Sustainable developments in Aviation.

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Executive Summary-

Aviation causes emissions which will grow as the industry grows. No single technological, operational or regulatory approach has a significant enough impact to reduce the emissions of aviation. Technical difficulties and long vehicle life span prevent next generation technologies significantly reducing radiative forcing by 2030 and limit the ability their ability to reduce radiative forcing by 2050. Operational policies will save emissions where it is economically sound to do so but are only capable of marginal efficiencies. Market regulation may reduce flight but mostly in those who rarely fly, creating further inequality in emissions sources. Carbon offsetting is unlikely to be performed at a scale to significantly reduce emissions and may be ineffective due to externalities.
If current low carbon strategies, like SAF, are used at a much more ambitious scale aviation emissions will be reduced. This could allow fewer emissions from the aviation sector *until* next generation technologies take over. This could be encouraged by a more effective cap and trade system like the EU ETS. Ultimately aviation is a very high energy sector which has become a norm within some groups. A reduction in demand in these groups may be just as important as any technological, operational or policy measure to reach a world that does not exceed +1.5°C.

Layman's Summary –

The aviation sector is responsible for a significant and growing proportion of climate change. This is due to their emissions and the way aircraft effect the chemistry of the atmosphere. Business are creating technology to reduce the emissions per flight. Governments are complementing this by creating laws and policies to try to reduce the climate change effects. However, immature technologies coupled with a slow replacement time for aircraft prevent next generation technologies being adopted quickly. This may prevent technology helping to meet internationally set guidelines on climate change such as the Paris Agreement. Equally, businesses will save emissions where it is saves money but won't change the overall system, limiting emission reductions. Additionally, laws and policies may reduce flight, but unspecific policies, like a general flight tax, doesn't reduce flying in frequent flyers, keeping emissions high. Two of the most popular solutions suggested are carbon offsetting and sustainable aviation fuels. Carbon Offsetting may reduce CO_2 entering the atmosphere, or even pull it out of the atmosphere. However, large scale implementation is required and there are doubts as to whether this is effective or sustainable in the long term. Sustainable aviation fuels could reduce the amount of CO_2 that enters the atmosphere in the short term whilst future technologies are still being developed. However, use of these sustainable fuels will have to be implemented much more rapidly than is currently being suggested. This could be encouraged by government CO_2 saving initiatives. Ultimately aviation is an energy intensive sector which is very popular in wealthier demographics. A reduction in demand may be just as important as any technological, operational or policy measure to prevent dangerous levels of global warming.

Acronyms and abbreviations:

AM –	Additive manufacturing
ASTM -	American society for testing and materials
CAAFI -	Commercial Aviation Alternative Fuels Initiative
CO_2 –	Carbon dioxide
e-fuel –	synthetic fuel
EU –	The European Union
EU ETS –	The European Union Emission Trading Scheme
FFL –	Frequent Flyer Levy
GHG –	Greenhouse Gases
Gt-	Gigatons
HEFA -	Hydro-processed Esters and Fatty Acids derived fuel
IATA –	International Air Transport Association
ICAO -	International Civil Aviation Organisation
km -	Kilometres
Kt –	Kilotons
LTO -	Landing and take-off
mph –	Miles per hour
NO_x –	Nitrogen oxides
KW-	Kilowatt
RF –	Radiative Forcing
RIN –	Renewables identification number
SAF –	Sustainable Aviation Fuel
TRL –	Technology readiness level
UNREDD +	- United Nations: Reducing Emissions from Deforestation in Developing Countries
US –	United States of America
WEF –	World Economic Forum

Introduction

Aviation is a fast, safe and affordable mechanism of travel. Its growing popularity is exemplified by sector growth of 32% between 2013 and 2018; an effective compound growth rate of 5.2% (Graver, Zhang and Rutherford, 2019). Flights create emissions and aviation is estimated to account for approximately 5-8% of global anthropogenic warming emissions (Gössling, 2020; Ritchie, Kemperman and Dolnicar, 2021). High energy intensity and growth meant aviation emissions were anticipated to grow 300% by 2050 prior to covid-19 (Higham, Ellis and Maclaurin, 2018). Therefore aviation, amongst other transport industries, is not on track to reach its climate targets in the EU (Figure 1) (WEF, 2020). Furthermore, aviation groups need to reduce emissions 18 – 35% in order to achieve a 1.5°C by 2030 scenario (Dichter *et al.*, 2020). Parties concerned over these highly concentrated emissions question the sustainability of aviation, creating a wide analysis of aviation emissions and helpful innovations.

This literature review will explore the changes occurring in the aviation industry in an effort to increase its sustainability. The different mechanisms can be broadly divided into three areas that reduce the warming effects of flying:

- Technological: Physical changes to the aircraft based on power, structure or fuel.
- Operational: How the sectors uses available information and behaviour to aid sustainability.
- Regulatory: The rules, taxes or incentives governments provide to the sector.

After describing these mechanisms in the results, the discussion will assess how feasible these are and how effective they will be at increasing the sustainability of the airline sector. The roadmap will then look at synergies between mechanism to reduce emissions in the context of reducing warming to within 2°C, as stated by the Paris agreement (United Nations, 2015).

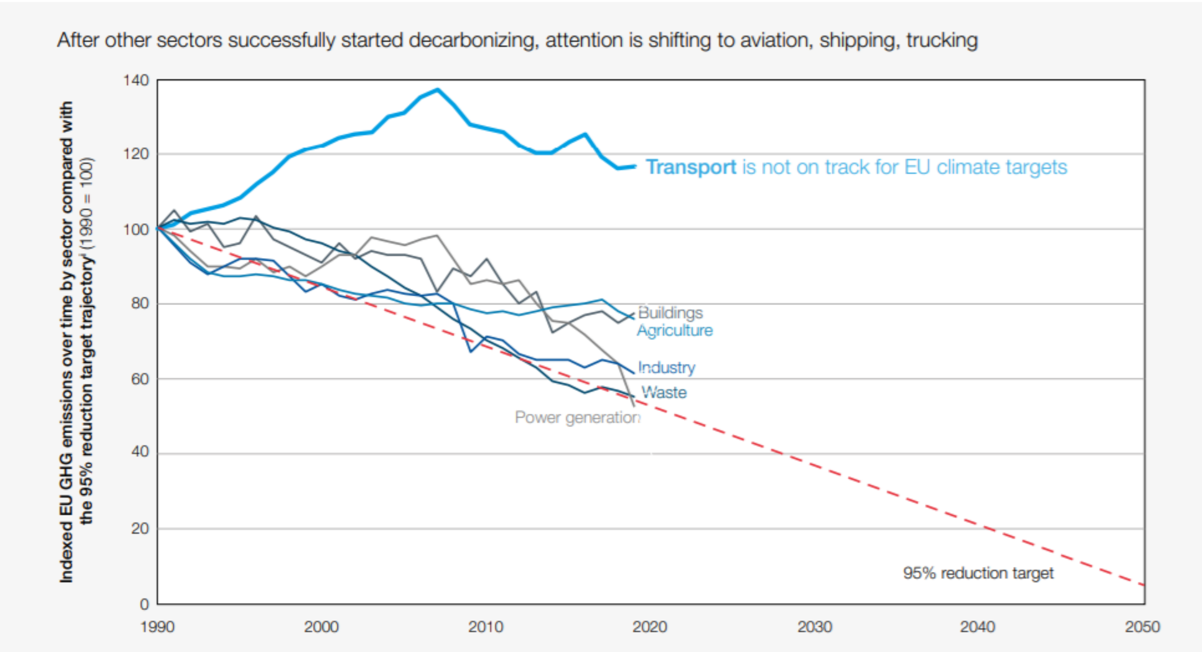

Figure 1. Greenhouse emissions per carbon intense sector with reference to 95% reduction target. Reused from WEF sustainable aviation report (2020)

Section 1: How does aviation affect the environment specifically.

Commercial aeroplanes affect the chemical composition of the atmosphere they travel through with their emissions, changing the environment (Figure 2) (Brasseur *et al.*, 2016). Some of these effects relate to *radiative force*, (heating effect) and is measured in Watts per M^{-2-} (Lee *et al.*, 2021). Carbon Dioxide (CO_2) emissions, Nitrous oxides (NO_x), changes to water vapour at altitude, cloud nucleation, contrail formation and aerosol production all cause radiative forcing (RF) (Balkanski *et al.*, 2010; Gregg and De Lépinay, 2015; Brasseur *et al.*, 2016; Bickel *et al.*, 2020)

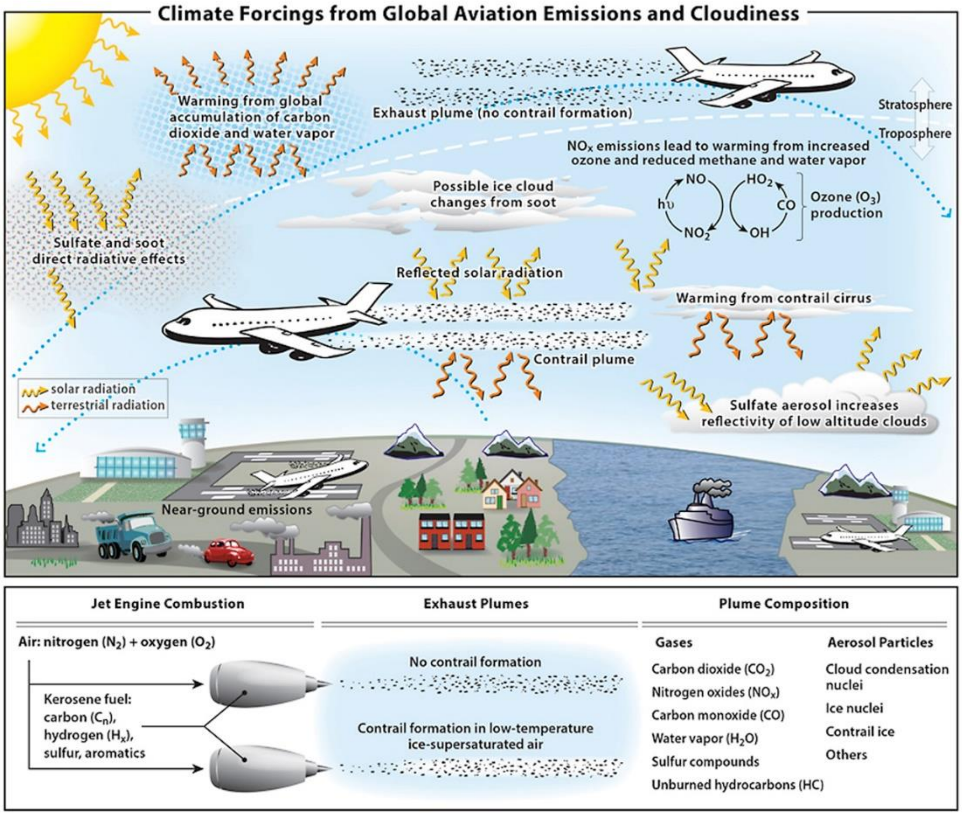

Figure 2. The complex effects of aviation related emissions that lead to radiative forcing in the environment. CO_2 and water vapour emitted at altitude increase radiative forcing. Contrail cirrus formation acts an insulation trapping heat at the surface of the planet. Nitrogen enriches ozone production. Ozone absorbs ultraviolet and infrared, increasing stratosphere warming. Some warming happens from near ground emissions like taxiing. Reused from Lee *et al.,* 2021.

CO_2, NO_x, water vapour and contrail formation are the most warming emissions. $CO_{2,}$ which has well characterised effects, is released through the burning of hydrocarbons such as Kerosene, the industry standard fuel. A modern jet engine in a twin jet aeroplane with 150 passengers releases 8,5 tonnes of CO_2 per hour whilst cruising[1] (EASA, 2019). Per stage of the flight the greatest intensity of jet fuel is burnt during take-off which means that short haul flights have the highest emission rate per kilometre and DEFRA provides values of 0.1580 and 0.1056 $KgCO_2$/RPK to short haul and long haul respectively (Jardine, 2009). There are additional CO_2 emissions at the ground level as taxiing and ground operation vehicles are frequently powered through burning hydrocarbons (Salihu, 2020).

Nitrous oxide is also produced by the burning of jet fuel at high temperature and pressures (McKinsey & Company, 2020) NO_x has the ability to react chemically to O_3 in the troposphere, enhancing O_3. O_3 absorbs infrared and ultraviolet radiation which has a warming effect whilst also

[1] For refence the typical CO_2e footprint of a UK citizen is around 12.7 tonnes per year.

depleting a small amount of CH_3 (Cohen *et al.*, 2018). Due to the imbalance in the longevity of O_3 and CH_3 this concentrates warming in the northern hemisphere, where more flights are flown and most NO_x is released (Lee *et al.*, 2008). Aviation related NO_x accounts for 7% of the EUs total NO_x output and has been increasing at a faster rate than other aviation related emissions, despite the opposite trend being seen in other high energy intensity sectors (EASA, 2019).

Water Vapour and contrails are less understood and potentially very warming aeroplane emissions. Water is released by aircraft travelling at high altitudes and increases the humidity in the stratosphere (Lee *et al.*, 2010). This has a high radiative forcing effect and may also contribute to conducting gradients of temperature from the tropics to the polar regions. Water vapour forms ice particles and combine with soot to help form contrails in otherwise ambient conditions. This forms clouds and in areas with high traffic can lead to consistent cloudiness (Mannstein and Schumann, 2005). This has a mixture of warming and cooling effects but is associated with net warming, and exclusively heat retention during the night (Lee *et al.*, 2021). Lee *et al.,* (2021) estimate that the total warming effects of non-CO_2 could be greater than the CO_2 effects and so both need to be strongly considered.

In summary, various emissions have a radiative forcing effect and technological, operational or legislative processes that wish to reduce the radiative force of aviation should be directed at these emissions.

Section 2: Where do emissions come from?

The sources of emissions are not equally distributed and there are a number of ways to analyse the distribution. These include:

- Domestic vs international .
- Private individuals vs Business flight.
- Frequent flyers vs world population.

This section describes the differences in emissions sources to highlight how different policies or behaviours can affect radiative forcing by targeting the greatest sources of emission.

This writing assignment will focus on commercial passenger emissions as commercial aviation accounts for 88% of all aviation emissions and 81% of this is from passenger related emissions. Of the approximately 1 Gt in CO_2 emissions in 2018 this means commercial aviation is responsible for approximately 710 Mega tonnes (Gössling and Humpe, 2020).

Firstly, analysis of international vs domestic commercial aviation suggests approximately 60% of emissions are international whilst 40% are domestic (IEA 2019a). Of the 2.566 billion domestic journeys[2] taken in 2018, 590 million were taken in the USA, 515 million in China, and 116 million in India (IATA, 2019a). International air travel accounts for 1.811 billion journeys per year as approximately 823 million separate 'trips'. International trips are differentiated by region with 25.6% of flying occurring in North America and 22.7% occurring in Europe. The Asia pacific region accounts for 32.5% with the rest of the world combined accounting for 19.2% (Figure 3) (Gössling and Humpe, 2020). Therefore, policies that tackle North America, China, India and Europe will have a greater effect on emissions than policies in other regions.

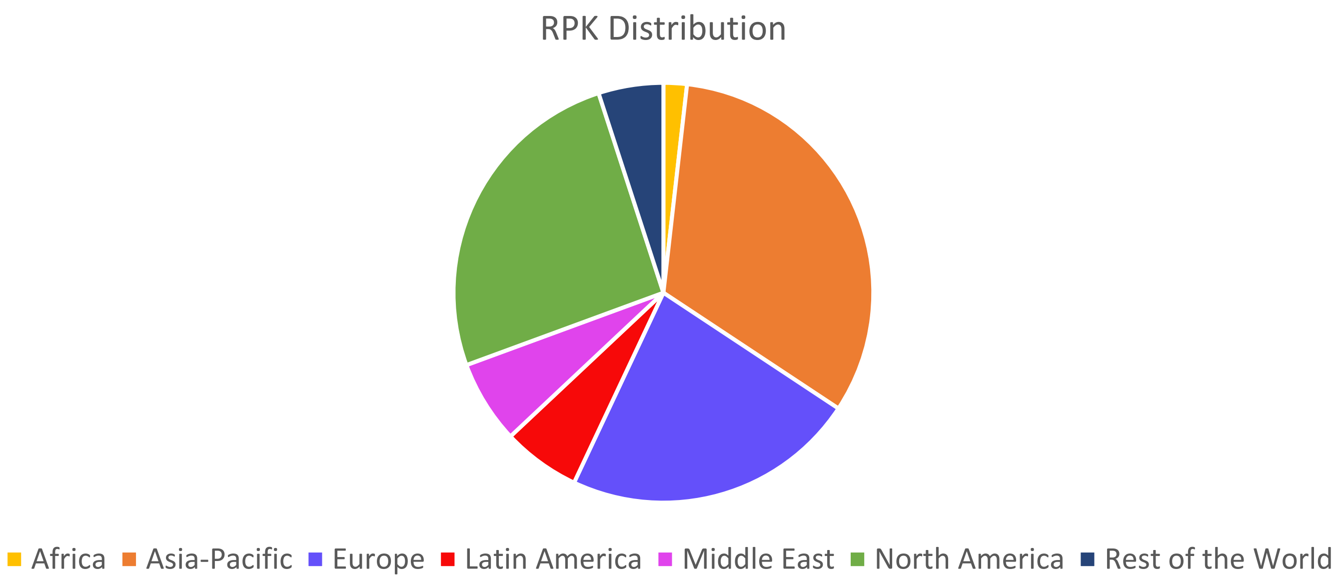

Figure 3. Distribution of revenue passenger kilometres based on global region. Data taken from Gossling and Humpe 2020 and visualised.

