Perspectives of hydrogen aviation

Alberto Boretti*  

Deanship of Research, Prince Mohammad Bin Fahd University P.O. Box 1664., Al Khobar 31952. Kingdom of Saudi Arabia

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Abstract. The perspective of hydrogen (H₂) aviation is discussed. While production of carbon dioxide (CO₂) free renewable H₂ is progressing towards costs comparable to those of today’s steam reforming of methane, at about 1-1.5 $ per kg H₂, the development of specific aviation infrastructure, as well as aircraft, is still in its infancy. Over the 21 years of this century, the most important manufacturers have only proposed preliminary studies, artist impressions more than detailed engineering studies. The major technical challenge is the fueling and safe and efficient storage of the H₂, requiring a complete redesign of infrastructure and aircraft. From a political perspective, negative is the speculation on the global warming potential of contrails, and the covid19 pandemic which has largely disrupted the aviation sector, with the future of mass transport at risk of drastic downsizing. Especially the “great reset” agenda, limiting mass transport also for other goals than the simple control of viral spreading during the pandemic, may harm the deployment of H₂ aviation, as elite aviation does not motivate huge investments in the use of a non-exhaustible fuel such as renewable H₂, leaving favored alternatives such as hydrocarbon jet fuels, and in the longer term electric aviation.

Keywords: aviation; CcH₂; CO₂ emission; H₂O emission hydrogen; LH₂

1. Introduction

In the global warming narrative, carbon dioxide (CO₂) emissions are responsible for global warming. Reducing the CO₂ emissions from aviation is claimed to have a sizeable impact on warming. Similarly, in the narrative of the shrinking carbon and hydrocarbon resources, there is a need for renewable energy sources to substitute fossil fuels. Hydrogen (H₂) produced from the splitting of the water molecule with renewable energy is the ultimate fuel of the future, free of CO₂ emissions, and considered completely renewable.

The motivation for H₂ aviation is thus a long-term alternative for jet fuels after depletion of “fossil” fuels, and a CO₂ emission-free fuel (even if the H₂O vapor emission may still have global warming potential according to other narratives, as discussed later).

H₂ is the most abundant element in the universe. However, it is freely available on earth only in negligible amounts. Splitting the water molecule to produce H₂ requires huge energy input. H₂ is a gas with extremely low density at ambient conditions. The volumetric energy density as a transportation fuel is extremely low, even adopting very low, cryogenic temperatures for liquid storage. Additionally, H₂ burns very easily, creating safety issues.
Fig. 1 Density of H$_2$ (a) and CH$_4$ (b) at different temperatures and pressures. Data from NIST (n.d.)

Table 1 Properties of alternatives to jet fuels based on H$_2$ and CH$_4$. Data from NIST (n.d.), Air BP (2000), and Lee et al. (2011)

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<td>Cryo CH$_4$</td>
<td>50</td>
<td>0.511</td>
<td>21.24</td>
<td>424.79</td>
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<td>110</td>
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<td>Cryo Compr CH$_4$</td>
<td>50</td>
<td>0.511</td>
<td>22.35</td>
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<tr>
<td>Cryo H$_2$</td>
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<td>71.329</td>
<td>1</td>
<td>20</td>
<td>liquid</td>
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<tr>
<td>Cryo Compr H$_2$</td>
<td>120</td>
<td>0.461</td>
<td>10.59</td>
<td>88.278</td>
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<tr>
<td>Jet A-1</td>
<td>43.15</td>
<td>0.251</td>
<td>34.69</td>
<td>804</td>
<td>1</td>
<td>298</td>
<td>liquid</td>
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<td>Jet A</td>
<td>43.02</td>
<td>0.251</td>
<td>35.28</td>
<td>820</td>
<td>1</td>
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Cryo-liquid CH₄ could be a viable solution permitting energy content of 21.24 MJ/liter vs. the 34.69 to 35.28 MJ/liter of jet fuels, with an affordable 110 K cryogenic tank, and limited overpressure of tanks. Cryo-liquid H₂ only permits an energy content of 8.56 MJ/liter, i.e. less than ¼ of jet fuels, at 20 K. Pressurizing the liquid H₂ permits to increase the energy density, as the liquid H₂ is still “compressible”, but the energy content is much less than jet fuels. Guaranteeing temperatures of about 20 K is demanding.

