INSIGHT

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Introduction

Destination Zero, ATI's 2022 technology strategy, describes a path to Net Zero aviation emissions and provides the roadmaps which can support that objective from an aircraft technology perspective[1]. This INSIGHT acts as a companion paper to *Destination Zero* by detailing the modelling of the emissions scenario presented in the strategy. It also presents a sensitivity analysis using alternative scenarios and offers an alternative and more complete view on how to visually represent aviation emissions. This INSIGHT shows that rapid, deep, and immediate decarbonisation needs to happen for the aviation sector to meet its climate goals and that any uncertainty can be mitigated by accelerating the adoption of zero-carbon and ultra-efficient aircraft, and the fuels that will power them.

18 AVIATION EMISSIONS: *Modelling the road to Net Zero 2050*

CONTEXT

The global air transport sector emitted more than 900 million tonnes (Mt) of CO_2 in 2019 plus an unreported quantity of other emissions including nitrogen oxides, sulphur oxides and carbon particulates. In that year, the estimated contribution of aviation to climate change was circa 3.5% of the total anthropogenic greenhouse gas emissions [2]. While the sector's emissions during 2020 dropped by nearly 70% because of the global COVID-19 pandemic [3], civil aviation is expected to recover to pre-pandemic growth rates [3] by the mid-late 2020s. This will make aviation one of the sectors with the highest year-on-year increase in emissions and, due to the lengthy design and development lifecycle and fleet refresh timelines, one of the hardest to decarbonise.

According to the International Panel on Climate Change (IPCC), the global economy can emit about 400 Gt of additional carbon, known as the carbon budget, before the global average temperature exceeds 1.5°C above the pre-industrial era[1] [4] [5]. According to ATI modelling, if no action is taken, aviation could contribute 38Gt (9.5%) to that carbon budget by 2050 [1].

Several national UK and international organisations have created decarbonisation roadmaps for aviation which vary according to assumptions made but are broadly consistent. They all show that a component of synthetic SAF and offset is required to allow them to reach Net Zero. This element represents a risk as it is not clear at present how this will be achieved. In 2021, the Air Transport Action Group (ATAG) published the second edition of the Waypoint 2050 report in which the aerospace industry sets a path towards zero carbon emissions by 2050 [6]. In 2022, the International Civil Aviation Organisation (ICAO) published its study on the feasibility of a long-term-goal for international aviation emissions. Three scenarios are presented, none of which reach Net Zero emissions by 2050 with in-sector measures alone [7]. In the UK, Sustainable Aviation published their decarbonisation roadmap for the UK aviation industry, setting a possible path for UK Net Zero aviation emissions, which also rely on market-based measures [8]. The ATI sustainability model allows us to explore how this dependence can be mitigated under a number of scenarios.

[1]Global average temperatures in 2022 are 1.2°C above the pre-industrial era.

ATI SUSTAINABILITY MODEL

The ATI sustainability model is a lifecycle emission tool developed to make an independent assessment of the possible aviation paths to Net Zero and to quantify the impact that ATI-funded technologies could have on aviation's climate impact.

Our baseline is built on the world fleet at the end of 2015, which corresponds to the extensively validated AIM baseline. The sustainability model uses correlations of GDP growth based on the Shared Socioeconomic Pathways of IPCC (1,2,3) to produce three growth scenarios: low, medium and high. The medium growth scenario was used for all the data presented in this INSIGHT. The 2019-2021 period has been corrected to account for COVID-19 traffic yearly change for both domestic and international operations, after which pre-pandemic growth scenarios are assumed. The growth scenarios vary for each region, region-to-region pair, and timeframe, producing nearly 250 individual demand growth rates for each scenario. More information about the assumptions, modelling approach and validation of the baseline can be found here [9] [10] [11].[2]