[2]Journeys is not the same as flights or passengers. 1 Person going to and from a destination is 2 journeys. A plane with 100 people on is 100 journeys.

Linked to the difference in international vs national are the differences between short, medium and long haul emissions. Flight ranges of above 7000 km make up approximately 20% of flight related emissions despite only making up 5% of total flights. Flights of 3000 km or less account for 90% of all flights taken and contribute around 50% of total CO_2 aviation related emissions (McKinsey & Company, 2020). Flights of less than 500 km make up only 5% emissions. The increase in emissions for long haul (7000 km +) is due to the increased number of passengers they fly, increasing their size, weight and fuel consumption. Additionally, greater distances require more fuel which adds further weight. However, due to having more passengers and flying more kilometres, the CO_2 per revenue passenger kilometre[3] is 75-90 g compared to short haul or regional which have CO_2 RPK of 110 g and 155 g, respectively (Graver, Zhang and Rutherford, 2019). Differences in RPK are due to take-off and ascent being more energy intensive than cruising. Therefore, short haul is more intense per kilometre, but long haul flies more kilometres and so has a greater effect. In the middle sits flights of around 3000 km which have the least carbon intensity.

One way to frame this is that the cumulative tally of all long haul flights (7000 – 13,000 KM) is approximately 20% whilst the much shorter ranges of 0-2000 are approximately 42% emissions, with considerably larger emissions per range of up to 13% (Figure 4). As higher ranges begin to be examined there are diminishing emissions per range; after 3001-4000 emissions permanently drop below 4% per range. This means targeting short haul ranges for innovation allows for gradual increases in ranges for new technologies to affect a disproportional percentage of emissions. This creates two avenues of exploration. One in which short range emissions are targeted for reductions due to the ease of reducing a high amount of emissions *per range*. The other is where long range

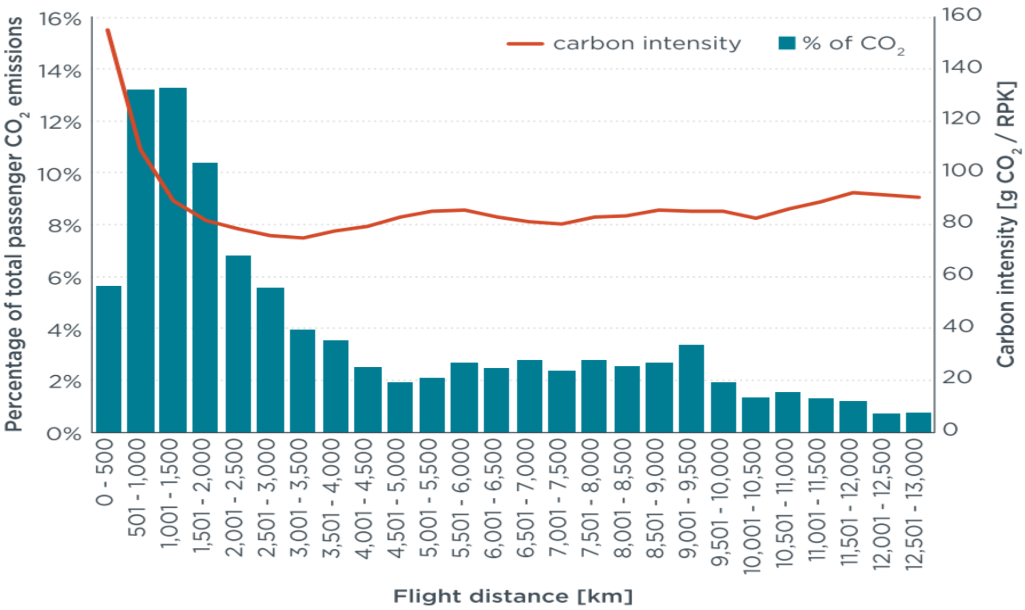

Figure 4. "Shows the percentage distribution of passenger aircraft CO2 emissions (the blue bars) and carbon intensity by stage length (the orange line) in 500 km increments"
Reused from Mckinsey and Company report on Sustainable aviation 2020.

[3] A measure of carbon intensity per passenger over distance.

emissions are targeted for innovation or policy changes due to being caused by a relatively small number of flights and thus a reduction in the emissions of *per flight* can have a disproportionately high effect on overall emissions of aviation.

Analysing frequent flyers against the world population gives an interesting analysis into the unequal distribution of flying. Inequality in emissions is understood with Ivan and Wood (2020) suggesting that top 1% of earners are responsible for 27% of emissions and this is reflected in aviation (Ivanova and Wood, 2020). Comparing world population against the number of flights taken suggests each person on earth flies approximately every 22 months, however, analysis shows that only 20% of the human population have ever flown and this is mostly within high income countries (Gössling and Humpe, 2020). Expanding on this, distribution isn't as clear as developed vs underdeveloped, many developed countries have citizens who never fly. Even in the USA, the greatest contributor to flying worldwide, 53% of the adult population do not fly (Heimlich and Jackson, 2018). Inequality exists within the 20% of those who do fly, with the most frequent 20% of flyers being responsible for 60% of flight related emissions (Brand and Preston, 2010). Therefore, policies that reduce the activities of frequent flyers are likely to have a greater effect than those which target all flyers.

Homing in on frequent flyers allows a brief analysis of the responsibility of business flights versus tourism flights. Business flyers account for only 12% of passengers but account for 75% of profits (Anthony, 2021) partially due to business flyers using first class 70% of the time (Gössling and Humpe, 2020) but is also related to business flyers being less responsive to price changes (Falk and Hagsten, 2019). First class and suites can represent 9.2 to 14.2 x more carbon footprint than economy class (Kwan, 2014). This means organisational policies that reduce flying for their staff will likely make a more proportional impact on emissions than policies that target the population as a whole.

Most of the radiative forcing effects of flying occur during take-off, assent and cruising as described briefly in section 1. However, a portion of the emissions and as such the radiative forcing comes from the ground during taxiing as part of a landing take off cycle (LTO). Typically aircraft use engines on low thrust settings to taxi but this is inefficient (Salihu, 2020). Additionally, aircraft may be forced to stop, using energy idling and accelerating which can increase fuel burn (Hao *et al.*, 2017). It is difficult to precisely estimate how much fuel is used as a proportion of a journey due to differences in journey time, aircraft type, taxi distance and meteorological conditions (M. Zhang *et al.*, 2019a; Kim and Baik, 2020). However, additional taxi-out time in the top 60 European airports is approximately 3.7 minutes which equates to slightly less than 50 kg on a short-range aircraft. Extra emissions at this level tie into air traffic management (ATM) which account for approximately 7%[4] of EU aviation emissions (Performance review Commision, 2021). ATM is for the most part a fragmented and national network which is typically non-transparent. Modifications at this level could lead to some low-tech low investment returns on sustainability through operational adjustments.

To summarise this section, emissions from aviation are global but concentrated into North America, Europe and China. Most of these emissions come from short and medium haul flights. However, a disproportionately high amount come from flights over 7000 km. Many of these emissions are

[4] This refers to the percentage of extra emissions caused by ATM and is not a reference to the foot print of processes such as taxiing or other parts of the LTO cycle.

caused by a very small number of frequent flyers who exacerbate the problem through the use of non-economy classes. Most emissions occur during normal progress during flight but ground operations and air traffic management are also sources. These statements create the frame through which it is possible to assess the following enhancements to sustainable aviation as seen through the lenses of technology, policy and operations.

Section 3: What technological operational and legislative processes have an effect on aviation associated warming?

This section summarises recently published literature found mostly in scholarly journals and company reports pertaining to increasing sustainability in aviation. Information here is presented as described in these reports whereas critical interpretation is found in the discussion.

Section 3.1: Technological related savings.

One mechanism that reduces radiative forcing is reducing the release of CO_2 and NO_x through enhanced aircraft design (Gregg and De Lépinay, 2015). This has always been a strong focus of aviation manufacturers as it reduces the cost for airlines to operate, creating a competitive advantage. Due to this, there has been 52% increase in efficiency since the year 1990, a 36.2% increase since the year 2000 and a 17.3% increase between 2009 and 2017 (IATA, 2019b). The consistent drive to increase fuel efficiencies across these time points reflects the persistent need to aim for more efficient design. This section will summarise some of the recent research describing technology driven efficiency.

3.1.1 – Enhancing efficiency through the next generation of power units

One of the key areas for innovation are the power units of the aircraft. These are the thrust force generating components that move aircraft. The Clean Sky 2 initiative is working with Rolls Royce to produce Ultrafan (Clean Sky, 2018). This combines technologies, aiming to reduce fuel burn by 9 – 12% and NOx emissions by 35 – 40% compared to 2014 state of the art models (Clean Sky 2, 2020). This uses a new geared architecture which enables lower fan speed in the engine allowing greater propulsion efficiency, requiring a much wider diameter of engine (Giesecke *et al.*, 2018). Additional technologies which make this possible include a more compact combustor and a high speed booster both of which are at technology readiness level 5 (Clean Sky 2, 2020).

Another engine type is the Contra-rotating Open Rotor (CROC) engine produced under the sustainable and green engine (SAGE) initiative. 2017 ground tests demonstrated a reduction of 14% of fuel used during operations compared to state of the art 2014 engines. The open engine has an extremely high bypass ratio due to not being encased but does create more noise (Clean Sky 2, 2020).

3.1.2 – Weight reduction through additive manufacturing and design

Reducing the weight of an aircraft by 20% can lead to a 10% fuel saving and so is an effective mechanism to increase efficiency (Zhu, Li and Childs, 2018). Additive manufacturing, also called 3D printing produces lighter weight, more complex and stronger parts than traditionally manufactured parts (Niaki, Torabi and Nonino, 2019). As well as the direct advantages of reducing fuel burn, the indirect advantages are on sight manufacturing reducing logistic footprints and reduced material usage. Products generated from additive manufacturing include the GE leap engine fuel nozzle (25% weight reduction), Airbuses' Cabin bracket (30% weight reduction) and Bombardier's compressor stators and sync ring brackets (50% weight reduction) and Pratt and Whitney's stator blades (50% mass reduction) (Kumar and Krishnadas Nair, 2017; Najmon, Raeisi and Tovar, 2019; Blakey-Milner *et al.*, 2021).

Manufacturing specific parts has the potential for significant reduction CO_2. The 3D printed nacelle bracket of an Airbus320 reduced the brackets entire lifetime CO_2 footprint by 40% for example (Blakey-Milner *et al.*, 2021), however approximately 90% of an aeroplanes weight is the airframe. To date, the largest part of the airframe produced using 3D printing is a partition between the seating area and the gally which has allowed a 45% weight reduction of this heavy piece (Wang, Chen and Yeh, 2019). Concepts exist for biomimetic bird wing like structures to reduce air frame weight that makes use of stronger 3D printed parts (Zhu, Li and Childs, 2018). Closer to actualisation, airbus are currently exploring producing 1 meter length airframe components to reduce the airframe mass (Najmon, Raeisi and Tovar, 2019).

Whilst not directly relevant to commercial aviation, several UAVs[5] have been almost completely 3D printed, including their airframe, considerably reducing weight (Roy and Mukhopadhyay, 2021), however this has been using plastic and so is not transferable to most commercial aircraft produced from metal alloys and on a much larger scale. Research estimates that a saving of potentially 217 million tonnes of green house gases could be achieved by 2050 using additive manufacturing. This uses a life cycle perspective when taking into account current fuel usage and fleet stock regenerations[6] (Huang *et al.*, 2016).

3.1.3 – Increasing laminar flow to increase efficiency.

Another mechanism to reduce emissions is to decrease drag. One advancement in increasing efficiency has been through trying to increase laminar flow through the air (Williams, 2017). Total cruise drag as a result of turbulent flow could be reduced by half with improved design (Beck *et al.*, 2018). Laminar flow technology is based on fixed wing aircrafts that use a 'swept' leading edge on the wing to reduce wave drag (Xu *et al.*, 2021). Having a swept angle of just 20 degrees with the addition of shock control bumps has been able to reduce a drag wave of 18.5% in both computational and wind tunnel experiments (Zhu *et al.*, 2019). Laminar flow is also being explored in the Clean Sky 2 initiative with their BLADE[7] experiments (Clean Sky 2, 2020). BLADE wing tips have already been utilised during test flights with an aim to reduce fuel usage by 5%. Looking to nature for inspiration, BASF and Lufthansa have begun adapting their cargo fleet with added sharkskin technology to reduce drag. The Riblet film has been shown to produce a minimal saving of less than 1% fuel usage but is ready immediately for use (BASF, 2021).

3.1.4 Sustainable aviation fuels

As well as targeting the fuel consumption, another way to reduce emissions, is to reduce the emissions of the fuel itself. One option being explored by the aviation industry is the use of 'sustainable aviation fuels' (SAFs) (Smith *et al.*, 2021) which are one of the International Air Transport Association's (IATA) 4 pillars for the transition to sustainable aviation (IATA, 2021). This is in line with the EUs Renewable Energy Directive II which is seeking for at least 14% of fuels used in the EU to be from more sustainable sources ((RED II) 2018/2001/EU). SAFs can be drop-in SAFs, defined by their ability to mix with currently existing infrastructure, and non-drop in SAFs, which require new infrastructure, such as hydrogen fuel tanks (Muijden *et al.*, 2021).

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[5] Unmanned Air Vehicles

[6] Essentially the rejuvenation of old aircraft with older technology for new ones which is a long process.

[7] Breakthrough Laminar Aircraft Demonstrator in Europe

Popular SAFs include biofuels which fix carbon from the atmosphere during their growth, reducing the overall carbon footprint. Examples of this include fuel generated from agricultural residues which have low 'well to wake[8]' emissions of 259g CO_2 per litre burned compared to traditional jet fuel which has a rate of between 2618 and 3074 g CO_2 per litre burned (Alam, Masum and Dwivedi, 2021; Smith *et al.*, 2021). Other sources can be industrial waste streams, cellulose rich products like wood or fats, oils and grease produced by crops like rape seed oil (Muijden *et al.*, 2021). Rape seed oil in particular is heavily exploited in the EU accounting for up to 38% of biofuel production in all industries (Ecofys, 2019). Anecdotally, around 8% of EU biofuel comes from animal fat stocks meaning it would no longer be vegetarian / vegan to fly (Ecofys, 2019).

Popular biological SAFs include synthetic paraffin derived (FT-SPK), Hydro-processed Esters and Fatty Acids derived (HEFA) and Alcohol derived (ATJ-SPK). These are compatible with existing fuel tanks with maximum blending ratios of up to 50%. Of these HEFA is a mature technology bosting a high conversion of feedstock into fuel of approximately 90% (WEF, 2020). HEFA is able to cut emissions down from 89g to 40g CO_2/MJ when compared to kerosene and used cooking oil HEFA has been used at concentrations of up to 23% in commercial aviation, cutting total emissions to 87% (EASA, 2019; Muijden *et al.*, 2021). Recently certified fuels include Hydro-deoxygenation production routes / Aqueous Phase Reforming. It is similar to HEFA but uses sugars in place of fats meaning it can also take agricultural residues. Due to its high level of technology readiness level it is expected to be implemented rapidly and play an important role in creating low carbon fuel (Muijden et al., 2021).

