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The Role of Sustainable Aviation Fuels in Decarbonizing Air Transport

Robert Malina, Megersa Abate,
Charles Schlumberger and
Freddy Navarro Pineda

MOBILITY AND
TRANSPORT
CONNECTIVITY SERIES

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Foreword

Transport is an imperative for economic and social development. It is the physical, social, and economic network that connects people to opportunities, goods to markets, and communities to prosperity. Improving the quality of transport infrastructure and services can help emerging economies address poverty and reduce inequality.

As emerging economies invest in their transport systems, they are faced with a difficult decision: Do they follow the traditional development of fossil fuel powered, road vehicle dependent transport systems—despite the now clear environmental consequences—or do they forge a new development path for the transport sector that is consistent with global sustainable development and climate goals? While the policies, infrastructure, and technologies that make up the traditional development pathway for the transport sector could be well-defined and present the path of least resistance, the many consequences of road vehicle dependent transport systems—including social exclusion, traffic fatalities and injuries, local air pollution, and the emissions of climate-warming greenhouse gases (GHGs)—show this trajectory to be too costly to continue to replicate.

While more complex, a development trajectory that encourages a multimodal and integrated transport systems could prove better for economic and social development while at the same time contributing to climate action. Emerging economies with less mature transportation systems have the flexibility to explore new ways to leverage more sustainable infrastructure, policies, and technologies to leapfrog the transport system development of higher-income countries and limit the sector’s GHG emissions before they grow. By pursuing a low-carbon transport development trajectory, emerging economies can avoid lock-in to traditional, high-externality transport systems and avoid the expensive retrofitting and replacing process that higher-income countries will be experiencing in the next few decades.

The World Bank’s Decarbonization of Transport flagship activity brings together the expertise of numerous international specialists and World Bank staff to identify and characterize low-carbon transport system development pathways for lower-income countries. Starting from the economic and social development goals of emerging economies, the flagship activity sets out to define policy actions, infrastructure investments, and technologies that can help build safer, more efficient, more inclusive, more resilient—and greener—transport systems. In a series of reports, the flagship activity identifies the fundamental challenges faced by passenger and freight transport systems in low- and middle-income countries and key “win-win” actions for development and climate action in the transport sector.

Nicolas Peltier
Director, Transport Global Practice
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Acknowledgments

This report was written by Professor Robert Malina (World Bank Consultant and Professor of Environmental Economics, Hasselt University), Dr. Megersa Abera Abate (Transport Economist, World Bank), Dr. Charles E. Schlumberger (Lead Air Transport Specialist, World Bank), and Dr. Freddy Navarro Pineda (Post-Doctoral Researcher, Hasselt University).

The report greatly benefited from the feedback of the following peer reviewers: Dominik Englert (Economist, World Bank), Samu Salo (Senior Industry Specialist, International Finance Corporation), Aymen Ali (Senior Transport Specialist, World Bank), and Dr. Florian Allroggen (Laboratory Executive Officer and Research Scientist, Massachusetts Institute of Technology). Robert Malina acknowledges a decade of support of research on sustainable aviation fuels by the United States Federal Aviation Administration (FAA) through the PARTNER and ASCENT Center of Excellences that allowed him to build up expertise in sustainable aviation fuel (SAF).

This report was developed as part of the World Bank's Decarbonization of Transport flagship activity led by Cecilia Briceño-Garmendia (Lead Economist), Bianca Bianchi Alves (Senior Transport Specialist), and Joanna Moody (Transport Consultant) with guidance from Nicolas Peltier (Director, Transport Global Knowledge Unit) and Binyam Reja (Global Practice Manager, Transport Global Knowledge Unit). Sara Sultan, Jonathan Davidar, Leszek Tymoteusz Zemke, Erin Scronce, and Xavier Bernard Leon Muller provided invaluable communications and dissemination support. Kara Watkins edited the report and Oleksiy Manuilov designed the report.

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Robert Malina is a Professor for Environmental Economics and Hasselt University in Belgium, and a Research Affiliate in the Department of Engineering at the Massachusetts Institute of Technology (MIT). His research is focused on holistic economic assessments in the field of energy, transport, and the environment, such as the challenge to marry the need of the aviation sector to significantly reduce emissions with people's desire to fly. Sustainable aviation fuels represent a core area of his research, in particular with regard to their economic and environmental viability and with regard to designing methods to appropriately account for those fuels in international climate regulation. Robert is heavily involved in the Fuels Task Group of the International Civil Aviation Organization (ICAO), where he leads one of the subgroups, and in several large-scale research projects on sustainable aviation fuels funded by the United States Federal Aviation Administration (FAA) and the European Union (EU) Commission. He is a member of the Scientific Advisory Body of the EU Joint Undertaking on Clean Aviation. Before coming to Hasselt University, Robert worked as Associate Director of the Laboratory for Aviation and the Environment at MIT, and as Associate Director of the Institute of Transport Economics at Muenster University in Germany. He holds a PhD in Economics from Muenster University.

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Freddy Navarro is a researcher in the fields of environmental life-cycle assessment (LCA), techno-economic assessment, and renewable energy. He is currently working in the Centre for Environmental Sciences at Hasselt University in Belgium on the economic and environmental viability of sustainable aviation fuels, and the inclusion of these fuels in international climate regulation. He obtained a PhD in chemical and biochemical sciences from the Autonomous University of Yucatan in Mexico. Before joining Hasselt University, he worked as a member of the LCA research line in the Advanced Biodiesel Cluster of the Mexican Center for Innovation on Bioenergy.

Abbreviations and Acronyms

ATAG	Air Transport Action Group
ATJ	alcohol-to-jet (isobutanol)
ATJ–SPK	alcohol-to-jet synthetic paraffinic kerosene
ATM	air traffic management
bpd	barrels per day
CAGR	compound annual growth rate
CANSO	Civil Air Navigation Services Organisation
CAPEX	capital expenditure
CH–SK or CHJ	catalytic hydrothermolysis synthesized kerosene
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EASA	European Union Aviation Safety Agency
EIA	U.S. Energy Information Administration
EJ	exajoule
ESG	environmental, social, and governance
ETC	Energy Transitions Commission
ETJ	alcohol-to-jet (ethanol)
EU	European Union
EU ETS	European Union Emission Trading Scheme
FAA	U.S. Federal Aviation Agency
FT	Fischer–Tropsch
FT MSW	Fischer–Tropsch municipal solid waste
FT–SPK	Fischer–Tropsch synthetic paraffinic kerosene
FT–SPK/A	Fischer-Tropsch synthetic paraffinic kerosene with aromatics
FOGs	fats, oils, and greases
GAEZ	global agroecological zones (model)
GDP	gross domestic product
GHG	greenhouse gas
gCO_2e/MJ	grams of carbon dioxide per megajoule
GJ_{SAF}	gigajoules of sustainable aviation fuel
$GtCO_2e$	gigatons of carbon dioxide equivalent
HC–HEFA–SPK	hydroprocessed hydrocarbons, esters, and fatty acids, synthetic paraffinic kerosene
HEFA	hydroprocessed esters and fatty acids

HEFA–SPK	hydroprocessed esters and fatty acids, synthetic paraffinic kerosene
HFS–SIP	hydroprocessed fermented sugars to synthetic isoparaffins
IACO	International Civil Aviation Organization
IATA	International Air Transport Association
IEA	International Energy Agency
ILS	instrument landing system
IPCC	Intergovernmental Panel on Climate Change
IRENE	International Renewable Energy Agency
ITF	International Transport Forum
$kgCO_2$	kilograms of carbon dioxide
kg/m^3	kilograms per cubic meter
kt	(metric) kiloton
LIC	low-income country
LMIC	low- and middle-income country
MACC	marginal abatement cost curves
MJ/kg	megajoule per kilogram (MJ/kg)
MSP	minimum selling price
MSW	municipal solid waste
Mt	million (metric) tons
Mt_{SAF}	million (metric) tons of sustainable aviation fuel
$MtCO_2e$	million (metric) tons of carbon dioxide equivalent
NAS	National Academies of Sciences, Engineering, and Medicine
NBC	nonbiogenic carbon
NDC	nationally determined contribution
NPV	net present value
OECD	Organisation for Economic Co-operation and Development
PBN	performance-based navigation
PKM	passenger-kilometer
RPK	revenue passenger-kilometer
RSB	Roundtable on Sustainable Biomaterials
SAF	sustainable aviation fuel
SIP	synthetic (or synthesized) isoparaffins
tCO_2e	(metric) ton carbon dioxide equivalent
tkm	ton-kilometer (metric)
WEF	World Economic Forum

Executive Summary

The air transport sector is an integral part of economic growth and development. As the only available means of transporting passengers and goods across the globe within a single day, air transport provides critical connectivity between regions and better access to global markets. The creation of these benefits, however, leads to detrimental impacts on the environment and public health, including the emissions of climate-warming greenhouse gases (GHGs).

As demand for air travel continues to grow, the decarbonization of aviation is key to achieving climate goals by mid-century. Domestic and international transport was responsible for 20 percent of global GHG emissions in 2019 and the sector experienced the fastest annual emissions growth between 2010 and 2019 (at 1.8 percent per year). Within the transport sector, the direct contribution of aviation emissions is 12 percent, the second largest after road transport at 70 percent, while shipping and rail contributed 11 percent and 1 percent respectively. Prior to the COVID-19 pandemic, combustion emissions from global aviation were estimated at around 2.5 percent of global carbon dioxide (CO_2) emissions. When including other GHG emissions and aviation-induced cirrus cloudiness, Lee et al. (2021) estimate that in the year 2018, aviation accounted for 3.5 percent of total net anthropogenic effective radiative forcing. During the same period, domestic and international aviation have been growing faster than road transport emissions, with average annual growth rates of +3.3 percent and +3.4 percent respectively. If aviation were unmitigated, however, it could be responsible for 22 percent of global emissions by 2050 (Cames et al. 2015).

This report presents decarbonization options for global aviation out to the year 2050. It accounts for a basket of measures including: (1) demand change for air transport; (2) technological improvements to the aircraft system; (3) improvements related to airline operations, air traffic management (ATM) operations, and ground operations; and (4) sustainable aviation fuels (SAFs). The geographical scope of the report is global, and it accounts for GHG emissions from both domestic and international aviation.

This report emphasizes SAF as the main mitigation option that can most readily realize substantial GHG emission savings for air transport in the medium term (for example, the next 5 to 10 years). Sustainable aviation fuels (SAFs) is the term used by the aviation industry to describe a set of fuels that can be sustainably produced and generate lower CO_2 emissions than conventional kerosene on a life-cycle basis. In the context of international regulation developed under the International Civil Aviation Organization (ICAO), SAF is defined more precisely as a renewable or waste-derived aviation fuel that meets a set of Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) Sustainability Criteria, including a GHG emission reduction criterion.

Despite being widely recognized as critical for decoupling emissions growth from market growth in the airline industry, SAF currently accounts for only 0.1 percent of global aviation fuel demand and costs 2 to 5 times more than conventional jet fuel (IATA 2020a). While recent experiments have shown that airplanes can safely fly with 100 percent SAF,[1] it is currently deployed as a drop-in fuel with up to 50 percent blend. The past three years have seen a significant deployment increase of SAF from airlines. In 2019, they committed to 40 million liters of SAF, followed by a 55 percent jump in 2020 to 80 million liters, leaping again to 120 million liters in 2021 (Singh 2022). This buoyant demand has been catalyzed by relativity consistent signals on carbon pricing and the tightening of SAF blending mandates in major aviation markets, which in turn has led to increased production commitments.

Recent years have seen significant momentum in the production and uptake of SAF, but these efforts are concentrated in higher-income countries. Between 2012 and March 2022, there have been 320 separate announcements of SAF production from 171 different companies, primarily based in the Organisation for Economic Co-operation and Development (OECD) countries. The dominance of OECD countries is also visible in the magnitude and distribution of SAF offtake agreements publicly available from the ICAO. As of March 2022, airlines and intermediate entities have committed to buying approximately 19,163 metric kilotons of SAF, accounting for approximately 89 percent of the announced SAF production capacity. Nearly all (96 percent) of the offtake agreements have been made from companies based in OECD countries, which indicates the challenge for companies based in low- and middle-income countries to secure SAF volumes.

Looking forward to 2050, SAF production can meet a large share of projected demand for jet fuel and reverse the upward trajectory of air transport emissions, but only if production expands beyond OECD countries. Diffusion modeling out to the year 2050 for low, mid, and high SAF production scenarios shows that SAF volumes are forecasted to reach approximately 108 million metric tons, 216 million metric tons, and 331 million metric tons respectively. This accounts for 23 percent, 47 percent, and 72 percent of the total forecasted jet fuel demand in 2050. In the most optimistic case (the high scenario), GHG emissions reduction can be stabilized at pre-pandemic levels in the 2020s and be reduced to around 2010 levels due to the large-scale use of SAF. Compared to 2050 emissions in the continuation of the current trends scenario, emissions can be reduced by up to 57 percent. In all three scenarios, production volumes to the year 2025 are concentrated in OECD countries, with their production shares ranging from 92 percent to 98 percent. The low SAF production share (2 to 8 percent) of non-OECD countries in the short-term scenarios sharply contrasts with their share in total jet fuel burn, which in 2018 totaled approximately 42 percent.

To reach net-zero emissions in air transport by 2050, large-scale SAF deployment will need to be combined with technological and operational improvements. Within the diffusion model, additional technological and operational improvements can reduce life-cycle GHG emissions to approximately 279 to 477 million tons, which is up to 78 percent lower than total CO_2 emission for 2050 considering a business-as-usual scenario (compared to a 57 percent mitigation potential with SAF deployment alone. Opportunities

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[1] United Airlines operated a 100 percent SAF-powered flight on December 1, 2021, with passengers on board. Read "Sky's The Limit: First Passenger Flight Powered by 100% Sustainable Aviation Fuel Marks New Milestone," for a description of the historic flight, available on the Honeywell website: https://pmt.honeywell.com/us/en/about-pmt/newsroom/featured-stories/uop/first-passenger-powered-by-100-percent-saf-marks-new-milestone.
Similarly, Airbus, Dassault Aviation, ONERA, the French Ministry of Transports, and the Safran Group flew an experimental flight in late 2021 to analyze the impact of 100 percent SAF on ground and in-flight emissions. For more information, read the press release, "First A319neo Flight with 100% Sustainable Aviation Fuel" (Safran Group 2021).

for filling the gap to net-zero emissions by 2050 outside of what is modeled here lie in further decreasing the SAF GHG emission intensity by, for example, increased use of 100 percent fossil carbon-free power to SAF technologies, or by the limited use of carbon offsets. It is important to note that the high reduction estimate here is based on optimistic assumptions about the SAF project's success rates, low GHG emission intensity per unit SAF produced, and a disruptive change in aircraft technology, all of which will require significant investment and policy incentives to be realized.

While current and near-future SAF production is primarily planned in OECD countries, significant, untapped production potential is emerging in low- and middle-income countries. Already, non-OECD countries play an important role in providing feedstock for road transportation biofuels. For example, in the European Union (EU), 59 percent of the feedstock used for biodiesel in the year 2018 originated from outside the EU, with Indonesia, Malaysia, and Argentina representing the largest non-EU feedstock providers. While it is difficult to distinguish between feedstock sourced from developed and developing countries, it is estimated that SAF feedstock potential in non-OECD countries is equivalent to a production of approximately 510 million tons of SAF, out of which approximately two-thirds (345 million metric tons) could come from non-food feedstocks. Among those, lignocellulosic energy crops and municipal solid waste (MSW) form the most important feedstock categories. All non-OECD world regions considered here can contribute significantly to the total potential. For comparison purposes, SAF demand in the high SAF scenario in 2050 amounted to approximately 331 million tons, which is similar to the production potential of non-food feedstocks in non-OECD countries.

The emergence of a SAF industry in developing countries could have significant benefits for the economy as well as for climate. SAF production can speed up rural development as shown in studies dealing with Mexico, Southern Africa, and Brazil. It could also lead to the generation of new jobs, additional income for farmers, and improved environmental and health conditions due to SAF-induced improvements in waste management practices. Given the projected increase in population and gross domestic product (GDP), it is expected that MSW generation in developing countries will double by 2050, and many of these countries already now suffer from a lack of proper MSW collection and landfilling and associated environmental and health issues, which further motivates the usage of MSW as a feedstock for SAF production. In our analysis, approximately 25 percent of the nonedible SAF feedstock potential comes from MSW, and as such, the valorization of MSW as a feedstock for SAF production provides an important opportunity for increased MSW collection in developing countries.

Reaching projected SAF production volumes will require significant capital expenditure (CAPEX) that could be beyond the reach of developing countries without assistance. Model estimates show annual greenfield plant investment in the high scenario peaks at approximately US$124 billion.[2]This is equivalent to more than 370

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[2] The CAPEX values are so-called "nth" plant estimates, and as such, they might be underestimating the required investment in the early years of technology development, while overestimating the future investment into fully matured technologies. The CAPEX calculations are based on greenfield investments, and as such a substantial use of retrofitting, repurposing, or colocating might decrease the required investment value. We also note that these CAPEX estimates are for the full plant and given that for most SAF pathways these plants produce multiple outputs, only a share of total CAPEX is directly attributable to the SAF fraction produced.

Model estimates show annual greenfield plant investment in the high scenario peaks at approximately US$125 billion, which equals to more than 370 SAF-producing facilities coming online during the peak years in the late 2030s or early 2040s- the periods of highest SAF production growth. For comparison purposes, 2019 investments into new petroleum refining capacity totaled approximately US$54 billion, and peak solar energy investment was approximately US$190 billion.[3] Seen this way, decarbonization of aviation through the scale-up of SAF is relativity cheaper compared with historical investment in renewables.

Despite high CAPEX needs, SAF-specific marginal abatement cost curves (MACC) for the years 2030 and 2050 show that SAF can be a cost-effective solution for decarbonization of air transport. By 2030, highly mature and low-cost feedstock pathways, such as hydroprocessed esters and fatty acids (HEFA) waste oils, could already produce negative marginal abatement costs. Other types of SAF, depending on feedstock type and assumptions on future conventional jet fuel prices, would have costs of greater than US$100 per ton of carbon dioxide equivalent (tCO_2e) abated. The SAF volumes needed for a rapid SAF production ramp-up as forecasted in the high SAF production scenario can be realized at relatively low costs (below US$150 per tCO_2e abated), even under nonoptimistic assumptions on GHG emission performance and conventional jet fuel prices. Costs could decrease to close to zero by 2030 if ambitious policies are employed that incentivize the use of low-GHG emission SAF and drive up conventional jet fuel prices. For the year 2050 and under the assumption of aggressive policies for mitigating climate change that drive up prices of conventional jet fuel and set working incentives to improve the SAF GHG performance, the results presented in this report indicate large volumes of SAF could be provided at below zero—or close to zero—abatement costs.[4]

Collective action from policy makers, industry, and financiers is needed to overcome the economic and technological challenges to scale up SAF production and use. Existing policy-incentive frameworks originally designed to incentivize biofuel use in terrestrial and maritime transport could also be modified to prioritize aviation-biofuel use. In places where more optionality in the sustainable and renewable energy markets for these modes exists, implementation of stronger financial incentives that favor SAF production and use would be warranted. Three major types of policies that can increase the financial viability of SAF production and de-risk investments include the following: (1) Market-based measures that cover aviation emissions and aviation GHG offset systems—either directly (in the case of carbon taxes) or indirectly (in the case of emissions trading scheme)—put a price on the release of GHG emissions; (2) SAF mandates that require the production and/or use of a certain amount of SAF, which usually increases over time; and (3) cost-related policies such as feedstock subsidies, capital grants, and loan guarantees.