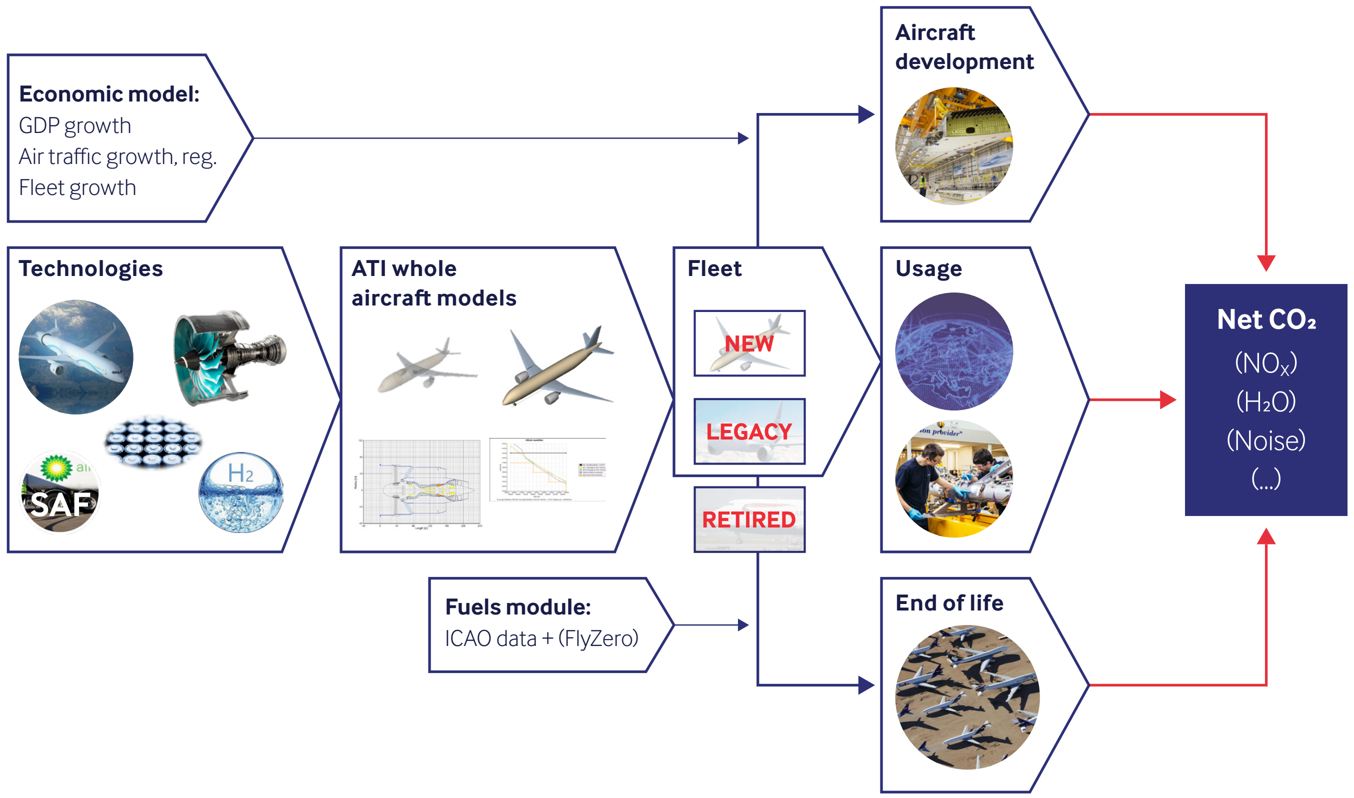

Figure 1 *– Schematic of ATI's sustainability model*

In addition, ATI has included aircraft modelled in-house. These are ultra-efficient aircraft models which demonstrate the potential benefits of sustainable technology adoption. They are described briefly in this INSIGHT but a more in-depth description will be released in separate publications.

Using these aircraft models and a legacy fleet composition, also modelled by the ATI, the sustainability model calculates tailpipe emissions at a fleet level for scenarios defined by the user. The model also includes a fuels module that calculates the upstream fuel emissions of conventional aviation fuels (CAF) as well as sustainable aviation fuels (SAF) from 28 different feedstocks. The material emissions associated with the manufacture of the aircraft are also estimated from the weight and material breakdown of the aircraft. These, however, are not reported here as they are minor (<0.1%) compared to the tailpipe and upstream fuel emissions.

[2]The model was produced by the Air Transport Analytics (ATA) consortium, comprising Air Transport Analytics Ltd and Ellondee Ltd. It is based on the Aviation Integrated Model (AIM) which has been extensively documented and validated.

MODEL COMPONENTS

Emission reductions through ultra-efficient aircraft technologies

Figure 2 - ATI's ultra-efficient widebody model

Ultra-efficient widebody and narrowbody aircraft were modelled by the ATI's whole aircraft team with Ellondee Ltd. to predict the fuel burn, performance, and component weights of the next generation of ultra-efficient aircraft. The modifications to the aircraft compared to existing platforms included increased bypass ratio engines, high aspect ratio wings, and a higher uptake of composite materials. General characteristics of these future aircraft platforms are presented in table 1.

	Regional	Narrowbody
Design range (NM)	3,450	7,750
Passengers	160	300
Wing span (m)	41.24	59.4
Engine BPR	14.8	15.4
Fuel burn reduction vs reference (2015 technology)	20%	16%

***Table 1** - ATI's ultra-efficient aircraft models top level characteristics*

Emission reductions through zero-carbon aircraft

Figure 3 - ATI's narrowbody zero-carbon aircraft

The results presented on the decarbonisation pathway chart are for CO_2 emissions only, with the in-flight impact of zero-carbon aircraft calculated by zeroing[3] the fuel burn of those platforms for the aircraft class and range specified. Further details on the hydrogen consumed in-flight and the emissions of producing this hydrogen are given below. Table 2 presents some characteristics of the FlyZero aircraft family, which were used to calibrate the quantity of hydrogen required to power the zero-carbon aircraft fleet.

	Regional	Narrowbody	Midsize
Maximum range (NM)	1,500	2,400	5,750
Passengers	75	180	279
Wing span (m)	31	39.3	52
Engine BPR	turboprop	13	13
Energy improvement vs reference (2015 technology)	8.6%	23%	29%

***Table 2** - ATI zero-carbon aircraft models top level characteristics*

[3] As no carbon is will be produced at the tailpipe.

Emission reductions through operations

Based on historical trends, the model includes an improvement in load factor of 0.8% per year for all regions and aircraft classes up to a maximum of 95%. This encapsulates some growth in the number of seats per aircraft, as well as the rate at which they are filled. The baseline model also accounts for a fuel use inefficiency factor to account for air traffic management inefficiencies and wind impacts. An annual improvement in operational and infrastructure efficiency of 0.1% was also applied aligned with the ATAG scenario O2 [6].