The preferred short-term pathway for H₂ aviation is based on cryo-compressed storage, mutated from automotive applications, with increased H₂ density and insulated pressure vessels (Ahluwalia et al. 2010, Ahluwalia et al. 2016, Moreno-Blanco et al. 2019, Moreno-Blanco et al. 2020, Moreno-Blanco et al. 2019, Moreno-Blanco et al. 2018, Petitpas and Aceves 2018). This is more than 10 years old technology (Brunner, 2011). As shown in Table 1, liquid jet fuels such as Jet A-1 or Jet A have specific energies 43.15 and 43.02 MJ/kg, and energy densities of 34.7 and 35.3 MJ/L, thanks to densities of 804 and 820 kg/m³. While H₂ has a specific energy of 118 MJ/kg, the density in normal conditions of H₂ gas is very low, 0.08 kg/m³. The energy density is only 0.0094 MJ/L. H₂ has a critical temperature of only 33.145 K, a critical pressure of 12.964 bar, and a critical density of 31.263 kg/m³. Improvements in energy density of H₂ stored onboard aircraft are needed, and this requires high pressure and low (cryogenic) temperatures.

It must be mentioned that while the combustion of hydrocarbons produces CO₂ and H₂O vapor, for example, methane

\[
\text{CH}_4 + 2\cdot \text{O}_2 \rightarrow \text{CO}_2 + 2\cdot \text{H}_2\text{O}
\]

combustion of hydrogen only produces H₂O vapor but in larger amount for same heat released,

\[
\text{H}_2 + \frac{1}{2}\cdot \text{O}_2 \rightarrow \text{H}_2\text{O}
\]

If we take φ as the hydrogen to carbon ratio,

\[
\phi = \frac{\text{H}}{\text{C}}
\]

we have

\[
\text{CH}_\phi + (1+\frac{1}{2}\cdot \phi)\cdot \text{O}_2 \rightarrow \text{CO}_2 + \frac{1}{2}\cdot \phi \cdot \text{H}_2\text{O}
\]

This gives a water-to-fuel mass ratio of 9/(1+12/φ). With H₂, φ=∞, and the water-to-fuel mass ratio is 9. With CH₄, φ=4, and the water-to-fuel mass ratio is 2.25. Thus, burning H₂ there is an H₂O vapor production of 9/120=0.075 kg/MJ, while burning CH₄ there is H₂O vapor production of 2.25/50=0.045 kg/MJ. With jet fuel, which is a mixture of heavy hydrocarbons with a lower average H/C ratio, the H₂O vapor production in kg/MJ further reduces. If we take φ=1.9, then the water-to-fuel mass ratio is 1.23, and burning jet-fuel thus translates into an H₂O vapor production of 0.0286 kg/MJ.

In the following two sections we consider two of the major issues in using H₂ as aviation fuel, the storage onboard an aircraft, and the implication on global warming of the increased H₂O vapor emission.

### 2. Hydrogen aircrafts

Cryo-compressed H₂ (CcH₂) refers to the storage of H₂ at cryogenic temperatures in a tank pressurized at 250 to 350 bar, in contrast to current liquid H₂ (LH₂) that refers to storage at cryogenic temperatures and near-ambient pressures (Ahluwalia, Peng, and Hua, 2016). CcH₂ overcomes many of the shortcomings of compressed gas H₂ (cH₂) or LH₂ tanks opening new possibilities. CcH₂ tanks permit storage of liquid, supercritical cryogenic, or two-phase saturated liquid and vapor H₂.
Compared to near ambient pressure LH2 tanks, the dormancy is larger in CcH2 tanks because the allowable pressure is larger. CcH2 tanks also have higher heat receptivity as the H2 is vented at a higher temperature. This further increases dormancy. Venting is greatly reduced. When the tank reaches the ambient temperature at allowable pressure, the H2 density is nonetheless 30% of the initial liquid density. Ullage space could be eliminated in CcH2 tanks as H2 is supercritical at a pressure larger than 13 bar. The maximum storage density is also higher with CcH2 because liquid H2 is to some extent compressible.

