Aviation and climate change: becoming a climate-neutral industry

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INTRODUCTION AND BACKGROUND

In 2019, the aviation industry contributed 2.1% of all human-induced carbon dioxide emissions and approximately 12% of all carbon emissions from the transport sector (ATAG, 2020). As the aviation industry begins its recovery in the post-pandemic world, it's contribution to carbon emissions and climate change will increase relative to other transport modes. This is in part, due to the rapid expansion of aviation expected in the post-pandemic period which will see more passenger carriage and aircraft operations. It is also due to higher power and energy requirements of aircraft operations which makes it difficult to transition to alternative energy sources that are able to deliver the payload and range performance achievable with existing fossil fuel sources. At the same time, the rapid electrification of surface transport modes such as cars and heavy goods vehicles reduces their contribution to climate change, resulting in a proportional increase in the climate impact of aviation. However, the aviation industry has had a successful history of developing new technologies and operational practices to drive efficiency and reduce environmental impact. During periods of high fossil-fuel prices, airlines have placed greater emphasis on introducing technology and developing practices to reduce fuel burn, helping to reduce operational cost and emissions. According to Schafer and Waitz (2014), aircraft fuel burn reduced by 70% between 1960 and 2000.

Although improvements to aircraft, engines and operational procedures have enabled aviation to become relatively more efficient and environmentally friendly, the continued rate of development is unlikely to fast enough to meet decarbonisation targets. Instead, alternative fuel and energy sources provides the best hope for radical improvements. The most promising of these technologies is electric-battery aircraft and hydrogen-powered aircraft. However, these sources have their own challenges particularly in terms of airport infrastructure developments and logistics to accommodate new aircraft.

From a commercial perspective, there are also pressures for the industry to become greener. In the last decade, investors and shareholders have been demanding more sustainable practices by airlines and airports, and passengers are becoming more environmentally conscious when travelling. In some countries, there has been evidence of declining air travel demand. In the first three quarters of 2019 average monthly demand for domestic air travel in Sweden fell by 8.7% compared to 2018 (Gossling et al. 2020).

Aviation's contribution to climate change is not just limited to carbon dioxide emissions. Aircraft engines also emit oxides of nitrogen (NO_x) which have a net warming impact, in the short-term, due to the formation of atmospheric ozone (Lee, 2018). In addition, water vapour and soot emissions from engines may form condensation trails (contrails) depending on atmospheric conditions. These line-shaped clouds reflect incoming solar radiation (cooling effect) but also trap outgoing radiation (warming effect). The net effect is that of warming and contributes to climate change; an effect which is further enhanced if contrails evolve into long-lasting cirrus clouds.

Furthermore, the period of aviation's growth and expansion over the last half century has coincided with a period of rapid climate change with average surface temperatures increasing by 0.2ºC per decade (Allen et al. 2018). The associated extreme weather events, sea-level rises and changes to other weather phenomenon has and will continue to impact aviation operations. For example, coastal airports may need to build sea defences and airlines may need to plan for more frequent and severe in-flight turbulence. Therefore, not only does aviation impact to climate change, but a changing climate also impacts the aviation industry. Thus, climate change is a significant component for the operational and commercial sustainability of the industry.

The objectives of this chapter are to:

- Explain how the aviation industry contributes to climate change through carbon and non-carbon emissions.
- Explore the efforts to reduce and mitigate climate impacts by various aviation stakeholders including aerospace manufacturers, airlines and airports.

- Assess the impact of climate change on aviation in terms of aircraft operations and passenger demand and commercial impact.
- To explore the development of a range of alternative fuel and energy sources which have the potential to accelerate decarbonisation and enable to the industry to become climate-neutral.

CLIMATE CHANGE

The issue of climate change is receiving more and more attention in society. It's impact is widespread affecting almost every part of the globe. In almost every human activity there is a climate footprint and therefore the work of all industries and their organisations is becoming more scrutinised. The aviation industry has developed a reputation of being amongst the most contributing to climate change, despite the evidence suggesting that the contribution is small in relation to total human-induced greenhouse-gas emissions.

Climate change is not a newly discovered environmental issue. At the end of the 19th Century, the Swedish Chemist and Nobel laureate, Svante Arrhenius suggested that higher concentrations of carbon dioxide (CO_2) in the atmosphere would result in warmer atmospheric temperatures (Arrhenius, 1896). It is worth noting that changes to the Earth's climate due to natural causes such as volcanic eruptions and changes in ocean circulation patterns have been occurring for millions of years. However, significant changes to global climate due to human activity has only occurred since the start of the industrial revolution. The United Nations, Framework Convention on Climate Change considers the role of human activity in their definition of Climate Change as follows:

"a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." (UN,1992)

Human activity causes the release of greenhouse gas emissions, which trap heat from solar energy and have a warming impact on the atmosphere. The primary source of emissions has been the burning of fossil-fuels such as oil and gas. The main greenhouse gases include carbon dioxide, methane, nitrous oxides, fluorinated gases and water vapour. Not all gases are the same and their warming potential, concentration and lifetime in the atmosphere vary. For example, compared to carbon dioxide, methane has a greater ability to trap heat but it's lifetime in the atmosphere is approximately 10-12 years, whereas the lifetime of carbon dioxide is of the order of tens of thousands of years. Over a 100-year period, methane has a global warming potential approximately 25 times greater than carbon dioxide. However, the rate of release and the long lifetime of carbon dioxide has meant that it has become the main focus of attention in the effort to reduce greenhouse gas emissions.

Probably the most accurate record of recent carbon dioxide concentrations in the atmosphere are those from the Mauna Loa Observatory in Hawaii where daily continuous measurements have been taken since 1958. Figure 1 shows the measured data with a steady increase of CO_2 concentrations from 313 parts per million in 1958, passing 400 parts per million in 2013 to the current level of 420 parts per million more recently.

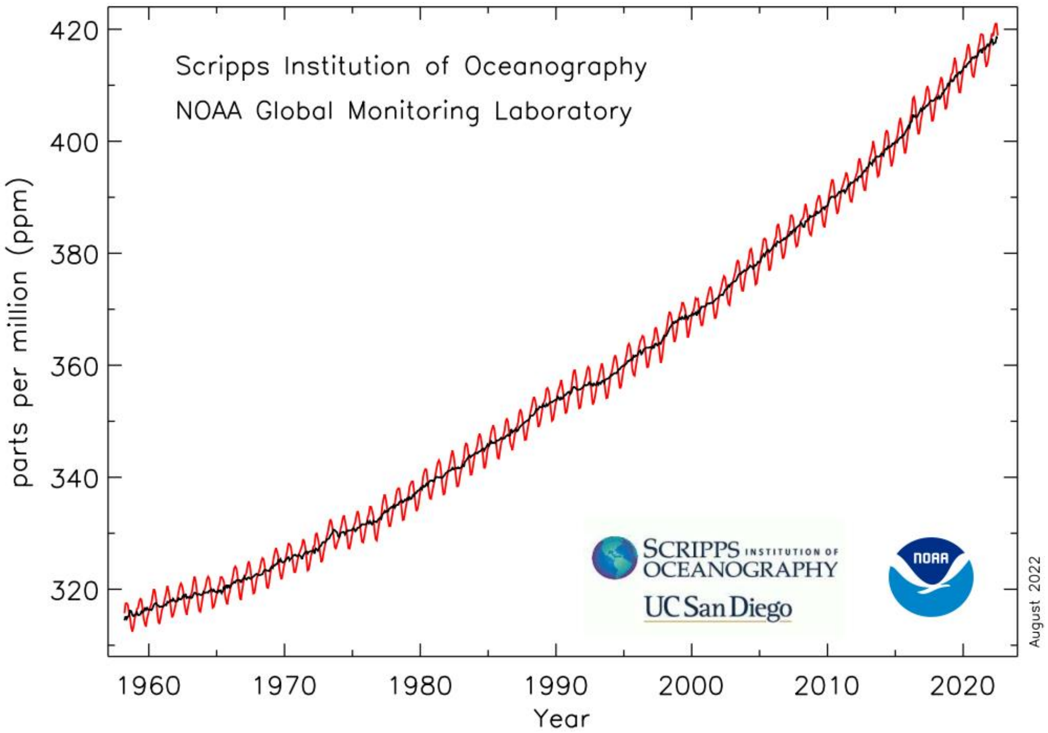

Figure 1. Carbon dioxide measurements since 1958 taken from the Mauna Loa Observatory in Hawaii, US.

[Source: Global Monitoring Laboratory – Earth System Research Laboratories, National Oceanic and Atmospheric Administration, United States Department of Commerce, https://gml.noaa.gov/ccgg/trends/]

Figure 2 shows the correlation between CO_2 concentrations (measured from ice core samples) and atmospheric temperature over the last 400,000 years. The fluctuations align almost perfectly and indicate the sensitivity of the Earth's climate system to atmospheric composition. If the current trend in CO_2 concentrations continue the average global surface temperature will be 1.5ºC warmer than pre-industrial times by 2035 and 2-3ºC warmer by 2100 (IPCC, 2021).

