Aviation Net-Zero CO_2 Transition Pathways

Comparative Review

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Executive Summary

Transitioning towards net-zero carbon dioxide (CO_2) emissions by 2050 is the greatest challenge for the air transport industry. The aviation industry took the momentous decision to reach net zero CO_2 emissions in 2021, followed by ICAO member states in 2022. To achieve this ambition, a basket of measures that covers aviation energy transition, aircraft technology breakthrough, operational improvements, market-based measures, and policy support is required. Given the significant uncertainties associated with this journey, there will not be a single universal pathway for the sector to reach net zero by 2050. Hence, various organizations have developed net-zero CO_2 pathways for air transport, including the International Air Transport Association (IATA), the International Energy Agency (IEA), the International Civil Aviation Organization (ICAO), the Air Transport Action Group (ATAG), the International Council on Clean Transportation (ICCT), Mission Possible Partnership (MPP), DESTINATION 2050, and the U.S. Federal Aviation Administration (FAA). Meanwhile, numerous academic studies on aviation net-zero transition have also been published in leading scientific journals.

This report provides the first comprehensive review of fourteen leading net-zero transition roadmaps for the aviation sector. By breaking down the massive amount of information discussed in those roadmaps into various aspects for comparison, the report aims to help airlines and stakeholders better understand their critical differences and similarities. Specifically, the report compares the selected roadmaps in terms of their scope, key input assumptions, modeled aviation energy demand, respective CO_2 emissions, and the emissions reduction potential by different mitigation levers.

Some key findings from this analysis include:

1) Possible pathways to net-zero emissions by 2050 differ significantly across the roadmaps, depending on the main vision a roadmap aims to convey on how aviation decarbonization technologies and solutions may evolve. Given the different purposes of the roadmaps, one roadmap may put greater importance on certain mitigation levers than others.

2) All roadmaps assume that SAF will be responsible for the highest amount of CO_2 reductions by 2050, contributing to 24%-70% (with a median value of 53%) of the CO_2 emissions reductions compared to the corresponding baseline emissions levels. However, this wide range of possible contributions from SAF also suggests uncertainty in its global supply, which depends on feedstock availability, production costs, as well as supportive action from governments and financiers.

3) Technology and operation efficiency improvement are expected to have a relatively consistent role in the net-zero transition process, together contributing to about 30% of the emissions reduction in 2050.

4) The emissions savings by hydrogen- and battery-powered aircraft are also highly uncertain across the roadmaps, depending on whether a strong pro-hydrogen policy is adopted as well as a rapid decline of renewable energy prices, which enables the fast uptake of the electricity-based technologies.

5) The baseline emissions modeled in the roadmaps have a direct impact on the amount of CO_2 emissions that need to be abated by 2050. Thus, apart from the demand growth rates used in a given roadmap's baseline, it is also important to understand what is and is not included in the baseline (e.g., energy efficiency improvement in the pipeline versus a frozen technology in 2019).

6) The demand impact of net-zero transition on aviation emissions is modeled only in a handful of roadmaps, where a limited emissions reduction contribution by less than 10% is expected. However, a strong demand management policy would double this impact according to the IEA Net Zero 2050 roadmap.

7) To achieve net zero in 2050, almost all the global roadmaps suggest that the aviation sector will need help from market-based measures and carbon removals to bridge the gap (ranging from 95 $MtCO_2$ to 370 $MtCO_2$) between their residual emissions and net zero emissions in 2050. Even if carbon removal technologies are considered an 'out-of-sector' mitigation measure, it is still critical to develop these technologies as they will play a key role in supplying CO_2 as the feedstock for producing power-to-liquid (PtL) fuels.

1. Background

Owing to its almost exclusive dependence on petroleum-based jet fuel as the energy source today, the aviation sector faces a great challenge to transition towards net-zero carbon dioxide (CO_2) emissions by 2050. However, the airline industry is committed to this ambitious goal following their collective announcement at the 77th International Air Transport Association (IATA) Annual General Meeting in 2021. Member States of the International Civil Aviation Organization (ICAO) also agreed to a long-term aspirational goal (LTAG) of net-zero CO_2 emissions by 2050 in 2022. Reaching this ambitious target will require rapid CO_2 emissions reduction in the aviation sector while the demand is expected to continue to grow, particularly strongly in emerging economies. Under this setting, numerous organizations and researchers have developed their net-zero roadmaps for the aviation sector with different possible pathways, plans, and transition options.

Table 1: List of net-zero roadmaps and scenarios reviewed in this study.

ID	Scenario Name	Organization	Published Year
1	Net-Zero Roadmap S2	International Air Transport Association (IATA)	2023
2	Net-Zero 2050 Roadmap (2023 update)	International Energy Agency (IEA)	2023
3	Long-Term Aspirational Goal (LTAG) Integrated S2: Increased/further ambition scenario, medium traffic growth	International Civil Aviation Organization (ICAO)	2022
4	Long-Term Aspirational Goal (LTAG) Integrated S3: Aggressive/speculative scenario, medium traffic growth	International Civil Aviation Organization (ICAO)	2022
5	Vision 2050 Breakthrough Scenario	International Council on Clean Transportation (ICCT)	2022
6	Prudent (PRU) Scenario	Mission Possible Partnership (MPP)	2022
7	Optimistic Renewable Electricity (ORE) Scenario	Mission Possible Partnership (MPP)	2022
8	Biofuel + PtL scenario, middle demand scenario	Dray et al. (2022) published in *Nature Climate Change*	2022
9	Biofuel + Hydrogen scenario, middle demand scenario	Dray et al. (2022) published in *Nature Climate Change*	2022
10	Waypoint 2050 S1: pushing technology and operations	Air Transport Action Group (ATAG)	2021
11	Waypoint 2050 S2: aggressive sustainable fuel deployment	Air Transport Action Group (ATAG)	2021
12	Waypoint 2050 S3: aspirational and aggressive technology perspective	Air Transport Action Group (ATAG)	2021
13	DESTINATION 2050 net zero scenario for European aviation	Royal Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics (SEO)	2021
14	The US Aviation Climate Action Plan scenario	The United States Federal Aviation Administration (FAA)	2021

These pathways provide valuable insights for the aviation sector to make net-zero transition plans. However, it remains challenging for the aviation community to meaningfully compare across the existing net-zero transition pathways for several reasons. Firstly, each scenario may have different background assumptions about factors outside the aviation sector, such as socio-economic drivers of air transport demand, fuel prices, geopolitical developments, and the level of priority the aviation sector gets for scarce resources. Secondly, the existing net-zero pathways differ in purpose and scope. For example, some may focus on what would be needed for the aviation sector to reach net zero by 2050, combining CO_2 emissions reduced by both the within-sector mitigation measures as well as the out-of-sector carbon removal technologies and market-based measures. In contrast, other roadmaps may focus on what level of CO_2 emissions reduction the aviation sector is capable of achieving by 2050 based on the maximum potential of the within-sector mitigation measures. Lastly, the existing roadmaps adopted different demand modeling approaches. Some use a top-down approach with pre-determined demand growth rates, and the transition measures are applied on top of this growth as 'gap fillers' to reduce the emissions to net zero by 2050, while some use a bottom-up approach where aviation demand growth is modeled to reflect the impacts of different transition measures on demand.

