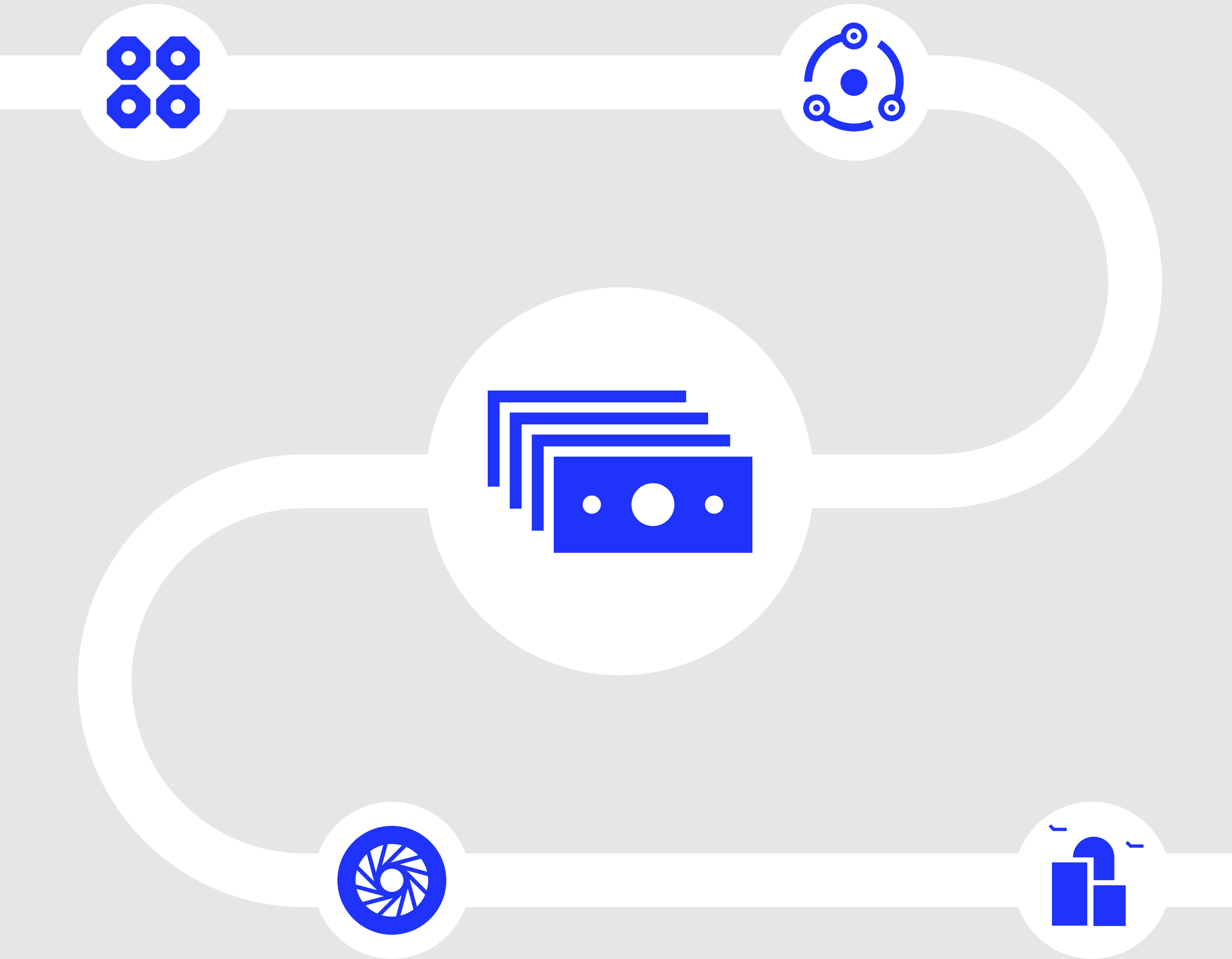
September 2024

Finance
Net Zero CO_2 Emissions Roadmap

IATA Sustainability and Economics



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Glossary

ASTM
American Society for Testing and Materials

AtJ
Alcohol-to-Jet

CAF
Conventional Aviation Fuel

Capex
Capital expenditure

CDR
Carbon Dioxide Removal

CORSIA
Carbon Offsetting and Reduction Scheme for International Aviation

DAC
Direct Air Capture

EEUs
Eligible Emissions Units

FCI
Fixed capital investment

FOG
Fats, Oils, and Greases

FT
Fischer-Tropsch

GHG
Greenhouse Gas

HEFA
Hydro processed Esters and Fatty Acids

ICAO
International Civil Aviation Organization

IEA
International Energy Agency

LCA
Lifecycle Emissions Assessment

Mt
Million tonne

MSP
Minimum Selling Price

MSW
Municipal Solid Waste

MWh
Megawatt-hour

mbbl/d
million barrels per day

NPV
Net Present Value

OPEC
Organization of the Petroleum Exporting Countries

Opex
Operating expenses

PtL
Power-to-Liquid

PV
Photovoltaic

R&D
Research and Development

SAF
Sustainable Aviation Fuel

TEA
Techno-Economic Assessment

TWh
Terawatt hour

US
United States

USD
United States Dollar

WC
Working Capital

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Executive summary

The Paris Agreement, signed by as many as 195 Parties to the Convention, adopted the long-term goal of keeping the rise in global surface temperature to well below 2° Celsius above pre-industrial levels. The airline industry supports this long-term goal and is committed to achieving net zero CO_2 emissions from air transportation by 2050. The efforts of airlines and their partners in this context cannot be analyzed as a transportation issue. Air transport's energy transition is part of the global energy transition and the Paris Agreement's mission to limit global warming.

In this Net Zero CO_2 Emissions Finance Roadmap, we provide estimates for the transition costs that the airline industry will likely face. We also analyze the capital investments needed to build the number of new facilities that will produce the sustainable aviation fuel (SAF) that is the primordial solution to airlines' transition by 2050. These facilities will produce renewable fuels also for other industries and uses in the global economy. In this way, the air transport industry's transition is, of course, inextricably linked with the world's energy transition.

We calculate the transition cost of SAF use as the minimum selling price of SAF minus the price of conventional aviation fuel (CAF), multiplied by the amount of SAF needed by air transport for each year of the transition. The transition costs of other main mitigation levers, such as CORSIA offsetting, hydrogen for powering aircraft, and carbon removals are also estimated. For the whole transition period, from 2024 to 2050, we estimate this cost at USD 4.7 trillion. That represents an annual average transition cost of USD 174 billion, though it rises from USD 1 billion in 2025 to a rather eye-watering USD 744 billion in 2050.

Our estimated total transition cost is in line with other published roadmaps. With the expected growth in global RPK from 2024 to 2050, adding the USD 744 billion transition cost would double airlines' fuel cost in 2050 compared to a "no-transition" case and at the 2024 average jet fuel price. As a result, the share of airlines' fuel cost in total costs is likely to increase from the current 25%-30% levels to 45%, with another 3% of the total costs being the transition cost from the use of carbon removals in 2050, all else being equal. This doubling of fuel costs cannot be absorbed by airlines' profit margins (3% net expected in 2024). Assuming that under the "without transition" case, airlines will achieve a 6% operating profit margin in 2050, as is expected in 2024, there would be a USD 601 billion revenue gap in 2050 for the air transport industry to reach breakeven under the net zero transition. Putting the transition cost in perspective in this way should make it blatantly clear that policy support is urgently required to bring the cost of the transition solutions down and to minimize their premium over fossil fuels.

We also estimate the number of new plants needed to produce SAF, across four major pathways and over time. There are a number of variables that will influence how many new facilities that will need to be built. Most important of all is arguably the proportion of SAF production in refineries' total output. In a sense, SAF competes with other products at the refinery, such as biodiesel, and if SAF were to achieve the highest possible share in the product mix, the total number of new plants needed over the entire transition period could fall from about 6,700 to 3,400 (low SAF yield scenario and high SAF yield scenario, respectively). That is not far off a 50% reduction in the number of plants, and therefore also in the capital needed to build these facilities. The total capital investments required to build new renewable fuel plants over the whole transition period are estimated at USD 4.2 trillion in the high SAF yield case, and at USD 8.1 trillion in the low SAF yield case.

Both the overall number of plants and the corresponding financial needs can be reduced further by maximizing co-processing capabilities at existing refineries. Co-processing involves inserting a bio-based intermediate into existing petroleum refineries for simultaneous processing with petroleum feeds. This will increase SAF volumes immediately as it does not require the lead time nor the investments for plant construction. While this is a rare near-term lever and therefore one to be used absolutely, its potential is nevertheless rather limited—we expect about 3 million tonnes of SAF to be produced from co-processing in 2030, but that would still be about 11% of total SAF production that year (i.e., 24 million tonnes). In terms of capital investments over the whole transition period, co-processing could help save USD 347 billion (from building 266 fewer new plants), equal to nearly 3 years' worth of average annual capital investment needs in our high SAF yield case. This further capex savings from co-processing SAF will bring the total capex needed to a minimum level of USD 3.9 trillion.

Policy makers must provide early and strong support to help direct capital to the production of renewable fuels and other solutions that will benefit not only air transport but importantly also many other industries as the world economy grapples with the energy transition. Concrete steps on the way are analyzed in the IATA Policy Roadmap.[1] The analysis presented in this Finance Roadmap shows that air transport's net zero CO_2 emissions goal is attainable, comparable in many ways to the solar and wind energy transitions, and similarly critically dependent upon policy makers' concerted efforts to make it happen.

1 IATA (2024), Net Zero CO_2 Transition Policy Roadmap.

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1. Overview

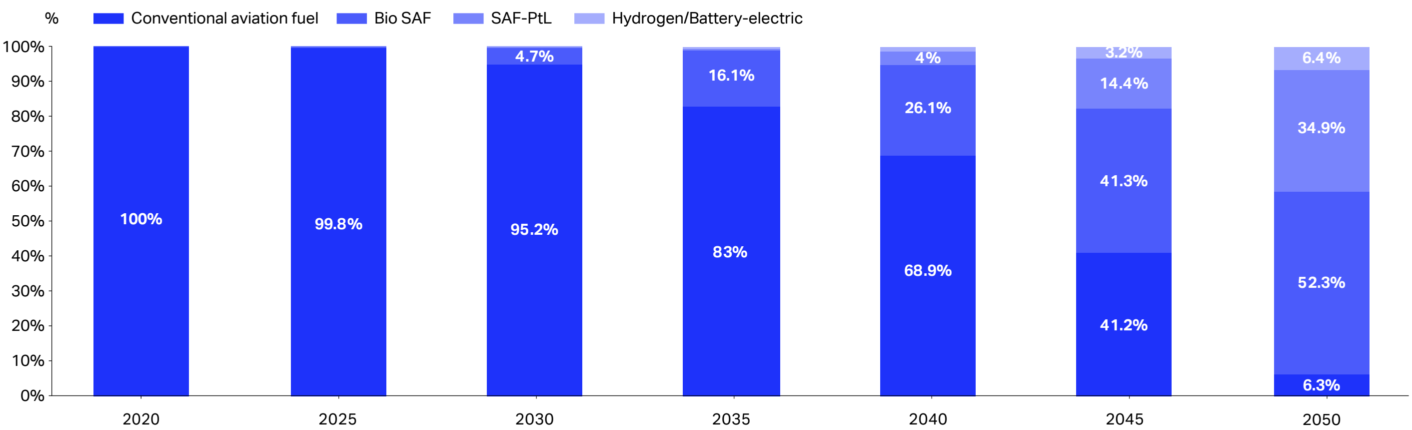
In 2023, IATA released five roadmaps to pave the way for the global airline industry to reach net zero CO_2 emissions by 2050. These roadmaps outlined key milestones for aircraft technology, energy and fuel infrastructure, operations, policy, and finance to achieve on the way to the net zero target. This report deepens the analysis from the 2023 IATA Finance Roadmap and provides a detailed quantitative assessment of the magnitudes of financial requirements on the journey to net zero CO_2 emissions.

1.1 IATA Finance Roadmap

The main challenge regarding the air transport industry's transition to net zero CO_2 emissions—as for the global energy transition—is the necessity to replace, progressively, petroleum-based fuels with alternative cleaner energies, including SAF, hydrogen, and renewable electricity. This transition would imply that the share of conventional aviation fuel (CAF) in air transport's in-flight energy demand will have to decrease from 100% in 2020 to, in our estimation, around 6.3% in 2050 (Chart 1). SAF produced from sustainable biomass sources (bio SAF) is expected to be the dominant solution to replace fossil-based fuel in the industry's energy transition to 2050. The bio-SAF share in total fuel consumption is likely to increase from about 5% in 2030 to 52% in 2050. Meanwhile, SAF produced by CO_2 and renewable electricity (Power-to-Liquid, or PtL) will start to play a meaningful role from 2040 and account for about 35% of the total in-flight energy demand for the air transport industry in 2050. Hydrogen and battery will also play their part in the energy transition process, albeit with a limited potential on the 2050 horizon at 6%. On the other side of 2050, the landscape will most likely look different.

Inevitably, the transition will involve extra costs. The additional costs to airlines will result from using SAF and hydrogen to replace CAF in powering aircraft, from purchasing carbon credits to offset the CO_2 emissions from international flights under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and from utilizing carbon removals to compensate airlines' residual emissions by 2050. All these costs will directly affect airlines' operating cost (opex) structure. Our analysis allows us to estimate the corresponding transition cost of each mitigation option over 2023-2050. The transition will also require substantial and indispensable capital investments (capex), notably for the SAF ramp-up. Our analysis will focus on the magnitude and distribution of the capex necessary to build the requisite number of new renewable fuel facilities for SAF production to meet the rapidly rising demand and allow airlines to reach the net zero goal by 2050.

Chart 1: Share of in-flight energy demand by energy sources under the IATA Roadmap,[2] %



Source: IATA Sustainability and Economics

2 IATA (2023), "Aircraft Technology Net Zero Roadmap", page 15.

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1.2 The cost of the transition to the air transport industry

In this roadmap, we define the cost of the transition as the additional total cost that the air transport industry will need to cover when they adopt various mitigation options in the net zero transition, over and above the price of CAF.[3] We further quantify the outright additional cost of new solutions. The transition cost of using SAF is defined as the premium between the minimum selling price (MSP, see Box 1) of SAF and the unit price of CAF, multiplied by the amount of SAF production that would be needed in that particular year for the airline industry to stay on track to the net zero target. However, for carbon removal and CORSIA Eligible Emissions Units (EEU),[4] the transition cost is the unit price multiplied by the quantity. In section 2 we provide a detailed assessment of the net zero transition cost for airlines over 2023-2050.

1.3 The capital investments needed to build new renewable fuel facilities

Separate from airlines' transition costs, the capital investment needed to build new renewable fuel facilities for SAF production is a prerequisite for making any net zero transition plan possible. These costs will eventually be passed on to airlines as a part of the SAF MSP, as well as to other customers of the resulting refined output (renewable diesel for road transport, for instance), but the upfront costs will need to be shouldered by fuel producers. The capital cost of a new renewable fuel plant depends on the plant size and the type of production pathway used. The total number of new facilities needed is a function of the overall SAF production output required for the transition and SAF production output per plant, with the latter in turn being a function of the facility size, the production pathway, and the chosen product output mix at the facility.[5] We provide a quantitative assessment of the total number of renewable fuel facilities required each year for SAF production to meet demand, and the associated capital investments between 2023 and 2050, in section 3.

Box 1: Minimum Selling Price (MSP) of SAF

The Minimum Selling Price (MSP) is the fuel selling price that aligns with the target real discount rate and a Net Present Value (NPV) of zero.[6] In other words, the MSP is the price at which fuel suppliers will sell SAF to airlines without losing money and allowing them to cover their cost of capital. Ultimately, airlines are most likely to pay a premium price for SAF on top of the MSPs, which is the product price of SAF.

When determining SAF MSPs, fuel suppliers will make sure that the MSPs can cover the capital costs (including capex) of the renewable fuel plant, the fixed operating cost (opex) for producing the fuel, the non-feedstock variable opex, the cost of feedstock, and any taxes associated with selling the fuel.[7] Importantly, depending on the SAF production pathway, the shares of the above components of SAF MSPs could vary significantly. Moreover, additional processes and feedstocks are involved in renewable fuel production compared to those used for fossil fuels. These facts will limit the potential for lowering the MSPs over time for certain SAF types and will most likely ensure an enduring premium over the price of conventional aviation fuel.

6 International Civil Aviation Organization (2022). Guidance on potential policies and coordinated approaches for the deployment of SAF.
7 Bann, S.J., Malina, R., Staples, M.D., Suresh, P., Pearlson, M., Tyner, W.E., Hileman, J.I. and Barrett, S. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. Bioresource Technology, 227, pp.179–187.

