SUMMARY

The transition to low-carbon aviation cannot rely on technological solutions alone. Government regulations are also required to increase the cost of aviation emissions. Due to the urgency of meeting the global emissions reduction targets set out in the United Nations 2015 Paris Agreement, it will be necessary to implement these regulations within the next decade.

This paper examines the current "*Sustainability Strategy*" laid out by senior figures from the world's leading aerospace manufacturers – demonstrating why the solutions proposed will not contribute to effective decarbonisation, in the necessary timescales, without crucial emissions pricing.

It highlights the **urgent need** to question our industry leadership (who may well have retired in 5-10 years' time) about their assumptions for future aviation emissions.

1. INTRODUCTION

Recently, awareness of climate change has become heightened. It's widely understood that flying is one of the most environmentally damaging activities in terms of energy use and emissions. Therefore, one of the most effective things we can do, to reduce emissions, is to limit air travel.

There is a moral imperative, and equally a strong business imperative, to acknowledging this. The companies who prepare most robustly for an inevitable shift in market conditions will emerge most competitive over the next couple of decades, and will be best placed for future growth.

Unfortunately, these developments have resulted in a strong response from the aviation industry to avoid air travel reductions. There have been attempts to mislead the general public, investors, politicians, and colleagues about the impact of flying – and the actions required to limit it.

In this paper I'll examine each of the '*sustainability*' solutions commonly proposed by the industry, and attempt to unpick the reality behind their claims. Hopefully this will be educational, insightful, and will convince **you** to start planning for a future of high emissions pricing.

2. INDUSTRY SUSTAINABILITY STRATEGY

In mid-2019, under increased pressure from climate activists, the world's largest aviation companies released a joint statement at the Paris Air Show, setting out the industry "*sustainability strategy*" [1]. This downplays aviation's environmental impact, and contains numerous other misconceptions that are regularly repeated through marketing and news stories on this subject. Each of these topics are scrutinised below.

3. ENVIRONMENTAL IMPACT

The aviation industry is eager to highlight that flying *only* produces **2-3%** of global CO_2 emissions [1].

This is true, but it's still a significant amount: if aviation was a country, it would rank amongst the top 10 emitters [2], ahead of nations like Brazil, Mexico, and the UK. Furthermore, when projecting forward, we expect other sectors to decarbonise. This means it may produce closer to **25%** of global CO_2 emissions by 2050 [3][4]– a **very** large share.

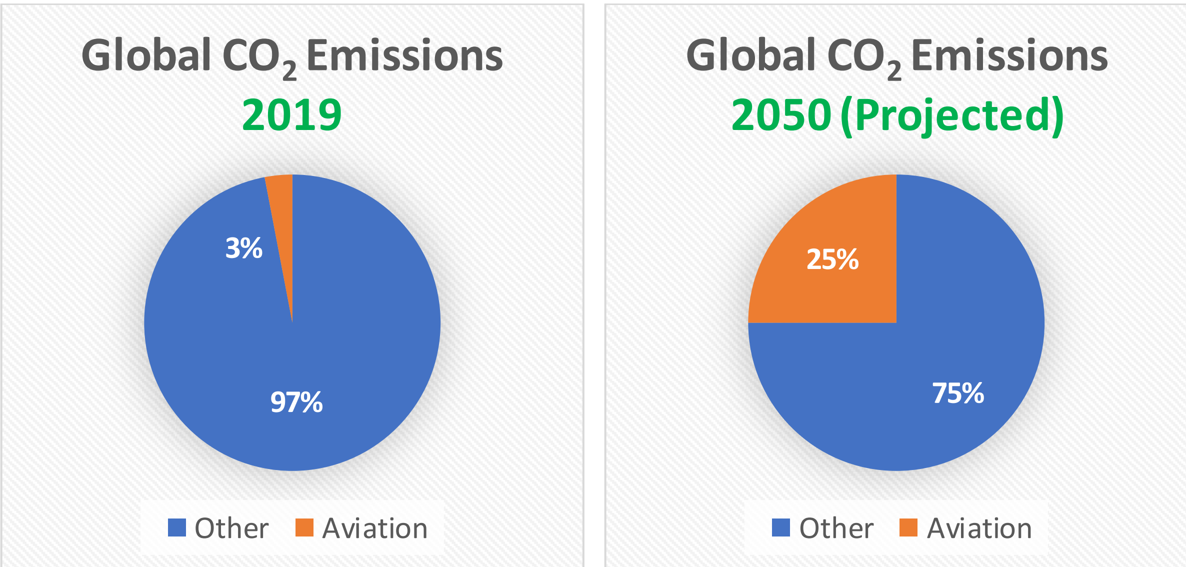

Figure 1: Aviation's Share of Global CO_2 Emissions, 2019 (current) vs. 2050 (projected)

It's also important to understand the effects of non-CO_2 emissions such as nitrogen oxides (NOx), and water vapour contrails. The latest science estimates that the non-CO_2 impacts from flying have an even greater global warming effect than the CO_2 emissions and comprise about 2/3 of aviation's net radiative forcing. These contribute such that aviation emissions are currently warming the climate at approximately **three times** the rate of that associated with its CO_2 emissions alone [5]. This should dispel any perception that aviation's total climate impact is relatively small.

Despite this, non-CO_2 impacts are not accounted for in any existing regulations: the national greenhouse gases (GHG) inventory submissions to the UNFCCC, the CORSIA scheme (see Section 8.), nor the EU Emissions Trading System (ETS). They are currently dismissed by the International Civil Aviation Organization (ICAO) as being too scientifically uncertain to warrant necessary action [6]. This draws unfortunate parallels with the tobacco industry and fossil fuel industry's tactics of emphasising scientific uncertainties in cancer and global warming studies [7][8].

4. EFFICIENCY

The next common misconception is that flying can be decarbonised by making aircraft more efficient every year. Efficiency gains are enabled by improved operations, more aerodynamic wings, use of lighter materials such as carbon fibre, larger engines (for greater propulsive efficiency), and higher temperature and pressure capable materials in the engine cores (for improved thermal efficiency).

This leads to misleading statements such as: "*since the advent of jet technology, carbon-dioxide emissions from aviation have reduced by 80%*" [9] and diagrams like this:

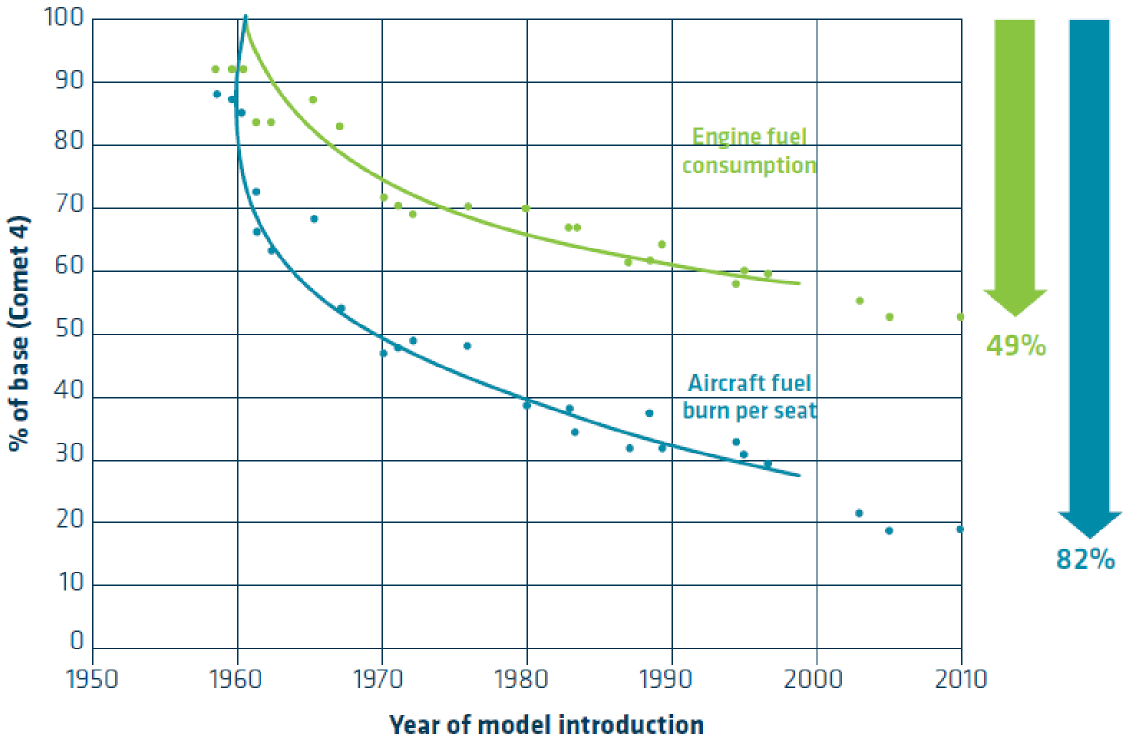

Figure 2: Fuel efficiency gains since the early jet age [10]

It's correct that these improvements have resulted in emissions reduction **per passenger mile flown**. However, they've also resulted in a **reduced cost of flying** and meanwhile, the last few decades have also seen a rapid increase in global wealth. The Australian airline *Qantas* say that in 1947 an Australian earning an average wage would have taken 75 weeks of saving their entire salary in order to afford a return flight to London. Today, they can save enough in less than 1 week [11].

This combination of lower cost flying (enabled by the efficiency gains), coupled with an increased global population who can afford to fly, has resulted in a **rapid growth** in air travel (doubling every 15 years) that has far outstripped the efficiency savings:

Figure 3: Historic Air Traffic Growth (Revenue Passenger Kilometres = RPK) [12]

Prior to the COVID-19 pandemic, Airbus had projected that air traffic will double again by the mid-2030s, and then again by 2050. This would amount to an **8-times increase** from year 2000 levels.

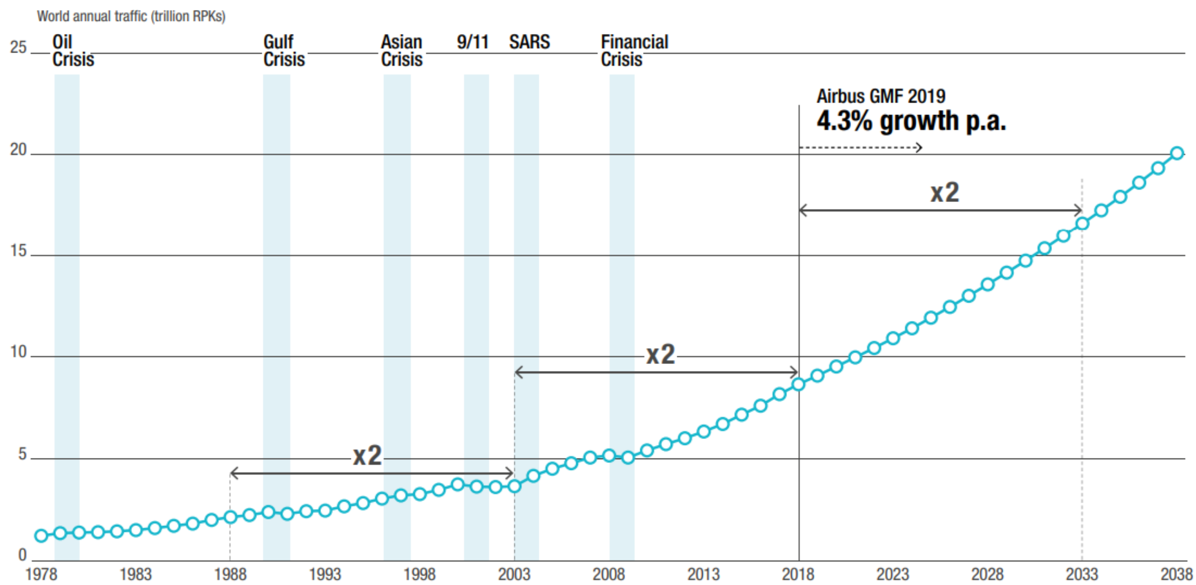

Figure 4: Projected Air Traffic Growth (Revenue Passenger Kilometres = RPK) [12]

The earth's atmosphere isn't affected by emissions per passenger mile, but rather by total emissions produced every year. This has been **rapidly increasing**, rather than decreasing:

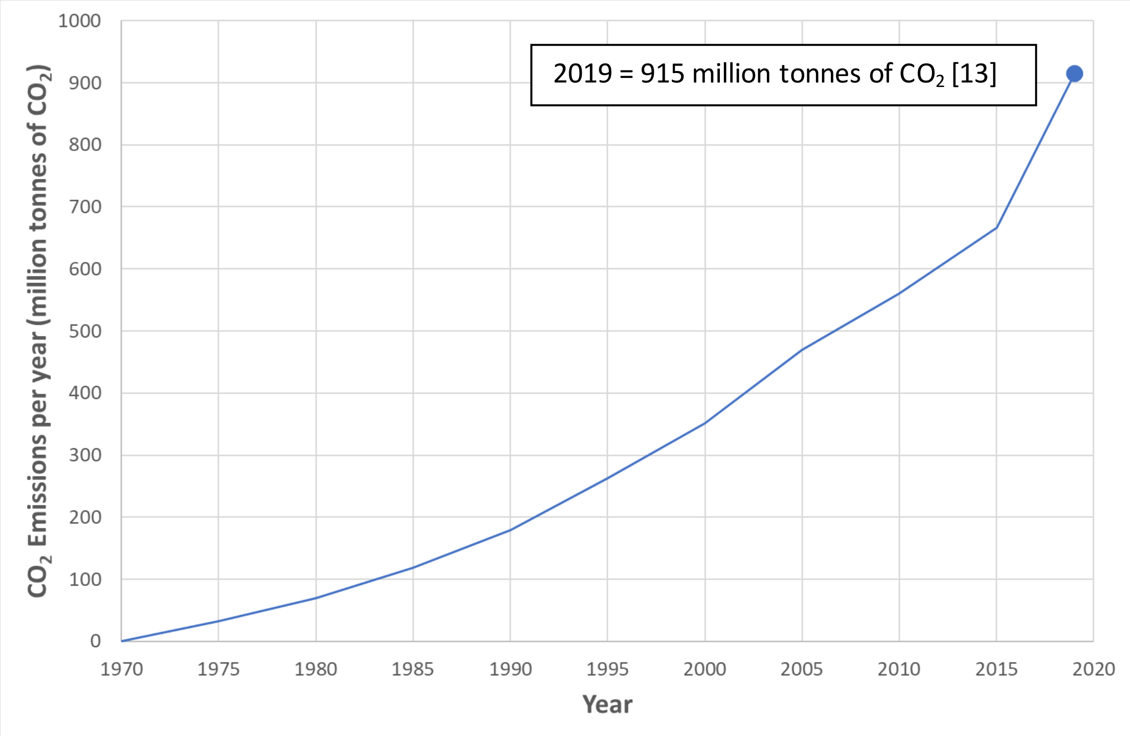

Figure 5: Total Annual Aviation CO_2 Emissions (1970-2019)

We should project that aircraft emissions will continue to grow on a similar trajectory if efficiency improvements continue. Unless: **effective regulations are applied** to limit air traffic growth.