Without comprehensively assessing the critical differences mentioned above, it is difficult for stakeholders to compare these net-zero transition pathways and the levers of action they rely upon. However, there is no such analysis thus far in this regard. To fill this gap, this report aims to provide a holistic review of fourteen major global and regional net-zero CO_2 pathways, with a focus on what modeling approaches these roadmaps adopted in their analysis, what mitigation options are considered, what developments would be needed in these options for the aviation sector to stay on track with the net-zero transition, and how much CO_2 emissions reduction these transition measures would collectively contribute to making the aviation sector generate zero CO_2 emissions by 2050. Table 1 shows the fourteen roadmaps reviewed in this report.

2. Roadmap Scope

The net-zero roadmaps selected in this report all have their own scope (Table 2). In terms of regional coverage, ten roadmaps cover the global aviation market, two focus on international aviation, and two look at a certain regional market specifically. The roadmaps also differ in their aviation activity coverage. The IATA, ATAG, IEA, and DESTINATION 2050 roadmaps focus on commercial passenger traffic only, while Dray et al. (2022) and ICCT cover commercial passenger and cargo traffic. Roadmaps developed by ICAO, the US FAA, and MPP cover a wider scope, where some even cover all types of air traffic, including military and government flights and general aviation.

In addition, the boundary condition for the lifecycle of aviation fuels is different across the roadmaps. For example, eight of the fourteen roadmaps consider just the Tank-to-Wake (TTW) portion of the emissions of conventional jet fuel, which only covers the emissions generated from the combustion of the fuel on the aircraft. The remaining six roadmaps use the Well-to-Wake (WTW), or full lifecycle of conventional fuel, which covers emissions from both the fuel production and the combustion of conventional jet fuel. All the roadmaps, however, consider the lifecycle emissions of Sustainable Aviation Fuel (SAF), given that the reductions in CO_2 of SAF are gained during the Well-to-Tank (WTT) portion, which covers the emissions generated in the fuel production phases. For this portion of the lifecycle (WTT), all reports consider CO_2e, i.e., the CO_2 plus any other emissions generated during the production of the fuel or collection of the feedstock. Five roadmaps apply a CO_2e metric to the TTW portion of the life cycle, accounting for aviation's non-CO_2 emissions during the flight operation phase.

Table 2 also shows if market-based measures (MBMs) and carbon removals have a role as the 'out-of-sector' mitigation measures in the selected roadmaps. MBMs include the EU Emissions Trading Schemes (ETS) and the ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Carbon removals typically consider technologies such as carbon capture and storage (CCS) and direct air capture (DAC) to absorb CO_2 emissions generated from industrial processes or even from atmospheric air. Eight roadmaps reviewed in this study rely on MBMs and carbon removals as critical 'out-of-sector' measures to help the aviation sector reach net zero by 2050. Notably, when not considered a standalone emissions mitigation option, CCS and DAC are often assumed to play a key role in supplying CO_2 as the feedstock for producing power-to-liquid (PtL) fuels; therefore, developing carbon removal technologies is critical for all net-zero transition scenarios reviewed.

Table 2: Roadmap scope, jet fuel lifecycle emissions boundary, and the role of MBMs/carbon removals.

Scenario Name	Region Coverage	Aviation Activity Coverage	TTW Emissions Scope	Aviation fuel lifecycle boundary	Reaching net zero by 2050 through MBMs / Carbon Removals (Y/N)
IATA Roadmap S2	Global	Commercial passenger	CO_2 only	TTW	Y
IEA Net-Zero 2050 Roadmap	Global	Commercial passenger	CO_2 only	TTW[1]	Y
ICAO LTAG S2 (International), Mid	International aviation	Commercial passenger + cargo + business jet	CO_2 only	TTW	N
ICAO LTAG S3 (International), Mid	International aviation	Commercial passenger + cargo + business jet	CO_2 only	TTW	N
ATAG Waypoint S1	Global	Commercial passenger	CO_2 only	TTW	Y
ATAG Waypoint S2	Global	Commercial passenger	CO_2 only	TTW	Y
ATAG Waypoint S3	Global	Commercial passenger	CO_2 only	TTW	Y
DESTINATION 2050 (EU+)	Europe (all flights within and departing from the EU+ region[3])	Commercial passenger	CO_2 only	TTW	Y
ICCT Breakthrough	Global	Commercial passenger + cargo	CO_2 only	WTW[2]	N
MPP PRU	Global	Commercial passenger + cargo, public sector (e.g., military, government), and general aviation	CO_2 + non-CO_2	WTW	Y
MPP ORE	Global	Commercial passenger + cargo, public sector (e.g., military, government), and general aviation	CO_2 + non-CO_2	WTW	Y
Dray et al. (2022) Biofuel + PtL, Mid	Global	Commercial passenger + cargo	CO_2 + non-CO_2	WTW	N
Dray et al. (2022) Biofuel + Hydrogen, Mid	Global	Commercial passenger + cargo	CO_2 + non-CO_2	WTW	N
US Aviation Climate Action Plan	Domestic US + all international flights departing from US airports	Commercial passenger + cargo, business jet, and general aviation	CO_2 + non-CO_2	WTW	N

Note:
[1]Although only TTW is considered in the IEA aviation model, the emissions related to fuel extraction, refining, etc., in the WTT phase are accounted for in the IEA's global energy and climate model (GEC), of which aviation is a part.
[2] On average, WTW emissions of fossil jet A fuel are about 20% higher than the TTW emissions.
[3] EU+ region covers EU 27, the United Kingdom (UK), and the European Free Trade Association (EFTA).

3. Comparing Model Input, Assumptions, and Model Output of the Roadmaps

The forward-looking nature of the roadmaps means that regardless of what net-zero pathways a roadmap follows, it would require a model to project CO_2 emissions from the aviation sector based on different technological, operational, fuel, and economic assumptions. All the roadmaps reviewed in this paper use a modeling approach to different extents and make different assumptions in their models to project CO_2 emissions of the aviation sector to 2050. This section compares the model inputs and key assumptions of the selected roadmaps and then discusses differences in the corresponding model outputs in detail.

3.1 Model Input and Key Assumptions

Traffic demand for air transport is a key driver of the industry's emissions. How fast the demand will grow from the current level directly impacts the amount of CO_2 emissions the industry needs to abate by 2050. The selected roadmaps adopted different approaches to project the demand (Table 3).

Table 3: Air traffic demand projections in the selected roadmaps.