Under EU guidance SAF feed stock cannot come from land changing of high carbon areas, e.g primary forests, which ensures production of SAFs do not damage other environments (EASA, 2019). One way to avoid this is the use of algae to produce biofuels which can grow in a variety of water conditions and don't compete for land, although current blending limits are only at 10%, limiting their effectiveness (Muijden *et al.*, 2021). To completely remove fuel production from land use, SAFs can come from municipality waste and British Airways have a partnership with Velocy to generate waste based fuel from 2025. This reduces GHG emissions of up to 70% per tonne replaced but also has the indirect effect of reducing methane associate landfill, *and* the fuel contains less contrail associated soot particles (British Airways, 2019).

In addition to the biobased fuels, there are the non-bio e-fuels such as power to liquid synthetic fuels (Drünert *et al.*, 2020). These are generated from hydrogen being reacted with CO_2 captured from either direct air capture or from high carbon industry like steel works. This can be used to create a synthetic gas which once liquefied can be used in a partially modified jet engine as a 50% blend (ICAO, 2019d). If CO_2 is captured from the air and the process takes place using renewable energy and the system boundary does not include the production of the facilities and transport of materials, it can be said that this fuel would be almost 100% carbon neutral (Muijden *et al.*, 2021). Whilst they do require water as a key ingredient, this is less than is required to grow crops or algae and so they outperform non-waste products from bio-fuels on water (ICAO, 2019d). Similarly, they are not associated with issues concerning nitrogen or phosphate deposition that are associated with farming. Synthetic fuels also have less soot and alkaline which are thought to contribute for up to

[8] The overall emissions throughout the whole processes from extraction to burning (Life cycle analysis).

15% of radiative warming through their generation of contrails, providing another benefit to SAF (Gossling *et al.*, 2021).

Due to the factors of cost and availability the current target for SAF usage for 2030 set by IATA is a modest 5% of total fuel (IATA, 2021). However, the One World Alliance of aviation carriers which includes several national airlines, including in the US and UK, have signed up to the WEF recommendation to use 10% by 2030 (One World, 2021). Jetblue have gone one step further aim to reach around 8% by 2023, fixing a ten year deal of SAF that will prevent around 1.5 million tonnes of CO_2 being released (Business Wire, 2021b). For perspective, a substitution of 10% Kerosene for SAF could lead to a modest decrease in CO_2 emissions from 5% - 9% depending on the specific SAF used and so will not be appropriate stand-alone mechanism. Additionally, aviation is expected to grow annually by around 5% per year until 2030, with this growth negating the modest decrease in emission (EuropeanCommission, 2021).

3.1.5 – Hydrogen fuel

Hydrogen is an alternative fuel for aviation. This is attractive due to its high energy density of 120 MJ/ KG which is 3x greater than Kerosene (Baroutaji *et al.*, 2019). This can come in the form of H_2 liquid hydrogen or a Hydrogen cell both of which offer promising reductions in environmental impact of powered flight (McKinsey & Company, 2020). Hydrogen eliminates in flight CO_2 emissions as the burning of H_2 produces water vapour and NOx. Whilst both of these have radiative warming effects the levels of NOx emitted are only 10% of those emitted by kerosene engines (COMINCINI, 2018). Due to the burning properties of hydrogen the NO_x formed may diffuse faster and have a shorter residence time, further reducing the effect of NO_x. Additionally the water vapour that is produced is made from larger, heavier crystals which should precipitate faster and as such have less of a warming effect (McKinsey & Company, 2020). Assuming that hydrogen was isolated using sustainable energy, hydrogen power could potentially reduce the radiative warming effects of aviation from 50 – 90% (McKinsey & Company, 2020). Hydrogen also has multiple production routes, with biological mechanisms also being possible. This includes gasification which uses high temperatures to extract hydrogen from biomass but also includes fermentation and anaerobic fermentation, possible at ambient temperatures. This adds redundancy to the system making it more resilient (Muijden *et al.*, 2021).

Non-drop-in fuels require large changes before these technologies are implementable. This is due to the extremely low temperatures (20 kelvin) requires for liquid hydrogen use. A large cooling system in addition to other adaptations would significantly increase the weight of an aircraft as the specifications of the tanks requires a lengthening of the aircraft's fuselage. The tank would increase proportional to mission length but energy density needs to increase to *at least* 2 KW/Kg including the cooling system before it is viable. Therefore until 2040, hydrogen power is more likely to be used for exclusively short range journeys (McKinsey & Company, 2020).

Currently Zeroavia are producing 'zero emissions' hydrogen fuel cell drive trains for light aircraft with up to ten passengers which can travel for 300-500 miles. This uses renewable energy to create the hydrogen and small wing-based hydrogen tanks to power propellers. However, these will not be commercially available until 2024 limiting their current application (ZeroAvia, 2021). There are additional tests for fuel cells to be used in place of diesel engines for the auxiliary power unit of aircraft which is responsible for features like climate control (McKinsey & Company, 2020). Hydrogen technology is also being considered for the cargo sector. ASL have also recently signed an letter of intent with the aim to retrofit their cargo planes with hydrogen fuel trains and supply them using Universal Hydrogen™ (Business Wire, 2021a). Whilst cargo makes up only around 16% of aviation, differences in the logistic demands of freight versus passengers could make this an area to develop the technology.

3.1.6 – Electric aircraft offer an emissions alternative to carbon based fuels
An interesting but potentially distant technology is the use of electric aeroplanes. Electric motors use an alternating current which powers rotor rotation (Muijden *et al.*, 2021). This is interesting as energy transfer from electricity is more efficient than current propulsion technology meaning less waste (Gnadt et al., 2018). Using electricity to generate propulsion could decouple combustion associated from revenue passenger kilometres and thus reduce CO_2 and non CO_2 related emissions to 0 depending on how electricity was generated (Schäfer *et al.*, 2019). The advantages of this are that electricity is said to have a higher well to wake efficiency than both kerosene and hydrogen. This is because for every 1 KW of electricity generated, approximately 800 Watts can be used to drive the power train of an electric vehicle in comparison to just 380 Watts for hydrogen or 270 Watts[9] for crude oil (Moghbelli, Halvaei and Langari, 2007; Baxter, 2020)

Current options being addressed are hybrid vehicles and 'more electric vehicles' which replace some mechanical and pneumatic mechanisms with lighter electrified systems that require less maintenance (Gnadt *et al.*, 2018). In Hybrid engines an electric motor *and* a combustion engine power a fan, often using the battery for the most intense parts of the journey and thus reducing the CO_2 / RPK to something more in line with a long haul flight (Muijden *et al.*, 2021). This mechanism could also be used to reduce contrail formation in super saturated regions where they are more likely to occur Some older designs have included turbo electric designs which convert gas to electricity with an onboard generator giving greater efficiencies for engines and remove emissions at sensitive parts of the flight which can reduce contrail formation (Friedrich and Robertson, 2015). Building on this, the Airbus E-Fan X uses one electric turbine in conjunction with three kerosene engines (Malkin, 2018).

As battery technology increases there is a movement towards fully electric air vehicles with the forefront of research focussing on short distance, light weight planes (Gnadt *et al.*, 2018). This includes the three fully electric aircraft currently in production which all have ranges of less than 100 nautical miles (185 km)[10] and are designed for two passengers which would therefore not be relevant for reducing emissions for commercial aviation but does give an indication of technology readiness level. Similarly, Rolls Royce have produced the fastest electric plane, capable of over 300 mph, as a one seater propeller plane as a mechanism to push the boundaries of technology (Vaughan, 2020). This one-propellor electric plane isn't capable of replacing commercial aviation but helps with skills development for a range of partners with an interest in developing the technology. The current issue is that batteries have a low gravimetric energy density and may account up to 60% of a typical air crafts weight, reducing the ability to carry passengers and making it less economically feasible (Schäfer et al., 2019). As an example 'Alice' an all-electric 9 seater luxury vehicle with a 820 kWh battery is 51% battery by weight (Blain, 2021).

[9] This figure is slightly outdated and based on automobiles but can be considered in the correct range.
[10] This is about as far as Brussels to Amsterdam

3.2 Operational changes as a low-tech mechanism to reduce emissions.

Without the need for technical advancement, some reductions to the environmental impact of flying can be achieved through operational changes. Operational change in this context refers to changes in the operation of airports, airliners or passengers. These can be enabled by technologies but don't require the technological modification of aeroplanes. This can take the form of alternative taxiing mechanisms, integrated air traffic control and changes to the routes planes take during their destinations. The following section explores how recent developments in operational mechanisms could reduce the radiative forcing of aviation.

3.2.1 – Reducing warming whilst flying

Flight routes are determined by cost and congestion but taking into account their emissions profile at different altitudes has also been discussed (Matthes *et al.*, 2021). Matthes *et al.,* (2021) used simulations to determine that flying at a lower altitude can decrease the radiative forcing effects by 22%. This large saving in radiative forcing is due to a reduction in the formation of enhanced ozone, NO_x and contrails. Additionally, the effects of water vapour are less warming in the already humid lower levels of air. These effects would create a saving of 33% of radiative forcing, however, the increased CO_2 emissions associated with flying through denser air negate some of the savings. Similar operational mechanisms have been suggested to target just contrail formation. By analysing contrail forming flights researchers determined that just 2% of flights over Japan contributed towards 80% of the contrail related radiative forcing in this region. They argued that selectively diverting 1.7% of these flights by modifying altitudes by +/- 2000 feet (depending on the season) could reduce warming contrail formation by up to 59.3%. (Teoh *et al.*, 2020). Building on this, they suggested a low risk strategy where no extra fuel was burnt, thus reducing the emission on long lasting CO_2, that was still able to reduce 20% of contrail related warming (Teoh *et al.*, 2020). Taking this a step further, researchers in the FLYATM4E group began redirecting traffic based purely on warming effect. They found that in high contrail forming weather conditions 50% of the non-CO_2 warming could be reduced with a minor increase of just 0.75% of fuel burn (Lührs *et al.*, 2021).

3.2.2 – Reducing emissions on the ground through efficient taxiing

Innovation in ground operations such as taxiing could reduce emissions. Taxiing is typically performed using aircraft engines and accounts for up to 120,000 kg of fuel used at fort worth international airport[11] daily (Nikoleris, Gupta and Kistler, 2011). A medium aircraft will typically use around 360 kilograms of kerosene if it uses both engines for a 15 minute taxi (Khadilkar and Balakrishnan, 2011). Small stochastic changes in arrival and departure can create disruptions which are then able to increase emissions by up to 6% (Bagamanova and Mujica Mota, 2020).

Changing to using Robotic taxiing systems, such as Taxibot[12], has been simulated to be able to create a reduction of 18% CO_2 emission over a 1 year period with the utilisation of multiple Taxibot units (Khammash, Mantecchini and Reis, 2017). Another Simulation based at Montreal Airport suggested increasing Taxibots could reduce taxiing fuel usage from 67,677 gallons to 5,688 gallons per day (Δ93.6%), when 26 Taxibots were in use (Salihu, 2020).

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[11] A large hub airport.
[12] A semi-autonomous tow-truck.

Solutions that require no technological involvement at all include delaying flights until they can taxi without impediment to take off. This has been simulated to reduce overall fuel usage by as much as 2% in specific airports (Hao *et al.*, 2017). Simulations at Mexico airport were able to support the findings at Montreal airport and were able to decrease emissions by 4.5% by taking an 'Emissions and Delay-Aware stand approach (E-DASA) (Bagamanova and Mujica Mota, 2020). This approach changed taxiing operations in regard to both reducing delays and emissions of aircraft through allocation of gates and organisation of landing/take of cycle. The emissions savings could be the equivalent of off-setting 873 vehicles per year (Bagamanova and Mujica Mota, 2020). The delay vs emissions approach has also been used in simulations that take into account airport specific conditions using Shanghai airport as a case study (M. Zhang *et al.*, 2019b). Using a Pareto analysis Zhang *et al.,* (2019) were able to determine optimum taxiing mechanisms using 'wait points' to reduce delays and emissions. They also measured the effect of this on different aircraft finding that the larger B747 could save nearly 150kgs using a fuel efficient taxiing strategy whilst the smaller A320 saved 28 kg of fuel (M. Zhang *et al.*, 2019b).

In Europe, the addition of the network manager system by Eurocontrol has been implemented at 18 airports accounting for 34% of take-offs in the European flight controlled area. This has saved a taxi-out time of approximately 0.25 – 3 minutes depending on the airport and has saved approximately 34,000 tonnes of fuel which is estimated to be around 7.7% of ground operations emissions and equates to around 25,000 short haul flights a year[13] (Eurocontrol, 2016).

In summary, recent studies looking into modification of taxiing as a mechanism to reduce emissions have suggested mechanisms to reduce radiative forcing, specifically through reduction in CO_2 emissions. This is pertinent in both short haul and long-haul flights. For short-haul flights, small emissions savings can account for a significant percentage of the overall emissions as the overall emissions are lower. For long-haul flights, the greater weights and energy involved on the ground means that efficiency can have significant absolute savings, even if these are only a small percentage of the flight's emissions.

3.2.3 Reducing emissions through air traffic control

An important part of the landing and take-off cycle (LTO) is the descent and ascent operations. Continuous descent operations and continuous ascent operations can be improved on as currently only 33% of airlines have a policy for continuous operations. Data from the EU for 2017 shows a number of airports, especially those in northwestern Europe, have delays during this phase of aviation. Better communication between ground operations and pilots before planes enter their control sphere could reduce the need for non-continuous descents. Improving descent operations could target approximately 145 kg of CO_2 per flight and scaled up the EU operational level annually this could save 0.75 million tonnes of CO_2 (Eurocontrol, 2018b). To use another metric, 145 kg accounts for the full carbon offset of two passengers from London Gatwick to Schiphol on an a320. This area has also recently been improved through a reduction in the distance between aircraft, allowing for greater runway efficiency usage and less waiting times in holding patterns. This was done through analysis of the different vortexes planes make based on their size and wing span and

[13] This is an estimate based on the emissions for a short haul flight (3-4 tonnes).

weather conditions. Based on these variables a time-based rather than distance based separation is calculated which allows more continuous use of runways (Eurocontrol, 2021).

3.2.5 – Voluntary carbon offsetting as a mechanism to offset emissions

Whilst users of air transport have little ability to control an aircraft's component parts its fuel mix or their flight path one action consumers can take is to offset their carbon. Voluntary carbon offsetting is the processes whereby individuals pay a fee for a third party to balance their emissions, often through natural mechanisms like planning trees which will absorb carbon over their life time (Ritchie *et al.*, 2020). Alternatively, companies like Atmosfair can use the money to invest in carbon reducing technologies and thus offset emissions that would otherwise be caused (Gabriel and Sedding, 2018). This is referred to as additionality whereby the action leads to a reduction of carbon that would have occurred in a business as usual situation (World Bank Group, 2016). Currently, the price in the voluntary market for one tonne of carbon offset is around approximately $3-6 (US) (Hamrick and Gallant, 2018). Offsetting can make the individuals flight carbon neutral and has the added benefit of improving air quality in the region where the offset happens and could also be fundamental in reducing species extinction (Li *et al.*, 2018; Zhang *et al.*, 2021). This is a popular mechanism with 80% of respondents saying they would be willing to pay $2 US for a carbon neutral flight and 46% saying they would be willing to pay more at least $20.00 US for a carbon neutral flight (Dichter *et al.*, 2020). At a price of $4 dollars per tonne and emissions of around 4 tonnes for a short haul flight this is a very price efficient mechanism for consumers. The popularity of offsetting is showing an upwards trend with the amount of carbon being offset through Atmosfair™ increasing by 40% in 2018 (Bösehans, Bolderdijk and Wan, 2020).

Despite the ability to offset large amounts of carbon at a low price and an increase in environmental consciousness carbon offsetting for any price is reported to be much closer to 10% of air passengers (Zhang *et al.*, 2021). One reason cited for a lack of uptake of voluntary offset is trust in the offsetting mechanism due to issues with the efficacy, motivation and long term ability of carbon offsetting (Lang, Blum and Leipold, 2019). Co-benefits can increase their attractiveness including environmental benefits, like biodiversity, social benefits like community building or economically benefits like sources of income (Zhang *et al.*, 2021). Rather than trying to make Carbon offsetting more appealing, another option would be to increase awareness and education on how damaging air travel can be as this has been shown to be a potent predicter of carbon offsetting (Lu and Wang, 2018). Lu and Wang (2018) point to the low carbon offsetting seen in relation to aviation as due to the lack of awareness stating that only 30% of Australian and 32% of EU flyers had heard of carbon offsetting. To summarise, voluntary carbon offsetting is an underutilised function which both burdens and empowers the consumer to theoretically reduce the carbon footprint of their flight to none.