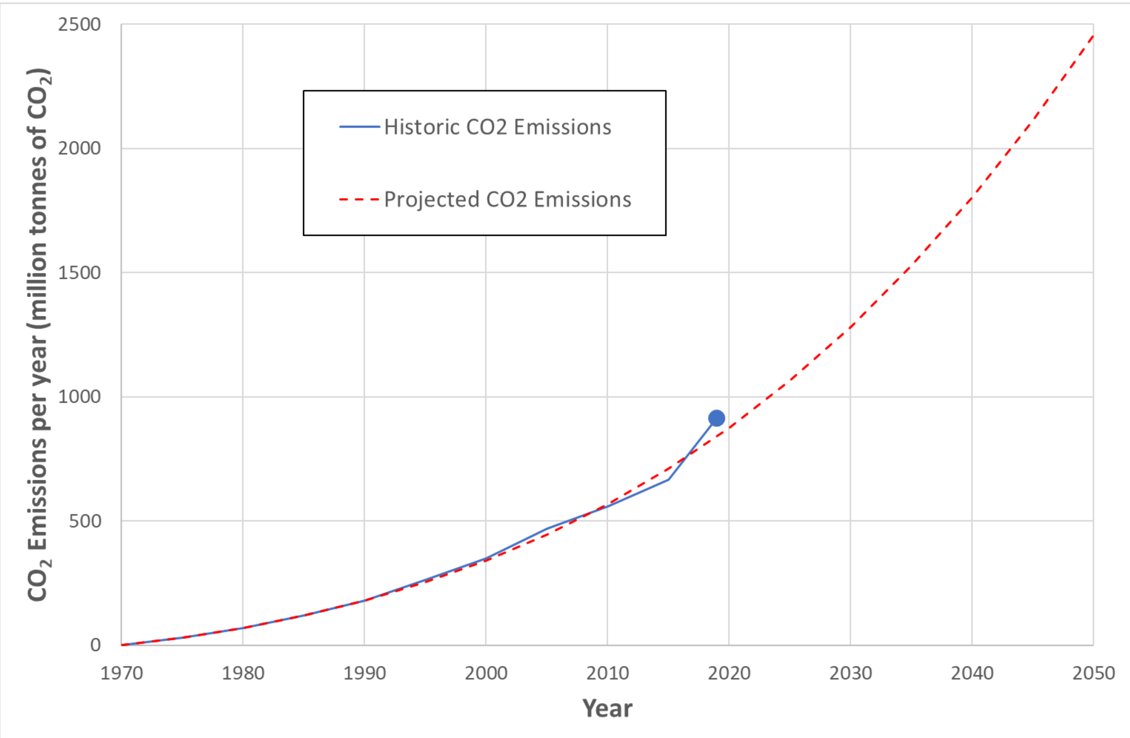

Figure 6: Total Annual Aviation CO_2 Emissions (1970-2019) and Projected CO_2 Emissions Trend

The key takeaway here is that in a **poorly-regulated** industry, efficiency improvements may be used to grow the market and increase emissions, not reduce them [14]. Therefore, efficiency gains don't de-facto result in reduced emissions or energy consumption, and cannot be relied upon in isolation.

5. ELECTRIC FLIGHT

Another common misconception is that electrification will soon help us to fly while producing zero emissions. There's been talk of a 'third era' of aviation: first there were propeller aircraft powered by piston engines, then airliners powered by jet engines, and now the *age of electric flight* is apparently upon us [15].

As an aerospace engineer, there's a lot to get excited about: new electric aircraft developed by start-ups like Eviation and Lilium are really breaking the mould of conventional design. Electrical systems allow us to unlock new aircraft and engine architectures, such as distributed propulsion:

Figure 7: Eviation Alice [16], and Lilium Jet [17] aircraft – both featuring forms of distributed propulsion

However, this is only a near-term (i.e. next 10 years) solution for very short-range flights, with a very limited payload: e.g. an aircraft carrying fewer than 10 passengers, flying for less than 1 hour.

It's a medium-term (i.e. next 20 years) solution for regional flights, but these are really a competitor to public transport such as: coach, rail or ferry services. Those are more efficient modes of transport and are a better use of the limited low-carbon electricity we're able to generate from renewables (generation won't be decarbonised for decades, so we need to minimise energy consumption in order to reduce fossil fuel use).

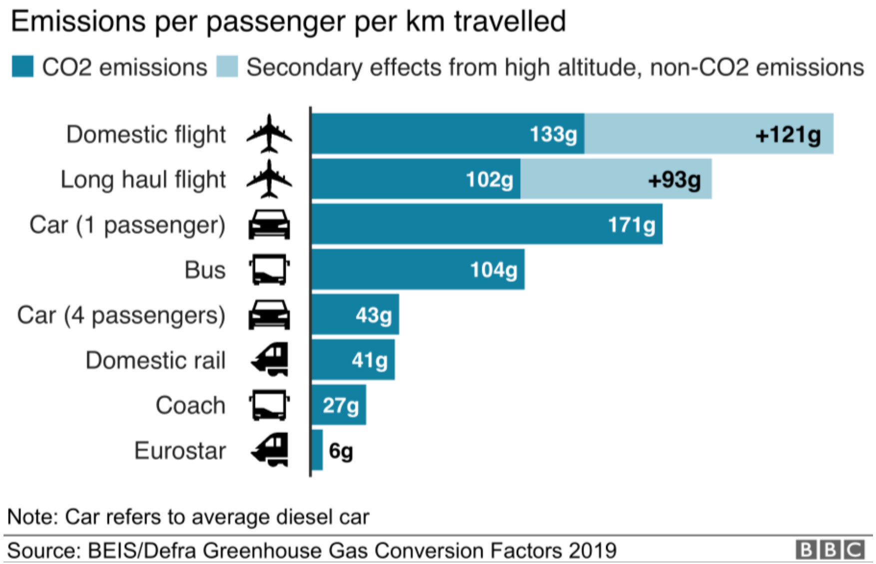

Figure 8: Emissions from various modes of transport (all fossil fuel powered, showing relative efficiency) [18]

Crucially, it isn't a competitor for most commercial flights: as 80% of aviation emissions come from passenger flights further than 1,500km, and electric flight can't compete at that range [14].

The issue is that current electrical motor, generator, transmission, and storage (battery) technology is far too heavy to displace jet fuel and engines. As such, electrical technology will only augment the jet engine for the foreseeable future: e.g. more-electric engine accessories such as electrical fuel pumps, for pumping jet fuel into the combustors.

The Chief Technology Officer of Airbus has stated that "*even assuming huge advances in battery technology, with batteries that are 30 times more efficient and 'energy-dense' than they are today, it would only be possible to fly an A320 airliner for a fifth of its range with just half of its payload*" [14].

The key takeaway is that electric flight will not help the current climate crisis. We'll exceed the global carbon budget for 1.5°C of global warming within the next decade or so [19]: before electric flight is viable, and before we've decarbonised electricity generation.

6. HYDROGEN FLIGHT

Airbus recently unveiled three "ZEROe" hydrogen powered aircraft concepts. They've marketed these as the "*first climate neutral zero-emission commercial aircraft*" [20].

