FACT SHEET 7:

Liquid hydrogen as a potential low-carbon fuel for aviation

This fact sheet aims to explain how current aviation fuels operate before providing descriptions of how alternative fuel options, like sustainable aviation fuels (SAF) and liquid hydrogen, could help meet the rigorous climate targets set by the aviation industry. Secondly, this document explores the limitations and opportunities of liquid hydrogen when it comes to the manufacturing, safety, current uses and outlooks. This document concludes with a discussion on policy, mandates and incentives on the topic of hydrogen as a potential fuel for aviation.

Introduction – Why hydrogen?

Aircraft fly thanks to a combination of air and a combustion process that occurs in the aircraft engines. The primary source of energy is the fuel. Each kilogram of fuel, which would occupy less than 1 litre of volume, contains a significant amount of energy, 42.8 MJ [1]. If we could convert the energy of a 1L bottle of fuel into electric energy to power a cell phone, the battery would last for over 2 months. This energy is extracted in the combustion chamber of the engine in the form of heat; Compressed air enters the combustion chamber and gets heated up to temperatures nearing 1,500°C. This hot high-pressure air is what ultimately moves the aircraft forward. Kerosene is composed of carbon and hydrogen (hence it's a hydrocarbon fuel). When the fuel is completely burned, these carbon and hydrogen molecules recombine with oxygen to create water vapor (H_2O) and carbon dioxide (CO_2) (Fig.1).

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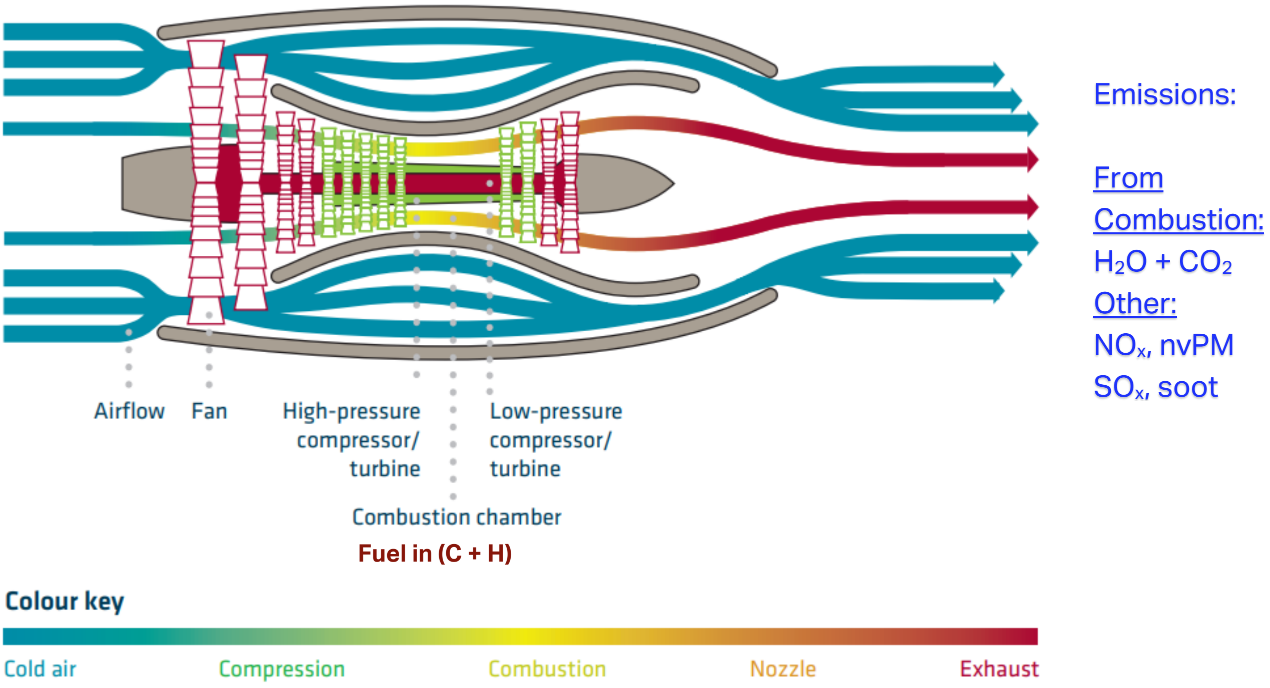