Scenario Name	Demand modelling approach	Demand response	Multiple demand scenarios	CAGR[1] (2019-50)	Demand metric	Demand in 2030 (trillions)[2]	Demand in 2050 (trillions)[2]
IATA Roadmap S2	Bottom-up[3]	No	N	2.9%	RPK	12.71	21.55
IEA Net-Zero 2050 Roadmap	Bottom-up	Yes	N	2.1%	PKM (same as RPK)	10.97	16.55
ICAO LTAG S2 (International), Mid	Top-down	No	Y, Mid	3.8%	RPK	8.10	13.12
ICAO LTAG S3 (International), Mid	Top-down	No	Y, Mid	3.8%	RPK	8.10	13.12
ICCT Breakthrough	Top-down	Yes	Y, Central	2.7%	RPK	11.73	19.96
MPP PRU	Top-down	No[4]	N	2.5%	RPK	10.64	19.22
MPP ORE	Top-down	No	N	2.5%	RPK	10.64	19.22
Dray et al. (2022) Biofuel + PtL, Mid	Bottom-up	Yes	Y, Mid	3.4%	RPK	13.10	24.24
Dray et al. (2022) Biofuel + Hydrogen, Mid	Bottom-up	Yes	Y, Mid	3.3%	RPK	13.10	23.26
ATAG Waypoint S1	Top-down	No	Y, Central	3.1%	RPK	12.39	22.35
ATAG Waypoint S2	Top-down	No	Y, Central	3.1%	RPK	12.39	22.35
ATAG Waypoint S3	Top-down	No	Y, Central	3.1%	RPK	12.39	22.35
DESTINATION 2050 (EU+)	Top-down	Yes	N	2.0%	Passengers Enplanements	0.9 billion	1.4 billion
US Aviation Climate Action Plan	Top-down	No	N	3.3%	RPM	1.31 (2.11 in RPK)	2.90 (4.67 in RPK)

Notes: [1] ICAO LTAG roadmaps CAGR covers 2018-2050; DESTINATION 2050 roadmap CAGR also covers 2018-2050.
[2] The reported demand is for different geographic coverage; see Table 2 Region coverage.
[3] Although the IATA roadmap uses the AIM model, the demand forecasts are aligned with the IATA passenger forecast.
[4] Demand changes due to video conferencing, mode shifts, etc., are not modeled in MPP's main scenarios but as sensitivity analysis.

A top-down approach uses a pre-determined compound annual growth rate (CAGR) between the base year and 2050 to extrapolate air traffic demand by 2050. Under this approach, demand growth is a model input. With this pre-determined demand growth rate, CO_2 emissions associated with the demand under the business-as-usual case (i.e. energy for aviation is still 100% provided by petroleum-based jet fuel by 2050) are estimated as the baseline. Then, different mitigation options are applied to reduce emissions from the baseline level until the industry reaches net zero by 2050.

As a result, the transition measures are the 'gap fillers' between the baseline CO_2 emissions and the net-zero emissions. Some studies assume an energy efficiency gain through technology embedded into this growth, so the baseline emissions grow slower than the demand (IATA S2, for example). Other analyses freeze technology at a given year and extrapolate emissions at the same growth rate as the traffic growth (US Aviation Climate Action Plan).

In comparison, some roadmaps adopt a bottom-up approach that projects the demand using econometric models, where demand growth measured by CAGR is a model output rather than a pre-determined value. Hence, the bottom-up models enable roadmaps to adjust the demand growth based on the impacts of various factors on demand during the net-zero transition. Factors that may affect aviation demand include the higher price of air travel due to economic measures on sustainability (e.g. the EU Emissions Trading Schemes), the higher price of air travel due to increased cost of the energy transition in aviation (e.g. higher costs of using SAF), the changing consumer behavior (e.g. more teleconferencing rather than business travel), and demand management policy measures (e.g. banning short-haul flights). With this bottom-up approach, aviation demand growth and its corresponding total CO_2 emissions could change with the impact of the net-zero transition on demand as well as the emissions reduction from the transition measures applied.

Notably, a top-down model could still exogenously capture the potential price impact on demand by adjusting its pre-determined CAGR to a lower value based on their assumed price elasticities (e.g. the ICCT Breakthrough and DESTINATION 2050). Similarly, a bottom-up model may turn off the demand response mechanism to price changes in its demand forecasts, such as the IATA Roadmap. Therefore, the demand modeling approach and the demand response mechanism shown in Table 3 could be decoupled features depending on the specific use case.

As shown in Table 3, the majority of the roadmaps use the top-down approach, where a pre-determined CAGR of demand is used as a model input. In comparison, the four transition pathways developed by IATA, IEA, and Dray, et al. (2022) projected the demand in a bottom-up manner, where they all used the open-source, econometric-based UCL Aviation Integrated Model (AIM2015) in their demand forecasting (although the IATA roadmap does not use the demand response function in the AIM model). The demand growth is, therefore, one of the model outputs in these roadmaps. An example on this point is Dray et al. (2022), where the demand growth (middle demand scenario) for the *bio-SAF bridging power-to-liquid (PtL)* scenario is 3.4% per year while demand growth for the *bio-SAF bridging liquid hydrogen (*LH_2*)* scenario is 3.3%, despite both using the same 'middle demand' set of external socioeconomic demand drivers.

To better reflect the uncertainties in future aviation demand, eight roadmaps have multiple scenarios on the demand growth rates. However, only Dray et al. (2022) and ICAO LTAG provided possible transition pathways under all three demand scenarios. The remaining six roadmaps only used their central demand growth scenarios throughout the analyses or conducted separate sensitivity analyses for other demand scenarios. Table 3 shows the demand growth rates (CAGR) used in the selected roadmaps. Notably, all the global roadmaps (see Table 2) produce comparable demand in their corresponding central demand scenarios by 2030 and by 2050, except for the IEA Net Zero 2050 roadmap. This is because the IEA roadmap relies heavily on avoided demand (by 20% in 2050 compared with the baseline) from demand management and economic measures, making its demand growth over 2019-2050 the lowest at 2.1% per year among all the scenarios.

Table 4: Comparison of the key assumptions on transition measures in the roadmaps.