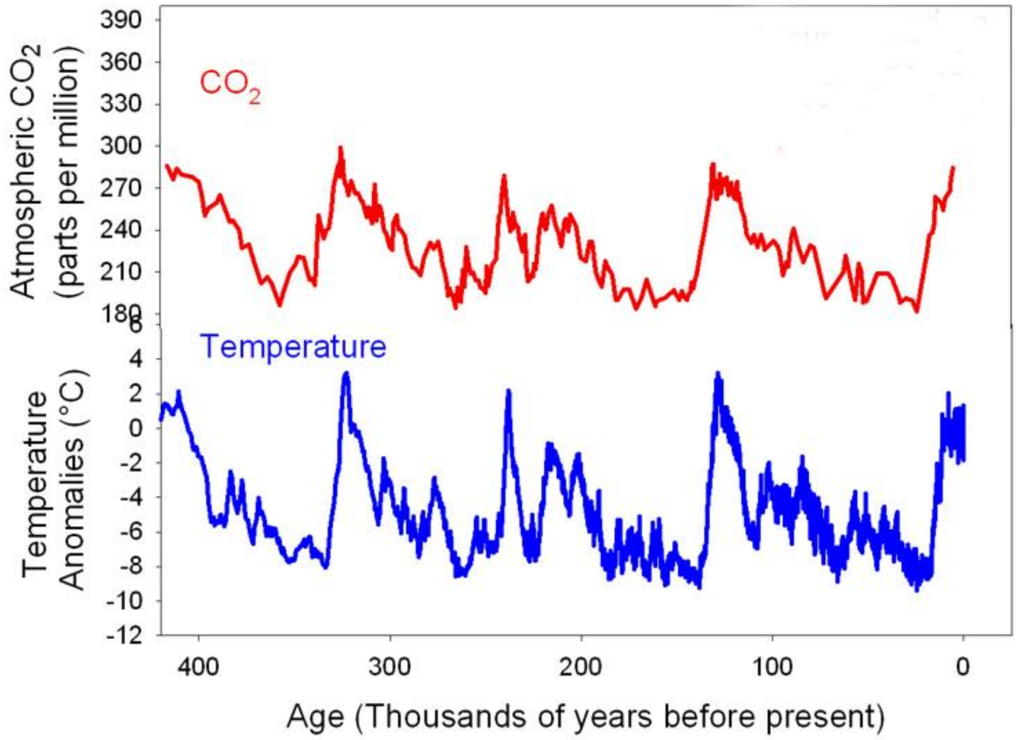

Figure 2. Correlation between atmospheric carbon dioxide concentration and temperature
Source: Petit et al. (1999)

AVIATION CARBON EMISSIONS

Aviation's contribution to climate change is primarily from the release of carbon dioxide emissions from a variety of sources. These can be broadly described as being direct and indirect sources. Direct sources include the combustion of jet fuel in aircraft engines, emissions associated with the production and assembly of aircraft and the emissions associated with airport operations including terminal buildings and cargo facilities. Indirect emissions include for example, the transport of passengers travelling to and from the airport, the construction of infrastructure and the broader supply chain that serves the industry.

Direct aircraft emissions are primarily from the main engines and the auxiliary power unit (APU) located towards the rear of the aircraft which supplies electrical power during ground operations. There is a linear correlation between engine thrust and fuel consumption and between fuel consumption and carbon dioxide emissions. The most energy intensive phase of operation is during take-off and initial climb when engine thrust is approximately 75-100% of maximum thrust. During the take-off run, fuel burn can vary depending on aircraft and engine type, weight, meteorological conditions, airport elevation and engine thrust settings. Fuel burn values have been observed to vary between 39kg for an Airbus A321 aircraft to 102kg for a Boeing 747-400 aircraft at full thrust (Koudis et al. 2017). This phase of flight is relatively short compared to the cruise phase where engine thrust is typically 35-50% of maximum thrust. A typical narrow-body aircraft engine operating in the cruise will burn 2,700kg of jet fuel per hour. Every kilogram of jet fuel burned releases 3.16 kilograms of carbon dioxide, resulting in 8,500 kilograms of carbon dioxide per hour. There are also other greenhouse gas emissions including 3,300kg of water vapour, 30kg of nitrogen oxides, 2.5kg of sulphur dioxide as well as carbon monoxide, hydrocarbons and particulate matter (EASA, 2019). The descent, approach and landing phases of flight are relatively less energy intense and fuel burn for most flights is between 1-7% of the total. Table 1 shows the percentage of fuel burn by flight phase for a range of routes from London. The longer the flight distance, the larger the proportion of fuel burn in the cruise phase. For shorter flights, fuel burn at the airport during taxi-in and taxi-out could be as much as 16% and possibly more at congested airports where taxi-times are longer.

Route	Aircraft Type	Taxi-Out	Take-Off	Climb	Cruise	Approach	Taxi-In
London to Dubai	**A380**	1.8	0.6	1.5	94.5	1.0	0.6
London to Hong Kong	**A350**	1.1	0.4	1.1	96.3	0.7	0.4
London to New York	**B777**	1.7	0.6	1.4	94.6	0.8	0.9
London to Athens	**A320**	3.6	1.2	3.1	89.0	2.0	1.2
London to Helsinki	**A321**	3.7	1.6	3.9	87.3	2.4	1.1
London to Madrid	**A320**	6.0	1.9	4.8	82.5	3.1	1.8
London to Lisbon	**A320neo**	3.6	1.7	4.4	86.4	2.7	1.2
London to Geneva	**A320**	8.5	2.8	7.3	75.4	4.7	1.5
London to Edinburgh	**A319**	11.4	3.5	8.9	68.1	5.8	2.3
London to Paris	**A319**	11.2	4.0	10.3	62.3	6.7	5.5
Average		**5.3**	**1.8**	**4.7**	**83.6**	**3.0**	**1.6**

Table 1. Fuel burn percentage by phase of flight for various routes and aircraft type
Source: Robertson (2022)

In absolute terms, the energy requirements of aircraft operations are such that a single-aisle aircraft operating a one-way short-haul trip between Paris, in France and Madrid, in Spain would generate the same total carbon dioxide emissions generated by 3 people in a whole year. Similarly, a single 13-hour flight operating from Paris to Singapore would generate the same levels of carbon dioxide emissions as one person would in their entire life.

In-flight fuel burn is heavily dependent on aircraft weight. In the cruise phase, heavier aircraft require more lift generation. The two main mechanisms for generating lift are to increase the aircraft speed or increase the flight angle of the aircraft. Both mechanisms increase the drag force which would slow the aircraft down. To maintain constant speed, the engines need to generate more thrust by increasing the fuel flow rate, thereby causing more emissions. To fly the same distance, the higher fuel flow rate for heavier aircraft means that more fuel needs to be carried which in turn increases the weight of the aircraft. Later in the chapter, the efforts of aircraft designers and airlines to reduce weight is discussed.

The main aircraft emissions at the airport occur during the taxiing phase and the turnaround process. During taxi, the aircraft engines are close to idle during which thrust is approximately 7% of maximum. An Airbus A320 aircraft taxiing with both engines at idle for 10 minutes typically burns 140kg of fuel and emits 450kg of carbon dioxide. In comparison, the four-engine Airbus A380 burns 630kg of fuel and releases nearly 2000kg of carbon dioxide over the same time period (ICAO, 2022). Turnaround emissions are more difficult to quantify and depend on turnaround time which can vary from less than 30 minutes for short-haul low-cost operator to more than 3 hours for a long-haul operator. As soon as an aircraft arrives on stand, the APU is switched on and the main engines are switched off. Unless an external power and cabin air source are available, the APU will remain switched on during the duration of the turnaround. Padhra (2018) observed the average turnaround time for a short-haul European airline was 42 minutes, during which the APU fuel burn was on average between 40kg (if external power was available) and 67kg (if external power was not available). The corresponding carbon dioxide emissions were between 126 kg and 212 kg per turnaround.

In addition to climate impact, aircraft engine emissions also contribute to poor air quality in and around an airport. To account for aircraft emissions that take place outside the airport boundary and contribute to poor air quality around the airport, the International Civil Aviation Organisation (ICAO) has developed a standard Landing and Take-Off (LTO) cycle. The LTO cycle includes emissions up to 3000ft above airport level and assumes that the aircraft engines operate at 100% thrust (take-off) for 0.7 mins, 85% thrust (initial climb) for 2.2 mins, 30% thrust (approach) for 4 minutes and 7% thrust (idle) for 26 mins. This standard approach enables fuel burn and emission comparisons between different aircraft and engines. The LTO cycle carbon dioxide emissions for a Boeing 787 Dreamliner aircraft (Trent-1000 engines) is 5473kg while the similar size Boeing 767 aircraft (RB211 engines) has an LTO emission of 6055kg, a difference of 10%.