Figure 1 Schematic of a turbofan engine adapted from: [2]

Carbon dioxide will always be created as a by-product of burning a carbon-based fuel. The only way to reduce CO_2 products is to burn less fuel, and this is done by improving the efficiency of aircraft, improving the way aircraft operate or reducing the amount of time the engines are on. Technological improvements allow the aircraft flying today to be up to 80% more fuel efficient compared to 60 years ago. However, further reductions are becoming more and more challenging. The efficiency of flight has increased considerably, but moving large numbers of passengers (100-400) at a high speed, over a large distance, will always require significant energy.

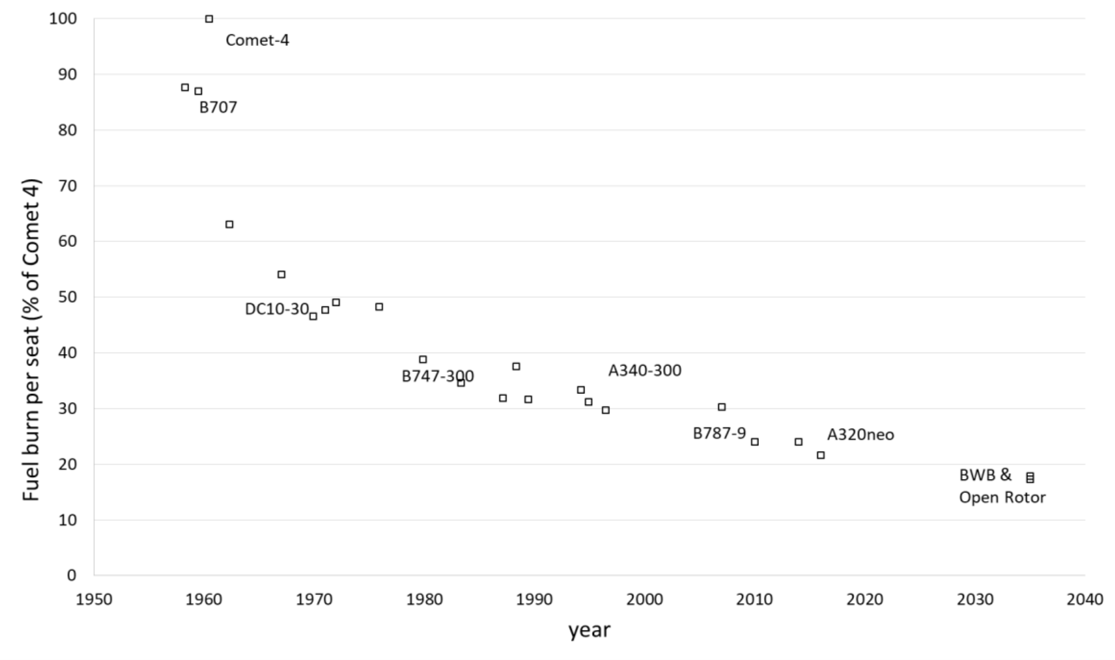


Figure 2 Aircraft fuel efficiency over time, adapted from: [2]

Technologies, which in principle could improve fuel economy further, are starting to face negative tradeoffs which limit their application. For example, making the aircraft's wings longer and thinner could reduce induced drag, but the structure to support such long wings would be too heavy and the fuel benefits would be offset by the extra weight. Larger engines (greater fan diameter) could improve propulsive efficiency, but the associated weight and drag create a penalty that at some point can offset the fuel benefit. Further significant improvements must come from revolutionary aircraft technologies which will make aircraft look considerably different than today. This will all come with the associated challenges in infrastructure, training, and adaptation ranging from passengers to air navigation providers. However, even with these technologies fossil fuels could potentially remain in use due to their unparalleled cost and energy content. As seen in Fig.2, as technology improves over time, it becomes harder to achieve significant fuel burn reductions. Revolutionary technologies plotted in the figure after 2035, promise reductions of up to 40% compared to today's best technology, nevertheless, compared to the first jet aircraft it becomes visible that the margin for improvement is lower every time.