Scenario Name	Technology efficiency improvement (MJ/RPK p.a.)	Operational efficiency improvement (MJ/RPK p.a.)	SAF share by 2030[1]	Average SAF cost ($/tonne) by 2030[2]	SAF share by 2050[1]	Average SAF cost ($/tonne) by 2050[2]	PtL entry year	Hydrogen aircraft entry year	Electric aircraft entry year	Hydrogen / Electric share by 2050[1]
IATA Roadmap S2	2019-2050: -1.1%	2019-2050: -0.2%	6%	N/A	90%	N/A	2021	2030	N/A	5%
IEA Net-Zero 2050 Roadmap	2019-2050: -2.0%		11%	N/A	70%	N/A	2030	By 2040	By 2040	11%
ICAO LTAG S2 (International), Mid	2018-2050: -0.9%	2018-2050: -0.3%	13%	1432 (1.79 $/L)	72%[3]	1440 (1.80 $/L)	2021	N/A	N/A	N/A
ICAO LTAG S3 (International), Mid	2018-2050: -0.2%	2018-2050: -0.4%	21%	1360 (1.70 $/L)	98%	1336 (1.67$/L)	2021	2045	N/A	2%
ICCT Breakthrough	2019-2034: -1.1% 2035-2050: -2.2%	2019-2050: -0.6%	15%	1464 (1.83 $/L)	79%	1184 (1.34 $/L)	2030	2035, regional and NB up to 3400 km	2030, 9-19 seat commuters only up to 500 km	21%
MPP PRU	2019-2030: -1.5% 2030-2050: -2.0%		13%	1417	86%	1096	2025	2040, up to 2500 km	2040, up to 1000 km	15%
MPP ORE	2019-2030: -1.5% 2030-2050: -2.0%		15%	1178	66%	765	2025	2035, no range limitation	2035, up to 1000 km	34%
Dray et al. (2022) Biofuel + PtL, Mid	Modeled	Modeled	10%	1000 (1.25 $/L[4])	100%	592 (0.74 $/L)	2025	2035, up to large WB aircraft	2045, up to large NB aircraft	negligible
Dray et al. (2022) Biofuel + Hydrogen, Mid	Modeled	Modeled	10%	1032 (1.29 $/L[4])	47%	904 (1.13 $/L)	2025	2035, up to large WB aircraft,	2045, up to large NB aircraft	53%
ATAG Waypoint S1	2019-2050: -1.1%	2019-2050: -0.2%	N/A	1061	90%	878	2030	N/A	N/A	N/A
ATAG Waypoint S2	2019-2050: -1.1%	2019-2050: -0.1%	N/A	1061	90%	878	2030	N/A	N/A	N/A
ATAG Waypoint S3	2019-2050: -1.1%	2019-2050: -0.1%	N/A	1061	90%	878	2030	2035, 100-210 seats NB	2025, up to 19 seats	10%
DESTINATION 2050 (EU+)	2018-2050: -1.2%	2018-2050: -0.3%	6%	2686 (2274 €/t)	66%	1949 (1650 €/t)	2030	2035, NB intra-EU+ only, up to 2000 km, 165 seats	2030, small class aircraft	21%
US Aviation Climate Action Plan	2019-2030: -1.1% 2030-2050: NA	2019-2030: -0.4% 2030-2050: NA	10%	N/A	88%	N/A	2025	N/A	N/A	N/A

Note: [1] Share in total flight phase energy use.
[2] Weighted average SAF costs by SAF volumes of various SAF types if volumes are available, if not, simple average of all SAF types.
[3] The remaining 28% of fuels are provided by lower carbon petroleum fuels (LCAF) in the ICAO S2 scenario.
[4] Dray et al. provide SAF costs in the early 2020s instead of 2030.

Besides air transport demand growth, the selected roadmaps also make assumptions about other key input variables that have direct impacts on the final CO_2 emissions by 2050 (Table 4). Typically, assumptions are made for various mitigation measures, including technology efficiency improvement, operational efficiency improvement, the share of Sustainable Aviation Fuels (SAFs) in the total aviation energy demand and the expected SAF costs, the share of hydrogen and electricity in the total aviation energy demand, and the entry into service years of different aircraft technologies. Table 4 provides a summary of the assumptions made on these critical model input variables in the selected roadmaps.

Emissions reduction from conventional aircraft technology efficiency improvement is a result of replacing old aircraft with newer and more energy-efficient aircraft in the fleet. The improvement is often measured by a reduction in energy use in megajoules (MJ) per revenue passenger kilometers (RPK). Given that currently, there are only a few new aircraft projects under development and the fleet replacement rate is generally low, most of the roadmaps assume, on average, about 1.0% per year improvement in energy efficiency from today to 2050. However, some roadmaps have more aggressive assumptions on the annual fuel efficiency improvement, such as the ICCT Breakthrough roadmap, which assumes a 2.2% per year fuel efficiency improvement from new types of aircraft introduced since 2035.

Improvements in aircraft operational efficiency could also contribute to emissions reduction. Options in this transition measure include an increase in aircraft load factor, optimized air traffic management, single-engine taxi, etc. Notably, not all roadmaps provide specific emissions reduction estimates from individual operational efficiency measures, and hence, comparing only the same elements included in operational efficiency across the roadmaps is challenging. However, all roadmaps assume that energy intensity reduction from operational efficiency gains will be lower than that of the technology efficiency improvement, and on average, the energy intensity reduction rate is at 0.1%-0.2% MJ/RPK per year (p.a.) The ICCT Breakthrough scenario again has the most aggressive assumption on this, with 0.5% MJ/RPK p.a. intensity reduction from higher load factor and an extra 0.1% MJ/RPK p.a. reduction from traffic efficiency improvements. As shown in Table 4, some roadmaps put the efficiency improvement from technology and operations together, while others report the two efficiency improvements separately. If putting the two levers together for all roadmaps, the total efficiency improvement from technology and operation is about 1.0%-1.5% per year in most roadmaps. However, the ICCT Breakthrough scenario and the two MPP scenarios assume 2.0% per year or higher efficiency gains from the 2030s, which is a stretch based on MPP's consultations with industry experts.

Sustainable Aviation Fuel (SAF) is assumed to deliver the highest emissions savings in the energy transition of the aviation sector to reach net zero by 2050. SAF consists of two broad categories: fuels produced from biomass resources, known as bio-SAF, and fuels produced from CO_2 and electricity through synthetic processes, known as synthetic SAF or Power-to-Liquid (PtL). As a 'drop-in' fuel, SAF can be directly used in conventional jet-engine powered aircraft without any changes to aircraft and airport infrastructure (once the fuel has been blended and certified as ASTM 1655 jet fuel). Despite this unique advantage, in 2023, SAF volumes just reached 0.5 Mt and had a negligible share in total aviation energy use. All the net-zero roadmaps indicate that to be on track to reach net zero by 2050, the share of SAF in total aviation energy demand must be at least 5-6% by 2030 (Table 4). For example, the recent ICAO declaration on the third Conference of Alternative Aviation Fuels (CAAF/3), aims to achieve a 5% reduction in CO_2 emissions by 2030 on international aviation. The ICAO LTAG S3 models the highest share of SAF at 21% by 2030 for international aviation, followed by 15% in the ICCT Breakthrough and the MPP ORE. Notably, for those higher 2030 SAF use estimates, the speed with which infrastructure can be ramped up is also a key constraint for SAF production, given that the number of SAF facilities planned to be built by then may not meet the high SAF demand. By 2050, SAF is expected to account for 65%-100% of the total energy demand for aviation, depending on whether any other clean energy sources, such as green hydrogen-powered aircraft, are considered in the given roadmap.

How fast SAF can penetrate the global aviation energy supply depends on feedstock availability and SAF production costs relative to fossil jet fuels. Currently, SAF is about 2-6 times more expensive than fossil jet fuels, and the future prices of SAF remain highly uncertain. Nine roadmaps in Table 4 provide their assumptions on average SAF costs in 2030 and 2050 (in brackets are the average costs of the original values reported in the roadmaps), which shows that SAF prices are anticipated to decline over time. However, how competitive the SAF prices will become depends also on future fossil jet fuel prices and carbon abatement costs.