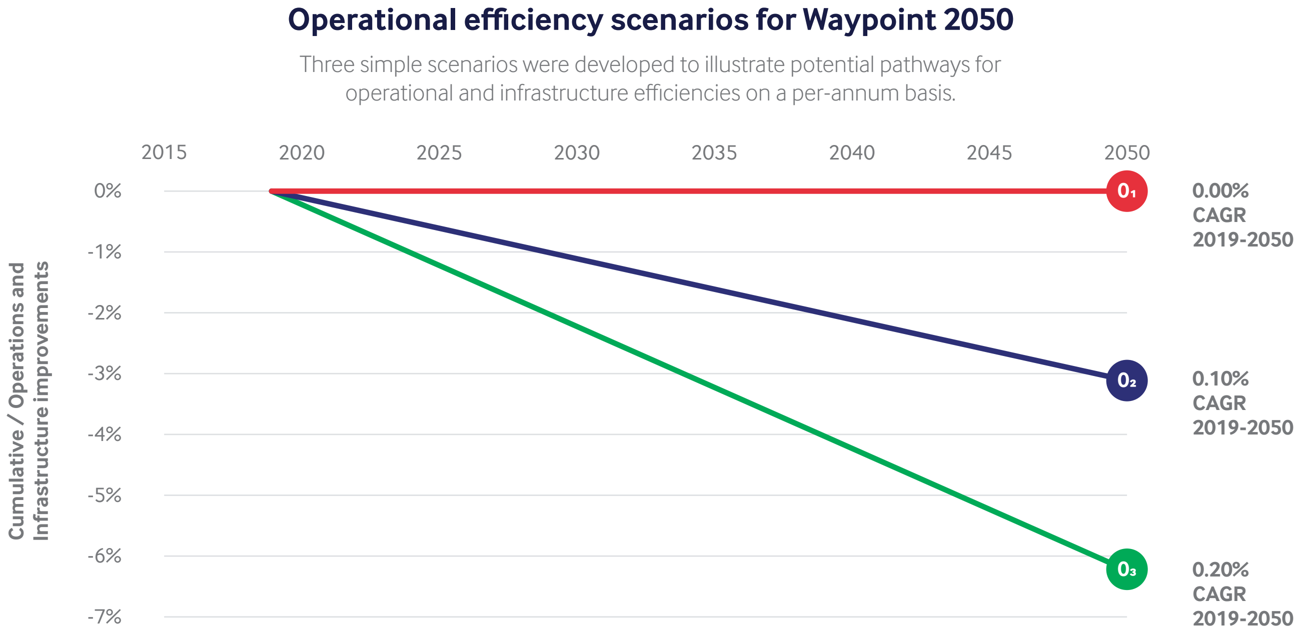

Figure 4 *- ATAG's pathways for operational and infrastructure efficiencies*

Emission reductions through sustainable aviation fuels

Sustainable aviation fuels from bio-feedstock sources have been accounted for by assuming that global uptake has an average lifecycle emission reduction factor (ERF) of 80% compared to kerosene. This is constant over time, so the ERF is the same for 2020 as it is for 2050. This accounts for the need to balance the decarbonisation of the grid and transportation methods required to process and transport the SAF against the need for feedstocks which have a lower ERF. The Fuels report of ICAO's Long Term Aspirational Goal feasibility study also predicts relatively constant ERF in time for three different fuel scenarios, with ERFs of 63-73% depending on the scenario [12]. These fuels were assumed to be restricted in feedstock availability in-line with the results presented in reference [13].[4]

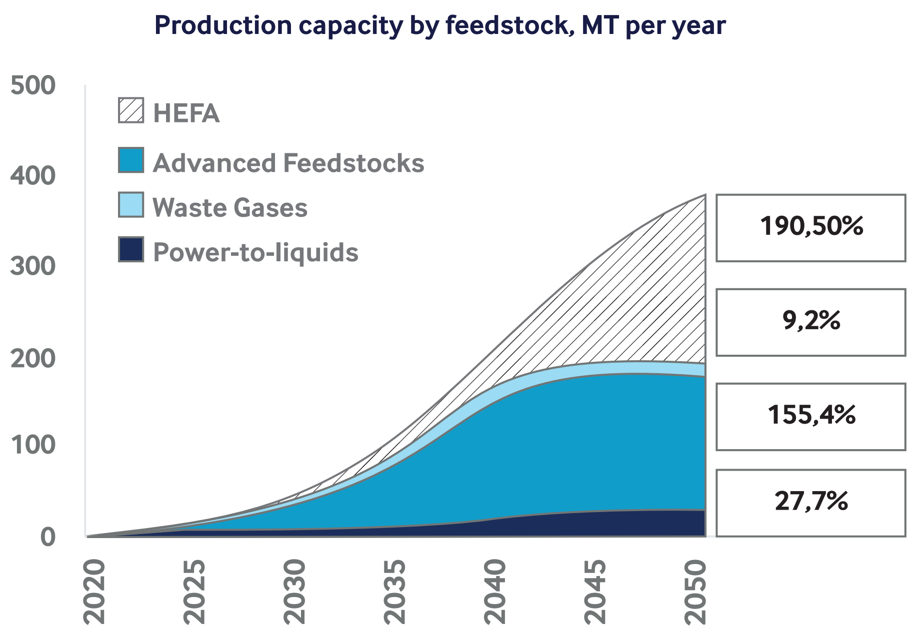

Figure 5 *- ICF SAF production capacity by feedstock, Mt/year [13]*

[4]The contributions from SAF were accounted for assuming that all the feedstocks available are converted into SAF following the curve in figure 5 (from [13]) for HEFA, waste gases and Advanced Feedstocks. Power-to-Liquids were excluded at this point but considered separately, since the source study for the feedstocks ([13]) does not include an exhaustive analysis for PtL.

CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has three phases of implementation and applies only to international aviation emissions which exceed the 2019 baseline [14]. For this analysis it was assumed that all ICAO member states participate on CORSIA from the pilot phase, that the baseline does not change throughout the phases, and that the scheme is extended until 2050. This is done for illustrative purposes only and is not based on any prediction or forecast.

Description of the Destination Zero scenario

The ATI Destination Zero scenario for aircraft replacement is shown in figure 6 [1]. The scenario assumes a 5-year production ramp-up period for entry into service of new aircraft over the following timelines:

- Regional ultra-efficient aircraft enters service in 2028 with 100% uptake of new deliveries.
- Narrowbody ultra-efficient aircraft enters service in 2032 with 100% uptake of new deliveries.
- Regional zero-carbon aircraft (range 1500nm) enters service in 2035 with 50% of new deliveries, the remaining 50% continues to be regional ultra-efficient.
- Narrowbody zero-carbon aircraft (range 2400nm) enters service in 2040 with 50% of new deliveries, the remaining 50% continues to be narrowbody ultra-efficient.
- Widebody ultra-efficient aircraft enters service in 2040 with 100% of new deliveries.
- Midsize zero-carbon aircraft (range 5250nm) enters service in 2050 with 50% of new deliveries.