Sustainable Aviation Fuels

A possible solution to help push the curve down to almost 100% reduction in emissions lies in the fuel used to power the engines. Sustainable aviation fuels (SAF) – carbon based, would still produce the same CO_2 emissions from combustion, however they can be offset by the manufacturing process of the fuel over the lifecycle. The offset in emissions for some cases of SAF can be as high as 80% [1], until SAF reaches a higher level of production it will be difficult to completely replace kerosene fuels.

Liquid Hydrogen

Another alternative is to use liquid hydrogen (LH_2) as a fuel. Hydrogen is the most abundant element in the universe and in its liquid form, contains about **2.5 times more energy per kilogram** than kerosene [3]. When burning, hydrogen only produces water vapor as a by-product, since the fuel has no carbon content to start with. With regards to local air quality, hydrogen combustion produces **up to 90% less nitrogen oxides** than kerosene fuel, and it eliminates the formation of particulate matter [4]. From an environmental and energy content perspective, hydrogen has abundant potential. An advantageous l criteria for any fuel is high energy density, inexhaustibility, cleanliness, convenience and independence from foreign control [3]. Liquid hydrogen achieves the criteria, along with the potential to completely eliminate combustion emissions. Another useful feature of hydrogen is that it can be used as a replacement of liquid fuel or as a fuel cell for electrical power. Electrical fuel cells could be suitable for short-range aircraft while hydrogen combustion would be suitable for long-range and higher payloads. Hydrogen fuel-cells are already common devices found in cars, buses, and aircraft servicing vehicles [5].

Liquid hydrogen fuel has a lower volumetric density than kerosene. It is estimated that to complete a given mission, despite the aircraft requiring a lower mass of fuel, the space that this fuel would occupy would be around 4 times larger than that of kerosene [6]. This presents a challenge for airframe designers and would require significant redesign of conventional airframes.

Water vapor is another greenhouse gas produced by the combustion of fuel, and although the radiative forcing (difference between the energy absorbed through the Earth's atmosphere compared to the energy that is reflected back into space) is lower than that of CO_2, it still contributes towards global warming. Hydrogen combustion would produce about 2.6 times more water vapor than kerosene fuel. In a study about the climate change effects of hydrogen aircraft, Ponater et al. [7] evaluated the individual and accumulated effects of the emissions of a hydrogen-based flight to a kerosene-based flight. The study concluded that the positive effects of a zero-CO_2 combustion, would offset the drawback of increased water vapor exhaust. Moreover, CO_2 has a lifetime in the atmosphere of up to

100 years, while that of water vapor can go from a few days up to 1 year [4]. Regarding condensation trails, due to the absence in solid particles at the exhaust of the engine when burning hydrogen, ice crystals have no-where to nucleate, so the number of water crystals formed at the exhaust would decrease. Nevertheless, due to the increased amount of water vapor exhaust, the crystals that do nucleate, would have a larger size. The overall effect is expected to decrease the radiative forcing effect of contrails. The end result, according to the study would mean that the radiative forcing from aviation could be 20-30% lower by 2050 and 50-60% by 2100 if LH_2 aircraft were introduced [7]. The effects of cirrus induced clouds, however, will need careful analysis, and more research into the radiative forcing of hydrogen combustion by-products to increase the certainty of these predictions.

Like any solution, LH_2 comes with challenges. Some of these include ensuring safety (in production, handling and use), establish sustainability within production as well as the costs required for new infrastructure to implement and store liquid hydrogen. These challenges and opportunities will be addressed in the following sections of this fact sheet.

