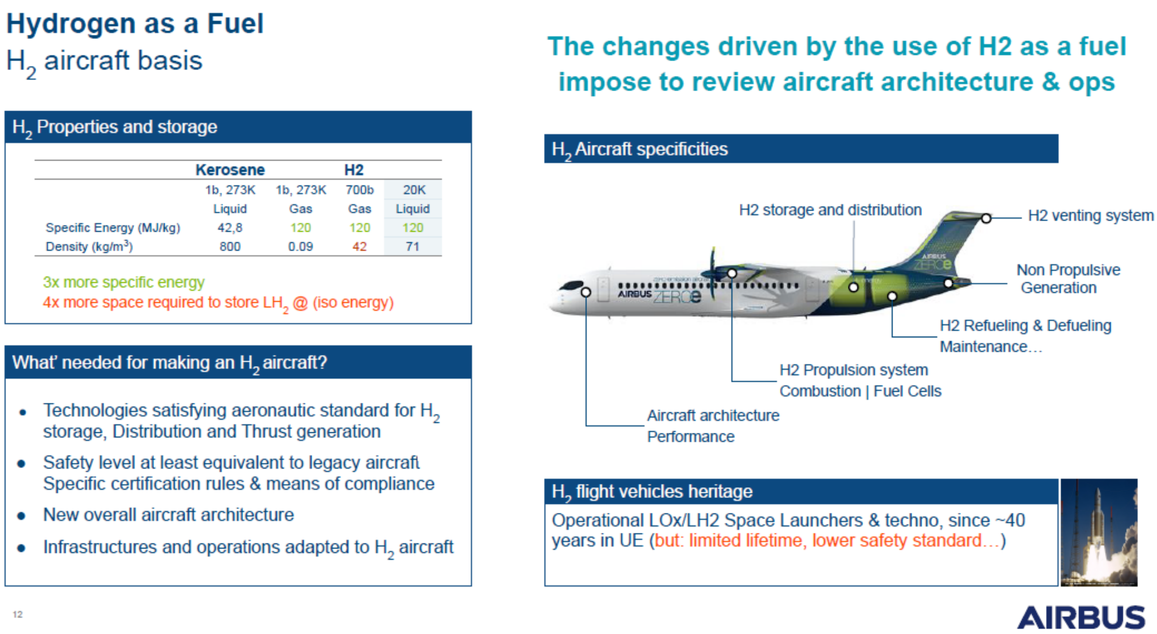
Annexe 10 - Airbus Projects

Appendix 10.1 Regional short-haul concept

Guillaume Faury, Airbus CEO declared in an interview to Aviation Week dated 5 July 2022:

> However, the liquid hydrogen-powered aircraft Airbus plans to develop for 2035 will not be a direct replacement of today's single-aisle products. "Our first aircraft will probably be near the smaller size [of less than 100 passengers with a range of 1,000 nm], but it's just my guess, not the conclusion of the study," Faury says. "It is going to be more regional." Faury also pointed to the fact that "a very large number of flights are below 1,000 nm."
>
> The narrowing down of the first aircraft in Airbus' ZEROe program to a regional profile would still leave a requirement for a potentially conventional replacement of today's large narrowbodies in the 2030s.
>
> In spite of the technology challenges, Faury remains strongly supportive of hydrogen as a future fuel. "Will it be a big share of the carbon savings by 2050? No, it will still be small, there will be initially one plane and to be there in 2035 we need to start now," he says. "[But] at the end of the century, hydrogen will be a very significant part of the fuels we are using."

The complexity of the development of aircraft propelled by hydrogen, as well as the necessary concomitant development of the associated logistics mean that the first commercial development could concern a concept of **regional** or even "**super regional**" aircraft with a capacity of 100 pax and a range of around 1000 NM for entry into service around 2035.



The gain on emissions of other direct or indirect greenhouse gases (NO, NO2, CH4, O3) linked to the use of LH2 remains to be assessed.