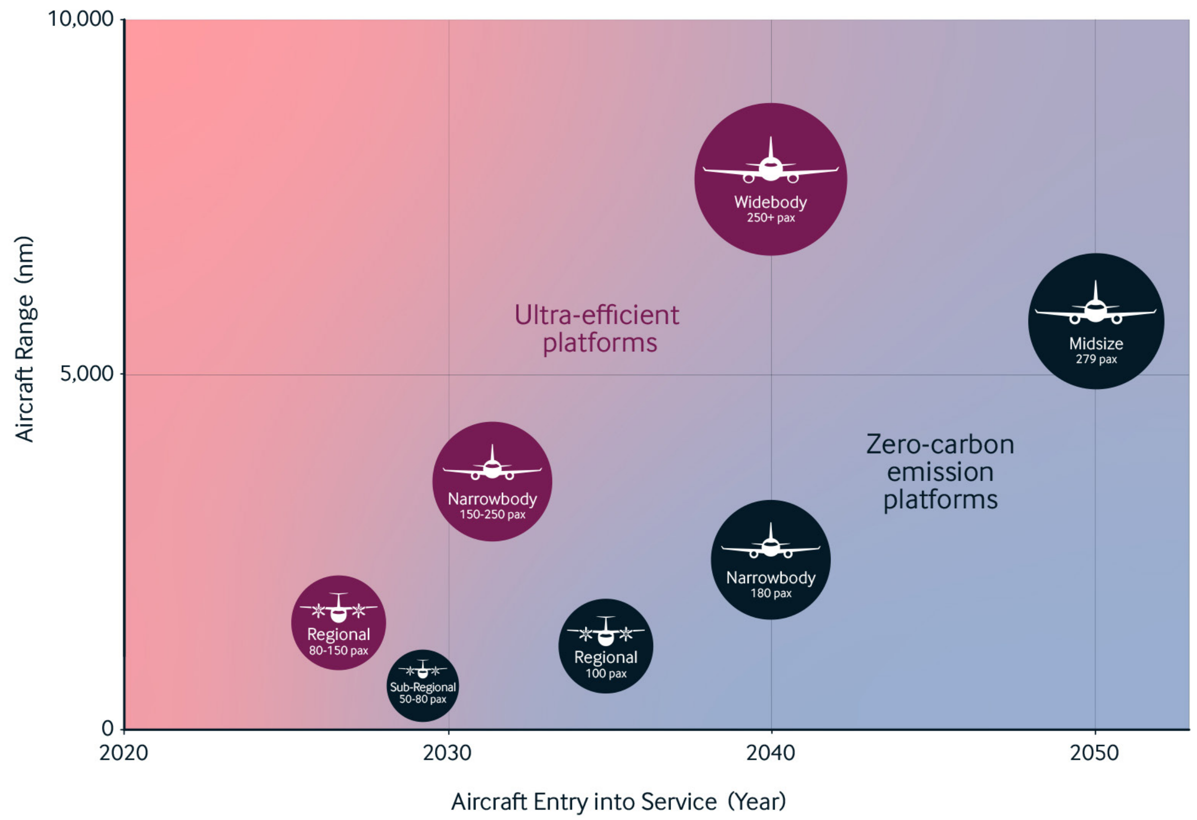

Figure 6 *- ATI Destination Zero market scenario*

DESTINATION ZERO DECARBONISATION ROADMAP

The ATI analysis of the pathway to Net Zero by 2050 is shown in Figure 7. Our modelling shows that technology advancements reducing tailpipe emissions, improvements in operations and reductions in the lifecycle emissions of fuels and international market-based measures, all contribute towards keeping carbon emissions roughly at 2019 levels out to 2050. These reductions, however, are not enough to drive emissions to Net Zero, and additional measures will be required to achieve that target. These are shown in the light blue wedge as further opportunities to reduce emissions via a combination of synthetic hydrocarbon fuels such as power-to-liquid and further carbon offsets beyond those already included in CORSIA. Accelerating the entry into service of new aircraft platforms and the uptake of more efficient technologies and fuels will reduce the need for these out-of-sector measures to reach Net Zero. In that sense, the light blue wedge is a risk to our long-term objectives which needs to be mitigated.