Challenges and Opportunities

Manufacturing process

Hydrogen is difficult to utilize in its natural form as it is extremely light and buoyant. . It usually can be found bonded to other atoms like oxygen (in water) or carbon (mostly in natural gas or methane). Hydrogen is naturally found as a gas rather than a liquid, as it boils at -253 °C, therefore, to transport it as a liquid it needs to be cooled or compressed. Since H_2 is not naturally accessible in nature, it needs to be manufactured. There are two main processes to extract H_2 into a usable form. Water molecules (H_2O) can be separated into H_2 and O, or hydrocarbon molecules can be mixed with steam (H_2O) and produce hydrogen (H_2) and carbon dioxide (CO_2). There are many feedstocks for hydrocarbon molecules such as methane, or pure carbon and many ways to produce enough electricity to separate water into hydrogen and oxygen. Below is a figure that summarizes some of the chains that can lead to the production of pure hydrogen [8].

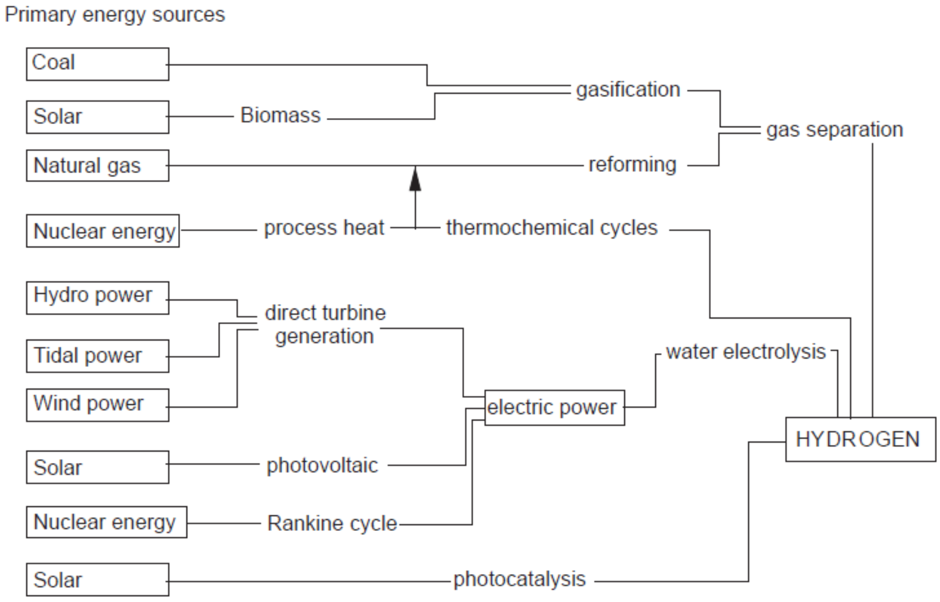


Figure 3 Routes for Hydrogen manufacture, from: [6].

Figure 4 Hydrogen manufacturing processes and uses. From: [14]

Safety

Safety has always been the number one priority for all the stakeholders involved in the aviation industry. Transporting, handling and burning liquid fuel is such a normal procedure that the common passenger doesn't stop to think about the complex processes, trainings and regulations that go into making the entire production chain safe. Hydrogen, like gasoline or kerosene is also flammable and is also a hazardous substance. The safety of any process needs to be assessed based on the probability that a certain event will happen, combined with the consequences of such an event, if it were to happen. Many studies have been conducted evaluating specific physical aspects of different fuels and comparing them to hydrogen. Those studies show that certain characteristics of hydrogen make it safer as a fuel than kerosene, while other characteristics make it more dangerous.