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[3] Global oil refining statistics for 2019 provided by Statista. View the data online: "Global Oil Refining Investment by Regions." https://www.statista.com/statistics/465938/global-oil-refining-investments-by-region/.

[4] In order to indicate the magnitude of total abatement costs, we assume a starting SAF abatement cost of US$200 per tCO_2e abated in 2025 that linearly decreases to zero by 2050. For the high SAF scenario, this yields total abatement costs between 2025 and 2050 of US$879 billion, or US$34 billion on average, per year. For comparison purposes, the total revenues of global airlines in 2019 reached US$838 billion, with profits amounting to US$25.9 billion (IATA 2020b).

The public and private finance sector also has a role in steering investment into SAFs through green/climate financing. While the role of climate finance in the air transport sector is still in its infancy and limited to a few projects related to green energy at airports or aircraft fleet renewal, SAF-related projects could build on the significant green financing experience in the biomass and bioenergy sector.[5] In addition, the finance sector has the scope to collectively set climate-aligned investment principles to achieve the 1.5 degrees Celsius (ºC) targets. This can be done by defining sustainability criteria for aviation related infrastructure portfolios and establishing a transparent and rigorous GHG emissions accounting from new investments. Public-private partnerships are also warranted to de-risk projects of low maturity through blended finance, concessional loans, capital grants and/or long-terms guarantees.

Aviation decarbonization policies, including those aimed at promoting the SAF industry, should be integral to countries' broader climate targets and actions on energy transition and agricultural and environmental sustainability. There should be a comprehensive public policy and regulatory framework that defines production incentives needed to increase supply and lower costs, while incentivizing SAF usage to ensure offtake. To be effective, high-level policy commitments must be accompanied by the development of financing schemes (including guarantees instruments), easement of environmental licensing, and promotion of exports to meet the growing demand for SAF. Should SAF production increase require an expansion in cultivation area, public and private institutions must ensure that such expansion happens sustainably within the agricultural frontier, and with no significant effect on the natural ecosystems.

Finally, continued support for sustainable aviation-fuel research and development is needed. This should include the development of feedstock supply chains, new and innovative production technologies, and the development of innovative business models that increase the value of all products and by-products of SAF production operations. As the SAF production and distribution network becomes global, a deeper analysis is also needed to design the structure of biomass feedstock and refined fuel products transportation, whether distributed or centralized, in streamlined supply chains.

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[5] SAF biorefinery projects are frequently (partially) financed through green financing. For example, in early 2021, the SAF producer Neste Corporation issued a US$500 million green bond (Neste 2021a), part of which will be used in accordance with Neste's Green Finance Framework (Neste 2021b) to fund the expansion of Neste's SAF production capacity. Since 2017, the State of Nevada Department of Business and Industry has issued green bonds to the amount of US$175 million, which loan the proceeds to Fulcrum Bioenergy to finance Fulcrum's waste to SAF biorefinery in Nevada (Morgan Stanley 2019). A similar approach is followed for Fulcrum's proposed waste to fuel biorefinery in Gary, Indiana, for which the Indiana Finance Authority is issuing US$375 million in environmental improvement revenue bonds to a subsidiary of Fulcrum Bioenergy (Fulcrum Bioenergy 2021).

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Chapter 1: Aviation and Climate Change

Key Messages from Chapter 1

- Air transport represents an integral part of economic growth and development, where we see a significant unmet demand for aviation. Therefore, if no action is taken to decarbonize the sector, continued growth in demand will threaten climate goals at the global scale.
- Direct emissions from jet fuel combustion in domestic and international aviation already account for 12 percent of CO_2 emissions from the transport sector and as much as 2.5 percent of global CO_2 emissions.
- From 2010 to 2018, domestic and international aviation had average annual emission growth rates of +3.3 percent and +3.4 percent respectively—much higher than the growth rate for the transport sector as a whole (+1.8 percent).
- Aviation emissions are largely caused by flights originating in high-income countries; low- and middle-income countries account for only 10 percent of global CO_2 emissions from aviation.

The air transport sector represents an integral part of economic growth and development. Air transport is the only available means of transporting passengers and goods across the globe within a single day. The aviation industry is a major global economic sector, securing approximately 88 million jobs and creating an economic impact of US$3.5 trillion in the year 2018 (ATAG 2020a). It creates significant benefits to countries by providing connectivity between regions that leads to better market access, which in turn, allows for better labor pooling, expansion of exports and inputs, diffusion, and spillover of knowledge, innovation, and technology, along with increased foreign direct investment (Lenaerts et al. 2021; Lakshmanan 2011). The creation of these benefits, however, leads to detrimental impacts on the environment and public health, in particular, due to aviation-attributable global climate change, air pollution, and noise.

Aviation affects the climate system through: (1) the combustion-related production or formation of carbon dioxide (CO_2), nitrogen oxides (NOx), soot, and sulfate aerosols; and (2) contrail cirrus (that is, linear contrails and resulting cirrus cloudiness) (EASA 2020). Combustion related CO_2 emissions increased by a factor of 6.8 from 1960 to 2018. In 2018, total combustion-related CO_2 emissions from aviation were estimated at 1.04 billion tons, or 2.5 percent of global CO_2 emissions and as much as 12 percent of emissions from the transport sector (Lee et al. 2021).[1] When accounting for emissions from the full life cycle of jet fuel, carbon dioxide equivalent (CO_2e) emissions are approximately 17 percent higher (ICAO 2019). And when including other greenhouse gas (GHG) emissions and aviation-induced cirrus cloudiness, Lee et al. (2021) estimate that in the year 2018, aviation accounted for 3.5 percent of total net anthropogenic effective radiative forcing.

While currently accounting for a relatively small share of total CO_2 emissions, domestic and international aviation have been a key contributor to the high growth rate in emissions from the transport sector overall. For the period 2010 to 2019, the transport sector was the fastest growing source of CO_2 emissions globally, with about 1.8 percent annual emission growth. During the same period, domestic and international aviation had average annual emission growth rates of +3.3 percent and +3.4 percent respectively (Crippa et al. 2021; Minx et al. 2021). While aviation CO_2 growth has been approximately proportional to average CO_2 emission growth from all sectors from the 1990s to the beginning of the 2010s, in the mid- to late 2010s emissions in the aviation sector increased stronger than the global average, driven by relatively large increases in traffic. Despite the fact that energy efficiency improvements in aviation were considerably larger than in road transport, gains were far outweighed by even larger increases in activity levels from growing demand for air travel (SLoCaT 2021; Lee et al. 2021).

The environmental impacts of aviation come at a substantial cost to society. A recent study published by the European Commission (van Essen et al. 2020) estimates that in the year 2016 an €33 billion or 69 percent of the €48 billion total environmental costs of air transport in the European Union (EU) were caused by climate change. Grobler et al. (2019) estimate the marginal climate costs of aviation per unit fuel burned; they estimate mean climate costs of aviation, including both CO_2 and non-CO_2 effects at US$200 per metric ton of jet fuel used.

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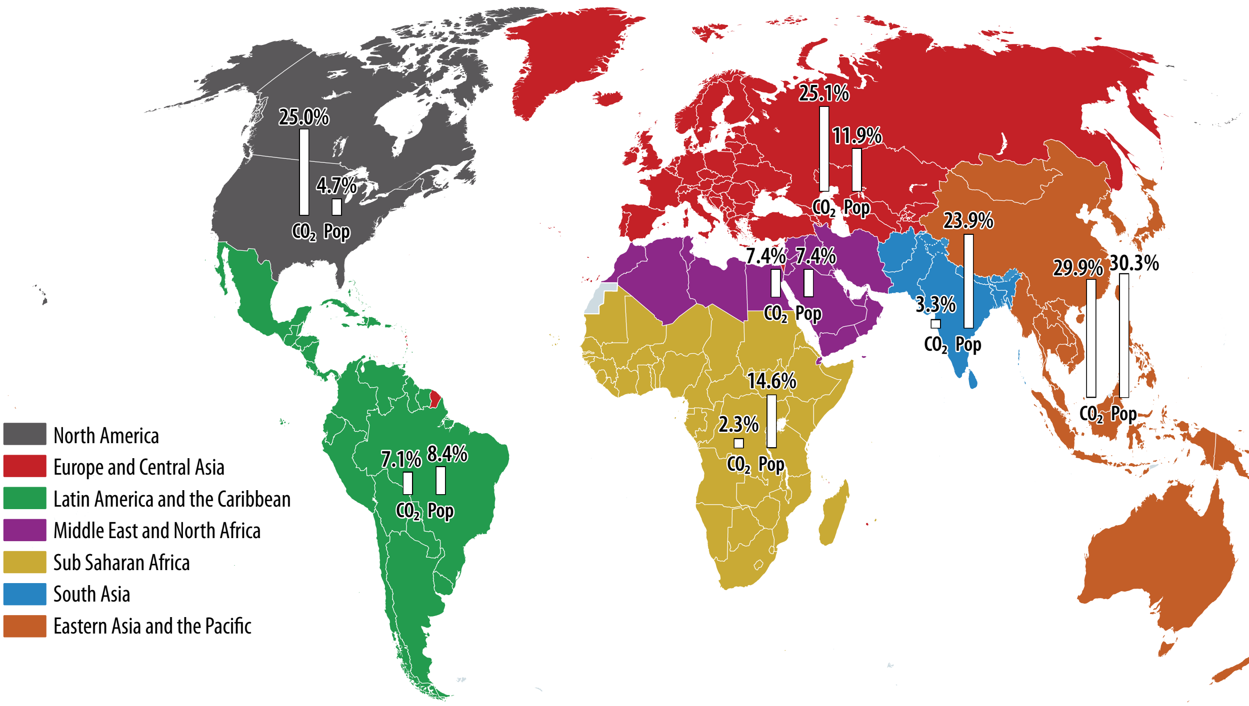
[1] The Lee et al. (2021) estimate includes emissions from both military and civil aviation. Using the United States Energy Information Administration (EIA) commercial aviation jet fuel demand for the year 2018 and combustion emissions of 3.16 kilograms CO_2 per kilogram of fuel, we estimate commercial aviation CO_2 combustion emissions at 973 million tons.

Aviation emissions are largely caused by flights originating in high-income countries. A total of 62 percent of combustion CO_2 emissions from passenger aviation operations in the year 2018 were caused by flights originating from this country group, while the group only accounts for 16 percent of the global population (Graver, Zhang, and Rutherford 2019). In contrast, low- and middle-income countries (LMICs) and low-income countries (LICs) represent 49 percent of the world population but only account for 10 percent of global CO_2 emissions from aviation. A similar pattern emerges when comparing emission share and population share by regions (figure 1.1).

Figure 1.1. CO_2 Combustion Emissions of Aviation and Population, by Region



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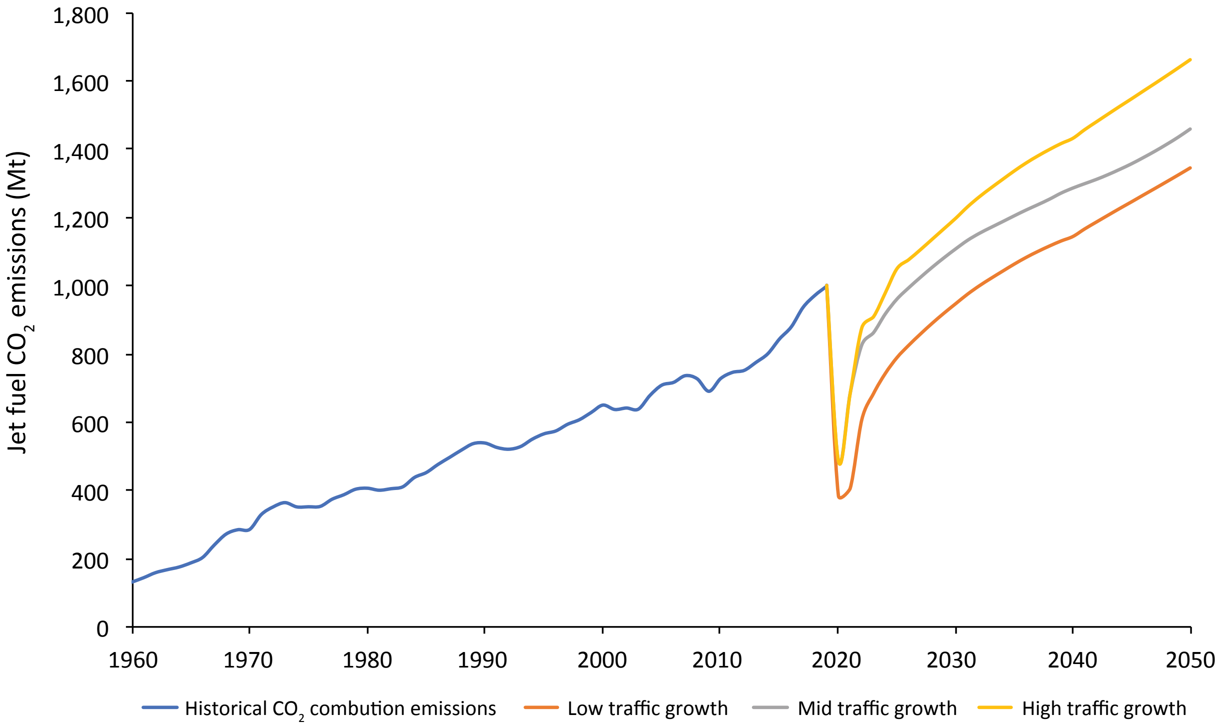
Source: Original figure produced for this publication.

Note: CO_2e combustion emissions shares are based on data provided by the International Council for Clean Transportation using the method outlined in Graver, Zhang, and Rutherford (2019). The original source estimated emissions per flight and attributed them to specific countries based on the location of the departure airport. Reported country-specific results are aggregated to regions here.

Figure 1.2. CO_2 Combustion Emissions of Global Aviation: Historical Emissions and Forecast Out to 2050 Assuming a Continuation of Historical Efficiency Trends



Source: Original figure produced for this publication, with historical CO_2 emissions from 1990 to 2018 based on EIA jet fuel demand data. For the year 2019, demand data was taken from Statista. The forecast of CO_2 emissions is based on ATAG (2020a) fuel burn projections out to 2050. The analysis is purely based on jet fuel combustion-related CO_2 emissions. For all years, a CO_2 emissions factor of 3.16 kilograms of carbon dioxide ($kgCO_2$) per kilogram of jet fuel is assumed.

Despite the sharp decline in aviation activities due to the COVID-19 pandemic, emissions from aviation could increase by 71 percent (over 2019 levels) by mid-century. The pandemic has had an unprecedented impact on global aviation activity, with annual passenger traffic in the year 2020 decreasing by 66 percent compared to 2019 levels, and total passenger volumes shrinking to levels of the late 1990s. However, recent traffic forecasts adjusted for COVID-19 still expect a significant increase in aviation activity out to the year 2050, with the compound annual growth rate of revenue passenger-kilometers (RPKs) for 2019 to 2050 ranging from 2.7 to 3.5 percent (ATAG 2020b), which in the absence of additional emission's reduction measures, will lead to an increase in GHG emissions as well. More specifically, using fuel burn projections out to 2050 produced by the Air Transport Action Group, or ATAG, from their "continuation of current trends scenario"[2] and the above-mentioned range for RPK growth, we can estimate that total CO_2 emissions combustion in 2050 will be between 1,340 and 1,660 million tons of CO_2 (and 1,570 to 1,945 million tons when accounting for jet fuel life-cycle emissions), an increase by 38 to 71 percent compared to 2019 levels, if no additional actions to decrease the carbon intensity of aviation beyond historical efficiency increases are taken (see figure 1.2).

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[2] The "continuation of current trends" scenario assumes that historical fuel efficiency improvements due to aircraft replacement, aircraft operations, and load factor increases continue into the future.

As the demand for air transport continues to increase, a clear need has emerged to define a more climate-friendly development pathway for the sector. This report assesses and quantifies the decarbonization options for global aviation out to the year 2050. It accounts for a basket of measures, including the following: (1) demand change for air transport; (2) technological improvements to the aircraft system; (3) improvements related to airline operations, air traffic management (ATM) operations, and ground operations; and (4) sustainable aviation fuels (SAFs). A particular emphasis is placed on SAF as the only mitigation option that can potentially realize high GHG emission savings in the medium term (that is, the next 5 to 10 years). We estimate SAF production out to 2050 for a set of policy-informed scenarios and calculate the associated GHG emission reduction for each scenario as well as the required capital investment. We estimate the SAF production potential for developing countries and outline opportunities and hurdles of SAF deployment in these countries.

The geographical scope of this report is global, and it accounts for GHG emissions from both domestic and international aviation. Wherever possible, GHG emissions are reflected for the full fuel life cycle, which includes emissions from the combustion of jet fuel as well as upstream emissions from feedstock extraction, transportation, and conversion, along with fuel transportation. The target year of the analysis is 2050 and the transition path to the year 2050 is outlined as well.

The remainder of this report proceeds as follows: Chapter 2 discusses the available literature on the GHG emission reduction potential of technology change, operational improvements, demand-side measures, and sustainable aviation fuels. Chapter 3 takes a high-resolution look at the potential contribution of SAF for decarbonizing aviation in the short term, and out to 2050, and discusses SAF production challenges and opportunities in developing countries. It also develops a marginal abatement cost curve for SAF and associated GHG emissions reductions and capital expenditure (CAPEX) requirements and options for accelerating SAF production and deployment. Finally, chapter 4 summarizes and concludes.

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Chapter 2: Decarbonization Options for Aviation

Key Messages from Chapter 2

- Aviation is only partially covered by international climate regulation. In addition to emissions reduction efforts currently being led by ICAO, and industry initiatives, commitments on aviation are needed as part of the nationally determined contributions to achieve climate goals.
- While their relevance and applicability is context specific, the decarbonization of aviation involves the following considerations: (1) technological improvements to the aircraft system; (2) improvements related to airline operations, air traffic management operations, and ground operations; (3) measures that influence the demand for air transport; and (4) sustainable aviation fuel (SAF).
- Technological and operational improvements to decarbonizing the sector are universally applicable. But demand-side measures which aim to reduce air travel demand, through higher taxes or a shift to other modes, need to minimize significant negative impacts on connectivity. This is particularly relevant in developing countries, where air transport is already heavily taxed though remains often to be the only feasible means of long-distance travel, given poor railroad and road infrastructure links, and limited availability of fast internet for videoconferences.
- The development of SAF is the most promising mitigation option for realizing high greenhouse gas emissions savings in the medium term and SAF production and deployment is a burgeoning green business opportunity for low- and middle-income countries.