3 The forecast price of CAF assumes that current average refining yield is maintained. Should refining yields for jet kerosene increase to compensate for falling production of other middle distillate products, the price of CAF could possibly go up to cover higher production cost. The additional cost of CAF to the airlines arising from this potentially higher price is not considered in our calculations.
4 EEUs are subject to the CORSIA Emissions Unit Eligibility Criteria which consist of a set of principles by which the programs are assessed for the eligibility to supply emissions units to CORSIA. The CORSIA Emissions Unit Eligibility Criteria are approved by the ICAO Council.
5 All refineries produce a mix of products and the share of each product in the mix will be optimized to maximize profits. As such, SAF competes with other refined products for prominence in the product mix of refineries.

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2. The cost of the transition to the air transport industry: 2023-2050

Understanding the potential costs involved in the energy transition is essential for all stakeholders to be able to analyze the current situation and make plans for the future. Here we assess the transition costs that airlines might face when adopting different transition measures based on the IATA Net Zero CO_2 Emissions Roadmaps (2023), with a particular focus on the transition cost of using SAF.

2.1 Overall transition cost for 2023-2050

We define the transition cost as the additional cost that the air transport industry will likely need to pay for adopting new solutions, which gradually replace the use of CAF and bring the industry to net zero CO_2 emissions by 2050. The transition levers considered in this assessment are SAF, hydrogen (H_2) used for hydrogen-powered aircraft, carbon offsets via CORSIA, and carbon removals. We do not include the costs of fleet replacement and operational improvement by airlines, although these two are also important options for the net zero transition. The reason for this is that fleet replacement and improvements in operational efficiency are daily business for airlines, and the costs associated with these two measures are already embedded in airlines' current investments and operating cost structures. While hydrogen-powered aircraft will be significantly different in aircraft design compared to conventional aircraft, when they enter into service in the mid-2030s, the latest economic assessment shows that short-range hydrogen aircraft would have similar costs to conventional aircraft throughout the lifecycle, from production and acquisition, operation (flights and maintenance), to end of life.[8] In addition, hydrogen-powered aircraft will most likely replace old regional jets in the short-range market by 2050, thus having only limited fleet penetration. Due to the constraints in battery technology, battery-electric aircraft are expected to cover even shorter distances by 2050 compared to hydrogen-powered aircraft. Therefore, electric aircraft are also excluded from our explicit consideration in the estimation of transition costs.

There is of course considerable uncertainty around any estimates of this kind. We would argue, though, that the estimated transition costs presented here are most likely to be at the lower end of any future possible range (abstracting from future policy measures). We have not endeavored to identify a top of the range transition cost, which would have to include corporate mark-ups and further assumptions about energy market dynamics that lie outside of the purposes of this analysis.

8 Ramm, J., Rahn, A., Silberhorn, D., Wicke, K., Wende, G., Veatriki Papantoni, Linke, F., Kühlen, M. and Dahlmann, K. (2024). Assessing the Feasibility of Hydrogen-Powered Aircraft: A Comparative Economic and Environmental Analysis. Journal of Aircraft, pp.1–17.

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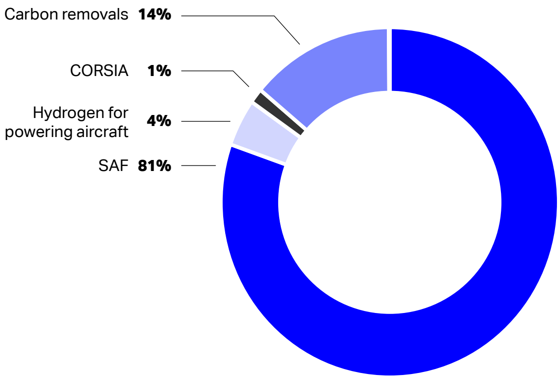
The annual total required transition costs are expected to increase significantly from USD 0.12 billion in 2023 to USD 19.1 billion in 2030, reaching USD 744.4 billion in 2050 (Chart 2). The substantial increase in the annual total transition cost is largely driven by the significant growth in SAF use based on the IATA Net Zero CO_2 Emissions Roadmaps and the expected price differential between SAF MSPs and CAF unit prices. Similar to the calculation method for the SAF transition cost, the transition cost associated with using hydrogen-powered aircraft is derived by first taking the premium between H_2 MSP[9] and the unit price of CAF[10] and then multiplying the premium price by the H_2 production amount specifically for powering the hydrogen aircraft, taking into account the difference in the energy mass density between H_2 and CAF. Additionally, CORSIA will be a crucial component of the transition between 2024 and 2035.[11] Beginning on 1 January 2024, CORSIA requires airlines to offset their emissions from international aviation using carbon credits called Eligible Emissions Units (EEU). The EEUs are calculated to equate to one tonne[12] of CO_2 emissions to be offset; hence, the transition cost of CORSIA is the projected unit price of EEUs multiplied by the CORSIA EEUs demand for international aviation.[13]

As illustrated in the 2023 IATA roadmaps, carbon dioxide removal (CDR) will play a critical role in bringing the air transport industry to net zero in 2050. However, given the lack of consensus regarding how much CO_2 emissions will need to be removed in the years before 2050, we derive the transition cost of CDR in this analysis by estimating the carbon removal capacity that could become available to the air transport industry. With the available CDR capacity, airlines may or may not use CDR before 2050, depending on a given airline's transition plans and the CDR unit price. The projection of the unit price of CDR is based on existing literature regarding the current price and typical learning rate of the technology.[14] Considering that carbon removal technology is still in its early stages, there is a high degree of uncertainty around our estimated transition cost of CDR.

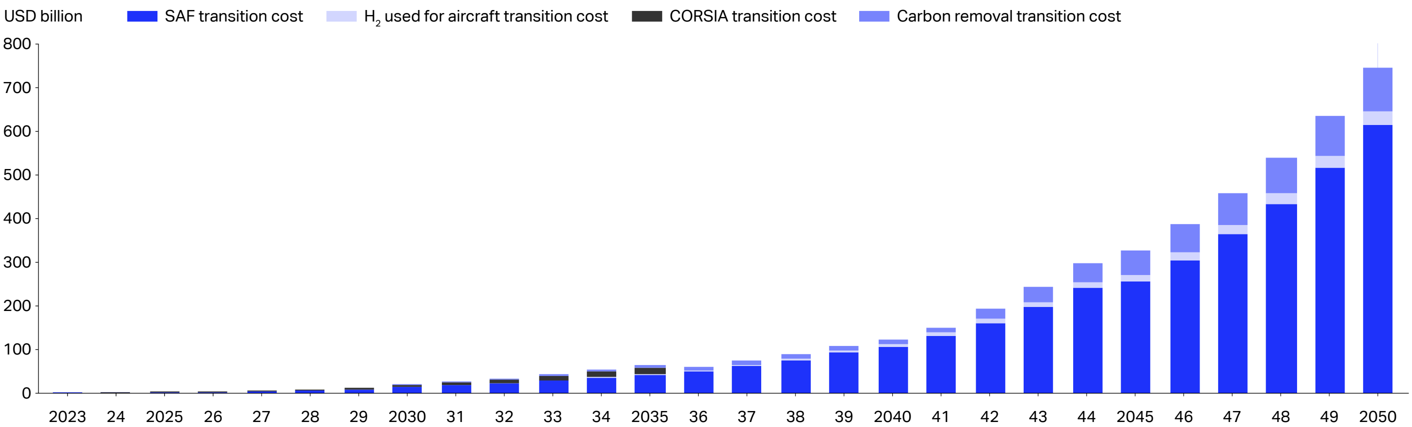
The cumulative transition cost of the four principal mitigation measures is about USD 4.7 trillion between 2023 and 2050. The transition cost of using SAF is expected to make up the largest share at 81% (equivalent to USD 3.8 trillion), followed by the transition cost of CDR at 14% (equivalent to USD 0.6 trillion). The cost of using H_2 for hydrogen-powered aircraft to replace conventional petroleum-based aircraft accounts for 4% of the total transition cost (equivalent to USD 0.2 trillion), due to its relatively limited flight range and the small market share in the fleet composition by 2050.[15] CORSIA, as an intermediate solution (2024-2035) before the scale-up of the aviation cleaner energies, will account for 1% of the total transition cost (Chart 3). The estimated total transition cost may sound daunting when it first meets the eye, therefore, Appendix 3 provides an analysis to put the transition cost needed into perspective.

Chart 3: Breakdown of the cumulative transition cost by major mitigation lever, 2023-2050, share of total, %



Source: IATA Sustainability and Economics

Chart 2: Annual transition cost associated with major net zero transition measures, 2023-2050, USD billion



Source: IATA Sustainability and Economics

9 Aerospace Technology Institute (2021). FlyZero Reports Archive – Aerospace Technology Institute.
IRENA (2018). Hydrogen from renewable power: Technology outlook for the energy transition.
10 S&P Global Commodity Insights (2024).
11 Here, we have considered that CORSIA would run out in 2035 as it is currently intended without taking into account its potential review and role beyond 2035.
12 IATA writes US English; however, when referring to units of 1,000 kilograms, we write tonne instead of ton.
13 The transition cost of CORSIA is calculated based on IATA's estimates of the demand for CORSIA EEU and the unit price released in September 2023.
For more details, see IATA (2024), Net Zero CO_2 Transition Policy Roadmap.
14 IEA (2022). Direct Air Capture: A key technology for net zero. OECD eBooks.
Ozkan, M., Nayak, S.P., Ruiz, A.D. and Jiang, W. (2022). Current Status and Pillars of Direct Air Capture Technologies. iScience, 25(4), p.103990.
15 For more details, see the IATA (2023), Aircraft Technology Net Zero Roadmap.

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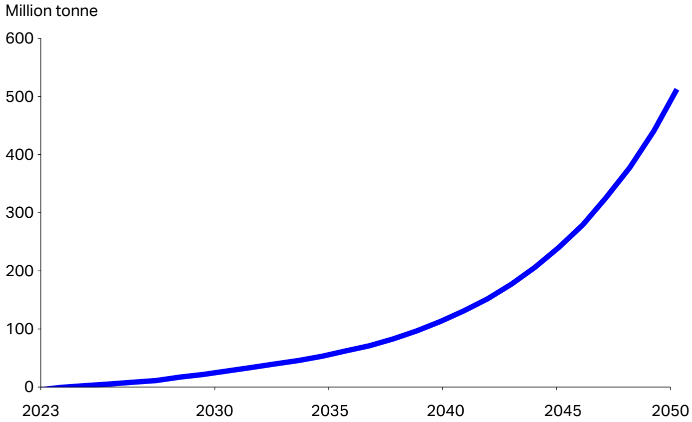
2.2 The transition cost of using SAF

SAF will account for the largest share of the total transition cost for airlines between 2023 and 2050 (Chart 3). The annual total transition cost of SAF shown in Chart 2 is the sum of the transition cost of SAF produced by the four major production pathways considered in this analysis, namely Hydro-processed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (AtJ), Fischer-Tropsch (FT), and Power-to-Liquid (PtL). These four SAF production pathways are expected to scale up in deployment with different market shares over time, even though HEFA is the only commercially available SAF production pathway today.

According to the IATA Net Zero CO_2 Emission Roadmaps, global SAF production output will grow exponentially between 2023 and 2050 (Chart 4). In 2024, SAF is expected to account for a mere 0.5% of global jet fuel production, equivalent to 1.5 million tonne (Mt), which is nevertheless triple the 2023 amount of 0.5 Mt.[16] To stay on track on IATA's net zero transition trajectory, SAF production needs to increase to 24 Mt in 2030, to 111 Mt in 2040, and to 512 Mt in 2050 (Chart 4).

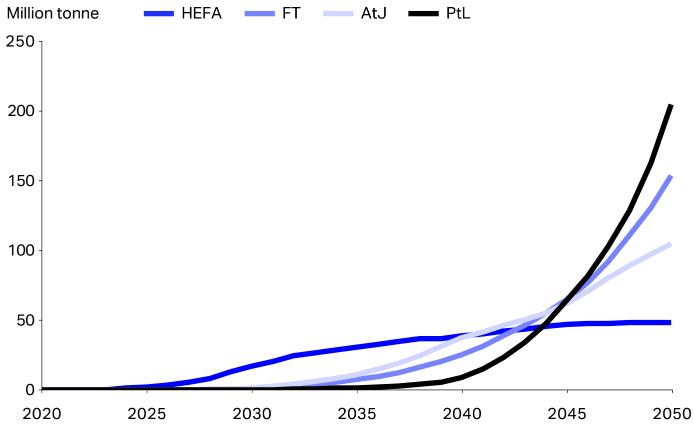
The four SAF production pathways will contribute to the overall SAF production output at different paces over time (Chart 5). In the early years (i.e., 2023-2030), the SAF production volume will come almost solely from HEFA, with its market share of total SAF production declining slightly from 100% in 2023 to 85% in 2030 as alternative pathways reach commercial viability. After 2030, the production of SAF from AtJ and FT pathways will increase gradually and their shares of the total will rise from 9% and 5% to 20.5% and 30%, respectively, by 2050. In contrast, SAF produced from HEFA will only account for 9.5% of the total SAF production in 2050, due to the limited feedstock availability for this production pathway. It is important to note that a declining share does not mean, in this case, a drop in the volume produced. Instead, it implies that the total HEFA SAF volume output will stabilize at about 49 Mt per year between 2045 and 2050 (Chart 5), at which point the feedstock availability for HEFA SAF will be maximized.[17] In comparison, the amount of SAF produced by AtJ, FT, and PtL will exceed HEFA's production between 2040 and 2045, reaching 105 Mt, 154 Mt, and 205 Mt per year, respectively, by 2050.[18] The share of SAF produced from PtL is expected to increase substantially from 3.5% of the total SAF production in 2035 to 40% in 2050 when the technology becomes commercially mature, owing to its theoretically unlimited feedstock supply of CO_2 and renewable electricity. Before the other technologies mature, it remains crucial to maximize the potential of SAF production from HEFA in the short-to-medium term to support air transport's transition in the relatively near term.

Chart 4: SAF production output needed for the net zero transition, million tonne



Source: IATA Sustainability and Economics

Chart 5: SAF production output by pathway, 2020-2050, million tonne



Source: IATA Sustainability and Economics

16 IATA (2024), Global Outlook for Air Transport: Deep Change, June 2024.
17 This estimated share of HEFA in 2050 is within the range of existing studies based on global SAF feedstock availabilities, including:
ICF (2021). Fueling net zero: How the aviation industry can deploy sufficient sustainable aviation fuel to meet climate ambitions.
Becken, S., Mackey, B. and Lee, D.S. (2023). Implications of preferential access to land and clean energy for Sustainable Aviation Fuels. Science of The Total Environment.
18 SAF quantities needed for the net zero transition were modelled using the open-source Aviation Integrated Model (AIM2015) by UCL in the 2023 IATA Net Zero Roadmaps. For more details, please see IATA (2023). Energy and New Fuels Infrastructure Net Zero Roadmap.

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Besides the SAF production volumes, the other key parameter needed to calculate the SAF transition cost is the price of SAF. From the SAF procurement perspective, the SAF price should cover both the production cost of SAF as well as the markup that fuel suppliers will charge airlines to generate profits. However, estimating the future SAF price with the markup is very challenging and data is not available for tracking the premium between SAF price and SAF production cost. Therefore, this roadmap uses the MSP of SAF as a proxy for the price of SAF (Box 1). The MSP is set to break even on investment (including the cost of production and the cost of capital) for a given SAF production pathway over a given time period.[19]

To obtain the endogenously consistent SAF MSPs based on SAF production output from a given size of a renewable fuel facility, SAF production pathways, feedstock type, and feedstock price, this roadmap uses the open-access SAF techno-economic assessment (TEA) models[20] developed by Brandt et al. (2021). The TEA models have been widely used by numerous organizations, including ICAO[21] and the International Energy Agency.[22] The version of the TEA models used in this roadmap calculates SAF MSP cost for the USD 2021 cost year, which is the latest year where all values required in the model are available. The TEA models enable users to change input parameters regarding SAF facility size, feedstock types, feedstock price, and product yields for a given SAF production pathway. Hence, using the TEA models, this roadmap estimates the SAF MSPs and the associated capital costs of HEFA, AtJ, FT, and PtL plants based on the SAF production output from the plant. Table 1 depicts the key assumptions used for the HEFA and PtL production pathways for the above parameters to derive the corresponding SAF MSPs as an example.