The introduction of such aircraft will depend on considerable R&D efforts and the development of hydrogen production and airport refuelling structures at international but also regional airports.

According to a source: 'If these planes only account for a little less than 25% of CO2 emissions, they could be of interest in terms of local transport policy but also of the market, particularly in Europe (about 75% of flights are 1000 NM or less but carry 150 to 200 pax). In particular, low cost companies like Easyjet or Ryanair could be interested in it'.

https://www.rolls-royce.com/media/press-releases/2022/19-07-2022-easyjet-and-rr-pioneer-hydrogen-engine-combustion-technology-in-h2zero-partnership.aspx

'These planes could respond to possible flight restriction policies that could be put in place at the local level by presenting a zero CO2 alternative'.

Only 10 of the Mercure, an aircraft aimed at the market for stages of less than 1,000 km, were produced and only used by Air Inter. Launched by Dassault in 1969 with the help of the French State, in view of the distribution of short and medium-haul flights (90% of flights of less than 1000 km), it turned out that the airlines preferred airplanes with more versatile use and longer range (B737 and A320). Would there be a hydrogen niche for short flights?

Opinion : The more the H2 niche shrinks, the less the investment in R&D is justified. Invest in radically new aircraft, significantly different from the rest of the fleet in their operation, just to compensate for possible political restrictions on some domestic flights? Wouldn't they be too small to be profitable on heavy traffic lines, too complex for really small regional lines, useless on lines already doubled by efficient TGVs (Paris-Bordeaux, etc.).

Since SAFs will be available and simple to use due to their 'drop-in' capacity, and that "by construction" they will respond quite well to the need for decarbonization, what would be the point of putting this segment of the market on a hydrogen diet?

Appendix 10.2 Questions about a potential hydrogen medium-haul preliminary project

Among the three hydrogen aircraft concepts presented by Airbus, a medium-haul uses liquid hydrogen to power two conventional turbojet engines.

Assuming all definition and safety points resolved, a group of AAE/C2E engineers attempted to carry out a pre-project study of such a medium-haul H2 based on an A321- neo capable of stages of around 2000 NM with around 180 passengers (A321 neo-H2).

What are the difficulties of this type of project? How can they be resolved? How long will it take? What would be the hydrogen production needs to refuel these planes? With what energy to manufacture this hydrogen? What would be the direct operating costs compared to using SAF? How would this solution provide an answer to the climate challenges of air transport?

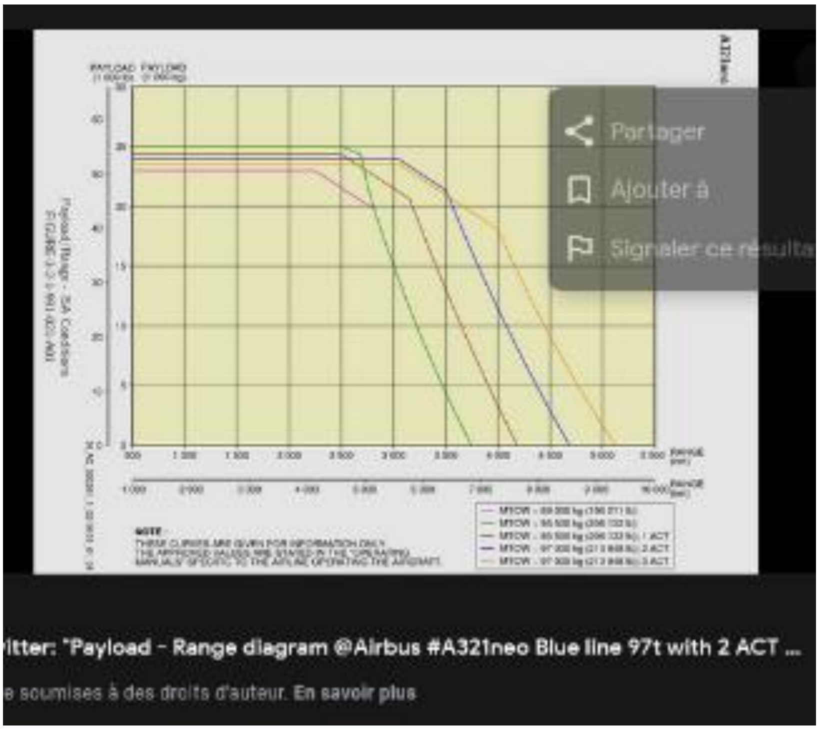
<u>A321 neo-H2 estimated characteristics </u>(tbc values)
Max Take-Off Weight (MTOW) = 97 t (the one of A321 neo)