3.3 – The effects of legislation on Sustainability

Whilst technological progress may increase efficiency and lead to marginal savings in aspects of aviation, there is growing support for legislation to play a role in curbing emissions (Kantenbacher *et al.*, 2018). Currently there are at least 61 carbon pricing schemes set at bloc, international and national level (World Bank Group, 2020). These include the IATA scheme, CORSIA and the EU scheme, The EU emission trading scheme (Gössling and Humpe, 2020; Heiaas, 2021). Carbon emission schemes could reduce demand through increased prices and use the money generated through schemes to offset emission (Valdés and Comendador, 2021). Curbing demand through a tax rate of $0.4/kg kerosene [14] has been modelled to reduce emissions by up to 13% due to deceased fuel usage suggesting it could work (Valdés and Comendador, 2021). The next section will provide a brief explanation of these schemes and their effects.

3.2.1. CORSIA as a strategy to reduce international aviation emissions

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a cap and trade system generated by the International Civil Aviation Organisation (ICAO); a UN body. The scheme will cap emissions for international aviation at the 2020 level and them offset overshoots. The idea is first to decouple growth from carbon emissions and then begin to reduce net emissions to 50% of the 2005 level. CORSIA will include all operators with more than 10,000 tonnes per year with flights that exceed 5,700 kg take-off weight. The scheme, that has been agreed on by all 193 ICAO members, works as a pilot phase from 2021 – 2023 and then a subsequent first phase and second phase which ends in 2035 (Prussi *et al.*, 2021). The pilot phase is voluntary but 76 states has committed to joining up representing coincidently approximately 76% of the worlds related CO_2 emissions and 88% of current global traffic (Lyle, 2018). This scheme will not affect small, island or landlocked nations or those which have poor economic development (EASA, 2019). However, to booster these smaller nations the ACT-BUDDY scheme was initiated. These are capacity building activities that act as training for less developed countries. Technical experts from donor countries can help less developed countries develop plans for emissions monitoring and regulation. These partnerships encourage greater coordination (ICAO, 2019b). Despite the devastation to the airline industry which has occurred due to covid, the ICAO website suggests the measures will still be activated on the current deadline[15].

Decoupling growth can mean the use of carbon offsetting which has been mentioned previously (Prussi *et al.*, 2021). To reduce the amount of carbon offsetting an airline is obliged to do they may also use CORISA eligible fuel which are SAFs. The SAFs must first be certified by the Committee on Aviation Environmental Protection (CEAP) who can analyse the well to wake emissions of the fuels (ICAO, 2019a). CORSIA has also gone further and created a life cycle assessment methodology paper to help developers understand the logic behind the SAF reductions and how to ensure new fuels meet their demands (ICAO, 2019c). Their stipulations include that fuel must be lower than 90% of the carbon intensity of Kerosene and is not obtained from land with high carbon stock[16] but also relates to more nuanced issues like soil, biodiversity and water usage (Prussi *et al.*, 2021). The amount of emissions CORSIA will offset varies widely between sources. Sources suggest between 0

[14] Which would be a 72% increase in price according to the author.
[15] https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-and-Covid-19.aspx
[16] This is related to the idea of land usage changes.

and 0.3 Gt of carbon equivalents offset pe year will occur between 2020 and 2030 leaving approximately 0.75 Gt of *carbon* emissions each year. From the period of 2020 to 2035 (the period in which CORSIA's goals are set) this would leave to approximately 12 Gt of unmediated emissions. Exempted emissions from other nations would also contribute another 4.5 Gt over this period (Lyle, 2018). Other data suggest a more optimistic 80% of additional emissions from 2020 onwards to be offset as a result of CORSIA between 2021 and 2035 (The European Commission, no date).

3.3.2 UNREDD+ as an effector for offsetting

CORSIA doesn't affect less developed countries but these countries can still contribute towards the offsetting market. The United Nations reducing emissions from deforestation in developing countries (UN-REDD+) programme provides financial benefits for developing countries for carbon offsetting. This created $230 million in revenue for countries which have made significant progress towards carbon offsetting (Lim, 2020). This isn't directly relate to aviation but can be thought of as the effects end of the process where the carbon is offset as many airlines are the supporters of these programmes (Becken and Mackey, 2017).

3.3.2 – EU ETS scheme as a mechanism to reduce the climate impact of aviation

The EU ETS scheme has been developed for reducing carbon emissions in Europe and aviation was added to the scheme in 2008 (EC, 2009, Directive 2008/101/EC). Permits are generated based on historical levels of emissions and slowly reduced to create a squeeze on companies. This creates a market effect where low emitters can sell their extra permits creating extra revenue. As the squeeze continues, there becomes a greater financial incentive to invest in technologies or operations that reduce emissions and advanced the field rather than lose money to the trading scheme (Heiaas, 2021). This was effective at reducing sulphur emissions in the US (Nikopoulou, Cullinane and Jensen, 2013).

EU ETS this has been found to have reduced emissions by around 3.8% between 2008 and 2016 (Bayer and Aklin, 2020). Research into the schemes effects on aviation in Norway, The Netherlands, France and The UK has found that a 10% saving was seen in emissions between 2005 and 2012 due to the implementation of the EU ETS (Dechezleprêtre, Nachtigall and Venmans, 2018). Dechezleprêtre *et al.,* (2018) Found these mostly came during the second phase of the trading scheme where CO_2 per tonne prices rarely fell below 10 euros per tonne. They are also mostly driven by the larger firms. Confirming this is findings from Fageda and Texido (2020) who found 23% reduction in tickets bought on specific routes as a result of the EU ETS based on a difference in difference methodology. This was found to be more effective at reducing the operations of low cost airlines such as Ryanair which work on tighter margins (Fageda and Tiexido-Figueras, 2020). However, other researchers find that savings may be as low as -1.5% and insignificant (Heiaas, 2021).

One mechanism that can be used to assess the difference the EU ETS scheme has made on aviation is through the proportion of cost spent on credits. In 2019, EASA *et al.* suggested it was as little as 1.5% (EASA, 2019), compared to approximately 30% spent on fuel . This suggests it may not be enough of an incentive to change to SAF which as previously mentioned may cost 3-4 times more. Another mechanism would be to compare overall emissions vs offset emissions within EU flights covered by the scheme. Of 163 million tonnes of carbon emissions, 27 million were offset generating net emissions of around 136 million tonnes in 2017. EU emissions were predicted to increase to 198

Mt by 2020, of which 32 were predicted to be offset (EASA, 2019). This shows whilst the cap and trade scheme does help reduce net emissions from the European aviation sector but is a long way from carbon neutrality.

3.3.3 – Market based aviation policy aim to reduce national aviation emissions

In addition to bloc-wide schemes, the effectiveness of individual national policies for reducing aviation have also been examined with a wide array of conclusions. In Europe, several countries have their own carbon pricing initiatives in addition to EU ETS.

In Germany a carbon tax was set for €12.88, €32.62 and €58.73 for short, medium and long haul flights respectively (FCC Aviation, 2021). Research using synthetic data suggests the carbon tax has reduced flying in Germany marginally (2%) but a significant amount of this flight has been displaced to bordering countries without the tax thus reducing the environmental benefits (Borbely, 2019). In the centre of the country where this was not possible the same number of flights occurred at a greater cost suggesting a price inelasticity in this region. Whilst a significant change in flight wasn't observed, approximately €1.25 billion were raised in taxes which could significantly offset the carbon released (Borbely, 2019). However, other researchers focussing on the German aviation tax observed a larger effect using a difference-in-difference approach (Falk and Hagsten, 2019). They found a drop of 9% in flights in 2015 and 5% in 2016, with most of the loss of flights occurring at so-called low cost airports, typically defined by carriers such as Ryanair. They repeat the point argued by Borbely (2019), that price inelastic commuters continued to fly meaning this tax targeted mostly holiday makers and so was unfair (Falk and Hagsten, 2019).

Based on Falk and Hagsten's approach (2019), Warras (2020) analysed the effects of the aviation tax in Norway and Sweden. They found no significant difference in international travel for either country after tax was implemented, suggesting this was price inelastic for consumers (Warras, 2020). Interestingly there was an effect domestically with 10% and 24% fewer domestic flights in Sweden and Norway domestically suggesting that so-called unnecessary flight is reduced (Warras, 2020).

The UK implemented Air passenger duty as a mechanism to reduce CO_2 emissions and raise revenue in 2007. All flights leaving the UK are liable to pay the tax and flights which travel further are given a higher tax. The UK treasury modelled that the tax would cut emissions by approximately 0.3 Mt of CO_2 per year, however recent studies have shown it to have only a modest impact on UK greenhouse gas emissions (Álvarez-Albelo, Hernández-Martín and Padrón-Fumero, 2017).

In Australia the Clean energy Futures levy added up to $24.1 AUD per tonne CO_2 equivalent but this was not shown to reduce airtravel from the period of 2012 to 2014 (Markham *et al.*, 2018). It appeared that airlines did not wavier their price in relation to the tax, thus creating no change in demand for air travel. Whilst this was not profitable it allowed airlines to maintain their market share which is vital for their long term growth (Markham *et al.*, 2018).

In Canada a carbon tax of 30 Canadian dollars per ton of CO_2 has been established and will be levied on all domestic aviation flights (Dichter *et al.*, 2020). This is expected to have significant effects on domestic aviation, especially as the price per ton will increase every year to a massive 170 Canadian dollars per ton by 2030 (Harvie *et al.*, 2020).

New Zealand was the first country to include an emissions trade and cap scheme (ETS) for aviation called NZ ETS. This affected the suppliers of fuel meaning the cost was transferred to airlines indirectly, they could opt in to take the cost which could then allow its transferral to consumers (New Zealand Government, 2016). No research was found on what effect this has had but its worth noting that New Zealand is a highly isolated island nation meaning price demand is less likely to be elastic.

In addition to existing carbon / aviation charges, there are new proposed incentives to reduce aviation related emissions in the Netherlands and France. In the Netherlands a flight tax has been passed by government which introduces taxation on freight and a blanket €7 euros tax on all tickets regardless of destination. Models from Grebe and Kouwenhoven (2019) predict this will lead to 3.2% reduction in flying from the Netherlands. This will manifest as a proportion of passengers travelling by other means of transport (1/2), through a neighbouring country (1/3) or not travelling at all (1/10). In France, the decision has been made to directly curb flights by introducing a short haul flight ban (Macola, 2021). Analysis has shown that whilst only 3% of intra-european flights could be replaced by rail without significant reduction, a large portion of this exist within France (Avogadro *et al.*, 2021). Avogardo *et al.,* (2021) estimate this could replace 20% of seats without an increased wait time, 27% with an increase of wait time of 15% or less. The specific routes which have been banned by the French government include Paris to Bordeaux / Lyon / Nantes / Rennes and Lyon to Marseille. Data based on CO_2 emissions per RPK per typical carrier and air craft that are involved in these routes this will likely create a reduction of 4.8% of flight related carbon emissions for France (Grogan, 2021).

The United States of America is a country that significantly contributes to aviation related emissions through its domestic aviation. Therefore, to tackle aviation, reduction in the US domestic market will be necessary. However, there are no policy schemes, planned or implemented, for U.S. airlines to cap emissions from aviation[17]. Despite this, research has been conducted into how a CORSIA like scheme may work in the US domestic market (Chao *et al.*, 2019). Chao *et al* (2019) concluded that this policy had a 3.5% chance to reduce emissions by 50% compared to 2005 level (an aim of the international policy) but that the most likely outcome was a 20% increase.

Whilst the US does lack an aviation emissions cap scheme that is not to say it is not exploring policy matters to reduce aviation related emissions. The Biden administration has proposed a new tax credit which would cut cost to aviation industries if they were able to reduce their emissions by 50% as a mechanism to promote SAF (The White House, 2021). Similarly, the US also has the Renewable fuel standard which allocates renewable identification numbers to sustainable fuels. Producers of renewable fuels are benefitted by the financial reward associated with renewable identification number in a similar mechanism to how an organisation might purchase a European ETS credit (Wardle, 2019). Similarly to the EU ETS, the price of an RIN changes in accordance to the market (EPA, no date) . To enable this the US is invested in the Farm-to-fly scheme. This is a private-public partnership that promotes the generation of the SAF mentioned previously with specific focus on the biobased fuels like HEFA with the aim to generate a billion gallons of SAF. The advantages of these schemes is the ability to start creating knowledge networks through combining stakeholders.

[17] That is not to say taxes do not exist on US flights, only that these are not specifically aimed at pollution such as the 9/11 security tax or international arrival / departure tax. (Ford *et al.*, 2020).

This kick starts the private organisations involved to begin profitable, scalable biofuel production (CAAFI, 2019).

One interesting idea for taxation of flight is through a frequent flyers levy (FFL). This could work as a scale whereby the more a person flies in a calendar year the higher the fee they must pay each time. Modelling by the New Economics foundation predicted that FFL may reduce the amount of flights taken by the wealthiest 20% of the population by as much as 30%. As this group are the most likely to fly, this is much more effective than a standard blanket flyers tax which appears to have a greater effect in reducing the flying habits of lowest 20% of earners (Chapman *et al.*, 2021).

3.3.4 – European policy initiatives for enhanced efficiency of air traffic control.

Taking an alternative approach to market based measures, the EU created the Single European Sky initiative. SES created functional airspace blocks which are air space regions that optimise flight paths regardless of national border. The key performance indicators for this system are shortest route vs plotted route and plotted route vs taken route as measures of efficiency. The other measured factor is performance in arrival sequencing and metering area where ground level operations are measured. (Muijden et al., 2021).

The European functional airspace blocks are monitored by The Network Manager. The Network Manager is an operational entity that works in Europe to reduce in flight delays by working with operational stakeholders such as airport and airlines and national air traffic control (Muijden et al., 2021). Since becoming operational The Network Manager was able to reduce inflight delay time by 13.3% within 2 years (The European Commission, 2015). An increase in the number of flights has made average delay time per flight go up in recent years from a low of 0.6 minutes per flight to 1.83 in 2018, well above the 0.5 min target set in the air traffic management master plan (SESAR JU, 2020). Interestingly, 23% of delay minutes come from London Heathrow, despite accounting for only 6% of flights providing a clear target for a location to improve in Europe. Assessing The Network Manager using the above mentioned KPIs shows that excess related CO_2 emissions over the period of 2012 – 2017 have been stable. This may initially seem like a negative but this is during a period of growth in aviation which suggests that there is a proportional increase in efficiency. The key areas to work in are still flight during arrival and flight during route which make up 70%˜ of the excess emissions (Muijden et al., 2021). Since those figures were published, the **on route** flight efficiency was improved on from 97.2% to 97.5% by the work manger which would account for approximately 29.7 million kilometres flown at 2019 level (Performance review Commision, 2021). It is worth noting, this level of efficiency is impressive but the limitations of growth are very obvious, especially as 100% efficiency is not possible due to weather and danger conditions. There are other areas where efficiency can still be increased.

Looking forward, to actualise the Single European Sky Europe has also created the public private joint undertaking SESAR which aims to create a more integrated sky through stakeholder management. This has generated a multiphase plan which aims to: increase automation, defragment European air space, begin higher space operations and allow information to travel freely. This aims to reduce CO_2 emissions per flight by 1.6 tonnes from an average of 16.6 tonnes in 2012 (SESAR JU, 2020). This would be a massive 30% reduction in the CO_2 footprint of flights under 1000km which make up nearly 20% of flight related emissions (Muijden et al., 2021).

Discussion:

4.1 Introduction to discussion

The previous section makes reference to various technical, operational and regulatory mechanisms to increase the sustainability of aviation. This section aims to analyse these mechanisms in terms of their feasibility and effectiveness. These mechanisms can also be considered in a temporal context with some being revolutionary but distant and others being limited but ready. In regard to the temporal context it is valuable to remember the IPCC suggests cutting global emissions by half by 2030 to keep warming to 1.5°C (Rogelj *et al.*, 2018). Providing context, figure 5 shows the disparity between how the aviation industry may grow and reductions of emissions needed to counter this.