19 For more details, see Pavlenko, N., Searle, S., and Christensen, A. (2019). The cost of supporting alternative jet fuels in the European Union. The International Council on Clean Transportation (ICCT), Working Paper 2019-05.
20 Brandt, K., Geleynse, S., Martinez-Valencia, L., Zhang, X., Garcia-Perez, M., & Wolcott, M. P. (2021). Alcohol to jet techno-economic analysis, v. 2.2. Washington State University. Brandt, K., Tanzil, A. H., Martinez-Valencia, L., GARCIA-PEREZ, M., & Wolcott, M. P. (2021a). Fischer Tropsch techno-economic analysis, v. 2.2. Washington State University. Brandt, K., Tanzil, A. H., Martinez-Valencia, L., GARCIA-PEREZ, M., & Wolcott, M. P. (2021b). Hydroprocessed esters and fatty acids techno-economic analysis, v. 2.2. Washington State University.
21 ICAO (2024). SAF rules of thumb.
22 IEA Bioenergy Task 39 (2024), Progress in Commercialization of Biojet/ Sustainable Aviation Fuels (SAF): Technologies and policies.

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Table 1: Key assumptions for SAF production from HEFA and PtL facilities, and corresponding MSPs using the TEA models[20]

Year	Plant maturity	Feedstock type	Feedstock price (USD/tonne)	Plant size (tonne/year of feedstock)	The assumed growth rate of the facility size/5 years	High SAF yield (tonne SAF produced/ tonne distillate)	SAF production (mn liters/year)	SAF production (Mt/year)	Average SAF MSP (USD/tonne)
HEFA									
2002	n[th] plant	FOGs, vegetable oil	FOGs: 580 Vegetable oil: 820	710,000	n/a	71%	550	0.44	1,181
2025	n[th] plant	FOGs, vegetable oil	FOGs: 600 Vegetable oil: 840	710,000	n/a	71%	550	0.44	1,206
2030	n[th] plant	FOGs, vegetable oil	FOGs: 620 Vegetable oil: 860	710,000	n/a	71%	550	0.44	1,238
2035	n[th] plant	FOGs, vegetable oil	FOGs: 640 Vegetable oil: 880	710,000	n/a	71%	550	0.44	1,263
2040	n[th] plant	FOGs, vegetable oil	FOGs: 680 Vegetable oil: 920	710,000	n/a	71%	550	0.44	1,313
2045	n[th] plant	FOGs, vegetable oil	FOGs: 740 Vegetable oil: 980	710,000	n/a	71%	550	0.44	1,394
PtL									
2020	Pioneer plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 300 Waste CO_2: 50 Green H_2: 6000	250,000	0%	50%	40	0.03	6,169
2025	Pioneer plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 280 Waste CO_2: 45 Green H_2: 5500	250,000	0%	50%	40	0.03	5,850
2030	n[th] plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 240 Waste CO_2: 40 Green H_2: 4000	425,320	30%	50%	69	0.06	3,894
2035	n[th] plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 200 Waste CO_2: 30 Green H_2: 2800	607,600	30%	50%	99	0.08	3,144
2040	n[th] plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 150 Waste CO_2: 25 Green H_2: 2000	868,000	30%	50%	141	0.11	2,613
2045	n[th] plant	CO_2 from DAC, waste CO_2 and green H_2	DAC: 100 Waste CO_2: 20 Green H_2: 1400	1,240,000	30%	50%	200	0.16	2,181

Source: IATA Sustainability and Economics, ICAO (2024) SAF rules of thumb, and Brandt et al. (2021)

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It is assumed that the MSP of a given SAF production pathway will change over time thanks to the increase in the facility scale and the corresponding variability in the associated capital cost (capex), operating cost (opex), and feedstock price. To make sure that the facility size of a given production pathway is technically feasible from an engineering aspect, this roadmap uses the most likely facility scales of different SAF pathways from ICAO SAF rules of thumb[21] as benchmarks.

As HEFA is the only commercially mature pathway (i.e., nth plant) so far and there has been a rapid expansion of new HEFA facilities,[22] its typical facility scale is fixed at the benchmark level with a total SAF production of 550 million liters per year (equivalent to 0.44 Mt/year). In comparison, between 2020 and 2030, there will only be pioneer PtL plants with a SAF production output of 40 million liters per year (equivalent to 0.03 Mt/year). Starting in 2030, PtL plants are expected to become commercially mature (i.e., nth plant), and the facility size will grow by 30% per five years till it reaches the benchmark level of producing 200 million liters SAF per year (equivalent to 0.16 Mt/year) in 2045. Although not shown in Table 1, for AtJ and FT, we assume that the two pathways will only have pioneer plants between 2020 and 2025.[22] From 2025, the facility size will increase by 30% per five years for AtJ and by 20% per five years for FT, respectively, until their SAF production per plant reaches the corresponding benchmark levels (i.e., 700 million liters/year for AtJ plants and 160 million liters/year for FT plants) in 2050. The assumed facility growth rates are based on expert consultation, considering how mature the SAF production pathway is currently as well as the constraints imposed by feedstock availability.

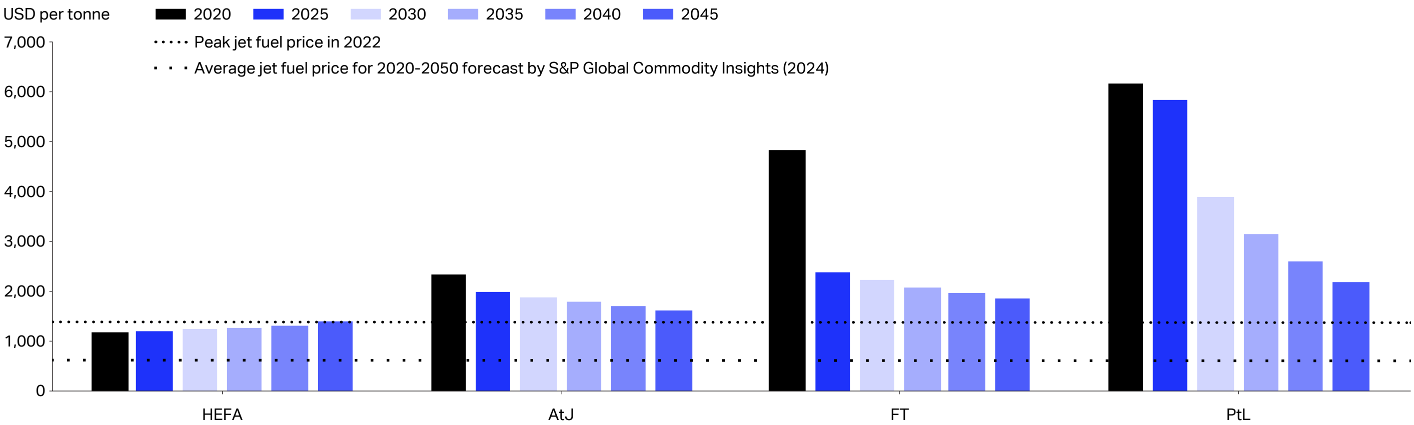
As facility scale and the associated capex and opex can differ significantly, so too can the MSPs of the same SAF pathway depending on the type of feedstock used. We estimate the MSPs of HEFA using FOGs (i.e., tallow and used cooking oil) and vegetable oil (i.e., soybean oil) as feedstocks. FT feedstocks used in our estimations are municipal solid waste (MSW), forest residues, and agricultural residues, while AtJ feedstocks are ethanol and isobutanol.

PtL uses green hydrogen and CO_2 from either direct air capture (DAC) or industrial waste gases as feedstocks. Based on our assumptions of how the feedstock prices might change over time for each pathway (Table 1), as well as the endogenously determined capex and opex under a given facility size derived in the TEA models, we estimate the average MSPs across feedstock types for the four major SAF pathways over 2020-2050 (Chart 6). For simplicity, the SAF MSPs only change every five years between 2020 and 2050.

HEFA MSPs are expected to increase somewhat over time as HEFA feedstock becomes more expensive because of stringent supply and demand dynamics. In contrast, the average MSPs of the other three production pathways will all decrease over time. Average SAF MSPs of the pioneer plants are considerably higher in the early years for PtL at about USD 6,200/tonne over 2020-2024 and USD 5,900/tonne over 2025-2029 (PtL stays in pioneer phase until then). For the pioneer plants of the FT pathway, we expect about USD 4,800/tonne over 2020-2024, and for AtJ it would be about USD 2,300/tonne over 2020-2024 (Table 1). Once these production pathways become commercially mature, the average MSPs are expected to decline significantly. With the gradually increasing facility scale (except HEFA, see Table 1) of the nth plants and the decreasing feedstock prices, by 2045, the average MSPs of AtJ, FT, and PtL will drop to around USD 1,600/tonne, USD 1,900/tonne, and USD 2,200/tonne, respectively. Notably, the significant decline in the PtL MSPs is based on an aggressive assumption that green H_2 and DAC prices will decrease rapidly after the technology matures (Table 1).[22]

Despite the considerable declines in average SAF MSPs over time, they still exceed the recent peak CAF price in 2022,[23] except for HEFA. Furthermore, compared to the average CAF price between 2020 and 2050 forecast by S&P Global Commodity Insights (2024), the estimated average SAF MSPs are far more expensive. The significant price gaps between the average SAF MSPs and the average CAF prices are, therefore, the main reason for the substantial transition costs of using SAF over 2023-2050 (Chart 2).

Chart 6: Average MSPs of major SAF pathways per 5-year period over 2020-2050, USD per tonne



Source: IATA Sustainability and Economics

23 For more details, see IATA (2024). Jet Fuel Price Monitor.

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3. Capital investment needed to build new renewable fuel facilities: 2023-2050

The capital investment needed to build renewable fuel facilities for SAF production is a prerequisite for the air transport industry's transition to net zero. We assess the total number of new facilities required each year to ramp up SAF production sufficiently for air transport to reach net zero CO_2 emissions by 2050 and the associated capital investments required per year between 2023 and 2050.

3.1 Methods and assumptions

Based on the SAF production output required as per the IATA Net Zero CO_2 Emissions Roadmaps (Chart 4 and Chart 5), we estimate the total number of new renewable fuel plants needed for SAF production and the corresponding capital investment over 2023-2050. We assume that all new facilities for a given fuel-production pathway are built identically and in a representative size. The representative size of HEFA facilities is fixed at the most likely scale of the n^{th} plant (i.e., SAF production output of 550 million liters per year) based on ICAO's SAF rules of thumb (Table 1), while the facility sizes of AtJ, FT, and PtL pathways, after their pioneer plant phases, are expected to grow by 30%, 20%, and 30%, respectively, every 5 years until they reach the corresponding benchmark SAF production levels (Table 1).

After determining the representative facility scales by production pathway over time, we use the TEA models[20] to estimate the corresponding capex of different facility scales for each pathway for the years 2020, 2025, 2030, 2035, 2040, and 2045 (Table 2). Thanks to economies of scale, as the facility size increases, the per-unit capex falls after adjusting for the assumed 2% rate of inflation in the TEA models. Importantly, the final SAF production output of a plant depends on the product yields of SAF versus those of the other various distillates produced by the plant. If SAF is not optimized in the product mix, the SAF yield will be lower, meaning that the volume of SAF produced per plant will be lower. In such a case, a greater number of new plants would be needed to produce the required SAF volumes. Consistency across key parameters (such as total distillate yields and SAF yield) used in calculating the capex is achieved by the fact that ICAO's SAF rules of thumb are also based on the TEA models by Brandt et al. (2021).

In our baseline case for the estimation of the capital investment needs, we assume a rather optimistic SAF product yield,[24] set at the high end of their theoretical maximum per SAF pathway, i.e., 71% for HEFA, 70% for AtJ, 50% for FT, and 50% for PtL (Table 2). The high SAF product yields for HEFA, AtJ, and FT are taken directly from the TEA models' settings, and the 50% SAF yield for PtL is set based on a recent report by the German Environment Agency.[25] Under these high SAF yields, the target SAF production output per plant can be met with a relatively smaller number of renewable fuel facilities. We can then estimate the minimum possible total capex needed for building these new facilities. However, SAF product yields could be significantly lower than their theoretical maximum levels. We estimate the impact on capex needs of lower SAF product yields in section 4.1.

According to existing studies,[7,20] it generally takes three years to build a new renewable fuel plant (and about two years for planning and approval before the construction), and the typical lifetime of a plant is 20 years. The capex of a plant consists of the fixed capital investment (FCI) and the working capital (WC), which is set as 20% of the FCI. The necessary capex tends to be unevenly distributed across Year 1, Year 2, and Year 3 of the construction period, at 8%, 60%, and 32%, respectively, of the overall capex.[20] Consequently, to understand how much total capital investments are needed for building the required facilities each year, we need to first estimate the number of plants that are at different construction stages in that year and then allocate the corresponding shares of the capex before aggregating to obtain the total capital investment needed for that year (Appendix 1).

24 In this roadmap, SAF yield is measured by tonne SAF produced/tonne distillate produced, as shown in Table 2. Alternatively, SAF yields can be measured by tonne SAF produced/tonne of feedstock, which is calculated as the total distillate yield multiplied by the SAF share in total distillate produced. For example, if taking the alternative SAF yield measurement, the SAF yield of HEFA would be 0.83 x 71% = 59%.

25 German Environment Agency (2022). Power-to-Liquids: A scalable and sustainable fuel supply perspective for aviation.

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Table 2: Key input parameters and the average capex estimated per SAF production pathway

Production pathway	Representative SAF production output per plant (Mt/year)	Total distillate yield (tonne distillate produced/ tonne feedstock)	High SAF yield (tonne SAF produced/tonne distillate produced)	Corresponding average capex per plant (USD mn)
HEFA	2020: 0.44 2035: 0.44 2045: 0.44	FOGs: 0.83 Vegetable oil: 0.83	71%	2020: 452 2035: 460 2045: 474
AtJ	2020: 0.06 2035: 0.27 2045: 0.56	Ethanol: 0.60 Isobutanol: 0.75	70%	2020: 140 2035: 227 2045: 394
FT	2020: 0.03 2035: 0.08 2045: 0.13	MSW: 0.31 Forest residues: 0.18 Agricultural residues: 0.14	50%	2020: 1,094 2035: 1,013 2045: 1,478
PtL	2020: 0.03 2035: 0.08 2045: 0.16	DAC: 0.20 Waste CO_2: 0.20	50%	2020: 636 2035: 722 2045: 1,413

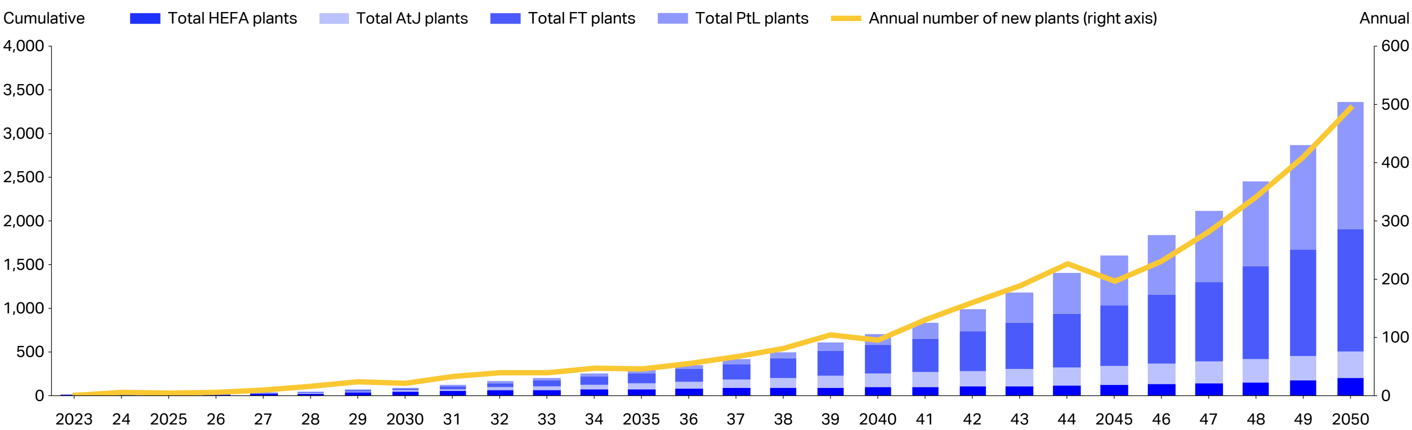
IATA Sustainability and Economics, ICAO (2024) SAF rules of thumb, and Brandt et al. (2021)

3.2 Capital investments needed to build new renewable fuel plants: The baseline case

Assuming that SAF yields are at the high end of their theoretical maximum per production pathway (the baseline case), the estimated number of cumulative new facilities for SAF production between 2023 and 2050 is about 3,400 (Chart 7, left axis), thanks to the gradual increase in facility scales over time. The annual number of new renewable fuel plants needed is expected to rise from single digits before 2025 to about 100 in 2040 and to reach about 500 in 2050 (Chart 7, right axis). The split in the number of cumulative new renewable plants per production pathway is presented in Chart 7.