The energy transition in the aviation sector will clearly not happen at the same speed or at the same scale. For example, compared to bio-SAF production which is already available at commercial scale, PtL fuels are assumed to be available only from mid-2020s or 2030 in the majority of the roadmaps. In addition, hydrogen-powered aircraft are largely assumed to enter the market in the mid-2030s with limited range, while battery-electric aircraft will come in about the same time but serve even shorter-range markets (Table 4).

3.2 Model Output

With the projections on demand growth (either top-down or bottom-up) and assumptions on the key transition measures, the output of the roadmaps typically reports total aviation in-flight energy demand, the demand for SAF, annual CO_2 emissions, and the emissions reduction by each mitigation lever compared to the baseline emissions levels between their corresponding base year to 2050. In some roadmaps, cumulative CO_2 emissions are also reported in the context of an assumed aviation's carbon budget for the 1.5 °C or 2 °C temperature rise goals. Table 5 compares the key outputs from the selected roadmap.

As shown in Table 5, the global roadmaps by IATA, ATAG, and Dray et al. (2022) produce relatively comparable projections for aviation flight-phase energy consumption in 2030 and 2050 under their corresponding central demand growth scenarios. In comparison, the IEA and ICCT roadmaps have the lowest energy consumption estimates for 2050, followed by the MPP scenarios. The low energy use from the IEA roadmap is attributed to the demand management measures applied by 2050, and the ICCT and MPP scenarios have this output due to the assumed stretching annual fuel efficiency rates described earlier (Table 4). Notably, only the European DESTINATION 2050 roadmap expects aviation total in-flight energy consumption to decline from the 2030 levels in 2050.

Demand for SAF is projected to increase significantly from 2030 to 2050 across all the roadmaps. However, the shares of bio-SAF and PtL in the total SAF consumption vary widely by the corresponding model assumptions. As the most crucial model output metric of the roadmaps, CO_2 emissions from the aviation sector in 2050 are shown in Table 5. Here, we deliberately report the emissions without accounting for emissions reduction from market-based measures (MBMs) and carbon removals to compare the residual emissions in 2050. Among all the global roadmaps, the US Aviation Climate Action Plan roadmap expects zero residual emissions in 2050, even without the help of MBMs and carbon removals (Table 2). For the roadmaps that have residual emissions in 2050, the ICCT Breakthrough scenario produces the lowest residual emissions of 70 Mt, while IATA expects the largest residual emissions. ICAO LTAG S2 reports 495 Mt residual emissions but is for international aviation only.

Seven transition roadmaps also report cumulative CO_2 emissions between the corresponding base year to 2050 (Table 5). However, these cumulative emissions levels should be compared with caution because the total emissions are not all calculated on the same basis. For example, in Dray et al. (2022), fossil Jet A emissions are calculated for the whole lifecycle (i.e. WTW CO_2 emissions), while in the MPP report, only CO_2 emissions from the combustion of fuel (i.e. TTW CO_2 emissions) are calculated for fossil jet fuel. Therefore, the different bases will particularly affect the cumulative emissions levels.

To provide a comprehensive comparison of the emissions reduction potential by transition measures as the model output of the roadmaps, Figure 1 shows the percentage contribution of various transition options to the net-zero emissions in 2050, compared to their corresponding baseline emissions. The IEA Net Zero 2050 is the only roadmap that does not report emissions reduction associated with each transition measure in 2050 and thus is not included in Figure 1.

Table 4: Summary of the key output metrics from the roadmaps.

Scenario Name	Energy demand in 2030[1]	SAF use in 2030	Energy demand in 2050[1]	SAF use in 2050	CO_2 emissions in 2030	CO_2 emissions in 2050[2]	Reports cumulative CO_2 (Y/N)
IATA Roadmap S2	16.7 EJ	24Mt	22.0 EJ	512 Mt (bio-SAF: 305, PtL: 207)	1115 Mt	465 Mt	N
IEA Net-Zero 2050 Roadmap	14.6 EJ	34 Mt[3] (bio-SAF: 32 PtL: 2)	15.3 EJ	238 Mt (bio-SAF: 112, PtL: 126	932 Mt	208 Mt	N[4]
ICAO LTAG S2 (International), Mid	9.3 EJ	28 Mt (bio-SAF: 13, PtL: 15)	15.4 EJ	257 Mt (bio-SAF: 189, PtL: 68)	612 Mt	495 Mt	Y (17.0 Gt for 2020-2050)
ICAO LTAG S3 (International), Mid	9.1 EJ	47 Mt (bio-SAF: 20, PtL: 27)	14.4 EJ	329 Mt (bio-SAF:140, PtL: 189)	555 Mt	203 Mt	Y (12.0 Gt for 2020-2050)
ICCT Breakthrough	14.2 EJ	51 Mt (bio-SAF: 46, PtL: 5)	16.3 EJ	315 Mt (bio-SAF: 100, PtL: 215)	1093 Mt	70 Mt	Y (21.5 Gt for 2020-2050)
MPP PRU	14.5 EJ	42 Mt (bio-SAF: 35, PtL: 7)	19.5 EJ	369 Mt (bio-SAF: 220, PtL: 149)	1160 Mt	102 Mt	Y (18.0 Gt for 2022-2050)
MPP ORE	15.3 EJ	51 Mt (bio-SAF: 36, PtL: 15)	20.9 EJ	302 Mt (bio-SAF: 80, PtL: 222)	1138 Mt	95 Mt	Y (17.5 Gt for 2022-2050)
Dray et al. (2022) Biofuel + PtL, Mid	16.2 EJ	37 Mt (bio-SAF: 33, PtL: 4)	24.4 EJ	560 Mt (bio-SAF: 152, PtL: 408)	1256 Mt	90 Mt	Y (27.3 Gt for 2019-2050)
Dray et al. (2022) Biofuel + Hydrogen, Mid	16.2 EJ	33 Mt (bio-SAF: 33)	22.8 EJ	260 Mt (bio-SAF: 260)	1254 Mt	103 Mt	Y (26.5 Gt for 2019-2050)
ATAG Waypoint S1	16.1 EJ	42 Mt (All bio-SAF)	25.3 EJ	381 Mt (bio-SAF: 191, PtL: 190)	905 Mt	146 Mt	N
ATAG Waypoint S2	16.1 EJ	58 Mt (All bio-SAF)	25.3 EJ	445 Mt (bio-SAF: 193, PtL: 252)	905 Mt	166 Mt	N
ATAG Waypoint S3	16.1 EJ	44 Mt (All bio-SAF)	25.3 EJ	330 Mt (bio-SAF: 191, PtL: 139)	905 Mt	116 Mt	N
DESTINATION 2050 (EU+)	2.4 EJ	3.2 Mt (bio-SAF: 2, PtL: 1.2)	2.1 EJ	32 Mt (bio-SAF: 13, PtL: 19)	113 Mt	22 Mt	N
US Aviation Climate Action Plan	4.1 EJ	9 Mt	5.4 EJ	106 Mt	204 Mt	0 Mt	N

