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Decarbonising aviation

The route to net zero for the travel and tourism industry

Mark Frary. *Decarbonising Aviation*
WTM, London November 2020

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Introduction

The end of 2019 may seem like a long time ago now but back then things other than masks, lockdowns and vaccines were making the headlines – the environment for one, with Swedish teenager Greta Thunberg as its vocal champion. Australia's devastating bushfires were a grim warning, if one were needed, of the dangers of climate change – 13 million hectares destroyed and more than a billion animals killed thanks to record-breaking average temperatures across the country. The fires even further contributed to the problem, with a further 434 million tonnes of CO_2 emitted into the atmosphere.

Few could have imagined how 2020 would turn out. Hundreds of thousands dead with the death toll still rising and travel between countries severely restricted or even banned for the majority.

Yet despite the horrors of Covid-19, this involuntary cessation of international travel has shown us that it may be possible to prevent the climate crisis from getting worse.

The closure of borders due to the Covid-19 pandemic has shown us very clearly the aviation sector's contribution to carbon emissions. One piece of research[1] estimates that daily carbon dioxide emissions in aviation were 60% lower in early April 2020 than the average 2019 level, with some 1.7 million tonnes less CO_2 being emitted every day into the atmosphere as a result.

Pandemic or not, aviation's contribution to the climate crisis is a problem that needs a solution. It is not just the aviation sector's problem – travel and tourism as a whole needs to recognise the problem. We currently stand at an important crossroads in travel and tourism, where the direction we take will make an enormous difference to our destination.

In June 2020, in recognition of this important moment, World Travel Market convened a symposium bringing together a group of leading experts to look at the problem of how to decarbonise aviation.

1. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement, Corinne Le Quéré et al, *Nature*, 19 May 2020, https://www.nature.com/articles/s41558-020-0797-x

The symposium was put together by Dr Harold Goodwin, Professor of Responsible Tourism at Manchester Metropolitan University and advisor to World Travel Market, Professor Paul Peeters, professor of sustainable transport and tourism at Breda University of Applied Sciences in the Netherlands and international aviation policy analyst Chris Lyle.

The virtual event (you can watch again at https://responsibletourism.wtm.com/Upcoming-Events/virtual-events/), brought together leading scientists working on decarbonising aviation:

- Dr Harry Lehmann of Germany's Umwelt Bundesamt (Federal Environment Agency);
- Dr Carola Kantz of Germany's VDMA (Mechanical Engineering Industry Association) Power-to-X applications working group;
- Dr Marc Stettler, senior lecturer in transport and environment, Centre for Transport Studies at Imperial College London;
- Joris Melkert, senior lecturer, faculty of aerospace engineering, TU Delft
- Daniel Juschus, aerospace engineering masters student;
- Professor Pericles Pilidis, UK representative of ISABE, TU Delft
- Professor Gustavo Alonso, school of aerospace engineering, Universidad Politecnica de Madrid;
- Gerard Rijk, equity and financial analyst, Profundo;
- Job Rosenhart, senior advisor on the sustainability of aviation, Ministry of infrastructure and water management, Netherlands.

This white paper is one of the outputs of that symposium and it looks at the following:

- the scale of the sector's growing carbon problem;
- why the sector has been slow to change;
- evaluating the effectiveness of various proposed methods to decarbonise aviation;
- the fuel and aircraft technologies being developed;
- why decarbonising aviation will need massive investment;
- why global co-operation on standards and implementation of these technologies is imperative.

Dr Harold Goodwin, the symposium's co-organiser, says:
"The climate crisis gathers pace and there is no longer time for procrastination."
"The travel and tourism sector should expect more of the aviation industry and we need to press for change."
"There is an alternative. The tourism industry should require governments to force the aviation sector to develop and adopt zero-carbon fuels before there is a forced reduction in flying."

The problem

Travel and tourism is one of the world's biggest industries.

According to the World Travel and Tourism Council[2], travel accounts directly and indirectly for 10.3% of global GDP - some US$8.9 trillion – and supports around 330 million jobs, that is 1 in 10 jobs around the world.

For some countries, particularly small island nations such as Aruba, the British Virgin Islands and the Maldives, tourism is the main driver of GDP and their principal source of employment[3]. For some developing countries, aviation is also necessary to enable them to import food, medicines and technology for their development.

As well as aviation's substantial contribution to the global economy, it also makes a significant contribution to global carbon emissions. According to the International Council on Clean Transportation, aviation accounted for 2.4 to 2.8% of all carbon dioxide emissions from fossil fuel use in 2018[4].

This is not the whole problem either. If you take into account non-carbon effects such as nitrous gases, soot and other particulates and the production of contrails, aviation may account for up to 5% of the global warming problem.

The mass tourism of the past six decades has brought us to this point and - despite economic downturns – it has shown no signs of abating. In 1950 the United Nations World Tourism Organisation (UNWTO) recorded 25 million international tourists, a figure that had grown to 1.5 billion in 2019[5&6].

2. https://wttc.org/Research/Economic-Impact

3. https://wttc.org/Research/Economic-Impact/moduleId/1445/itemId/91/controller/DownloadRequest/action/QuickDownload

4. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7468346/pdf/main.pdf and https://theicct.org/publications/co2-emissions-commercial-aviation-2018

5. https://www.e-unwto.org/doi/pdf/10.18111/9789284419029

6. https://www.unwto.org/world-tourism-barometer-n18-january-2020

And it should be recognised that international tourism covers only about 20 to 25% of all tourism in the world[7]. Currently, large domestic tourism markets such as China are outgrowing international tourism with already 3.3 billion domestic tourists in 2013[8]. That amounts to continuous growth of 3 to 4 per cent every year. Before the pandemic, Airbus in its 2019 Global Market Forecast[9] predicted that air traffic would continue to grow by an average of 4.3% annually over the next 20 years while Boeing's Commercial Market Outlook predicts traffic growth of 4.6% to 2038[10].

While the 4.6% global growth predicted by Boeing does not sound too significant it equates to a doubling of air traffic every 15 years and ten times more air travel by the end of this century[8].

The Covid pandemic has decimated air traffic (see the red line in **figure 1** below) but IATA is predicting that growth will return to 2019 levels by 2024 at the earliest, with overall traffic in 2025 currently forecast to be around 10% lower than predicted before the crisis[11].

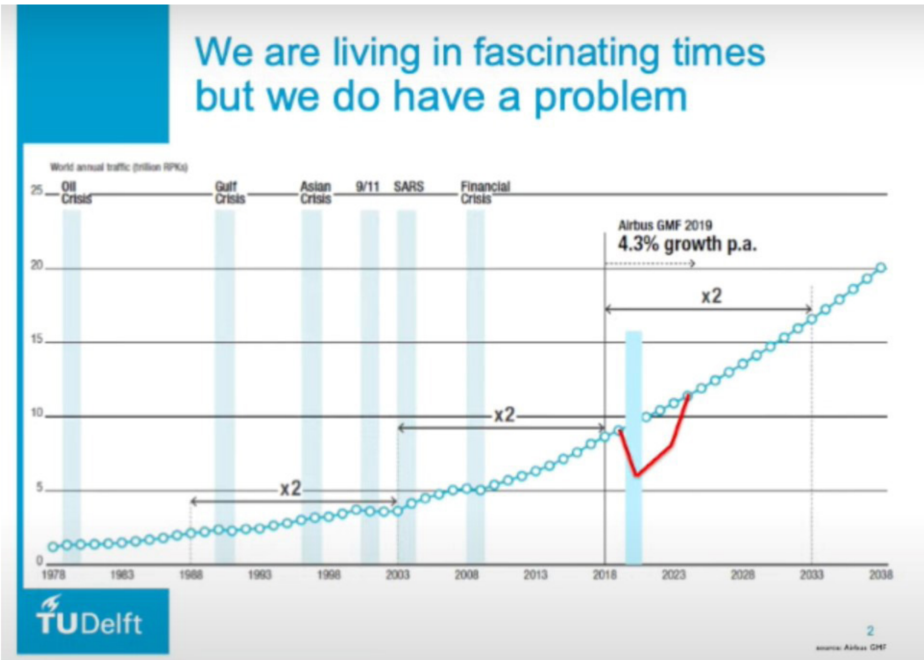


Figure 1:
A blip in air traffic growth?

7. Peeters, P. M. (2017). *Tourism's impact on climate change and its mitigation challenges. How can tourism become 'climatically sustainable'?* (PhD). Delft University of Technology, Delft.

8. Meng, W., Xu, L., Hu, B., Zhou, J., & Wang, Z. (2016). Quantifying direct and indirect carbon dioxide emissions of the Chinese tourism industry. *Journal of Cleaner Production*.

9. https://www.airbus.com/aircraft/market/global-market-forecast.html

10. https://www.boeing.com/commercial/market/commercial-market-outlook/

11. https://www.iata.org/en/iata-repository/publications/economic-reports/covid-19-outlook-for-air-travel-in-the-next-5-years/

It is not going to be an even recovery. Covid has caused and continues to cause a dramatic economic downturn and new working practices have emerged from this, including a wider adoption of video conferencing and this is likely to cause a long-term reduction in business travel as organisations recognise efficiencies. However, tourism is likely to rebound as people have spent longer in their homes and they are going to need a little bit more relief through visiting other places.

Many believe that when a Covid-19 vaccine is created – although it is not certain it will be – then aviation will continue on its former growth trajectory, although as the pandemic has dragged on the recovery some see a recovery happening a lot less sharply. However, many believe that issues other than the environment, such as overtourism, will mean that traffic dips below the blue line.

