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Perspectives of hydrogen aviation

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Abstract. The perspective of hydrogen (H_2) aviation is discussed. While production of carbon dioxide (CO_2) free renewable H_2 is progressing towards costs comparable to those of today's steam reforming of methane, at about 1-1.5 $ per kg H_2, 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 H_2, 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 H_2 aviation, as elite aviation does not motivate huge investments in the use of a non-exhaustible fuel such as renewable H_2, leaving favored alternatives such as hydrocarbon jet fuels, and in the longer term electric aviation.

Keywords: aviation; CcH_2; CO_2 emission; H_2O emission hydrogen; LH_2

1. Introduction

In the global warming narrative, carbon dioxide (CO_2) emissions are responsible for global warming. Reducing the CO_2 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 (H_2) produced from the splitting of the water molecule with renewable energy is the ultimate fuel of the future, free of CO_2 emissions, and considered completely renewable.

The motivation for H_2 aviation is thus a long-term alternative for jet fuels after depletion of "fossil" fuels, and a CO_2 emission-free fuel (even if the H_2O vapor emission may still have global warming potential according to other narratives, as discussed later).

H_2 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 H_2 requires huge energy input. H_2 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, H_2 burns very easily, creating safety issues.

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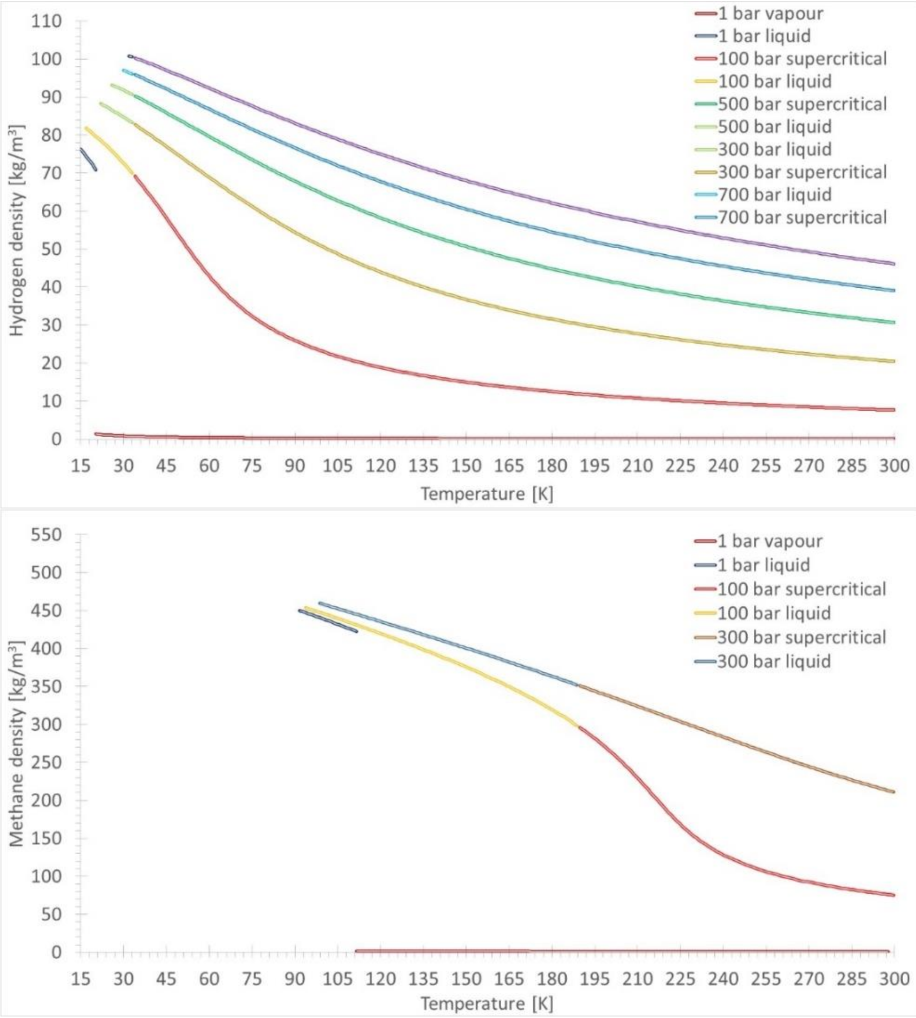

Fig. 1 Density of H_2 (a) and CH_4 (b) at different temperatures and pressures. Data from NIST (n.d.)