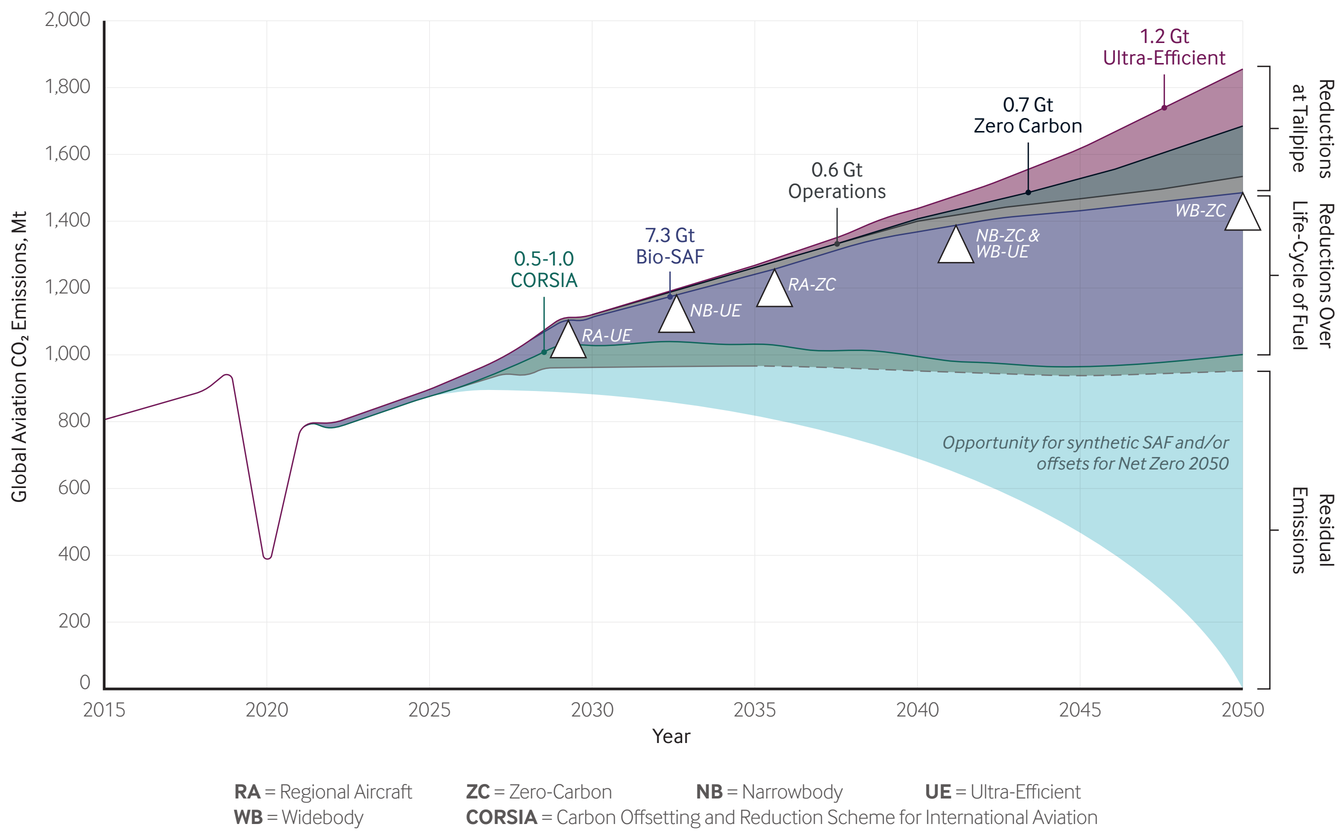

Figure 7 - ATI Destination Zero carbon roadmap for global aviation CO_2 emissions

If no action is taken to reduce carbon emissions in the sector, by 2050 aviation emissions could be 1,890 Mt, double what they were in 2019. However, our model shows that with technology advancements, 374 Mt of CO_2 can be avoided at the tailpipe; 177 Mt from ultra-efficient aircraft, 152 Mt from zero-carbon aircraft and 45 Mt from more efficient operations. This leaves ~1,500 Mt of emissions to be addressed if legacy and ultra-efficient aircraft continued to be fuelled by conventional aviation fuels such as Jet A-1. To address this, 485 Mt of SAF will be required by 2050, a huge increase on the current global supply of 0.05 Mt. However, due to feedstock limitations, our analysis considers that only 41% of that fuel can be replaced by bio-SAF (193 Mt), compensating for 486 Mt of tailpipe CO_2 emissions through their production process. This leaves about 950 Mt of CO_2 still to be addressed by the sector through further measures like carbon offsets and synthetic hydrocarbon fuels.

If the global economy was to consume its carbon budget, the IPCC predicts that the atmosphere would exceed the 1.5°C temperature threshold. Cumulatively, if no action were taken, aviation could consume 38 Gt (9.5%) of that carbon budget. Figure 7 shows that the cumulative reduction potentials of the different measures analysed sum to nearly 11 Gt of reductions, or 2.75%.

In Figure 7 the reductions achieved through ultra-efficient and zero-carbon aircraft technologies are because either the aircraft consume less fuel, or they consume a fuel that has no carbon. The reductions associated with improved flight operations are from avoiding unnecessary fuel consumption in holds, delays, diversions, or inefficient flight trajectories. Whilst there are still in-flight carbon emissions associated with SAF, they are partially compensated for over the lifecycle of the fuel (see [15] for details).

The Destination Zero scenario predicts that 193 Mt of bio-SAF, 16 Mt of hydrogen and 289 Mt of kerosene or synthetic fuel will be needed to power aviation by 2050. The carbon emissions associated with the manufacture and transportation of these fuels are often ignored when accounting for aviation carbon emissions, except for SAF. Figure 8 shows an example of three fuels: kerosene, SAF (from HEFA-Tallow [16]) and hydrogen (made with renewables but liquefied from UK grid energy [17]). The figure shows that before the fuels are consumed, they all have a carbon footprint associated to them which relates to their whole lifecycle. In the case of kerosene and hydrogen this value is positive, as carbon has been emitted during their production. SAF has a negative value, from the carbon the feedstocks absorbed from the atmosphere during their production and the emissions which were avoided through feedstock collection. The net carbon emissions from consuming SAF are greater than zero because SAF combustion, processing, and transportation emits carbon.[5] Hydrogen fuel produces no CO_2 emissions when consumed but does have a carbon footprint associated with the energy required to make, transport, and liquefy it, offering an 88% reduction compared against kerosene over its lifecycle with the assumptions outlined below.