Commitments to Decarbonize Aviation

Aviation is only partially covered by international climate regulation. While greenhouse gas (GHG) emissions from domestic aviation are reported in national emission inventories and are subject to national emission commitments, emissions from international aviation are reported outside of national inventories and remain outside of reduction commitments.[1] Instead, Article 2.2. of the Kyoto protocol assigned the International Civil Aviation Organization (ICAO) as the body responsible for negotiating sector-specific emission reductions for international aviation and for implementing emissions-reduction measures. The Paris Agreement, however, does not mention a role for ICAO in meeting the goal of the Paris agreement while at the same time calling for economy-wide decarbonization under Article 4 (T&E 2018). Until nationally determined contributions (NDCs) become truly economy-wide, including commitments on aviation emissions comes to fruition, emissions reduction efforts remain under ICAO's control.

In 2010, the ICAO assembly agreed to a goal of carbon-neutral growth for aviation from 2020 onwards that was supposed to be met by a basket of measures including technological and operational measures, sustainable aviation fuels (SAFs) as well as market-based measures (ICAO 2019). Since then, the most important piece of ICAO legislation to achieve carbon-neutral growth is arguably the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was adopted by the ICAO assembly in 2016. CORSIA requires airlines to buy carbon offsets or use SAFs to ensure that total carbon dioxide (CO_2) emissions attributable to international aviation remain stable (ICAO 2019). ICAO is currently working on a more ambitious emission reduction goal to replace the current goal of carbon-neutral growth.

At the national level, many countries have set goals for zero or near-zero carbon emissions from aviation by 2050, with recent announcements made by, among other countries, the United States (The White House 2021) and the United Kingdom (UK DfT 2021). Along with others, these countries are incentivizing the transition with pricing measures such as carbon or passenger taxes, emission-trading schemes, and public investment in research and development (ITF 2021).

On the industry side, in October 2021, the International Air Transport Association (IATA), the trade body of the global airline industry, committed to the goal of net-zero aviation by 2050 (IATA 2021), with the emission reductions coming as much as possible from in-sector measures, including new aircraft technology—such as radical new concepts for aircraft shape and energy sources, more efficient operations on the ground and in the air, and SAFs (figure 2.1). A limited role is foreseen for out-of-sector emissions abatements, such as carbon capture and sequestration, and carbon offsets (not discussed in this report).

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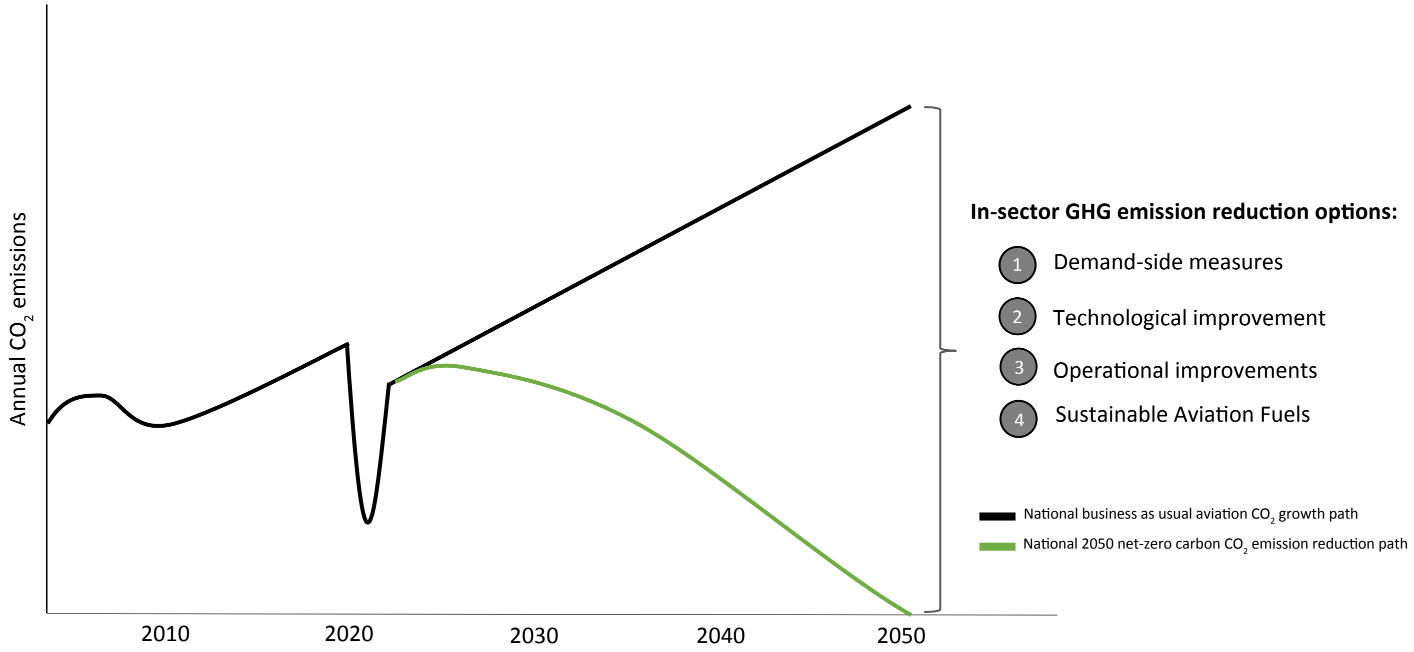
[1] The UNFCCC does not specifically cover emissions from international shipping and aviation. Reporting emissions from international transport is at the discretion of each country. While the International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO) have established emissions reductions targets, only strategies to improve fuel efficiency and demand reductions have been pursued, and there has been minimal commitment to new technologies. For more information, see the IPCC Sixth Assessment Report: Mitigation of Climate Change (IPCC 2022) submitted by Working Group III and approved in April 2022. Report landing page: https://www.ipcc.ch/report/ar6/wg3/; Full report: https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf).

Figure 2.1. Illustrative Business as Usual Development of CO_2 Emissions from Aviation and Net-Zero Carbon Emission Reduction Path Out to 2050, with In-Sector GHG Emission Reduction Options



Source: Original figure produced for this publication.

While carbon offsets can provide a cheap option for stabilizing and decreasing aviation emissions in the short term, solutions within the air transport system itself are needed for deep decarbonization of the global economy. Offsets simply shift the emissions reduction burden to nonaviation sectors, which does not lead to sufficient GHG emissions reductions in the medium to long term.

The following discussion reviews the available literature on the GHG emission reduction potential of demand-side measures, technology-related measures, operational measures, and SAFs.

Demand-Side Measures: Avoid and Shift Strategies

Contrary to the supply-side measures discussed later, demand-side measures do not aim to decrease the fuel efficiency or GHG emissions intensity of air transportation, instead, they aim at decreasing aviation's climate impact by reducing air transport activity. This can be brought about by either suppressing demand or encouraging a shift of demand to other transportation modes or videoconferencing.

AVOID STRATEGIES

"Avoid" strategies primarily aim at suppressing air travel demand through price increases.[2] The expectation is that higher prices will lead to reduced demand for air travel, which in turn leads to reduced air transport emissions. However, the price increases due to a carbon-tax or other price-increasing measures are dependent on the interaction between the price elasticity of demand and income elasticity of demand.[3]

With regard to *price elasticity*, existing studies show that carrier-level elasticities are higher than market-level elasticities, which in turn are higher than elasticities at the national level (significantly less than 1.0 in absolute terms).[4] This can be explained by the availability of better alternatives at the carrier or market level than at the national level.[5] This implies a global price increase of air travel due to a (carbon) tax or similar measures will only lead to a less than proportional decrease in travel. The study also finds that—as expected, given the relatively low number of alternatives—business travelers have a lower price elasticity than leisure travelers.

With regard to the *income elasticity*, the evidence synthesis shows all available empirical studies that account for income yield positive income elasticities, and, "virtually all of these studies estimated income elasticities above one, generally between +1 and +2." (Intervistas 2007). This implies that air travel changes at a higher rate than income changes. This is important because it implies that potential reductions in emissions due to price-induced demand reductions can fast be eliminated if income levels are increasing. In other words, demand for air transport is more strongly influenced by income changes than by price changes (Eurocontrol 2020).

The relatively low air transport demand responses to pricing signals are also highlighted by existing empirical studies that investigate the effect of fuel or CO_2 taxes. In a global analysis, Valdés, Comendador, and Campos (2021) simulated the effect of the immediate introduction of a time-fixed fuel tax of €0.333 per liter (€133 per ton of CO_2) on global aviation emissions. They estimate this tax could reduce emissions by 13 percent in 2050, compared to a do-nothing baseline. For the U.S. domestic passenger market, Pagoni and Psaraki-Kalouptsidi (2018) estimate a fixed carbon price of almost US$300 per ton of CO_2 implemented immediately would be needed to reduce demand enough for emission levels in 2050 to decrease by 50 percent compared to 2005 levels. In a study that focused on lower levels of carbon prices (on the order of US$20 per ton of CO_2), Markham et al. (2018) find no evidence that the existence of such carbon prices in Australia reduced the amount of domestic Australian air travel. In line with these empirical analyses, a recent paper (Eurocontrol 2020), argues, "there is little evidence that taxing aviation per se leads to lower CO_2 emissions; nor do raising fuel prices or ticket prices reduce CO_2 emissions."

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[2] Some debate does occur in the policy arena on the effects of banning (certain types) of short-haul air traffic. Bans can have significant detrimental effects on connectivity if no feasible alternatives exist, and this measure is therefore not discussed further in this report.

[3] While the price elasticity of demand indicates how air travel demand reacts to increases in the price of air travel, the income elasticity indicates how air travel demand reacts to changes in income.

[4] The most recent comprehensive review on air transport elasticities was conducted for the International Air Transport Association by Intervistas (2007). Available online via IATA.

[5] Passengers can more easily switch to a different carrier to reach their destination (carrier level) or switch their departure or destination airport (market level), than switch the country of departure or arrival.

The evidence base shows that very high taxation rates would be required to significantly decrease aviation demand, yet such demand decreases could be recovered quickly as incomes increase globally (see the discussion on aviation taxation in box 2.1). Even worse, high taxes could have significant negative impacts on connectivity, especially in developing countries, where air transport is already heavily taxed, though it often remains the only feasible means of long-distance travel, given poor railroad and road infrastructure links, and limited availability of fast internet for videoconferences.[6]

Box 2.1. Taxation of Aviation

The International Civil Aviation Organization (ICAO) distinguishes between aviation charges and taxes. While charges are levied to cover the costs of providing facilitates and services for aviation, taxes are levied by the government to raise revenues that might (also) be applied to nonaviation purposes (ICAO 2000). Taxes levied in aviation come in different forms, including, but not limited to aviation fuel taxes, ticket taxes, security taxes, and value-added tax (VAT)/sales taxes (ACI 2020). Given their price-raising and demand-suppressing effect, taxes can also be used for environmental reasons.

Likely, the most discussed type of aviation tax in the context of decreasing aviation emissions is the fuel tax. This is because countries do not only usually exempt jet fuel used on their territory for international flights from taxes, but with the exception of 15 countries, governments also do not levy taxes on fuel sold for domestic aviation, with the highest excise tax on jet fuel levied in Hong Kong at 0.70 cent per liter. Countries outside of the Organisation for Economic Co-operation and Development (OECD) with an excise tax on jet fuel include Armenia, Lao People's Democratic Republic, Myanmar, Philippines, Thailand, and Vietnam (CE Delft 2019).

ITF (2021) concisely explains the legal background of fuel taxes for national and international aviation. For domestically used jet fuel, international law does not provide any taxation restrictions. However, as outlined above, few countries currently levy fuel taxes for domestic aviation. In the European Union (EU), a mandatory tax exemption of jet fuel used for EU-domestic aviation is contained in the 2003 Energy Taxation Directive (European Commission 2003). At the time of writing, the EU is discussing an amendment of the Energy Taxation Directive that would end this mandatory exemption, and to implement a minimum tax rate for aviation fuel on intra-EU flights that would be set at approx. €0.4 per liter for the year 2023 (Eurocontrol 2021). For jet fuel used in international aviation, the Chicago Convention exempts jet fuel on board of arriving aircraft from taxation

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[6] In many African and central Asian countries, service providers and operators continue to impose prohibitive duties on air travel. Fees and charges for the use of infrastructure, including taxes, are also particularly high despite the low quality of airport services. Fuel, which represents the airlines' largest cost, is often distributed by cartel-like entities that squeeze cash out of foreign airlines. Moreover, fuel needs to be transported over long distances in many landlocked in these regions—a problem exacerbated by poor infrastructure.
For more information, see the following World Bank (2022) publication: "The COVID-19 Pandemic and African Aviation: Policy Note."

by the destination country, and a 1993 ICAO council resolution stipulates that fuel taken onboard at the point of departure should also be exempt from taxation at the departure country. While ICAO resolutions are not binding, most countries adhere to the 1993 resolution, and the exemption of jet fuel from taxation on international routes is codified in bilateral air service agreements.

CE Delft (2019) conducts a comprehensive analysis to estimate the tax burden for domestic and international aviation in the EU and selected non-EU countries, including ticket taxes, VAT, taxation on aircraft fuel, and environmental-oriented taxes. The study estimates the average per-passenger tax for EU-domestic aviation amounts to approximately €22, and for international aviation to approximately €13. Outside Europe, the highest taxes among the countries are levied in Australia for both domestic and international traffic (approximately €20 and €40 per passenger respectively), with relatively high rates also prevalent in countries such as Mexico, Oman, Armenia, and Bahrain, and for international traffic in Brazil.

Source: Word Bank analysis.

DEMAND SHIFT STRATEGIES

A second potential demand-side measure is to incentivize a shift to other, less carbon-intensive transportation modes, such as high-speed rail or digital communications, such as videoconferencing.[7] There have been successful examples of a partial substitution of short-haul flights by high-speed rail products in both Europe and Asia—for example, between Madrid and Barcelona, Frankfurt and Cologne, Seoul and Daegu, and Tokyo and Sendai—see Zhang, Graham, and Wong (2018), but short-haul traffic has not been substituted at large scale to date. This is because of significant modal shift barriers that include passenger preferences on connecting itineraries requiring an air-rail connection step, lack of seamlessness of those connections, and the required infrastructure investment needed for an expansion of high-speed rail (Finger, Bert, and Kupfer 2014). Zhang et al. (2018) analyze the substitution effect of high-speed rail as a function of transportation distance in East Asia. They find such a substitution effect in markets with travel distances up to 1,000 kilometers, with the most significant effect in short-haul routes below 500 kilometers.

Even if a larger share of short-haul air traffic was switched to high-speed rail, the emissions benefit would remain relatively small. In a recent study, Bleijenberg (2020) estimates that 6 percent to 11 percent of CO_2 emissions of intra-European routes could be avoided, corresponding to 2 percent to 4 percent of emissions of all jet fuel uplifted

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[7] With regard to alternative transportation modes, we limit our scope to high-speed rail as the main competitor for (short-haul) aviation. We note that technologies currently under development, such as the hyperloop system, could potentially emerge as future competitors in some markets. They could, depending on the origin of the energy used in the systems, potentially realize greenhouse gas (GHG) emission benefits compared to air travel (Hirde et al. 2022).

in Europe, if high-speed rail routes were extended to cover all larger cities in Europe. According to the ETC (2018), a shift of one-third of all short-haul flight traffic to high-speed rail globally would lead to a 10 percent emissions reduction in aviation due to the higher share of medium and long-term traffic in global air traffic.

Before the COVID-19 pandemic, the potential for videoconferencing as a substitute for air travel was generally estimated to be low, but this is changing.[8] During the COVID-19 pandemic with air travel impossible or significantly impeded, videoconferencing has played a crucial role in maintaining or building up personal and business relationships. No robust evidence exists, to date, with regard to the degree to which videoconferencing will replace air travel once flying becomes feasible again. A choice experiment for the London air transport market indicates that participants in this experiment might only regard virtual substitutes for business travel as a temporary replacement, and that travelers might return to traveling as soon as safely possible (Manca et al. 2021). Based on results from interview experts, Suau-Sanchez, Voltes-Dorta, and Cugueró-Escofet (2020) indicate interviewees do not expect a radical impact of videoconferencing on air travel post-pandemic, but that videoconferencing and other digital means might reduce the propensity of some executives to fly. At the same time, a recent (September 2021) study, conducted by the World Resources Institute among its staff members, reports an 80 percent increase in staff reporting that business travel reduction is possible, compared to surveys conducted prior to the pandemic (Hernandez et al. 2021). Ultimately, whether the COVID-19 pandemic will lead to a structural change in business travel behavior can only be elicited ex-post.

Technology Measures

Most technological changes to the aircraft and its engines affect GHG emissions through changes in *energy efficiency*. This includes, for example, the use of lightweight materials, aerodynamic improvements, and increased engine efficiency. Some emerging aircraft and engine technologies such as (hybrid-) electric propulsion or hydrogen-powered aircraft enable the use of low-carbon energy, and directly impact the GHG *emission intensity* of aviation.