Carbon - not necessarily flying - is the problem

The abundant energy at low cost that fossil fuels have enabled has brought the world benefits in education, health and in reducing poverty but the environmental and climatic cost of using them is becoming unacceptably high. How can we remove the carbon but still focus on the benefits?

The problem for aviation – and by extension about 25% of travel and tourism – is that the aviation sector is moving much more slowly than other sectors in combatting carbon emissions.

One of the major challenges is the long life and high capital investment into commercial aircraft and the associated slow pace of change. It will take up to the end of this century to first develop a whole range of small to large and short- to long-haul types of zero-emission planes and to replace the existing fleet once these new types come on the market.

In July, British Airways announced that it was grounding its Boeing 747 fleet. A spokesman told the BBC, "It is unlikely our magnificent 'queen of the skies' will ever operate commercial services for British Airways again due to the downturn in travel caused by the Covid-19 global pandemic."[12]

12. https://www.bbc.com/news/business-53426886

The 747 first entered into commercial service half a century ago – an eon for most industries – and while there have been technological improvements over that time, there have not been step-changes, largely because the industry is so capital-intensive. The fundamental issue is that while there technological and operational improvements have reduced emissions per unit, these have been substantially outweighed by growth in traffic.

This means that if air traffic continues to grow unabated at historic rates then aviation's carbon problem grows substantially unless something radical happens.

While other contributors to carbon emissions look to be able to reduce their share of the carbon pie dramatically, aviation has a harder challenge ahead. One study says that if international flights grow by 5% a year in the years to 2050, aviation would be responsible for a whopping 27% of the carbon budget that would allow global warming to be restricted to 'just' 1.5 degrees Celsius – the aspirational target strongly recommended by the IPCC and mentioned in the Paris Agreement that most of the countries in the world signed.

As a result, there is increasing criticism of aviation and as the impacts of climate change become more prominent and more dangerous for more and more people, we can expect the criticism of aviation to grow louder.
Despite this, domestic and international travel and tourism, of which 22% is powered by aviation, bring much to the world, aside from the contribution to the global economy and supporting so much employment worldwide. Tourism improves cultural awareness and, if managed responsibly, can raise living standards and, arguably, help protect endangered species and heritage sites.

If it were not for its growing carbon problem, aviation is seen by many as a force for good. As an airline executive once said: “Flying is not the problem, carbon is.”

Figure 2 below shows what doing nothing will do. It shows combined domestic and international travel and tourism’s projected carbon emissions assuming business as usual (including fleet renewal) until the end of the century and aviation makes up the greatest share of these emissions. The orange curve shows what was agreed for all sectors and households together in Paris in order to limit temperature rises to 2 degrees Celsius while the blue line represents the aspiration to keep this limit to 1.5 degrees. By 2100, aviation will be responsible for four billion tonnes of CO_2 per year if nothing is done. Even though aviation covers less than a quarter of all tourism trips in the world, it is responsible for over half of the current emissions and its share increases to over 75% by the end of the century. This also problematic when we take into account that ‘zero-emission’ technology is proven for road and rail transport and for hotels, but still a challenge for aviation. But it is not impossible if long-term a concerted action is started now.

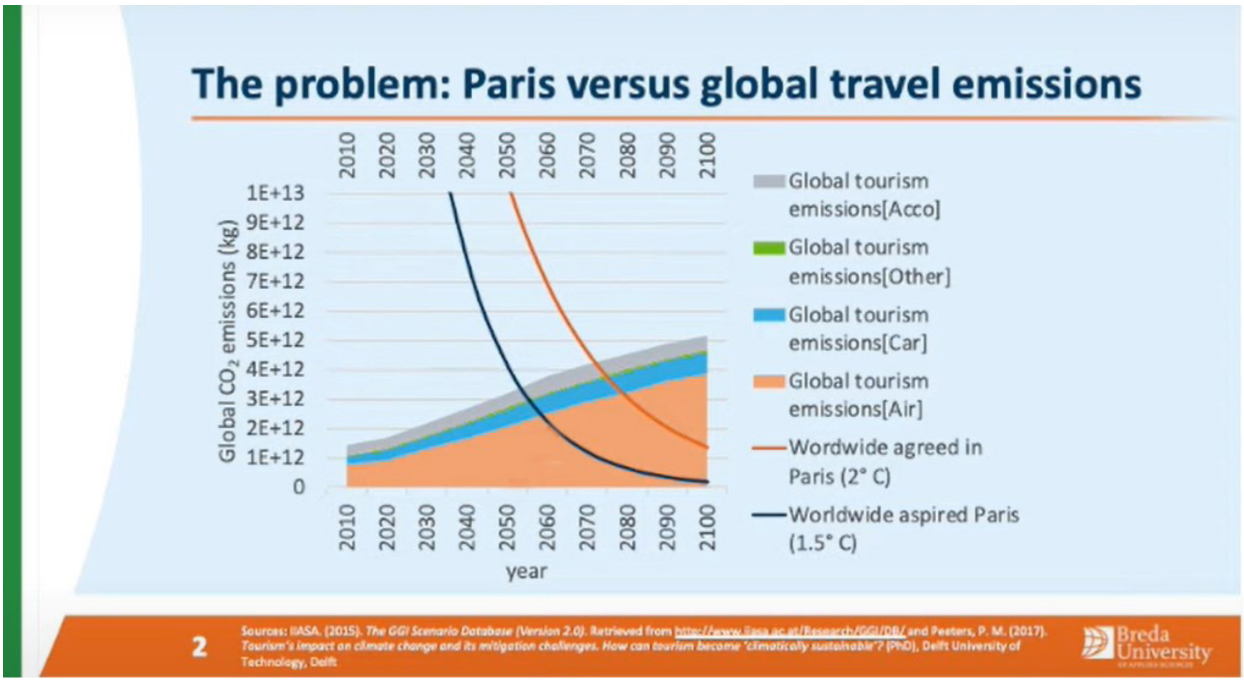


Figure 2: A looming carbon crisis

It is also likely that as we move forward, an increasing number of climate-related incidents – such as the Australian bushfires – will see the public and governments demand faster action.

To limit the temperature rise to 2°C, the world needs to stay below a total of 1,000 billion tonnes of emissions. At the current level of emissions, this amount will be reached in 2030, making it impossible to avoid a full climate disaster. The travel and tourism sector must act now.

Carbon - not necessarily flying - is the problem

The United Nations Framework Convention on Climate Change (UNFCCC), ratified by 197 countries, is a treaty that aims to prevent "dangerous" human interference with the climate system

Various agreements have been made that are intended to operationalise the UNFCCC, such as the Kyoto Protocol and the Paris Agreement.

The Kyoto Protocol, adopted on 11 December 1997, is the commitment made by industrialised countries to limit and reduce greenhouse gases (GHG) emissions under the United Nations Framework Convention on Climate Change.

It only binds developed countries, and places a heavier burden on them under the principle of "common but differentiated responsibility and respective capabilities", because it recognises that they are largely responsible for the current high levels of GHG emissions in the atmosphere.

The Protocol specified that Parties should address international aviation emissions though the International Civil Aviation Organization (ICAO).

Owing to a complex ratification process, it entered into force on 16 February 2005. Currently, there are 192 Parties to the protocol but it effectively lapses this year. The 2021 United Nations Climate Change Conference (COP26) in Glasgow will provide future direction.

The Paris Agreement was an accord adopted on 12 December 2015 at the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change held in Paris from 30 November to 13 December 2015.

Its goal is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.

The Paris Agreement covers emissions caused by domestic use of aviation fuels and tacitly may also cover international use. This will be discussed further at COP26.

The Agreement has since been ratified by 189 countries and states, although on 4 November 2019, the US government announced it would withdraw from the agreement on 4 November 2020.

Offsetting the carbon problem

Carbon emissions are a global problem – it does not matter where a tonne of carbon dioxide enters the atmosphere, it always contributes to global warming. This universality does however lead to the idea of carbon offsetting.

This is the acknowledgement that reducing carbon emissions from aviation fuel and aircraft in the short term is difficult but that carbon can be reduced in other sectors or through dedicated schemes, such as tree planting or replacing dirty cooking stoves with cleaner alternatives.

The cost of offsetting varies dramatically from a few US cents to tens of dollars. One tree planting scheme charges around US$17 to offset a tonne of CO_2, for example.

Offsetting does have a problem. There have been cases where the programme which was supposed to deliver the carbon reductions never actually happened, such as the high profile case in which the Vatican paid to offset its carbon emissions through the planting of trees in rural Hungary. The trees were never planted.[15] The Vatican case is not a rare exception. A report issued by the European Commission shows that only 2% of more than 5,000 offset projects studied did deliver the promised reductions, some 80% certainly not.[16]

ICAO's response to the decarbonisation challenge is Corsia (Carbon Offsetting and Reduction Scheme for International Aviation), an initiative intended to address any annual increase in total CO_2 emissions from international civil aviation solely through carbon offsetting.

Corsia was originally designed to use the average level of CO_2 emissions from international aviation covered by the scheme between 2019 and 2020 as a baseline upon which emissions in future years are compared. However, this was amended in June 2020 because of the Covid pandemic and 2019 emissions will now be used as the baseline.[17]

The scheme is initially voluntary and is run in phases until 2035 when all countries that have an individual share of international aviation activities in year 2018 above 0.5 per cent of total RTKs or are in the top 90% of traffic generating countries are expected to participate. However, participation by countries is not mandatory.