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)

	Energy content (LHV) [MJ/Kg]	Latent heat of vaporization (HVAP) [MJ/kg]	Energy content (LHV) [MJ/L]	Density [kg/m^3]	Pressure [bar]	Temperature [K]	State
Cryo CH_4	50	0.511	21.24	424.79	1	110	liquid
Cryo Compr CH_4	50	0.511	22.35	446.91	300	110	liquid
Cryo H_2	120	0.461	8.56	71.329	1	20	liquid
Cryo Compr H_2	120	0.461	10.59	88.278	300	22	liquid
Jet A-1	43.15	0.251	34.69	804	1	298	liquid
Jet A	43.02	0.251	35.28	820	1	298	liquid

Cryo-liquid CH_4 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 H_2 only permits an energy content of 8.56 MJ/liter, i.e. less than ¼ of jet fuels, at 20 K. Pressurizing the liquid H_2 permits to increase the energy density, as the liquid H_2 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 H_2 aviation is based on cryo-compressed storage, mutated from automotive applications, with increased H_2 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/m^3. While H_2 has a specific energy of 118 MJ/kg, the density in normal conditions of H_2 gas is very low, 0.08 kg/m^3. The energy density is only 0.0094 MJ/L. H_2 has a critical temperature of only 33.145 K, a critical pressure of 12.964 bar, and a critical density of 31.263 kg/m^3. Improvements in energy density of H_2 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 CO_2 and H_2O vapor, for example, methane

$$CH_4 + 2\cdot O_2 \rightarrow CO_2 + 2\cdot H_2O$$

combustion of hydrogen only produces H_2O vapor but in larger amount for same heat released,

$$H_2 + \tfrac{1}{2}\cdot O_2 \rightarrow H_2O$$

If we take φ as the hydrogen to carbon ratio,

$$\varphi = H/C$$

we have

$$CH_\varphi + (1+\tfrac{1}{4}\cdot\varphi)\cdot O_2 \rightarrow CO_2 + \tfrac{1}{2}\cdot\varphi\cdot H_2O$$

This gives a water-to-fuel mass ratio of $9/(1+12/\varphi)$. With H_2, $\varphi=\infty$, and the water-to-fuel mass ratio is 9. With CH_4, $\varphi=4$, and the water-to-fuel mass ratio is 2.25. Thus, burning H_2 there is an H_2O vapor production of 9/120=0.075 kg/MJ, while burning CH_4 there is H_2O 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 H_2O vapor production in kg/MJ further reduces. If we take $\varphi=1.9$, then the water-to-fuel mass ratio is 1.23, and burning jet-fuel thus translates into an H_2O vapor production of 0.0286 kg/MJ.

In the following two sections we consider two of the major issues in using H_2 as aviation fuel, the storage onboard an aircraft, and the implication on global warming of the increased H_2O vapor emission.

2. Hydrogen aircrafts

Cryo-compressed H_2 (CcH_2) refers to the storage of H_2 at cryogenic temperatures in a tank pressurized at 250 to 350 bar, in contrast to current liquid H_2 (LH_2) that refers to storage at cryogenic temperatures and near-ambient pressures (Ahluwalia, Peng, and Hua, 2016). CcH_2 overcomes many of the shortcomings of compressed gas H_2 (cH_2) or LH_2 tanks opening new possibilities. CcH_2 tanks permit storage of liquid, supercritical cryogenic, or two-phase saturated liquid and vapor H_2.