Table 1 comparison of safety parameters between kerosene and hydrogen

	Hydrogen	**Kerosene**
Auto-ignition temperature	✓	✗
Buoyancy	✓	✗
Diffusivity	✓	✗
Spill Hazard	✓	✗
Burning time	✓	✗
Lower Flammability limit	✓	✗
Flammability range	✗	✓
Leakage detection	✗	✓
Leakage Avoidance	✗	✓
Flame detection	✗	✓
Minimum ignition energy	✗	✓

For instance, the auto-ignition temperature of hydrogen is considerably higher than that of kerosene (550 °C vs 220 °C), also hydrogen is about 14 times lighter than air, so if spilled it quickly diffuses and the vapors rises and disperses, rather than accumulating at ground-level [17]. Since hydrogen is a gas that is already present in the atmosphere, a spillage would not represent an environmental hazard in the same way compared to a fossil fuel spill. The minimum ignition energy of hydrogen, however, is considerably lower than that of other carbon-based fuels, therefore, a weaker spark can cause ignition. Moreover, the flammability range is wider meaning the concentrations in the air required to have a fire are wider for hydrogen (4-76%) than for kerosene (1.4-7.6%) [3]. On the other hand, the lower flammability limit is higher for hydrogen than kerosene (4% vs 1.4%). This means that if the concentration of kerosene in air is more than 1.4%, a fire can occur, however this number is 3 times larger for hydrogen. The hydrogen flame is invisible, and the gas is odorless making it difficult to detect leaks or to fight a hydrogen fire if it that cannot be seen. Since H_2 is such a small molecule, leaking through cracks or pores is a possibility if the tank is not properly insulated, and this is associated to a higher risk due to the reasons outlined before, demonstrating that proper insulation is fundamental.

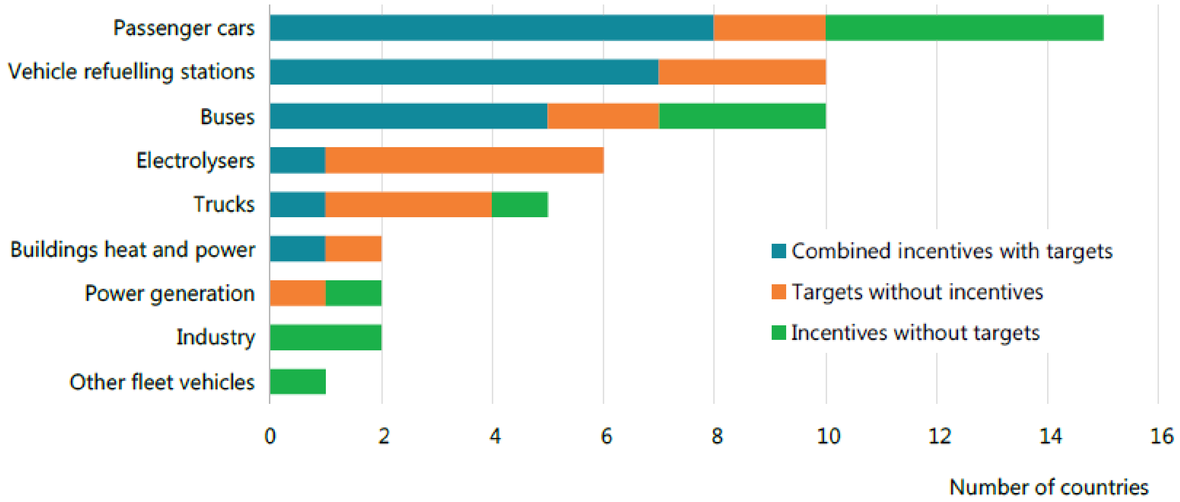
Current uses and outlook

In the transport sector, in 2018, there were 381 hydrogen refueling stations world-wide for the automotive sector. One third of these stations are in Japan, with the other big contributors being Germany, France, the United States, and South Korea. The stations supply a fleet of over 11,000 cars, a number which was 56% lower the year before [14]. There are also about 500 passenger buses, 400 trucks, 100 vans and over 25,000 forklifts operating on hydrogen world-wide [14]. It is forecasted that the hydrogen vehicle market will grow anywhere between 600,000 and 2.5 million by 2030-5 [15]. In 2015, Japan developed a plan to invest $378 million into developing hydrogen infrastructure that includes refueling stations and incentives for people to purchase hydrogen vehicles [21]. In Germany the first two hydrogen-cell powered trains in the world were installed in 2018,and are now doing a routine 100 km journey in northern Germany.