Energy efficiency in aviation is often approximated by fuel efficiency, that is, the mass of fuel required to produce a unit of output, such as transporting one passenger or one unit of cargo for one unit of distance. Common metrics used are mass of fuel per ton-kilometer (tkm), or mass of fuel per passenger-kilometer (pkm). Fuel efficiency is, among other things, impacted by aircraft and engine technology, the seating density in an airplane, and its load factor. Aircraft technology determines the weight and the aerodynamics, which in turn are important drivers of fuel efficiency. Engine technology affects fuel efficiency through the thermodynamic efficiency and propulsive efficiency of the engine system (with the product of the two called overall efficiency) (NAS 2016). Modern gas turbine engines

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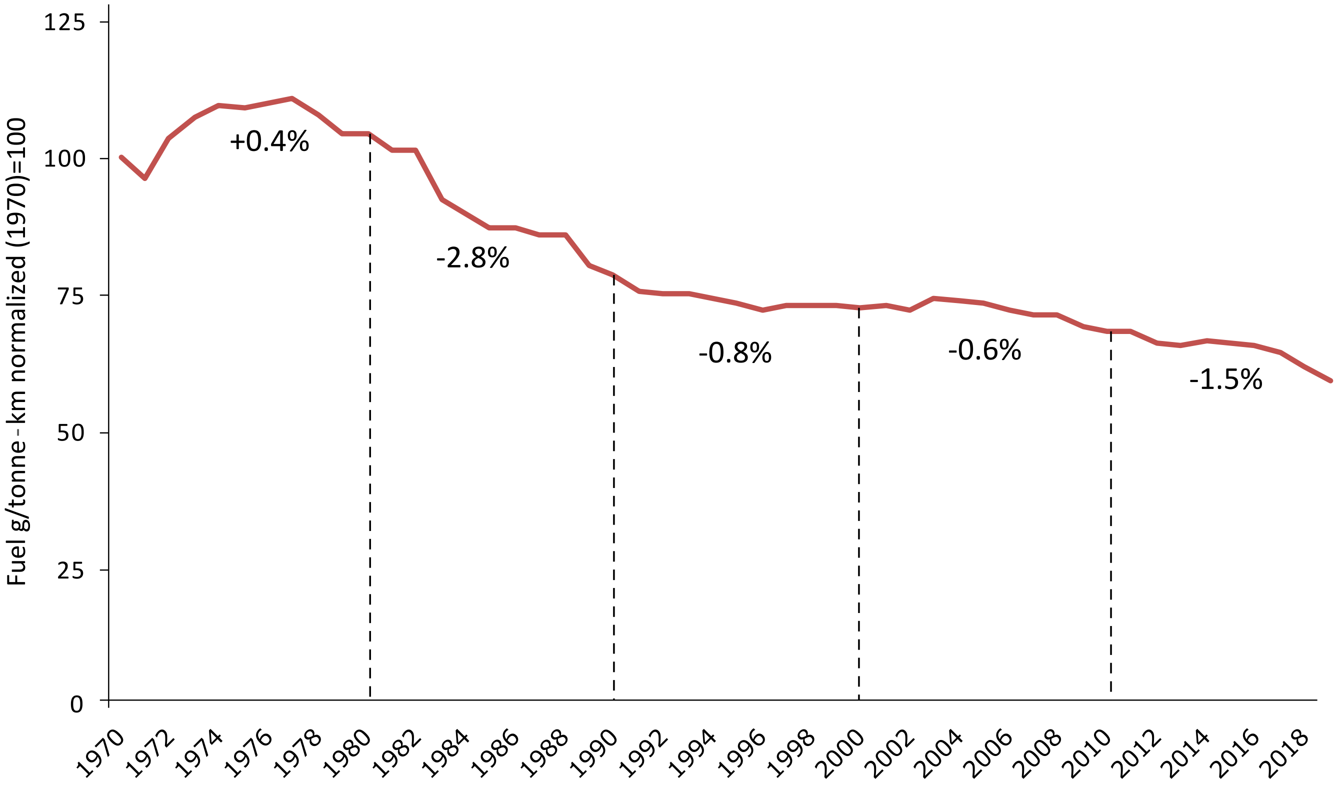
[8] For example, the Energy Transition Commission (ETC) argues, "Videoconferencing could, in principle, also reduce the need for business travel, especially as previously modest adoption of videoconferencing accelerates, quality improves and cost declines. Business travel, however, and the perceived importance of face-to-face contact may well limit the impact on air travel demand, and might not induce more than a 2 percent cut in total aviation emissions."

exhibit an overall efficiency of approximately 40 percent (NAS 2016). Seat density and load factor have an impact on fuel efficiency as the marginal fuel needs for one additional passenger or one unit of cargo is lower than the average fuel requirements, due to the empty weight of the aircraft. (IPCC 1999).

Fuel costs are a major driver of total airline costs, and, therefore, airlines have a strong intrinsic interest to increase fuel efficiency. Moreover, seat density and load factor also have an important revenue component (Holloway 2008) and as such, can be assumed to be optimized to a large extent already.

Historically, new aircraft generations realize higher fuel efficiency than existing ones due to improvements in aircraft and engine technologies. For example, the overall engine efficiency of new aircraft has increased from approximately 30 percent in the mid-1970s to the 40 percent seen to date, with thermodynamic efficiency and propulsive efficiency on average increasing annually by 0.4 percent and 0.3 percent respectively (NAS 2016). The use of lightweight composite materials such as carbon-fiber reinforced plastic has increased in the last 30 years, with the structure of Airbus's most recent new aircraft model, the A350, being made from 53 percent composite material (Bachmann, Hidalgo, and Bricout 2017). Due to these advancements in aircraft and engine technology development, fuel efficiency has significantly increased in the past decade (figure 2.2), with fuel burn per tkm in 2019 approximately 40 percent less than in the year 1970.

Figure 2.2. Fuel Efficiency Development 1970 to 2019



Source: Figure adapted from data obtained from ICCT, based on analysis by Zheng and Rutherford 2020. Percentage changes provided in the figure refer to the average annual change of fuel efficiency in a specific decade.

Table 2.1. Fuel Efficiency and CO_2 Emissions Impact of Select Radical New Aircraft Technologies

Area	Technologies considered	Earliest feasible year of availability for commercial aviation	Fuel efficiency change[a]	CO_2 emissions change[a]
Airframe configuration	Strut-braced wing Double-bubble Blended-wing body	2035 2035 2040	up to 53% up to 56% up to 50%	proportionate to fuel efficiency change
Structure and materials	Morphing wing technology	2030	up to 8%	proportionate to fuel efficiency change
Propulsion technology	Open Rotor Boundary layer ingestion Hybrid-electric propulsion Electric propulsion with battery or fuel cells Hydrogen combustion engines	2030 2035 2030 2035 2035	up to 30% up to 9% not specified not specified not specified	proportionate to fuel efficiency change up to 40% up to 100%[b] up to 100%[c]

Source: Figure adapted from data based on IATA (2019) and Fuel Cells and Hydrogen 2 Joint Undertaking (2020), and complemented by Yutko (2017).
Note: a. Compared to current aircraft of similar size and range. b. When only using renewable energy. c. When only using fully green hydrogen. Some technologies exhibit additional co-benefits besides fuel efficiency/GHG emission savings (for example, air pollution decrease, decreased noise exposure), and/or additional environmental costs (for example, additional noise exposure). See IATA (2019) for details.

An analysis outlined by Kharina, Rutherford, and Zeinali (2016) quantifies the fuel efficiency improvement potential of a set of technological advancements for "conventional"[9] aircraft designs related to the weight of the aircraft, its aerodynamic drag, and engine efficiency (such as, for example, advanced composite materials and composite sandwich construction; low friction coatings; natural and hybrid flow; and advanced turbofan and open rotor engines). The study only accounts for cost-effective options, that is, improvements for which the additional investment (and potentially maintenance) costs are lower than the savings in fuel costs over the lifetime of the airplane. The authors estimate the implementation of such cost-effective fuel efficiency measures in the three domains of structures, aerodynamics, and engines in future aircraft could reduce aircraft-specific fuel consumption by approximately 25 percent and 40 percent by 2024 and 2034, respectively, compared with current state-of-the-art aircraft. These values are in line with estimates provided by the IATA (2019).

IATA (2019) also conducted an assessment of fuel efficiency (and CO_2 emissions) improvements through radical new aircraft technologies in the areas of airframe configuration, structure, and materials as well as propulsion, with the latter comprising both radical new designs for gas turbine engines, and hybrid and fully electric airplane concepts. A radical new aircraft technology not covered by the IATA study is the development of hydrogen combustion engines. For those, estimates on CO_2 emissions savings were taken from a recent study funded by the European Union (EU) (Fuel Cells and Hydrogen 2 JU 2020). The results of the IATA and Fuel Cells and Hydrogen 2 study are summarized in table 2.1.

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[9] "Conventional aircraft" here denotes aircraft with conventional tube and wing design and nonhybrid gas turbine engines.

The 2019 IATA study also points to the significant lead times required for the development and implementation of these radical new aircraft, including mandatory adaptations of the air transport system. Moreover, the study cautions, “while it is very likely that the technical development of these new aircraft concepts could be achieved within the next two to three decades, there are economic and commercial constraints that might delay or even prevent their implementation.” As a consequence, it is estimated that under optimal framework conditions the first radically new airframe concept could enter into service around 2035. Given that aircraft are used for several decades—the average age of an aircraft that retired in 2019 was approximately 23 years[10]—it takes a significant number of years from the entry of service of a novel aircraft generation for this new generation to make a noticeable contribution to fleet-wide fuel efficiency. This implies that even if a radical new aircraft generation that shows a 50 percent fuel efficiency improvement compared to current designs was to enter service in the mid-2030s, it would take an additional 20+ years for these benefits to materialize across the entire fleet. This diffusion gap is also visible in a recent comprehensive analysis of the feasibility of a long-term aspiration GHG emission reduction goal for international aviation published by ICAO in early 2022 (ICAO 2022). Some options exist for bridging this “diffusion gap” through retrofitting the existing fleet by, for example, winglets, riblets, and lightweight cabin furnishing. However, these retrofitting impacts are limited, with fuel efficiency improvement estimates ranging from 6 percent to 12 percent (IATA 2019). Additional fuel savings could be realized utilizing engine retrofitting; however, this measure would not be cost beneficial for airlines without significant (monetary) incentives to do so (Schaefer et al. 2016).

Evans and Schaefer (2013) assessed to which extent the emergence of fuel-efficiency increasing technologies leads to a rebound effect. Such an effect occurs when a more fuel-efficient technology that is introduced drives down marginal costs for a service, which in turn generates additional demand for this service. The authors’ simulations indicate a moderate rebound effect of new aircraft technology, with every 1 percent reduction in aircraft specific energy use leading to a reduction of systemwide energy use of 0.81 percent.

Taking all of the above together, it can be concluded a significant decarbonization potential exists through technological measures, especially in the long term. Impacts in the short term and medium term are constrained by: (1) the long fleet turnover times of 20+ years that will limit the benefits of technological developments, even if those measures could be implemented in new aircraft within the next few years; and (2) the additional research and development efforts still required for more radical design and propulsion concepts.

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[10] Statistics on the average age of airplanes when removed from the global fleet provided by Statista.com. See the data online: “Average Age of Airplanes Removed from the Global Aircraft Fleet from 2005 to 2019, by Aircraft Type.” https://www.statista.com/statistics/622600/average-age-of-jets-when-removed-from-service-by-type/

Operational Measures

Operations pertain to a range of activities, including the flying of the airplane (airline operations), the control and monitoring of the airplane by air traffic management (ATM operations) as well as operational activities at the airport (ground operations). Similar to technological changes, operational measures largely impact fuel efficiency, that is, they aim to decrease fuel use for a given amount of aviation output. Some measures, such as a switch to fixed electrical ground power and preconditioned air can have a direct GHG emissions effect as well.[11]

In the context of the United States, Hileman et al. (2013) attribute the performance gap between designed aircraft energy intensity and actual aircraft energy intensity to the following factors: (1) actual load-factors being lower than 100 percent; and (2) the existence of operational inefficiencies in the area of airplane operations, ATM operations, and ground operations. For ATM operations, the Energy Transitions Commission (ETC) (2018), estimates the fuel efficiency potential of more flexible routing and optimized flow management, minimizing flight distances and decreasing aircraft waiting times on the ground at 5 to 9 percent, depending on the geographical coverage of the improvements.

Kar, Bonnefoy, and Hansman (2010) estimate the total CO_2 reduction potential from operational improvements to amount from 9 to 13 percent. The finding is based on a broader assessment of 11 different operational improvements in the three areas of ground operations, ATM operations, and airline operations, such as the fuel efficiency and emissions-reduction potential of fixed electrical ground power units, single engine taxiing, aircraft queue management, and controlled pushback, flying at optimal cruise levels, continuous descent approaches, optimized flight routes, and lower cruise speeds.

Operational improvements show relatively low total CO_2 emissions reduction potential compared to the size of the decarbonization challenge, at a global level. However, existing estimates are usually based on European or U.S. data, and as such, they might underestimate the efficiency potential in developing countries. For example, with regard to ATM in Africa, the Civil Air Navigation Services Organisation (CANSO), the trade organization of the global air traffic management industry, has identified five key challenges that should be addressed to increase the efficiency and safety of aircraft operations. These challenges range from lack of safety management systems for some air navigation service providers, the lack of appropriate ATM infrastructure, a shortage of financial and human resources, insufficient training, and lack of separation between provision of air navigation services and responsibility (Johari 2019). More specifically, concerning modern ATM infrastructure and operational procedures, Africa is considerably lagging behind (AFI Plan Secretary 2019).

Operational improvements have much shorter development and diffusion times—especially in comparison with many technology related improvements—and can therefore

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[11] See the case study on fixed electrical ground power, published as part of the "Aviation Benefits Beyond Borders" initiative of the commercial aviation industry, represented by the Geneva-based Air Transport Action Group (ATAG): https://aviationbenefits.org/case-studies/fixed-electrical-ground-power/.

be implemented at scale in the short- and medium-run already (Hileman et al. 2013). Many developments and implementation activities are currently ongoing to realize the fuel and emissions benefits of operational improvements in both developed and developing countries. In the United States and the EU, for example, the NextGen system in the United States (Post 2021) and the EU Single European Sky Initiative, or SESAR (Motyka and Njoya 2020) aim to increase airspace capacity, decrease congestion by minimizing detours and optimize aircraft descents.[12] With regard to developing countries, the World Bank Group has set up initiatives to improve operations of the air transport system (see box 2.2).

Box 2.2. GHG Mitigation through Air Transport Operational Improvements: Lessons from World Bank Projects

Airport Operational Improvements

The recent series of Caribbean Regional Air Transport Connectivity Project targets operational improvements with meaningful climate change mitigation impacts. The Port-au-Prince Toussaint Louverture Airport (PAP) taxiway improvement project in Haiti would result in a reduction in greenhouse gas (GHG) emissions due to the taxiway system enhancements, which provide an operational savings of about 5 minutes per aircraft turnaround. Specifically, the proposed taxiway improvements for PAP are anticipated to reduce aircraft-related GHG emissions by about 95 kilograms of carbon dioxide (CO_2) per aircraft turnaround. At current demand levels, this represents a reduction of about 1.25 million kilograms of CO_2 annually. These GHG emissions reductions are based on the jet fuel consumption savings associated with reduced aircraft arrival and departure delays (due to lower runway occupancy times) and reduced taxiing distances.

In 2018, with the World Bank's support a green and environmentally friendly airport was built in Shangrao in China's Jiangxi Province. The project demonstrated the feasibility of developing and operating an environmentally sustainable airport and improved regional connectivity, thus facilitating the growth of tourism for employment and poverty reduction. Shangrao Sanqingshan Airport was recognized as a green airport, featuring energy efficient architecture and airport layout design, ground aircraft auxiliary power unit, energy efficient equipment and infrastructure, stormwater reuse system, and ground source heat pump system. It was awarded the Excellence in Design for Greater Efficiencies (EDGE) green building certificate in early 2019. According to the EDGE evaluation, the airport achieved 24 percent energy savings, 42 percent water savings, 38 percent building materials embodied energy savings, and 24 percent operational CO_2 savings.

ANSP Operational Improvements

The Saint Lucia–Caribbean Regional Air Transport Connectivity Project[a] would result in a reduction in GHG emissions at Hewanorra International Airport (UVF) due to the benefits associated with the new instrument landing system (ILS) for

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[12] Definition for "continuous descent" provided by Skybrary, online: https://www.skybrary.aero/index.php/Continuous_Descent.

runway including a reduction in flight arrival delays, diversions to other airports, and cancelations during poor weather conditions. The benefit would derive from reduced aircraft arrival weather minima associated with the advanced guidance capabilities of the ILS (that is, aircraft would be able to safely land in conditions with lower cloud ceiling and less visibility). The energy-efficient equipment and lighting to be procured would further contribute to climate change mitigation and help achieve the Port of Spain Declaration of 2014, which aims to reduce regional CO_2 emissions by 40,000 tons per year through performance-based navigation (PBN) implementation by December 2016.

Source: World Bank analysis.
Note: a. Read more about the project in the published report, available online: https://documents1.worldbank.org/curated/en/862751590976869165/pdf/Saint-Lucia-Caribbean-Regional-Air-Transport-Connectivity-Project.pdf.

Sustainable Aviation Fuels

Given the limited potential of the above alternatives to address aviation's decarbonization challenge, a wide consensus has emerged that emissions abatement needs to come from low carbon fuels. The most immediate action to achieve carbon-neutral flying is the investment in, and rapid scale-up, of SAF production and use. Studies have demonstrated that with innovative regulatory mechanisms and clear demand signals, sufficient sustainable feedstocks are available to meet the projected jet fuel demand for global aviation in 2030 (WEF 2020).

According to the "Alternative Fuels: Questions and Answers" page on the ICAO website (see: https://www.icao.int/environmental-protection/Pages/AltFuel-SustainableAltFuels.aspx), *sustainable aviation fuels* is the term used by the aviation industry to describe a set of fuels that can be sustainably produced and generate lower CO_2 emissions than conventional kerosene on a life-cycle basis. In the context of ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), SAF is defined in Annex 16, Volume IV, as a renewable or waste-derived aviation fuel that meets a set of CORSIA sustainability criteria.

Feedstocks for SAF include, but are not limited to, waste and vegetable oils, starchy and sugary crops, lignocellulosic biomass such as energy grasses, short-rotation trees, and agricultural and forestry residues, municipal waste, and waste gases. These materials can be converted into jet fuel through different conversion technologies. SAF can also be produced via so-called power-to-liquid technologies, in which green hydrogen produced in an electrolyzer using renewable electricity and water is synthesized with carbon dioxide/carbon monoxide (CO_2/CO) to hydrocarbons and then, finally, converted into SAF (Schmidt et al. 2020). The CO_2/CO needed for the process can be sourced as waste gases from industrial activities, from the atmosphere by direct air capture, or via biomass gasification (Dietrich et al. 2018, Isaacs et al. 2021).

SAF is chemically similar enough to conventional, petroleum-derived jet fuel they can be blended and used with the existing aircraft engine and fuel system. The maximum allowed blending percentage is specified in the fuel certification process by ASTM International (formerly known as the American Society for Testing and Materials). As of December 2021, nine conversion pathways have been certified by ASTM. These pathways are listed in table 2.2 with their maximum blending percentage and year of approval, and a schematic overview of these pathways is available as figure A.1 in appendix A. Tests are ongoing to establish if higher blending percentages up to pure SAF usage are compatible with aircraft engine and fuel systems—see, for example, Airbus (2021). The term "sustainable" in SAF implies these fuels have to satisfy a set of sustainability criteria.

Table 2.2. Overview on ASTM–International-Approved SAF Production Pathways

Fuel	Approved feedstocks	Year of	Approved blending percentage
Fischer-Tropsch synthetic paraffinic kerosene (FT–SPK)	Synthesis gas (syngas) from the gasification of biomass, coal and natural gas, or other industrial processes	2009	50%
Hydroprocessed esters and fatty acids, synthetic paraffinic kerosene (HEFA–SPK)	Lipids that come from plant and animal fats, oils, and greases (FOGs)	2011	50%
Hydroprocessed fermented sugars to synthetic isoparaffins (HFS–SIP)	Sugars	2014	10%
Fischer-Tropsch synthetic paraffinic kerosene with aromatics (FT–SPK/A)	Synthesis gas (syngas) from the gasification of biomass, coal and natural gas, or other industrial processes	2015	50%
Alcohol-to-jet synthetic paraffinic kerosene (ATJ–SPK)	Ethanol and isobutanol from any source	2016	50%
Lipid coprocessing	Lipids (plant oils and animal fats)	2018	5%[a]
Catalytic hydrothermolysis synthesized kerosene (CH–SK, or CHJ)	Lipids that come from plant and animal fats, oils, and greases (FOGs)	2020	50%
Hydroprocessed hydrocarbons, esters, and fatty acids, synthetic paraffinic kerosene (HC–HEFA–SPK)	Bio-derived hydrocarbons, fatty acid esters, and free fatty acids, currently only recognized source *Botryococcus braunii*	2020	10%
FT biocrude coprocessing	Fischer-Tropsch (FT) derived biocrude feedstocks	2020	5%[a]

Source: The blending requirement for coprocessed SAF has a substantially different meaning than for other SAF, as the fossil fuel and SAF are produced at the same time in a coprocessing approach. We also note that the blending limitations for SAF are a function of the properties of the specific type of SAF compared to the required properties in order for the blended fuel to meet the jet fuel specifications. Generally, the more dissimilar the properties between a type of SAF and conventional jet fuel, the lower the allowed blending percentage.