Critics point out that although ICAO have to approve the offsetting schemes used these are not on top of what countries must do anyway.

Under Corsia, airlines can offset CO_2 savings by using alternative fuels. However, this is unlikely to be used in the short term because of the much higher prices of those alternatives at present compared to the unrealistically low prices of current carbon offsets.

15. https://www.csmonitor.com/Environment/2010/0420/Carbon-offsets-How-a-Vatican-forest-failed-to-reduce-global-warming

16. https://www.oeko.de/publikationen/p-details/how-additional-is-the-clean-development-mechanism

17. https://www.consilium.europa.eu/en/press/press-releases/2020/06/09/aviation-emissions-eu-adopts-its-position-on-adjusted-corsia-baseline-to-take-account-of-the-consequences-of-covid-19-pandemic/

The June 2020 revision of the baseline to 2019 led The Economist to argue that Corsia “defangs an already mostly toothless carbon-offsetting scheme”.[18]

Corsia’s critics say that it fosters a lowest common denominator approach. It may be that allowing for regional differences may actually result in a greater reduction in carbon. For example, the EU’s Emission Trading System, if fully applied to all European international aviation, would have a bigger impact than application of Corsia worldwide.[19]

Carbon taxes

The introduction of a carbon tax attempts to reduce demand for aviation by increasing the cost of a ticket or to incentivise the use of sustainable aviation fuels, such as biofuels and so-called e-fuels, over the use of fossil-based Jet A and A-1, the most widely used fuels in aviation.

There have been a number of suggestions of a carbon tax on aviation. In November 2019, the finance ministers of Germany, France, Sweden, the Netherlands, Italy, Belgium, Luxembourg, Denmark and Bulgaria issued a joint statement calling on the European Commission to introduce an aviation tax to help counter the environmental effects of aviation.

However, a CE Delft study into carbon tax showed[20] that an aviation tax in the Netherlands would not lead to fewer flights. Instead it would lead to a shift in traffic segments and any such tax would have only modest impacts on CO_2 because “the tax itself is likewise fairly modest (several percent of the average ticket price) and because of serious capacity restrictions at Schiphol Airport, in particular. This is one example of the main problems with an environmental tax: high and effective taxes are politically almost impossible to implement.

While it is likely that a carbon tax would not reduce demand significantly, their absence is discriminatory in comparison of other modes of transport.

18. https://www.economist.com/business/2020/07/04/airlines-blame-covid-19-for-rowing-back-climate-commitments

19. https://www.mdpi.com/2071-1050/11/20/5703

20. https://www.cedelft.eu/en/publications/2145/economic-and-sustainability-impacts-of-an-aviationtax

To be effective, rates of carbon taxes would need to be very high in order to make fossil fuels more expensive than sustainable aviation fuels, perhaps at levels of 100 to 500%. Some suggest that only a combination of carbon taxes and e-fuel subsidies will be possible where taxes are lower than these projected rates because they cover only a small share of all aviation fuels. Mandating an increasing share of e-fuels in aviation fuel and ringfencing any carbon taxes raised to fund their development seems much more likely to succeed.

It is also the case that large, international companies are generally very good at avoiding taxes.

Reducing demand for travel

In the couple of years we have come to know the term *flygskam* or flight shame – the shame that some travellers have for taking flights that contribute so much to climate change.[21]

There is certainly some evidence to show that some people are changing their travelling habits. A survey carried out by the European Investment Bank before the pandemic showed that three quarters of Europeans are committed to flying less in order to fight climate change .

Even though many people love to travel (or have to travel in the case of business travel) and many professionals in then tourism industry believe the impact of flygskam is unlikely to make much of a dent into the predicted 4 to 5% annual increase in air traffic, there are some signs of the contrary. In Sweden, domestic air travel declined suddenly after the *flygskam* movement surged and domestic carrier BRA started to ditch jet aircraft and made 363 employees redundant in 2019.[22] German domestic air travel started to clearly decline during 2019 while national and international rail travel surged.[23] The same development could be seen in the Netherlands, where in 2019 13% more people booked an international rail ticket, building on growth in 2018.[24]

Indeed, the signs are that as soon as lockdowns have been relaxed during the Covid pandemic, the desire to travel comes surging back.

21. https://www.eib.org/en/surveys/2nd-citizen-survey/new-years-resolutions.htm
22. https://standbynordic.com/bra-to-ditch-jet-aircraft-sacks-363-staff/
23. https://www.bloomberg.com/news/articles/2019-12-19/german-air-travel-slump-points-to-spread-of-flight-shame
24. https://www.globalrailwayreview.com/news/94803/travelling-internationally-rail-increases-netherlands/

A more severely restrictive way of reducing demand for aviation is to introduce a cap on airline slots or on airline operations by route although these would have to be global in scope to avoid restricted demand on some routes simply being pushed onto other routes where slots are not constrained.

Restricting aviation would also push travellers onto other modes of transport, such as cars and trains, and away from long-haul travel, where a modal shift is not practical.

The long-haul problem

Not all flights are equal. **Figure 3** shows that longer flights require proportionately more fuel. The 1% of flights globally that are longer than 8,000 kilometres consume 20% of all the aviation fuel and therefore contribute more to the emissions problem.

This means that we desperately need a solution for long-range aircraft if we are to solve the carbon problem.

Figure 3:
10% of the flights,
50% of the problem

Energies for the future

The easiest way to replace fossil-fuel-based Jet A aviation fuel is to use a sustainable alternative fuel (SAF). SAFs typically come in two types, those made from biomass – biofuels – and those made directly from CO_2 - e-fuels produced using a power-to-liquid process. The big advantage is that SAFs can already safely be mixed up to a level of 50% with fossil-based Jet A fuel and used in current aircraft and engines.[25] SAFs also have the advantage that existing fuel logistics and infrastructure can be used as they are.

The cost of SAFs are some 2.5 times those of fossil kerosene and the expected reduction of costs has not been found in a recent study.[26] It is unlikely these costs will go below those of fossil fuels within the next decades without strong policies aimed at developing the market. Therefore, there will need to be policies mandating mixing of SAFs with kerosene as well as carbon taxes and subsidies. This will induce mass production, which then will lead to cost savings but it is unlikely these will become cheaper than Jet A.

Some countries - Germany, the Netherlands, France, Norway, UK - have already begun setting unilateral targets for the use of SAF mixtures. The Netherlands is most ambitious with a 2030 goal of using at least 14% sustainable aviation fuels in fuel blends with a goal to replace all fossil fuels in aviation with SAF by 2050.

Of course, mandates will only solve the problem when these are globally adopted by a majority of countries. A strong incentive for countries to implement mandates would be to include international aviation bunker fuels into the Paris agreed National Determined Contributions (NDCs) that determine the national emission reduction pathway. Currently, the responsibility for international bunkers is with ICAO and resulted in the ineffective Corsia scheme.

However, SAFs – and biofuels in particular - also have issues that may slow their adoption. As a result, the aviation sector needs to look at completely new aircraft concepts such as electric and hydrogen fuel cell powered flight which both require completely new aircraft designs from scratch.

25. Source: Alternative Fuels Data Center, US DoE, https://afdc.energy.gov/fuels/emerging_hydrocarbon.html

26. https://www.sciencedirect.com/science/article/pii/S1361920919312222?via%3Dihub

This will take decades to develop and again decades to fully penetrate the world fleet. Therefore: SAF for the short-term and electric/hydrogen for the long-term, but both developments need full focus from now onwards.

a. Biofuels

Biofuels are those fuels which are created from plants, algae or animal waste rather than from fossil fuel sources. They can be derived from existing crops or from specially grown crops designed for producing fuels. They are considered as a renewable energy source because they can be readily regrown.

The two main types of biofuel are ethanol and biodiesel. Ethanol, which can be blended with petrol, can be derived from plants that contain a lot of sugar or starch, such as sugar beet or wheat.

Biodiesel is obtained by combining vegetable or animal fats, such as recuperated cooking oil from restaurants, with alcohol and can be combined with ordinary diesel fuel.

In 2007, Greenflight International, founded to demonstrate biofuel technologies, operated a military L29 jet trainer from Nevada's Reno-Stead airport on 100% biodiesel. In 2008, Virgin Atlantic flew a Boeing 747-400 flew from London to Amsterdam using a 20% mix of coconut and babassu oil in one of its engines.

Since then, more than 150,000 flights have been operated using biofuel but only five airports worldwide offer regular biofuel distribution, according to the IEA.[27] To put that into context, that is less than the total number of flights operated worldwide every day.[28]

One of the problems is that chlorophyll, the chemical in plants that converts sunlight into usable energy, is very inefficient: a typical plant will only convert 0.1 to 0.2% of the sunlight it receives. Algae do better but even after much genetic engineering only achieve 1 to 3% efficiency. By comparison, the very best solar panels can achieve efficiencies of more than 40%.

27. https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off

28. https://www.businessinsider.com/most-flights-ever-225000-flightradar24-flight-tracking-2019-7

This low efficiency means that biofuels need very large areas of land to generate the energy required. For instance, Europe could cover a maximum of 10% of its aviation bunker fuels by biofuels in 2030.[29] In many cases, biofuel production land needs to be fertile and wet enough to grow feedstock crops. Such large land requirements often lead to conflicts with ecosystems, forests, agriculture, and food production. Even though many international agreements and protocols have tried to avoid this, it has happened before and the risks of using biofuels as an alternative to kerosene are high.