At 20 K, H2 is liquid. Density is 71.28 kg/m3 at 1 bar, and it is 86.09 kg/m3 at 220 bar. At 298 K, H2 is gas up to 13 bar of pressure, then it is supercritical. Density is only 0.08 kg/m3 at 1 bar, and it is 20.55 kg/m3 at 300 bar. Storage of H2 should be better liquid, thus there is the convenience of cooling down the H2. There is also convenience in compressing the H2, especially when gas. At 700 bar of pressure, H2 is liquid up to 32.957 K (density 96.155 kg/m3). Then it is supercritical. At 78.957 K, density is still 80.210 kg/m3. At 298 K, density is 39.24 kg/m3. At 239.96 K, the density is 45.88 kg/m3. The CcH2 tank can be fueled with more expensive H2 liquid for extended range, and less expensive compressed H2 gas for short-range (Ahluwalia, Peng, and Hua, 2016).

Aircraft fuel tank research in the literature minimal, more information is available for automotive applications (Brunner, 2011), (Ahluwalia, Peng, and Hua, 2016), (Ahluwalia, Hua, Peng, Lasher, McKenney, Sinha, and Gardiner, 2010).

Table 2 below (from Adams, 2020) presents storage options being considered for automotive applications. Most of the challenges are to store efficiently and safely H2 onboard the aircraft (Stetson, 2015). Dormancy is the time until the system has to vent due to pressure build-up from heat leakage and warming of H2. Insulation high efficiency and small degradation are concerns. Outgassing of volatile components from composites, H2 permeation, the durability of composites in high pressure and thermal cycle environments, the match between composites and liners, cycling between brittle and elastic phases, micro-cracking, and definition of certification and testing procedures are major hurdles requiring R&D (Stetson 2015).

More challenging is the design of lightweight tanks for liquid H2. Tanks of the required storage capacity and weight, and safety, are the key enabler of H2 aviation. Gravimetric index 35% long range and 38-55% long range are required Synergistic tank design for integration into the fuselage is important The shape is also non-cylindrical or spherical. The use of advanced materials is
Fig. 2 (a) Turbofan 120-200 passengers and 2,000+ nm range, (b) Turboprop up to 100 passengers and 1,000+ nm range and (c) not conventional “blended-wing body” design up to 200 passengers for 2,000+ nm range. Courtesy Airbus

necessary. Reliability of components (such as cryogenic pumps, sensors, valves, actuators), lifetime, reduced maintenance, safety, and certification (Clean Sky 2 Joint Undertaking, Fuel Cell & Hydrogen 2 Joint Undertaking 2020).

Many exercises have been conducted to understand the potentials of LH₂. Most of them are
based on combustion engines (turbojets, internal combustion engines) concepts. More recently, fuel cell electric engines have also been proposed. Examples of LH₂ aviation concepts are proposed in (Stetson 2015, Clean Sky 2 Joint Undertaking & Fuel Cell and Hydrogen 2 Joint Undertaking 2020, Westenberger 2003a, b, Westenberger 2008, Airbus 2020a, b, c, Szondy, 2019, Scholz 2020). All these cases refer to concepts, more than real attempts to design and fly novel aircraft. Most of the exercises refer to LH₂ – lower temperature, minimal pressurization of tanks - rather than ccH₂ – higher temperature but highly pressurized. Differences are however minimal in these studies only proposing hypothesis of tanks volumes and weights in classic and novel aircraft designs.

The most relevant disadvantages of H₂ aviation are reported in (Scholz, 2020) which consider LH₂ tanks. Aircraft must be modified or redesigned. New airport infrastructure is necessary. H₂ must be produced, transported, and liquefied. For the same range with the same aircraft envelope, space must be found for nearly cylindrical H₂ tanks. If the size of the aircraft increases to accommodate the H₂ tanks with the same payload, the aircrafts have higher zero-lift drag. According to (Scholz, 2020), short-range H₂ aircrafts have 5% larger operating costs. In long-range H₂ aircrafts, the operating costs may increase by 15%. Despite insulation, the warming of H₂ in LH₂ tanks produces gas H₂ to be used in flight. On the ground, rising pressure following warming would require blown off. A refueled aircraft with LH₂ tanks cannot be left standing at the airport. Refueling has to be done quickly shortly before departure. Flight operations are less flexible as a consequence of these restrictions (Scholz 2020).