The possible contribution of SAFs to decarbonizing aviation results largely from their potentially lower GHG emissions intensity per unit fuel.[13] The climate benefit of SAF stems from the displacement of fossil carbon with biogenic or recycled carbon: Plants absorb carbon dioxide during photosynthesis and this CO_2 is then released back into the atmosphere during fuel combustion, thereby closing the carbon cycle and keeping CO_2 atmospheric levels "constant." On the contrary, the CO_2 sequestered in crude oil has been absorbed from the atmosphere millions of years ago, and its release back into the atmosphere increases atmospheric CO_2 concentrations. Recycled carbon (for example, fermentation of gases rich CO first to alcohols, and then to SAF) can provide a climate benefit due to the avoidance of additional CO_2 emissions from virgin crude oil usage. Direct CO_2 air capture can be interpreted as another form of carbon recycling, and the CO_2 captured can be used in combination with renewable electricity to produce liquid hydrocarbons. Appendix A provides more detail on the GHG emission performance of SAFs.

While the CO_2 combustion and the CO_2 and non-CO_2 emissions of sustainable aviation fuels for the other life-cycle steps have been extensively studied, less evidence is available about the non-CO_2 combustion-related climate impacts of SAF. A recent study (Voigt et al. 2020) reports the finding of an at-altitude flight campaign in which exhaust and contrail characteristics were measured by either burning standard jet fuel or a blend of conventional jet fuel and low-aromatic SAF. The study finds that contrails from the burning of the SAF blend have less soot and fewer and larger ice crystals, and that the warming from these contrails was lower than those produced from conventional jet fuel burning. The authors argue, "meaningful reductions in aviation's climate impact could therefore be obtained from the widespread adoption of low aromatic fuels." However, an earlier study by Caiazzo et al. (2017) simulates changes in contrail formation for the United States when conventional jet fuel is replaced with paraffinic sustainable aviation fuels. They find two competing effects: On the one hand, the relatively high water emissions index of paraffinic SAF leads to an increase in contrail occurrence, while the larger diameter crystals at lower number concentrations lead to a reduction in contrail optical depth and albedo. Overall, these authors estimate the net change in contrail radiative forcing ranges from -4% to +18%.

To summarize, in order to decarbonize aviation, a mix of measures is required. Within this basket of measures, SAFs will need to play a major role given they are the only option that can generate significant GHG emissions reduction in the medium term.

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[13] Sustainable aviation fuel (SAF) use can have a relatively small impact on fuel efficiency as well. See EASA (2020).

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Chapter 3: Sustainable Aviation Fuels' Contribution to Decarbonizing Aviation in the Short Term, and Out to 2050

Key Messages from Chapter 3

- Production volumes of sustainable aviation fuel (SAF) and offtake agreements to the year 2025 are concentrated in OECD countries, with their production shares ranging from 92 percent to 98 percent. The low SAF production share of non-OECD countries sharply contrasts with their share in total jet fuel burn, which in 2018 totaled approximately 42 percent.

- The SAF feedstock potential in non-OECD countries is estimated to be equivalent to a production of approximately 510 million tons of SAF, out of which approximately two-thirds (345 million metric tons) could come from nonfood feedstocks.

- Diffusion modeling out to the year 2050 for high scenarios shows that SAF volumes are forecasted to reach 331 million metric tons. This accounts for 72 percent of the total forecasted jet fuel demand in 2050, leading to greenhouse gas (GHG) emissions reduction of 57 percent below business as usual growth.

- Combining technological and operational improvement with large-scale deployment of SAF can reduce life-cycle GHG emissions to approximately 279 to 477 million tons, which is up to 78 percent lower than the total CO_2 emissions for 2050. Opportunities for filling the gap to net-zero emissions by 2050—outside of what is modeled in this report—lie in further decreasing the SAF GHG emission intensity by, for example, increased use of 100 percent fossil-carbon-free power to SAF technologies, or by the limited use of carbon offsets.

- SAF-specific marginal abatement cost curves for the years 2030 and 2050 show that for a highly mature and low-cost feedstock pathway such as hydroprocessed esters and fatty acids (HEFA) waste oils, marginal abatement costs could be negative by 2030.

- Reaching projected SAF production volumes will require annual greenfield plant investment in the high scenario which peaks at approximately US$125 billion. While that might be beyond the reach of developing countries without assistance, decarbonization of aviation through the scale-up of SAF is relativity cheaper compared with historical investment in renewables in the energy sector.

- Countries can improve the financial viability of SAF production through market-based measures, mandates, and cost-related measures combined with increasing usage of climate financing building on past experiences in the biomass and bioenergy sector in general.

SAF Production Announcements

Between 2012 and March 2022, 171 different companies posted 320 separate sustainable aviation fuel (SAF) production announcements, a number based on an in-house database on active SAF plants, SAF plants in construction, and announced SAF projects in order to develop a market outlook for SAF out to the year 2025.[1] An announcement in the database is defined as a specific biorefinery project (with each entry representing a separate SAF project). Defunct facilities are kept in the database, but are coded separately. The database contains information on the company, location of the plant, conversion technology, feedstocks, and announced or estimated SAF production capacity.

For this study, the announcements have been classified into two categories:

1. Those with an explicit and quantified target to produce SAF.
2. Those that mention an intention to produce SAF as a coproduct, but which do not disclose a production target.

For the latter, SAF production capacity was estimated considering the reported overall fuel production capacity and assumption on conversion process-specific jet-fuel ratios (see table 3.1).

Table 3.1. Assumed Jet-fuel Ratios, by Process Technology

Process	Low range	High range	References
FT–SPK	43%	73%	Zang et al. (2021); Tanzil et al. (2021[a])
HEFA–SPK	14%	67%	Pearlson et al. (2012); Pereira et al. (2017); Tanzil et al. (2021[a])
ATJ–SPK	54%	79%	Tanzil et al. (2021[a])
CH–SK	32%	41%	Eswaran et al. (2021); Pereira et al. (2017); Tzanetis, Posada, and Ramirez (2017)
Lipid coprocessing	7%	16%	Kwasniewski (2016); Tanzil et al. (2021[b])

Source: Original calculations produced for this publication, based on the references noted in the table.
Note: Jet fuel ratios show the volumetric share of SAF in the total output slate of a biorefinery that uses a certain conversion technology. FT–SPK = Fischer–Tropsch synthetic paraffinic kerosene; HEFA–SPK = hydroprocessed esters and fatty acids, synthetic paraffinic kerosene; ATJ–SPK = alcohol-to-jet synthetic paraffinic kerosene; CH–SK = catalytic hydrothermolysis synthesized kerosene.

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[1] The database is maintained by the University of Hasselt. Earlier versions of this database have informed analyses and policy-decisions at the Committee Aviation Environmental Protection of the International Civil Aviation Organization.

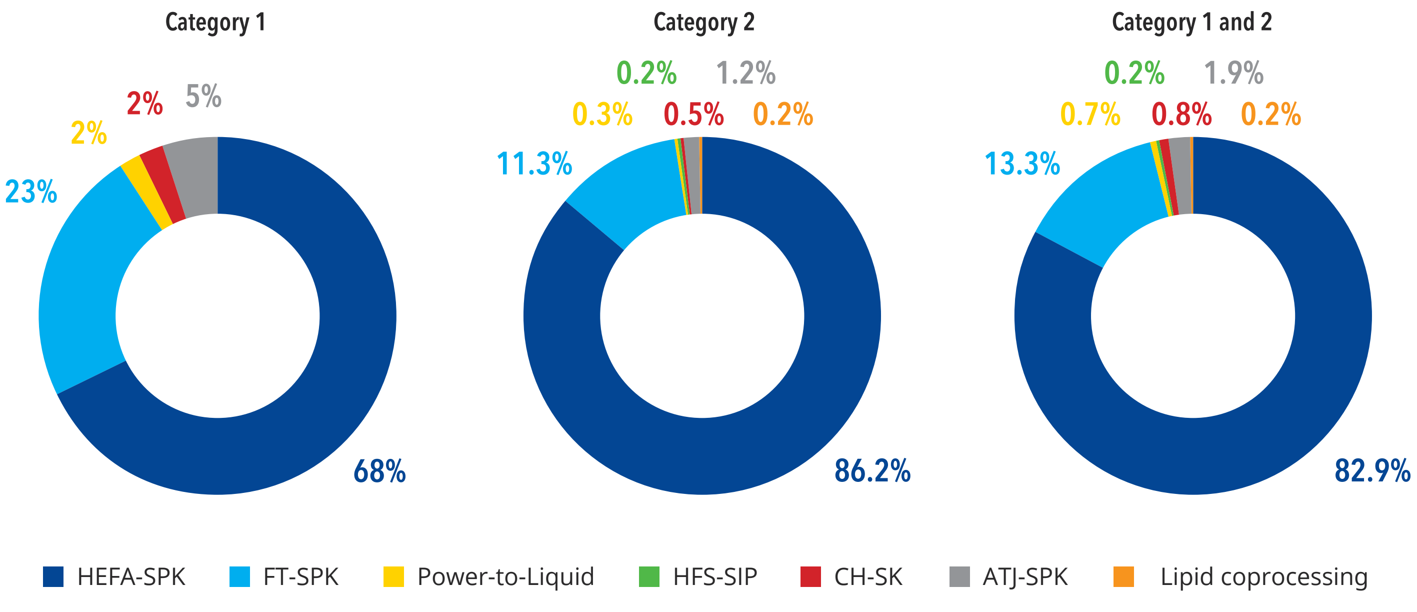
Table 3.2 shows the sum of announcements by year and category from 2022 to 2025. Note that for category 2 SAF, a range based on the assumptions from table 3.1 is shown. For comparison purposes, the Air Transport Action Group (ATAG) expects the year 2025 fuel burn to reach close to 300,000 kilotons, so the maximum estimated replacement share of conventional jet fuel by SAF in 2025 is approximately 7.5 percent. Figure 3.1 shows that for both category 1 and category 2 facilities, hydroprocessed esters and fatty acids (HEFA) forms the dominating technology, accounting for more than three-fourths of the volumes of running or announced production in category 1 and category 2 facilities, with Fischer–Tropsch accounting for most of the remaining volumes.

Table 3.2. Annual SAF Production 2022 to 2025 Based on Company Announcements, by Category

Year	Category 1 SAF production	Category 2 SAF production (kilotons)	Sum total (kilotons)
2022	1,447	1,935 – 11,286	3,382 – 12,733
2023	1,854	2,285 – 14,116	4,139 – 15,969
2024	4,229	1,095 – 16,641	5,323 – 20,870
2025	4,703	878 – 16,751	5,581 – 21,454

Source: Original calculations produced for this publication.
Note: Category 1 production is directly taken from the announcements. For category 2 production, a range is estimated based on the product slates from table 3.1.

Figure 3.1. Announced SAF Production in 2025, by Conversion Technology



Source: Original figure produced for this publication.
Note: SAF volumes are based on announcements of fuel producers for category 1 facilities. For category 2 facilities, the pie chart is based on the high jet share from table 3.1. HEFA–SPK = hydroprocessed esters and fatty acids, synthetic paraffinic kerosene; FT–SPK = Fischer–Tropsch synthetic paraffinic kerosene; HFS–SIP = hydroprocessed fermented sugars to synthetic isoparaffins; CH–SK = catalytic hydrothermolysis synthesized kerosene; ATJ–SPK = alcohol-to-jet synthetic paraffinic kerosene.

Scenario Construction and SAF Projection Approach Out to 2050

Given the position of SAF in its technology life cycle (ascent phase), we model the SAF ramp-up as an evolutionary process in which a new technology (SAF) diffuses through the market and gradually replaces the existing technology (conventional, crude-oil derived jet fuel). Diffusion models have been used widely in the past to model and forecast the demand for emerging energy technologies (Ang and Ng 1992; Höök et al. 2011; Morrison et al. 2016). These models assume an S-shaped growth curve with increasing growth rates up to an inflection point after which growth rates are decreasing until saturation of the market. The several types of diffusion equations available differ, among other things, with regard to their functional flexibility and the degree of exogenous assumptions needed. A brief review of the main features of these diffusion models can be found in Ang and Ng (1992).[2]

Similar to other emerging energy technologies, such as road-transportation biofuels, wind, and solar energy, SAF uptake—and the associated greenhouse gas (GHG) emissions reductions—will be strongly influenced by policies (for examples, see Ebadian et al. 2020; Lewis and Wiser 2007; Sahu 2015). Options include market-based measures (carbon pricing, cap and trade systems, offsetting systems), cost-related measures (feedstock subsidies, loan guarantees, capital grants), and SAF blending and uptake mandates (see the discussion on “Incentives for SAF Production and Use” in chapter 4 for details).

We account for the influence of policies by constructing three SAF scenarios as shown in table 3.3. These scenarios differ with regard to the following: (1) the type of facilities accounted for (facilities with or without a dedicated SAF production target); and (2) the realization share (SAF entering the market as a percentage of the raw announcements), the jet fuel distillation ratio (actual for existing plants, low or high as per technology shown in table 3.1 for planned plants), and the assumed GHG emission reduction per unit of SAF.

Table 3.3. SAF Scenario Description

Scenario	Type of facilities accounted for	Jet-fuel distillation ratio	Realization share	GHG emission reduction per unit SAF[a]
Low	Cat 1 only	As announced	25%	50%
Mid	Cat 1 & Cat 2	As announced for Cat 1,	50%	65%
High	Cat 1 & Cat 2	low for Cat 2	75%	80%

Source: Original calculations produced for this publication.

Note: a. Compared to conventional, petroleum-derived jet fuel whose life-cycle emissions are set at the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) baseline of 89 grams of carbon dioxide per megajoule (gCO_2e/MJ) (ICAO 2019).

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[2] We select the logistic model as market equation due to its widespread used in the literature for similar demand (forecasting) problems (Cai et al. 2016; Höök et al. 2010; Höök et al. 2011; Mohamed and Bodger 2003).

The scenario definitions allow estimating SAF volumes and associated GHG emission reductions for a space of outcomes driven by more pessimistic or optimistic assumptions on the market development of SAF and its associated emission impacts. As such, the low scenario in which only companies that have already announced the amount of SAF they want to produce are included, and for which the large majority of production announcements are assumed to fail to be realized, is representative of development of a market in which SAF production does not receive significant policy support. GHG emissions per unit SAF are assumed to be higher than in the other scenarios, as this lack of policy support might impede the expansion of the SAF portfolio into lower emissions, but higher-cost feedstock-to-fuel pathways (for example, energy grasses or power-to-liquid pathways). At the other end of the scenario spectrum, the high scenario assumes high realization rates for all facilities that plan to produce SAF (irrespective of whether these facilities have an explicit SAF target or not), the highest feasible SAF share in total finished fuel output and high GHG emission reductions per unit of SAF.[3] The GHG emissions reduction per unit SAF in table 3.3 are derived from the emission values developed at the International Civil Aviation Organizaiton (ICAO) within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), with the low scenario representing a mix of SAF with relatively lower GHG emission reduction potential (50 percent), rising to 80 percent in the high scenario. For perspective and as examples, an 80 percent emission reduction could be achievable with waste oil hydroprocessed esters and fatty acids (HEFA), or the use of lignocellulosic biomass in a Fischer–Tropsch (FT) or alcohol-to-jet (ATJ) process, and a 50 percent emission reduction with a mix of waste oils and vegetable oil HEFA, and sugar-based ATJ process.

We used the scenario-specific time series data derived from the short-term announcements to inform the diffusion model: Equation (1) shows the formula in the logistic model used:

$$y(t) = \frac{S}{1 + a \cdot A^{-b \cdot t}}$$

with ***y(t)*** as the expected SAF production by the year ***t***, ***S*** the asymptote of the model (saturation level), and ***a***, ***A*** and ***b*** constant parameters of the model. We set the asymptote ***S*** at the expected mid-growth total jet fuel demand in 2050 as forecasted by ATAG (2020). The other parameters were estimated by data fitting by minimizing the squared errors. The fitting requires at least 10 historical data points and the resulting model is suitable for medium- and long-term projections (Hanke and Wichern 2010). The data used for the fitting exercise was generated by using the scenario definitions outlined above. We constructed three SAF volume time series out to 2025 (one each for the low, mid, and high scenarios) and fit the logistic model to this data.

The goodness of the fitting exercise was measured using the coefficient of determination ***(R^2)*** as stated elsewhere (see Posch, Grubler, and Nakicenovic 1988). The ***R^2*** estimated for the low scenario was 0.94 and 0.97 for both mid and high scenarios.

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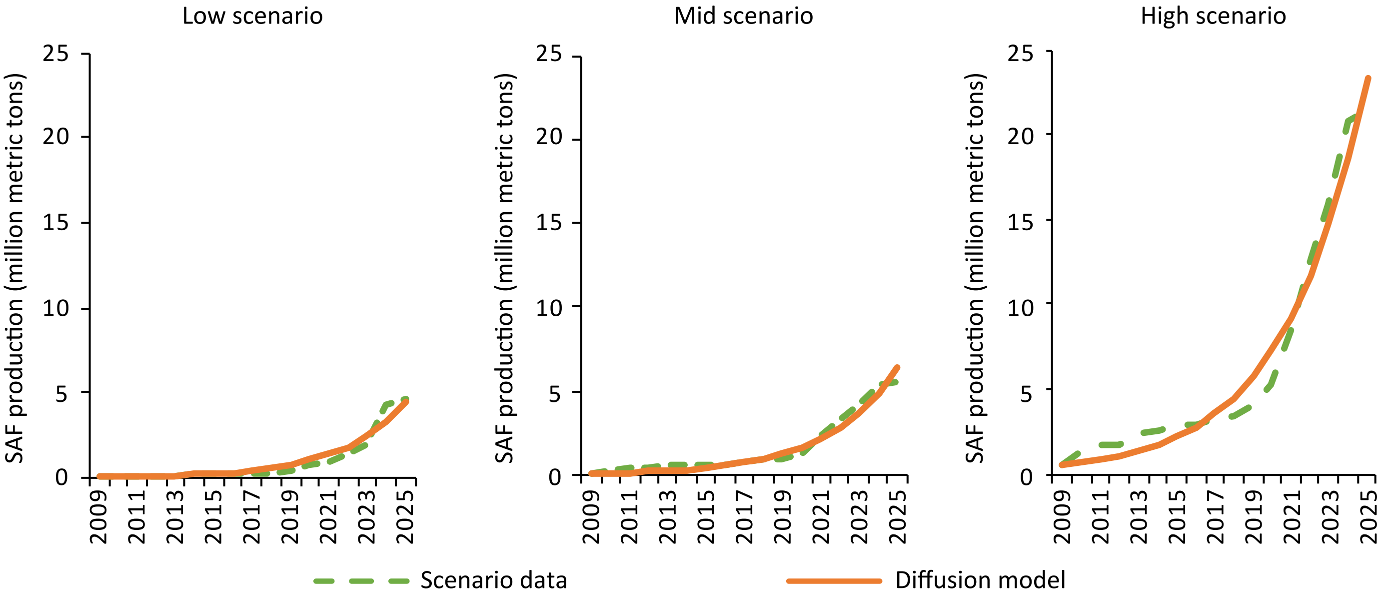
[3] The GHG emission reduction rates assumed are motivated by the lowest relevant GHG emission reduction allowed under both the United States Renewable Fuels Standard and the European Union Renewable Energy Directive II for our low scenario, the emission reduction per unit fuel estimated by Staples et al. (2018) for our mid scenario, and by low GHG emission intensity SAF types from the CORSIA list for our high scenario.