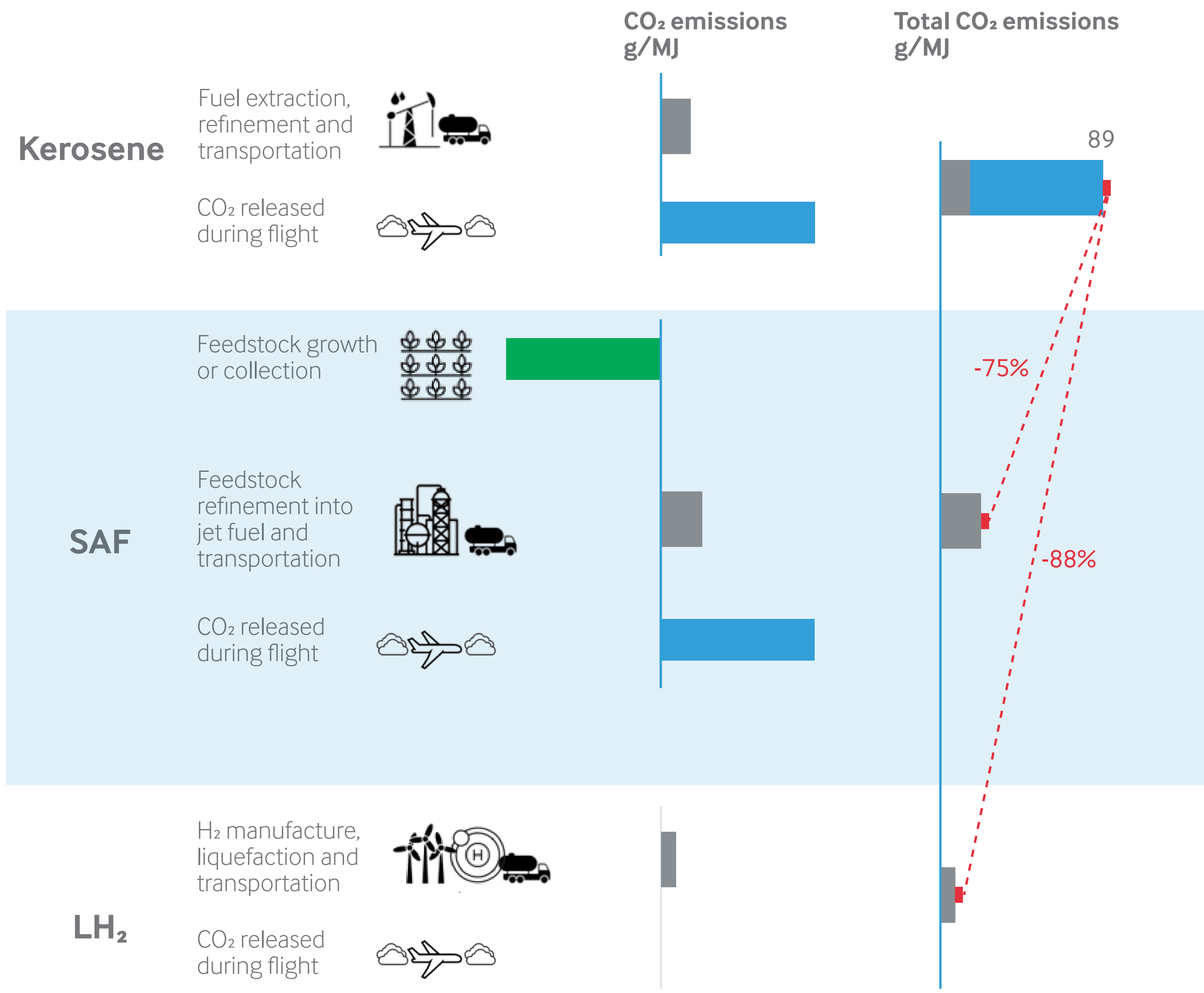

Figure 8 - Lifecycle emissions of kerosene, SAF and liquid hydrogen CE

[5]An example of a HEFA-SAF was used for this example due to its commercial availability today, however in the analysis carried out by the ATI it was considered that the mix of all feedstocks for all SAF pathways provide a lifecycle emission reduction factor of 80%.

Alternative view

To assist full aviation lifecycle evaluations, this can also be shown as a combined tailpipe/fuel upstream emissions chart. Figure 9 separates the tailpipe emissions from the fuel emissions. The upper part of the graph shows the reductions associated with avoiding carbon from being emitted at the aircraft, the tailpipe-avoided emissions (continuous lines). The lower part of the graph shows the fuel upstream emissions, representative of the upstream fuel production emissions. The addition of both parts of the graph gives the total lifecycle emissions for the baseline (red dashed line) and the ATI Destination Zero scenario, which represents the total emissions after all reductions and efficiency gains have been applied (grey dashed line).

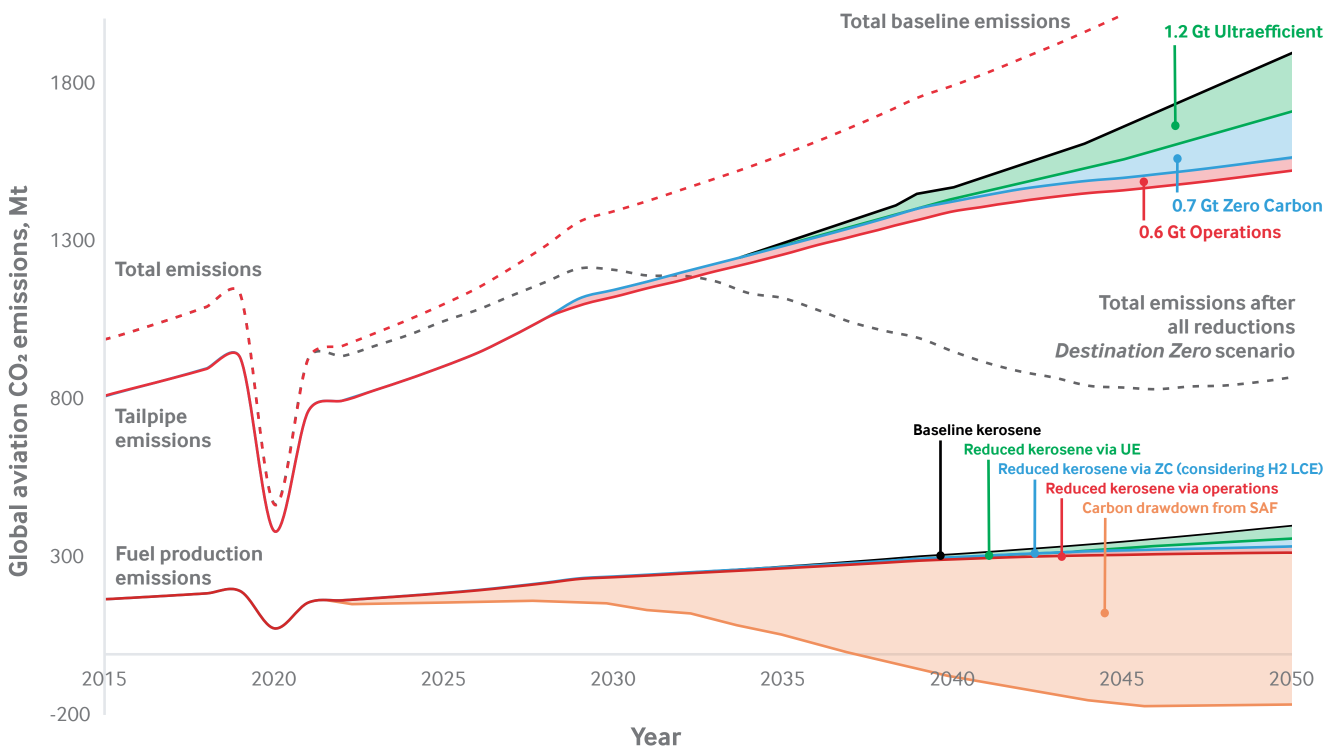

Figure 9 - Alternative representation of the Destination Zero decarbonisation roadmap, including tailpipe and all fuel upstream emissions

In the period from 2015-2021 all fuel upstream emissions are associated to the manufacture of kerosene This, added to the tailpipe emissions, give the total aviation well-to-wake emissions. Towards 2030, the fuel mix is expected to be different, with SAF increasing rapidly. By 2050, large quantities of SAF are available and hydrogen is increasing in volume, further decreasing both the tailpipe and the fuel upstream emissions. The total aviation emissions for 2050 are 872 Mt, excluding additional reductions from advanced synthetic fuels (like PtL), carbon offsets or market-based measures.