The other main airport emissions include those from passengers and airport staff travelling to and from the airport and ground service vehicles such as fuel and catering trucks. Figure 3 shows the carbon footprint breakdown for London Heathrow Airport in 2017. The carbon footprint is approximately equal for aircraft and non-aircraft sources.

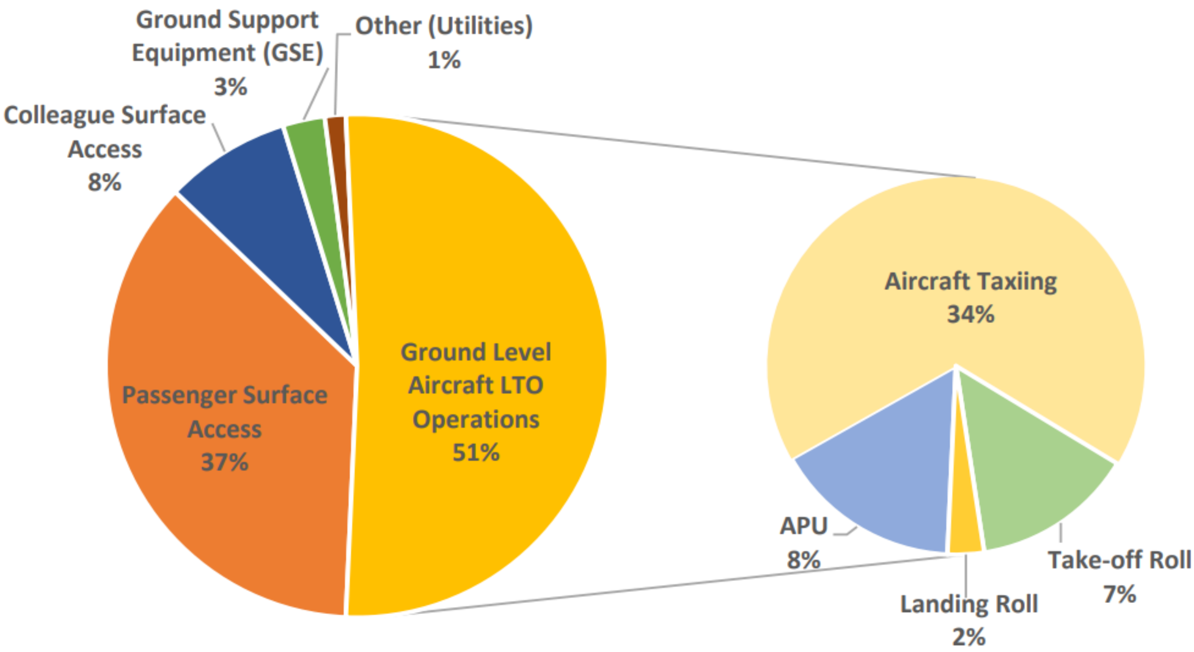

Figure 3. Percentage carbon footprint share for London Heathrow Airport in 2017
Source: Heathrow (2018) and Walker (2018).

MITIGATION OF AVIATION CARBON EMISSIONS

Efforts to mitigate aviation carbon emissions have focussed on three main areas; improvements in aircraft and engine design, improvements in operational practices and developing greener airports and infrastructure.

The most effective method to reduce aviation's climate impact is to improve the efficiency of aircraft and engines such that fuel burn and emissions are reduced. Quantifying improvements is challenging due to the large variations in aircraft passenger capacity and range. The metric most often quoted for comparison purposes is the fuel consumption per passenger per km. Using this metric, aircraft manufactured in 2014 were 45% more fuel efficient than those produced in 1968 (Kharina and Rutherford, 2015). It is expected that from now until 2045, aircraft fuel efficiency will improve by 0.98% per annum (ICAO, 2019). The vast majority of design improvements have come from the engines. When Boeing produced the first commercial jet aircraft, the Boeing 707 in 1958, the Pratt and

Whitney JT3D engine consumed 53kg per hour per kilonewton of thrust at maximum thrust setting. By 1994, when the Boeing 777 was introduced, it's General Electric GE90 engines consumed 33kg per hour per kilonewton. The main design feature that has contributed to the improvement is the increase in the bypass ratio of the engines. The bypass ratio of an engine is the ratio of the mass of air that bypasses the core of the engine to that which passes through the core of the engine and is mixed with fuel for combustion. The higher the by-pass ratio, the greater the propulsive efficiency. Earlier engines such as the Pratt and Whitney JT3D engine had a bypass ratio of 1.4:1. More recent engines such as the Pratt and Whitney PW1100G used to power the Airbus A320neo aircraft have a bypass ratio of 12.2:1. Recent improvements in engine efficiency have come from the use of gears which enable the fan blades to rotate at a different speed to the low-pressure compressor which enables optimisation and improved propulsive efficiency.

Additional fuel burn and emissions reductions come from aerodynamic improvements which help to reduce drag. Lift generation from the wings causes wingtip vortices which reduce their ability to generate lift. Additional lift is achieved by flying at a higher angle of attack which also induces more drag. Reducing the induced drag can be achieved by installing wingtip devices such as winglets and sharklets. According to Guerrero et al. (2020), winglets can achieve fuel burn reduction of 4-6%. The inclusion of winglets does require strengthening of the wings which add weight to the aircraft. For short flights, the additional weight cancels out the fuel saving benefits of the winglet and therefore they are more effective on longer flight sectors.

Advances in aerospace materials have enabled stronger and lighter aircraft structures resulting in lower fuel burn and emissions as explained earlier. In particular, the higher proportion of composite materials has enabled aircraft structural weight to reduce by 20%. The Boeing 787 Dreamliner, shown in Figure 4, consists of 80% composite materials by volume and 50% by weight (Boeing, 2022). This weight reduction leads to a 20% reduction in carbon emissions compared to an aluminium aircraft. Estimates suggest that by 2050, if the global fleet of aircraft transitioned to composite aircraft, carbon emissions could be reduced by 14-15% relative to a fleet that maintains its existing aluminium-based configuration (Timmis et al. 2015).

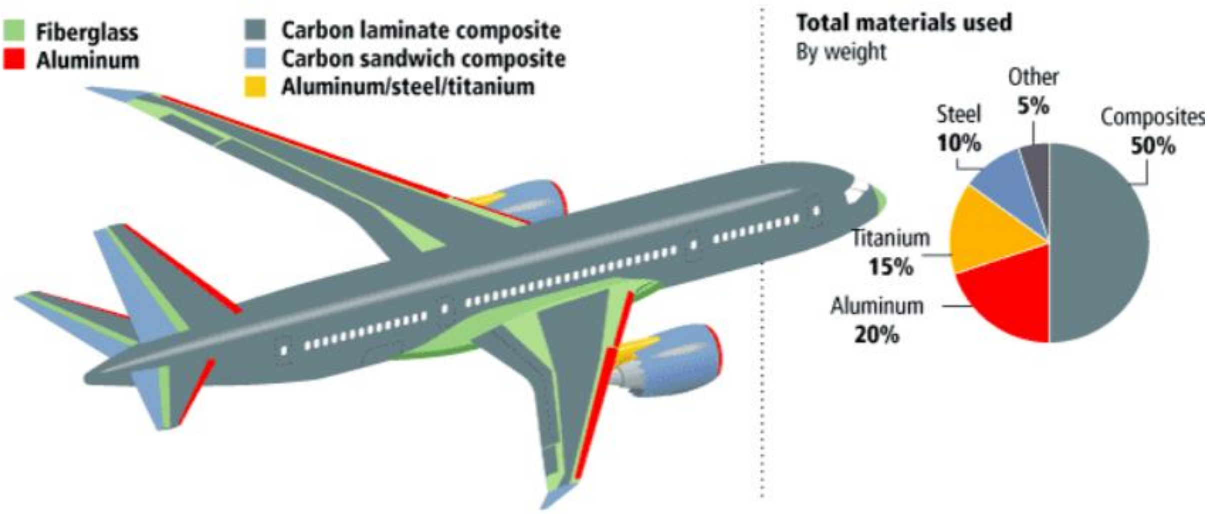

Figure 4: Diagram of the Boeing 787 Dreamliner aircraft showing the use of composite materials by weight.
Source: Aly (2017)

While aircraft and engine improvements have resulted in the greatest reductions in fuel burn and emissions, further reductions can be achieved once the aircraft is delivered to the operator, which is most cases is an airline customer. Two of the same aircraft operated by different airlines can have different climate impacts depending on their business model, routes, maintenance operations and internal operating policies. A common practice among all operators is to reduce aircraft operating weight. This can be achieved by, for example, reducing catering weight, installing lighter seats and carpet, converting in-flight books, magazines, flight charts, manuals and documents to digital format, reducing galley weight and reducing passenger baggage allowances. In any case, such initiatives must maintain flight safety and protect commercial revenue. A general rule-of-thumb for most aircraft is that for every 100kg of weight reduction, the aircraft consumes 3kg less fuel per hour (de Moor, 2020). In addition to emission reductions, this can result in significant reductions in direct operating costs due to lower fuel carriage and maintenance costs.