We're likely to see small and medium aircraft powered by hydrogen over the next couple of decades, and hydrogen does look good at first glance of its chemical properties. For example:

- hydrogen (fuel cell) power can only produce water – there's no CO_2 or other GHGs produced
- hydrogen has a high energy density with respect to weight:
  - on a mass basis, it has nearly three times the energy content of jet fuel
  - 1kg of hydrogen has 120 MJ of energy, versus 44 MJ for jet fuel, and 1 MJ for batteries

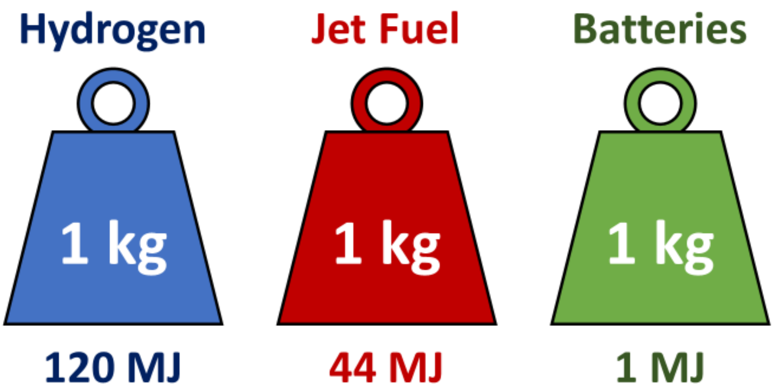

Figure 9: Relative mass energy densities of different fuels

However, it has some critical disadvantages:

- hydrogen fuel cells require electric motors etc. with associated high weight
- hydrogen combustion may produce NOx (which is a GHG)
- both methods produce water vapour which has a global warming effect [5]
- hydrogen has a lower energy density by volume than jet fuel
  - it exists as a gas in atmospheric conditions, so needs to be compressed or liquified by cooling it to extremely low temperatures (-253°C) to achieve a reasonable volume – this requires a lot of energy, and results in complex and heavy storage containers
  - even liquid hydrogen has a density of 8 MJ/litre whereas kerosene has a density of 32 MJ/litre, so the equivalent energy storage requires 4x the volume:

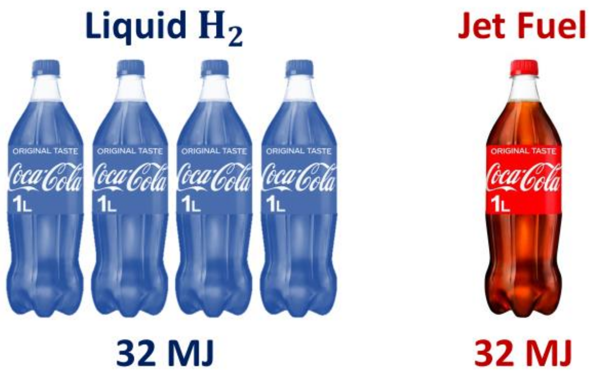

Figure 10: Relative volume required of Liquid Hydrogen for equivalent energy in jet fuel

This high volume will require a re-design of medium & long-haul aircraft fuselages and either:

1. Increased aircraft size, increasing drag at a given flight speed:

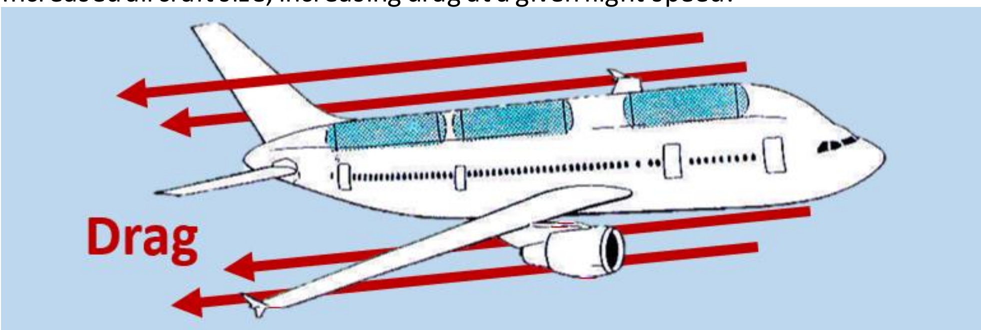

Figure 11

2. Identical aircraft size, but reduced numbers of passengers:

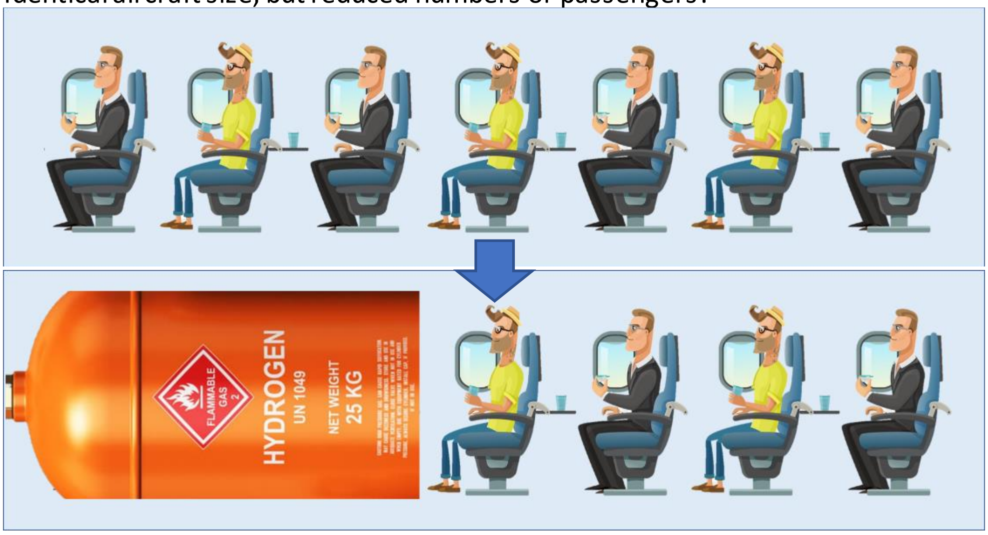

Figure 12

Both of these options will increase the cost of flying: as the result is either a loss of efficiency, or the flight cost being spread between fewer paying customers.

Hydrogen production is also an issue:

- the majority used today is still produced from methane (a fossil fuel) [21]
- until the electrical energy supply has been completely decarbonised, producing it using electrolysis (from water) will still generate carbon emissions [22]

- electrolysis is inefficient and very energy intensive
- liquid hydrogen is currently **5-6 times** the price of jet fuel [23], and it will take many decades to become cost-competitive in an unregulated market

Fundamentally, hydrogen flight is possible, but we have a very long way to go until it's a reality for most air travel. Where it is introduced, it will also remain far more expensive than fossil fuel powered flight. Unless: **effective emissions pricing is applied**.

7. SUSTAINABLE AVIATION FUELS

The industry claims that the solution to this energy storage problem is to keep burning jet fuel. However, this will be created from carbon already in the atmosphere, rather than from fossil fuels extracted from deep underground (which emit additional carbon to the atmosphere when burned):