Figure 3.2. Fitting of Logistic Model to Scenario Data Out to 2025



Source: Original figure produced for this publication.
Note: The scenario data out to 2025 (dashed green lines) was generated using the scenario assumptions outlined above. This data was used to estimate the parameters a and b of the logistic equation. The resulting SAF volumes are shown as the solid orange lines, per scenario.

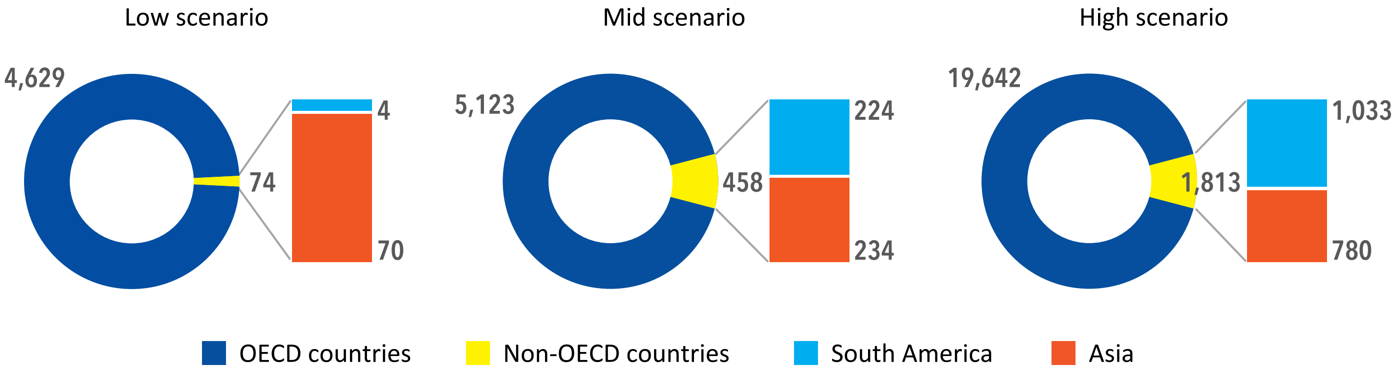
Figure 3.2 compares the diffusion model results to the scenario data used for the fitting of the diffusion equation.

Analysis of the spatial distribution of SAF production volumes shows that in all three scenarios it is concentrated in the Organisation for Economic Co-operation and Development (OECD) countries, with their production shares ranging from 92 percent to 98 percent (figure 3.3). For the high scenario (with the highest overall SAF volume), Asia and South America account equal for the remaining 2 percent to 8 percent of non-OECD share. This low SAF share of non-OECD countries in the short-term SAF scenarios is in sharp contrast to their share in total jet fuel burn, which in 2018 totaled approximately 42 percent (IEA 2021).

With no detailed information available on expected feedstock sourcing, it is difficult to distinguish between feedstock sourced from developed and developing countries in our analysis. However, developing countries play an important role in providing feedstock for current road transportation biofuels. For example, in the European Union (EU), 59 percent of the feedstock used for biodiesel in the year 2018 originated from outside the EU, with Indonesia, Malaysia, and Argentina the largest non-EU feedstock providers (European Commission 2020). Moreover, as shown in the section, "SAF Production Challenges and Opportunities in Developing Countries" later in this chapter, a significant SAF feedstock potential is emerging in developing countries as well.

Figure 3.3. SAF Production in 2025, by Scenario, OECD and Non-OECD Countries

Kilotons



Source: Original figure produced for this publication.

The magnitude and distribution of SAF offtake agreements made publicly available by ICAO[4] show the dominance of the OECD region. As of March 2022, airlines and intermediate entities have committed to buying approximately 19,163 kilotons of SAF; this accounts for approximately 89 percent of the announced SAF production capacity (category 1 and category 2). Nearly all (96 percent) of the offtake agreements have been made from companies based in OECD countries, which indicates the challenge for companies based in developing countries to secure SAF volumes.

SAF Production Out to 2050, and Associated GHG Emissions Reductions and CAPEX Requirements

Diffusion modeling out to the year 2050 for the low, mid and high scenarios shows that SAF volumes are forecasted to reach approximately 108 million metric tons, 216 million metric tons and 331 million metric tons respectively (figure 3.4). This accounts, respectively, for 23 percent, 47 percent, and 72 percent of the total forecasted jet fuel demand in 2050.[5] Translating these SAF replacement rates into GHG emission reductions, figure 3.5 depicts historical and forecasted GHG emissions of aviation (accounting for life-cycle GHG emissions with the exception of non-CO_2 jet fuel combustion emissions) for the case of complete coverage of jet fuel demand by crude oil-derived kerosene.[6] In the most optimistic case (the high scenario), GHG emissions reduction can be stabilized

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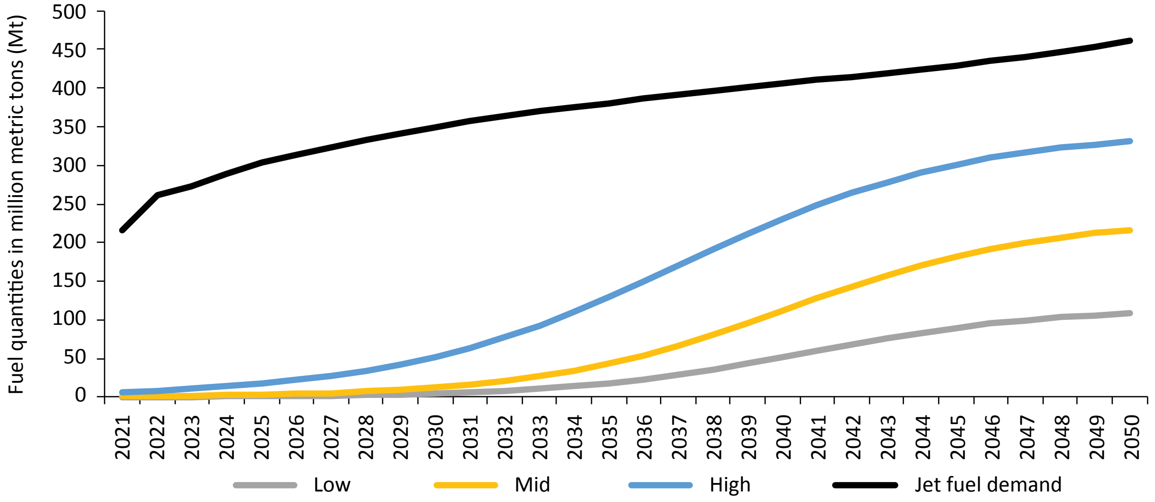
[4] Details available online, via ICAO: https://www.icao.int/environmental-protection/GFAAF/Pages/Offtake-Agreements.aspx.

[5] As mentioned above, WEF (2020) estimated nonfood crop based SAF feedstock availability to be around 500 kilotons SAF-equivalent metric tons, which is significantly higher than the feedstock demand estimated here.

[6] The jet fuel demand projection is taken from Air Transport Action Group's "continuation of current trends" scenario (ATAG 2020), which assumes a 3 percent traffic growth per annum on average out to 2050, a continuation of current aircraft development cycles and performance with a gradual introduction of next generation of tube-and-wing concepts into the fleet from the early 2030s, but no deployment of radical new aircraft concepts, and a continuation of historical operational and load factor improvements. This is compared to life-cycle emissions from the three SAF scenarios, in which crude-derived kerosene is partially displaced by SAF over time. The underlying data is presented in table 3.4 by scenario in five-year steps.

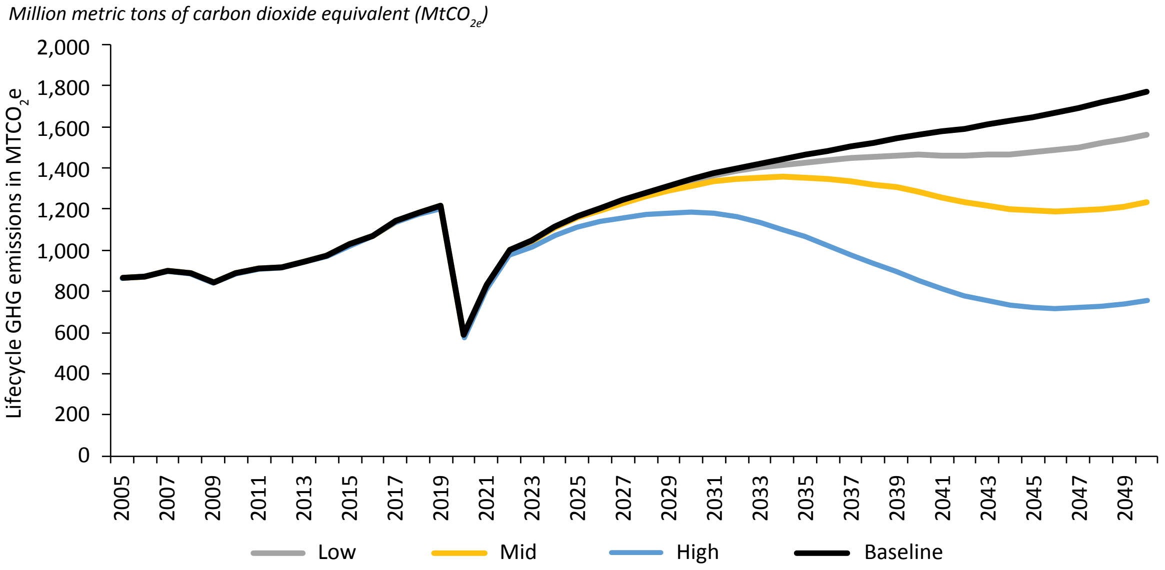
at pre-COVID levels in the 2020s and be reduced to around 2010 levels due to the large-scale use of SAF. Compared to 2050 emissions in the continuation of the current trends scenario, emissions can be reduced by up to 57 percent. Note the high reduction estimate is based on optimistic assumptions about SAF projects' success rates, and on a low GHG emission intensity per unit SAF produced, both of which will require significant investment and policy incentives to achieve.

Figure 3.4. SAF Production Projection, by SAF Scenario, out to 2050, Compared to Projected Jet Fuel Demand



Source: Original figure produced for this publication.
Note: Total jet fuel demand (black curve) taken from the "continuation of current trends scenario." See ATAG (2020).

Figure 3.5. Life-Cycle GHG Emissions Due to the Use of SAF Compared to a Petroleum-Derived Baseline Out to 2050



Source: Original figure produced for this publication.
Note: The baseline is derived from the "continuation of current trends' fuel demand projection by the Air Transport Action Group out to 2050 (ATAG 2020), and assumes zero SAF usage and conventional, petroleum-derived jet fuel with a life-cycle GHG emissions intensity of 89 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) of fuel. No adjustments have been made for the slightly higher energy density of SAF compared to conventional jet fuel. The green area depicts the range of GHG savings.

Table 3.4. SAF Volumes by Year and Scenario, and Associated GHG Emissions Reduction Compared to a Baseline, Where the Complete Jet Fuel Demand Is Satisfied by Petroleum-Derived Jet Fuel

Kilotons (kt) and million metric tons (Mt)

Year	Low		Mid		High		Conventional jet fuel baseline	
	SAF (kt)	CO_2e reduction[a]	SAF (kt)	CO_2e reduction[a]	SAF (kt)	CO_2e reductiona	Jet fuel demand (kt)	CO_2e (Mt)
2025	1,107	0.2%	3,220	0.7%	17,537	4.6%	303,510	1,167
2030	4,679	0.7%	12,493	2.3%	52,442	12.0%	349,954	1,346
2035	17,964	2.4%	43,377	7.4%	129,430	27.2%	380,653	1,464
2040	51,430	6.3%	111,551	17.8%	230,602	45.4%	406,378	1,562
2045	89,743	10.5%	182,435	27.7%	300,891	56.1%	428,866	1,649
2050	108,218	11.7%	216,435	30.5%	331,046	57.4%	461,091	1,773

Source: Original table produced for this publication.

Note: a. Carbon dioxide equivalent (CO_2e) emission reductions are computed by comparing total GHG emissions to satisfy total jet fuel demand in each year when partially satisfied with SAF compared to a baseline in which total demand is fully satisfied by petroleum-derived jet fuel.

The baseline is derived from the "continuation of current trends" fuel demand projection by the Air Transport Action Group out to 2050 with a compound annual growth rate (CAGR) of revenue passenger-kilometers (RPKs) of 3 percent (ATAG 2020), and assumes zero SAF usage and conventional, petroleum-derived jet fuel with a life-cycle GHG emissions intensity of 89 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) of fuel. No adjustments have been made for the slightly higher energy density of SAF compared to conventional jet fuel.

By 2050, SAF production under the low and high scenarios reaches 4.6 and 14.3 exajoules (EJ) respectively. Some estimations indicate that primary bioenergy availability by the same year could reach about 41 EJ and 510 EJ respectively, under the most pessimistic and optimistic assumptions. These values fall to 14 EJ and 330 EJ when considering exploitation efficiency (Staples et al. 2018). Thus, feedstock availability, as a whole, will not necessarily represent a drawback in the development of the future SAF production industry as long as sufficient priority is given to using these feedstocks for aviation compared to other purposes. However, the feedstock portfolio for SAF production is expected to change sharply as production capacity increases. In the short-term, HEFA is forecasted to contribute greatly to total SAF production; however, given the limitations on lipid feedstocks with regard to availability and price, other feedstocks—such as municipal solid waste (MSW), sugary crops, and lignocellulosic biomass—start playing a bigger role in the feedstock portfolio over time.

Potential emission savings from technology and operational changes pale in comparison to SAF diffusion scenarios (figure 3.6).[7] The left side of the figure (panel a), combines SAF usage scenarios with emission savings from hybrid/electric aircraft for short range flights in the less than 100 passenger segments entering the fleet in the late 2030s, and operational improvements beyond historical trends (the "pushing tech and ops" scenario). The right side of figure 3.6 (panel b), combines SAF usage scenarios with even higher levels of ambition with regard to technological change, where in addition to the

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[7] We account for two additional technological and operational scenarios developed elsewhere (ATAG 2020) that push technological development beyond the further improvement of classical tube-and-wing, kerosene-powered aircraft.

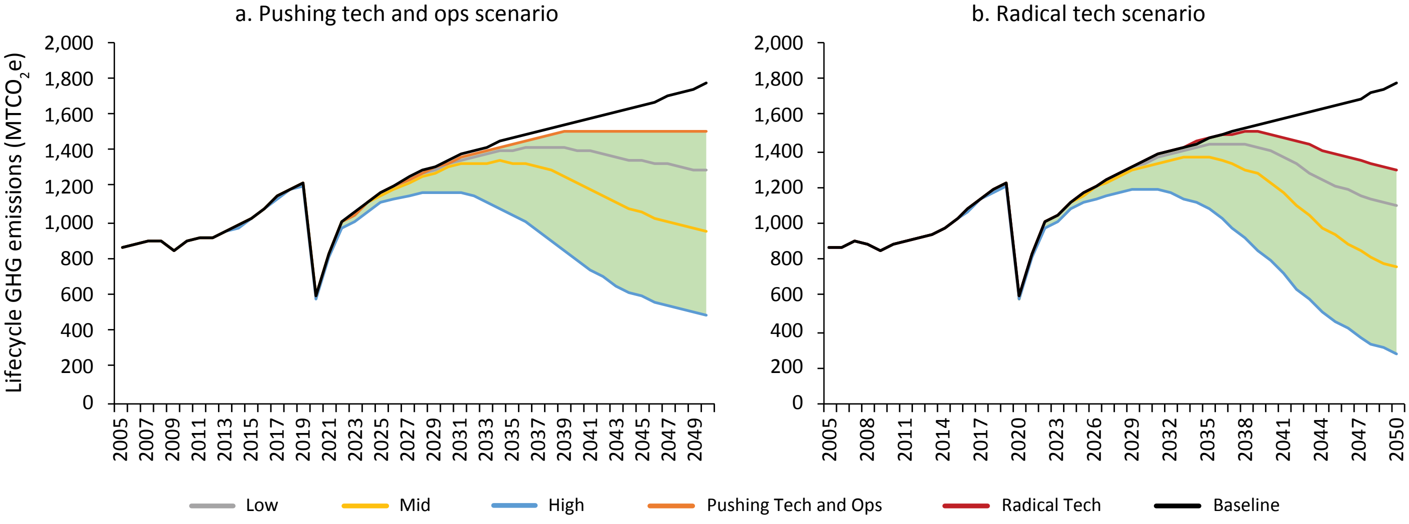
introduction of small-size hybrid and electric aircraft for short-haul routes, zero-emission larger aircraft as well as radical new aircraft designs enter the fleet in the late 2030s (the "radical tech" scenario). Neither the advanced to radical new aircraft technologies nor the acceleration of operational improvements alone suffice to even maintain prepandemic aviation emission levels.

Combining technological and operational improvement with large-scale deployment of SAF can reduce life-cycle GHG emissions to approximately 279 to 477 million metric tons, which is up to 22 percent of total CO_2 emissions for 2050. Opportunities for filling the gap to net-zero emissions by 2050 outside of what is modeled here lie in further decreasing the SAF GHG emission intensity by, for example, increased use of 100 percent fossil carbon-free power to SAF technologies, or by the limited use of carbon offsets. Notably, the high reduction estimate here is based on optimistic assumptions about the success rates of SAF projects, low GHG emission intensity per unit SAF produced, and a disruptive change in aircraft technology—all of which will require significant investment and policy incentives to be realized.