Flight operations procedures can also lead to significant emission reductions. For example, conducting reduced engine taxi between the runway and stand at the airport can reduce fuel burn and carbon emissions by up to 33% (Airbus, 2004). Modern aircraft systems are now able to compute the optimum speed and altitude inflight, to minimise fuel burn and emissions. This information is displayed on the flight management system in the cockpit and can be requested by the flight crew to air traffic controllers. Indeed, air traffic management provides some of the best opportunities to improve flight efficiency. Although aircraft fly from point to point (waypoints) in the airspace, air traffic controllers are sometimes able to offer shorter routes reducing flight distance, flight time and emissions. Parts of the airspace may also be permanently closed for commercial air traffic due to military airspace allocation. In Europe in recent years, the implementation of Flexible Use of Airspace (FUA) has removed the permanent segregation of civil and military airspace and instead airspace segregation is temporary, based on real-time usage within a specific time period. This enables airlines to operate more efficient flight plans with reduced in-flight emissions.

The vertical trajectory of aircraft is also managed by air traffic controllers. Providing uninterrupted climbs and descents can reduce the need to apply additional engine thrust, helping to reduce emissions. These climb and descent profiles are known as Continuous Climb Operation (CCO) and Continuous Descent Operation (CDO). Robinson and Kamgarpour (2010) conducted a study of CDOs in the US and found that the estimated savings were less than 25 kg for over 45% of the flights, and less than 100 kg for over 87% of the flights. In Europe, a Eurocontrol study estimated that the theoretical maximum benefit of CCO and CDO operations were up to 350,000 tonnes per year (over 1m tonnes of carbon dioxide emissions). However, it was noted that the achievement of 100% CCO and CDO across the European network was not possible for a number of reasons including safety, weather, capacity and controller workload.

CLIMATE IMPACT OF NON-CARBON EMISSIONS

While the focus of governments, industry bodies and aviation stakeholders has been on reducing carbon dioxide emissions, the aviation industry is also beginning to better understand the climate impact of non-carbon effects. The main effects are due to emissions of sulphate and soot aerosols, the emissions of nitrogen oxides and the formation of condensation trails (contrails). The climate impact of these effects is often quantified in terms of the ‘Radiative Forcing’ (RF) metric. Radiative forcing is the net energy flux in the atmosphere caused by each of these effects and is measured in terms of Watts per metre squared (W/m^2). A positive net RF represents warming effect in the atmosphere, while a negative net RF represents a cooling effect.

The radiative forcing associated with the emissions of nitrogen oxides is complicated to estimate due to multiple secondary effects. Nitrogen oxides present in the atmosphere are associated with the formation of ozone which is a greenhouse gas and therefore causes a warming effect. On the other hand, nitrogen oxide contributes to the destruction of methane which is a potent greenhouse gas and therefore has a cooling effect on the atmosphere. The overall impact is estimated to result in a positive RF (warming effect). The emission of sulphate aerosol particles helps to reflect solar radiation back to space and therefore cause a cooling effect. Soot particles emitted from aircraft engines are often small, non-volatile black particles that trap infrared radiation leading to warming. Both sulphur and soot particles are likely to have an indirect effect of cloud formation which can have both a warming and cooling effect depending on the altitude and characteristics of the clouds.

Aircraft condensation trails (contrails) form another significant non-carbon impact of aviation. On clear days, aircraft flying in cold and humid conditions can be seen forming line-shaped clouds referred to as contrails. Contrails were first observed in 1915 (Ettenreich, 1919) and the theoretical framework for their formation was first presented in 1941 (Schmidt, 1941). Contrails form when water vapour particles emitted from the engines latch onto soot particles, emitted by engines or naturally-occurring in the atmosphere. If the ambient temperature is less than approximately -40^{o}C the water freezes to form ice crystals. The physical characteristics of the contrail depend on water vapour and soot concentrations which can vary depending on the fuel type. Many of the contrails observed have a short lifetime and disappear within a matter of minutes. However, if aircraft are flying in atmosphere where the relative humidity with respect to ice is greater than 100% (ice-supersaturated), contrails can persist for hours and may evolve into cirrus clouds. Like clouds, contrails reflect incoming solar energy back out to space creating a cooling effect, but they also absorb outgoing surface radiated energy creating a warming effect. The net effect is usually a warming of the atmosphere. In fact, some studies suggest that the global warming impact of contrails could be as much as a third to a half of the total impact from all the carbon emissions ever emitted by aircraft. For persistent contrails, recent studies suggest a radiative forcing value between 4 and 16 mW/m^2. When including the impact of contrails which have evolved into cirrus cloud, estimates of radiative forcing are between 12 and 86 mW/m^2. The large variations in radiative forcing estimates occur because the science of contrails is not very well understood. Net radiative forcing is strongly influenced by the physical characteristics of contrails. These characteristics depend on the following variables:

- The amount of water vapour and particles present in the atmosphere occurring naturally or added by the jet engine exhaust
- The temperature, humidity and pressure of the ambient atmosphere
- The wind and turbulence characteristics of the atmosphere
- The wingspan and size of the aircraft
- The propulsive efficiency of the jet engines
- The type and blend of fuel used to power jet engines

All these factors determine the size and shape of ice-crystals present in the contrails, the width and depth of contrails, the evolution of the contrail dimensions over time and the lifespan of the contrails.

Figure 5 summarises the radiative forcing due to aviation from multiple components from pre-industrial times to 2005. It should be noted that the level of scientific understanding for many of the non-carbon effects is low resulting in high levels of uncertainty.

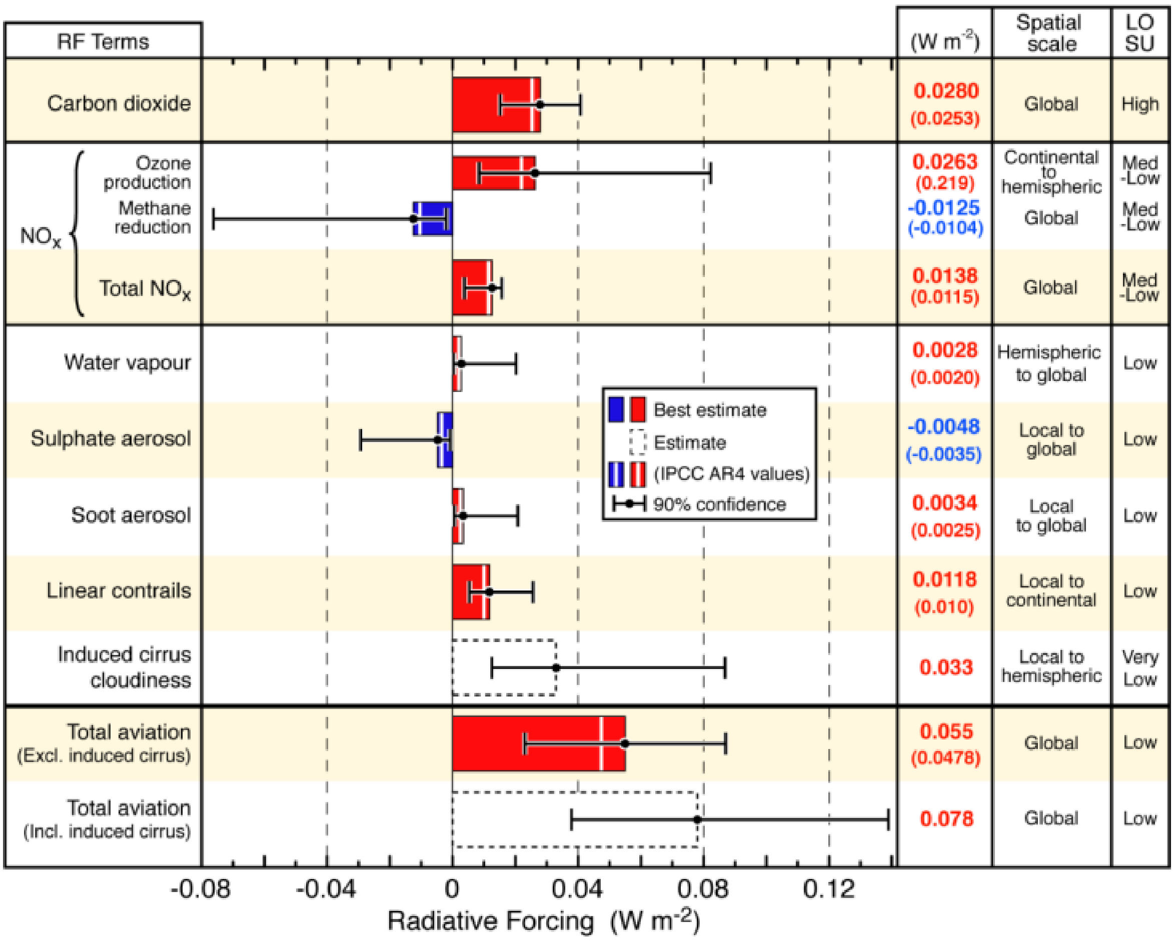

Figure 5. Radiative forcing components in Watts per square metre from global aviation as evaluated from preindustrial times until 2005. Error bars represent the 90% likelihood range for each estimate. The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right.
Source: Lee (2018)