In Figure 9, a lifecycle emission for hydrogen of 1.237 $kgCO_2/kgH_2$ was assumed based on the findings of the ATI FlyZero project's sustainability report [17]. This assumes that hydrogen is produced off-site with purposedly built renewable energy, transported to the airport via gaseous hydrogen pipeline and liquefied on-site with grid energy (UK mix). The FlyZero findings show that the lifecycle emissions of hydrogen could be as high as 3.46 $kgCO_2/kgH_2$ if the hydrogen was produced from UK mix grid energy, and as low as 0.84 $kgCO_2/kgH_2$, if it was produced and liquefied from renewables. For comparison, ICAO considers values of 0.67 and 1.032 $kgCO_2/kgH_2$ for 2035 and 2040 respectively [12]. The quantity of hydrogen usage was estimated using a flight efficiency factor for the FlyZero concept aircraft, which predicts that regional aircraft could be 2% less energy efficient and narrowbody aircraft 7% more energy efficient than the equivalent technology level aircraft powered by kerosene or SAF [18].

This analysis shows that if lifecycle emissions are considered for fossil fuel kerosene against those for SAF, hydrogen and battery power, then the baseline of the environmental impact of aviation is increased by close to 20%, demonstrating a need to reduce emissions through the whole lifecycle of aviation.

Sensitivity analysis

The scenario represented in Destination Zero is illustrative of what is possible if that specific decarbonisation route is taken. ATI has done a sensitivity analysis on this and produced alternative scenarios to illustrate the effect of different decarbonisation roadmaps. The Destination Zero scenario is compared with two alternates in Figure 10 where the sector moves faster (Ambitious) or slower (Conservative) towards Net Zero.

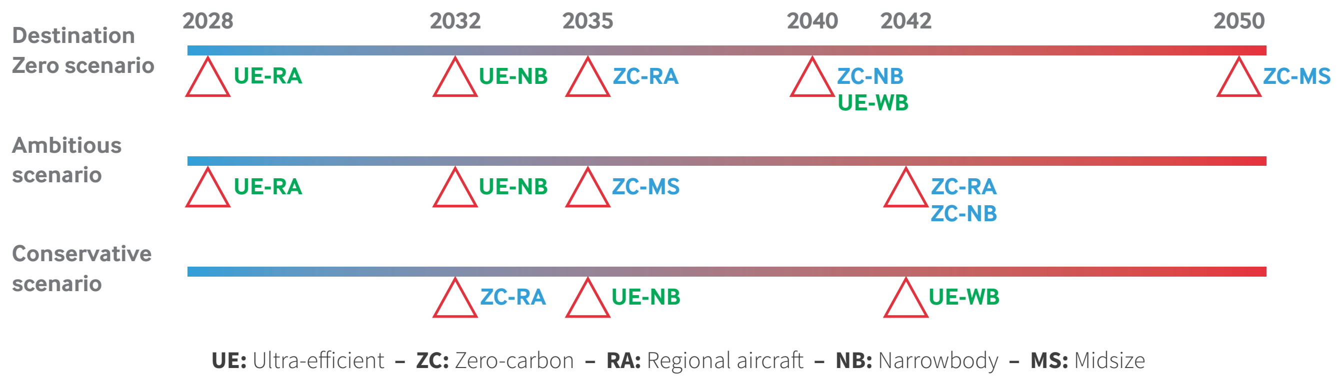

Figure 10 - Market entry points across the three decarbonisation scenarios

The Ambitious scenario has the same aircraft as the Destination Zero scenario (zero-carbon and ultra-efficient for all aircraft classes) but assumes the zero-carbon midsize aircraft (ZC-MS) enters the market first. This was identified by ATI's FlyZero project as providing the highest emissions reductions at the lowest airport infrastructure cost. This is because larger aircraft flying longer distances account for a larger share of CO2 emissions than regional or narrowbody. To enable their operation, fewer airports would need to be fitted with hydrogen, as it would only be required in hubs. This Ambitious scenario would double the reduction in carbon emissions achieved by zero-carbon aircraft by 2050 and would provide the lowest overall emissions of all three scenarios. Despite this, the tailpipe emissions by 2050 would still be 1,447 Mt (5% lower than the Destination Zero case) and this would still require further mitigation with synthetic SAF and carbon offsets to reach Net Zero.

The Conservative scenario assumes hydrogen aircraft are deployed for the regional market only but with 100% of deliveries and that no other hydrocarbon-powered regional aircraft are introduced. The narrowbody and widebody markets are powered by hydrocarbon fuels all the way through to 2050 and ultra-efficient platforms enter service at later dates than those suggested in Destination Zero. This results in the smallest reduction in overall emissions by 2050 with residual tailpipe emissions of 1,627 Mt by 2050 (7% higher than the Destination Zero case) requiring additional mitigation through synthetic SAF and offset to reach Net Zero.