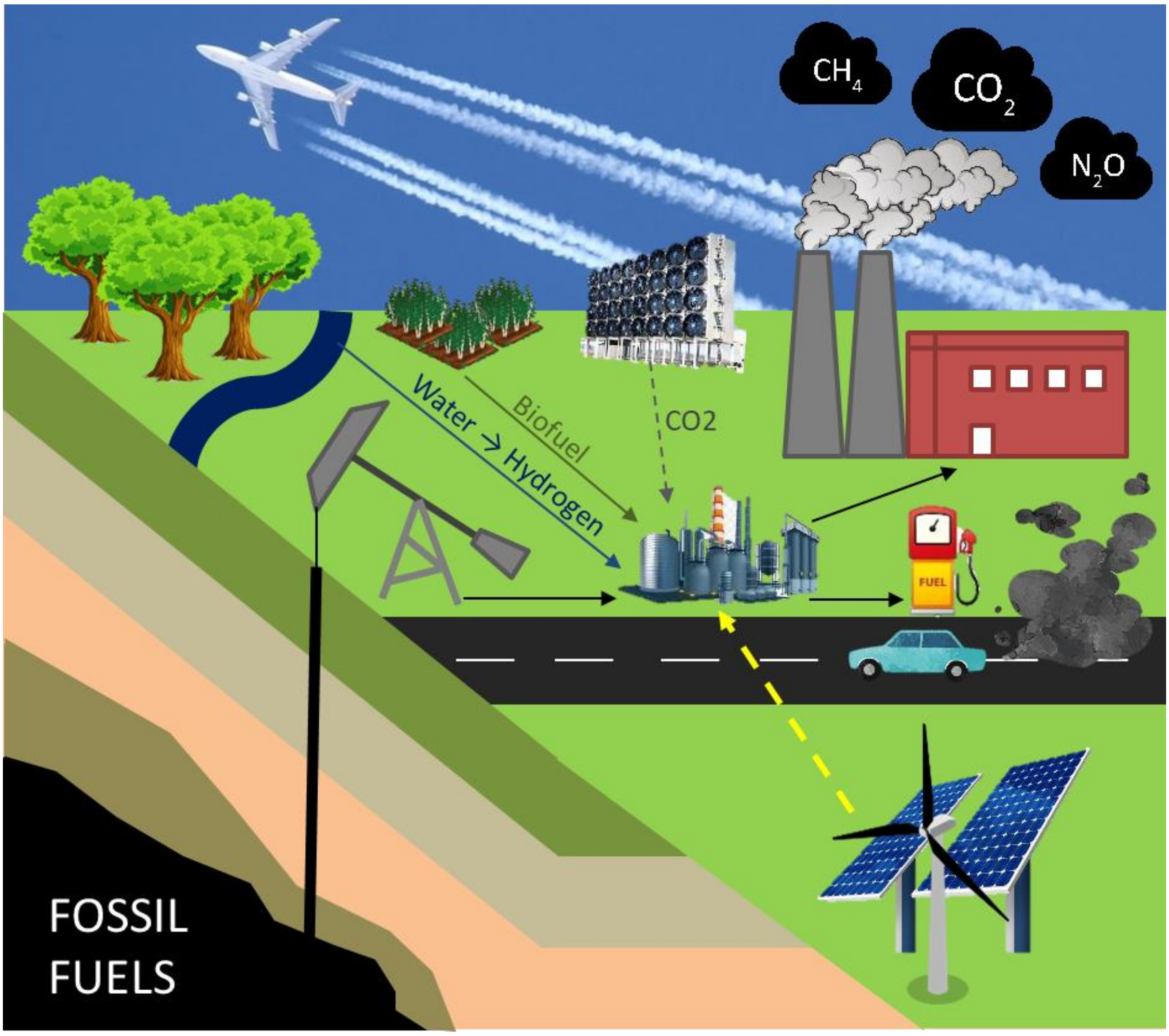

Figure 13: SAF pathways – Biofuel or Synthetic Fuel (from Hydrogen + CO_2)

There are various ways of creating these alternative so-called "Sustainable Aviation Fuels" (SAF):

7.1. Biofuel

Biofuel is produced using agricultural crops, municipal waste from cities, or used cooking oil.

The most cost-effective biofuel is fuel-from-waste, however there is a limited amount of waste available and nowhere near enough required for the quantities of fuel consumed by aircraft.

Fuel-from-crops isn't a sustainable or scalable solution either. For context, the wheat required to meet today's aviation needs in biofuel, equates to almost as much as **humanity's entire food calorie requirement** [24]. There simply isn't enough land on the planet to keep covering it in even more biofuel crops, while leaving enough space for wildlife, and feeding a growing human population. Particularly not at a time when land and water resources are scarce, we're already rapidly deforesting the planet, and many can't afford to eat.

7.2. Synthetic Fuel

Synthetic fuel (Synfuel), which is a liquid hydrocarbon, is produced by synthesising hydrogen with carbon using a process called Fischer-Tropsch [25]. Hydrogen can be produced from water using electrolysis, and carbon can be sucked from the air using a process called 'Direct Air Capture' [26][27]. If all of these processes are powered by low-carbon electricity, then this could significantly decrease emissions (up to 80% reduction claimed [28]) relative to fossil fuels.

However, there's a catch: the technology is still in its infancy and all of the processes used are energy intensive and inefficient – so they waste renewable energy at every stage. Using an optimistic (50%) power-to-fuel efficiency assumption, producing enough synfuel for the UK aviation industry in 2018 would have required **more than three quarters** of the existing grid capacity, all year:

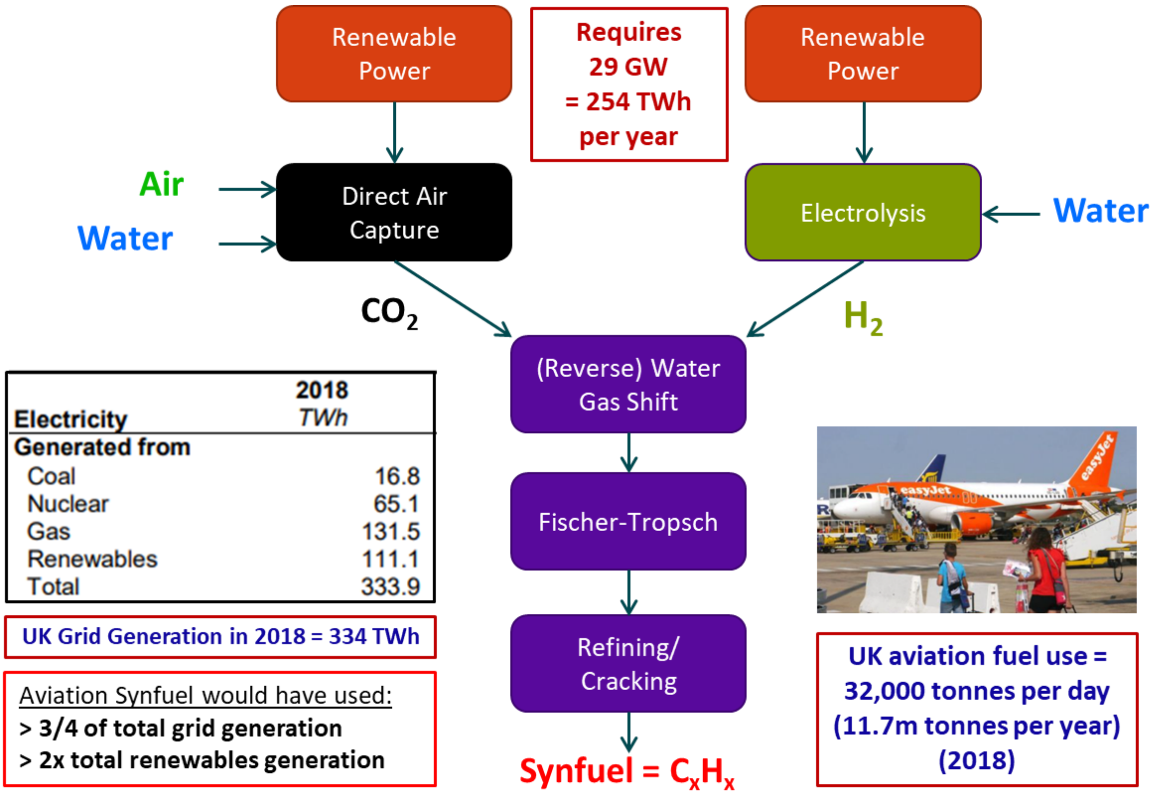

Figure 14: Example Calculation for UK Aviation Fuel Consumption

The following chart shows the projected cost of synfuel and liquid hydrogen, versus a baseline cost of fossil fuel kerosene:

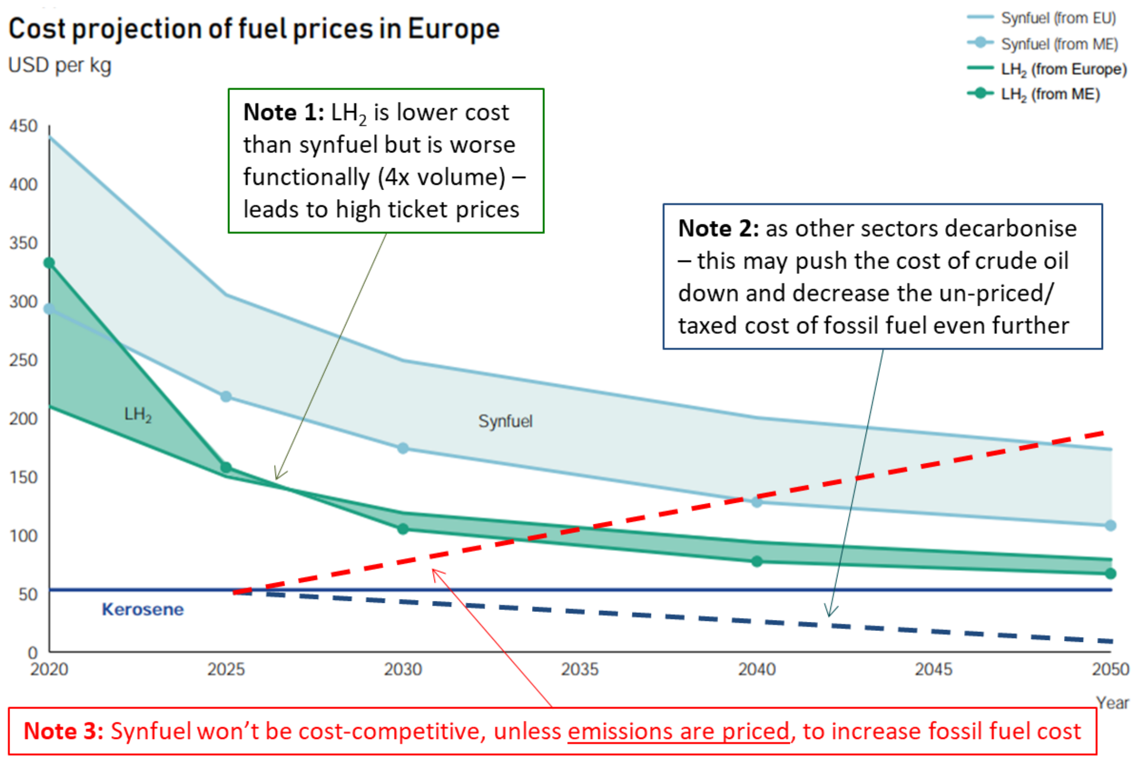

Figure 15: Projected Synfuel and LH_2 prices per kg, relative to a kerosene baseline [23]

Even as the processes are improved and the infrastructure is scaled, synfuel will likely remain **3-5 times** the price of conventional fuel for the coming decades. It's also very important to note that as other sectors (e.g. ground transport) decarbonise and reduce the demand for oil: the price of fossil fuel may reduce, as supply outweighs demand – increasing the price gap further.

The key takeaway messages are:

- biofuels can't be scaled sustainably and should be removed from consideration. **Any discussion of biofuels just confuses things, and provides false hope.**
- synthetic fuels can be scaled, but waste vital renewable energy, and won't be cost-competitive with conventional fossil fuels. Unless: **effective emissions pricing is applied**.

8. CARBON OFFSETTING

The final misconception is that existing carbon offset schemes will be effective in reducing emissions.

International aviation and shipping are the only two sectors that aren't covered by the emissions reduction targets, set out in the 2015 Paris Agreement. Instead, in 2016 the industry came up with something called the "*Carbon Offsetting and Reduction Scheme for International Aviation*" (CORSIA) which apparently enables 'carbon neutral growth' from 2020, through the use of offset credits [29].

The idea is that airlines will have to buy credits when they emit carbon, and those credits will then go towards reducing carbon elsewhere. Essentially: I don't want to reduce *my* emissions, so I'll pay somebody else who promises to emit less.

However, the CORSIA scheme has numerous weaknesses [30]:

- it's voluntary from 2020, and only becomes mandatory after 2027
- the scheme isn't legally binding: there are no enforcement mechanisms to ensure compliance
- it only applies to CO_2 and ignores non-CO_2 emissions, despite their large climate impact [5]

- it only applies to emissions in excess of 2019 levels, so for the considerable future, **the majority of carbon emissions will not be offset**:

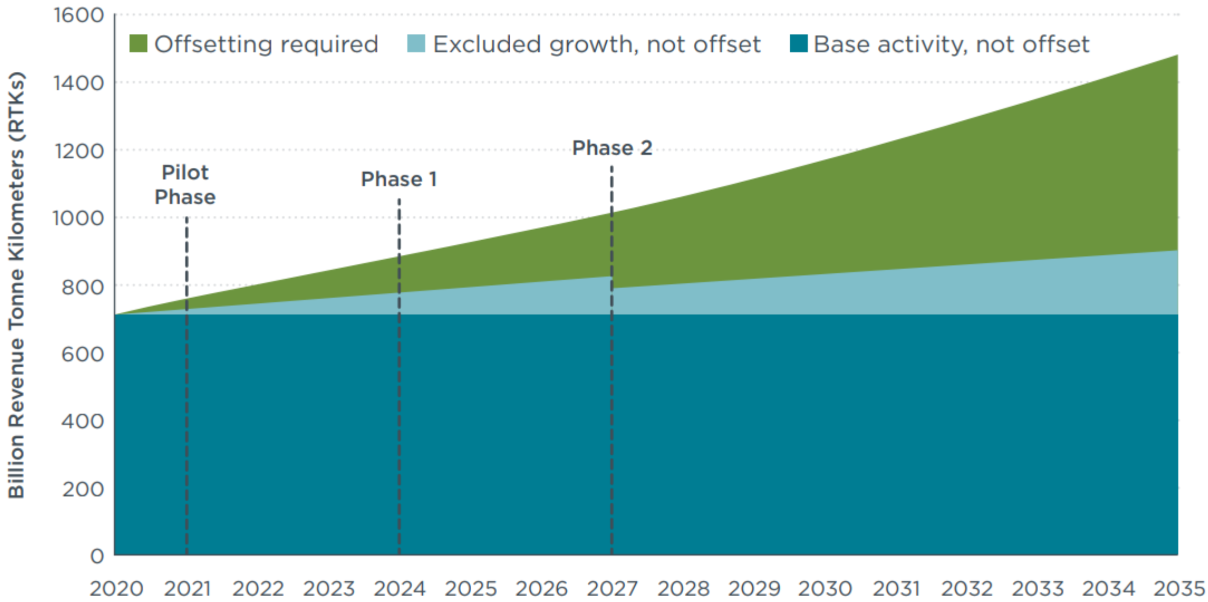

Figure 16: International RTK coverage of CORSIA based on current commitments [31]

- CO_2 emissions are offset using types of schemes which have so far proven very ineffective [32]
- the offset credits are simply **far too cheap** per tonne of CO_2. For example, they will cost far less than $10 per tonne of CO_2. As a comparison, industrial CO_2 capture is currently closer to $1000 per tonne [27] and is projected to (best case) reduce to $100 per tonne over the next few decades [26]. This doesn't even include the costs of then storing the carbon, after it's captured: deep underground or deep under the sea.

The takeaway messages are:

- the CORSIA terms are weak
- the majority of emissions (pre-2019 levels of CO_2 and all non-CO_2) won't be offset
- for the emissions that are offset, the offset credits are far too cheap

Therefore, it appears we need another much stronger measure: to replace, or add, to CORSIA.

9. EMISSIONS PRICING

It has been shown that each '*sustainability*' solution proposed by the industry won't work in isolation, without more effective measures to increase the cost of burning conventional kerosene.

This is required to ensure that efficiency improvements don't continue to reduce the cost of fossil fuel flight, and do actually result in emissions reductions being banked.