Since the net effect of contrails is of warming, a promising approach to reduce their impact on the climate is to fly aircraft in regions of the atmosphere where contrails are less likely to form. This can be achieved by flight planning the vertical and horizontal route of aircraft to avoid contrail forming regions. Several studies have shown that even small changes in cruise altitude could prevent contrail formation (Avila et al. 2019; Teoh et al. 2020). Due to the large volume of traffic in the airspace, it is more challenging to deviate from the planned trajectory in-flight. Therefore, climate-optimal flight trajectories need to be pre-planned as part of the flight-planning process. The first step is to forecast parts of the atmosphere that are cold and humid enough for contrails to form so that they can be avoided. The dynamic nature of the atmosphere means contrail conditions vary on an hourly-basis and over a few hundred metres. Seasonal changes to the atmosphere mean that at any specific location, the frequency of contrail conditions will vary throughout the year. Figure 6 shows the average percentage coverage of ice supersaturated regions in US airspace between November 2014 and September 2015 at different flight level altitudes. Contrails are most likely to form between flight levels 320 and 350 and in the months of June, July, August and September.

Flight Level	Nov-14	Dec-14	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15
380	0	0	0	0	0	0	2	4	4	4
370	2	1	0	0	2	3	9	13	14	13
360	1	1	0	0	2	2	9	12	11	12
350	5	6	3	2	6	9	18	23	23	19
340	10	14	8	6	15	17	26	28	30	26
330	2	3	2	2	4	7	11	11	11	11
320	12	22	15	12	21	24	24	26	24	23
310	8	11	9	5	10	10	9	9	10	7
300	4	6	3	2	5	7	5	5	6	4
290	8	13	10	5	14	15	9	5	7	6
280	3	7	4	2	7	7	4	1	2	2
270	4	8	5	3	9	5	3	1	1	2
260	2	3	2	1	3	2	1	0	0	1
250	3	5	4	2	4	1	0	0	0	1
240	2	2	2	1	2	1	0	0	0	0
230	1	1	1	0	1	0	0	0	0	0
220	1	1	1	0	1	0	0	0	0	0

Figure 6. Average percentage coverage of Ice-Supersaturated regions (ISSR) in US airspace from flight level 220 to flight level 380 between November 2014 and September 2015.
Source: Avila and Sherry (2016)

CLIMATE IMPACT AND ADAPTATION

The impact of aviation-related emissions on climate change is now widely acknowledged and relatively well understood. However, our knowledge of how the changing climate impacts the aviation industry is less well understood. Since the medium in which aircraft operate is our atmosphere, any changes, for example due to climate change, will have an impact on aviation. The main climate impacts for aviation are at airports, where risk to operations and infrastructure are the main concerns, and in-flight where a more energetic atmosphere may pose a risk to flight safety. A comprehensive summary of the impacts is provided by Ryley et al. (2020) and Gratton et al. (2022).

In a warmer atmosphere, air particles move further apart and therefore the density of the air reduces. Density is an important physical parameter for aircraft operations. The forces of lift and drag generated by an aircraft are dependent on the density of air such that if the density of air is reduced, the ability of the aircraft to generate lift reduces and vice versa. Engine performance is also negatively impacted by lower air density since thrust force is reduced. During take-off, the reduced ability of the aircraft to generate lift and thrust results in a longer take-off distance on the runway. Some of the largest airports around the world have very long runways and therefore an increased take-off distance is less of a concern. However, at smaller regional airports and those located on some islands, runway length could be limited and aircraft may not be able to depart safely within the regulated limits. A study by Gratton et al. (2020) considered the impact of climate change on take-off performance for an Airbus A320 aircraft at some Greek airports. Figures 7a and 7b show the average minimum daily temperature and average wind speed trend at Chios Airport, one of the airports studied. Between 1974 and 2017, on average, the temperature increased by 0.75^{o}C per decade and wind speed decreased by 0.23 knots per decade. The increase in temperature and reduction in wind speed resulted in the take-off distance increasing by an average of 8m per year for an Airbus A320 operating at maximum take-off weight.

When an aircraft is unable to take-off in the runway distance available, airlines have to reduce the weight of the aircraft by offloading payload such as cargo, baggage and passengers. A lower weight reduces the lift force requirement of the aircraft, enabling aircraft to take-off in a shorter distance. For the island of Chios, the required reduction in payload was equivalent to 38 passengers and their baggage for the period between the A320's entry into service in 1988 and 2017. Offloading payload reduces airlines ability to generate revenue and profit leading to a direct negative impact on airlines ability to be financially sustainable on some routes. A degradation in aircraft take-off and climb performance is also expected to lead to further negative impacts such as higher noise levels in the vicinity of airports due to shallower climb paths and slower climb to cruise altitude resulting in more fuel burn, though there are currently no studies that have quantified these impacts.

At some airports climate change is resulting in very warm temperatures, heavy precipitation and convective activity. These extreme weather events may cause airfield flooding, ground subsidence, inundation of underground infrastructure, loss of utilities provision such as electrical power, heat damage to the airport surface and disruption to surface access (Burbidge, 2018). Infrastructure damage can pause operations, delay and/or cancel flights and cause disruption to passenger and freight journeys. Airports may end up with large financial costs to repair and maintain critical infrastructure and potential loss of revenue. A warmer climate is also resulting in higher sea-levels due to the melting of sea ice and thermal expansion of the oceans. This increases the risk of airport flooding for coastal airports. A recent study assessed more than 14,000 airports worldwide and concluded that a 2^{o}C rise in global temperature would place 100 airports below mean sea level (Yesudian and Dawson, 2021). This could happen by year 2100 and the highest risk airports were identified as Suvarnabhumi Airport in Bangkok, Thailand and Shanghai Pudong Airport in China. Coastal airports have four main adaptation choices. They can:

(i) Protect the airport by constructing sea defences
(ii) Raise the airfield to move operations above mean sea-level
(iii) Relocate the airport away from coastal areas and
(iv) Reclaim or float the airport to remain above mean sea-level

All of these adaptation measures involve very expensive engineering work and could cost hundreds of millions of dollars. For example, the estimated cost of building a sea defence wall, 1km long and 1 metre high could be as high as $70million. Some cities and countries have the space and finance available to invest in adaptation measures, move airports inland or absorb flights into neighbouring airports. However, many locations and especially those most reliant on airports for tourism, food and medical supplies will struggle to find alternative airport locations or investment to keep pace with the sea level rise.

In-flight operational impacts due to climate change are likely to lead to flight delays and inefficiencies. For example, a higher frequency of convective weather leading to thunderstorms could halt aircraft refuelling and cause flight routes to be extended to avoid such weather. The North Atlantic air traffic region is one of the most studied in terms on climate impact. A key meteorological feature of this region is the jet stream, a conveyor belt of strong wind that moves air flow from west to east and is located at an altitude similar to the cruise altitude of aircraft. A series of jet streams are found in the mid-latitudes and occur because of the rotation of the earth and the difference in temperatures between the tropical equatorial regions and the cold polar regions. Flights operating from west to east such as from New York to London benefit from the presence of a strong jet stream because the winds carry the flight across the Atlantic at a faster ground speed reducing flight times by a few hours in some cases. However, flights travelling from east to west often encounter strong Jetstream headwinds which increase flight times. Due to climate change, there is evidence that the strength and shape of the Jetstream is changing which will inevitably impact aircraft operations and flight routings. Williams (2016) showed that if carbon dioxide levels were to double, the strengthening of the jet stream winds across the Atlantic are likely to cause shortening of eastbound flights and lengthening of westbound flights. For a round-trip across the Atlantic the reduction in flight time in one direction and the increase in flight time in the opposite direction would not cancel out and the net impact would be an increased flight time of more than 90 seconds. This may not sound like much but prior to the Covid-19 pandemic there were more than 300 round trips per day along the North Atlantic Corridor. If each flight took 90 seconds longer the collective additional flight time per year would be more than 2000 hours and would add $22 million to the fuel cost for airlines.

An even more concerning impact of changes to the Jetstream in on flight safety. At the boundary of fast-moving winds within the Jetstream and the slower moving airflow around it, vertical wind shear can be generated. This wind shear causes instability in the atmosphere known as clear-air turbulence. When flying through turbulent airspace, passengers experience a bumpy flight. In some severe cases of turbulence, injuries to passengers and crew and damage to aircraft have occurred. Studies have shown that if future carbon dioxide concentrations are double that of the pre-industrial period, changes to the jet stream would not only increase the frequency of turbulence but also the strength (Williams and Joshi, 2013). Figure 7 shows the difference in turbulence intensity in the North Atlantic flight corridor for a double CO2 scenario compared to pre-industrial CO2 concentrations for the winter season. The rectangular box between Ireland and Canada represents the area of airspace most likely to be taken by flights between Europe and North America.