Actual capital expenditure (CAPEX) for a specific SAF project is highly dependent on the conversion technology used, with fuel-output adjusted CAPEX varying by one order of magnitude between the highest and lowest-CAPEX pathways (Bann et al. 2017). High CAPEX does not necessarily translate into high minimum SAF selling prices (that is, low

Figure 3.6. Life-Cycle GHG Emissions Reduction from the Use of SAF and Additional Technological and Operational Improvements, Compared to a Petroleum-Derived Baseline Out to 2050

Million metric tons of carbon dioxide equivalent ($MtCO_2e$)



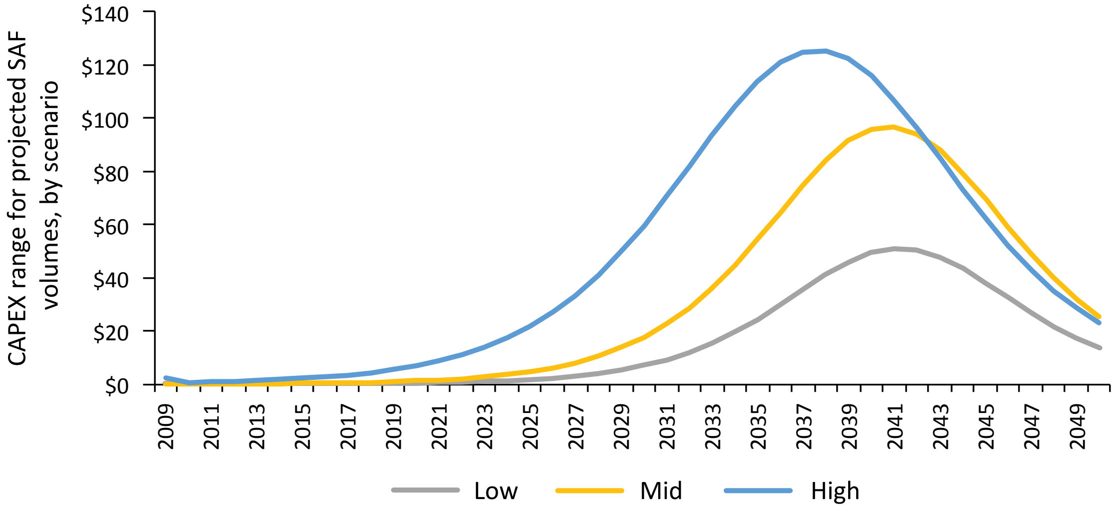
Source: Original figure produced for this publication

Note: Baseline emissions 2005 to 2019 are historical life-cycle emissions. The baseline emissions from 2020 onward are derived from the "continuation of current trends" fuel demand projection by the Air Transport Action Group out to 2050 (ATAG 2020) and assume zero SAF usage and conventional, petroleum-derived jet fuel with a life-cycle GHG emissions intensity of 89 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) of fuel. The "pushing tech and ops" scenario is derived from the ATAG1 fuel burn scenario (ATAG 2020), and the "radical tech" scenario is derived from the ATAG3 scenario, in both cases assuming again a life-cycle GHG emissions intensity of 89 gCO_2e/MJ for conventional, petroleum-derived jet fuel. No adjustments have been made for the slightly higher energy density of SAF compared to conventional jet fuel. The green areas depict the range of additional GHG emissions reductions from the use of SAF in addition to the technological and operational improvements.

economic viability), as the SAF selling price is influenced by other factors beyond CAPEX such as the operational costs and the amount and value of coproducts. For example, Bann et al. (2017)'s mean SAF selling prices for HEFA from soybean oil and FT from municipal solid waste are within 5 percent of each other, while the CAPEX requirements are approximately 5 times higher for the latter pathway than the former. Consequently, we expect a technology mix of high- and low-CAPEX conversion pathways to emerge in the market, and to capture this mix we take the mid-cost CAPEX estimate of the 10 feedstock-to-fuel pathways considered in Bann et al. (2017) of US$331 million for a nominal facility size of 2,000 barrels per day (bpd).

Figure 3.7. CAPEX Estimates for the Production of Projected SAF Volumes, by Scenario Out to 2050

US$, billions (2020)



Source: Original figure produced for this publication

Note: Assumes a jet fuel share in total output of 65 percent, representative of an average SAF-optimized product share (WEF 2020) and greenfield investment. Capital expenditure (CAPEX) for a nominal capacity of 2,000 barrels per day (bpd) derived as mid-point estimate of the CAPEX of SAF production pathways assessed in Bann et al. (2017).

Translating the SAF production volumes into CAPEX estimates shows that annual investment in the high scenario peaks at approximately US$125 billion. This is equivalent to more than 370 SAF producing facilities coming online during the peak year in the late 2030s or early 2040s—as the periods of highest SAF production growth (figure 3.7). For comparison purposes, 2019 investments into new petroleum refining capacity totaled approximately US$54 billion.[8] Note that SAF plants usually produce multiple outputs and that the CAPEX shown is for this full output share. The CAPEX values are so-called "nth" plant estimates, and as such we might be underestimating the required investment in the early years of technology development, while overestimating the future investment into fully matured technologies. The CAPEX calculations are based on greenfield investments, and as such a substantial use of retrofitting, repurposing, or colocating might decrease the required investment value (see, for example, de Jong et al. (2015).

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[8] Statistics on global oil refining investment by region provided by Statista.com. See the data online: "Global Oil Refining Investment by Regions." https://www.statista.com/statistics/465938/global-oil-refining-investments-by-region/.

SAF Production Challenges and Opportunities in Developing Countries

PRODUCTION CHALLENGES

The current and short-term future (in 2025) production of SAF in non-OECD countries accounts for only 2 percent to 8 percent. Several reasons account for this lack of planned production including the following: *(potential) lack of feedstocks, social and environmental issues, financing challenges, technological and infrastructure issues, and lack of policy support.* Table 3.5 summarizes the empirical findings from recent SAF-specific studies in developing countries.

Lack of policy support: The industry shares a broad agreement that the strong growth in announcements of SAF projects in OECD countries is largely driven by actual or expected policies implemented in those countries to speed up the decarbonization of the economy. However, very few non-OECD countries have introduced—or are actively pursuing the introduction of—SAF-incentivizing policies, and the lack of such incentives is regularly identified as a major barrier (White 2018; Weber 2018; RSB 2020; RSB 2021; Gomez Jiminez 2017; Serafini 2017). A notable exception is Indonesia with its domestic SAF mandate. Brazil is an example of a country that used strong incentives to push the large-scale use of domestically produced sugarcane-ethanol into the road transportation fuels market (Stattman, Hospes, and Mol 2013). Although recently a general ambition was developed to establish policies for SAF as part of the Brazil Fuels of the Future Program (Invest in Brazil 2021), no strong incentives exist, to date. For international aviation, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) provides a pathway-specific monetary incentive for uplifting SAF, irrespective of location, but this incentive is not high enough to compensate for the high initial costs of SAF compared to conventional jet fuel (Wang et al. 2021); as such, it cannot drive SAF into the market on its own. For perspective, ICAO expects the monetary incentive provided by CORSIA for the use of SAF to be at best around US$32 per ton of CO_2 abated through the use of SAF (ICAO 2022).

Social and environmental issues: SAF production in developing countries using local feedstock might face the same sustainability hurdles than those of first-generation feedstocks, including the following: land-tenure issues, increase in food prices due to competition for arable land, labor exploitation, or pressure on primary forests or other valuable ecosystems (Colmenares-Quintero et al. 2020; Johari et al. 2015; Selfa et al. 2015; Mukherjee and Sovacool 2014). As shown below, however, a relatively large potential exists for local sustainable feedstock production in developing countries with limited land-use competition and without conversion of high-carbon or biodiverse lands.

Another social issue pertinent as a hurdle for decarbonization in developing countries lies in the induced increase in (energy) prices that might be difficult to absorb for lower income countries, and lower income segments of society (Fay et al. 2015). While this argument could be valid in the context of electricity and road transportation fuels needed to satisfy basic needs for all income segments of society, it is less valid in the context of aviation fuel. Even in OECD countries, the propensity to fly is higher in higher-income segments of society, and this pattern can be assumed to be even more pronounced in low- and middle-income countries (LMICs). In the EU, for example, the 20 percent highest income households accounted for more than half of all expenditure for air travel (Hopkinson and Cairns 2020). In Colombia, findings from a survey indicate that 54 percent of all inhabitants have never flown in a plane and that 87 percent of those people are considered poor (Portafolio 2016). Therefore, a potential increase in prices for air services due to the use of SAF might largely be borne by relatively high-income segments of society.

Financing challenges: Lack of sufficient access to financing has been identified as a major hurdle for the deployment of decarbonization technologies in developing countries in general. This is presented by Fay et al. (2015) succinctly: “The challenge of the low-carbon transition starts with tackling the chronic lack of financing for productive investments that plagues most developing countries and the need to find new sources of financing and to leverage existing ones.” To the best of our knowledge, no SAF-specific analysis on financing restrictions currently exists. For the United States, Bann et al. (2017) estimate the amount of capital expenses for a Fischer–Tropsch municipal solid waste (FT MSW) SAF plant of 2,000 bpd capacity at approximately US$500 million. The required investment in developing countries is potentially even higher due to higher risk-premiums. To put this in perspective, the investment into one plant is similar to the individual investment into important infrastructure projects in Africa, such as the Abidjan–Ouagadougou transport corridor, the Serenje–Nakonde Road Project, or the Ruzizi III Hydropower Project.[9] That said, the main challenge to accessing infrastructure financing is not the absolute size of capital required but good project preparation, which in the case of SAF should clearly demonstrate climate cobenefits.

Technological and infrastructure-related barriers: These have been identified in several studies (see White 2018; Weber 2018; and RSB 2021). For example, a feasibility study for SAF production in Kenya (White 2018) finds the lack of feedstock collection infrastructure and refining infrastructure as well as a lack of technical expertise in the area of SAF production are a major impediment for the development of a domestic SAF industry. Similarly, an ICAO study on Burkina Faso (Weber 2018), makes the point that the development of a domestic SAF industry in Burkina Faso requires, among other things, significant technology transfer to address several pre-existing infrastructural deficits.

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[9] Statistics on the costs of selected infrastructure projects in Africa provided by Statista.com. See the data online: “Costs of Selected Infrastructure Projects in Africa.” https://www.statista.com/statistics/1086666/infrastructure-projects-africa-cost/.

Table 3.5. Recent Studies on SAF Production in Non-OECD Countries and Major Hurdles Identified

Country	Publication year	Study partners (among others)	Main hurdles identified							References
			Poor or no research/ technical expertise	Lack of a collection/ refining infrastructure	Lack of access to funding	Lack of economic incentives	Incipient or nonexistent biofuels policy	Sustainability issues	Unsuitable land to scale up cultivation	
Kenya	2018	ICAO	x	x	x	x	x		x	(White 2018)
Burkina Faso	2018	ICAO	x	x	x	x	x			(White 2018)
Brazil	2021	Stakeholders of the Brazilian Biojetfuel Program		x			x	x		(BBP 2013; Cortez et al. 2015; RSB and Agroicone 2021)
South Africa	2020	Stakeholders of Project Solaris			x		x	x		(RSB 2020)
Ethiopia	2021	Boeing	x	x	x	x	x	x	x	(RSB 2021)
India	2021	Stakeholders of the *Clean Skies for Tomorrow* India community		x	x		x			(WEF 2021)
Dominican Republic	2017	ICAO	x	x	x		x			(Gomez Jimenez 2017)
Trinidad and Tobago	2017	ICAO		x	x		x		x	(Serafini 2017)

Source: Original table produced for this publication.
Note: ICAO = International Civil Aviation Organization.

PRODUCTION OPPORTUNITIES

A SAF feedstock potential in non-OECD countries is equivalent to a production of approximately 510 million metric tons of SAF, out of which approximately two-thirds (345 million metric tons) could come from nonfood feedstocks (table 3.6).[10] Among those, lignocellulosic energy crops and MSW form the most important feedstock categories. All three non-OECD world regions considered here can contribute significantly to the total potential. For comparison purposes, SAF demand in our high SAF scenario in 2050 amounted to approximately 331 million metric tons, which is similar to the production potential of nonfood feedstocks in non-OECD countries.

The emergence of a SAF industry in developing countries would have significant benefits for these countries. SAF production can speed up rural development as shown by studies

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[10] Details of the modeling approach for feedstock availability are presented in appendix B.

dealing with Mexico (Rivero et al. 2016), Southern Africa (Mudombi et al. 2021), and Brazil (La Rovere, Pereira, and Simões 2011; Rodrigues, da Silva Silva, and Correia-Silva 2019). It could also lead to the generation of new jobs, additional income for farmers, and improved environmental and health conditions due to SAF-induced improvements in waste management practices.

Table 3.6. Feedstock Availability by Type and World Region, Year 2050

Kilotons of sustainable aviation fuel (SAF)

Year	LAM	ASIA/REF	MAF	Total non-OECD
Food crops (starchy, sugary, vegetable oil crops)	62,190	51,143	49,895	163,229
Food crop residues	5,354	34,802	17,401	57,557
Forestry residues	7,138	6,654	2,855	16,647
Lignocellulosic energy crops	40,758	33,541	92,072	166,370
Municipal solid waste (MSW)	10,954	57,578	20,749	89,281
Waste fats, oils, and greases (FOGs)	4,351	8,495	3,007	15,853
Total for all feedstocks	130,744	192,213	185,980	508,937

Source: Original table produced for this publication.
Note: Based on modeling approach from Staples et al. (2018). Main assumptions are shown in tables B.1 and B.2 in appendix B. Only SAF-equivalent volumes are shown here, total fuel output is higher as the jet makes up only some fraction of total output (see table B.2 in appendix B). Latin America and the Caribbean (LAC); Asia and former reforming economies of Eastern Europe and the former Soviet Union (ASIA/REF); the Middle East and Africa (MAF); and the Organisation for Economic Co-operation and Development (OECD).

For Sub-Saharan Africa, Fischer et al. (2019) estimate significant SAF production and job potential. The study uses the global agroecological zones (GAEZ) model, as we do in our developing countrywide production potential analysis. It applies a sustainability criterion for feedstock production in compliance with the criteria of the Roundtable for Sustainable Biomaterials, or RSB (RSB 2016), including considerations for food security and environmental sustainability such as the preservation of high-carbon and biodiverse land and wetlands, and a life-cycle GHG emissions reduction of the SAF sourced from a certain batch of feedstock from a specific location of at least 60 percent. Under these stringent sustainability criteria, the study estimates a production potential in Sub-Saharan Africa of 70 to 261 million tons of RSB-compliant SAF. The production of these amounts of SAF feedstock could create between 11 and 20 million additional jobs in Sub-Saharan Africa, depending on the feedstock split and agricultural practices assumed. Additional employment opportunities from SAF production or transportation are not accounted for, implying even larger gains.

According to recent estimates from India, the production of 360 million metric tons of SAF creates about 120,000 new full-time jobs outside of the agricultural sector (20 percent direct, 25 percent, indirect, 35 percent, induced, and 20 percent initial) and the production of each 30 million metric tons of SAF from agricultural residues benefits more than 45,000 farmers by increasing their incomes by 10 to 15 percent (WEF 2021). For the FT MSW pathway, one commercial-scale plant could create 1,000 to 1,100 full-time jobs directly at the plant and approximately 6,000 to 6,500 additional jobs across the MSW SAF supply chain.

Given the projected increase in population and gross domestic product (GDP), it is expected that MSW generation in developing countries doubles by 2050 (World Bank 2018), and many of these countries currently suffer from a lack of proper MSW collection and landfilling and associated environmental and health issues (Hoornweg and Bhada-Tata 2012; Troschinetz and Mihelcic 2009), which further motivates the usage of MSW as a feedstock for SAF production. In our analysis, approximately 25 percent of the nonedible SAF feedstock potential comes from MSW, and as such, the valorization of MSW as a feedstock for SAF production provides an important opportunity for increased MSW collection in developing countries (Nizami et al. 2017).

We note this analysis of SAF feedstock potential in developing countries does not include power-to-liquid technologies that rely on a carbon source and (renewable) electricity as core inputs. Given the high potential for the production of electricity from nonbiomass renewable sources (especially solar energy), we recognize an additional SAF production opportunity not covered in this report (Shahsavari et al. 2018).

SAF Abatement Costs

To shed light on the costs of emissions reductions from the use of SAF, a marginal abatement cost curve (MACC) is constructed, in which the GHG emissions reduction potential from the use of SAF is contrasted with the costs of reducing a metric ton of emissions. The curve is built by estimating for each SAF type the GHG abatement costs and GHG reduction potential and by stacking them up according to the merit order. Results for the years 2030 and 2050 are depicted in figure 3.8 and figure 3.9 respectively. For both points in time, two distinct MACCs have been developed, with the two differences according to the obtainable emissions reductions achievable and the assumed costs of conventional jet fuel.[11] The vertical lines in the figures show the GHG emissions abated in gigatons of carbon dioxide equivalent (GtCO_2e) attributable to the SAF production volumes forecasted through the market diffusion modeling for each of three SAF production scenarios (low/mid/high).

The curves show waste oil conversion has the lowest absolute abatement costs per metric ton of carbon dioxide equivalent (tCO_2e), due to the combination of low GHG emissions and low production costs of this mature pathway, followed by the other lipid types. The relatively better performance of both oil-bearing crops on degraded land and oil cover crops is a result of their positive impacts particularly on soil and biomass carbon sequestration that partially compensate for higher production costs compared to waste

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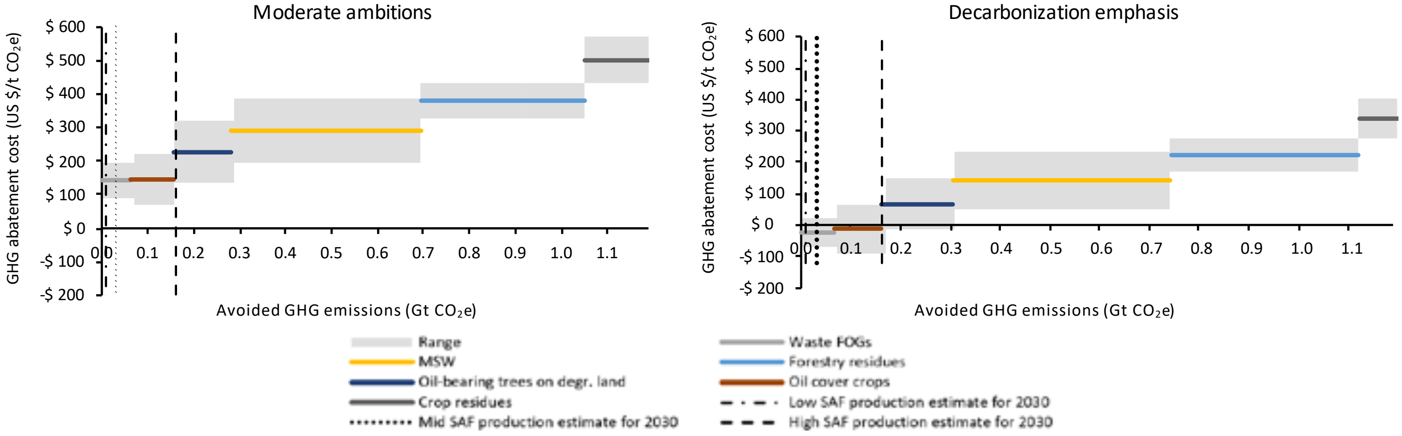
[11] As such, the left marginal abatement cost curve (MACC) ("moderate ambition") are indicative of a situation in which moderate GHG emissions reduction for each SAF pathway have been achieved (modeled as the mid-point of the GHG emission range obtained from CORSIA), and in which the future year conventional jet fuel price follows the EIA (2021) "business-as-usual forecast." In contrast, the right SAF MACC is indicative of a situation in which a higher emphasis is placed on reducing GHG emissions, which leads to a SAF portfolio that has lower GHG emissions (modeled as the minimum of the range obtained from the CORSIA values), and a high conventional jet fuel price. We note that our MACC are derived from a private perspective (that is, the additional costs for an airline to abate one metric ton of CO_2e through the use of SAF), and that societal abatement costs might be different from those estimated here. For example, the social marginal abatement costs might be lower than the private if externalities of conventional jet fuel are not appropriately accounted for, or higher, if price increases of conventional jet fuel due to tax increases go beyond those warranted by the internalization of externalities. Please refer to appendix C for details on how the marginal abatement costs are constructed.

oil HEFA. The next feedstock in the merit order is MSW, whose beneficial GHG emission performance is combined with a relatively mature conversion technology. The remaining feedstock types show significantly higher abatement costs across the scenarios and points in time.