PtL and FT plants are expected to make up the largest shares in 2050 (43% for PtL and 42% for FT), while HEFA and AtJ plants together will only account for 15% of total new facilities in 2050. The significantly higher number of FT and PtL plants is due to their expected large shares in overall SAF production (Chart 5) as well as the relatively smaller facility sizes even after 2045 that can be delivered for these pathways. SAF production per plant is estimated at only 0.13 Mt/year for the FT plant and 0.16 Mt/year for the PtL plant, respectively, over 2045-2050, compared to 0.56 Mt/year for the AtJ plant and 0.44 Mt/year for the HEFA plant (Table 2). The annual number of new plants needed keeps rising, except for the years when the representative SAF plant sizes increase to the next level (Table 2), as per our assumptions. As SAF production per plant becomes larger in these transition years, fewer new plants are needed to meet the incremental SAF production compared to the previous year. However, this plant size advantage is soon offset by the rapid growth in the required SAF production volumes in the following years, which brings the annual number of new facilities needed back to the overall increasing trend. The discontinuity is merely the result of the assumptions made regarding the periodic—every 5 years—increase in the plant size.

Chart 7: Cumulative and annual number of new renewable fuel facilities needed over 2023-2050, baseline case (with high SAF product yields)



Source: IATA Sustainability and Economics

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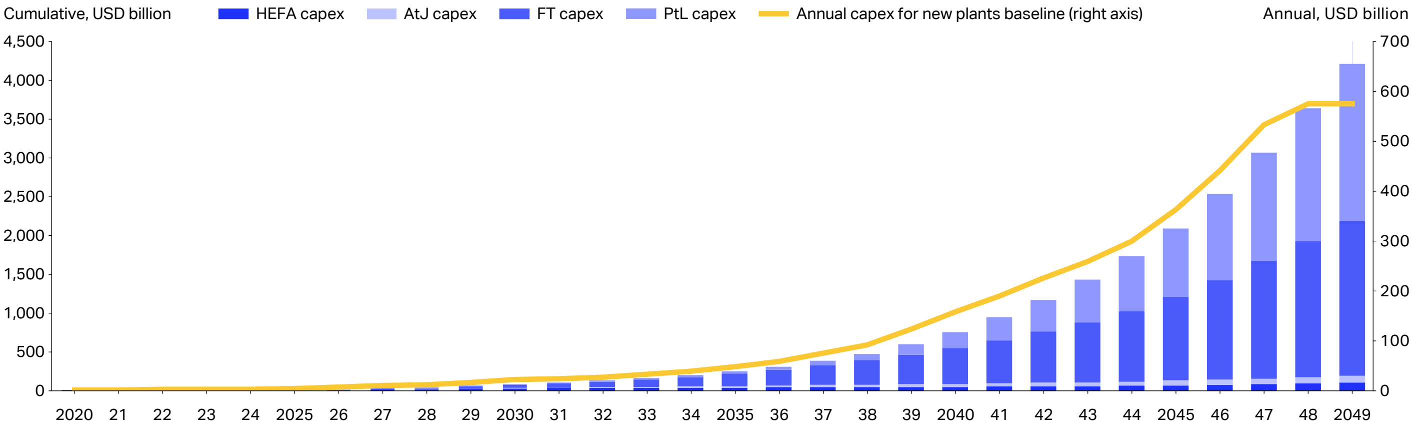
Chart 8 illustrates the corresponding cumulative and annual capex needed for building the new plants. Under the baseline case, the minimum total capex required between 2020 and 2049 is about USD 4.2 trillion (Chart 8, left axis). Notably, as discussed previously (Appendix 1), for a SAF plant to be fully operational, its construction must have begun three years earlier. Therefore, Chart 8 depicts the capital investment needed each year over 2020-2049 to make sure the required new facilities for SAF production can be fully operational between 2023 and 2050. Compared with Chart 7, even greater shares of the capex are taken by PtL and FT plants in 2050, both at about 48%. The fact that FT and PtL plants are more expensive to build compared to HEFA and AtJ (see Table 2) also explains the dominant shares of the former shown in Chart 8.

The annual capex (Chart 8, right axis) will grow substantially from USD 0.45 billion in 2020 (to kick off the construction of the plants for SAF production in 2023) to USD 10 billion in 2027 (for SAF production in 2030). In this analysis, the annual capex needed for building new facilities is expected to peak in 2048, reaching USD 576 billion. We assume that the annual capex will stay at this level after 2048. The future change in the annual capex for new renewable fuel plants depends on the number of new facilities that would be required after 2050 to keep air transport at the net zero CO_2 emissions level, which is beyond the scope of this roadmap. The annual average capex needed to build the new facilities over the 30-year period is about USD 128 billion per year.

Chart 8: Cumulative (left) and annual (right) capex needed for building new renewable fuel facilities over 2020-2049, baseline case (with high SAF product yields), USD billion



Source: IATA Sustainability and Economics

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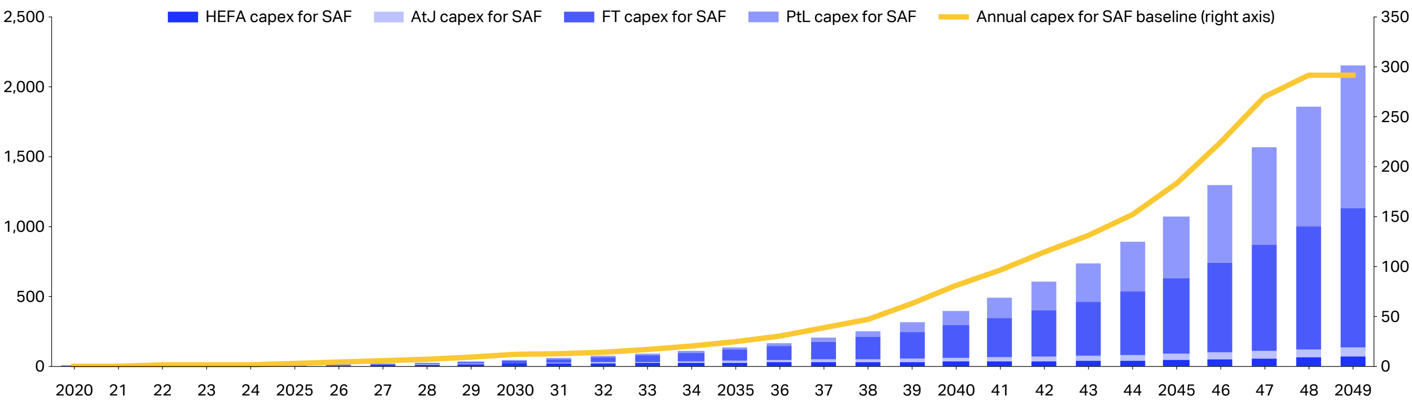
It is very important to understand that the new renewable fuel plants necessary to meet the air transport industry's demand for SAF, will also produce other renewable fuels, such as renewable diesel and renewable gasoline, alongside the SAF, as all refineries make a mix of products.[26] Therefore, strictly speaking, the share of total capex that could be attributed to the airline industry's energy transition via the final SAF MSPs should be that corresponding to the SAF product yield. However, the entire plant needs to be built for any SAF to be produced, and so the full capital investment must happen before the share of total investments can be attributed to different fuel users based on the product mix of the new facility. Assuming the higher end of product yields (see Table 2), i.e., 71% for HEFA, 70% for AtJ, 50% for FT, and 50% for PtL in the baseline case, the capex directly attributable to air transport is shown in Chart 9, per pathway and for the period 2020-2049.[27]

Out of the USD 4.2 trillion total capital investment required for new renewable fuel facilities over 2020-2049, about USD 2.1 trillion directly relates to the SAF production needed for the air transport industry. From the annual perspective, the capex associated with SAF production will increase from USD 0.3 billion in 2020 to USD 11.9 billion in 2030 and eventually reach about USD 291 billion in 2048. The annual average capex associated with SAF production over the 30-year period is about USD 72 billion per year, representing 56% of the total average annual capex under the baseline case.

Chart 9: Cumulative (left) and annual (right) capex associated with SAF production over 2020-2049, baseline case (with high SAF product yields), USD billion



Source: IATA Sustainability and Economics

26 In 2023, the average share of conventional aviation fuel in US petroleum refineries' product mix was 9%, according to the US Energy Information Administration, Petroleum Supply Monthly, March 2024, preliminary data.
27 This is an illustrative analysis, and a more detailed assessment would be required to apportion capex share across products.

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4. How to reduce the financial needs for the transition: The role of policy support and co-processing

4.1 Save on capital investments by maximizing SAF output at refineries

Our baseline case assumes rather optimistically that SAF product yields regarding all four major pathways are at the high end of their theoretical maximum levels. However, these maxima might not be reached if it is not cost-effective for refineries to produce SAF, and if global energy demand[28] or policy incentives favor the production of other renewable energy products rather than SAF.[22] If SAF yields are lower, the number of new facilities needed to produce the required amount of SAF would have to rise, and this would drive the necessary capex higher. Here we compare the difference in our estimates from assuming either high or low product yields and identify the impact on the total capex associated with airlines' energy transition.

Depending on the production pathways used, the product yields of SAF can vary substantially because certain pathways are more limited in their capacity to lift the SAF share in the product mix of that refinery.[29] Additionally, modifying the SAF product yields in a production pathway can come at the expense of a reduced yield in the overall product stream.[22] Using the TEA models, we estimate how many additional new facilities and the associated capital investments that would be needed if SAF product yield shares are at the low end of the overall biofuel product slate, compared with the baseline case. The high and low SAF yields used in this analysis are close to the possible ranges of jet fractions in the overall product slate by different production pathways estimated in previous studies (Table 3).[22,25,30]

Table 3: SAF yields, share of total, %, per yield assumption and production pathway

SAF yields (tonne SAF produced/tonne distillate produced)	HEFA	AtJ	FT	PtL
High yield (baseline case)	71%	70%	50%	50%
Low yield	20%	35%	40%	20%

Source: IATA Sustainability and Economics, ICAO (2024) SAF rules of thumb, and Brandt et al. (2021)

28 Logically though, the rapid electrification of road transport should reduce global demand for biodiesel and create a vacuum in the refinery product mix for SAF to fill.
29 IATA Sustainability and Economics (2024). Chart of the Week: Sustainable Aviation Fuels Pathways and Product Slate.
30 Van Dyk et al. (2019). Assessment of likely maturation pathways for production of biojet fuel from forest residue.

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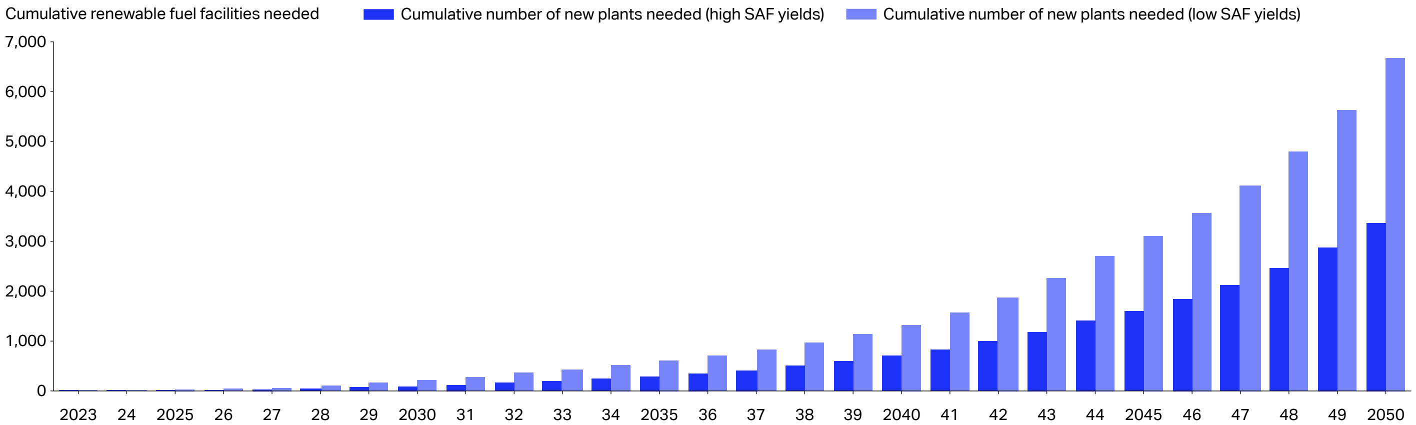
Regrettably, the low SAF yields in Table 3 better reflect the current preference of refineries due to cost-effectiveness reasons. In fact, existing policy incentives have generally made it more economically attractive to produce more renewable diesel than SAF. Compared to the baseline case, the low SAF yield case would require an additional 3,300 renewable fuel facilities to be built (about 6,700 in total) between 2023 and 2050 to provide the necessary SAF production volumes (Chart 10). The cumulative number of new plants needed is almost double that of the baseline case.

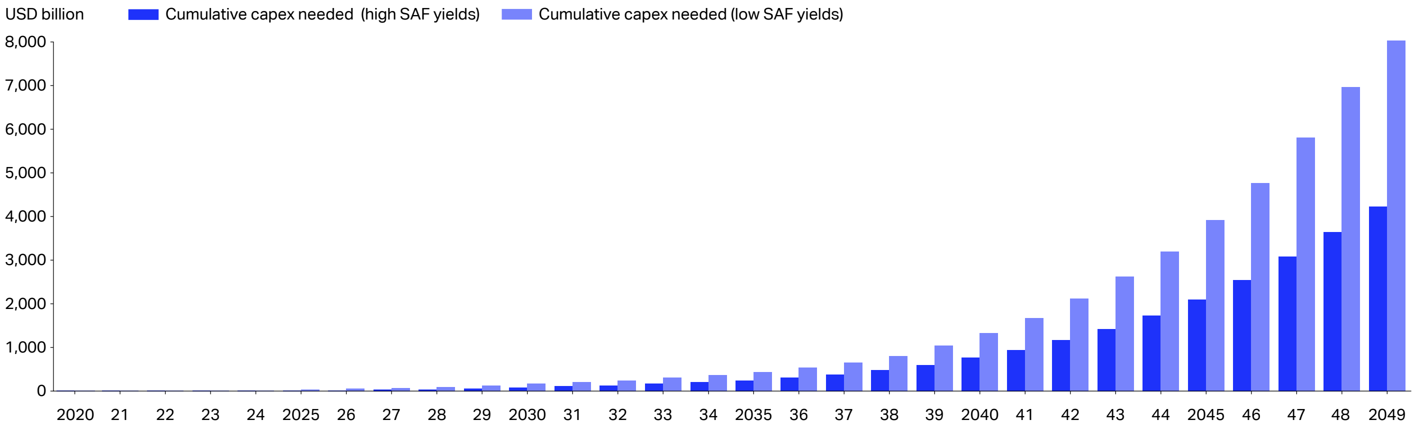
Due to the additional facilities needed under the low SAF yield case, the cumulative capital investment would increase to about USD 8.1 trillion from USD 4.2 trillion in the baseline case, over the period 2020-2049 (Chart 11). In other words, increasing the product yield of SAF in total renewable biofuel production would reduce the overall capital investment required for air transportation's decarbonization by USD 3.9 trillion on the 2050 horizon, or not far off 50%. Policy support will likely be required to ensure high SAF yields at biorefineries.

Chart 10: Cumulative number of new renewable fuel facilities over 2023-2050: High SAF yields (baseline case) versus low SAF yields



Source: IATA Sustainability and Economics

Chart 11: Cumulative capital investment needed for new facilities 2020-2049: High SAF yields (baseline case) versus low SAF yields, USD billion



Source: IATA Sustainability and Economics

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4.2 Save on capital investments by maximizing co-processing for SAF

Co-processing for SAF production at existing petroleum refineries has great potential to reduce further the capital investment needed for new renewable fuel facilities. Co-processing involves the insertion of a bio-based intermediate into existing petroleum refineries for simultaneous processing with petroleum feeds.[22] SAF production by co-processing can increase SAF volumes immediately as it does not require the lead time for plant construction. The more SAF production that can be delivered from co-processing in existing refineries, the less SAF production will need to come from the construction of new facilities, translating to an immediate and direct saving in terms of the total capital investment compared to the baseline case.