Note: [1] **Flight phase demand only.** [2] **CO_2 emissions without MBMs and carbon removal in 2050.**
[3] **IEA reports SAF consumption in EJ, and here we convert EJ to Mt using the SAF energy density at 0.044 Pj/kt.**
[4] **Although the cumulative emissions are not explicitly published in the IEA report, one can, in principle, extract an approximate number from their published emissions trajectory on page 94.**

As shown in Figure 1, seven roadmaps, namely ATAG S1-S3, IATA Roadmap S2, DESTINATION 2050, and the two MPP roadmaps, achieve net zero CO_2 emissions by 2050 with the help of MBMs (including the EU ETS and CORSIA) or carbon removals. In comparison, the two roadmaps by Dray et al. (2022), which do not consider offsets and carbon removals, have 3% of residual emissions in 2050. Similarly, the

ICCT Breakthrough roadmap does not include the 'out-of-sector' measures and has 3% of the CO_2 emissions remaining by 2050. Among the roadmaps that consider MBMs and carbon removals, the IATA net zero roadmap has the largest share (i.e. 20%) of residual emissions to be mitigated by MBMs or carbon removals in 2050, while other roadmaps all have less than 10% residual emissions to mitigate through the 'out-of-sector' measures. The two ICAO roadmaps have 32% and 13% of residual emissions from international aviation in 2050, respectively, which could rely on the ICAO's CORSIA offsetting system to mitigate, should CORSIA be extended beyond its current 2035 remit. However, the ICAO roadmap did not specify if offsets will be applied.

Technology efficiency improvements for conventional aircraft have a relatively consistent share at about 20% in 2050, with the highest share from the US Aviation Climate Action Plan roadmap (29%) and the lowest share from the IATA Roadmap S2 (7%). The relatively low share of technology improvement in the IATA roadmap is because the roadmap already includes all the current technological improvements on the pipeline (e.g. it assumes A320neo will replace all the A320) in its baseline case. In comparison, the US roadmap uses the baseline case where aircraft technology is assumed to be frozen in 2019

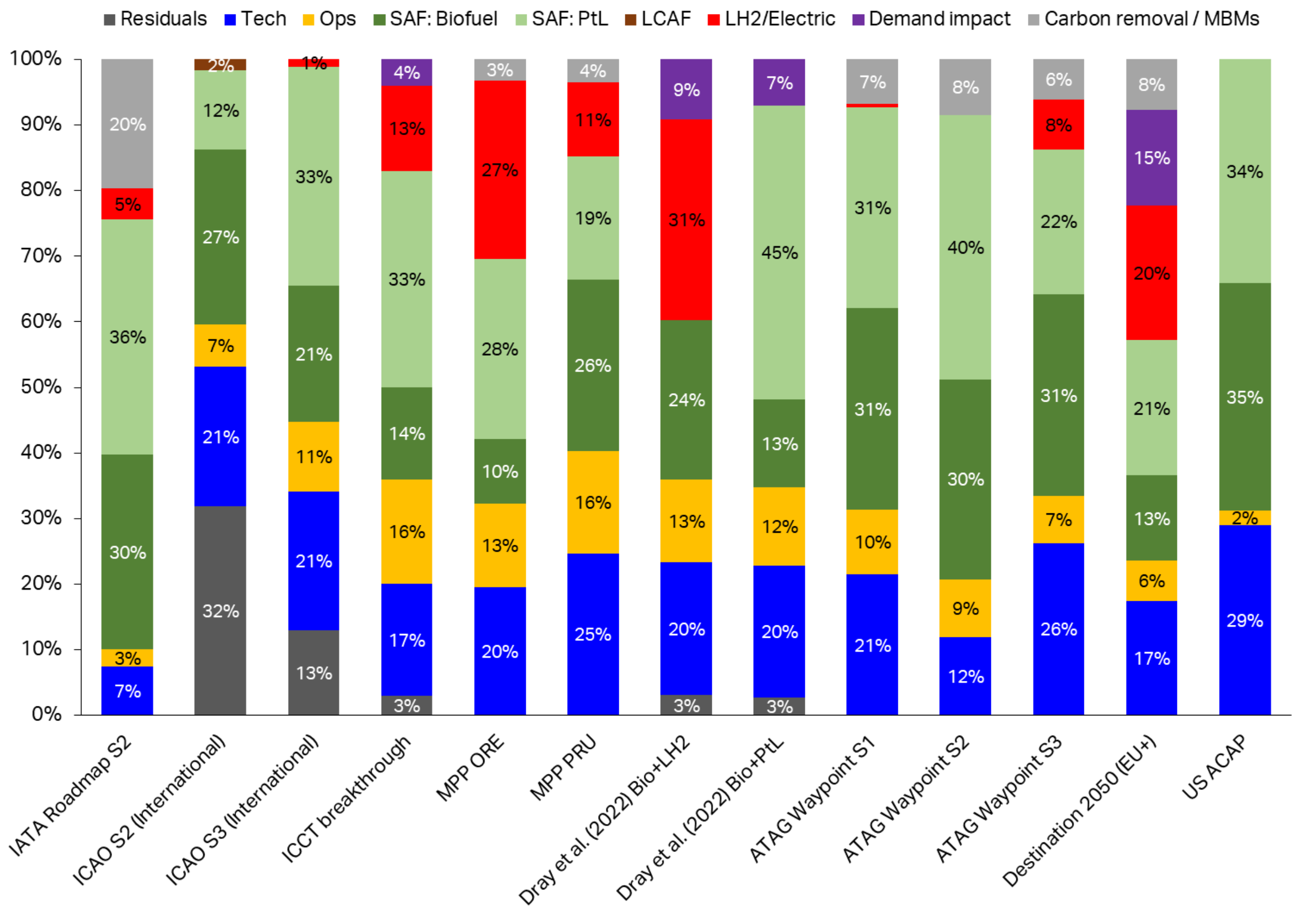

Figure 1: Emissions reduction potential by transition measures in 2050, comparing across all roadmaps except the IEA Net Zero 2050.

Operational efficiency improvements will play a smaller role in the reviewed roadmaps, typically below 10%. However, in the ICCT Breakthrough and the MPP PRU roadmaps, the emissions reduction from operational improvement accounts for more than 15%, due to their ambitious assumptions in this aspect discussed earlier. For example, the ICCT Breakthrough has an assumption that all airlines will achieve 90% of the maximum payload by 2050 to push the operational efficiency improvement to reach 0.6% per year (Table 4).

Notably, although the roadmaps give relatively consistent contributions to emissions reductions under technology and operational improvements, they have different definitions regarding how the improvements are counted. Besides the example discussed already comparing the IATA roadmap versus the US Aviation Climate Action Plan roadmap, some roadmaps consider the replacement of previous-generation aircraft with current-generation aircraft as a technological improvement, while others consider only the replacement of aircraft with newer-generation designs as an improvement.