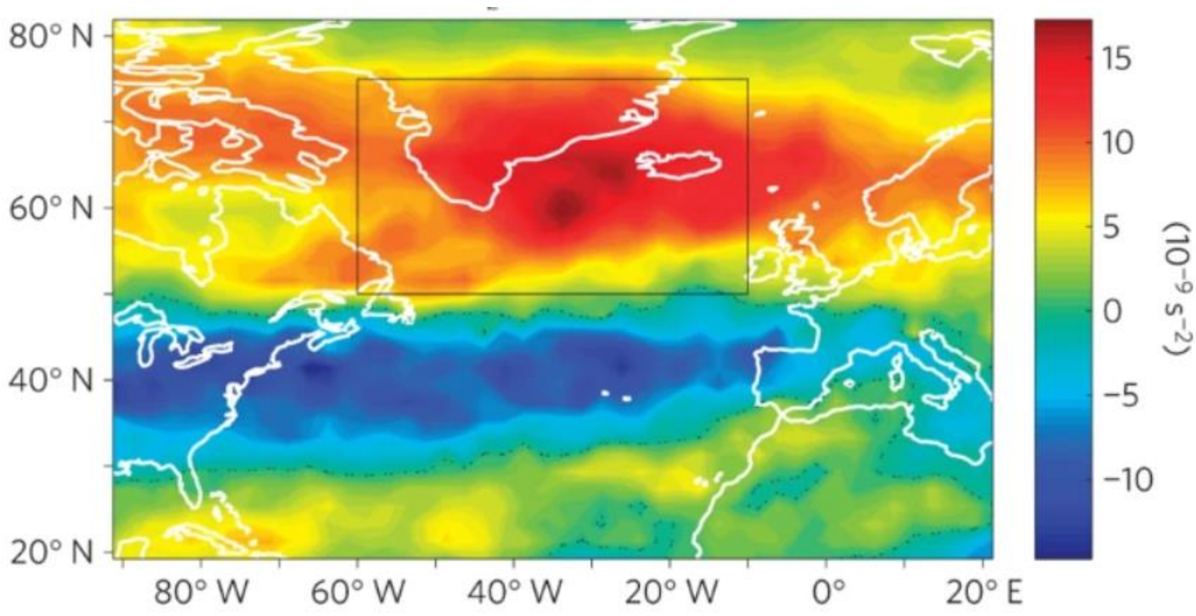

Figure 7. Spatial patterns of North Atlantic flight-level winter clear-air turbulence in a changing climate. The quantity shown is the median of variant 1 of Ellrod's turbulence index, computed from 20 years of daily-mean data in December, January and February at 200 hPa.

Source: Williams and Joshi (2013)

Recent scientific research is shedding light on many other impacts of climate change on aviation. In addition to the operational impacts, changing passenger demand and travel patterns is also likely to have a commercial impact on airports and airline operators. Therefore, the need to understand how aviation will be impacted in the future is crucial to the sustainability of the aviation industry.

ALTERNATIVE ENERGY SOURCES AND DECARBONISATION

Since the dawn of commercial aviation, aircraft have been powered by fossil-fuels, most notably kerosene-based fuels. In recent decades, the climate impact of using such fuels has led scientists and technologists to develop alternative energy sources. Here we consider three alternative fuel and energy sources that are likely to replace fossil-fuel sources in the medium to long term.

In aircraft engines, kerosene can be replaced, in part, by synthetically-produced liquid fuels, collectively known as sustainable aviation fuels (SAF). Where the raw source of the fuel is biomass derived from used cooking oil, household and business waste and from plants and trees, SAFs are commonly referred to as biofuels. Biofuels are drop-in fuels since very little, if any, modification to existing aircraft and engines is required.

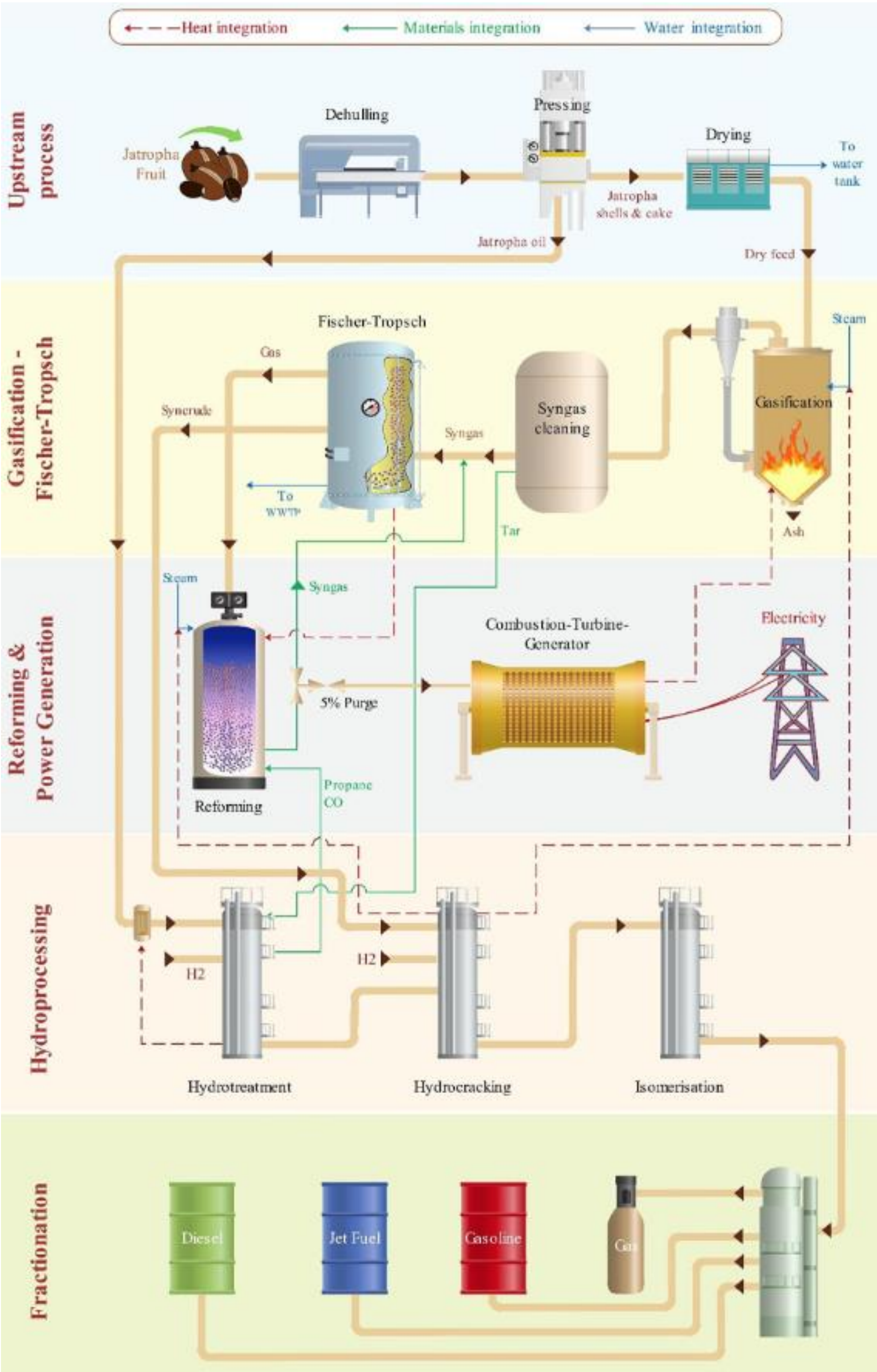

Figure 8. Flow diagram of the integrated process for converting jatropha fruit into jet fuel.
Source: Alherbawi et al. (2021)

Figure 8 shows the process of converting jatropha fruit into jet fuel. Biofuels are considered as being sustainable because plants grown as feedstock have already absorbed carbon dioxide from the atmosphere, before being released back into the atmosphere during combustion and therefore the net carbon emissions are zero. However, the production process, transportation of feedstock and distribution of the processed fuel to airports all involve the emission of greenhouse gases and therefore biofuels are not completely carbon neutral. Carbon emission reductions are usually 20-90% compared to kerosene-based jet fuel. Current regulations mean that biofuels needs to be blended with traditional kerosene-based jet fuels up to a maximum percentage of 50%. The operational feasibility of using biofuels has resulted in multiple airlines around the world trialling their use in commercial flights. In 2008, Virgin Atlantic Airlines in the UK became the first airline in the world to operate a commercial flight powered by a biofuel blend. By 2019, 150,000 flights had made use of biofuels. Greater usage of biofuels is partly due to airports making the fuel available through an efficient supply chain and storage facilities. By 2021, 5 airports including Oslo, Stockholm, Bergen, Los Angeles and Brisbane airport had a regular supply of biofuels ready to be used by airlines serving those destinations.