Another issue with biofuels is that the land use and the whole process of producing the fuels from raw biomass also have consequences for the climate, which is studied in so-called life-cycle analysis using the best performing biofuels with 80% lower CO_2 emissions than fossil-based Jet A would mean that with ten times the aviation volume by the end of this century and assuming aircraft to be 50% more efficient by then, we still end up with the same emissions. This means that biofuels cannot reduce emissions to zero, which we need to reach by 2050 according to the IPCC 1.5°C report. [30]

b. E-fuels from the power-to-liquids (PtL) process

While biofuels can help to reduce CO_2 emissions, they come with a range of issues that could be far from beneficial, requiring much legislation to avoid. Also, the life-cycle emissions are far from zero. Recently, an alternative has emerged for aviation: e-fuels.[31] These 'electro-fuels' are created by mixing water and pure CO_2 and a lot of renewable energy. The CO_2 can initially be taken from a chimney, but only for as long as it smokes. This is an important point as under the Paris Agreement, all chimneys will eventually stop smoking CO_2.

The ultimate solution is to capture CO_2 directly from the atmosphere using direct air capture (DAC). This process has been demonstrated and some systems are already on the market, such as that that by ClimateWorks.[32] With DAC the carbon cycle can be fully closed and zero emissions can become reality.

29. De Jong, S., Stralen, J., Londo, M., Hoefnagels, R., Faaij, A., & Junginger, M. (2018). Renewable jet fuel supply scenarios in the European Union in 2021–2030 in the context of proposed biofuel policy and competing biomass demand. *GCB Bioenergy*, 0(0). doi:10.1111/gcbb.12525

30. IPCC. (2018). *Global Warming of 1.5 °C. Special Report* (ISBN 978-1-5264-6112-). Cambridge UK

31. Schmidt, P., & Weindorf, W. (2016). *Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*. Dessau-Roßlau

32. https://www.climateworks.org/programs/carbon-dioxide-removal/

Figure 4 shows the advantages of PtL over biofuels in terms of the range that an Airbus A320neo could achieve per hectare of land used an also graphic representation of the water usage by the various technologies.

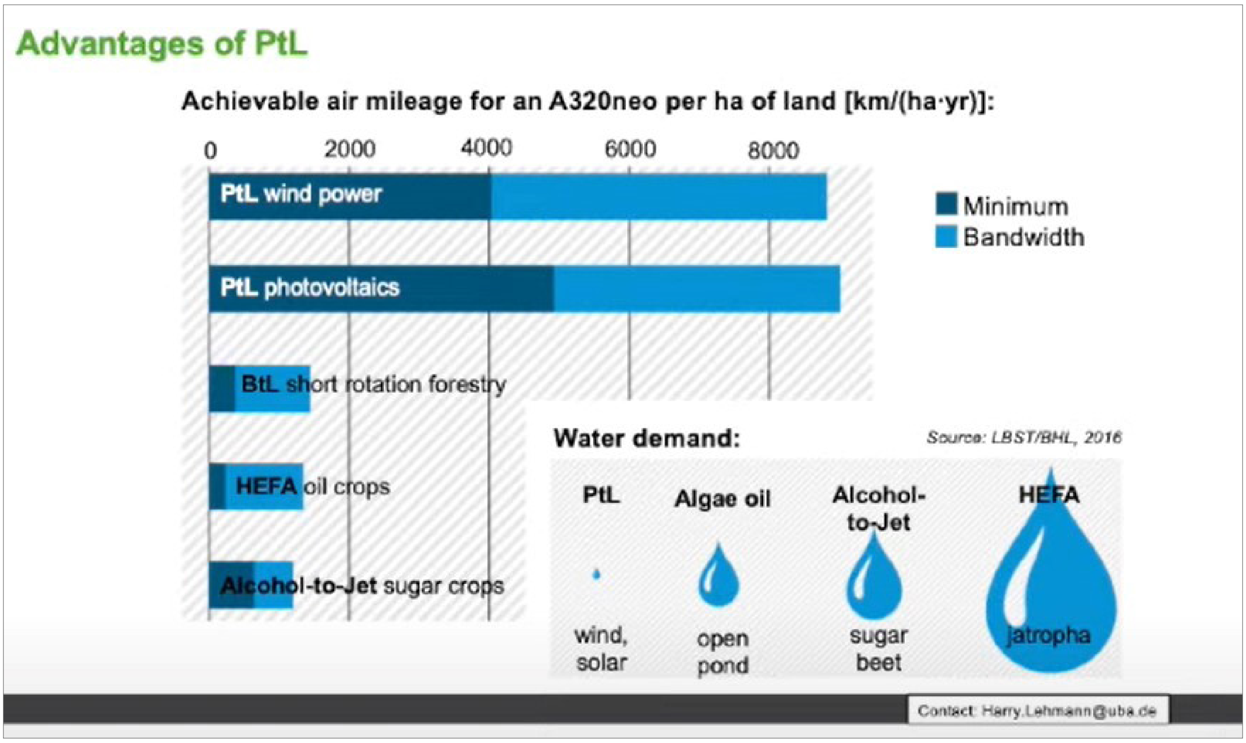


Figure 4: Land and water usage of PTL and biofuels

It is estimated[33] that the global market for PtL will be 20,000 TWh by 2050, around half of today's global demand for crude oil meaning that aviation needs to be prioritised.

Yet delivering PtL requires policy instruments such as a carbon tax plus subsidy schemes to remove the current price differential with kerosene or a mandatory mixture quota or both. Furthermore, investment is required for accelerating remaining elements of technical development and funding start-ups.

33. International Aspects of a Power-to-X Roadmap, https://www.frontier-economics.com/media/2642/frontier-int-ptx-roadmap-stc-12-10-18-final-report.pdf

The PtL process is not just about replacing existing refinery processes to get a single sustainable product at the end but transforming them to yield a spectrum of products. **Figure 5** below shows how renewable energy sources can be used to produce kerosene but also hydrogen, methanol and other products. The beauty of this is that it enables individual products to be produced more cheaply. This diversity also makes it more attractive to investors.

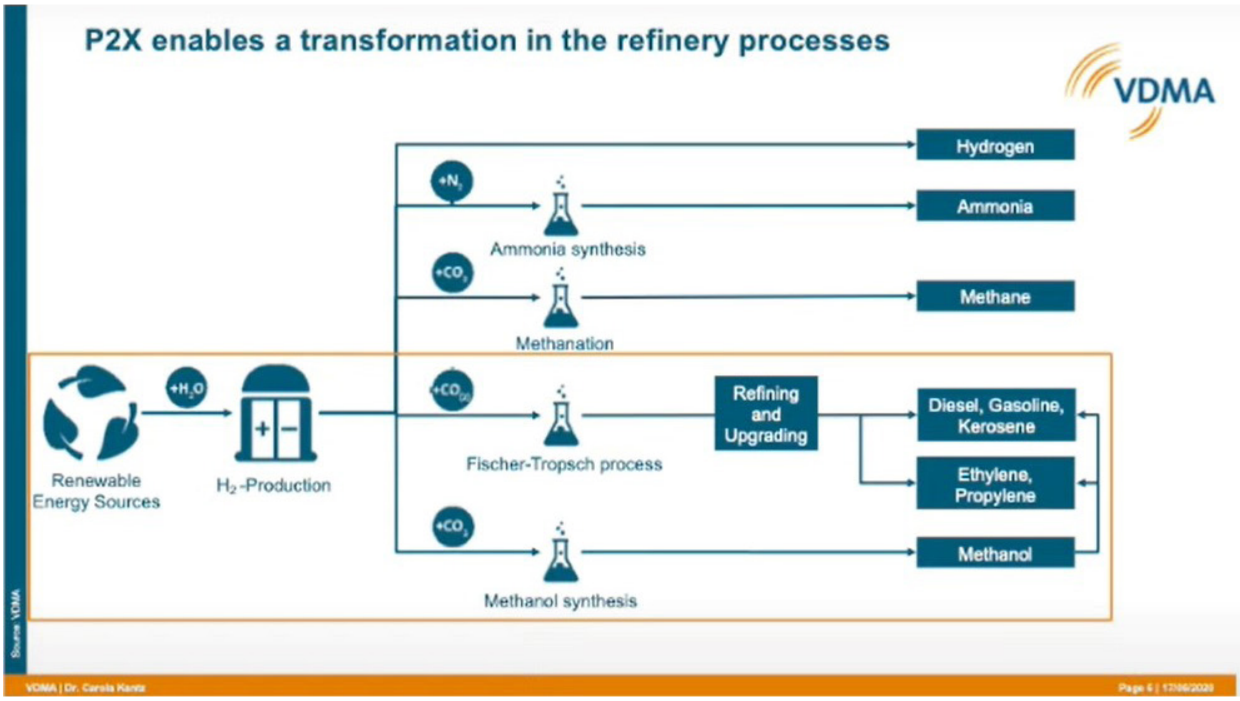


Figure 5: Land and water usage of PTL and biofuels

Despite concerns about the technological readiness of PtL, it has been demonstrated by breaking down the process into different pathways, that there is a high degree of readiness on the constituent parts as well as for the interfaces between those parts.

The biggest barrier is that to do this at an affordable cost, there needs to be a business case for manufacturing bigger plants. Therefore, government intervention with mandatory increasing mixing rates is essential.

If we do adopt mandatory mixing rates, what will happen to air fares?