SAF accounts for the highest share of emissions reduction across the majority of the roadmaps, ranging from 24% to 70%, with a median value of 53%. The lowest SAF share is from the bio-SAF + LH_2 scenario by Dray et al. (2022), given that this scenario aims to assess how net zero might be achieved using hydrogen under a strong hydrogen adoption policy. In this roadmap, bio-SAF will be used as a bridging fuel to liquid hydrogen, thus only accounting for 24% of the total emissions reduction constrained by biomass availability to aviation. The second lowest SAF share (34%) is by the DESTINATION 2050 (EU+) roadmap, due to the strong focus on hydrogen-powered aircraft for intra-European aviation. On the other hand, other roadmaps heavily rely on SAF in the net-zero transition, and the roles of bio-SAF and PtL vary significantly. PtL is expected to contribute more to emissions reduction than bio-SAF in 2050 in most of the roadmaps, with the exceptions of the ATAG S3, ICAO S2, and the bio-SAF + LH_2 scenario by Dray et al. (2022). Besides Dray et al. (2022), which deliberately excluded PtL from this scenario for its research experiment, as discussed previously, in the ATAG S3, PtL is expected to play a relatively smaller role compared to the ATAG S2 because of greater emissions reductions from hydrogen- and electric aircraft and technology improvement. For ICAO LTAG S2, PtL is assumed to have a slower deployment, thus resulting in the largest residual emissions in 2050 among all roadmaps.

Hydrogen and battery-electric aircraft have a minor role in 2050 in ten out of the fourteen roadmaps studied, which contrasts sharply with DESTINATION 2050 (EU+), bio-SAF + LH_2 scenario by Dray et al. (2022), ICCT Breakthrough, and MPP PRU and ORE roadmaps. Again, this can be attributed to the main messages these roadmaps aim to convey. The greatest share of hydrogen-powered aircraft (31%) is from the bio-SAF + LH_2 scenario by Dray et al. (2022), which focuses on how net zero might be achieved using hydrogen under a strong hydrogen adoption policy. Similarly, the MPP ORE roadmap also has a very aggressive role (27% of the global aviation emissions reduction in 2050) for hydrogen-powered aircraft, given that the roadmap aims to evaluate how electricity-based technologies such as PtL and hydrogen-/battery-electric aircraft could deliver net-zero aviation by 2050 if there is a faster cost decline of renewable electricity. The DESTINATION 2050 (EU+) roadmap also has a strong focus on hydrogen-powered aircraft, which seems reasonable given that hydrogen aircraft will mainly operate in the intra-EU+ market for flights shorter than 2000 kilometers. On the other hand, the ICCT Breakthrough and MPP PRU roadmaps, despite having relatively more balanced shares of emissions reduction from various mitigation levers, also allocate 11-13% of the emissions reduction to hydrogen and electric aircraft, compared to the 5%-8% of the reduction from the ATAG S3 and the IATA Roadmap S2.

Four roadmaps, namely DESTINATION 2050, ICCT Breakthrough, and Dray et al. (2022), consider the emissions reduction from the demand impacts of the net-zero transition. The demand impacts are relatively small, typically below 10% in these roadmaps, except for DESTINATION 2050 (15%), where 2% of the reduction is attributed to the reduced demand from higher ticket prices due to the EU ETS, 12% is resulting from the reduced demand from higher ticket prices due to the use of SAF, and 1% is attributed to the reduced demand from higher ticket price of taking hydrogen-powered flights. Notably, a more unique case is the IEA Net-Zero roadmap, despite not being included in Figure 1. In this roadmap, 20% of the emissions reduction is expected to come from avoided demand through demand management measures.

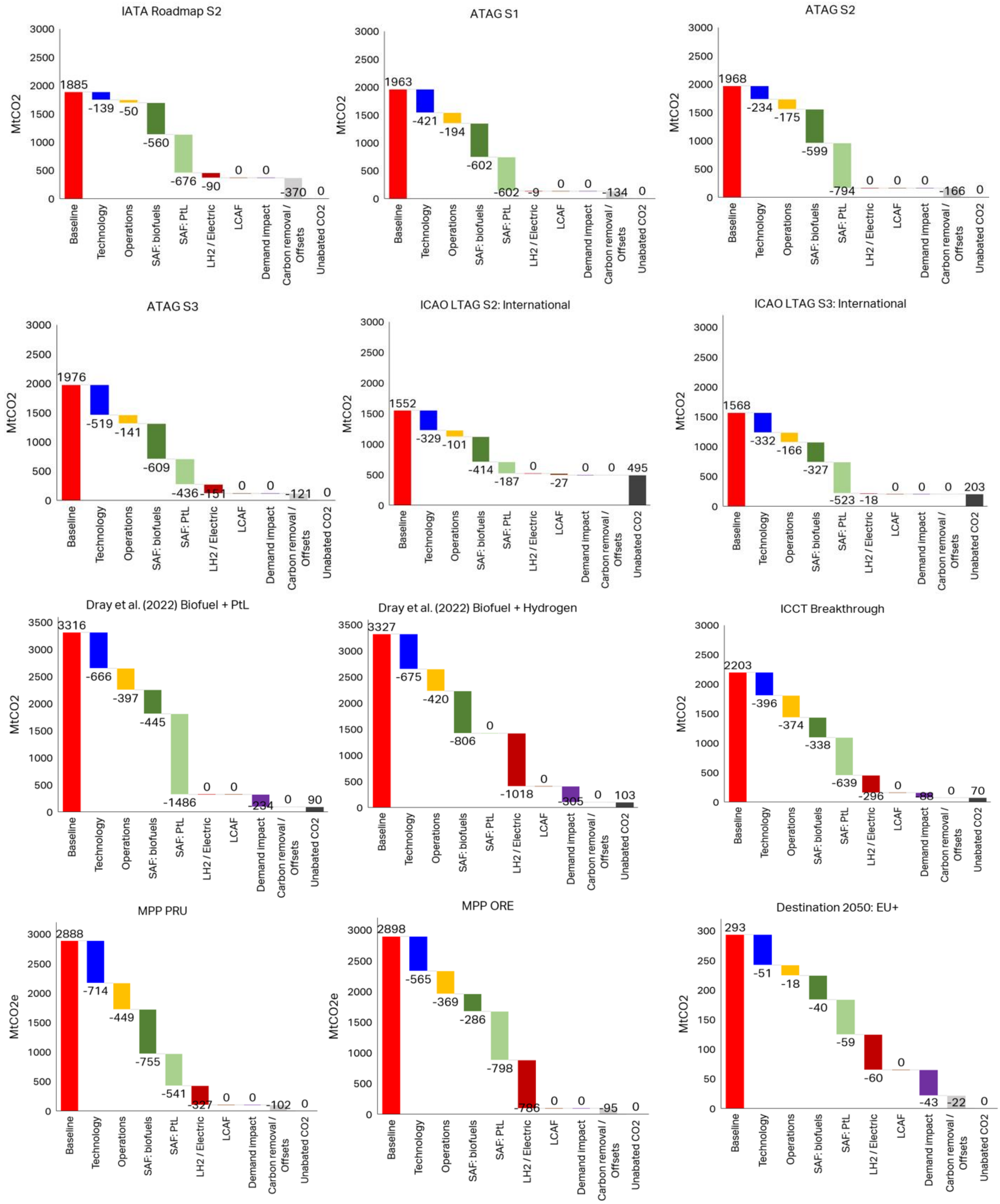

Figure 2: Emissions reduction by mitigation measures in 2050 in absolute terms.