Additional benefits of biofuels include lower emissions of other gases and particles which can help to improve air quality and may even reduce the formation of contrails. Biofuels generally contain less impurities and therefore produce less emissions such as sulphur dioxide. Less impurities also means lower emissions of soot particles which contribute to the formation of contrails. A study by Brauer et al. (2021) involved the measurement of engine emissions in the cruise phase of flight for an aircraft powered by a 49% biofuel blend. The measurements showed a 40% reduction in ice particle numbers, halving the optical depths of contrails and therefore reducing climate impact. While the use of aviation biofuels are considered to be friendlier for the environment there are some challenges and limitations. Firstly, the infrastructure for the production and distribution of biofuels is less well established than that for crude oil and therefore the current cost of producing biofuels is too high to stimulate large scale demand. Secondly, a large amount of biomass is required to produce a small quantity of biofuel. Currently, a tonne of biomass can at best produce 100 litres of biofuel. To meet the high demand for jet fuel, biomass would have to be produced especially for the purpose of creating biofuels. This would add significant pressure on land use and global food supply creating a moral and ethical issue in relation to global food poverty. So the current emphasis is on harvesting biomass from existing waste products to convert into jet fuel. Until radically new aircraft technology is developed and implemented, biofuels will provide one of the pathways to net zero carbon emissions in the short- to-medium term.

A more promising, though less well-established technology is the use of hydrogen as a fuel and energy source for aircraft. Hydrogen is the most abundant chemical element and its low mass is ideal for aviation. Hydrogen in its liquid form can be combusted directly in an aircraft jet engine. However, current practice for prototype aircraft is for hydrogen to be used as a compressed gas in a fuel cell which generates electricity which then powers propellers to generate a thrust force. In either case, hydrogen combines with oxygen in the atmosphere and emits water vapour and there are no carbon emissions at all. An even greater benefit of hydrogen-powered aircraft could be in relation to contrail formation. Existing aircraft form contrails due to the water vapour and soot particles that are emitted from engines. While hydrogen aircraft will emit significantly large amounts of water vapour, there will be little or no soot emissions and therefore the water vapour emitted would mainly need to combine with lower concentrations of background particles in the atmosphere to form contrails. The resulting contrails are likely to be thinner and short-lived leading to a lower atmospheric warming impact.

Despite the many benefits of hydrogen, there are also some challenges that have limited widespread use. Although hydrogen is an abundant element, it's natural form is often combined with other elements. For example, when combined with oxygen it forms water and when combined with carbon it forms methane. The challenge is to isolate hydrogen in an energy-efficient manner so that carbon emissions or other greenhouse gases are not generated in the process. An efficient process also keeps the production costs down and therefore is more commercially attractive to the aviation industry.

The four most common methods for producing hydrogen involve (i) steam methane reforming where hydrogen is produced from the mixing of natural gas and steam from heated water; (ii) coal gasification in which coal is combined with oxygen and steam leading to hydrogen as the by-product; (iii) pyrolysis which involves the separation of natural gas into hydrogen and solid carbon and (iv) electrolysis which uses electricity to split water into hydrogen and oxygen. The process used to produce hydrogen and its energy source determine a colour-coded description. Producing hydrogen from steam methane reforming produces a significant amount of carbon dioxide which has well-known impacts on climate change. This method is referred to as Grey hydrogen. If the carbon dioxide is captured and stored in the process, it is referred to as blue hydrogen. The process of pyrolysis also produces carbon but in the more convenient solid form rather than the gaseous form and is referred to as turquoise hydrogen. If the source of electricity used to carry out the process of electrolysis is from renewable sources such as wind and solar, it is referred to as green hydrogen. If the electricity source is nuclear power, it is referred to as pink hydrogen. Green hydrogen is by far the most decarbonised process. However, in 2019, less than 5% of global hydrogen production was green hydrogen and nearly 95% was grey or blue hydrogen. There are many barriers to this. For example, Green hydrogen is 2-3 times more expensive to produce than grey hydrogen. The current infrastructure is also very limited with the hydrogen distribution network in 2020 being only one fifth of a percent of that for natural gas. In addition to the production challenges, there are also further challenges when storing hydrogen. Hydrogen gas is highly flammable and liquid hydrogen has a very low temperature below minus 200 degrees Celsius. Therefore, high-pressure or heavily insulated tanks are required which prevent the fuel from being stored in aircraft wings like conventional kerosene-based fuel. Instead, the storage tanks would need to be located in the fuselage of the aircraft posing an additional challenge. Figure 9 shows a comparison of energy density by volume against the energy density by mass of a group of materials and technologies.

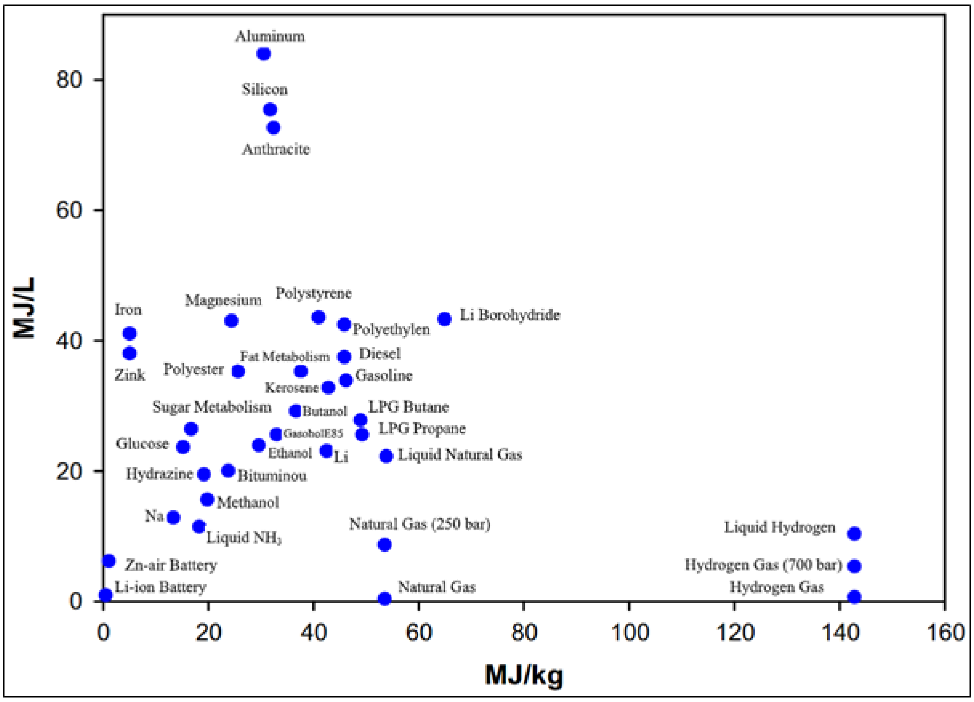

Figure 9. Comparison of the volumetric versus gravimetric energy density of a group of materials and technologies.

Source: Ehteshami and Chan (2014)

While the energy content per kilogram of hydrogen is three times greater than conventional kerosene-based jet fuel, it's energy content per cubic metre is three times less. Therefore, aircraft fuel tanks would need to be significantly larger than current tanks to achieve the same flight range. The larger tanks would reduce space for payload making hydrogen less attractive for airline revenue generation.

Assuming that economically sustainable hydrogen aircraft will be available in the next 30 years, the next challenge will be the planning and development of airport transportation and storage infrastructure to enable aircraft refuelling. Many of the world's airports have direct pipelines for kerosene-based fuel but there is little or no infrastructure for direct liquid hydrogen supply. Therefore, in the first cases, trucks are likely to be required to supply airports. A single truck could carry 5 tonnes of hydrogen which is a quarter of the energy content of one truck carrying kerosene-based jet fuel. This could lead to congestion around airports and additional carbon emissions if the trucks are not carbon-neutral. The storage of liquid hydrogen would also take up 4 times more space per unit of energy than current kerosene-based fuels requiring airports to make more space available on or close to the airfield.

The combustion of gaseous or liquid fuels to provide an energy source will inevitably lead to some form of emissions. Energy that comes from an electrical source has the benefits of zero in-situ emissions. For aviation, this has significant positive impacts on local air quality around airports. Zero emissions also means that contrails cannot form and therefore the non-carbon impacts of aviation are mitigated. If the electrical power has been generated from renewable sources such as wind and solar, then even the carbon impacts are eliminated. These benefits have encouraged designers of modern commercial aircraft to slowly transition towards becoming more electric. The Boeing 787 Dreamliner, for example, houses 6 electrical generators on board compared to traditional aircraft which have 3 generators. These generators are used to provide power for aircraft systems and lighting and also recharge the 2 sets of lithium-ion batteries on board the aircraft. Recent developments in electrical technology have enabled all-electric transportation modes, most notably in the automotive and rail industry. While several small prototypes of electric aircraft currently exist, it will be sometime before the introduction of all-electric commercial aircraft similar in size and range to existing regional aircraft. Battery technology is still not advanced enough to provide the high energy requirements of relatively high-payload, long-range flying.