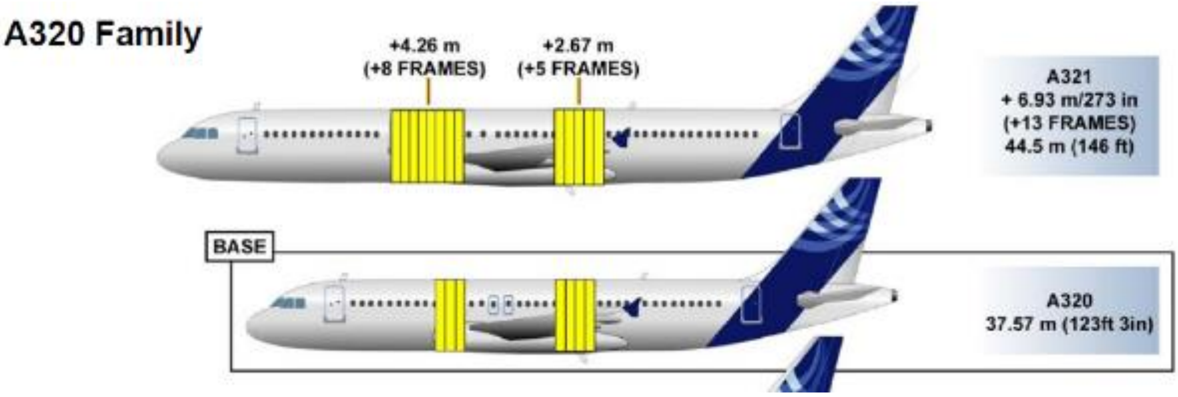
Empty Weight = 46.3 t (the one of A321 neo) + Δ LH2 changes

Payload/Range with Jet-A1 → 4000+ NM with16.2 t pax and 26 t of fuel

Propulsion 2*LEAP or 2*PW1100 modified to use H2. Thrust ~2*145 kN

It is assumed that LH2 can be installed over a length of 10m by removing around 90 to 100 seats.





Quantity of hydrogen on board: the internal dimensions of the fuselage limit the volume, and therefore the quantity of hydrogen to be carried. Although hydrogen is 2.8 times more energetic than kerosene, it is necessary to take into account an efficiency of the propulsion chain of at best 40%, lower than the efficiency of propulsion by kerosene estimated at 45%. Consequently, the 5 tons of hydrogen are equivalent to 12.5 tons of kerosene which could allow stages of just over 2000 NM (to be checked).