Compared to near ambient pressure LH_2 tanks, the dormancy is larger in CcH_2 tanks because the allowable pressure is larger. CcH_2 tanks also have higher heat receptivity as the H_2 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 H_2 density is nonetheless 30% of the initial liquid density. Ullage space could be eliminated in CcH_2 tanks as H_2 is supercritical at a pressure larger than 13 bar. The maximum storage density is also higher with CcH_2 because liquid H_2 is to some extent compressible.

At 20 K, H_2 is liquid. Density is 71.28 kg/m^3 at 1 bar, and it is 86.09 kg/m^3 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/m^3 at 1 bar, and it is 20.55 kg/m^3 at 300 bar. Storage of H_2 should be better liquid, thus there is the convenience of cooling down the H_2. There is also convenience in compressing the H_2, especially when gas. At 700 bar of pressure, H_2 is liquid up to 32.957 K (density 96.155 kg/m^3). Then it is supercritical. At 78.957 K, density is still 80.210 kg/m^3. At 298 K, density is 39.24 kg/m^3. At 239.96 K, the density is 45.88 kg/m^3. The CcH_2 tank can be fueled with more expensive H_2 liquid for extended range, and less expensive compressed H_2 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 H_2 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 H_2. Insulation high efficiency and small degradation are concerns. Outgassing of volatile components from composites, H_2 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 H_2. Tanks of the required storage capacity and weight, and safety, are the key enabler of H_2 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

Table 2 Storage options being considered for automotive applications

Storage Method	cH_2	cH_2	cH_2 Cold Gas	CcH_2	CcH_2
Storage Pressure	350 bar	700 bar	500 bar	350 bar	500bar
Liner	HDPE	HDPE	HDPE	2-mm SS	2-mm SS
Storage Temperature	288 K	288 K	200 K	62 K	67 K
Storage Density	24 g/L	40.2 g/L	42 g/L	71.2 g/L	76.7 g/L
Gravimetric Capacity	5.4%	4.2%	3.9%	7.5%	7%
Volumetric Capacity	17.7 g/L	24.6 g/L	23.4 g/L	35.5 g/L	44.2 g/L
CF Composite	61.9 kg	96 kg	54.5 kg	20 kg	29 kg
Cost	$13/kWh	$15/kWh	$13.3/kWh	$11/kWh	$12/kWh

(a)

(b)

(c)

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 LH_2. 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 LH_2 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 LH_2 – lower temperature, minimal pressurization of tanks - rather than ccH_2 – 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 H_2 aviation are reported in (Scholz, 2020) which consider LH_2 tanks. Aircraft must be modified or redesigned. New airport infrastructure is necessary. H_2 must be produced, transported, and liquefied. For the same range with the same aircraft envelope, space must be found for nearly cylindrical H_2 tanks. If the size of the aircraft increases to accommodate the H_2 tanks with the same payload, the aircrafts have higher zero-lift drag. According to (Scholz, 2020), short-range H_2 aircrafts have 5% larger operating costs. In long-range H_2 aircrafts, the operating costs may increase by 15%. Despite insulation, the warming of H_2 in LH_2 tanks produces gas H_2 to be used in flight. On the ground, rising pressure following warming would require blown off. A refueled aircraft with LH_2 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 LH_2 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 H_2, 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 LH_2 production costs (Westenberger 2003a) predicts a DOC crossover point LH_2 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 LH_2. The empty weight increases by 20 to 25% with LH_2. 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.

LH_2 aviation requires significant effort, from H_2 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 H_2. The liquid H_2 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

Fig. 3 Fuel cell “pod” propeller aircraft. Courtesy Airbus

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 η=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 downfalls 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_2O vapor is theoretically a greenhouse gas more powerful than CO_2, the much higher than Jet-fuel emission of H_2O 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_2O 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_2O vapor at high altitude. Somebody claims the H_2O 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_2O 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.