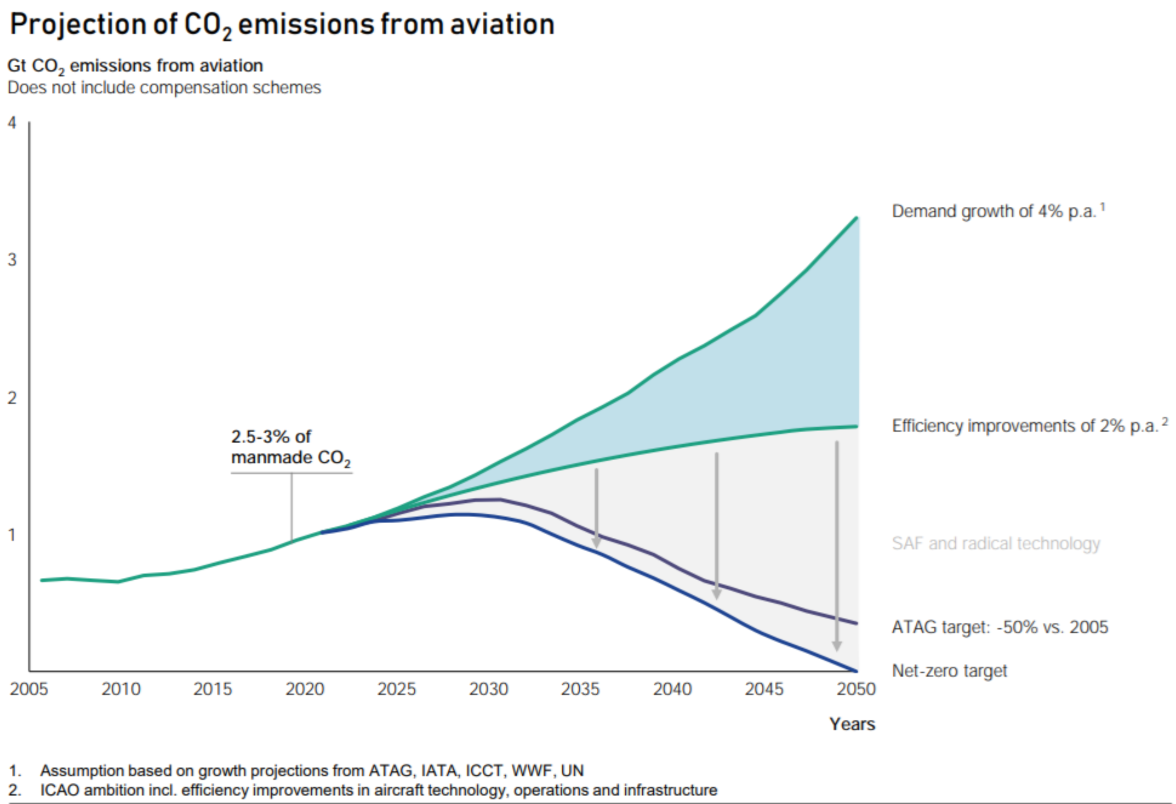

Figure 5– Projection of CO_2 emissions from aviation based on data from international stakeholders. Reused from Mckinsey 2018.

4.2 – Technological changes create efficiencies but these filter into common use slowly.

Since 1998 the concept of zero flight emissions has been suggested to be a technical possibility with hydrogen and battery power suggested to be the forefront (Peeters *et al.*, 2016). Technological innovations are an important mechanism for the development in the aviation industry due to their association with efficiency gains which translates into fuel saving. This is why since 2009 the industry has invested over $1 trillion (US) into new technology (IATA, 2019b). IATA point out that in backlogs alone of new aircraft waiting to enter the market there are already untapped fuel efficiency savings. This perspective also highlights the following problem with technological innovation: Aeroplanes are long lived vehicles with a mean life-expectancy in Europe of around 10 years for passenger and 21 years for cargo planes, and this is growing (EASA, 2019). Life expectancy increases as efficiency improvements are becoming smaller, meaning less fuel is saved by buying newer aircraft, reducing the long-term value of investing in new aircraft. Efficiencies are actually predicted to stall to less than 1% improvement a year through the 2020s (Peeters *et al.*, 2016). This helps explain why by 2050 approximately a quatre of all available seat kilometres[18] are still expected to be carrying 2014 technology (Clean Sky 2, 2020). The implications of this are obvious: a saving in fuel efficiency due to technology does not translate directly into a reduction in fuel burning for the global aviation fleet.

Another general issue with technological advancements is that it can be argued some of them are overhyped. For instance, whilst laminar flow technologies do exist, including those mentioned in the Clean Sky II technology evaluator, they have also been mentioned as far back as 1997. Similarly, hydrogen fuel has been mentioned as early as 1996 and has had a previous spike in publications in between 2008 and 2012. One interpretation of this is that discourse about technologies and 'tomorrow' helps misdirect conversation on carbon emissions today (Peeters *et al.*, 2016). A recent example of this is the Airbus and Boeing Fan X electric engine demonstration has recently come to an end despite years of collaboration (Shahan, 2020). The implications of this are that some technologies are not realised whilst affecting discourse.

Additionally, rapid growth of the industry exceeds the technological savings that occur (Markham et al., 2018). In Japan, adding more fuel efficient Boeing 747's increased the efficiency of airlines fleets by 1.3 Mt of CO_2 but this was cancelled out by increased operational frequency and distance (Kito *et al.*, 2020). In Europe, the years between 2014 and 2017 saw a 2.8% efficiency increase per year, but emissions still increased in these years (EASA, 2019). The implications of this are efficiency savings on an airline scale are dwarfed by the increase in demand on a global scale.

In summary, there is a lag phase between technology development and implementation that slows down reduction in emissions. This problem is compounded by a rapidly growing industry where increases to demand of fuel outstrip efficiencies in fuel usage. Additionally, technology redirects the aviation question from a societal problem to a technological problem. This is despite the fact that as previously mentioned most aviation emissions come from a small group frequently flying.

4.2.1 – Technologies which are available in the short term can create small but immediate reductions in emissions.

Light weighting through additive manufacturing (AM) as well as enhanced design can be a very easily implementable technology shift. To date Boeing has already installed thousands of parts including at least 4 new titanium alloy parts on the new Boeing Dreamliner emphasizing the high TRL of AM (Najmon, Raeisi and Tovar, 2019). This technology has important implications for resource usage as some components were able to save up to 95% of materials compared to normal drilling (Nickels,

[18] Like passenger seat kilometers but ignoring whether they are in use.

2015). It is estimated that 99% of an aeroplanes emissions are exhaust emissions rather than embodied emissions during construction but saving materials has implications for aspects like land use change. Reducing rare material usage can reduce mining and drilling saving emissions elsewhere and keeping ecosystems intact. Another obvious benefit of this is that saving materials and time in logistics makes designing highly precise and specific equipment more affordable (Najmon, Raeisi and Tovar, 2019). As such, it is highly feasible as there is a clear incentive for aircraft manufacturers to adopt these technologies.

Additive manufacturing parts are only partially associated with the lag effects described previously. In a given year, around 10% of engine parts are replaced due to wear. As a result, retrofitted AM parts can enter aircraft more rapidly. However, as mentioned in the results, 90% of the weight of an aeroplane is its airframe and these are not usually replaced until the aircraft is retired (Huang *et al.*, 2016). This means that whilst additive manufacturing can save weight on an aircraft, 90% of the aircraft's weight is unlikely to be affected until changes to the airframe are certified which could take longer. Therefore, light weighting in its current state can be considered highly ready but limited in savings capacity. This may change as new designs for airframes are designed and so this continues to be a useful area of research.

Laminar flow technologies have the potential to be short term emission savers. In 2018 Airbus announced they were nearly ready with the new wing from the BLADE project and it could be released by 2021 (Cummings, 2020). We may not have seen these technologies emerge due to the slim savings. Creating new wings and retrofitting new aircraft with wings is a very expensive processes. Whilst the BLADE wing does produce a 5% fuel saving this is likely to a theoretical maximum and does not take into account a range of problems including that planes have to fly slower to achieve these savings (Mach 0.74 in place of 0.85). Additionally laminar flow is disrupted by moisture or even insects (Wicke *et al.*, 2016). The outcome of this is that unless laminar flow technology improves to create greater fuel efficiencies, and these can be maintained, it is unlikely to be a design priority. Easier fixes, such as the biomimicry cladding which require no change to the actual design of the aeroplane have an immediate affect but are limited to a 1% saving. As such these are highly feasible but would have to be part of a catalogue of smaller technological chances in order to be considered effective.

Biogenic SAF - represents a mechanism through which airlines can reduce their emissions whilst changing very little about their operations making them an attractive prospect. As a result, biogenic SAF are in use today at various concentrations with market demand helping to push innovations in supply (Business Wire, 2021b). However in the very short term they are unlikely to increase massively (EASA, 2019). This is despite reports that the US can currently produce 10 million litres of jet fuel with SAF and has the potential to replace all jet fuel with SAF based on the available resources (NBAA, 2021). There are many biogenic SAFs and so this discussion will mentioned overarching points.

Currently SAFs are unavailable and expensive and as recently as 2016 the reported usage of SAFs in the EU was effectively 0% (Ecofys, 2019). This is despite the certification of HEFA in as early as 2011 (WEF, 2020). Of the previously mentioned fuels only HEFA has a 9/9 TRL and Figure 6 shows its status relative to other biogenic SAFS mentioned in literature (EASA, 2019). If HEFA is able to create such a significant CO_2 saving and newer technologies can build on this, why are there still problems with availability and price?

	HEFA	Alcohol-to-jet[i]		Gasification/FT
Opportunity description	Safe, proven, and scalable technology	—	Potential in the mid-term, however significant techno-economical uncertainty	—
Technology maturity	Mature	—	Commercial pilot	—
Feedstock	Waste and residue lipids, purposely grown oil energy plants[i] Transportable and with existing supply chains Potential to cover 5%-10% of total jet fuel demand	—	Agricultural and forestry residues, municipal solid waste[iv], purposely grown cellulosic energy crops[v] High availability of cheap feedstock, but fragmented collection	—
% LCA GHG reduction vs. fossil jet	73%–84%[ii]	—	85%-94%[vi]	—

Figure 6 – Comparing HEFA, Alcohol to Jet and Gasification via fisher trophic methods of forming biogenic SAF in terms of their maturity, feedstock and potential savings.

Reused from WEF (2020) Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.

Low availability is partially due to status of jet-fuels. In order to be accepted as a jet fuel, fuels must past examination by the American society for testing and materials (ASTM) and the Commercial Aviation Alternative Fuels Initiative (CAAFI) Certification and Qualification (CAAFICQ) team. CAAFI data has been compiled into supplementary figure 1 to provide an overview of how ready the different technologies are. New jet fuel providers have to supply nearly a million litres of fuel to be tested which can be a barrier to entry for smaller scale novel fuels due to the costs. So far only 8 fuels are ASTM certified. Furthermore, the regulations assess safety and performance and not commercialisation which means that passing the ASTM checks is not necessarily an indication of uptake by the aviation industry (Muijden *et al.*, 2021).

A lengthy certification processes and unoptimized supply chains means commercialisation is a problem as SAFs are thought to be in the range of 3-5 times more expensive than regular fuel (ICAO, 2019d). Fuel cost is approximately 30% of an airlines costs and as a result, a 50% blend of SAF + Kerosene would be 2.5x as expensive as a lower end estimation. When considering the US used 101 billion litres of fuel commercially in 2019 alone the scale of a 2.5x price increase becomes apparent (Alam, Masum and Dwivedi, 2021).

Another issue for biogenic SAFs is that they may compete directly or indirectly for land usage. An example of direct land competition is when a farmer is incentivized to grow biogenic fuels on land which was previously natural. This was seen in the US when payments for renewable fuels exceeded the amount farmers were paid to keep their land natural by the EPA (Wardle, 2019). Indirect competition is very difficult to measure but can occur when a farmer reuses their agricultural waste for biogenic fuel instead of to livestock feed. This means livestock owners increase demand for food elsewhere. This raises an ethical problem as an increase in biofuels could therefore be associated with an increase in food prices. The increase in price would most likely be caused by the wealthiest as these people are shown to be the most likely to fly (Gössling and Humpe, 2020). It would likely have the greatest effect on those poorest as common sense suggest these people are the least likely to be able to absorb a food price shock. This could mean a switch to biogenic SAFs reduces carbon emissions for the wealthy at the expense of those who pollute the least: the poor (Ivanova and Wood, 2020). As such, there are questions as to whether biogenic SAF can be produced in the quantities required to sustainable replace jet fuel (Schmidt *et al.*, 2018).

Mechanisms to avoid both the price point problems and the food competition problems have been suggested By Alam *et al.,* (2021). Carinata can produce SAF, coproducts and protect topsoil on farms during winter seasons when nothing is grown on them. If complemented with RIN credits, the break-even price of selling Carinata SAF could be between $0.12 to -$0.66 / L and provide a 65% relative carbon savings compared with conventional aviation fuel (Alam, Masum and Dwivedi, 2021). Another mechanism would be to avoid food stuff and replace this with domestic waste municipal solid waste. The world produces waste ubiquitously and the world bank estimates there are around 2 billion metric tons of solid waste annually, often poorly sorted. Non-reusable plastic, food waste and others could produce around 115 million metric tons of SAF through the gas/Fischer tropic pathway (WEF, 2020). The additional benefit is that often organisations will pay to have these resources removed adding to the economic feasibility.

To conclude, the drop-in advantages of biogenic SAF, abundance of feedstock and large emissions savings make them a timely, relevant and feasible as a mechanism to reduce aviation associated emissions. This is likely to synergise with governmental regulation that gradually increases their price competitiveness. In real terms, the emission of SAF still translates into carbon entering the atmosphere, even if it comes from biomass with a potential to be re-absorbed. This could lead to SAF acting as a stop-gap between the old kerosene burning technologies and newer cleaner technologies such as power to liquid, electric or hydrogen.

More electric aircraft are a short term technological fix which could help develop battery technology and reduce emissions, acting like SAF as a stop-gap until more mature technologies can fill its place.

4.2.2 – Medium term technologies represent large increases in efficiency and harm reduction, but their slow progress may prevent an overall reduction in emissions.

Power trains like the Ultrafan and the CROR are exciting developments for sustainability but may be further away. The CROC is the more developed technology with already existing ground demonstrations showing a saving of 14% of fuel efficiency compared to 2014 models (Clean Sky 2, 2020). However, concerns for CROR are due to its safety issues. Being an open rotor model there is no casing to restrict the blades spinning off. This could cause serious damage to the airframe and passengers within. The rotors are additionally larger and so cannot be retrofitted onto conventional aircraft. This has even led to CROR engineers Safran™ conceding it may not be chosen as a future technology (Cueille, 2019). Despite this Safran have just released new challenge Rise (Revolutionary Innovation for Sustainable Engines) to assert they will try to reach a 20% fuel saving by the middle of next decade. This technology will run on either SAF or hydrogen and be a mechanism to test new technology (Polek, 2021). Whilst encouraging to see the demonstration continuing, one concerning aspect is that the CROR demonstrator has not made any major developments since 2017. The adoption of new buzz word technologies and a new date, pushed back to vaguely 15 years provides lots of new opportunities for funding from programmes like Clean Sky II, without a product that has actually been proved to work. As such the previous CROR, without the new adaptations has been in effect paused at TRL 6. One way to evaluate the new 20% CO_2 reduction by 2035 is to compare it to aviation growth. With a compound growth rate of 2% per year emissions will grow to 135% of today's emissions. As such in real terms emissions will grow and this technology alone would be insufficient to reduce the emissions of the aviation industry.

The Ultrafan by Boeing is less developed and has only recently began construction for demonstration (Rolls-Royce, 2021). The Ultrafan is not one technology but instead a series of technological improvements which combine to complete a new era of propulsion. Like the CROR, revolutionary architecture in adding a gear box into the engine makes this an extra challenge. The current TRL levels of 5 for many of these technologies suggest this could be some way away from being operational. Like the CROR they promise a fuel efficiency saving of 25% and additionally will modify their engine to be 100% SAF run. Previous estimations provided by Clean Sky II suggested that it would be ready for their 2030 target. Clean Sky also predict a fuel saving of a more modest 10% compared to the 2014 level but also mention the impressive potential for 40% NO_x savings (Clean Sky 2, 2021). Whilst the group maintain they will complete the first set of TRL 6 tests by 2022 they have also suggested they may put the project 'on ice' until market demand requires that airlines increase their efficiencies (Sampson, 2021). Therefore, the Ultrafan concept may be an important step to reduction of emissions, especially in NO_x but lack of market demand is likely to prevent it from impacting aviation before growth of the industry exceeds its efficiency gains.

4.2.3 Still distant technologies should be a talking point but not a sustainability strategy until they can be proven at a meaningful scale.