Different layouts of the LH₂ tanks are proposed in (Westenberger 2003a) for the different aircraft categories. Balancing the aircraft’s center of gravity is important. The heavy tanks produce a 25% higher aircraft empty weight vs. jet fuel aircraft. However, thanks to the higher energy content of the H₂, the maximum take-off weights with tanks “full” reduce. Because of the larger and heavier tanks, the energy consumption per nautical mile (nm) of the mission increases. According to (Westenberger 2003a), the Direct Operating Costs (DOC) for a 1,000 nm mission will increase by 25% vs. today's values with jet fuels. Factoring reducing future LH₂ production costs (Westenberger 2003a) predicts a DOC crossover point LH₂ and jet fuel aircraft somewhere about 2040.

Different configurations for the different aircraft categories are also discussed in (Westenberger, 2003b). There is no “standard configuration”. The take-off weight of long-range aircraft reduces by 15% with LH₂. The empty weight increases by 20 to 25% with LH₂. The energy consumption per nautical mile (nm) of mission increases by 8 to 15%. This is mostly the result of a larger volume, translating into a larger wetted area, resulting in a larger drag, as well as a larger average weight during flight. (Westenberger 2003b) comments as the many unconventional configurations proposed such as “blended wings” do not have clear advantages.

LH₂ aviation requires significant effort, from H₂ production, distribution, storage, infrastructure to safety (Airbus, 2020a).

Airbus has recently publicized three concepts of zero-emission commercial aircraft to be introduced by 2035 (Airbus, 2020b). These concepts, Fig. 2, are named “ZEROe”.

The turbofan design (a) for 120-200 passengers has a range of 2,000+ nm which permits transcontinental routes. The aircraft is powered by a gas-turbine combustion engine working with H₂. The liquid H₂ will be stored and distributed via tanks located behind the rear pressure bulkhead. This is a traditional design only modified for the storage of hydrogen, with a drastically reduced capacity vs. todays’ aircrafts of the same shape.

The turboprop design (b) for up to 100 passengers has a range of 1,000+ nm which permits
shorter routes. The turboprop engine is also powered by a gas-turbine combustion engine working with H$_2$. By taking the specific energy use as proportional to the size of the aircraft, the relative volume of the hydrogen tanks reduces by reducing the nautical miles of the route.

The “blended-wing body” design (c) for up to 200 passengers and 2,000+ nm flight routes. In this non-conventional design, the wings merge with the main body. The extraordinarily wide fuselage permits several options for H$_2$ storage and the layout of the cabin. This more theoretical concept may permit much larger relative volumes of hydrogen tanks ideally for longer missions.

Propulsion in the above concept aircrafts is supposed to be by jet turbines. There is an ongoing study to design high efficiency $\eta=40$-50%, low NOx, reliable, long-lasting combustion turbines (Clean Sky 2 Joint Undertaking, Fuel Cell & Hydrogen 2 Joint Undertaking, 2020).

Propulsion maybe also in some cases by electric propeller with fuel cells (Szondy, 2019), (Airbus, 2020c). Electric aircrafts enjoy strong support towards solar photovoltaic and wind energy production, electric cars, and battery energy storage. However, today’s Li-Ion batteries still have in between many other downsides including economic, environmental, and resource depletion, also low energy density per unit volume and unit mass, which make impossible medium-to-long-haul aviation. Thus, electric aircrafts may better use fuel cells and LH$_2$ tanks. The fuel cells drive the electric propulsion system. The low temperature of the LH$_2$ storage provides opportunities for higher efficiency superconducting energy transmission and higher power motors (Airbus, 2020c).

The radical “pods” design (Airbus, 2020c) includes six removable fuel cell propeller propulsion systems. Some of the designs of Fig.2 can also be intended as fuel cell aircraft. Fig. 3 presents a more explicitly declared fuel cell H$_2$ aircraft adopting 6 pods in up to 100 passengers and 1,000+ nm range aircraft. Scalability to larger aircrafts is under investigation.