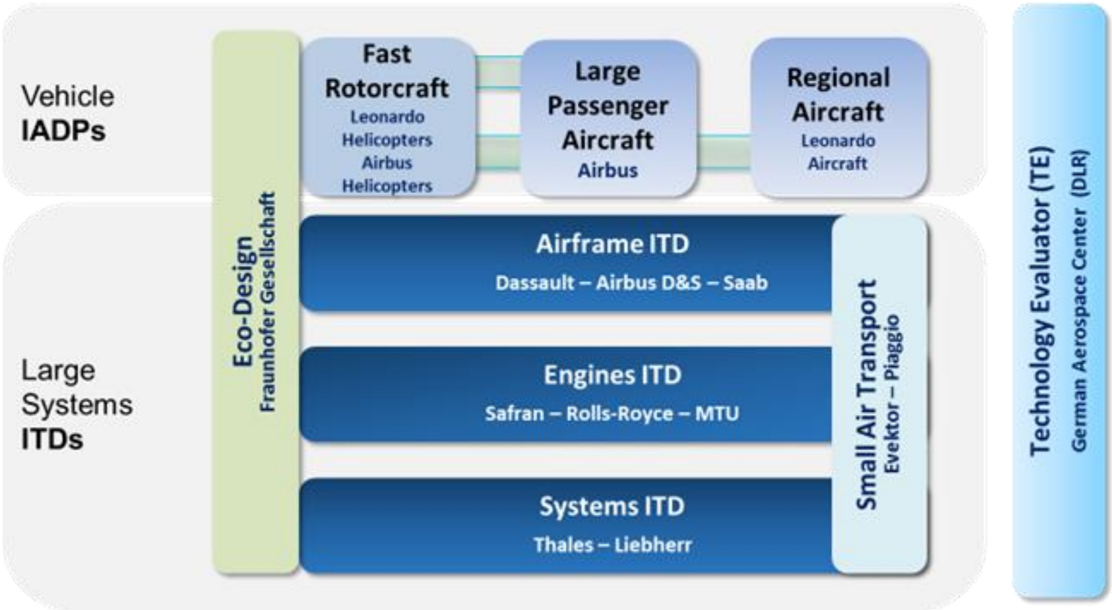
Architecture of the propulsion chain: the hydrogen must be heated and pressurized to 150 bars before supplying the engines, which requires the installation of heat exchangers with a power of around 1 to 2 MW.

Ranges: Where can you go with 5 tons of hydrogen? Subject to a mass budget which takes into account approximately 10 tonnes for the mass of H2 tanks with a gravimetric index of 0.35 (mass of liquid hydrogen / mass of tank + LH2), and the delta masses linked to all the evolutions of the systems, engines and structure, with a total that would not exceed the maximum take-off weight of current aircraft, it appears that these aircraft would be able to perform stages of around 2000 NM (3700 km), but with a payload capacity passengers reduced to around 150 passengers.

Appendix 11: Summary of Clean Aviation JU activities (as of October 2022)

Predecessor: Clean Sky 2 - 2014-2023 - 1755 M€ funding

- CS2 Structure



- Socio-economic impact of the CS2 programm: refer to https://www.clean-aviation.eu/sites/default/files/2022-07/Socio-economic_study_on_the_impact_of_Clean_Sky_2.pdf)

Clean Aviation program (2022-2030)