The co-processing of HEFA-lipids was approved by ASTM D1655[31] in 2018, and the co-processing of FT liquids was approved in 2020, both of which have a co-processing limit of inserting no more than 5% bio-based intermediates alongside the crude oil streams.[22] Expanding the blending limit to 30% is currently under review by an ASTM subcommittee, but this work has not been finalized. The potential of co-processing for SAF production could be limited by the availability of fats and oil greases, showing that policy support for feedstock rationalization and for promoting research and innovation for new feedstocks using municipal and agricultural waste is crucial.[32]

The potential amount of SAF that could be produced via co-processing can be estimated based on the global total refinery capacity for catalytic cracking, hydrocracking, and middle distillate desulphurization, as well as the possible blend ratios used during co-processing.[33] According to OPEC,[34] the global capacity for catalytic cracking, hydrocracking, and middle distillate desulphurization is 19.5 million barrels per day (mbbl/d), 11.5 mbbl/d, and 32.9 mbbl/d, respectively. For a 10% blend ratio for the total capacity of these three operations, a total amount of 6.4 mbbl/d (296 Mt/year) bio-based intermediates could be inserted into existing refineries to produce low-carbon intensity fuels, including SAF.[33]

In addition to the amount of lipid and FT liquid feedstocks required for co-processing, we also need to estimate how much refining capacity can be converted to co-processing low-carbon intensity fuels globally and the possible co-processing limits based on the refinery situation in different world regions. For the former, we use global crude oil refinery capacity forecasts by world region between 2030 and 2050 from S&P Global Commodity Insights (2024). Global total refinery capacity is expected to decline from 105.3 mbbl/d in 2030 to 85.9 mbbl/d in 2050. North America, Europe, and Asia Pacific will all have lower refinery capacities in 2050 compared to the 2030 levels, whereas Latin America, Africa, and the Middle East are expected to remain at the same refinery capacities in 2050 as in 2030 (Table 4).

Table 4: Estimation of the maximum SAF production potential from co-processing, 2030-2050

Region	Global refinery capacity (mb/d)				
	2030	2035	2040	2045	2050
North America	19.8	17.8	16.1	14.4	12.7
Latin America	7.8	7.8	7.8	7.8	7.8
Africa	3.3	3.3	3.3	3.3	3.3
Europe	22.3	19.8	18.7	17.3	15.9
Middle East	11.4	11.4	11.4	11.4	11.4
Asia Pacific	40.9	39.4	38.1	36.5	34.9
Total	**105.3**	**99.4**	**95.2**	**90.5**	**85.9**

Our assumptions on the potential refining capacity that can be converted for co-processing

Our assumptions on the co-processing limits by regions

Our assumptions on the product slate for SAF in co-processing by regions

Region	Total SAF production potential (Mt/year)				
	2030	2035	2040	2045	2050
North America	0.7	1.9	2.5	5.3	8.8
Latin America	0.2	0.3	0.8	1.1	2.2
Africa	0.1	0.1	0.2	0.3	0.3
Europe	0.8	2.1	2.9	6.1	11
Middle East	0.2	0.2	0.8	1.1	1.6
Asia Pacific	0.7	1.4	4	6.6	9.7
Total	**2.6**	**5.8**	**11.2**	**20.4**	**33.6**

Source: IATA Sustainability and Economics. Global Refinery Capacity forecasts obtained from S&P Global Commodity Insights (2024)

31 ASTM International, formerly known as the American Society for Testing and Materials, is a standards organization that develops and publishes voluntary consensus technical international standards for a wide range of materials, products, systems, and services. Some 12,575 apply globally.
32 For more details see the IATA (2024), Net Zero CO_2 Transition Policy Roadmap.
33 IEA Bioenergy Task 39 (2022), Recent progress in the production of low carbon-intensive drop-in fuels – Standalone production and coprocessing.
34 OPEC (2023), World Oil Outlook 2045.

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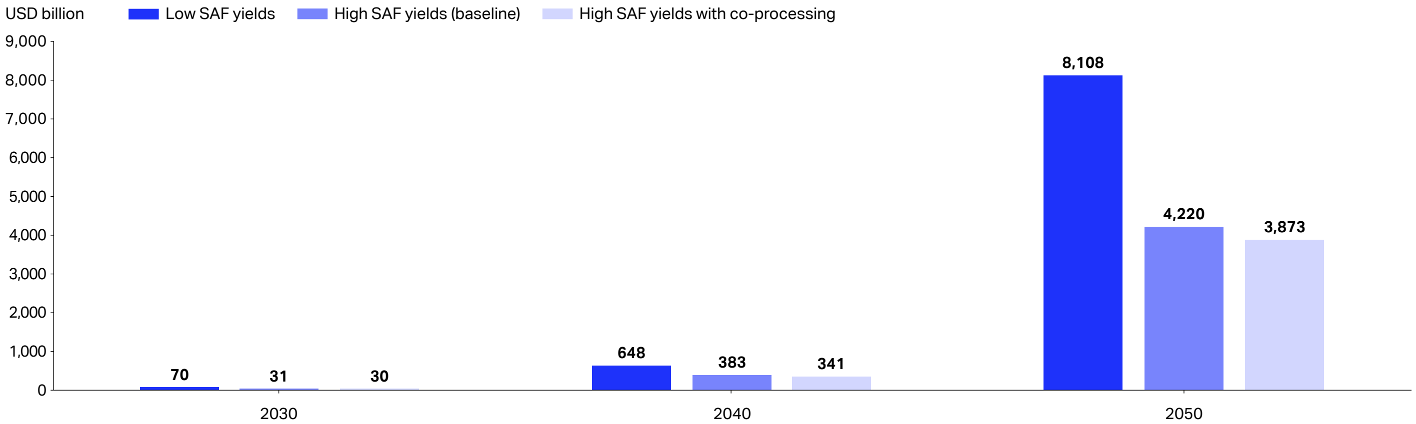
Of the world's total refining capacity, only a limited proportion is expected to be converted to facilitate co-processing (Chart 12). Following consultations with industry experts and the findings in available studies, it is assumed that North America and Europe could convert up to 30% of their total refinery capacity to co-processing by 2050 from our assumed 10% level in 2030. Asia Pacific and the Middle East can be expected to convert 5% of their refining capacity to co-processing in 2030, with this share increasing to 20% and 15%, respectively, in 2050. Latin America is also anticipated to have 20% of its refinery capacity converted for co-processing in 2050, up from 7% in 2030. Africa will likely see its co-processing capacity gradually rise from 5% in 2030 to 10% in 2050.

The total co-processing capacity will be curtailed by the limitations placed by ASTM mentioned above, and by the fact that the feasible blend ratios of bio-based feedstocks vary according to the type of feedstock, the oxygen content of the feedstock, and the refinery infrastructure and catalysts available in different regions (Table 4).[33] We assume that the co-processing limit will remain at 5% across all world regions in 2030 and that regions will then increase the average co-processing limits to different degrees over time. No region is expected to exceed a 30% limit by 2050.

Co-processing with bio-based feedstocks can produce different types of low-carbon intensity fuels, including SAF. Therefore, the product yields of SAF from co-processing are assumed to be 15% between 2030 and 2040 and 20% between 2045 and 2050, across all regions. With all the information and assumptions described above, it is estimated that the maximum potential of SAF production via co-processing will be 2.6 Mt/year in 2030, led by Europe, North America, and Asia Pacific. By 2050, co-processing is likely to produce up to 34 Mt SAF. The SAF produced from existing facilities through co-processing, therefore, reduces the SAF production required from new facilities by these amounts.

Chart 12: Cumulative capex required per scenario: High SAF yields (baseline case), low SAF yields, and co-processing with high SAF yields, USD billion



Source: IATA Sustainability and Economics

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Co-processing uses lipids and FT liquids, and the resulting SAF production would therefore substitute volumes from the HEFA and FT pathways. Given the technology readiness levels and the feedstock availability of these two production pathways, it is assumed that 80% of the SAF produced via co-processing will replace the corresponding amount of SAF produced by HEFA between 2030 and 2035, and the remaining 20% will replace SAF produced by FT over the same period. Between 2036 and 2040, the ratio becomes 50% and 50%, i.e., the SAF produced via co-processing is split equally to replace the amount of SAF produced by the two pathways. As the feedstocks of HEFA become increasingly scarce after 2040, the ratio changes to 20% and 80%, where the FT liquids provide the majority of bio-based intermediates, thus replacing a larger amount of SAF produced by the FT pathway between 2041 and 2050.

A scenario with high SAF yields combined with maximized co-processing, will diminish the need for building 266 new production facilities and cut the cumulative investment needs by USD 347 billion in 2050, compared to our baseline case (Chart 12 and see Table 4). This number is based on the assumption that the SAF production volumes via co-processing are fixed every five years between 2030 and 2050. The estimated cumulative capex savings from the reduced number of new facilities needed are estimated at about USD 1 billion in 2030, and around USD 42 billion in 2040. These estimates only consider the avoided capital investments for building new facilities when up to 34 Mt of SAF can be produced through co-processing. However, converting existing refineries for co-processing does not come without cost. In fact, higher co-processing limits would require greater investment in refinery infrastructure to manage operational issues like heat quenching, catalyst loading, higher H_2 requirements, corrosion etc. At this point, estimating the capital cost associated with co-processing conversion is beyond the scope of this roadmap and will require deeper dive into the refinery configuration and modeling work.

Clearly, the SAF yield in biorefineries is a tremendously important variable in terms of determining the total capital investment needs for enabling the transition. The maximization of SAF production yields can halve the total capex costs compared to current common yields. This finding should be a strong incitement for policy makers to focus on this issue.

In comparison, co-processing does not have the same sized impact on total capex as yields, but USD 347 billion worth of lower capex would eliminate the need for nearly three years' average capex compared to the base case total needs. In terms of policy sequencing, this is one to do immediately, while we are waiting for new plants to come online.[35]

35 IATA (2024), Net Zero CO_2 Transition Policy Roadmap.

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5. Net Zero CO_2 Emissions Finance Roadmap

Entire period **2024-2050** | Overall transition cost: **USD 4.7 trillion** | Overall number of new renewable fuel facilities needed: **3,096 – 6,658** | Overall capex needed: **USD 3.9 – 8.1 trillion**

Transition cost

Number of new renewable fuel facilities

Capital investment (capex)

Immediate term until end of 2025

Transition cost: about **USD 2.0 billion**

SAF transition cost: **USD 1.4 billion**

CORSIA transition cost: **USD 0.6 billion**

Number of new facilities needed: **15 – 28**

Best-case scenario (high SAF yields with co-processing):
15 new plants (with optimized SAF yields, fewer plants are needed to produce the required amount of SAF)

Worst-case scenario (low SAF yields):
28 new plants (with current low SAF yields, more new plants are required)

Capex: **USD 7.1 to 17.2 billion**

Best case scenario: **USD 7.1 billion**

Worst case scenario: **USD 17.2 billion**

Capex savings from optimized SAF yields: **USD 10 billion**

Mid-term 2026–2030

Transition cost: about **USD 46.7 billion**

SAF transition cost: **USD 32.9 billion**

CORSIA transition cost: **USD 13.2 billion**

Hydrogen for aircraft transition cost: **USD 0.2 billion**

CDR transition cost (optional): **USD 0.4 billion**

Number of new facilities needed: **63 – 187**

Best-case scenario:
63 new plants (co-processing starts to have a more meaningful role in SAF production, yielding 14 fewer new plants needed relative to the case with only optimized SAF yields)

Worst-case scenario:
187 new plants needed

Capex: **USD 65.9 to 136.3 billion**

Best case scenario: **USD 65.9 billion**

Worst case scenario: **USD 136.3 billion**

Capex savings:
USD 70.4 billion (USD 69.6 billion saved from optimized SAF yields, and USD 0.8 billion saved from co-processing)

Long-term 2031–2050

Transition cost: about **USD 4.7 trillion**

SAF transition cost: **USD 3.8 trillion**

CORSIA transition cost: **USD 0.1 trillion**

Hydrogen for aircraft transition cost: **USD 0.2 trillion**

CDR transition cost (optional before 2050): **USD 0.6 trillion**

Number of new facilities needed: **2,938 – 6,443**

Best-case scenario:
2,938 new plants (3,173 new plants avoided from optimized SAF yields, and 266 new plants avoided further from co-processing)

Worst-case scenario:
6,443 new plants needed

Capex: **USD 3.8 to 7.9 trillion**

Best case scenario: **USD 3.8 trillion**

Worst case scenario: **USD 7.9 trillion**

Capex savings:
USD 4.1 trillion (USD 3.8 trillion saved from optimized SAF yields,and USD 0.3 trillion saved from co-processing)

Net Zero CO_2 Emissions

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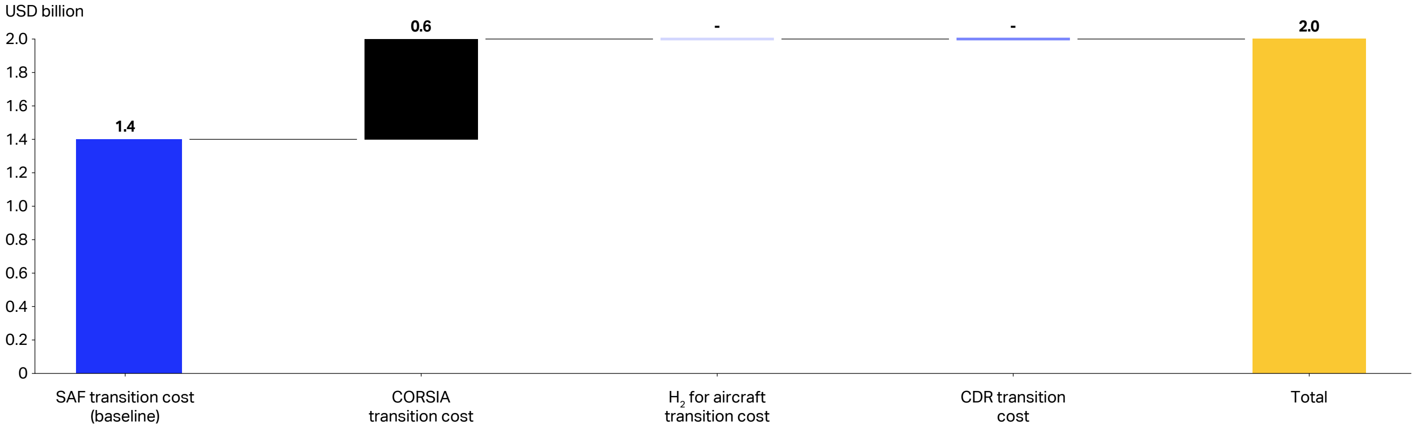
Based on our analysis, we now distribute the finance needed to deliver net zero CO_2 emissions in air transport over the immediate- (2024-2025), mid- (2026-2030), and long- (2031-2050) terms.

5.1 Immediate finance needs: 2024-2025

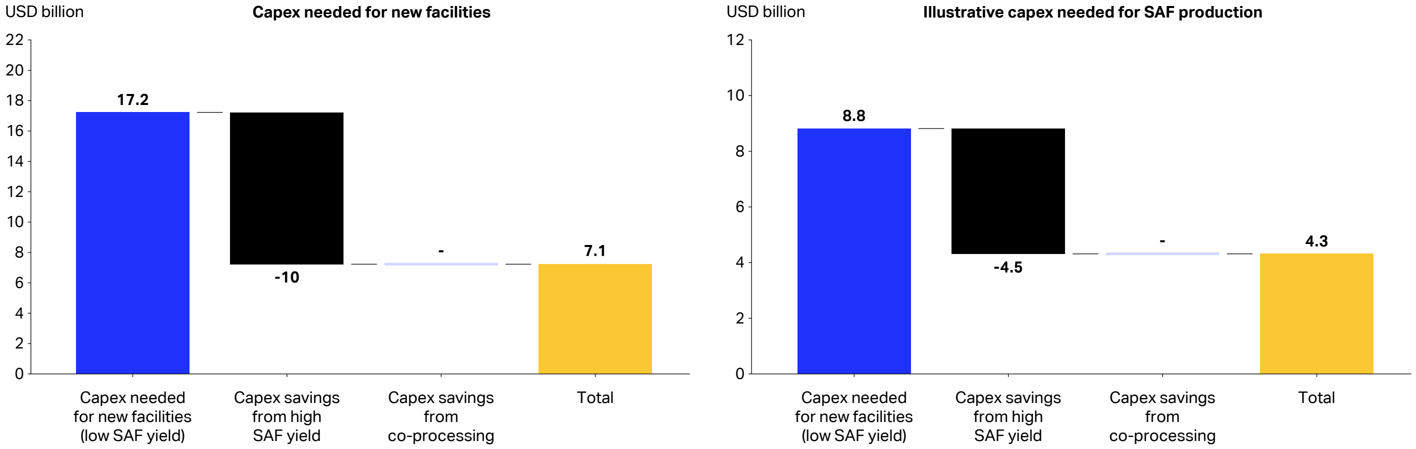
In the immediate term, the air transport transition cost is mostly associated with SAF use (Chart 13). In the baseline case, a total of USD 1.4 billion would be needed to start the energy transition from conventional aviation fuel to SAF. Another USD 0.6 billion would be needed for airlines to purchase CORSIA EEUs, depending on airlines' EEUs procurement strategies for the first phase (2024-2026) of the scheme. As for the immediate capital investment needs for building new renewable fuel facilities (Chart 14, left), about USD 17.2 billion would be required if SAF were not prioritized in renewable fuel production. In comparison, this amount of capex could be reduced by USD 10 billion under our baseline case, where SAF is prioritized and yields are high. In addition, due to the current very limited SAF volumes produced by co-processing, we only expect co-processing to yield meaningful capex savings by 2030. Overall, the capex needed for building new renewable fuel facilities is expected to be about USD 7.1 billion at the minimum. Although the entire plant needs to be built for any SAF to be produced, the total capital investment will not be only for fulfilling airlines' fuel demand directly. Therefore, we estimate that out of the total capex of USD 7.1 billion, about USD 4.3 billion would be attributable to SAF production in the immediate term under the baseline case (Chart 14, right).