Going forward, if the market is better regulated to ensure that efficiency savings exceed air traffic growth, then emissions will actually reduce, rather than increase as they've done historically:

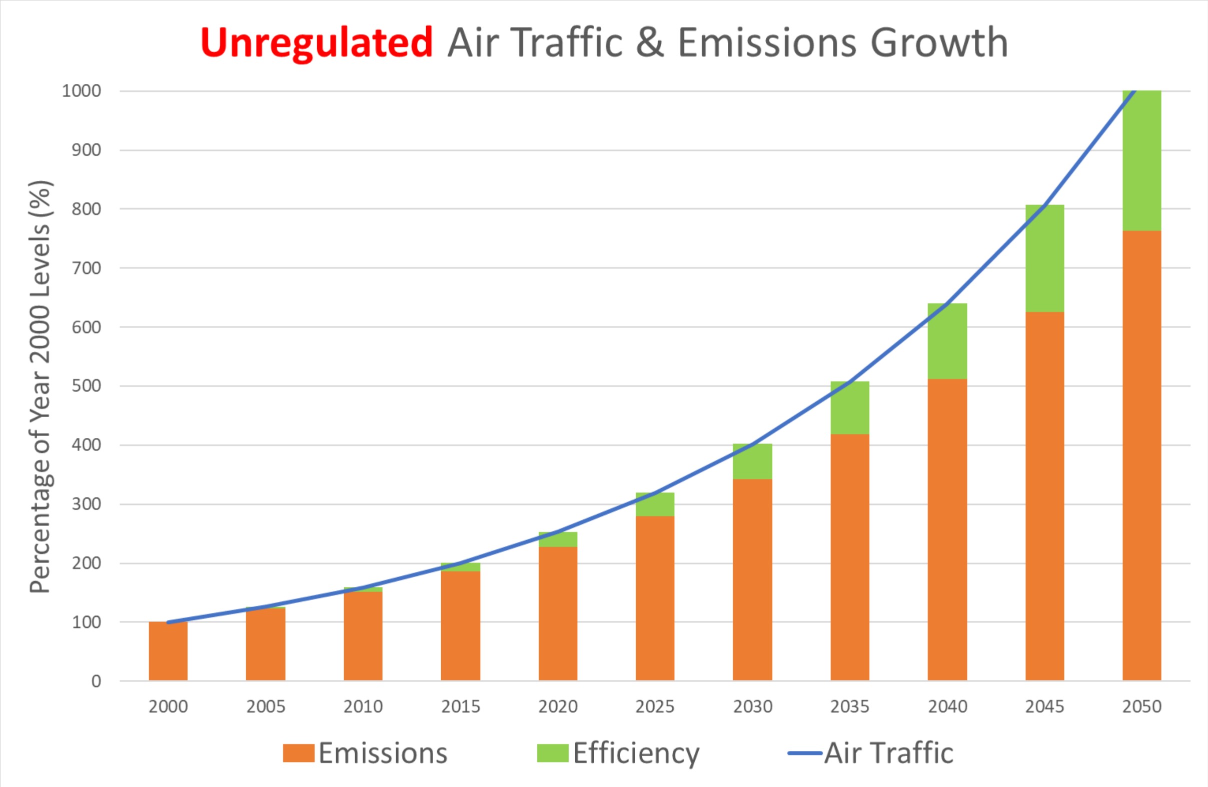

Figure 17: Example of Ineffective Emissions Regulation

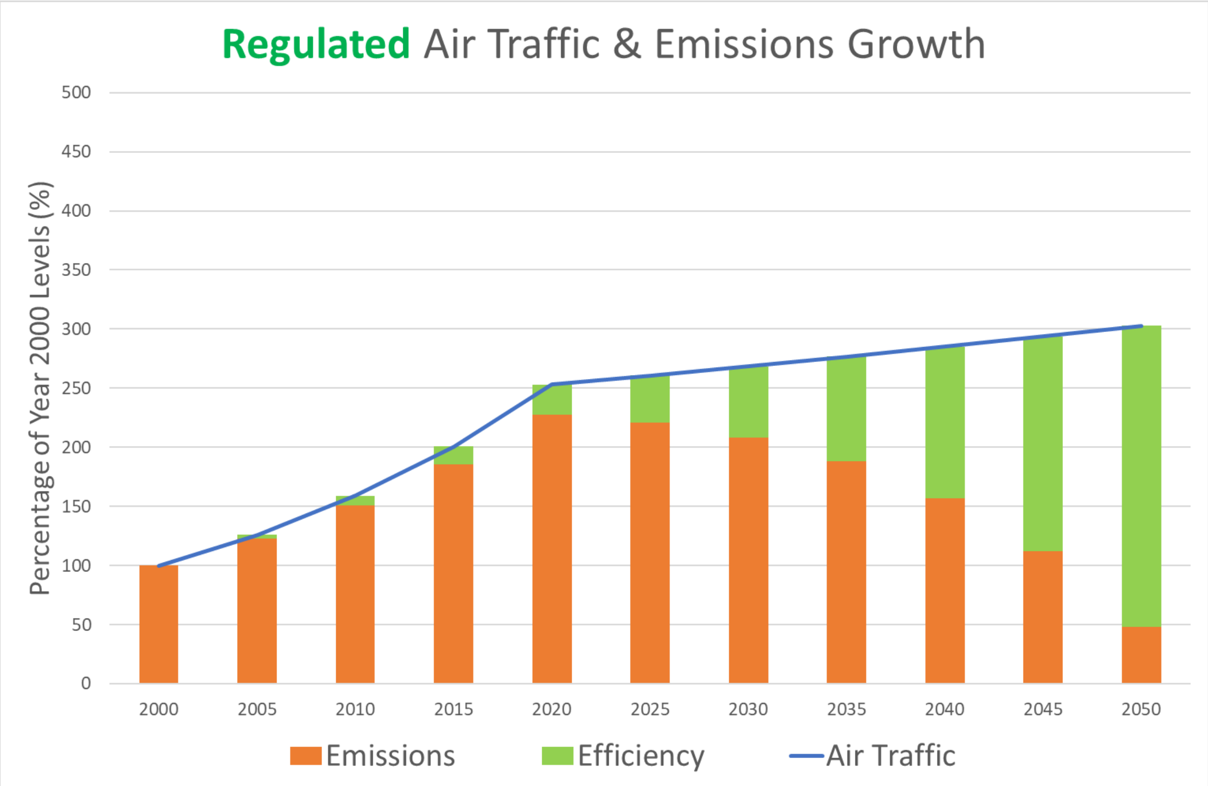

Figure 18: Example of Effective Emissions Regulation

The only way to effectively limit air traffic growth is to increase the cost of flying. The most effective approach would be to increase the price of jet fuel, as this also ensures lower-carbon alternatives such as electric flight, hydrogen, and synthetic fuel become more cost-competitive.

There are various approaches:

- remove fossil fuel subsidies
- remove jet fuel tax exemptions
- mandate airlines use a % quantity of more expensive synthetic jet fuel
- restrict airport growth
- introduce a frequent flyer levy [33][34]

All approaches will need to achieve the same outcome of increasing the cost of conventional jet fuel. The takeaway message is: as an industry, **we must acknowledge and prepare for this future reality**.

10. COVID-19 RECOVERY

Following the COVID-19 pandemic, air traffic has dropped across 2020, and will likely remain below 2019 levels for 2-5 years. The industry was hit hard, in part because it wasn't ready for such a crisis, and had been banking on largely uninterrupted growth.

The industry-defining question is now what magnitude of growth should be planned over the next few decades, whilst considering the climate crisis and necessary emissions pricing?