The “pod” configuration is based on 6 stand-alone H$_2$ fuel cell propulsion systems. Every “pod” has an 8 blades propeller. The “pods” are mounted under the wings. Each “pod” consists of the propeller, the electric motor, the fuel cell, the power electronics, the LH$_2$ tank, the cooling system, and a set of auxiliary equipment.

While battery-electric aircrafts have an expected range of 500-1,000 km maximum [12], LH$_2$ or CcH$_2$ aircrafts do not have any limitations, can use traditional aircraft design for ranges up to 10,000 km, with more revolutionary design needed for longer distances. LH$_2$ or CcH$_2$ aircrafts, same as electric aircrafts, require significant changes to the infrastructure [12].
3. Hydrogen water vapor emission

As H$_2$O vapor is theoretically a greenhouse gas more powerful than CO$_2$, the much higher than Jet-fuel emission of H$_2$O vapor with H$_2$ has to be considered carefully.

While the use of H$_2$ is mostly driven by environmental concerns about CO$_2$ emissions, there are also detractors of H$_2$ because of the environmental impact of H$_2$O emissions. It is an unfortunate circumstance that “science” is used by pressure groups to support one industrial development vs. another, and it is a matter of fact that lobbies supporting electric vehicles or traditional hydrocarbon fuels do not like H$_2$, as the combustion engine or fuel cell does not matter.

We must recall that the BMW 7 hydrogen with an H$_2$ internal combustion engine was denied the status of the zero-emission vehicle by the US CARB, arguing an internal combustion engine may burn lubricating oil within the cylinder and thus emit CO$_2$ [30]. This decision forced BMW and then other manufacturers to disinvest from R&D in an otherwise promising alternative of electric cars.

We must recall as the development of the BMW i3 Rex, an electric vehicle with a range extender gasoline internal combustion engine, was constrained in the further development by the US CARB since the time it was proposed at an exhibition [30]. The US CARB deliberated the internal combustion engine was to be used inefficiently only to reach a nearby recharging station for the batteries, thus supporting the use of large, rather small batteries, in non-hybrid electric cars.

We may also recall as Diesel-Gate started arguing that diesel vehicles were emitting over the never-defined real-world driving conditions more NOx than the emission certification values of chassis dynamometer driving cycles (Boretti 2017, Boretti 2019a, b). While there was certainly cheating in disabling the emission control, this cheating was motivated by improving performance and reducing fuel consumption while nominally matching dramatically more restrictive emission standards. Rather than translate into the request of vehicle compliant with other standards, the US EPA action determined the decision to stop working on internal combustion engines R&D, despite on a cradle-to-grave life cycle analysis (LCA) hybrid vehicles with internal combustion engines were certainly not less environmentally friendly than electric cars. Most of the huge fines to the VW group were then used to build recharging infrastructure for electric vehicles by specific suppliers.

There is no doubt H$_2$ green or white from splitting of the water molecule by using wind or solar energy is a fully renewable fuel. It is similar without any doubt that H$_2$ use in jet engines (or fuel cells) is free of CO$_2$ emission. There is however an open discussion about the contrails from H$_2$ use, i.e. the emission of H$_2$O vapor at high altitude. Somebody claims the H$_2$O vapor emission maybe even worse than the CO$_2$ emission for what concerns global warming, and that with H$_2$, there is a larger H$_2$O vapor emission than with jet fuels.

As here explained, the present effect of contrails on global warming is estimated by some as negligible, and by others as extremely relevant, with these latter more likely in error. Critical vs. the LH$_2$ aviation is (Scholz, 2020), overrating the effect of contrails. Their arguments are however questionable. There is no irrefutable evidence that contrails contribute to global warming in a significant amount.