Chart 13: IATA Finance Roadmap: Transition cost breakdown in the immediate term (2024-2025)



Note: Totals may not equal sums due to rounding
Source: IATA Sustainability and Economics

Chart 14: IATA Finance Roadmap: Capital investment needs in the immediate term (2024-2025), for all new renewable fuel facilities (left) and for the SAF share of those facilities (right)



Note: Totals may not equal sums due to rounding
Source: IATA Sustainability and Economics

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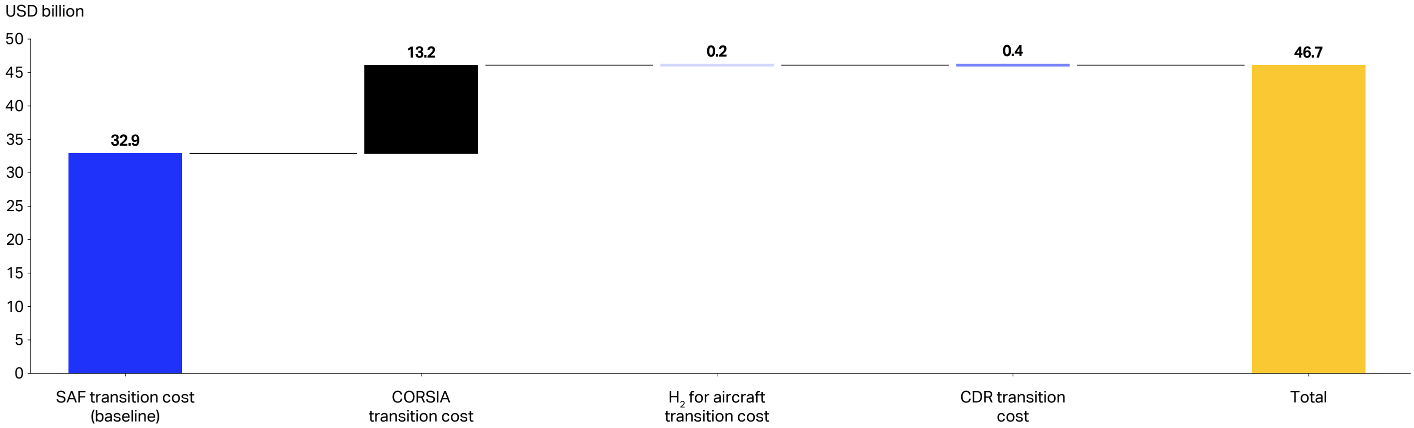
5.2 Mid-term finance needs: 2026-2030

Over the mid-term defined by this roadmap, SAF will still have a dominant role in the total transition cost required over 2026-2030. As SAF production volume increases from 3.8 Mt in 2026 to 24 Mt in 2030, about USD 33 billion would be needed under the high SAF yield case to replace CAF with SAF use in the mid-term. On the other hand, with CORSIA's increasing contribution through offsetting international air transport CO_2 emissions, the transition cost associated with this lever would be about USD 13.2 billion in the mid-term. Hydrogen-powered aircraft are expected to enter into service in the later years of this period, requiring about USD 0.2 billion as the associated transition cost. Finally, an additional USD 0.4 billion could be spent on carbon removals in this period if airlines chose to use this novel technology at the early stage (Chart 15). The total transition cost that could be incurred in the mid-term is about USD 46.7 billion.

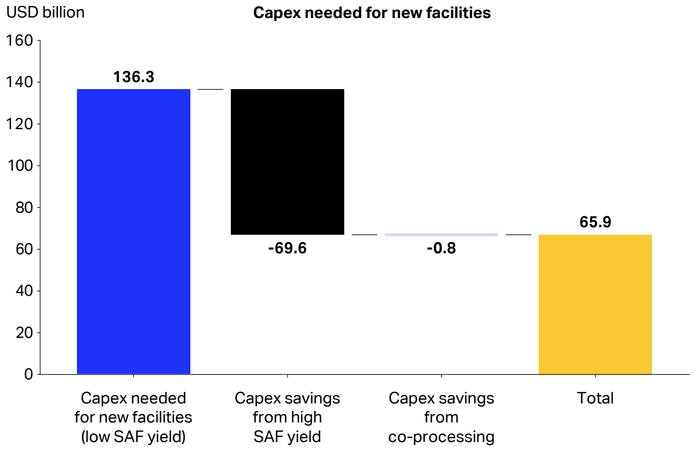
The capex needed in the mid-term to build new renewable fuel facilities under the low SAF yield case is estimated to be about USD 136.3 billion. By maximizing the SAF product yields, about USD 69.6 billion in capex savings could be achieved. In addition, co-processing is expected to produce increased SAF volumes in 2030, which would yield an additional USD 0.8 billion in savings of capital investment for building new plants. With the combined capex savings from high SAF yields and co-processing, the total capital investment needed in the mid-term could be as low as USD 66 billion, compared to USD 136.3 billion under the low SAF yield case (Chart 16, left). If the required capex were attributed to different fuel users based on the product mix of the new facility, USD 84.2 billion would be shouldered by the air transport sector (by paying for SAF MSPs which cover capex, see Box 1) under the low SAF yield case. In comparison, when both the high SAF yields and co-processing are applied, only USD 37.9 billion of the capex would be attributed to air transport in the mid-term.

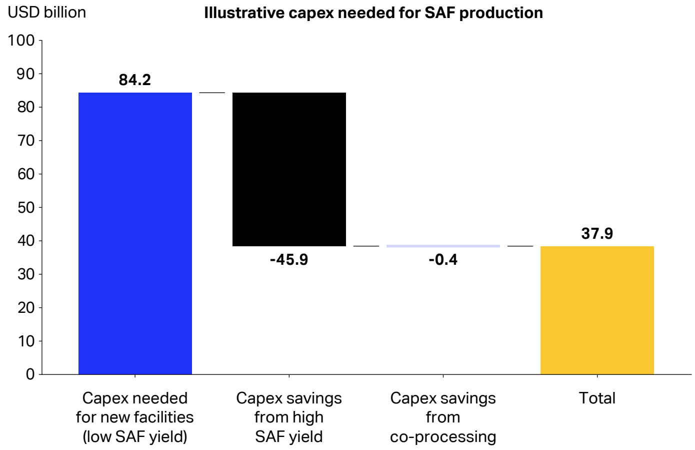
Chart 15: IATA Finance Roadmap: Transition cost breakdown for the mid-term (2026-2030)



Note: Totals may not equal sums due to rounding
Source: IATA Sustainability and Economics

Chart 16: IATA Finance Roadmap: Capital investment needs for the mid-term (2026-2030), for all new renewable fuel facilities (left) and for the SAF share of those facilities (right)





Note: Totals may not equal sums due to rounding
Source: IATA Sustainability and Economics

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5.3 Long-term finance needs: 2031-2050

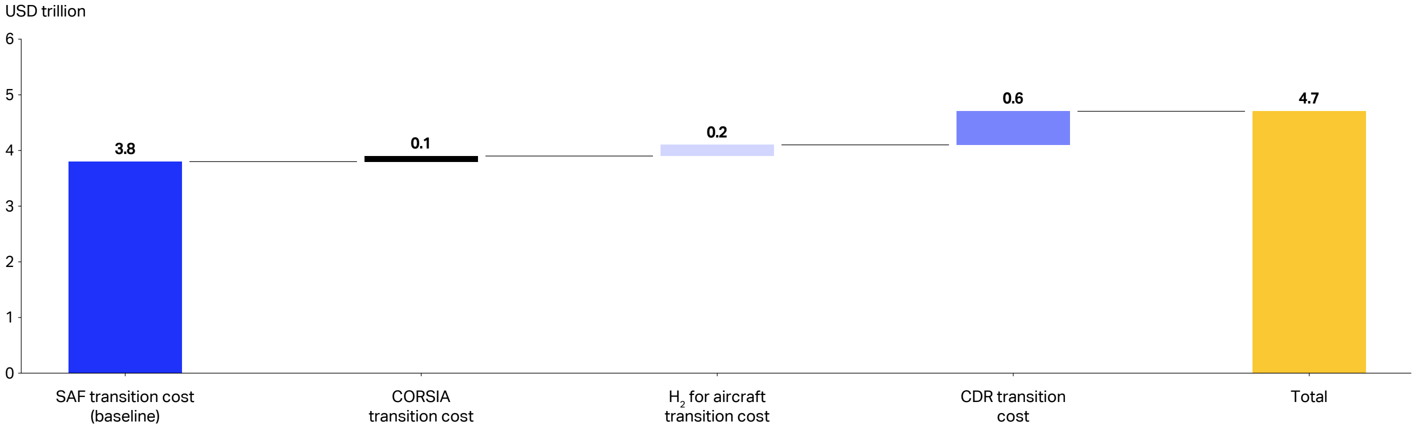
The total SAF transition cost from the baseline case (i.e., high SAF yield) is USD 3.8 trillion in the long term (Chart 17). The transition cost of CORSIA (only for 2031-2035) is about USD 0.1 trillion over this period, which is about USD 0.1 trillion less compared to the transition cost of using hydrogen for powering aircraft. The possible cost of using carbon removals (CDR) is about USD 0.6 trillion based on our estimated CDR unit price and the CDR capacity available for air transport. Airlines may or may not choose to use CDR before 2050, so this cost associated with CDR is mostly hypothetical. Overall, the total transition cost between 2031 and 2050 is estimated to be about USD 4.7 trillion.

To support this transition for the air transport industry, about USD 7.9 trillion of capital investment would be needed to build renewable fuel facilities between 2031 and 2050 if SAF product yields are not prioritized in renewable fuel production. In comparison, if SAF were given a high share in the renewable biofuel product mix (i.e., the baseline case), about USD 3.8 trillion would be saved in building new facilities to produce the required amount of SAF, bringing the total down to USD 4.1 trillion.

Furthermore, when we maximize the SAF production potential from co-processing using lipid and FT-liquids, an additional capital investment savings of about USD 0.3 trillion could be achieved over 2031-2050. Therefore, the minimum capex needed to build new renewable fuel facilities is about USD 3.8 trillion (Chart 18, left), if no further policies are implemented that can drive these costs and capital expenditure needs lower still.

In Chart 18 (right), about USD 2.7 trillion of the total capex (i.e., USD 7.9 trillion) is expected to relate directly to SAF production under the low SAF yields case, which we assume airlines will have to cover, as an illustration. However, if SAF product yields were maximized, fewer new facilities would be needed, and the corresponding capex for SAF production could be reduced by about USD 0.6 trillion. By producing SAF from existing facilities instead of building new ones, co-processing would further reduce the capex for SAF production by about USD 0.2 trillion. If all these SAF-favored policies were in place, the total capex that the air transport industry would need to cover between 2031 and 2050 would be about USD 1.9 trillion.

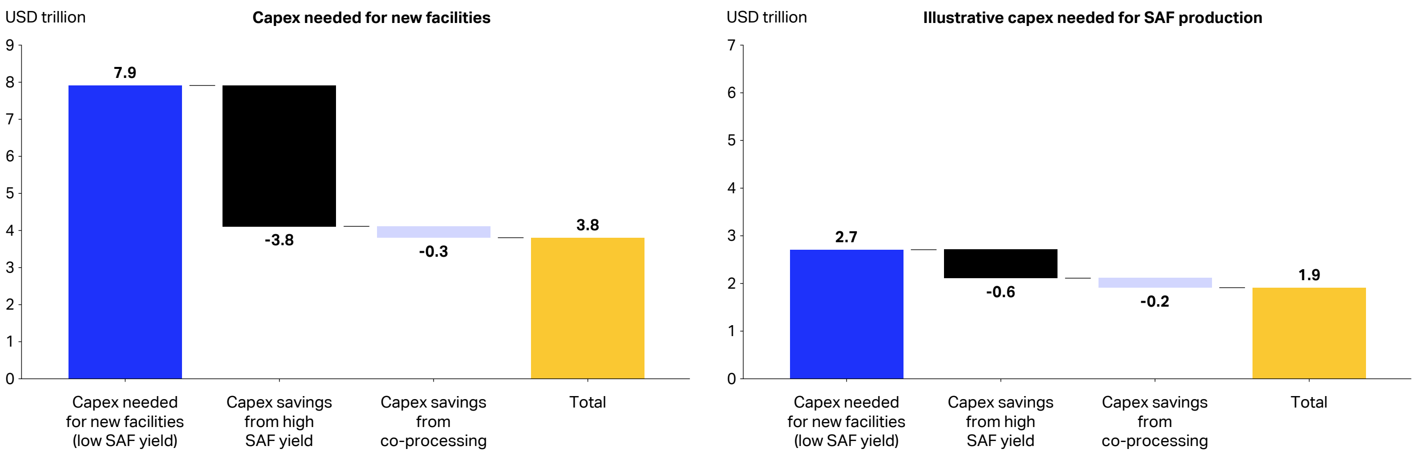
Chart 17: IATA Finance Roadmap: Transition cost breakdown in the long term (2031-2050)



Note: Totals may not equal sums due to rounding

Source: IATA Sustainability and Economics

Chart 18: IATA Finance Roadmap: Capital investment needs for the long term (2031-2050), for all new renewable fuel facilities (left) and for the SAF share of those facilities (right)



Note: Totals may not equal sums due to rounding

Source: IATA Sustainability and Economics

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5.4 Overall net zero transition finance needs for air transport

With the Finance Roadmap outlined above for the immediate (2024-2025), mid- (2026-2030), and long (2031-2050) terms, we now summarize the overall finance needs for air transport to achieve net zero CO_2 emissions by 2050.

Table 5: IATA Finance Roadmap summary, finance needs breakdown by period, USD billion

IATA net zero CO_2 emissions financing needs, USD billion	Immediate term (2024-2025)	Mid-term (2026-2030)	Long term (2031-2050)
Transition costs for use of SAF and other levers	**2.0**	**46.7**	**4,655.6**
Capital investment for new facilities, low SAF yield case	17.2	136.3	7,942.5
Capital investment for new facilities, high SAF yield case	7.1	66.7	4,139.7
Capital investment savings from high SAF yield production compared to low SAF yield case	10.0	69.6	3,802.8
Further capital investment savings from co-processing compared to high SAF yield case	< 0.01	0.8	346.7
Minimum capital investment needed for new facilities: high SAF yield with co-processing	7.1	65.9	3,793.0
Total capital investment range	**7.1 – 17.2**	**65.9 – 136.3**	**3,793 – 7,943**
Overall finance needs: Transition cost (2024-2050)		**USD 4.7 trillion**	
Overall finance needs: Capital investment (2020-2049)		**USD 3.9 – 8.1 trillion**	

Source: IATA Sustainability and Economics

For the immediate term (2024-2025), the annual average transition cost is about USD 1 billion, essentially for the use of SAF as other options are not available. Turning to the capex, if we consider the low SAF yield case as the worst-case scenario and the combined high SAF yield with co-processing as the best-case scenario, these estimates provide a possible range within which the capex needs will likely be situated. That range is between USD 3.6 and USD 8.6 billion per year (i.e., USD 7.1-17.2 billion in total) in the immediate term, for building new renewable fuel facilities for SAF production from now until the end of 2025.

Over the mid-term (2026-2030), the annual average transition cost is expected to increase significantly to USD 9.3 billion. Additionally, the annual average capex for new facilities is between USD 13.2 billion to USD 27.3 billion per year for the mid-term. The annual average capex that directly relates to SAF production would also increase to USD 16.8 billion under the worst-case scenario and to USD 7.6 billion under the best-case scenario.

In the long term (2031-2050), the challenge of meeting the financial needs of the net zero transition by the air transport industry itself becomes impossible without policy support. The annual average transition cost between 2031 and 2050 would be USD 232.8 billion if no public assistance were provided to bring down the price differential between SAF MSPs and CAF unit prices. In addition, the capex for building new renewable fuel plants ranges from USD 189.7 billion (the best-case scenario) to USD 397.1 billion (the worst-case scenario) per year. Considering only the capex that can be attributed directly to SAF production, the capex for the air transport industry would range from USD 96.4 billion per year to 136.6 billion per year under the best- and worst-case scenarios.