One technology that may remain elusive for a number of years is battery power for reasons of both TRL and energy supply. The promise of battery power is to remove direct emissions from flight but this may be difficult for a number of reasons. Whilst the potential is almost 100% emissions reductions Figure 7 shows that this is directly linked to the electricity generation profile of a country. Therefore in the US, powering with electricity could actually have a 20% greater warming effect than on jet fuel (Schäfer *et al.*, 2019). The answer to this is all electric aircraft should be run on 100% clean energy, however to power only journeys of 400-600 nautical miles (>1200 KM) would require almost 2% of all electricity consumption world-wide (Schäfer *et al.*, 2019). Based on 2019 mix of energy, this would be more than a 1/5th of all clean energy including that which comes from hydropower (Ritchie and Roser, 2019).

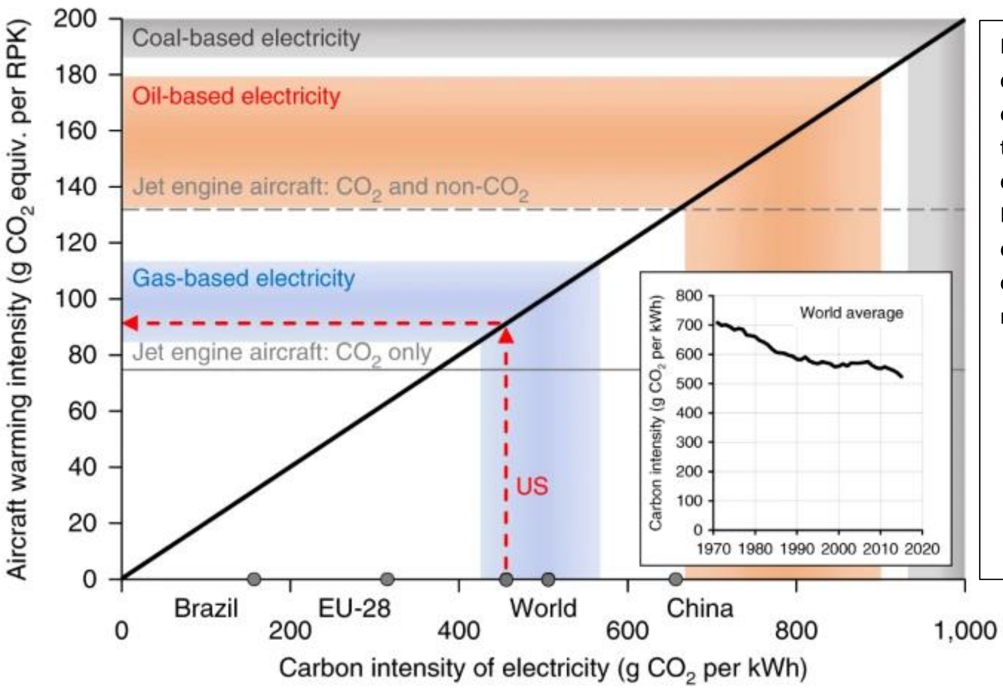

Figure 7 shows how the carbon intensity of electricity generation translates into g CO_2 equivalence warming per RPK. The X axis provides examples of specific states of group of states for reference.

As an aside to the current electricity issue, one of the ethical issues in climate change is the idea of equality or reconciliation. Developed nations have massive historic emissions compared to developing nations and developed nations also typically have higher renewables energy mix. Aviation allows a boost in exporting and tourism and thus has been strongly linked to GDP growth (Blanke and Chiesa, 2013; Kalayci and Yazici, 2016) One argument could be that there should be more pressure on developed nations to invest a higher proportion of their renewables into aviation given the developing nations are still using aviation associated emissions as a means to boost their GDP. This is also relevant as in Europe, limited ability for expansion means growth of the aviation industry is predicted to grow at a slower rate (Eurocontrol, 2018a).

Logistics aside, the reason electricity is considered a distant technology, and the only electric aircraft are short range and light, is the advances in the technology needed. Currently battery technology is capable of around 250 Wh/Kg which is 1.7% the energy density of kerosene preventing it from being used for flights of any notable distance (Schäfer *et al.*, 2019). Battery technology is developing and energy density has improved by up 10% per year, however, currently used Li-ion batteries have a theoretical maximum density of 387Wh/Kg meaning completely new technologies, like Li-sulpher or Li-oxygen must be explored (Crabtree, Kócs and Trahey, 2015; Muijden *et al.*, 2021). The adoption of Li-sulpher batteries could allow a power density of up to 2567 Wh/ Kg but adoption of new technologies means efficiency has the tendency to 'jump' rather than standard progress (Gnadt *et al.*, 2018). This means it is difficult to predict when a battery would have the power density to replace jet fuel would be created. An additional problem is that currently batteries have at least a two hour charge time which is almost incompatible with current airport business models which require high throughput. A swappable battery would have additional implications for airlines as well as a weight increase (Gnadt *et al.*, 2018).

Assuming a battery with somewhere in the region of an energy specificity of 2000 Wh/Kg was possible, when taking into account energy production and life cycle analysis of the battery, a reduction in radiative forcing of approximately 30% is possible assuming a typical modern energy mix of renewables and fossil fuels and all emission were taken into account (Schäfer *et al.*, 2019).

One reason it will be important to keep exploring alternative power like battery power is that global biofuel is predicted to rise by 2% annually to roughly 200 million metric tons in 2030 (Ecofys, 2019). There is a limited potential for biofuel based on land available due to competition with food and so moving away from biogenic fuels will be important if aviation wants to continue to grow sustainability. To use a contextual example, an area about the size of Uganda is required to produce 456 Mt of biofuel (Gossling *et al.*, 2021). Another motivation for this comes from organisations like Tesla who have shown that there is significant demand for battery power from consumers when it is available and have shown technologies which have existed for decades can be galvanised with enough pressure.

For an incredibly in-depth view at all the problems that face different battery technologies see Gnadt et al. (2018) but as a summary; the technology is significantly far from being ready to replace jet-fuel due to the precise chemistry involved with battery charging. Therefore, fully electric aircraft can remain a future mechanism to reduce aviation emissions but should not be part of the discourse on combating climate change for the next 10 to 15 years.

One mechanism to get around issues with battery storage are through hydrogen planes. Their fuel cell technology essentially replaces storing energy in a battery to storing energy in hydrogen which can then generate electricity or be burnt directly. However, hydrogen generation is also a distant technologies due to low technology readiness levels, infrastructure and issues with sourcing.

In order for hydrogen power to be clean, it would have to be produced using renewable energy. To power the amount of electrolysis that would need to supply an average airport would require about two gigawatts by 2050 based on current growth estimates. This is the equivalence of 4 large offshore windfarms. Whilst this is a large amount, there is scope within some countries plans for 2030 to start reaching these targets, although whether countries would want to channel vast amounts of their green energy potential into aviation is less certain (Muijden *et al.*, 2021). Another way to put this is to decarbonizing the aviation sector via hydrogen would require 20 to 30 x more renewables than are currently available as of 2020 (McKinsey & Company, 2020). To use an economic perspective, solar powered hydrogen costs approximately $7.30 (US) per kilo at today's market and is predicted to fall significantly to around $3.20 by 2030. This makes an average price of around 5 dollars per kilo throughout the decade of 2020-2030 making it roughly 10 times more expensive than jet fuel currently (WEF, 2020). Producing hydrogen requires electrolysers which are a surface based material like photovoltaics and fortunately these get cheaper at larger scales per unit cost which means that as hydrogen production increases it becomes more affordable. As the electrolysers double in size they decrease in price per unit by 25% (Schmidt *et al.*, 2018).

Assuming green hydrogen could be supplied the issue becomes connecting hydrogen supply to the aircraft. Unlike drop-in fuels hydrogen power will require significantly different infrastructure to operate. This may include near site liquid hydrogen production facilities, and a change to the way that fuel is added to planes with some suggesting plane refuelling lots may be necessary. The concept of onsite facilities could also be a benefit; hydrogen is incredibly abundant, meaning local sourcing reduces the logistical impacts of transporting hydrogen fuels in place of oil which can be difficult to access (Khandelwal et al., 2013). In the wider context of the environmental damage of oil spills which have occurred at a rate of around 4 times a year since 2000, the local production of hydrogen becomes increasingly appealing (Sönnichsen, 2021). Despite all the changes to infrastructure, the abundance of hydrogen coupled with high well to wake efficiency could see liquid hydrogen fall to within the price range of kerosene by 2050 (McKinsey & Company, 2020). Considering the time scale, infrastructure required and market demand, McKinsey & Company (2020) in consultation with airlines, airports research institutes and governments estimate that if adopted, hydrogen could decarbonise aviation by 40-50% by 2050.

Assuming the infrastructure for green hydrogen existed it would need to be usable in the plane. For short distance flights this would require a weight efficiency index in tanks of 35% and for long range an index of 38%. Current prototype designs provide a 20% index meaning this needs to be nearly doubled before long range flight is possible. Experts suggest this may take as few as 5 – 10 years (McKinsey & Company, 2020). A controversial opinion might be that hydrogen has and always will be 50 years away, but recent pushes from the public and private sector might mean that hydrogen is finally invested in enough to fully explore its opportunities (Kraan, 2020).

In summary, there are both technical and logistical difficulties in the conversion to hydrogen powered flight but incredible emissions savings and recent increases in financial backing may allow hydrogen powered to be realised. Due to the immaturity of the technology and the aforementioned difference between realisation of a technology and its wide scale implementation this is unlikely to significantly affect the emissions associated with aviation for at least another 20 years.

Power to Liquid is an exciting technology that also relies on hydrogen for hydrocarbon manufacture. Whilst this means PtL has the same high cost as hydrogen power it is not affected by the same problems with logistics as hydrogen and can be considered a drop in fuel (Schmidt *et al.*, 2018). As such it doesn't have the issues with differences in refuelling length of a revised refuelling system. This may reduce the overall cost of redesigning the infrastructure of plane refuelling and fuel delivery. To generate the carbon for power to liquid a number of mechanisms can be used including from methanol, direct air capture or industry exhaust capture.

Additionally, the cost could be offset by a number of things, for a starter by high polluters paying PtL manufactures to take their carbon. In a market ramp-up scenario industrial point source carbon would be sufficient to supply all PtL by 2030 dropping fuel price to as low as $2 (US). Although this would need to convert to carbon air capture by 2050 depending on market demand (Drünert *et al.*, 2020). One point mentioned by the WEF is that this shouldn't create a business case for polluting industries to create emissions if fuel producers are willing to buy them (WEF, 2020). Whilst direct air capture is expensive it also represents a breakthrough moment where the manufacture of aviation fuel would be directly removing carbon from the air. In my opinion, and not based on literature, this could create a scenario where energy companies move away from digging oil from the ground and instead synthesize it from the air. This could make countries which are oil poor but renewables rich able to potentially stockpile green fuel for a time when increased oil prices allow them to compete.

Although this technology is still immature relatively speaking, there have been plans to create a 100 MW Power to liquid plant. To produce 100 Kt of jet fuel annually around 600 MW would be required. Investment has also lead to a reduction in price per unit of several thousand euro per kilowatt equivalent to a few hundred in just ten years (Schmidt *et al.*, 2018). Therefore, whilst this technology is still immature and not able to replace jet fuel at any meaningful scale *now*, the drop-in ability and potential to make use of atmospheric carbon makes it a very attractive future prospect. The speed at which this technology is implemented is likely to be strongly related to the efficiencies of carbon capture technology and the pressure to which governments or markets place on low emissions travel (Kim, Dodds and Butnar, 2021).

4.2.4 – Some technologies will be synergistic creating further emissions reductions

Whilst most the technologies above are mentioned in isolation it is relevant that many would work synergistically. New engine types may only be ready in 10 to 15 years by which time the growth in demand of air travel would have negated their emissions reductions. However, given emissions reductions are tied to fuel saving reductions this means more efficient engines create less demand for SAF or Syn fuels. This translates to less pressure on bio stocks or less diversion of renewable energy to aviation.

Conversely some technologies are non-compatible. Whilst SAF and Syn fuels can work in the same tanks as regular jet fuel, hydrogen planes require a completely different type of fuel tank and delivery system. As a result, the planes would change design with elongated fuselages which would be in efficient to reverse back to normal kerosene based tanks.

4.2.5 – Closing remarks on technological mechanisms.

Technological mechanisms are an exciting prospect for aviation to increase its sustainability. The compatibility of some technologies, especially with the operational and regulatory mechanisms which will be explored, means that there could be incredible efficiency savings in the future. Conversely, the non-compatibility of some technologies may mean that clean technologies are left behind to avoid the converging of an aviation sector into, for instance, hydrogen vs electric or electric vs PtL. The current issues with technological mechanisms are they are not ready or used widely enough to help with the sustainability crisis now. Covid-19 has dramatically reduced demand for air travel with some researchers implying the industries culpability for the spread of pathogens (Gössling, 2020). Without exploring the human tragedy of this, the lack of demand equates to reduced emissions. This is due to take some years to recover from and as such removes some of the pressure for climate saving measures to be implemented straight away (Dube, Nhamo and Chikodzi, 2021). This gives the technologies slightly more time to mature and means smaller quantities of alternative fuels in real terms can make up a larger percent of overall fuel mix.

4.3 – General commentary on Operational changes

Huge technological steps are required to achieve sustainability in aviation long term, however, behavioural mechanisms represent a method to make aviation leaner and more effective without the massive investment and long turn-around times. The power of this has been seen in the Virgin Atlantic airways study performed by the national bureau of economic research in the US. They discovered simply informing pilots of aircraft they were taking part in a study saved up to 2.22 million kg of CO_2 over an 8 month/ 40,000 flight period (Gosnell, List and Metcalf, 2016). The limitation with behavioural problems is that they lack the revolutionary aspect of technology. Whilst they can lead to *efficiencies* this tends to be synonymous with reducing harm rather than preventing it. The other limitation is the very human limitation that pro-social behaviours can be reversed and are especially prone to being reversed if they cost time, energy or finance (van der Linden, 2018).

4.3.1 – In flight changes to operation represent possible large savings with limited changes for airlines.

Changes to flying altitudes have been long observed to reduce some of the warming effects of aviation especially around the 30 degree latitude (Frömming *et al.*, 2012). However, this is often associated with increased fuel burn as ascending and descending at different stages of the flight goes against the continuous ascent and descent efficiency bonuses (Eurocontrol, 2018b). This effectively exchanges short term intense warming to longer term less intense warming due to CO_2 emissions. This could be argued to be can-kicking but an alternative perspective would be that it is buying time. On balance, most researchers predicted relatively large savings in radiative warming effects for relatively small increases in CO_2 and so therefore it would be reasonable to engage in these behaviours at least experimentally. This could begin with the smallest disruptions, such as those by Toeh *et al.* (2020) that diversions of 1.7% of the fleet could affect nearly 60% of contrail formation.

The precise effect these mechanisms have is also largely dependent on the new technologies that occur at the same time. For instance, in a scenario where hydrogen based power trains replaced kerosene engines an increase in work done at altitude wouldn't be associated with increased CO_2. In that scenario reducing contrail formation in place of increased work done would be a logical emission reduction mechanism.

The challenges for these behaviours is that the extra work load on air traffic control may lead to problems elsewhere, potentially leading to delays and increased emissions. A related issue is that many of these studies use simulations from one country or bloc which ignores the political fragmentation that still exists in airspace with extreme examples including the current (October 2021) ban for European aircraft over Belarus (Boffery, 2021). An unrelated challenge to behavioural change is related to fuel burn. If changes to altitude require more fuel burn they could become extremely expensive and unappealing to airliners after a switch to more expensive fuels like PtL which could cost as much as 10x more than kerosene (Drünert *et al.*, 2020).

Due to the opportunity to reduce warming whilst potentially only diverting a small number of flights, changes to altitude could represent an interesting mechanism for airlines to reduce their emissions whilst they wait for new technologies to come in. It also shows a shift on focus from only reducing the CO_2 impacts to reducing all the radiative forcing. This is important in the discourse of climate change because it prevents polluting sectors from green washing efficiency as part of their climate strategy if these behaviours lead to other effects like increased nitrogen emissions.

4.3.2 Efficient taxiing is a great first step to reducing ground operation emissions–

Changes to taxiing have been shown to be an efficient mechanism to reduce some of the emissions of the LTO cycle and they have a really high feasibility. It could be possible to first implement really low tech ideas like continuous taxiing methods suggested by Hao (2017) immediately. This low hanging fruit will only create small increases in efficiency but has the benefit of institutionalising more sustainable mind sets. This can then transitions into the Emissions and Delay-Aware stand approach suggested by Bagamanova and Mujica Mota, (2020) where gate allocations and taxiing equipment begins to be considered from an environmental prospective. This then starts to reframe the LTO cycle as an environmental question as well as an efficiency one. These two approaches have no significant increase cost associated for the airport but could already start saving emissions.