Boeing appear to have completely ignored the imminent climate crisis in their recent market outlook for the next 20 years:

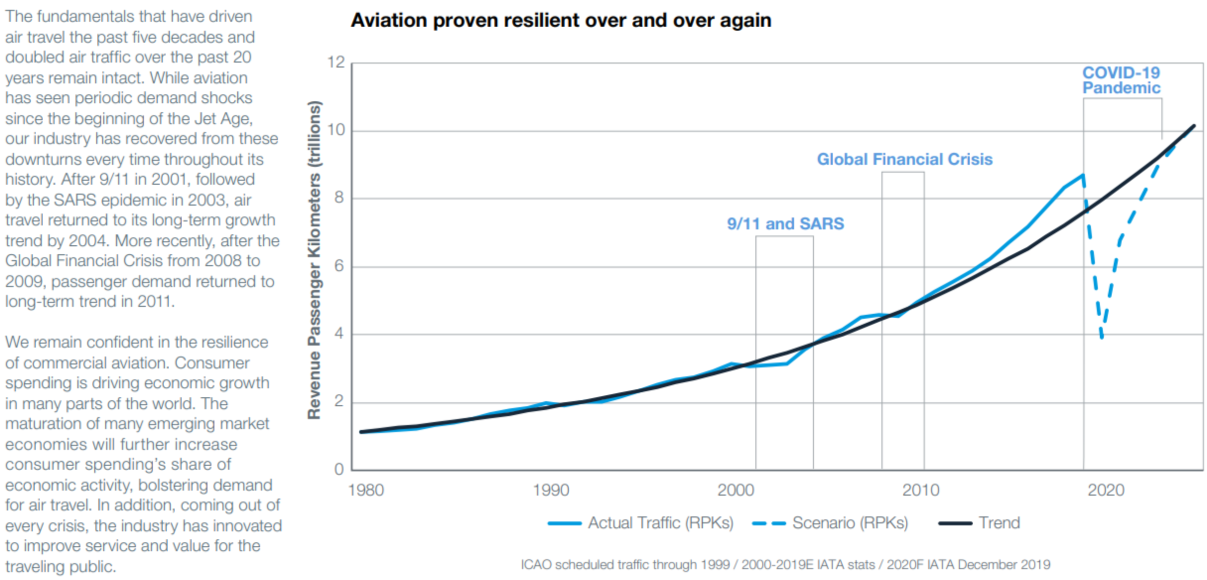

Figure 19: Boeing 'Commercial Markets Outlook': predicting return to historic growth trajectory [35]

Aviation emissions pricing is not a question of "*if*" but "*when*", and the climate crisis necessitates it must ramp up early this decade [19].

This could cause another, potentially larger industry crash (Figure 20).

However, if we emerge from COVID-19 aiming for a 'Green Recovery' with a roadmap of increasing emissions prices, we may be able to mitigate the impact on the industry (Figure 21):

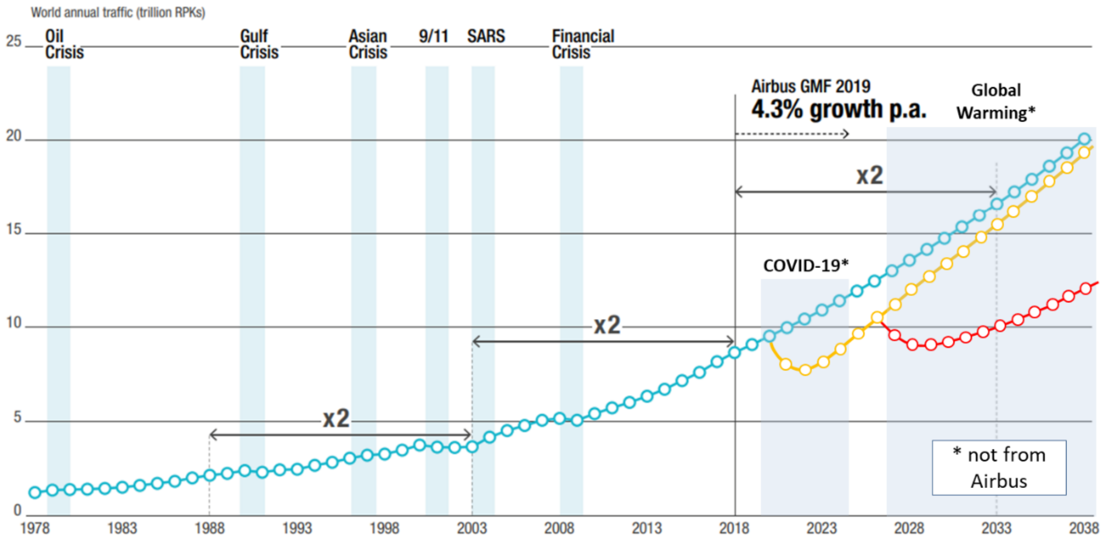

Figure 20: Airbus GMF [12] – amended to demonstrate potential impact of COVID-19 and Climate Crisis

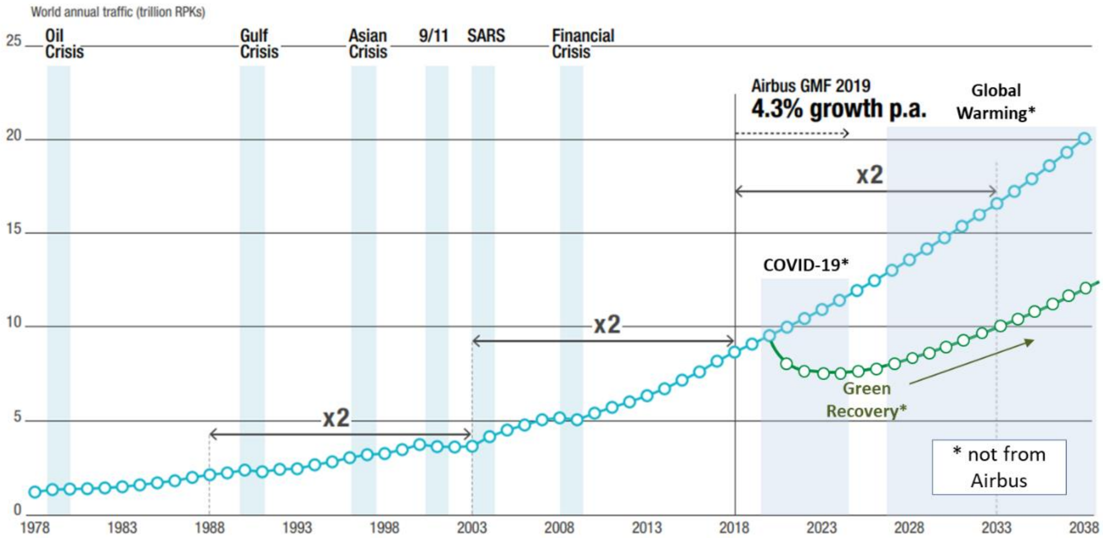

Figure 21: Airbus GMF [12] – amended to demonstrate potential 'Green Recovery' pathway

11. CONCLUSION

The transition to low-carbon aviation cannot rely on technological solutions alone. **Government regulations are also required to increase the cost of aviation emissions**. The implications of this are huge, and will affect thousands of aviation workers. The industry works on timescales that require planning 10-20 years ahead. This means it's of utmost importance for any company seeking to mitigate financial risk, and protect jobs over the long term, to consider the size and shape of these regulations **today**. It also means that any employee who cares about the future of their industry and the livelihood of their colleagues, should think very long and hard about what's most likely.

Costs per abated tonne of CO_2 equivalent have been estimated as [23]:

- Hydrogen for Regional and Commuter = less than US $60
- Hydrogen for Short- and Medium-Range = US $70 to $220
- Synfuel for Short- to Long-Range = US $210 to $230

The ultimate question is: **what have your leaders planned for?**

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