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Relating the projected transition costs to the profitability of the airline industry, we obtain a measure of the size of the challenge. In 2024, the net profit of the air transport industry is estimated to reach USD 30.5 billion, equivalent to a 3% net profit margin and to USD 6 per passenger—the price of a cup of coffee in some major cities. These numbers might appear exceptionally low—especially compared to the oil and gas sector and the financial sector where net profit margins are habitually ten times higher than those in the airline industry. However, this is a middle-of-the-range performance for the airline industry which has never seen a net profit margin in excess of 5%—that record was set in 2017. Awareness of these numbers ought to make it unambiguously clear to all that policy measures are urgently needed to bring the SAF MSPs down to levels that airlines can conceivably pay and still remain in business.

Regarding the capex needs, they can usefully be related to previous experiences with creating new energy markets. The solar and wind energy markets are stellar examples of what can be achieved when policy makers decide to make things happen. Our analysis of these experiences allows us to estimate the total sum of investments in the solar and wind energy markets at USD 5.3 trillion, or USD 280 billion per annum between 2004 and 2022. This is more than the total investment needed to realize air transport's decarbonization at USD 3.9 trillion or USD 129 billion per year between 2020 and 2049 in our best-case scenario (Appendix 2, Table 8). That puts air transport's challenge in perspective and makes it look utterly feasible in terms of the finance that needs to be raised.

Of course, we must acknowledge that we are not comparing like-for-like energy markets. SAF has processes and feedstock needs that will likely mean that price evolutions will not mirror those of solar and wind. Moreover, SAF production will be influenced by local factors to a higher extent than solar energy, which uniquely benefited from global supply-chain integration. Nevertheless, it is interesting to note that the larger sums associated with the solar and wind energy market creations were generated over a comparatively short period of 19 years. To be sure, R&D and other developments had been ongoing for decades prior to the unleashing of more significant funding for solar and wind, and this is an advantage not afforded many of the technologies concerned in air transport's transition. Still, the limited number of years to 2050 also looks less daunting when compared to the solar and wind energy experiences.

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Appendix 1
Estimating total capex needs per year: An example of PtL facilities

For a renewable fuel plant to be fully operational, its construction must have begun three years earlier.[15,22] Over the 3-year construction period, the necessary capex tends to be unevenly distributed across Year 1, Year 2, and Year 3, at 8%, 60%, and 32%, respectively, of the overall capex.[15] Below is an example of how we estimate the number of new PtL facilities, and the associated total capital investment needed over 2023-2050.

Table 6: PtL facility capex and the capex allocations over the 3-year construction period

Construction year	Capex share	Capex in 2020 (USD mn)	Capex in 2025 (USD mn)	Capex in 2030 (USD mn)	Capex in 2035 (USD mn)	Capex in 2040 (USD mn)	Capex in 2045 (USD mn)
1	8%	51	50	43	58	81	113
2	60%	382	378	321	433	605	848
3	32%	203	202	171	231	323	452
TOTAL	**100%**	**636**	**630**	**536**	**722**	**1,009**	**1,413**

Source: IATA Sustainability and Economics

This roadmap assumes that the scale of PtL facilities will increase from producing 40 million liters of SAF per year in the pioneer phase (2020-2029) to 69 million liters/year in 2030, 99 million liters/year in 2035, 141 million liters/year in 2040, and eventually reaching 200 million liters/year in 2045. Using the TEA models, the corresponding capex for each facility size is USD 636 million (2020-2024), USD 630 million (2025-2029), USD 536 million (2030-2034), USD 722 million (2035-2039), USD 1,009 million (2040-2044), and USD 1,413 million (2045-2050), respectively (Table 6). The total capex is distributed in the construction Year 1, Year 2, and Year 3 based on the capex shares shown in the table above. According to the IATA Net Zero CO_2 Emissions Roadmaps, SAF produced by PtL will become available from 2024 (Chart 5) and gradually increase over time. Therefore, the total capital investment for the new PtL facilities needed to meet the required production volume is calculated as below:

Table 7: Calculation method for the annual capital investment needed to build renewable fuel facilities

Year	PtL output (bn liters)	New plants needed	Construction starting year	Year 1	Year 2	Year 3	Annual total capex (USD mn)
2024	X	1	2021	1	0	0	51 x 1 = 51
2025	Y	1	2022	1	1	0	50 x 1 + 382 x 1 = 432
2026	Z	1	2023	1	1	1	50 x 1 + 378 x 1 + 203 x 1= 632
...	...	...	...	...	...	...	...

Source: IATA Sustainability and Economics

If in 2024, X billion (bn) liters of SAF will be produced from PtL, which only needs 1 (**in red**) PtL facility with 40 million liters of SAF production a year, the construction of this PtL plant must have begun in 2021, as Year 1 of the construction period. As shown in Table 7, the total capex of a PtL plant over the period 2020-2024 is USD 636 million, and Year 1 will incur 8% of the total capex, i.e., USD 51 million. Therefore, in 2021, the total capital investment for PtL facilities is only USD 51 million. Moving to 2025, the additional SAF production volume by PtL is (Y – X) billion liters, which will need one extra PtL facility in the same size (see Table 1, over 2020-2029, all PtL facilities are pioneer plants with 40 million liters of SAF production a year). Therefore, the plant that started construction in 2021enters Year 2 of its construction (**in red**) with 60% of the total capex allocated for this year (i.e., USD 382 million), and the extra plant (**in blue**) starts its Year 1 of construction. Notably, in 2025, the capex of a PtL plant is USD 630 million, and the amount to be spent on the extra plant for its Year 1 of construction is USD 50 million. Thus, in 2022, the total capex needed is 50 x **1** + 382 x **1** = USD 432 million (Table 7).

Following this logic, the total capex needs for each year between 2020 and 2047 are estimated. It is noteworthy that as renewable fuel plants typically have a lifetime of 20 years, meaning that a plant beginning its full operation in 2020 will retire in 2040. Therefore, the retired capacity is added on top of the original SAF production output in the next year to derive the new plants needed and the corresponding total capital investments.

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Appendix 2
Creating new markets: Lessons from solar and wind

If the efforts needed to bring air transport to net zero CO_2 emissions by 2050 seem daunting and maybe even overwhelming to some, it is helpful to examine previous experiences with the creation of new energy markets and learn from their success. The creation of the solar and wind energy markets benefited from substantial policy support and investments that enabled the gradual reduction of costs as technology scalability was enhanced. Initially, high capital costs and technological immaturity hindered the adoption of these renewable sources. However, through consistent government subsidies, involvement of the private sector, and targeted research and development, the unit cost of wind and solar power decreased dramatically (Table 8). Today, these renewable energy sources are competitive with traditional fossil fuel, and their share of total energy consumption quadrupled between 2013 and 2023, when it reached 13% of global electricity supplies.[36] As a result, the carbon intensity of global electricity generation dropped by 10% between 2009 and 2023.[37]

Solar

The remarkable success of solar photovoltaic (PV) technology today can largely be attributed to the pioneering efforts and investments of a few key countries—the US, Japan, Germany, and China. Together, these countries laid the foundation for the global expansion and affordability of solar PV technology.

The first solar panels were installed in the 1950s, but the ramp-up was rather slow over the next decades, with the first applications being developed for satellites and spacecraft where cost was not the limiting factor. When the world faced the oil crisis of the 70s, the US government allocated more than USD 8 billion to solar R&D to incentivize the renewable energy sector. As a direct consequence, the efficiency of solar panels doubled. When the oil prices normalized, the US administration cut its spending. Then, in the 1980s, Japan focused on R&D in small but powerful PV modules, generating mass installations in the 1990s. However, the most significant driving force for the technological scale-up was the feed-in tariff policy introduced in Germany in 2000, supporting the development of the market for renewables thanks to the German government committing to pay a preferential price over a period of 20 years. This created a boom in the installation of solar PVs which, in turn, helped drive production costs lower.

China, the country with the largest installed solar capacity today, had an almost non-existent domestic market in early 2000s, and the growing production of solar panels was almost entirely destined for Western countries. The 2008 financial crisis curbed PV exports, and the Chinese government introduced several incentives to maintain production volumes, as it saw the opportunity to become a global leader in renewable energy production.

In the early 2000s, there was only 1 GW of PV capacity globally, and by 2008 it had risen to 10 GW. From then on, the increase was logarithmic. Only four years later, the capacity had increased tenfold, and as of 2023 solar renewable energy capacity reached 1,6 TW.[38] The successful creation of the solar energy market would not have happened were it not for the reduction in the cost of generating electricity from this source. In 2009, solar PV's levelized cost of electricity was estimated at USD 359 per MWh. By 2021 it had fallen to USD 36 per MWh—a stunning 90% drop. This enabled solar to be at the forefront of cost competitiveness. Despite recent global supply chain disruptions and inflationary pressures that have almost doubled that cost, solar remains cheaper than any fossil fuel and nuclear energy (Table 8).

Not surprisingly, the primary source of funding for the development of solar technology came from the public sector. During an almost 30-year span between 1974 and 2003, governments spent around USD 300 million per year on R&D in solar PV.[39] Today, 85% of the investments in solar renewable energy are privately sourced while before 2005 the private sector was almost totally absent. We estimate that the total investment in solar energy has amounted to USD 2.9 trillion, which relates almost entirely to the 18-year period between 2004 and 2022.[40] Considering that the majority of investments were made between 2004 and 2022, that translates to USD 150 billion per year (Table 9).

36 CarbonBrief (2024), Analysis: Wind and solar added more to global energy than any other source in 2023.
37 Ember (2024), Global Electricity Review 2024.
38 IEA (2024). Photovoltaic Power Systems Programme, Snapshot 2024.
39 IEA (2024). Energy Technology RD&D Budgets.
40 IATA Sustainability and Economics estimates based on data from IEA, UNEP, IRENA.

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Table 8: Comparison of wind and solar PV versus other energy sources, generation cost and production

Energy sources	Generation cost (USD/MWh)				Electricity production (TWh)			
	2009	2013	2017	2023	2009	2013	2017	2023
Solar	359	104	50	60	23	134	443	1,305
Wind	135	70	45	50	342	629	1,127	2,015
CCGT*	83	74	60	70	4,200	5,000	6,000	6,500
Nuclear	123	105	148	180	2,650	2,400	2,580	2,600
Coal	111	105	102	117	8,000	8,900	9,500	8,800

* Combined-cycle gas turbine
Source: IATA Sustainability and Economics, IEA, World Energy & Climate Statistics – Yearbook, Lazard and Roland Berger

Table 9: Summary of investments in solar PV and wind

	Total (USD billion)			Period average (USD million)		
	1974-2003	2004-2022	1974-2022	1974-2003	2004-2022	1974-2022
Solar	27	2,830	2,856	0.9	149	58
Wind	13	2,400	2,413	0.4	126	49
Total	**40**	**5,229**	**5,270**	**1.3**	**275**	**108**

Note: excluding public non-R&D spending for 1974-2024.
Source: IATA Sustainability and Economics estimates based on data from IEA, UNEP, IRENA.

Wind

As with the case of solar energy, the modern wind energy industry gained momentum in response to the oil crises of the 1970s. In the early 1980s, the first three-bladed wind turbines were installed, and a decade later, Europe saw the emergence of its first offshore wind farms. While the US, Denmark, and Germany were pioneers in government investments in wind energy in the 20th century, China's ambitious drive toward renewable energy has positioned it as a major contributor to global wind capacity growth in the 21st century.

Much of the capacity that we see today was installed in the past twenty years. It is estimated that there were around 25 GW of available energy from wind turbines in 2000. By 2008, this number had quadrupled, and in 2023 it exceeded 1'026 GW.[41] From 2003 to 2022, around USD 2.4 trillion was invested in wind energy, which translates to almost USD 126 billion per year[42] (Table 8).

Despite the high unit costs associated with individual wind turbines and the complexity of building offshore fields, 65% of the installed capacity in 2022 was privately financed,[43] compared to 85% for solar energy. Nevertheless, offshore wind has become very competitive compared to fossil fuel-based energy sources. The levelized cost of production dropped by 62% between 2009 and 2023.

We estimate that total solar and wind investments amounted to USD 5.3 trillion[44] or USD 280 billion per annum between 2004 and 2022.[45] This is more than the total capex needed for SAF production to realize air transport's decarbonization under our best-case scenario, i.e., high SAF yield with co-processing, at USD 3.9 trillion or USD 129 billion per year between 2020 and 2049 (Table 5). That puts air transport's challenge in perspective and makes it look much more feasible in terms of the financing that needs to be raised.

41 IEA (2024), Wind.
42 IATA Sustainability and Economics estimates based on data from IEA, UNEP.
43 IEA (2024), Wind and IRENA (2024), Data.
44 In today's money.
45 IATA Sustainability and Economics estimates based on data from IEA, UNEP.

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Of course, we must acknowledge that we are not comparing like-for-like energy markets. SAF has processes and feedstock needs that will likely mean that price evolutions will not mirror those of solar and wind. Moreover, SAF production will be influenced by local factors to a higher extent than solar energy, which uniquely benefited from global supply chain integration.

Given that 2050 is just around the corner, the speed with which the finance for air transport's energy transition must be delivered could seem a greater challenge than the amount to be raised. However, the larger sums associated with the solar and wind energy market creations were generated over a comparatively short period of 19 years. To be sure, R&D and other developments had been ongoing for decades prior to the unleashing of more significant funding for solar and wind, and this is an advantage not afforded many of the technologies concerned in air transport's transition. Still, the limited number of years to 2050 also looks less daunting when compared to the solar and wind energy experiences.

Table 10: Cumulative investments in solar and wind (2004-2022) versus IATA estimated total transition costs and capex for air transport (2020-2049)

	Air transport net zero transition cost	Capex needed for renewable fuel plants	of which capex based on SAF yields	Wind	Solar	Wind & Solar
Amount	USD 4.7 trillion	USD 3.9 – 8.1 trillion	USD 2.0 – 2.8 trillion	USD 2.4 trillion	USD 2.9 trillion	USD 5.3 trillion
Time span	27 years (2024-2050)	30 years (2020-2049)	30 years (2020-2049)	19 years	19 years	19 years
Includes	• Incremental SAF use • CORSIA EEUs • Incremental H_2 use for powering aircraft • Carbon removal	• Plant capex (considering pioneer and n^{th} plant)	• The portion of capex directly relating to SAF production	• R&D costs • Plant cost • Policy and incentives costs	• R&D costs • Plant cost • Policy and incentives costs	• R&D costs • Plant cost • Policy and incentives costs
Feedstock costs	Included	Not included	Not included	None	None	None
Perspective	Cost to consumer	Cost to supplier	Cost to supplier	Cost to supplier	Cost to supplier	Cost to supplier

Source: IATA Sustainability and Economics

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Appendix 3
Too big a challenge? Putting the transition cost into perspective

While large, the total capex estimated over the 30-year time span for building new renewable fuel plants is comparable to investments made in the wind and solar energy sector, as shown in Appendix 2. Here we turn to the transition costs and find that these too are maybe less daunting than what first meets the eye.

The total transition cost from 2024 to 2050 is estimated at USD 4.7 trillion with the annual transition cost rising from USD 1 billion in 2025 to a rather eye-watering USD 744 billion in 2050. To gain some points of comparison and to help us put these numbers into perspective, Chart 19 can be helpful.

Looking at other published roadmaps with similar expected adoption of the different transition levers, we can see that the IATA roadmap finds a higher transition cost than the Long-Term Aspirational Goal (LTAG) reports by ICAO (Chart 19).[46] This is readily explained by the fact that the ICAO LTAG scenarios only consider CO_2 emissions from international air transport, which accounted for about 60% of global total RPK in 2023.[47] The IATA roadmap estimation is, on the other hand, below that found in the Waypoint 2050 report by Air Transport Action Group (ATAG),[48] which puts the cumulative transition costs to airlines over 2020-2050 at USD 5.3 trillion in the S2 scenario, and which estimations date from 2021. We can see that there is a degree of consistency among these estimations. Furthermore, the USD 4.7 trillion total transition cost required over the next 27 years is not too different from the total amount spent by airlines on fossil-based jet fuel over the past 27 years, at USD 3.8 trillion.[49] This means that airlines spent an average of USD 141 billion every year on fuel over this period (Chart 19).