Figure 6 shows how fares under a "business as usual" scenario might decrease (blue line). The orange line shows an e-fuel scenario with 100% mix rates in 2050, subject to any safety issues being resolved. In this scenario, fares stay level and below 2012 levels until 2040 and even start to reduce after 2070. This is the worst-case scenario for e-fuels, because it assumes the cost of producing e-fuels will not go down, which is a pessimistic assumption.

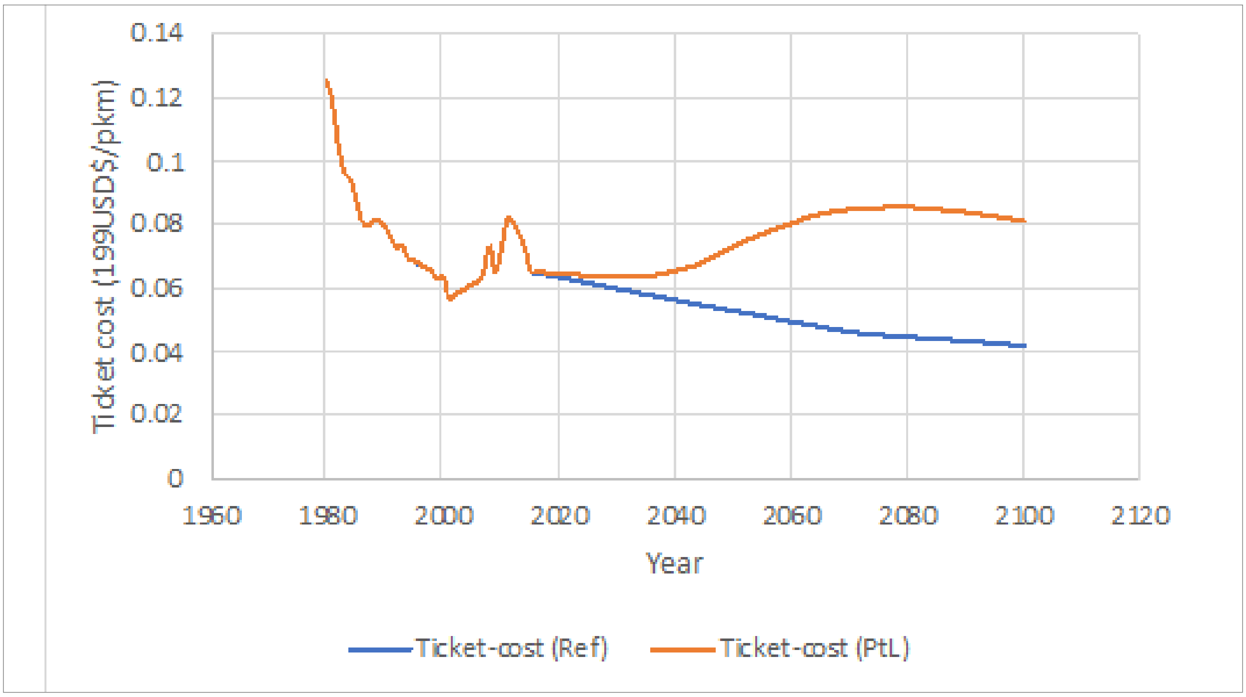


Figure 6: Ticket price development in a PtL world assuming e-fuels will always cost four times as much as fossil fuels.

The world's largest electrolyser is currently a 10MW facility in Fukushima, Japan[34] but the technology is scalable. In Germany, a consortium has got together to build the Westküste100 plant which is a five-year project with a 30MW electrolysis plant but scalable to 700MW. The electricity is generated in an offshore wind farm and CO_2 is provided by a cement factory.

34. https://fuelcellsworks.com/news/worlds-largest-hydrogen-plant-in-fukushima-opens/

The Norsk e-fuel project in Herøya, Norway that will use renewable energy and CO_2 provided through direct air capture to produce syngas.

The project has been set up by a consortium consisting of PtL technology company Sunfire, Climeworks steel company Paul Wurth and green investment company Valinor. The plant is expected to produce 10 million litres of renewable fuel annually by 2023 and 100 million litres by 2026 and the backers believe it will provide enough blended aviation fuel for the top five domestic aviation routes in Norway combined (Oslo-Trondheim, Oslo-Bergen, Oslo-Stavanger, Oslo-Tromso and Oslo-Bodo).[35]

Scaling up these technologies is key but there are significant barriers - the slow pace of increasing capacity, insufficiently high costs of carbon emissions currently ($25 a tonne in the EU ETS) and the relatively low cost of fossil fuels. We also need to be able to make electrolysers more cheaply than we can today.

To make the best efficiencies the large-scale plants that will be required to replace aviation fuel will have to be built close to the best places to generate renewable energy, such as the Middle East, Chile and Africa.

For PtL to be a viable alternative to kerosene, a number of changes will be needed in the market:

- organise the PtL market ramp-up;
- reform the EU Energy Tax Directive to use CO_2 pricing as leverage;
- increase pace of expanding renewable energy capacities in Europe;
- create international PtL markets by creating partnerships with interested countries;
- introduce tradable Guarantees of Origin to account for hydrogen from non-EU countries;
- incentivise carbon capture and use (see appendix 1) to initially fuel PtL and save money;
- introduce a market introduction programme;
- implement direct public procurement policies for PtL.

35. https://www.norsk-e-fuel.com/en/

c. Electric flight

Over the past decade, the number of electric vehicles on the world's roads has risen dramatically. In 2010, there were only about 17 000 electric cars globally. By 2019, this number had jumped to 7.2 million.[36] This will accelerate as many nations have said they will phase out internal combustion vehicles over the next two decades.

Will we see a similar trajectory in aviation?

There are two big differences between aircraft and road vehicles: energy-intensity and weight.

The energy-intensity is the amount of energy on board at the start of a trip. For an aircraft this is easily ten times higher than for a car because the distance the aircraft flies is ten times or more than a car. As a result, amounts of fuel per passenger tend to be an order of magnitude higher than for road vehicles. At the same time weight is a vastly more limiting issue for aircraft than in road transport.

When looking at which aviation fuels are best to use, engineers will typically look at what is known as their energy density. The gravimetric energy density is a measure of how much energy can be stored in a given mass – a vital consideration in an aircraft where minimising mass is important. Also, a fuel with a high volumetric energy density can store more energy in a fixed volume, e.g. a fuel tank, than one with a low volumetric energy density.

36. Global EV Outlook 2020, https://www.iea.org/reports/global-ev-outlook-2020

Figure 7 below compares energy densities for various potential aviation fuels:

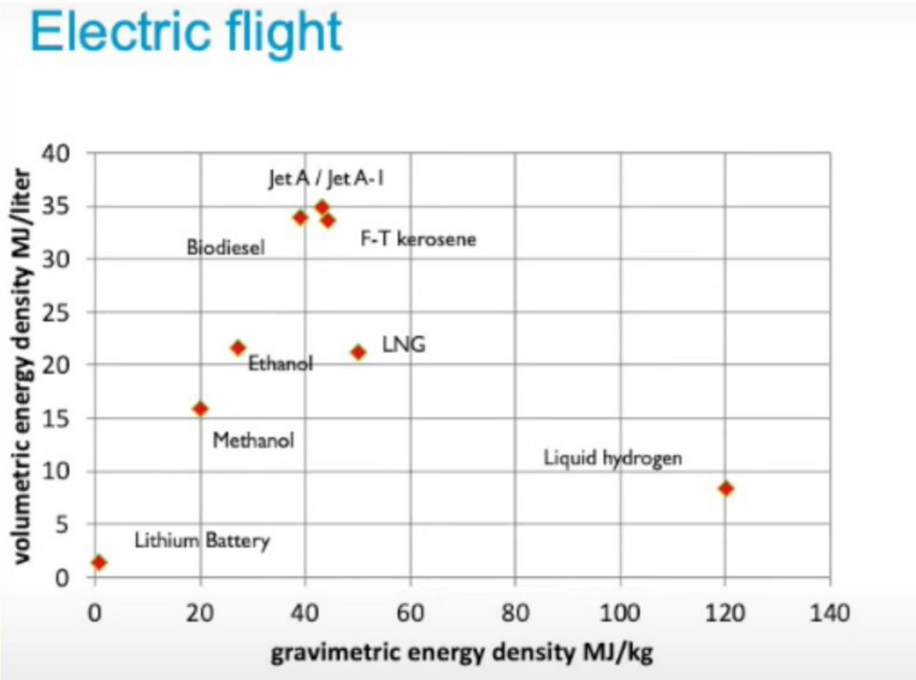


Figure 7:
Energy densities of different jet fuels

Lithium battery technology, at the bottom left of the chart, is currently a poor substitute for kerosene, at the top of the chart. No existing battery technology is available which combines both high gravimetric and volumetric energy density, explaining the lack of dots to the top right, which would present a potentially useful source of power for aircraft. Liquid hydrogen is better than Jet A because of its low weight, but it requires heavy tanks and larger storage volume, a scarce resource in any aircraft.

We could wait for better battery technology to come along but we may be waiting a long time. The energy density of batteries has improved by about 8% per year in the past decade but, for lithium, there is a physical limitation, that, even theoretically, restricts improvements to a maximum of three times the current performance. This is not good enough because aviation needs 15 to 20 times better. Even if you ignore the theoretical limit, then a continued improvement of 8% per year would still only deliver a useful battery after 2050.