Whilst highly feasible, there are still limits to the effectiveness of this strategy in terms of actual emissions saved. As previously mentioned, taxiing out uses about 380 kg whilst a twin jet plane with 100 passengers uses around 2,700 kg per hour (Khadilkar and Balakrishnan, 2011; EASA, 2019). This would mean for a one hour flight, taxiing would account for up to 12% of overall fuel used. This is still an important amount, especially when it can be reduced, but does not make up the bulk of emissions. In Bagamanova they suggest it would be possible to save the emissions associated with nearly a thousand flights a year through changes to taxiing in Mexico city airport (Bagamanova and Mujica Mota, 2020). However, due to the massive amounts of flights at Mexico city airport this translates to less than two days operations (SCT, 2019). In a similar vein, the eurocontrol manager mechanism has also saved around 7.7% of ground operations in the airspace it has authority over equating to 25,000 flights saved which translates to a single month at Schiphol airport, The Netherlands (Royal Schiphol Group, 2021). Therefore to extend on this, the addition of technical features like the taxi bot may be needed. This increases the efficiency of taxiing by 90% but unlike the other measures requires significant investment by airport and so therefore is less feasible than the other mechanism, especially as for the top end of efficiency savings which required an investment of dozens of taxibot robots (Salihu, 2020).

In summary, changes to taxiing represent a low tech, low hanging fruit approach to making marginal savings that can be easily adopted by airports. This could create a new discourse on LTO as an environmental question, especially as airports come under pressure from local communities to cause less environmental damage and pollution. Efficiency always has it limits however and so this can only be seen as a small part of the overall changes that will need to occur to reduce the radiative warming of airports.

4.3.4 – Air traffic control can only increase efficiency marginally and this should become the baseline.

Improvements in air traffic control represents a niche area for improvement that can be important to the whole network of airports. As with the shift to an environmental perspective in taxiing, measuring efficiency operations can become a cultural shift in airport management which once measured can be improved (Eurocontrol, 2018b). This also ties into the temporary 'Hawthorne effect' which shows that participants that know they are under scrutiny can provide positive or desirable results (McCambridge, Witton and Elbourne, 2014). This means by simply asking air traffic controller to start measuring continuous landing or ascent can improve it. Given only 33% of airports give training on continuous ascent and descent operations there is clearly a large segment where this can start to be implemented.

Much like the other behavioural aspects there is a clear and definite limit to efficiency and so this behavioural mechanism can only go so far. This can be highlighted by the air traffic review of 2020 which showed that in flight horizontal efficiency is currently at 97.5% meaning that the boundaries of efficiency will shortly be reached (Performance review Commision, 2021). This is also the case as 100% efficiency is not possible due to safety and weather (especially in a context where contrail forming weather would be avoided). Additionally, some practices are inefficient for air travel but better for ground operations. London airports for instance have a pre-determined 3 min holding pattern which reduces air inefficiency but allows the airport to maintain continuous runway use at its maximum efficiency of 40 landings per hour (Eurocontrol, 2018b). This highlights the difficulty with multi-stakeholder behavioural changes as what can be beneficial to the airliner may not be beneficial to the airport.

Due to the small margins for emissions reductions, the complexity of air space issues and the need to have some diversions as part of normal operations, this area should be optimised as much as possible but cannot be seen as a credible mechanism to reduce the climate impact of aviation. Rather maximum efficiency at this level should be considered the baseline of aviation emissions and short coming in these should be seen as a failure to organise airspace. This is especially true for national airspace.

4.3.5 – Personal Carbon offsetting empowers people but may not be effective.

Criticism of carbon offsetting is that it doesn't reduce the fossil fuel carbon emissions from a scientific perspective. When carbon is released into the atmosphere through the burning of fossil fuels it enters the biosphere where it can be sequestered into organic material. However organic carbon cycles between terrestrial, atmospheric and oceanic carbon giving it a life cycle of between 200 and 200,000 years for 70% of the carbon and a much longer life cycle for the remaining 30%. This means that whilst the carbon can be temporarily locked into an organic life form, like a tree, it does not have an equivalent effect as having not released the CO_2 (Becken and Mackey, 2017). One step further is that some CO_2 offsetting uses the concept of additionality, this is where CO_2 is released in place of emissions elsewhere (World Bank Group, 2016). This essentially accepts that carbon will be emitted but not as much will be emitted, from carbon neutrality perspective this is completely illogical and can be thought of mathematically as one plus zero equals zero. Of the airlines participating in carbon neutrality schemes, only 8% were using temporary carbon reduction methods, such as growing trees, whilst the other were using additionality credits (Becken and Mackey, 2017). Whilst measures like reforestation and aforrestation physically remove carbon from the atmosphere, they are also fragile due to issues like forest fires (Gössling and Lyle, 2021). Carbon offsetting can also be disputed in terms of its effectiveness. A report by the institute of ecology suggested that of the carbon emissions reductions mechanisms 85% of the current schemes were unlikely to cause additional reductions (Cames *et al.*, 2016) . This suggests that most carbon offsetting as a result of voluntary offset does not lead to less carbon entering the atmosphere.

In the short term, carbon offsetting *can* reduce atmospheric carbon from immediately and rapidly increasing and so a number of actions could help enhance this. Firstly greater information and education by airlines as currently airlines are found to have inaccurate or limited information on how offsetting is performed (Becken and Mackey, 2017). Ensuring that the carbon offsetting message comes from a trustworthy source, rather than expertise, has a significant positive effect on purchase intentions for Australian flyers (B. Zhang *et al.*, 2019). Yet offsetting as a longer-term solution is controversial. Some critics view it as an attempt at greenwashing. Many also worry that offsetting might relieve the pressure on buyers to reduce their emissions in other ways: they might feel better by offsetting and not consider enacting other emission-cutting measures (Dichter *et al.*, 2020).

In summary, carbon offsetting by individuals is unlikely to directly mitigate the actions of their flying. It is likely to help support and finance projects which will lead to less carbon being emitted elsewhere. As such it can represent a mechanism to empower those who feel they have to travel by air to try and reduce their climate impact. This should not be mistaken for being given a free pass to fly when it is not necessary. In terms of assessing its effectiveness in reducing the global emissions of aviation we can determine from its low uptake and low ability to prevent atmospheric carbon increasing that it ultimately not a useful strategy.

4.4 – Regulation

Regulation is an important step for the aviation processes with investment in low-carbon infrastructure ultimately being less expensive and better for the environment than high carbon strategies in the long term (Fisch-Romito and Guivarch, 2019). However, research suggests that high-carbon travel is now a social norm and an effective transition requires a policy led approach that can also stimulate moral concepts about flying (Higham, Ellis and Maclaurin, 2018). This is juxtapose to its current state which some consider to be too unregulated, especially as airlines in most countries don't pay VAT or tax on aviation fuel, partly thanks to the Chicago agreement (ICAO, 1944; Falk and Hagsten, 2019). There is currently appetite for more environmental regulation, especially those that are target at the airlines themselves rather than individuals and this may increase the effectiveness and longevity of proposed regulations (Kantenbacher *et al.*, 2018). The popularity of policy and the national appetite for policy is one of the ultimate determinants of its longevity and this can be seen with issues like the Paris agreement which has been signed up to, left and re-entered by successive US governments (Mcgrath, 2020; Milman, 2021). Similarly the UK has recently reduced its short haul air passenger tax by 50% to booster the individuals nations connectivity (The BBC, 2021). Therefore well intended policy is affected by transitions of power and the 'socio-political struggles', making it reversible and sensitive to pressure (Gössling and Lyle, 2021). This next section will analyse the various regulatory mechanisms in terms of their efficacy and feasibility in reducing aviation related emissions.

4.4.1 – The Carbon offsetting and reduction scheme for international aviation (CORSIA) has a limited capacity to reduce global emissions.

CORSIA is able to account for up to 80% of international emissions and so its effectiveness or ineffectiveness will determine whether international aviation is able to become sustainable in the coming decades. The main discussion points for CORSIA are typically

1. Who does it actually affect
2. To those it affects, what will be the effect

The literature is critical of CORSIA based on who it affects. This can be thought of as the scope of emissions covered by CORSIA. Firstly it only covers international aviation which accounts for 60% of all fuel used in aviation (Gössling and Humpe, 2020). Within that 60%, CORSIA only affects around 70- 80% of emissions (Lyle, 2018). In addition, until 2027 the scheme is largely voluntary meaning the exact amount of participation from nations is not known (Gössling and Lyle, 2021). This had led to comments that the that the scheme will not have a great effect until 2027. As the scheme progresses, every time a new nation decides to participate the baseline emissions also goes up meaning there is no standard definition of carbon neutral that countries aim for (Lyle, 2018). Finally, CORSIA was implemented through *Standards and recommendations* meaning it is not binding under international law (Gössling and Lyle, 2021). Therefore, the maximum cover is only around 48% of emissions, countries are not obliged to participate for a number of years and are under no penalties for non-compliance. This had led some to question its ambition and suggest instead it limits the scope of ambition within the industry (Lyle, 2018).

The literature is critical of those effects it has on the affected. This includes that CORSIA hasn't implemented reductions but instead wants to cause carbon offset of those levels of emissions above the 2020 level, which will mean around half a gigatons of *international* aviation emissions will go unchecked (Gössling and Lyle, 2021). Based on the AR5[19] scenario there are fewer than 120 GT left to emit between now and 2100 meaning aviation would be a significant portion of 'available' emissions. As well as ignoring large parts of CO_2 emissions, ICAO also does not account for non-CO_2 affects and these are not mentioned in the resolution (ICAO, 2016). Non-CO_2 effects make up more than half of the overall effects of aviation (Lee *et al.*, 2021). This suggests that even the emissions that are covered by CORSIA won't be reduced enough to help reach the Paris climate goals of limiting warming to well under 2°C.

To help reduce the CO_2 emissions CORSIA relies on carbon offset, the broad criticisms of which have already been explored in the voluntary carbon offsetting section. In specific regard to CORSIA, offsets can be gained through the use of SAF which would have the added benefit of stimulating the sector. The use of SAF in place of kerosene can be considered to reduce emissions compared to kerosene (EASA, 2019). Another benefit is that it has led to the production of ICAOs SAF LCA methodology which provides insight to users and producers of future SAF on how to generate more sustainable fuels (ICAO, 2019c). However, others have argued that the ability to offset will damage the development of SAF unless the carbon price is sufficiently high (Gössling and Lyle, 2021). This suggests CORSIA can help stimulate movement towards more sustainable fuel being used if feed in quotas of SAF are used (Gossling *et al.*, 2021). This may reduce demand of flight in the short term as prices rise and then go on to reduce the price of SAF, reducing emissions further.

In Summary, CORSIA represents an excellent initiative that has brought countries across the spectrum to commit to reducing their aviation emissions. However, the time scale, voluntary nature and limited emissions cover means that it is not likely to bring aviation in line with the required radiative warming reductions that are required by 2050 in order to reduce warming to 1.5°C by 2100.

EU ETS needs to increase its carbon pricing and regulation to be effective.

The EU ETS is the longest standing international carbon trading scheme in the world and the addition of aviation into it has probably helped to reduce emissions in the block as well as increase the efficiency of EU flights compared to their counterparts (Chao *et al.*, 2019). Interestingly the EU ETS scheme for aviation works as a useful example of how legislation can be altered counter productively. The EU ETS scheme initially also contained emission from extra-EU nations but the 'stop the clock' legislation pushed them back to 2024 to allow CORSIA to be implemented (Heiaas, 2021). This show the relative fragility of these systems. As a result the EU ETS covers around 9% of global emissions (Hemmings, Pache and Forsyth, 2020).

Under the EU ETS the emissions of EU aviation have grown by 28% suggesting that for a cap and trade system the EU ETS certainly isn't capping emission growth of aviation (Heiaas, 2021). One of the reasons for this is that aviation can unilaterally buy credits from other industries. This means they are relatively cheaper for aviation compared to other sectors. Effectively this means the increase in emissions in aviation is offset by decreases elsewhere but also means there is little

[19] This is one of the scenarios described by the intergovernmental panel on climate change based on simulations using current data on emissions vs temperature.

incentive for the aviation industry to cut their emissions. Another reasons for this was available credits have actually occasionally exceeded emissions meaning there has been no real cap affect (Ellerman and Buchner, 2007). An additional problem is that like CORSIA, EU ETS are not focussed on non-CO_2 warming effects. Analysis shows that means that under EU ETS only carbon emissions will go down, whilst radiative forcing will increase (Larsson *et al.*, 2019)

Despite criticism, the EU ETS scheme for aviation has been modelled to have had an effect on aviation at very little financial cost to the aviation sector (Dechezleprêtre, Nachtigall and Venmans, 2018). It is possible this is an example of the aforementioned Hawthorne effect and simply having the carbon saving metric in mind means aviation operators try to reduce emissions increasing. Another benefit of the EU ETS scheme is that it helps support CORSIA with some suggestions CORSIA can be used for extra-EU flights, e.g. London to Amsterdam whilst EU ETS can be used for internal bloc flights or domestic flights like Amsterdam to Eindhoven. This means overall more flights can be covered if these policies synergise (Larsson *et al.*, 2019).

In summary, the EU ETS scheme is not predicted to be sufficient in its current form to enable the EU to meet the necessary reduction in aviation related emissions (Larsson *et al.*, 2019). Additionally, low-global coverage means there are limits to the amount of emissions the EU ETS could actually help control. Most research suggest that the EU ETS has reduced carbon emissions, it is just simply not enough. Therefore the answer could be ramping the scheme up rather than abandoning it. This is in line with research that suggests flights in the EU are still severely undertaxed (Hemmings, Pache and Forsyth, 2020). To conclude, higher carbon prices and enforced regulation are required to allow the EU ETS scheme to reduce European aviation emissions in line with the 2015 Paris agreement.

4.4.2 National regulations can help reduce emissions immediately but have limited scope and may be reversed.

Carbon taxing in countries has been identified by The World Bank and mitigation specialists as a key mechanism for reducing the GHG emissions of nations (Markham *et al.*, 2018). This is due to individuals being more supportive of mechanisms that target corporations that have trickle down affects than consumers directly (Kantenbacher *et al.*, 2018). Based on the relatively positive response of individuals on market based measures, it has been asserted the most effective mechanisms would be national and international policies of increased CO_2 price and forced feed in quotas to stimulate the required reduction in aviation emissions (Gossling *et al.*, 2021).

Criticism of market based measures are that they rely on aviation using a cost benefit analysis to invest in new technologies in the long run so they avoid paying the carbon taxes. However, the price of much of the technology in aviation is so expensive and the new technologies so immature that this can often simply translate to the price being passed onto customers (Markham *et al.*, 2018). Whilst research shows that higher costs are associated with lower demand, reducing emissions, this isn't considered fair as it tends to target people on lower incomes (Falk and Hagsten, 2019; Chapman *et al.*, 2021).

A response to this might be that fair or not, lower emissions are lower emissions but figure 8 from is a reminder that it is only around 12% of flyers take over half the share of flights. The significance of this is that these frequent flyers can often be business trips which are more likely to be in business class, accounting for a higher proportion of energy use, and are less sensitive to price changes (Brons *et al.*, 2001; Gössling and Humpe, 2020). As a result, whilst a small proportion of people will no longer fly, this is unlikely to have a proportional effect on emissions. Similarly, some countries have inelastic flights due to geography. Norway, Sweden and the UK are all long countries with not direct attachment to central Europe and so price hikes here have been shown to not be affective at decreasing flight (Álvarez-Albelo, Hernández-Martín and Padrón-Fumero, 2017; Warras, 2020).