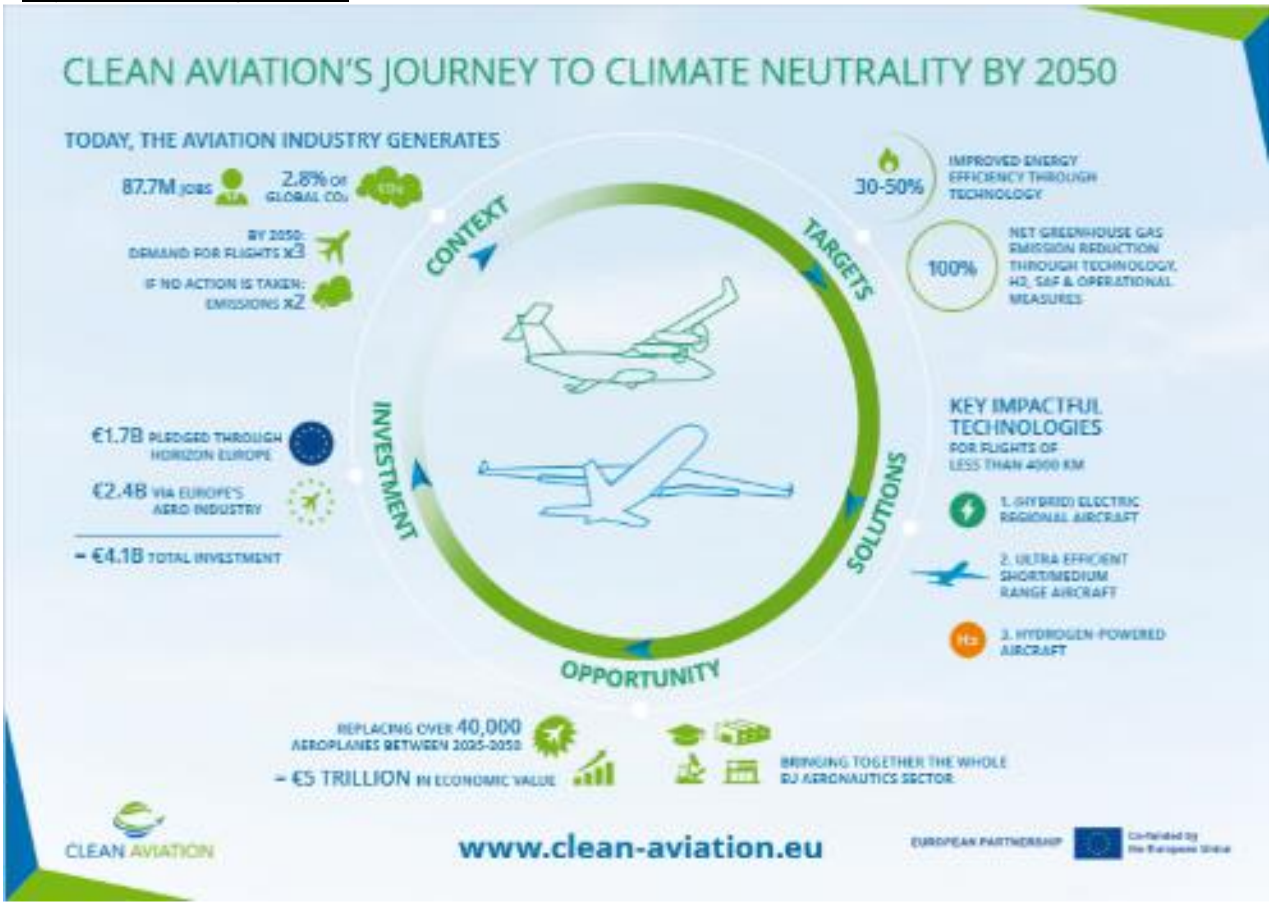
- Structure: **built** around three key *thrusts*, aiming at technology readiness TRL6 and aircraft EIS 2035:
  - H2 powered aircraft with disruptive enabling technologies
  - Ultra-efficient Short Medium Range aircraft
  - Hybrid-electric Regional Aircraft