Hybrids – using a combination of batteries and SAFs – are not much help. With road transportation, the emissions of hybrid cars are substantially lower than petrol cars.[37] However, most hybrid drivers always drive using the fuel rather than their battery.

The E-Fan X was a hybrid electric aircraft announced by Airbus, Siemens and Rolls-Royce in 2017. It would have been based on a Bae 146 with one of its turbofan engines replaced by a modified Siemens electric motor. It would have integrated a two-tonne battery. The project was cancelled in April 2020[38] in part due to the Covid pandemic and the need to cut costs. The aircraft would have saved less than 10% of carbon emissions and would have lost some space and weight for payload. Commercially, such hybrids are not a very good proposition.

In summary, battery technology is unlikely to be a solution to aviation's wider carbon problem, although it may find applications in air taxis and the lower end of general aviation, i.e. not mass air transport needs.

d. Hydrogen as fuel

A glance at **figure 7** highlights another possibility with a high gravimetric energy density – liquid hydrogen.

Liquid hydrogen can be used directly as a fuel in a gas turbine or other internal combustion engine or in a fuel cell to power electric engines.

Back in 2000, a European consortium of 35 partners led by Airbus Deutschland carried out a two-year analysis into of hydrogen as an aviation fuel. It found that aircraft would require fuel tanks four times larger than those in use at the time, increased energy consumption due to larger planes of between 9% and 14% and increased overall operating costs of 4% to 5%.[39] It was anticipated that the technical challenges presented by using hydrogen – not least the production of the industrial quantities of liquid hydrogen required – would take up to 15 years. In the event, this has not happened.

What has achieved more traction is the use of hydrogen in fuel cells.

37. https://www.fleetnews.co.uk/news/environment/2019/06/14/hybrids-offer-fastest-route-to-reduce-co2-says-emissions-analytics

38. https://www.airbus.com/newsroom/stories/our-decarbonisation-journey-continues.html

39. https://www.flightglobal.com/airbus-dusts-off-cryoplane-studies/76802.article

Fuel cells have been around for more than two centuries but potentially offer one route to reduce carbon emissions in aviation.

In a fuel cell, hydrogen and oxygen are combined in such a way that protons pass through a membrane which creates an electric current at an efficiency of 50-60%. The only emission is water vapour. Water vapour potentially can cause climate changing contrails at high altitudes, but electric aircraft will normally fly somewhat lower and if the water is released as water, the chances of contrails developing can be minimised.

In an aeroplane, the oxygen would be extracted from air in front of the wings while the hydrogen is stored as a liquid in fuel tanks; in many designs these tanks would be inside the aircraft's fuselage, rather than the wings as is usual in current jets. However, to make this type of aircraft larger and most efficient, the design of planes needs to be very different from conventional planes – the fuselage has to become a bit longer than usual and we may need to rethink where we put the engines, as shown in **figure 8**. By having the propellers close to the aircraft, it takes in slower moving air improving the aerodynamic drag properties of the aircraft.

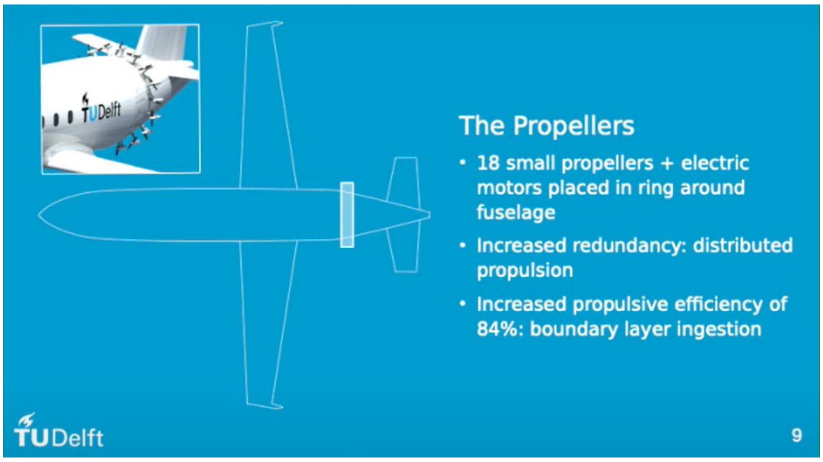


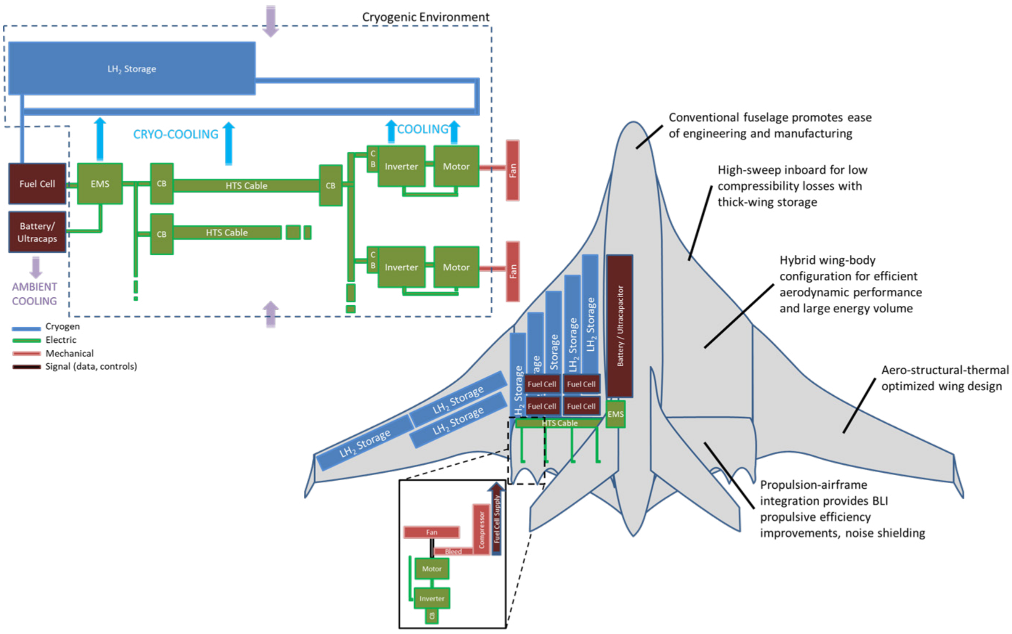
Figure 8:
New aircraft designs?

Yet this design only has 19 seats and to make a real impact on carbon emissions you need to match the number of seats in an aircraft like the Airbus A320 or Boeing 737 – 150 passengers at least.

Conceptual design studies on larger aircraft were presented in the 2000s.[40] Though they concluded that engine weights were far too high to allow for an efficient airliner, Electric engines have since improved very significantly thanks to the development of general aviation electric aircraft like Pipistrel. Also, Australia's MagniX now a low-weight, high power engine that has been used in several test flights in different aircraft.[41]

For a larger electric-powered aircraft, the range will have to be reduced because at some point the hydrogen tank will become too large. The speed of the aircraft will also need to be reduced. Some, including teams at TUDelft and NASA have looked at what such aircraft might need to look like.

Figure 9:
NASA's Cheeta concept



40. See for instance Peeters, P. M. (2000). *Annex I: Designing aircraft for low emissions. Technical basis for the ESCAPE project.* (00.4404.17). Delft and Snyder, C. A., Berton, J. J., Brown, G. V., Dolce, J. L., Dravid, N. V., Eichenberg, D. J., . . . Kundu, K. P. (2009). Propulsion Investigation for Zero and Near-Zero Emissions Aircraft. *NASA TM-215487.38*.

41. https://www.magnix.aero/

NASA's Cheeta - Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft – is a three-year US$6 million project with the Grainger College of Engineering.[42] The concept (shown in **figure 9**) would use cryogenic liquid hydrogen as an energy storage method and is intended to provide opportunities to use superconducting, or lossless, energy transmission and high-power motor systems to improve efficiency. Such an aircraft might cover short and medium ranges.

What about longer-range aircraft powered by hydrogen?

Research by Dr Pericles Pelidis at Cranfield shows what a long-range hydrogen aircraft might look like. They have taken a large two-decker and four engine aircraft like the A380 as the basis for their LH2 aircraft which comes in three varieties – medium, long and extended range.

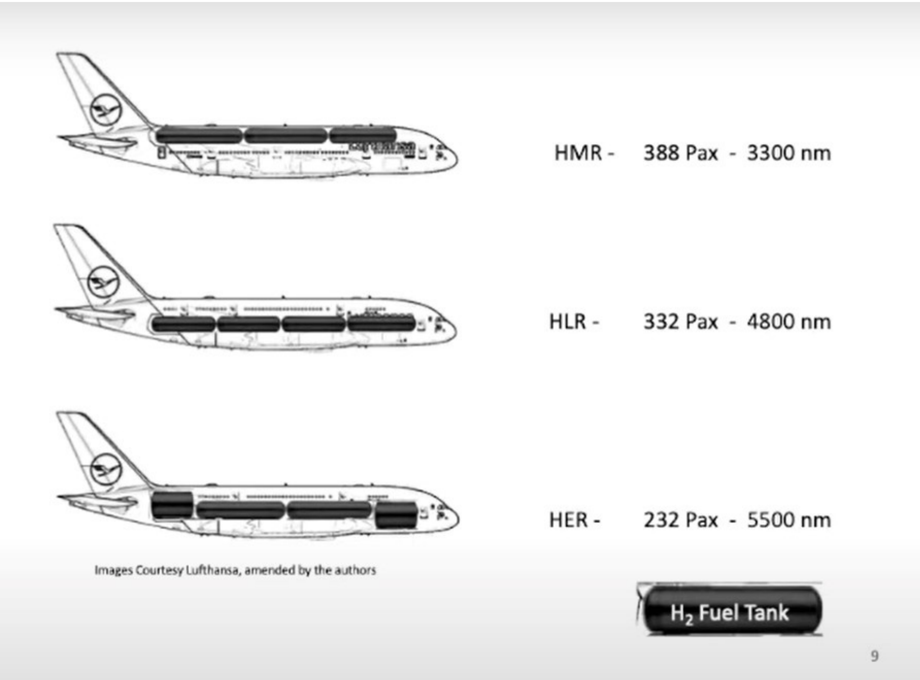


Figure 10:
What a hydrogen-powered long range aircraft might look like

42. https://grainger.illinois.edu/news/30918

The LH2 would have a gravimetric efficiency of 45%, means that for every kilo of hydrogen fuel it carries there would be 1.2 kilos of fuel tank to carry.