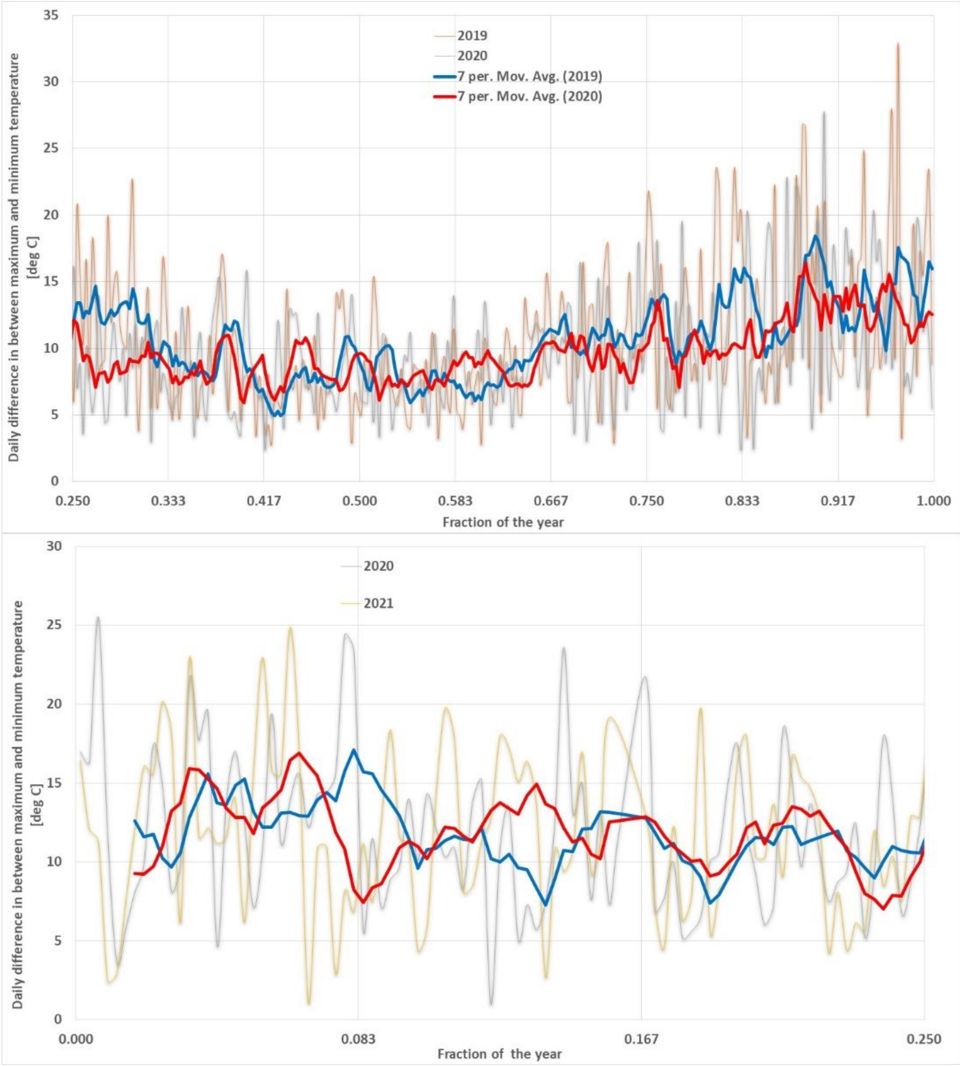

Fig. 4 Differences between the maximum and minimum daily temperatures in Melbourne Airport during the pandemic and the year before. (a) April to December 2019 compared to April to December 2020 and (b) January to March 2020 compared to January to March 2021