- **Targets**

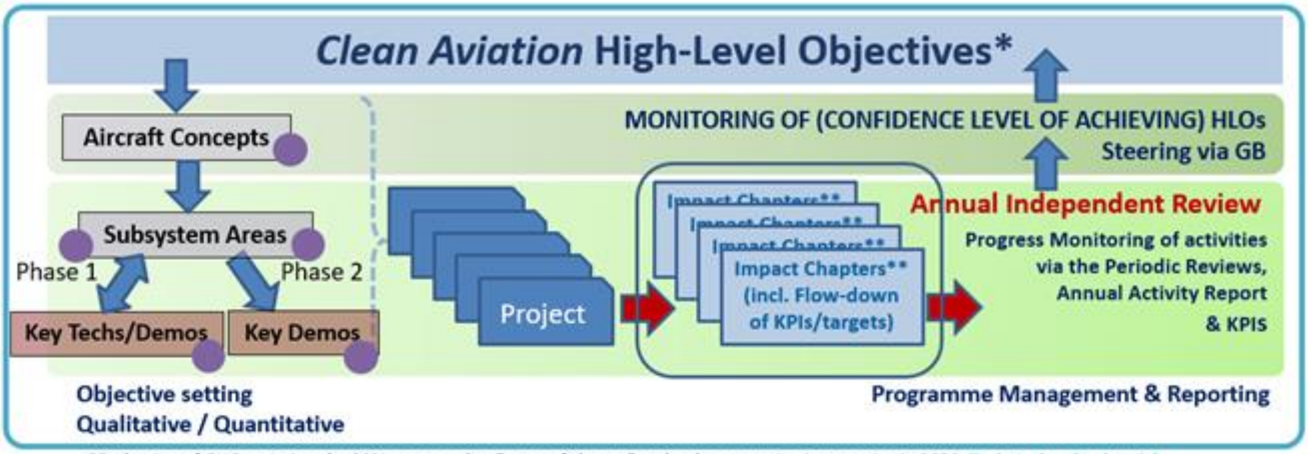
Aircraft Class	Key technologies and architectures validated at aircraft level	Earliest entry into service (EIS)	Fuel burn reduction (technology[1])	Net emissions reduction incl. fuel effect[2]	Current share of air transport emissions
Regional Aircraft	Hybrid-electric, distributed propulsion coupled with highly efficient aircraft configuration	~2035	-50%	-90%	~5%
Short-Medium Range Aircraft	Advanced ultra-efficient aircraft configuration and ultra-efficient gas turbine engines, ultra-high bypass	~2035	-30%	-86%	~50%

1. *defined as fuel burn reduction compared to 2020 state-of-the-art aircraft available for order/delivery*
2. *assumes full use of SAF at a state-of-the-art level of net 80% carbon footprint (or where applicable zero-carbon electric energy).*

- Impact Monitoring Framew



ork (schematic)



*Reduction of GHG emissions by 30% compared to "state-of-the-art" technology entering into service in 2020. Technical and industrial maturity geared towards EIS in 2035. See Article 55 of draft SBA establishing the Horizon Europe Joint Undertakings.
** with potential contributions from projects performed in other Horizon Europe parts/partnerships and/or at national/regional level

Specific targets / KPIs / Impact Indicators

- Overall vision / path to Climate Neutrality
- Programme planning
  - Initiation date : 2021
  - 1st phase ~ 2022-2026 – TRL 4/5
    - 1st call
      - Launch: March 2022 – 13 topics covering the 3 thrusts + transverse topics + 1 on coordination

- Indicative funding ~ 736 M€
- Call closure: June 2022 - Evaluation: July-August 2022
- Call outcome: Sept. 2022 - 20 projects retained (see next 2 pages)
- Final project definition & funding TBC by Dec 2022 (projects may start earlier)

- 2nd call
  - Launch: Spring 2023 - Indicative Funding ~ 153 M€
  - Topics considered (TBC subject to CA priorities & gaps analysis further to call #1)
    - LH2 fuel distribution technologies
    - Long Term Disruptive Technologies for Hydrogen-Powered Aircraft
    - Innovative Fuselage/Empennage Design for Hybrid-Electric Regional A/C
    - Digitalisation of the Design Process for Hybrid-electric Regional Aircraft
    - Sustainable Industrialisation of Short Range and Short-Medium Range A/C

- 2nd phase ~ 2026-2030 – TRL 6 (*towards EIS 2035*)

- Reference documents:
  - Call #1 text : CAJU-GB-2022-03-16 Annex-Call-1-topics-descriptions_published.pdf
  - Work prog. 2022-2023: CAJU-GB-2022-03-16-Amended-WP-Budget-2022-23_en.pdf
  - Strategic Research and Innovation Agenda: CAJU-GB-2021-12-16-SRIA_en.pdf

Call #1 Summary (1)