The claim that contrails drastically reduce local daily temperature difference max-min by several degrees C is wrong (Boretti 2021a), and based on the subjective reading of events. Two days of the clear sky for much other reason following the grounding of commercial aircrafts September 11 to September 13, 2001, were not proof clear sky may only exist without aviation and combustion fuels.
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Fig. 4 Differences between the maximum and minimum daily temperatures in Melbourne Airport during the pandemic and the year before. (a) April to December 2019 compared to April to December 2020 and (b) January to March 2020 compared to January to March 2021

(Travis, Carleton, and Lauritsen, 2002; Travis, Carleton, and Lauritsen, 2004) subjectively claimed after the two days of commercial aircraft grounded following September 11, 2001, that without contrails, the daily difference between the maximum and minimum temperatures was 1 °C higher than immediately before. While somebody warned as this could have been due to unusually clear weather during the two days (Kalkstein, and Balling Jr, 2004), somebody else (Science News, 2015; Bernhardt, and Carleton, 2015) claimed even larger variations of temperatures in between areas with or without contrails. In the southern US, the difference was widened by contrails of about 3.3 °C, and 2.8 °C in the US Midwest.

The dramatic reduction of flights after the pandemic – now 13 months – has shown no change
in the local daily temperature difference max-min close to airports (Boretti 2021a). Some data show the opposite of what is claimed by the supporters of the contrails argument to detract from the H₂ aviation (Boretti 2021a).

When comparing the Δt of the last 9 months of 2019 – normal air traffic – and the last 9 months of 2020 – severely disrupted air traffic, in Melbourne the average Δt was 10.63°C in 2019, it has been 9.69 °C in 2020, down rather than up almost 1 °C (Fig. 4).

Analysis from (Boretti 2021a). Other data from other stations, and flights statistic from the same reference.

In Sydney, the average Δt was 10.07°C in 2019, it has been 9.09°C in 2020, down rather than up almost 1°C; in Brisbane, the average Δt was 10.31 °C in 2019, it has been 10.09°C in 2020, down rather than up 0.22°C (Boretti 2021a). This does not prove that contrails have an opposite effect to what is portrayed in some narratives, only that their effect is much less than what is depicted, with many others forcing both natural and man-made affecting temperatures much more.

During the pandemic experiments, drastic reductions of more than 47% of the aviation emission of CO₂ have not produced any difference in the atmospheric CO₂ concentration after 13 months.

The reduction in the aviation sector was ~35% over the entire 2020, and ~47% in the last nine months of 2020. This has produced no change in the growth of the atmospheric concentration, as already noted in (Boretti 2021b), and Fig. 5. The atmospheric CO₂ concentration at Mauna Loa de-trended vs. the parabolic fitting curve is for the years 2019, 2020, and 2021 at the top of the variability band since 1976. During the latest 14 months of Covid19 restrictions, there is no difference vs. the immediately precedent 14 months. Again, this proves as the short-term benefits of CO₂ emission reductions from the aviation sector are largely overrated.

Quantitative claims from the use of models are often openly wrong. Fig. 6 compares the sea surface temperature from 1979 to 2021 from measurements and CMIP6 simulations. These are official measurements of ERSST and official computations by CMIP6. On average, the 68 models
dramatically overrate the warming that has occurred since 1979.

We may therefore conclude as the implications of contrails on global warming, and their effect on surface temperature (maximum and minimum temperatures getting closer), are speculations based on very subjective interpretation of temperature records, and the improper use of never validated computer models where you get answers proportional to the sensitivity factors you give as input.

As the modeling of contrails H₂O emissions in CMIP is even less reliable than the modeling of the CO₂ emission, already everything but accurate, the decision to progress towards H₂-based aviation or not should be based on more solid arguments than narratives about contrails.

4. Conclusions

H₂ aviation is possible, and it may happen soon providing there is a real will to progress towards a fuel that is renewable and therefore inexhaustible, and it is free of CO₂ emission, to balance the significant challenges. Not too much progress has been achieved to date in H₂ aviation, and most of the work done so far is very preliminary studies, artists' impressions, and marketing exercises more than real designs. This is because of the many hurdles, from production and distribution to infrastructure, to aircraft layout and design, which cannot be tackled without huge efforts.

The increased H₂O vapor emission burning H₂ is shown to be unlikely an environmental issue. The pandemic, and the "great reset" (Schwab and Malleret 2020), promoting the view of aviation restricted to the very few, is likely the main threat to future mass aviation with H₂. If the opportunity to fly will be limited to an elite, then also the need for something drastically different from today will drops. The idea behind the H₂ economy was the abundance of energy and fuels for
the whole of mankind. Aviation limited to a few does not need H₂. Opposite, a world of abundant energy, and mass aviation will definitively need H₂.

References