The LH2 would have a lower range than the A380 – 5,600nm for the extended range version compared with 8,000nm for the A380-800 – and carry considerably fewer passengers – 232 against 555.

There are few technical barriers to making an aircraft such as the LH2 happen but it will take commitment and, huge investment to get there, taking perhaps 15 years and tens of billions of dollars of research and development until a passenger version is in service.

Real-world progress with fuel cells is has been many times faster than those of battery-electric aircraft. Where for the latter it took some 15 years before a two-seater aircraft was able to cross the English channel, ZeroAvia managed to have a six-seater aircraft in the air within a matter of four years. ZeroAvia[43] is a US/UK company, dedicated to develop fuel cell aircraft. They are currently successfully test-flying two modified Piper M-class six-seat planes at Cranfield in the UK.[44]

In order for the use of hydrogen fuel cells to succeed, aircraft manufacturers need to play their role and start new aircraft programmes.

It is worth noting that when fuel cells or hydrogen long-range aircraft do come onto the market, perhaps by 2070, these aircraft will have a limited maximum range of say 8,000 kilometres. For the 1% of flights that are longer than this, travellers will need split flights into two. However, 99% of flights will be unaffected.

Changing how we fly

There is not one fuel technology that will be a panacea for the aviation industry; we need a range of different technologies and strategies to decarbonise aviation. We need to look beyond sources of fuel but also at how we fly.

43. https://www.zeroavia.com/

44. https://www.nacleanenergy.com/articles/39133/zeroavia-completes-world-first-hydrogen-electric-passenger-plane-flight

a. The contrail problem

As well as aviation's carbon problem, it also has problems associated with other effects – emissions of nitrous greenhouse gases, the creation of soot particles, and water vapour which can lead to the formation of contrails and increased cloud cover which can lead to increasing temperatures through radiative forcing.

The climate impact in terms of radiative forcing of these clouds and contrails is significant, comparable to or even greater than aviation's carbon dioxide emissions.

However, not all contrails are equal and not every flight will form a contrail – they depend on aircraft emissions, meteorological conditions, time of day and season, and the reflectivity of the earth's surface (albedo).

Already, research has shown that a 50/50% blend of aviation fuel with HEFA can reduce the number of soot particles emitted by 50 to 70%.[45] This is important because the soot particles act as so-called nucleation sites on which ice particles can form. It is expected this will also reduce contrails and contrail-induced cirrus clouds.

As well as reducing contrails by the fuel mix, there are other mitigation strategies available.

Research from Imperial College London published in February 2020[46] showed that the amount of contrails could be reduced by making small changes in flight altitude. The research looked at flights over Japan and took into consideration fuel consumption, emissions, meteorology and radiation.

The results showed that over the six weeks of study, 17.8% of flights formed contrails and these lasted on average 3.24 hours. The energy forcing due to the contrails was significant – 1.6 times that of the CO_2 produced by the flight. The results also showed that there is a diurnal pattern with greater warming at night because in daytime, the contrails reflect some sunshine into space.

45. Burkhardt, U., Bock, L. & Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Clim Atmos Sci 1*, 37 (2018). https://doi.org/10.1038/s41612-018-0046-4

46. Roger Teoh, Ulrich Schumann, Arnab Majumdar, Marc E. J. Stettler. Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. Environmental Science & Technology, 2020; DOI: 10.1021/acs.est.9b05608

That said, there are very different timespans for the effects of contrails compared to CO_2: the former may last for up to a day but once it dissipates its effect is essentially zero while the effects of carbon dioxide lasts hundreds of years.

What the research showed was that just 2% of flights contributed to 80% of the warming effect associated with contrails which says that diverting all flights to avoid contrails is unnecessary.

The parts of the atmosphere in which contrails form are very thin and by changing flight levels by just 2,000 feet you can avoid the regions where contrails are formed and make significant reductions in contrail forcing. If we diverted 1.7% of flights in this region, we would have reduced energy forcing by about 60%.

Other studies have shown an increase in CO_2 involved with changing flight paths but since the Imperial research involved changing altitude by a small amount and for a small number flights, the effect on CO_2 is small, just +0.27% for each diverted flight. Using zero-emissions e-fuel, the adjusted flight path could be optimised to almost entirely avoid contrails, without any CO_2 penalty.

E-fuels cannot eliminate the effects of contrails but may reduce those effects by 50% or more. Fuel-cell powered aircraft may even remove these effects completely. Continuing to use fossil fuels adds a carbon penalty because flying at non-optimal altitudes and routes increases fuel consumption by a couple of percent.

b. A return to hub and spoke

The hub and spoke system, where airlines have established centralised airport bases (hubs) and routes to and from origins and destinations (spokes) from those hubs grew from a realisation that airlines could achieve higher frequencies and load factors. This led to the growth of airports like Heathrow (as a hub for British Airways), Schiphol (KLM) and Changi (Singapore Airlines).In recent years, the evolution of long-range, narrow-bodied jets has seen a trend back towards direct services. Yet hubs have not disappeared. Instead, they have shifted from Europe and Asia to the Middle East and Africa: Dubai (Emirates), Abu Dhabi (Etihad), Qatar (Qatar Airways),Istanbul (Turkish Airlines) and Addis Ababa (Ethopian).

Some have suggested an adoption of a modified hub-and-spoke approach to decarbonise aviation – using electrically powered aircraft on shorter, spoke routes and e-fuels or hydrogen on the longer routes that connect hubs.

Box: Clean Aviation

A programme called Clean Aviation (www.clean-aviation.eu) will be the backbone of the European research and innovation agenda in aviation over the coming years. The initiative, part of the Horizon Europe framework, follows on from CleanSky and CleanSky2 initiatives.

At the time of the WTM symposium, the research agenda for Clean Aviation was still open for comment and was then passed to the commission for potential approval.

What is clear is that Clean Aviation will need to achieve the following:

- Exceptional research and technology effort to reduce energy needs and fuel consumption, while ensuring safety and competitiveness. Even if net zero then we need to be efficient in the production of fuels;
- Fast tracked R&D and deployment of sustainable aviation fuels by relevant actors for wide scale and economy viable within the next decade;
- Optimised green air operations and networks to fully exploit new aircraft and systems capability;
- A suitable global aviation regulatory framework.

The Clean Aviation trajectory defines two clear horizons:

- 2035: low emissions aircraft exploiting research results making accelerated use of sustainable fuels and optimised green operations;
- 2050: climate neutral aviation by exploiting future mature technologies coupled with full deployment of sustainable aviation fuels.

For Clean Aviation to have real impact, it needs to satisfy each of the following conditions:

- Strong pro-active EU support on global regulation standards and certification of products;
- Close alignment with EU policy, enabling a faster market uptake of green aircraft;
- Decisive and rapid acceleration in the production and deployment of sustainable aviation fuels under favourable economic conditions for all operators.

The investment scenario

The total capital invested in the aviation industry is more than US$5 trillion – some 1.5% of global wealth. By comparison the top US oil and gas companies represent less than $1 trillion and are most attractive to value investors while Microsoft on its own is worth more than $1 trillion.

The Covid crisis is having a severe impact on the aviation sector's finances. Airlines debt is forecast to increase by US$120 billion while Boeing's debt is set to increase by US$25 billion, according to Gerard Rijk, equity and financial analyst at Profundo.

However, as a result of Covid, the aviation industry will receive tens of billions of US dollars thanks to quantitative easing, government loans and guarantees. These investments will have attached conditions and make force airlines to make changes in strategy, particularly in relation to sustainability. Of all of the money provide by governments and central banks, the industry is likely to receive 2 to 5% of all of the support on offer.

There appears significant appetite for airline bailouts, €33 billion in the EU alone,[47] despite a survey for the Oxford Smith School of Enterprise and the Environment found that airline bailouts were the least effective economic stimulus measure based on speed of implementation, economic multiplier, climate impact potential, and overall desirability among 231 central bank officials, finance ministry officials and other economic experts in G20 countries.[48]

47. https://www.transportenvironment.org/what-we-do/flying-and-climate-change/bailout-tracker

48. https://www.smithschool.ox.ac.uk/publications/wpapers/workingpaper20-02.pdf

The environmental focus on the aviation sector is likely to increase dramatically after the pandemic is over, particularly as questions over climate, zoonotic diseases and inequality are raised and NGOs become more vocal.