	Destination Zero scenario	Ambitious scenario	Conservative scenario
2015 Baseline tailpipe emissions (Mt)	814	814	814
2050 tailpipe emissions (Mt)	1,519	1,447	1,627
2050 tailpipe + fuel emissions (Mt)	827	784	1,003
Cumulative tailpipe reductions from ZC (2022-2050)(Gt)	0.75	1.58	0.69
Cumulative tailpipe reductions from UE (2022-2050) (Gt)	1.24	1.00	0.75
Cumulative reductions from bio-SAF (2022-2050) (Gt)	7.3	7.3	7.3
% of Global Carbon Budget to 1.5°C (Inc. fuels and tailpipe emissions)	7.3%	7.2%	7.5%
bio-SAF required (2050), Mt	193	193	193
Hydrogen required (2050), Mt	16	30	10
Kerosene or synthetic fuel required (2050), Mt	289	266	323

***Table 4** - Summary of results for the three decarbonisation pathways*

Under each scenario, the bio-SAF reductions are constant as these are limited by feedstock availability and it is assumed that fuel usage never drops below the maximum expected SAF volumes. Total aviation emissions are reduced constantly until 2045 and then start increasing again (see Figure 11). This is because the maximum SAF volumes are reached and so any further increase in demand is covered by kerosene or hydrogen aircraft. The emissions for the Conservative scenario increase faster as this scenario considers hydrogen aircraft for the regional market only, so most of the additional demand is covered by kerosene-burning aircraft. The Ambitious scenario is the least affected due to the larger share of hydrogen aircraft. This could be greatly mitigated by the introduction of other pathways for synthetic kerosene, such as PtL.

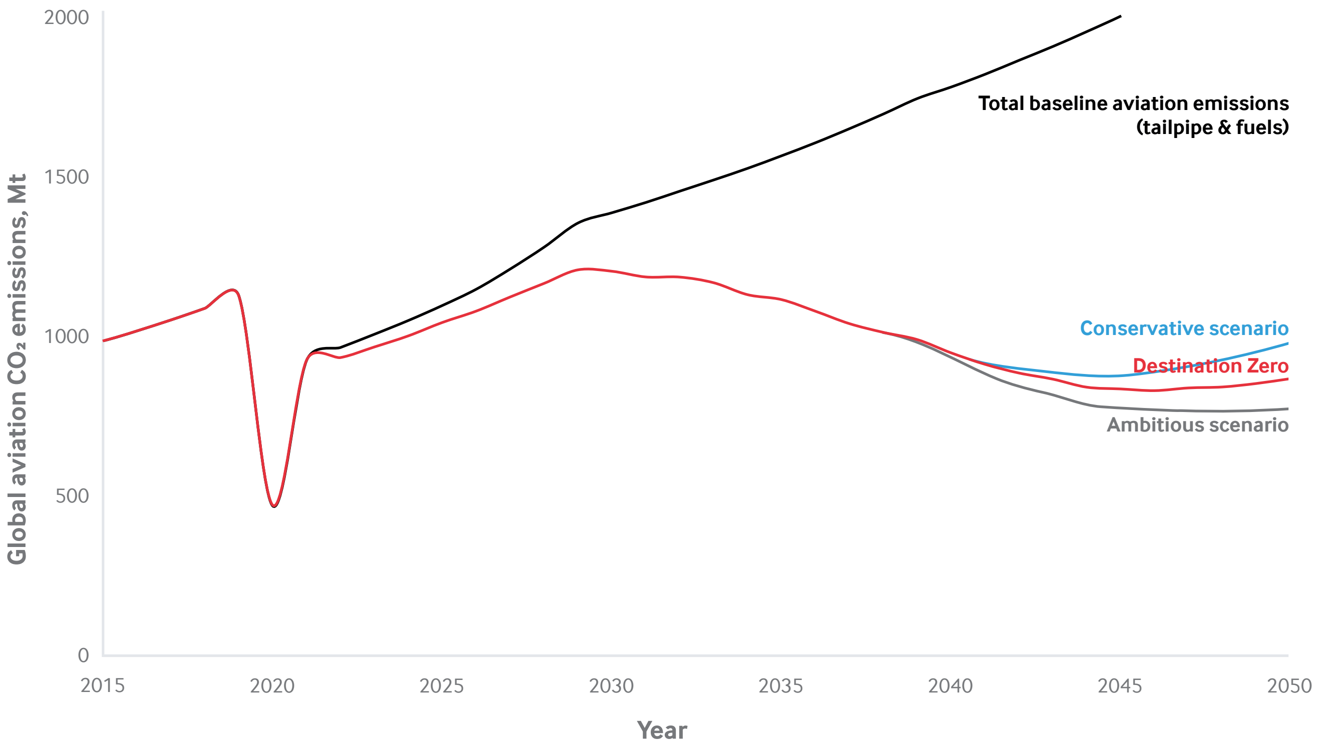

Figure 11 *- Graphic representation of the three ATI decarbonisation scenarios. This figure presents the total (tailpipe + fuel production) emissions which already include the bio-SAF contributions*

Beyond 2050, as more hydrogen aircraft come into service, total carbon emissions should continue to drop. However even if kerosene was fully replaced by SAF, total carbon emissions would not reach zero. This is because the SAF assumed lifecycle emission reduction factor is 80%, and hydrogen production also has a carbon footprint associated to it. Therefore, well beyond 2050 there will still be residual emissions associated with making these fuels. This highlights the importance of decarbonising the whole supply chain, and the need for continued investment in carbon capture and offsets.

CONCLUSIONS

This INSIGHT provides details on the modelling of CO_2 emissions and associated assumptions summarised in the ATI's Destination Zero 2022 technology strategy. It also extends the modelling into two additional market scenarios. The conclusions from the work are:

- Full lifecycle emissions for all aircraft energy sources together with tailpipe emissions need to be considered when comparing the overall impacts on sustainability. The ATI has developed a new graphical approach to allow a better understanding of total lifecycle aviation emissions.
- The introduction of bio-derived SAF and hydrogen will reduce total aviation emissions but will not achieve net zero carbon without additional measures such as carbon offsets and the development, industrialisation and deployment of synthetic SAF.
- Acceleration of technologies that improve the energy efficiency of aircraft is required to achieve the reduction of tailpipe emissions and minimise demand for both SAF and hydrogen.

This work highlights the scale of the decarbonisation challenge that the sector faces. It is clear that multiple avenues to reducing carbon emissions must be pursued as there is no single solution to the problem.

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WHO WE ARE

The **Aerospace Technology Institute** (ATI) is an independent not-for-profit company at the heart of aerospace research and development in the UK. Our mission is to raise UK ambitions and lead technology in air transport to maximise the UK's full economic potential. We do this by providing objective technical and strategic insight, maintaining a UK aerospace technology strategy, and together with Industry and Government, direct match-funded research investments – set to total £3.9bn between 2013 and 2026.

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