To further understand the emissions reduction potential of these mitigation measures across the roadmaps, Figure 2 shows the reduction in absolute terms in 2050 compared to the baseline emissions. From this comparison, it is clear that the baseline emissions have a direct impact on the amount of CO_2 emissions that need to be abated. The IATA Net Zero Roadmap S2 and the three roadmaps by ATAG have relatively similar baseline emissions levels in 2050 due to similar demand growth rates (2.9% p.a.

for IATA S2 and 3.1% p.a. for ATAG roadmaps, see Table 3) used in these roadmaps. In comparison, scenarios by Dray et al. (2022) have the highest baseline emissions among all the global roadmaps at about 3300 million tonnes (Mt) CO_2, following the 3.3-3.4% demand growth rates modeled in this study. The MPP roadmaps have the second-highest baseline emissions in 2050 at about 2900 $MtCO_2$. Notably, although the demand growth rate of the MPP roadmaps is only 2.5% p.a., it has a larger base by covering more aviation activities such as military and government flights and general aviation, thus higher baseline emissions.

In terms of absolute emissions reductions by various mitigation options, we found that the mitigation potential of a given option is determined again by the purpose of the roadmaps. Among all the global roadmaps, emissions savings from technology improvements range from 139 $MtCO_2$ (IATA S2) to 714 $MtCO_2$ (MPP PRU). The lowest value from the IATA S2 is because the roadmap already includes all the current technological improvements on the pipeline in its baseline case as discussed earlier, while the highest value from the MPP PRU is attributed to its stretching assumption of 2% p.a. improvement in fuel efficiency. Similarly, in terms of emissions reduction from operational improvements, the IATA roadmap (50 $MtCO_2$) has the most conservative view, while MPP PRU has the most ambitious estimates (449 $MtCO_2$).

Emissions reduction from bio-SAF ranges from 286 $MtCO_2$ (MPP ORE) to 806 $MtCO_2$ (bio-SAF + LH_2 scenario by Dray et al. (2022)). With a focus on achieving net zero through the electricity-based technologies such as PtL and Hydrogen/electric aircraft, the MPP ORE roadmap has a limited role of bio-SAF. In comparison, although the bio-SAF + LH_2 scenario by Dray et al. (2022) only uses bio-SAF as a bridging fuel to hydrogen, given that there is no PtL in this scenario, bio-SAF still contributes to a significant amount of emissions reduction by 2050. Similarly, PtL contributes to 0-1486 $MtCO_2$ reduction among the global roadmaps, with the lower limit from the bio-SAF + LH_2 scenario by Dray et al. (2022) and the upper limit from the bio-SAF + PtL scenario also from Dray et al. (2022). While these two extreme cases are assessed as experimental research, other roadmaps such as MPP ORE, ATAG S2, IATA S2, and ICCT Breakthrough all have a significant amount of emissions reduced via the use of PtL.

Finally, hydrogen and battery-electric aircraft play a role in seven of the roadmaps, but only in three scenarios, they represent a significant reduction by 2050. The bio-SAF + LH_2 scenario by Dray et al. (2022) and the MPP ORE, have specific settings for hydrogen development in their scenarios, which might be challenging to materialize globally, while the hydrogen share in DESTINATION 2050 (EU+) seems a reasonable path given that hydrogen aircraft will mainly operate in the intra-EU+ market for flights shorter than 2000 kilometers.

4. Conclusion

This paper provides the first comprehensive review of fourteen leading net-zero transition roadmaps for the aviation sector. By breaking down the massive amount of information discussed in the roadmaps into various aspects for comparison, the report aims to help airlines and stakeholders better understand these roadmaps in one go. Specifically, the report compares the selected roadmaps in terms of their scopes, jet fuel lifecycle boundaries, model input/key assumptions, and model output (i.e. total in-flight energy demand by 2030/2050, SAF use in 2030/2050, aviation CO_2 emissions in 2030/2050, and the emissions reduction potential by different transition measures).

Our review found that depending on the main message a roadmap aims to convey, it may project a greater and faster development in certain transition measures to help the aviation sector reach net zero by 2050. SAF is expected to achieve the highest amount of CO_2 reductions across all the roadmaps, contributing to 24%-70% (with a median value of 53%) of the CO_2 emissions reduction in 2050 compared to the corresponding baseline emissions levels. However, this wide range of possible contributions from SAF also suggests very high uncertainty in global SAF supply, which depends on feedstock availability and production costs of SAFs relative to fossil jet fuels. Technology and operation efficiency improvement are assumed to have a relatively consistent role in the net-zero transition process, together contributing to about 30% of the emissions reduction in 2050. In comparison, the emissions savings by hydrogen- and electricity-powered aircraft are also highly uncertain, ranging from 0% to 31% (with a median value of 5%) if including the hydrogen-focused research scenario by Dray et al. (2022). The demand impact of net-zero transition on aviation emissions is modeled only in four roadmaps, and it has a limited contribution to emissions reduction by less than 10% in 2050 in the global roadmaps reviewed, except the IEA Net Zero roadmap. Finally, to achieve net zero in 2050, almost all the global roadmaps suggest that the aviation sector will need help from market-based measures and carbon removals to bridge the gap between their residual emissions and net zero emissions in 2050. Even if carbon removal technologies are not considered an 'out-of-sector' mitigation measure, it is still critical to develop these technologies as they will play a key role in supplying CO_2 as the feedstock for producing power-to-liquid (PtL) fuels.

By comparing these roadmaps, this report is instrumental in helping airlines better understand the potential of reducing CO_2 emissions by different mitigation measures. Given that most of the transition measures for the aviation sector are not yet readily available, we believe there will not be a universal path to help the aviation sector reach net zero by 2050. Nevertheless, by looking into the existing roadmaps in detail, this report should become a useful reference point to help the aviation community navigate its way to net zero by 2050.

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Abbreviations

AIM 2015: Aviation Integrated Model by UCL Air Transport Systems Lab

Bio-SAF: Biofuel SAF

CAGR: Compound annual growth rate

CCS: Carbon capture and storage

CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

CO_2: Carbon dioxide

DAC: Direct air capture

EU ETS: The EU Emissions Trading Schemes

LH_2: Liquid hydrogen

LCAF: Lower carbon petroleum fuels

LTAG: Long-term aspirational goal

MBMs: Market-based measures

MJ: Megajoules

Mt: Million tonnes

PtL: Power-to-liquid fuels

RPK: Revenue Passenger Kilometre

RPM: Revenue Passenger Mile

RTK: Revenue Tonne Kilometre

SAF: Sustainable aviation fuels

TTW: Tank-to-Wake

WTW: Well-to-Wake

WTT: Well-to-Tank