TOPIC ref	TOPIC title	Indicative Funding M€	TRL (end of project)	Objectives	Proposal acronym	Coordinator	Dur. months /Nb partners
HPA-01	Direct Combustion of Hydrogen in Aero-engines	115	4 - 5		HYDEA	GE Avio	42 / 35
					CAVENDISH	Rolls-Royce	48 / 20
HPA-02	Multi-MW Fuel Cell Prop. System for Hydrogen-Powered Aircraft	50	4 - 5	Power 2 - 4 MW Fuel Cell stack eff ≥ 45%	NEWBORN	Honeywell	42 / 18
					HyPoTraDe	Pipistrel	36 / 6
HPA-03	Large Scale Lightweight liquid H2 Integral Storage Solutions	10	4 - 5	150 kg LH2, scalable to 600 kg H2	H2ELIOS	Aciturri	36 / 14
					fLHYing	Pipistrel	36 / 5

HPA-04	Near-Term Disruptive Technologies for Hydrogen Powered-Aircraft	(7 M€ - TRL5) ➔ Call #2					
TBD call#2	LH2 Distribution	➔ Call #2					
HER-01	Multi-MW Hybrid-Electric Prop. System for Regional Aircraft	75	4 – 5	Contribution ≥ 30% GHG emiss & ≥ 50% a/c fuel burn reduction *	AMBER HE-ART	GE Avio RRD	39 / 22 36 / 38
HER-02	Thermal Management Solutions for Hybrid-Electric Regional Aircraft	40	5 (sub-systems)	Min handling capable 1 MW / weight penalty < 30% vs convention.technology	TheMa4HERA	Honeywell	40 / 24
HER-03	Electrical Distribution Solutions for Hybrid-Electric Regional Aircraft	40	5 (sub-systems)	Voltage capability≥ 800 V weight penalty ≤ 20% vs convention.technology Thermal energy eff ≥95%	HECATE	COLLINS	36 / 38
HER-04	Innovative Wing Design for Hybrid-Electric Regional Aircraft	20	5 (overall wing system)	>15% FB reduction (integrated wing level) & contribution to 50% a/c FB reduction * Overall full wing structure weight reduction of 20%	HERWINGT	AIRBUS D & S	36 / 36
TBD call#2	Airframe Integrated Fuselage	➔ Call #2					
Call #1 Summary (2)							
SMR-01	Ultra Efficient Propulsion Systems for Short and SMR Aircraft	175	5 (system level)	Prop. Syst. FB reduction ≥20% & contribution to a/c FB reduction ≥ 30% (extended to 30% GHG emission reduction) *	SWITCH HEAVEN OFELIA	MTU Rolls-Royce SAFRAN	36 / 23 48 / 20 38 / 30
SMR-02	Ultra Performance Wing for Short and SMR Aircraft	55	4 - 5	Increased energy eff 10-13% integrated wet wing level / 15-17% dry wing, contributing to overall a/c FB / GHG reduction of 30% *	Up Wing	Airbus Ops GMBH	42 / 32
SMR-03	Advanced Low Weight Integrated Fuselage and Empennage for SMR (a/c powered by hydrogen)	40	4 (system level)	Fuselage weight reduction > 20% / min a/c energy consumption reduction of 15% and contribution to a/c GHG reduction 30% *	FASTER-H2	Airbus Ops GMBH	39 / 41
TRA-01 **	Architectures and technology integration for A/C concepts	90	≥ 4 for all key technologies	FB reduction ≥ 50% (Regional a/c) ≥ 30% (SR & SMR a/c) Energy reduction ≥ 15% (for H2 a/c) *	SMR ACAP HERA	Airbus Ops GMBH LEONARDO	42 / 31 48 / 48

TRA-02 **	Novel Certif. Methods & Means of Compliance for disruptive techno.	18	As per roadmap for maturity level to EIS 2035	Time to market & certification cost reductions = 30% * ^	CONCERTO	DASSAULT AVIATION	48
CSA ***	Develop Integrated EU Clean Aviation Regional Ecosystem	0.72	N/A	Foster synergies, networking,coordination, dissemination, etc.	ECARE	Aerospace Valley≥	24 / 4

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