Chart 19: Net zero transition cost in a comparative view

Historical total fuel cost for airlines
USD 3.8 trillion
Over the past 27 years (1998-2024)

Airline fuel cost in 2024 (forecast)
USD 291 billion

Global RPKs are expected to rise by
2.4 times
from 2024 to 2050

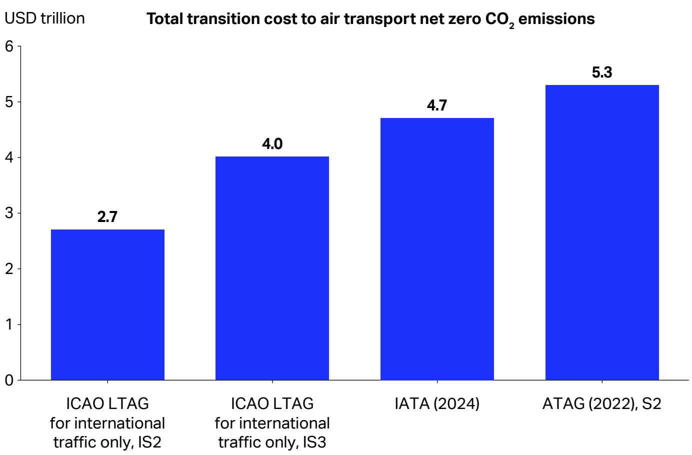
Without transition, airlines' fuel cost could reach
USD 692 billion
in 2050

With transition, the added cost could be
USD 744 billion
in 2050

This is equivalent to
2.1 times
the total cost of fuel in 2050, without transition and at the 2024 jet fuel price

Annual average historical fuel cost for airlines
USD 141 billion
Over the past 27 years (1998-2024)

Roadmaps	IATA (2024): updated Finance Roadmap	ATAG (2022): S2	ICAO LTAG (2022): IS2 and IS3 for international air transport
Time period	2024-2050	2020-2050	2020-2050
Time span	27 years	31 years	31 years



Source: IATA Sustainability and Economics, ATAG Waypoint 2050 (2021), ICAO CAEP LTAG-TG reports (2022)

46 ICAO Committee on Aviation Environmental Protection (ICAO CAEP), 2022. Report on the Feasibility of a Long-Term Aspirational Gaol (LTAG) for International Civil Aviation CO_2 Emissions Reductions, and the Special Supplement Report.
47 IATA Sustainability and Economics, 2023. Air Passenger Market Analysis December 2023.
48 Air Transport Action Group (ATAG), 2021. Waypoint 2050, Second Edition.
49 Based on IATA Sustainability and Economics statistics.

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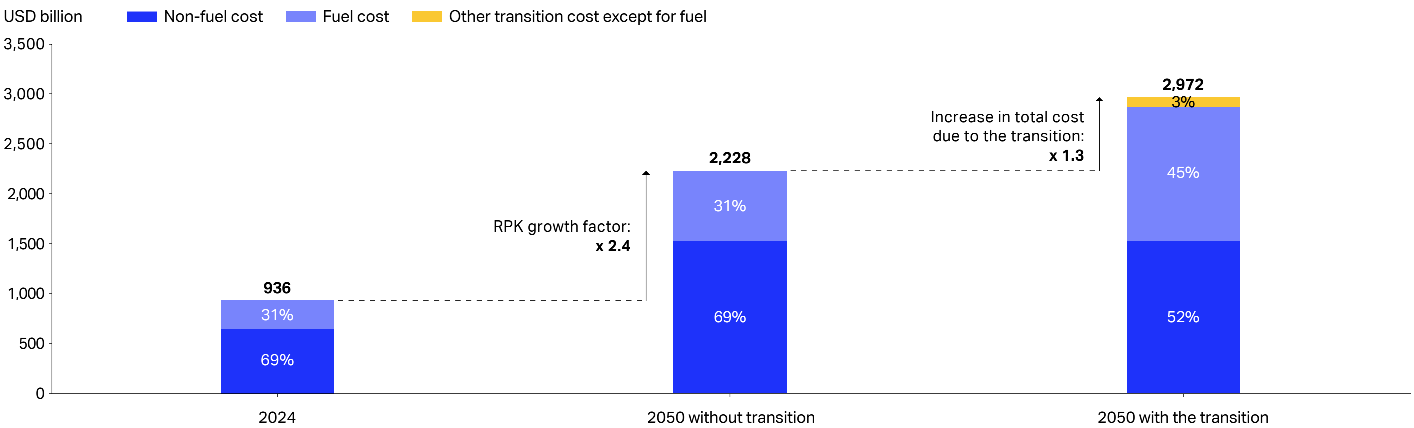
Annually, the transition cost would increase from USD 1 billion in 2025 to USD 744 billion in 2050, as a result of the increasing share of SAF in air transport's energy use, as well as the adoption of other mitigation measures. Given that the annual transition cost is the highest in 2050, we analyze how big a challenge this additional cost would be to airlines in that year. For perspective, the total fuel cost of airlines globally is expected to be USD 291 billion in 2024.[16] Airlines' fuel cost, as a function of fuel consumption, is driven by the growth in global air transport demand. IATA expects global RPK to be 2.4 times higher in 2050 than in 2024.[15] That would lead to a total fuel cost of between USD 526 billion and USD 692 billion in 2050 (the fuel cost in 2024 multiplied by the growth in RPK) where the former uses forecast fuel prices by S&P Global Commodity Insights[50] and the latter the 2024 average jet fuel price, both without considering any transition measures.[51]

The transition cost in 2050, which is estimated to be USD 744 billion in this roadmap, is added on top of the higher estimated fuel cost of USD 692 billion to take into account all the transition measures that could be implemented in that year. This would mean that airlines globally would need to pay about twice the costs of fuel that they would pay in a no-transition scenario when factoring in the necessary transition options in 2050, for a total of about USD 1,440 billion (Chart 19). The fuel cost increases related to the transition can also be considered in the context of fuel-price volatility. The price of jet fuel was as low as USD 47 per barrel in 2020 and as high as USD 136 per barrel in 2022, just to take a recent example.[16] While that volatility too is very challenging for airlines to manage, it is nevertheless a sign of great resilience that airlines can deal with such chocks.

We can gain more perspective regarding the relative magnitudes involved in the transition compared to other, habitual, and unavoidable costs, by considering the following most partial but yet illustrative analysis. Fuel typically accounts for about 25% of airlines' total costs, although this share is expected to be as high as 31% in 2024.[16] We expect the unit cost of airlines' non-fuel costs to remain stable on the 2050 horizon (even if hydrogen-powered aircraft were to enter into service in the short-haul market in the mid-2030s). Using the same RPK growth factor, we can derive the possible non-fuel cost in 2050, which is unaffected by the cost of the net zero transition (Chart 20). Applying the same RPK scaling factor also to the fuel costs in the "without transition" case, the shares of the two cost components will stay unchanged in 2050 compared to 2024. However, airlines' total cost will increase to USD 2,228 billion. In comparison, if we consider the cost of the net zero transition by adding the USD 744 billion to the fuel cost in 2050, the share of fuel cost will rise from 31% to 45% of airlines' total cost, with another 3% transition cost from the use of carbon removals in 2050. That would bring the total cost to USD 2,972 billion—about 1.3 times, or 30%, higher than in the scenario without transition (Chart 20).

On the revenue side, it is very challenging to estimate what it might be in 2050 under the net zero transition, given the likely evolving price-sensitivity of demand, especially when airlines adopt various transition measures at scale. Assuming simply that under the "without transition" case, airlines will achieve a 6% operating profit margin in 2050, as is expected in 2024, total industry revenue could reach USD 2,371 billion in 2050.[52] As a result, there would be a USD 601 billion revenue gap for the air transport industry to reach breakeven in the year of 2050 under the net zero transition. Hence, a trend evolution in airlines' revenues, based on the stated traffic growth assumption, could mean that the industry falls short of that amount in 2050, as it seeks to cover the cost increase related to the net zero transition. All other things being equal, this estimated shortfall needs to be anticipated by policy makers in such a way that the costs must decline, if airlines are to be successful in the net zero transition. This doubling of fuel costs cannot be absorbed by airlines' profit margins (3% net expected in 2024) and must be made more manageable thanks to the implementation of policies that target the price differential between SAF and conventional aviation fuel (CAF).

Chart 20: Potential impact of the net zero transition to airlines' total cost and cost structure in 2050



Source: IATA Sustainability and Economics

50 The forecast jet fuel prices by S&P Global Commodity Insights are used in the main content of this Finance Roadmap.
51 This is just a simplified way to illustrate the possible magnitude of airlines' total fuel cost in 2050 by assuming all energy would still be solely provided by fossil fuels in 2050, with the forecast fuel prices by S&P Global Commodity Insights and the average jet fuel price in 2024, respectively. In our net zero modeling, fuel consumption per RPK will decrease over time as a result of improved fuel efficiency; also, a separate jet fuel price forecast is used to derive the total fuel cost.
52 The total cost without transition in 2050 is estimated to be USD 2,228 billion (Chart 20), and to achieve the 6% operating profit margin, airlines globally would need to make a total revenue of USD 143 billion above the total cost, which is USD 2,371 billion.

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Appendix 4
Summary of Key Statistics of IATA Net Zero CO_2 Emissions Finance Roadmap

Table 11: Data table on IATA Finance Roadmap key statistics by year

Financing needs in net zero CO_2 transition	2025	2030	2035	2040	2045	2050
Annual transition cost, USD billion	1.4	19.1	65.1	123.5	325.9	744.4
SAF transition cost	1.0	14.1	41.3	106.5	255.1	614.4
CORSIA transition cost	0.4	4.5	15.3	-	-	-
Hydrogen for powering aircraft transition cost	-	0.1	1.7	5.9	15.9	31.5
Carbon removals transition cost	-	0.4	6.9	15.3	80.8	155.4
Cumulative transition cost, USD billion	**2**	**49**	**272**	**728**	**1,939**	**4,704**
Number of new renewable biofuel facilities needed	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Annual number of facilities needed, low SAF yield case	10	49	84	177	397	1,032
Annual number of facilities needed, high SAF yield case	5	21	46	96	197	494
Cumulative number of facilities needed, low SAF yield case	28	215	611	1,320	3,104	6,658
Cumulative number of facilities needed, high SAF yield case	15	92	298	702	1,605	3,362
Co-processing for SAF	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
SAF produced by co-processing, million tonnes	< 0.01	3	6	11	21	34
Cumulative number of new facilities avoided by co-processing SAF	-	14	27	77	167	266
Minimum cumulative number of facilities needed, high SAF yield with co-processing	**15**	**78**	**271**	**625**	**1,438**	**3,096**
Capital investment needed for new facilities, USD billion	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Annual capex needed, low SAF yield case	10	39	75	291	699	1,154
Annual capex needed, high SAF yield case	4	22	48	158	363	576
Annual capex savings from optimized SAF yield	6	17	27	132	336	579
Annual capex needed based on SAF product yield (for illustration), low SAF yield case	5	27	49	111	223	353
Annual capex needed based on SAF product yield (for illustration), high SAF yield case	3	12	25	80	184	291
Annual capex savings for SAF production from optimized SAF yield	3	15	24	31	40	62
Cumulative capex needed, low SAF yield case	17	153	428	1,305	3,887	8,096
Cumulative capex needed, high SAF yield case	7	74	243	750	2,087	4,214
Cumulative capex savings from high SAF yield production	10	80	185	555	1,800	3,882
Cumulative capex savings by co-processing SAF, USD billion	< 0.01	1	11	42	119	347
Minimum cumulative capex needed, USD billion	**7**	**73**	**232**	**707**	**1,968**	**3,867**

Source: IATA Sustainability and Economics

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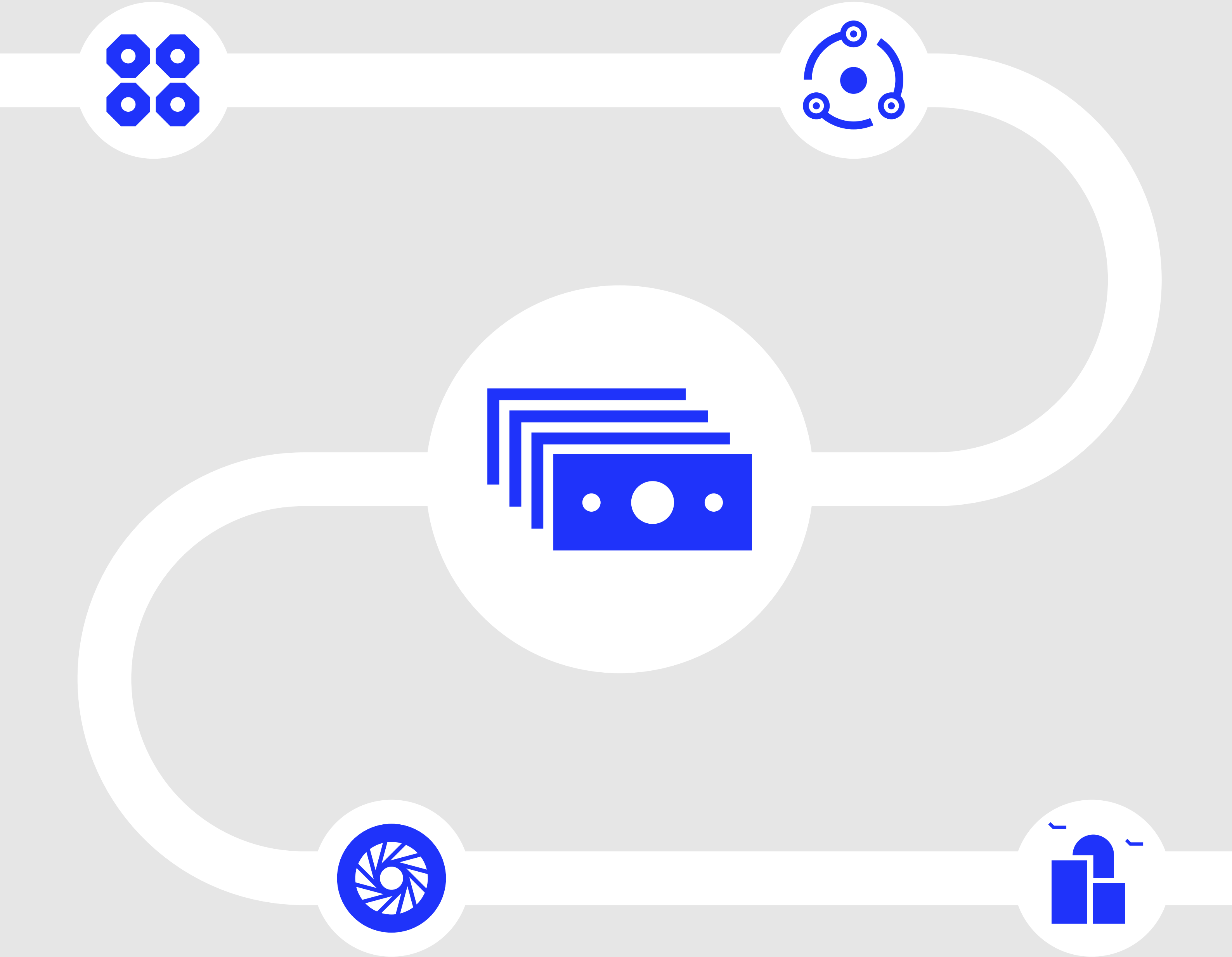
Table 12: Data table on IATA Finance Roadmap key statistics by transition period

IATA Net Zero CO_2 emissions financing needs, USD billion	Immediate term (2024-2025)	Mid-term (2026-2030)	Long term (2031-2050)
Transition cost for SAF use and other levers	2.0	46.7	4,655.6
SAF	1.4	32.9	3,750.7
Hydrogen for powering aircraft	-	0.2	205.3
CORSIA	0.6	13.2	50.5
Carbon removals	-	0.4	649.2
Capital investment for new facilities: low SAF yield case	17.2	136.3	7,942.5
Capital investment for new facilities: high SAF yield case	7.1	66.7	4,139.7
Capital investment savings from high SAF yield production compared to low SAF yield case	10.0	69.6	3,802.8
Further capital investment savings from co-processing compared to high SAF yield case	< 0.01	0.8	346.7
Minimum capital investment needed for new facilities: high SAF yield case with co-processing	7.1	65.9	3,793.0
Total capital investment range	**7.1 – 17.2**	**65.9 – 136.3**	**3,793 – 7,943**
Total new renewable fuel plants needed: low SAF yield case	28	187	6,443
Total new renewable fuel plants needed: high SAF yield case	15	77	3,270
Total new renewable fuel plants needed: high SAF yield case with co-processing	15	63	3,018
Total new renewable fuel plants avoided from co-processing	0	14	252
Total new renewable fuel plants needed range	**15 – 28**	**63 – 187**	**3,018 – 6,443**
Overall transition cost (2024-2050)		**USD 4.7 trillion**	
Overall capex needed (2020-2049)		**USD 3.9 – 8.1 trillion**	
Overall new renewable fuel plants needed (2024-2050)		**3,096 – 6,658**	

Source: IATA Sustainability and Economics



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