(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

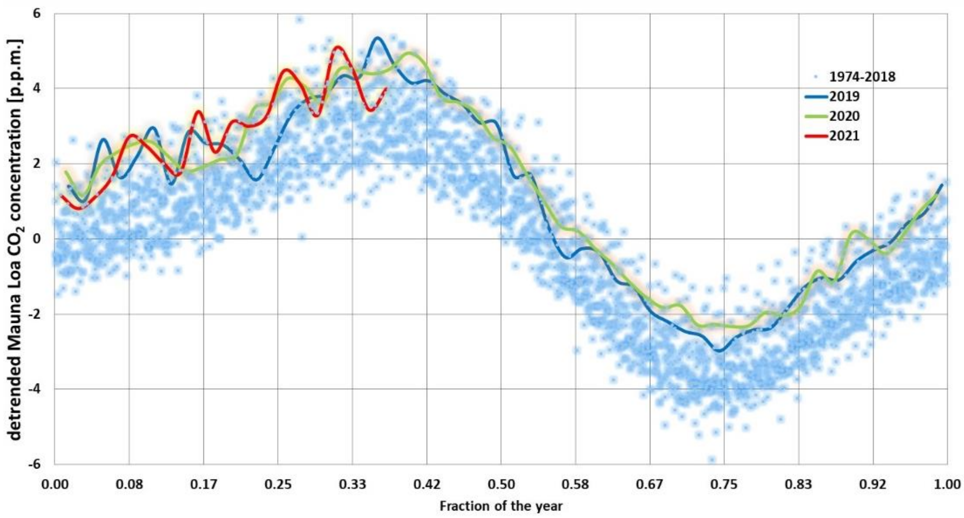

Fig. 5 Atmospheric CO_2 concentration at Mauna Loa de-trended vs. the parabolic fitting curve. Analysis from (Boretti 2021a)

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 H_2 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 CO_2 have not produced any difference in the atmospheric CO_2 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 CO_2 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 CO_2 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

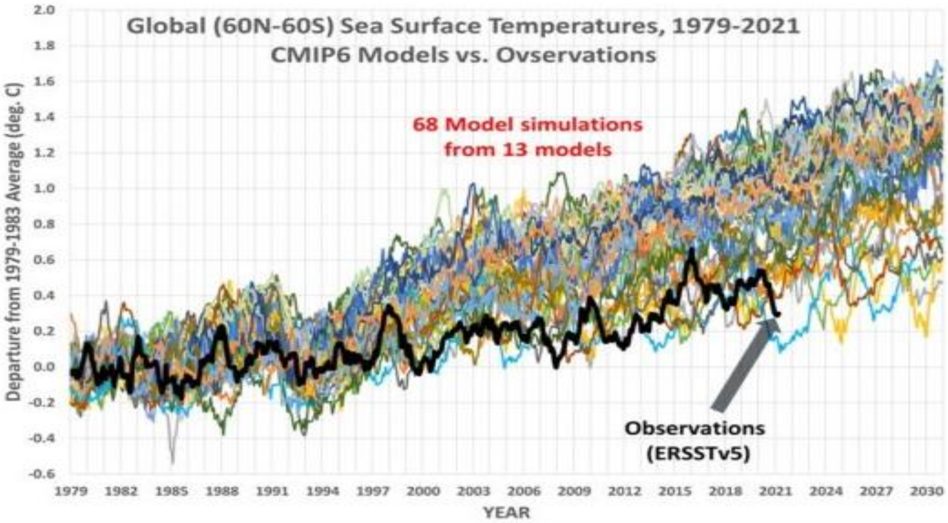

Fig. 6 Results of 68 CMIP6 simulations of global sea surface temperature SST compared with "measurements" from the ERSSTv5 database. The anomaly is relative to the 5-year average of 1979 to 1983. The Image is from (Spencer, 2021), Credit Roy Spencer

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 H_2O emissions in CMIP is even less reliable than the modeling of the CO_2 emission, already everything but accurate, the decision to progress towards H_2-based aviation or not should be based on more solid arguments than narratives about contrails.

4. Conclusions

H_2 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 CO_2 emission, to balance the significant challenges. Not too much progress has been achieved to date in H_2 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 H_2O vapor emission burning H_2 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 H_2. 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 H_2 economy was the abundance of energy and fuels for the whole of mankind. Aviation limited to a few does not need H_2. Opposite, a world of abundant energy, and mass aviation will definitively need H_2.

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