In the aviation sector, the Department of Energy of the United States announced a $250,000 fund to power air-side vehicles with hydrogen fuel cells [5]. Also, the use of H_2 fuel-cells for substitution of the APU or even for providing in-flight power to control surfaces or landing gear retraction is being considered [5]. Flight demonstrators have also been deployed in the past where full-sized aircraft have flown on liquid hydrogen. Future urban mobility projects expected to start flying in the early 2020s are also considering hydrogen fuel cells as a power source [23].

Policy, mandates, incentives

To date, over 50 policies or targets world-wide have been signed to support the development and implementation of hydrogen [14]. These incentives are spread around the world and include nations like the United Kingdom, India, the United States of America, Brazil, the European Union as a whole, Japan, Korea, New Zealand, Saudi Arabia and China. Figure 5 shows the mandates or policies by application type.



Note: Based on available data up to May 2019.

Figure 5 Number of incentives per type, from: [14]

The increased number of applications for hydrogen and the support of the individual country governments will help to increase the production in this low-emission fuel. The IEA forecasts that economies of scale can considerably reduce the prize of hydrogen as a liquid fuel or as a fuel cell. The price of fuel cells could drop in up to 75% by 2030 while fueling stations capital costs could half. The production of renewable hydrogen could also be considerably lower since by that time the costs from renewables are expected to decrease in 30% [14]. All of these incentives and increases in production could contribute towards making the implementation of hydrogen viable for use in the aerospace sector.

Conclusions

Hydrogen presents one potential solution, which could be combined with other measures, to fully decarbonize long-range flights. While electric technology must continue to be developed, based on current battery technology it is only feasible for short range flights and with limited payloads.

Hydrogen offers opportunities and limitations for the sector. An opportunity would be that burning hydrogen in a jet engine would result in only water vapor emissions. This fuel would almost entirely eliminate any carbon-related emissions, including Sulphur, particulate matter and nitrogen oxides. The architecture of aircraft would have to change considerably to adapt the larger tanks required for hydrogen flight. New aircraft designs would be required and may allow ideas such as blended wing body aircraft. This may produce some aerodynamic advantages, however a downside could be the time involved in certification of radical new aircraft, along with potentially substantial costs to redesign and certify new aircraft and operational infrastructure. This appears to be the single biggest challenge for hydrogen to be implemented on a widescale. Hydrogen use in the industrial, transport and domestic sectors is accelerating. Electrolyzing plants that make clean hydrogen were on average 0.1MW in size in the first decade of 2000, and currently are being build 100 times larger. There are plans to scale up to 100 MW in near future, showing an increase of1000 times from 20 years ago. With scaling-up making promising progress combined with the fast developments of renewable energy there is potential to substantially reduce the manufacturing costs of renewable hydrogen and therefore, increase the efficiency of its production. Thorough cost benefit analysis will be required to assess the true benefits of introducing hydrogen at scale. In the medium term, the primary hurdle will be the cost challenge of introducing and recertifying new aircraft designs, along with the associated requirement to replicate fuel distribution infrastructure.

Aviation is one of the hardest sectors to decarbonize because the large power requirement of an aircraft. It is especially difficult when combined with the significant development costs and time demanded -10 years on average to develop a new engine. In addition, carbon capture is still a distant and unproven option. The potential for a new aircraft or engine design is approaching its limit in terms of fuel efficiency, and as other sectors turn to renewable energy, aviation will need to consider all options for reducing its emissions to remain in line with the industry target of halving net CO_2 emissions by 2050 relative to 2005. While implementation challenges exist, liquid hydrogen is one option that could make a positive contribution towards sustainable growth of the industry.

Nomenclature

APU	Auxiliary Power Unit
C	Carbon
CO2	Carbon Dioxide
H	Hydrogen
H2O	Water (Vapor)
IEA	International Energy Agency
LH2	Liquid Hydrogen
MJ	Mega Joules
MW	Mega Watts
NOx	Nitrogen Oxides
nvPM	non-volatile Particulate Matter
O	Oxygen
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
Sox	Sulphur Oxides

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