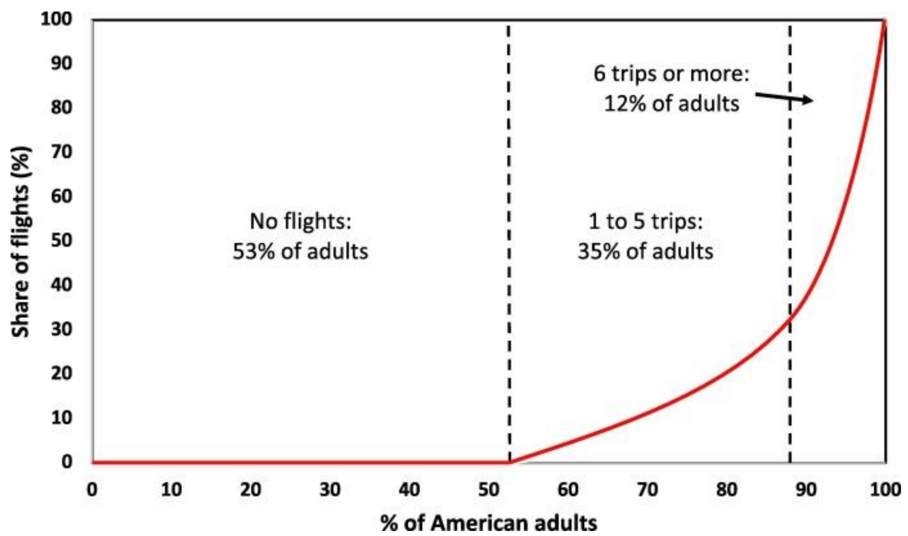

Figure 8. The share of flights taken from 3 segments, the 53% of American adults who do not fly, the 35% of adults who take 1-5 trips a year and the share of adults who take 6 trips or more a year. Reused from Gosling and Humpe 2020 - The global scale, distribution and growth of aviation: Implications for climate change.

Another criticism of national regulation is that they can lead to people simply hopping boarders to fly (Borbely, 2019). This can reduce their popularity with governments as high capacity aviation is related to economic growth and shifting that over to a neighbour or rival isn't good policy (Dimitrios and Maria, 2018). This is especially relevant in Europe where countries are small but is also relevant to the United States boarders with Canada and Mexico. Fortunately, this is not the case for India or China. A counter argument to this is that as nationally determined contributions become a greater market pressure under the Paris Agreement, displacing aviation to a neighbouring country could be a useful strategy to reduce a nation's emissions whilst enjoying the benefits of a close by airport.

Frances mechanism of banning short haul flights is thought to reduce the emissions by around 4.8% (Grogan, 2021) Whilst this is less than a 5% reduction in CO_2 eq emissions (not including non-CO_2 emissions), it has a direct effect on supply and thus also reduces potential future growth, making it less susceptible to being overcome by increases in demand when compared to other mechanisms like taxation. It has the added benefit of causing increased rail usage, allowing more infrastructure investment which was previously mentioned as a lower-cost mechanism to reduce emissions. However, aviation organisations make the arguments it is self-defeating as short haul flights would be the testing ground for some of the aforementioned technologies including hydrogen power and electric flight (Macola, 2021). This is also supported Mckinsey and Company (2020) who show that only 6% of emissions come from flights of less than 500 km.

Unlike the penal mechanisms in Europe the US has gone for a rewards based mechanisms, offering tax cuts to those who fly more sustainably (The White House, 2021). This is an interesting approach that could potentially be self-defeating from a sustainability point of view. An airline which increases their SAF mix would be subsidised and thus potentially cheaper, allowing a greater number of RPK and therefore more emissions. However, research suggests that tax breaks don't necessarily relate to significantly increases in service (Sobieralski and Hubbard, 2020). Whilst the tax breaks are an attractive opportunity it is also worth reflecting again on Markham's (2018) assertion that lack of readily available cost efficient alternatives to kerosene is a big boundary. Therefore, an airline operating profitably is unlikely to incur a large cost of SAF only to get the equivalent in tax breaks unless pushed by consumers. Consumer pressure has been shown to affect all aspects of a supply chain and so is a possible outcome (Wu, Zhang and Lu, 2018).

In summary, national mechanisms represent an opportunity to create discourse around sustainability and create inroads in reducing the emissions of industry. Their flexible nature makes them difficult to predict in the long term and the balanced nature of trying to appease business and reach international targets can water them down. National mechanisms also represent a political bottom up approach where nations begin to lead by example rather than wait for what is fair on an international stage. Whilst national aviation regulations are currently not reducing emissions significantly to reach Paris targets, they may present the bridge between a great technologies conception and the technologies use by creating incentives to upgrade technology faster.

5.1. Possible aviation Road map

This report has described technologies, operational changes and policies which are able to reduce the radiative forcing effects of aviation. In practice, innovation does not happen in silos and as a result it is likely a combination of options would be used to mitigate aviation emissions. This section will suggest possible combinations of mechanisms to reduce the radiative forcing of aviation. This is based on a range of assumptions which can all be challenged and is mostly illustrative. It represents one set of scenarios but many scenarios are possible which can have dramatic effects on the trajectory of emissions in the aviation sector, as described by the German Aerospace Centre (Leipold *et al.*, 2021).

First a baseline figure of equivalent emissions of around the 2018 levels of 1.4 gigatons of CO_2 eq (Gössling and Humpe, 2020). This also does not include private flight, cargo flight and military flight meaning this represents around 70% of emissions. Industry growth is given the arbitrary value of 1.5% per annum. That means between 2021 and 2050 the aviation industry could be expected to emit 53.3 Gt CO_2 eq if unchecked (Figure 9). This is just under half of the Gt emissions left using the

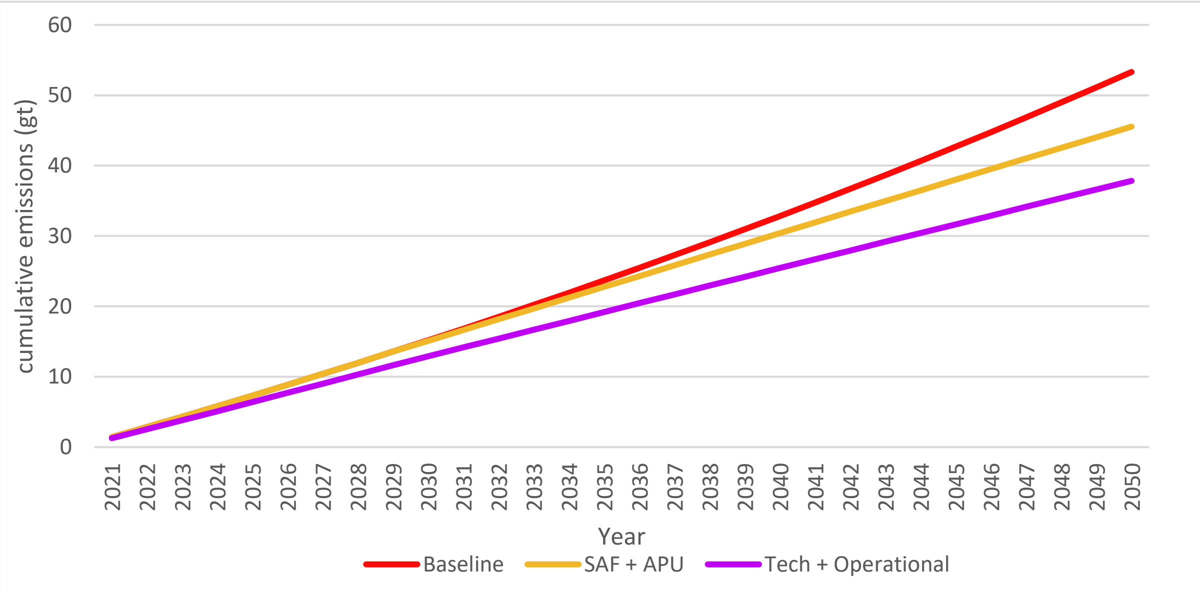

Figure 9. RED: Baseline emissions based on a 1.5% growth rate of the aviation industry from 2021 to 2050. Yellow: The effect of SAF and next generation APU (CROC / UltraFan) on emissions assuming specific rates of implementation. PURPLE: The effects of SAF + Next gen APU + various operational changes that could be made in synergy on cumulative emissions between 2021 and 2050.

AR5 scenario ‘available emissions’. Based on these figures, various mechanisms will be applied to measure how the cumulative total emissions are affected.

SAF is one of the four pillars of IATA’s sustainability drive. Assuming an adoption rate of 10% by 2030 and an increase in SAF and extra 2% used per year until 2050 50% will be used by 2050. If the SAF is considered to be 90% less carbon than traditional fuel this will create a saving of 5.6 Gt until 2050 bringing the emissions down from 53.3 Gt to 47.4 Gt without any other measures. Combining this with newer power units such as the ultrafan, an 11% CO_2 saving and a 35% nitrogen emissions saving is a reduction in 10.75% of the radiative forcing. Assuming 10% initial adoption by 2030 and 5% yearly adoption this will save an additional 2.2 Gt until 2050 bringing the total emissions down to 45.5 Gt CO_2 eq for the combination of SAF and advanced power trains.

SAF and advanced power trains can be combined with operational changes such as European single Sky *or* contrail avoidance strategies. Integrating airspace are popular as they are shown to increase capacity, reduce costs and are predicted to reduce the radiative warming of aviation by 10% (Debyser and Pernice, 2021). If this was applied globally and grew at a similar predicted rate to in Europe (8% per year) it could decrease emissions by 4.0 Gt on top of SAF and advanced power trains meaning final emissions are 41.5 Gt until 2050. Because contrail avoidance strategy goes against the principles in the single sky policies they are not synergistic. Therefore it must be considered separately. Assuming it was implemented immediately it could reduce contrail formation by 20% creating a 10% saving in RF at very low risk (Teoh *et al.*, 2020). If only the low risk strategy was used this would create a 4.55 Gt saving. This scenario will assume anti-contrail rather than single sky measures were adopted as this creates a final emissions of 41 Gt. Additionally, the single sky measures requiring greater international cooperation makes them less feasible.

Euro-controls efficient taxiing was predicted to save 7% of taxiing emissions. Given the high proportion of flights which are short haul, taxiing can have the arbitrary value of 10% of a flight emissions. Using the same assumptions as for single sky with all airports scaling this up until 2030 this has a tiny saving of 0.4 Gt . Therefore real innovation will have to take place to taxiing if it is to be used to increase sustainability in aviation. In the context where taxibot would be used in place of eurocontrol and all airports had fully electrified their ground vehicles by 2030 than 3.7 Gt emissions could be saved by 2050 bringing the cumulative emissions down to 37.8 Gt.

Combining the short and medium term technical and operational changes has provided a new baseline of emissions, market based measures can then be applied to this value to characterise their effects (Figure 10). CORSIA has a specific mandate of limiting emissions after roughly 1.4 Gt until 2030 after which it will begin to offset emissions until emissions are half of the 2005 level. Therefore it can be anticipated it will only offset 2.42 Gt from between 2021 and 2050 assuming the previous mechanisms are used. This means combining CORSIA + the technological and operational changes 35 Gt CO_2 eq are emitted.

If the EU cap and trade system is applied to all flights that enter, leave or are contained within the EU it affects 22% of global commercial aviation. In Scenario 3 of the EU ETS roadmap carbon offset cap requires all carbon is offset by 2030 (The European Commission, 2020). In a scenario where this was used in conjunction with the other technical and operational measures and CORSIA, this would lead to a reduction in 1.14 Gt meaning cumulative emissions of 34.3 Gt until 2050. Given this only affects 22% of the total flying emissions this is significant as when applied to the rest of the world this scenario would mean a saving of 15.7 Gt of carbon at meaning cumulative emissions of 22.1 Gt. This is highly aspirational as it assumes complete carbon capture from offsetting and complete international compliance but is shows that there is still a strong need for policy changes and international cooperation to reduce aviation emissions. It also shows the need for international policy to start accounting for the non-CO_2 effects in order to reduce radiative warming.

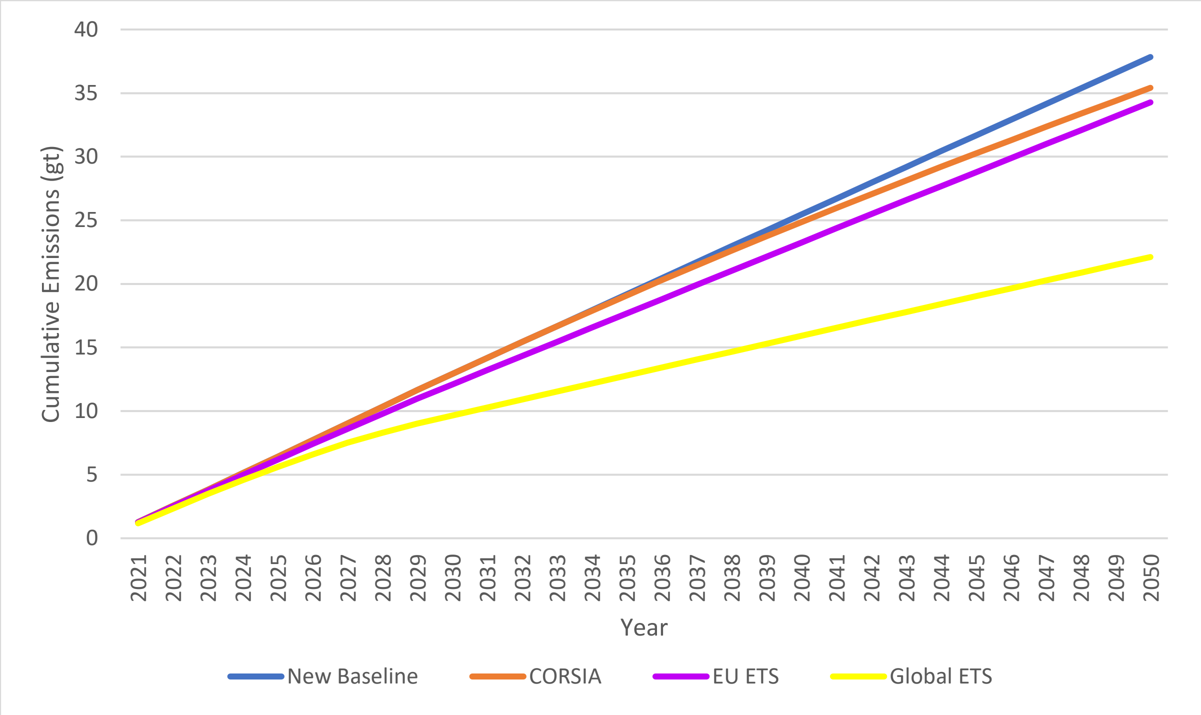

Figure 10. The cumulative emissions (CO_2 eq) between 2021 and 2050 under different scenarios. BLUE = The baseline of emissions if available APU and SAF are used and operational changes are implemented. Orange: The cumulative emissions if CORSIA is implemented at scale to offset emissions over 2020 levels. Purple: The cumulative Emissions if EU ETS is used in the EU on a cap and trade scenario presented by the European commissions without CORSIA. Yellow: Global implementation of an emission cap and trade on the cumulative emission from aviation used in place of CORSIA.

In summary technologies and operations will not be sufficient to reduce significant radiative warming by 2050 and so policies to negate or offset emissions will be required. However due to non-CO_2 emissions being ignored, policies will need to be enhanced to prevent significant warming.

6 – Concluding remarks.

The aviation sector is making impressive strides in increasing efficiency and developing future technologies. The current strategy appears to be to reduce emissions where efficiencies are financially feasible within current business models. This is conflating efficiency with sustainability through the perspective that every tonne of CO_2 saved is a tonne closer to carbon zero. This is combined with an assumption that future massive changes to technology, such as hydrogen, electric or PtL will rescue the aviation sector from a sustainability crisis. Therefore current measures are based on reducing the emissions *until* the next level technologies take over, working as a stop-gap. Government policies seem to mirror this perspective by trying reduce demand through taxes and offset charges. Reducing emissions in the short term whilst generating revenues to reduce further emissions through additionalities or direct removal schemes like tree planting. However, lack of reducing supply means that as the sector slowly increases in size, these marginal savings are negated. Additionally, most policies, operations and technologies are focussed on carbon and so there is significant oversight on what could account for up to 66% of the radiative forcing of aviation.

The combination of waiting for the future to save us and only tackling some sources of radiative forcing means that current policy, technology or operations will still lead to massive emissions from this sector. It is worth noting that IATA and CORSIA themselves also only intend to reduce emissions by 50% compared to 2005 levels by 2050 and this so isn't surprising. They do still have the potential to significantly reduce the amount of radiative forcing that comes until 2050 and this can be enhanced by ensuring that available methods are used. Most measures, like SAF, will incur much greater prices and this is likely to have the feedforward effect of reducing demand. If this can be complemented by effective offsetting than aviation will be responsible for less warming by 2050. There also needs to be a focus on improving other low carbon infrastructure to provide feasible alternatives. However, like all sustainability mechanism the wider system will have to be measured and the problem not simply shifted elsewhere. The wider question remains how much aviation should be used by individuals or organisations and what their role can be in achieving a less than +1.5°C world.

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