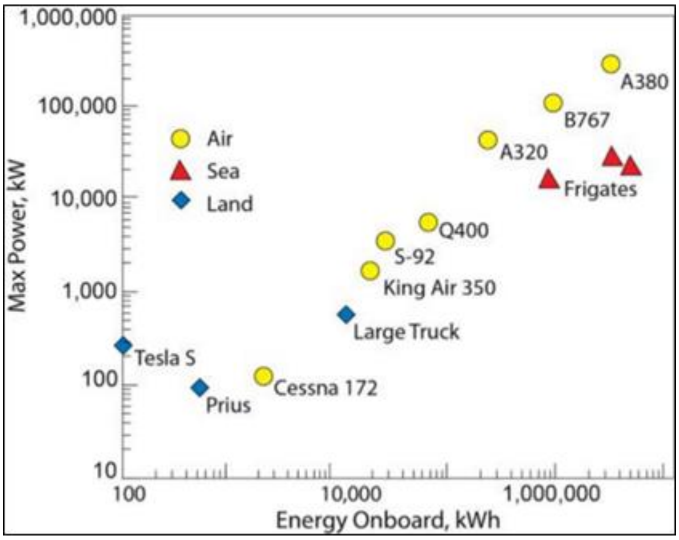

Figure 10. Maximum energy and power onboard a range of air, sea and land vehicles.

Source: Epstein and O'Flarity (2019)

Figure 10 shows the maximum power requirements for several land, sea and air transport vehicles against the energy carried on board these vehicles. Existing electric cars have relatively small power requirements of less than 200kW and carry the equivalent of 1000kWh of electrical energy. Small aircraft such as the Cessna 172 are of similar size to cars and many of the all-electric aircraft prototypes that currently exist are of this size. However, for larger commercial aircraft such as Q400 which conducts regional flights, the maximum power requirements at take-off are 30 times greater; a value that current batteries cannot provide in the space available on aircraft. A useful metric to consider is the energy per kg that an electric battery could deliver. In 2020, the best lithium-ion battery was able to provide 250Wh per kg. In comparison kerosene-based aviation fuel delivers 12,500 Wh per kg. The minimum requirement for a short-range electric aircraft would be 750-2000kWh per kg. The current rate of battery development is a doubling of energy per kg every 17 years. Therefore, it could be 30 years by the time the first all-electric commercial aircraft are introduced into service. The next major challenge for all-electric aircraft is the large amount of electricity that would need to be produced from renewable sources to power a global fleet of regional all-electric aircraft in a sustainable manner. Based on 2015 figures, this would equate to approximately 1% of the total worldwide electricity consumption. A more likely application of electrical power in commercial aircraft is through a hybrid-electric approach. Hybrid technology involves a combination of conventional fuel and electrical power to propel an aircraft forward. For example, energy intensive phases of flight such as take-off and climb could be conducted using jet engines powered by conventional fuel, while the taxi, cruise and descent phase could take place with electric power alone. Up until April 2020, Airbus, Rolls Royce and Siemens were working on a hybrid-electric aircraft concept based on the existing BAE 146 aircraft. The aircraft named E-Fan X would have one of the four jet engines replaced by an electrical motor. Hybrid-electric aircraft could also be flown strategically to reduce climate impact. For example, aircraft flying in ice-supersaturated regions of the atmosphere where contrail formation is likely could be powered by electrical means to prevent climate warming.

MARKET-BASED MEASURES FOR CLIMATE CHANGE

Many of the operational solutions for achieving a carbon-neutral aviation industry have already been implemented. Radical technological solutions are reliant on significant progress quickly or come with additional challenges such as infrastructure development. Another driver for minimising the climate impact of aviation is to introduce market-based measures (MBM). MBM's are economic instruments that penalise airlines and airports for their carbon emissions and/or incentivise activities to reduce carbon emissions. There are three main types of MBMs, namely, taxes and levies, carbon offsetting and emissions trading. Taxes and levies are revenues collected by the government in response to certain activity. For example, the government of a country may introduce or increase fuel taxes, navigation charges or airport charges to deter airlines from expanding their operations resulting in lower fuel consumption and carbon emissions. They also encourage airlines and airports to invest in methods to reduce carbon emissions such as newer aircraft. Since aviation is an international industry, taxies and levies are not popular as it creates an unlevel playing field in the market and may discourage foreign airlines from operating flights to a particular airport or country. Carbon offsetting involves the reduction of emissions in another sector or an increase in carbon storage to offset the emissions in your own sector. For example, the carbon emissions of a specific flight may be estimated and then the airline may invest in a voluntary carbon offset project such as reforestation that plants trees to absorb the equivalent carbon emissions. Offsetting is usually a more cost-effective method than an organisation reducing its own emissions. An emissions trading scheme (ETS) is a system whereby the government or a central authority issues a limited number of permits (caps) that enables an organisation or sector to emit the equivalent amount of emissions. Organisations can then trade permits with other organisations by selling excess permits (if emissions have been reduced) and buying additional permits if more emissions will take place. The scheme allows emissions targets to be met and adjusted as new technology enters the market. The European EU Emissions Trading Scheme has included the aviation sector since 2012. Under the scheme, all airlines operating in Europe regardless of their registration country are required to monitor, report and verify their emissions, and to surrender allowances against those emissions. They receive tradeable allowances covering a certain level of emissions from their flights per year.

The system has so far contributed to reducing the carbon footprint of the aviation sector by more than 17 million tonnes per year. Since the scheme covers airlines operating in Europe, but registered in non-European countries, it has been seen as unilateral and unfair. In particular, countries such as China, the

USA, Canada, Russia and Japan have strongly opposed the scheme claiming that it disadvantages developing countries and adds to airline operating costs. In response, in 2016, member states of the International Civil Aviation organisation (ICAO) adopted a global market-based method for aviation emissions termed, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The implementation of CORSIA is over three phases – two initial, voluntary phases (2021-2023 and 2024 – 2026) and a mandatory phase that would take place from 2027. During the initial phases, CORSIA only applies to international flights between states that have volunteered to take part. International flights to and from states that have not volunteered will be exempt. During the mandatory stage, which begins in 2027, CORSIA will cover all international flights, including those travelling to or from states that had not volunteered for the early phases. For fairness, the least developed nations, small island nations and nations with a very small share of international aviation traffic will be exempt. It is estimated that CORSIA will mitigate around 2.5 billion tonnes of CO_2 between 2021 and 2035, which is an annual average of 164 million tonnes of CO_2. This is equivalent to the total annual CO_2 emissions from the Netherlands across all sectors.

SUMMARY

Aviation’s impact on the environment, and in particular climate change is relatively small compared to other transport sectors such as road vehicles. However, as the industry begins its recovery in the wake of the Covid-19 pandemic, aviation traffic will increase rapidly and its contribution to climate change will increase. The primary contribution is through carbon emissions associated with aircraft operations, passenger and freight movement by surface transport to and from airports and emissions associated with airport operations, terminals and buildings. There are also non-carbon impacts due to the emission of nitrogen oxides at high altitude that cause an imbalance in radiative forcing and the emissions of water vapour and soot that can form contrails. The impact of the latter is less well-understood though likely to have a significant climate impact in addition to carbon emissions. The industry has recognised that operating more efficiently not only reduces climate impact but also reduces operating costs which contribute to the financial stability of the sector. Thus, airlines, airports, airspace managers and aircraft designers and manufacturers have placed a considerable amount of effort in developing and implementing environmental initiatives. Despite, year-on year improvements, the industry will still not achieve the target of net-zero carbon emissions by 2050 unless radical alternatives are found to kerosene-based fuels. Sustainable aviation fuels such as biofuels are a good short-term approach as net carbon emissions are lower. However, biofuels still result in tailpipe emissions and there are doubts as to whether sufficient feedstock is available to produce the volumes of biofuels required by the industry. The transition to electric aircraft is promising but the development of new battery-technology needs to be rapidly progressed to achieve financially sustainable commercial flights that can be operated with large payload and range. This is unlikely in the short-to-medium term given the historical rate of progress. The use of hydrogen as a fuel and energy source is gaining traction in the aviation industry with several trials and prototypes expected within the next decade. The large-scale green production of hydrogen fuel and the associated infrastructure required for storage and distribution in a safe and economical manner remain challenges. Alongside operational and technological developments, market-based measures such as the ICAO CORSIA initiative will be mandated from 2027 for which the industry must prepare now. Accelerating decarbonisation initiatives and achieving climate-neutrality are becoming more and more important as several recent studies have begun to highlight the negative impact of a changing climate on the industry. Rising sea-levels, heatwaves and more frequent and severe thunderstorms and in-flight turbulence are already impacting the industry and adaptation measures are being considered to maintain the sustainability of the industry.

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