There are also risks for investors if no action is taken on the climate:

- capital for the aviation sector will become more expensive;
- stranded assets if there is a structural reduction in the availability of slots;
- hikes in VAT and excise tax on kerosene;
- financing risk – higher spreads on loans and bonds;
- reputation risk – people want to work in a green industry.

Thanks to the focus on the environment before an during Covid, there is likely to be an increasing number of green and climate bonds and impact investors will follow sustainable development goals.

Technology investors are going to be interested in hydrogen and other green energy. However there will not be much interest from private equity, which is most interested in positive cash flows. There will also be the role of private wealth from the likes of Elon Musk and Jeff Bezos in the sector.

The EU's Green Deal will also see more money enter the sector.

How much can we reduce carbon emissions?

It is clear that we need to adopt a portfolio of solutions to beat aviation's carbon problem. There will of course be technological innovation in the decades to come but these, on their own, are unlikely to achieve complete decarbonisation.

Dr Paul Peeters' Global Tourism and Transport Model ($GTTM^{dyn}$) is a system dynamics model that describes the global aircraft fleet, global travel demand, economic and demographic development, technological development as a function of fuel cost, regulation and taxes.

It contains many feedback loops and a travel behaviour model based on psychological economics. It is not a simple extrapolation of the past but answers what-if questions and provides insights into long-term scenarios based on assumptions about certain technologies applied or measures taken. It also is able to show the long lead-times involved in radical changes. Even if an all-electric fuel cell airliner makes its maiden flight tomorrow, the current fleet would take decades to be replaced with such aircraft. So, time is a major issue and this is not a luxury the world can afford to avoid the worst of climate change.

The figure below shows the effect of the main measures discussed in this white paper: scenarios for introducing mandated mixes of e-fuels and, later, a fleet of hydrogen fuel cell electric aircraft. **Figure 11** shows the red business-as-usual scenario and the two grey Paris Agreement goals.

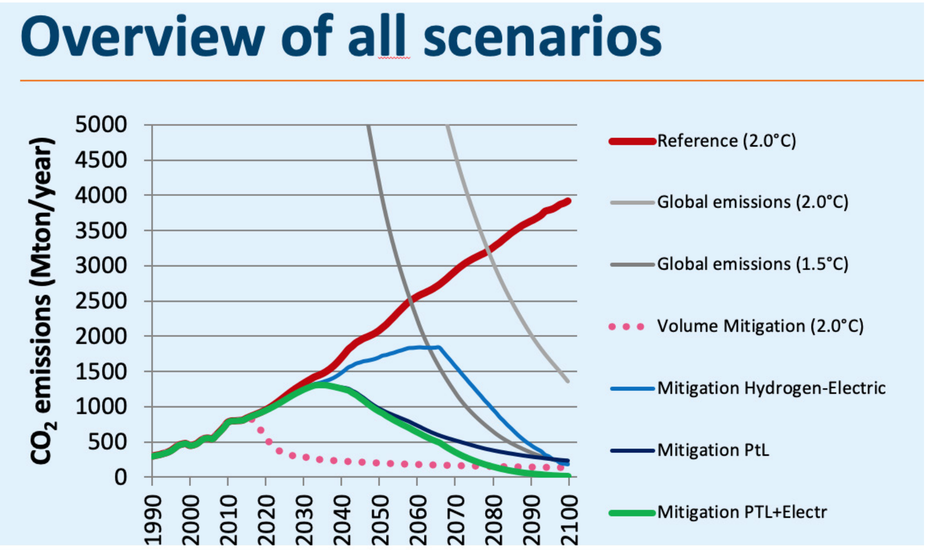


Figure 11: How can these measures achieve net zero for aviation?

When the aviation sector fails to massively adopt e-fuels and develop hydrogen, fuel cell and electric propulsion technology for the long term, a volume reduction (Volume mitigation) is the only way to 'save Paris'. Of course, this has big repercussions for parts of the tourism and travel sector.

Focusing only on completely new aircraft concepts like electric, hydrogen and technology (Mitigation Hydrogen-Electric) does eventually reduce the emissions to almost zero. However, these reductions would only start after a long delay because of the long lead time to develop such aircraft and to replace the whole global fleet of more than 25,000 aircraft. Therefore, the quick response should be to apply e-fuels (Mitigation PtL); however, emissions do not reach zero under that scenario. The combined scenario (Mitigation PtL+Electric), combines hydrogen, fuel cells and electric engines, provides a reasonable pathway to zero emissions.

A carbon tax on its own will not be sufficient on its own to cut emissions to the Paris levels. At the time of publication, the EU's Emissions Trading Scheme was running at $25 a tonne of carbon. Dr Peeters says that even with a carbon tax of $1,000 a tonne or air ticket taxes of 200% you would not get emissions down to sustainable levels.

If we stick to business as usual, Dr Peeters believes there will be a strong reduction in aviation volume (Volume Mitigation). This will not kill tourism because the revenue shifts to other modes of transport, such as rail and road and to somewhat longer stays and higher spending on accommodation. Another interesting point is that only some 22% of all trips are by air and would potentially be affected in such a scenario, while the other 78% can remain as they are and reduce emissions as agreed in Paris and developed through the national climate plans based on the NDCs.

Conclusion

Aviation clearly has a problem when it comes to carbon and despite the current blip in travel caused by Covid, there is little reason to believe that the desire to travel will not return once a vaccine is discovered or we learn to live with Covid's social distancing requirements. However, it is likely that demand for travel will be less than before the pandemic.

As those involved in the WTM symposium and in producing this white paper have said, a combination of several key technologies and measures can pave the way to the decarbonisation of aviation.

wtm responsible tourism
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As we have demonstrated in this white paper, the aviation sector will need to focus on e-fuels, not biofuels, and on hydrogen fuel cells, not batteries. These two combined can provide zero emissions within this century. However, this blended scenario will only become reality with e-fuel mandates, supported by taxes and subsidies, a sector-wide acceptance to pay the cost, and plenty of political determination.

The tourism sector calls on everyone with an interest in travel and tourism – governments, international organisations, airlines, aircraft manufacturers, airports, alternative fuel producers, academics and travellers themselves – to do their part. Without it, we may be forced into unsavoury choices on who is allowed to fly.

Tourism is at an important crossroads and a choice on direction must now be made. Leaving the decision for only a few more years will make the solutions far more radical and undesirable.

What can be done now to make decarbonising aviation a reality?

- Tour operators and destinations must insist that airlines adopt e-fuel mixtures and accept the higher cost for tickets associated with e-fuel use;
- Governments and international bodies must legislate for e-fuel mixtures;
- Airlines to make greater use of drop-in e-fuels, at least for the short- to mid-term, and explore other sustainable fuel options such as hydrogen for the longer term;
- Aircraft manufacturers must invest more in the development of zero-emission aircraft and speed up the pace of fleet replacement;
- Governments to withdraw support for the development of existing aircraft technology in favour of e-fuels and hydrogen fuel cells;
- International commitments to adopt carbon-friendly flight procedures, such as Single European Sky and avoiding parts of the atmosphere where contrails develop;
- More offsetting, using approved schemes, in the short term;
- Travellers must vote with their feet, forcing airlines to make the changes or switching to other modes of transport.

It is clearly time for the travel industry to address its carbon problem - there is a lot of denial but there is no alternative. We need to invest in it now if we are to have a viable travel industry going forward.

Appendix 1 - Carbon capture and storage

Carbon capture and storage (CCS) is the collection of carbon dioxide during electricity generation and other industrial processes and its storage underground in depleted oil and gas field or deep saline aquifer formations.

Carbon dioxide can be captured during industrial processes by a number of methods, including absorption of flue gas into a liquid such as monoethanolamine, separation through polymer membranes and cryogenic distillation.

According to the IEA,[49] there are only two large-scale CCS power projects currently in operation with a combined capture capacity of 2.4 megatons of CO_2 per year although this is way below what is expected to be needed to reach the IEA's 2030 sustainable development scenario of 310 $MtCO_2$ per year. In 2018, five new CCUS-equipped power plants were announced, bringing the total to 14 power plants in development globally. However, the Covid pandemic has put the brakes on this development.

A related concept is direct air capture where rather than capturing CO_2 at the point it is produced in an industrial process, it is extracted from atmospheric air.

Some argue that it is more cost effective to pursue CCS than synthetic fuels. In some locations around the world, there are cheap options for CCS but the decades of monitoring costs to ensure that carbon does not escape into the atmosphere are not factored into those costs. Building up the infrastructure to support CCS is also an expensive job.

There is also leakage to consider. Even small amounts of leakage can lead to all of the carbon dioxide escaping over long-term timescales.

49. https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage

CCU (carbon capture and utilisation) is a variant of this idea where the captured CO_2 is not stored but rather used to produce new products which sequester the CO_2 to prevent its release into the atmosphere. In some cases, CCU is also used to produce synthetic fuels. In this case, the carbon is released into the atmosphere which sounds counter-intuitive, but it is not so as long as it is temporary and does not hamper the reduction pathway of the industry delivering the CO_2 from its chimneys.

At California's Moss Landing power plant, 90% of the carbon dioxide is collected by 2006 start-up Blue Planet and combined with minerals to produce limestone which can then be used to produce cement or build roads, cutting the emissions that those industries make. Other projects seek to use carbon dioxide to produce textiles, plastics and other building materials.

With many of the solutions to the carbon crisis involving blending jet fuel with more expensive sustainable aviation fuels, there needs to be a global mandateotherwise you get distortions in the market. However, being a global body means that it sometimes takes longer to achieve consensus.