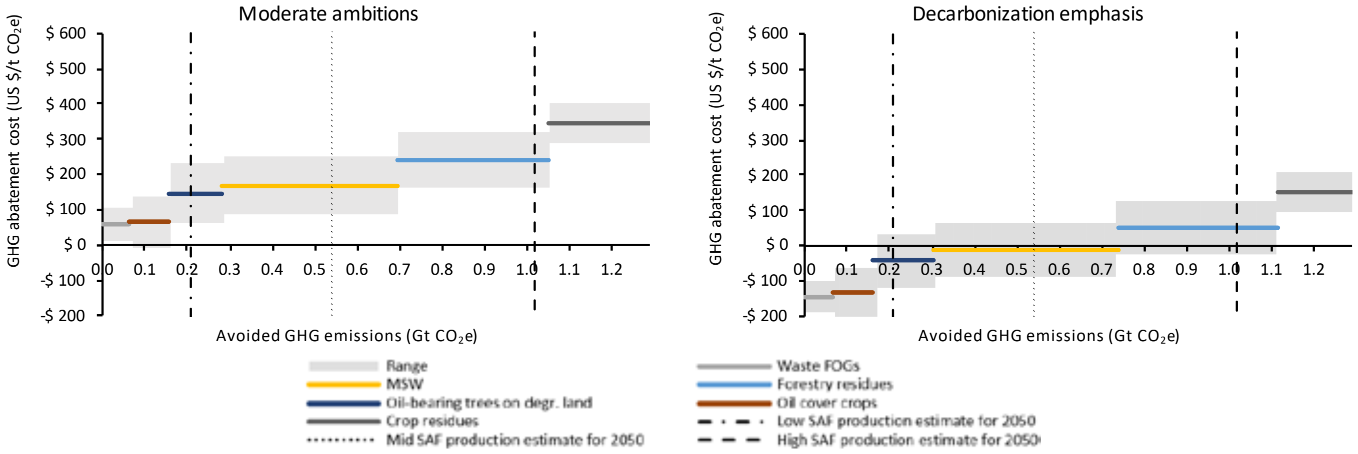
Figure 3.8. Marginal Abatement Cost Curves for SAF for 2030



Source: Original figure produced for this publication

Note: Grey areas show abatement cost ranges due to variability in SAF-production costs. $GtCO_2e$ = gigatons of carbon dioxide equivalent; tCO_2e = metric tons of carbon dioxide equivalent; MSW = municipal solid waste; FOGs = fats, oils, and greases.

Figure 3.9. Marginal Abatement Cost Curves for SAF for 2050



Source: Original figure produced for this publication

Note: Grey areas show abatement cost ranges due to variability in SAF-production costs. $GtCO_2e$ = gigatons of carbon dioxide equivalent; tCO_2e = metric ton of carbon dioxide equivalent; MSW = municipal solid waste; FOGs = fats, oils, and greases.

While noting caution[12] over the usage of the MACC results, they could provide some guidance on the costs of decarbonization from using SAF:

- First, the SAF volumes needed for a rapid SAF production ramp-up as forecasted in the high SAF production scenario can be realized at relatively low costs (below US$150 per tCO_2e abated), even under nonoptimistic assumptions on GHG emission performance and conventional jet fuel prices. Costs can decrease by 2030 to close to zero if ambitious policies are employed that incentivize the use of low GHG emission SAF and drive up conventional jet fuel prices.

- Second, for the year 2050 and under the assumption of appropriately ambitious policies for decarbonization of aviation, the results indicate large volumes of SAF could be provided at below zero, or close to zero abatement costs. To indicate the magnitude of total abatement costs, we assume a starting SAF abatement cost of US$200 per tCO_2e abated in 2025 that is linearly decreasing to zero by 2050. For the high SAF scenario, these yield total abatement costs between 2025 and 2050 of US$879 billion, or US$34 billion on average, per year. For comparison purposes, the total revenues of global airlines in 2019 reached US$838 billion, with profits amounting to US$25.9 billion (IATA 2020).

The positive abatement costs estimated in the near term are a consequence of SAF costs being higher than conventional jet fuel prices. For perspective, in the summer of 2021 SAF prices were, on average, approximately 5 times higher than those of conventional jet fuel (Brooks 2021) due to, among other considerations, small volumes of SAF availability that limit the ability to leverage learning effects and economies of scale and nonmature SAF technologies. WEF (2020) estimates the average cost gap between SAF and conventional jet fuel in the near term to be approximately a factor of two. Over time, SAF costs are expected to decrease further (WEF 2020). However, given the ease of converting crude oil into jet fuel, compared to converting many advanced SAF feedstocks such as, for example, residues, energy grasses, and MSW into SAF—a cost challenge for SAF might remain even in the medium term as long as conventional jet fuel is not getting substantially more expensive. The European Commission expects a price gap between SAF and conventional jet fuel to still exist beyond 2030, except for HEFA SAF (European Commission 2021), which is in line with the results of our 2030 abatement cost analysis. Significant policy support, therefore, will be needed to increase the development and market uptake of SAF technologies.

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[12] Note that significant variability exists with regard to the GHG emission performance and production costs within SAF pathways, often driven by locational factors that cannot be fully captured by the MACC ranges developed here. Moreover, there is significant uncertainty regarding future cost decreases of the different SAF technologies and the future price development of conventional jet fuel. As such, for concrete investment decisions, higher resolution analysis need to be conducted for the specific case at hand.

Incentives for SAF Production and Use

Three major types of policies exist that can increase the financial viability of SAF production: market-based measures, mandates, and cost-related measures.

1. *Market-based measures* such as carbon taxes, emissions trading schemes that cover aviation emissions, and aviation GHG offset systems, directly (in the case of carbon taxes) or indirectly (in the case of emissions trading scheme) put a price on the release of GHG emissions. They increase the economic viability of SAF usage by making the use of conventional jet fuel more expensive, which increases the willingness to pay for SAF, which in turn, increases the net present value (NPV) of SAF facility construction. In the case of carbon taxes or emissions trading schemes, the monetary incentive of SAF production arises from the reduction of tax payments and from a reduced need for emission allowance purchases (or increased ability to sell allowances), respectively. In the case of GHG offset systems, the monetary incentive for SAF results from the decreased need to purchase emission offsets. For all market-based measures, the monetary incentive for usage increases with the size of the GHG benefit of a certain type of SAF. Examples of aviation-related market-based measures include the European Union Emission Trading Scheme (EU ETS) and CORSIA. Regarding carbon taxes, the European Commission has in mid-2021 put forward a legislative proposal for charging taxes on aviation fuel taken up in the EU (European Commission 2021).

2. A *SAF mandate* requires the production and/or use of a certain amount of SAF, that usually increases over time. A mandate has several effects on the economic viability of SAF production: (1) Risk premiums are reduced due to increased certainty about the emergence and size of the SAF market. Reduced risk premiums reduce costs of capital, which in turn decreases CAPEX, increases NPV, and decreases the SAF minimum selling price (MSP); (2) Market growth of SAF is accelerated compared to a no-policy scenario, which accelerates cumulative learning, which drives down SAF production costs, increases NPV, and decreases MSP of SAF; and (3) The willingness to pay for SAF increases for blenders and/or end-users. Examples of SAF mandates include Norway and Sweden, who have prescribed a SAF mandate that will reach 30 percent in 2030, and Indonesia, which has a SAF blending mandate for domestic flights set to reach 5 percent by 2025 (SkyNRG 2021).

3. *Cost-related policies* can be divided into feedstock subsidies, capital grants and loan guarantees—see Wang et al. (2021) for details.

    a. *Feedstock subsidies* provide a monetary benefit, usually to the feedstock producer itself to decrease the operating costs of a fuel producing facility. It can also come in the form of a monetary incentive for the use of waste products that otherwise would have used landfill capacity. Decreased operating costs lead to higher NPV of SAF production and decrease the MSP of SAF. Examples include the United States Biomass Crop Assistance Program and the Brazil Social Fuel Seal (Wang et al. 2021).

b. *Capital grants* are offered by governments to contribute to the investment costs of fuel facility construction, thereby driving down facility CAPEX and improving the NPV of SAF production and decreasing the MSP. Capital grants are a widely used governmental means for accelerating the commercialization of emerging clean technologies (Owen, Brennan, and Lyon 2018).

c. *Loan guarantees* are given by a governmental entity to guarantee a bank loan given to a SAF producer. In case the SAF producer defaults on the bank loan, the guarantee will pay the loan back to the bank. This reduces the costs of debt of the SAF producer, which decreases the cost of capital and the required discount rate, which, in turn, increases NPV and decreases the MSP. Examples of a loan guarantee are the Rural Energy for America Program (Wang et al. 2021), or the U.S. Department of Energy's Innovative Energy Loan Guarantee Program.[13]

The importance of such cost-related policies was emphasized qualitatively in a recent survey by the International Renewable Energy Agency (IRENA), in which advanced biofuel producers identified the availability and cost of financing as a major barrier to investment into these fuels (IRENA 2019). More specifically, with regard to developing countries, a World Bank report stresses the importance of cofinancing of low-carbon projects by means of governments or multilateral developing banks (Fay et al. 2015). Wang et al. (2021) quantified the effect of hypothetical and actual cost-related policies on the economic viability (NPV and MSP) of a set of different SAF technologies. In line with an earlier analysis by Bann et al. (2017), they find that—depending on the feedstock and conversion technology—policy incentives in line with existing incentives for transportation fuels can significantly improve the economic viability of SAF production. For example, the required policy costs (measured in US$ per metric ton of carbon abated) to achieve a (mean) NPV of zero are found for several pathways to be below the monetary incentive provided to SAF under California's Low Carbon Fuels Standard.

The public and private finance sector has a role in steering investment into sustainable aviation fuels by means of *green or climate financing*.[14] Its role in the airline industry, however, is still in its infancy and limited to a few projects related to green energy at airports, or aircraft fleet renewal—see Blanshard and Vora (2020) for an overview. For example, in 2020, JetBlue Airways became the first airline globally to deploy a sustainability-linked loan. With this type of loan, the interest rate or commitment fee paid changes in accordance with the level of achievement of a set of ex-ante agreed-upon environmental, social, and governance (ESG) metrics, thereby proving an incentive to the borrower to fulfill the ESG targets (BNP Paribas 2020). On the airport side, the Royal Schiphol group in 2019 issued a green bond (nominal value €500 million) to fund green

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[13] For more information on the U.S. Department of Energy's loan program, see: "How LPO Can Support the Sustainable Aviation Fuel Grand Challenge," an online article dated September 9, 2021, published by the DOE: https://www.energy.gov/lpo/articles/how-lpo-can-support-sustainable-aviation-fuel-grand-challenge.

[14] Green financing is the umbrella term for any structured financial activity that has been created to ensure environmental benefits. It includes, among other things, green bonds and green loans. Different financial institutions, initiatives, regulators, and standard setters have developed their own approaches with regard to scopes across environmental, social, and governance (ESG) criteria, and different requirements for transparency and impact (Blanshard and Vora 2020). However, all relevant approaches require that 100 percent of the proceeds go to eligible activities. The sector has seen a significant growth over the past decade. For example, in the European Union in 2019, products that target specifically sustainable development objectives accounted for 11 percent of all assets under management (Kisielewicz et al. 2021).

buildings and clean transportation for the group's airports (Royal Schiphol Group 2019). While green financing for airport and aviation activity is still very small in scale, SAF-related projects can be built upon significant green financing activity in the biomass and bioenergy sector in general. SAF biorefinery projects are frequently (partially) financed by means of green financing. For example, in early 2021, SAF-producer Neste Corporation issued a US$500 million green bond (Neste 2021a), part of which will be used in accordance with Neste's Green Finance Framework (Neste 2021b) to finance the expansion of Neste's SAF production capacity.[15] Since 2017, the State of Nevada Department of Business and Industry issued green bonds for US$175 million that loaned the proceeds to Fulcrum Bioenergy to finance Fulcrum's waste to SAF biorefinery in Nevada (Morgan Stanley 2019). A similar approach is followed for Fulcrum's proposed waste to fuel biorefinery in Gary, Indiana, for which the Indiana Finance Authority is issuing US$375 million in environmental improvement revenue bonds to Fulcrum Centerpoint, LLC, a subsidiary of Fulcrum Bioenergy (Fulcrum Bioenergy 2021).

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[15] Read more about Neste's Green Finance Framework online: https://www.neste.com/investors/credit/green-finance.

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Chapter 4: Conclusions

This report has assessed and quantified the decarbonization options for global aviation out to the year 2050. It finds that a mix of different measures is needed to meet the industry's goal of zero net carbon air transport in 2050. Within this mix of measures, sustainable aviation fuel (SAF) will need to play a major role, as the only in-sector option that can already generate significant greenhouse gas (GHG) emission reductions in the medium term. Our SAF market diffusion analysis indicates a production path for SAF out to 2050 that would reduce aviation GHG emissions by up to 57 percent compared to the business-as-usual forecast. This would require an aggressive scale-up of the SAF industry post-2020 and the use of low-GHG intense fuels derived from, for example, waste oils, municipal solid waste (MSW), and agricultural and forestry residues, which would need to be incentivized by strong policy support. When large-scale deployment of SAF occurs in conjunction with strong technological and operational improvements in the air transport system, up to 78 percent of the carbon dioxide (CO2) emissions from aviation could be avoided in 2050, with the remaining reduction gap potentially filled by the use of SAF with even lower life-cycle GHG emissions than the ones assumed in this study and out-of-sector solutions, such as carbon offsets.

SAF-specific marginal abatement cost curves (MACCs) for the years 2030 and 2050 show that for a highly mature and low-cost feedstock pathway, such as hydroprocessed esters and fatty acids (HEFA), marginal abatement costs could be negative in 2030. Whereas other types of SAFs, depending on feedstock type and assumptions on future conventional jet fuel prices, would still yield abatement costs of greater than US$100 per metric ton of carbon dioxide equivalent (tCO2e) abated. For the year 2050 and under the assumption of aggressive policies for mitigating climate change that drives up prices of conventional jet fuel and set working incentives to improve the SAF GHG performance, our results indicate large volumes of SAF could be provided at below zero, or close to zero, abatement costs.

The review of the current and near-future SAF production revealed a strong dominance of facilities planned in the Organisation for Economic Co-operation and Development (OECD) countries, whereas a significant production potential is available in developing countries as well. The lack of planned SAF production capacity in developing countries is especially regrettable given the potential environmental, economic, and social benefits that SAF production could realize in these countries.

Building on the recent momentum that has laid a good foundation for SAF, this decade has the potential to be transformative—as the aviation industry and others begin to grapple with the effects of climate change. SAF, and biofuels in general, are potential levers that could be used to mitigate GHG emissions in the transportation sector, in both developed and developing countries. Countries can improve the financial viability of SAF production through market-based measures, mandates, and cost-related measures combined with increasing usage of climate financing to build on past experiences in the biomass and bioenergy sector in general.

Aviation is a significant and growing contributor to climate change, and as such, aviation decarbonization policies—including those aimed at promoting the SAF industry—should be a vital component of countries' broader climate targets and actions on energy transition as well as agricultural and environmental sustainability.1 A comprehensive public policy and regulatory framework should define production incentives needed to increase supply and lower costs, while incentivizing SAF usage. To be effective, high-level policy commitments must be accompanied by the development of financing schemes (including guarantees instruments), easement of environmental licensing, and promotion of exports to meet the growing demand for SAF. Should the increasing SAF production require an expansion in cultivation area, public and private institutions must ensure such expansion happens sustainably within the agricultural frontier, and with no significant effect on the natural ecosystems.

Finally, continued support for SAF research and development is needed. This should include the development of feedstock supply chains, new and innovative production technologies, and the development of innovative business models that increase the value of all products and by-products of SAF production operations. As the SAF production and distribution network becomes global, deeper analyses will be needed to design the structure of biomass feedstock and refined fuel products transportation, whether distributed or centralized, in streamlined supply chains. The study found that utilizing multiple transport modes in the chain lowers transportation costs and GHG emissions over long distances.

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1 A prime example is Colombia, which included the promotion of sustainable aviation fuel (SAF) as a key pillar in its Climate Action Law (Law 2169 of 2021) as it seeks to be carbon neutral by 2050. One of the key aviation-related announcements at the recent COP26 in Glasgow was the Memorandum of Understanding signed by the government of Colombia with Alder Fuels, a U.S.-based company. The announcement stated: "Colombia will tap into its agricultural infrastructure and incentivize local farmers to supply biomass feedstock for conversion into sustainable low-carbon crude oil. Alder Fuels will then use its refining process to convert forestry and crop residue as well as regenerative agricultural crops into drop-in replacement 'green' crude used for producing aviation fuel." The complete statement is available online: https://www.financecolombia.com/colombian-government-alder-fuels-sign-sustainable-aviation-fuel-mou//.

Appendices

Appendix A: Further Review of SAF-Related Studies

The use of SAF does not necessarily reduce greenhouse gas (GHG) emissions compared to conventional, petroleum derived jet fuel. The total GHG emissions are dependent on two main factors: (1) the emissions associated along the full fuel life cycle, that is, from the production of the feedstock, transportation of the feedstock, conversion of the feedstock into SAF, SAF transportation, and finally SAF combustion. Emissions can stem, for example, from the use of fertilizers for feedstock production, natural gas and electricity usage for SAF production, and diesel needs for feedstock and fuel transportation; and (2) emissions stemming from changes in land-use due to the production of SAF. These changes can be direct and indirect. Direct land-use change emissions stem from the conversion of land for SAF-feedstock production, for example, when grassland is cleared for soybean production. Indirect land-use change is a function of market-mediated responses to changes in feedstock demand by increased SAF production (Zhao et al. 2021). See figure A.1 for an illustration of the SAF production pathways.

Emissions from (1) and (2) together form the so-called life-cycle GHG emissions of SAF. These life-cycle GHG emissions vary significantly between different types of SAF. Moreover, significant variability can exist within a specific SAF pathway, driven by, for example, heterogeneity in agricultural practices for a specific feedstock, decisions with regard to the transportation of feedstock and finished fuels, or feedstock conversion efficiency. Despite this heterogeneity within SAF pathways, the International Civil Aviation Organization (ICAO) has established a set of default life-cycle assessment (LCA) values for use within its Carbon Offsetting Scheme for International Aviation, or CORSIA (ICAO 2021). These include emissions along the full life cycle, including induced emissions from land-use change. They cover combustion carbon dioxide (CO_2) emissions, and CO_2 and non-CO_2 emissions for the other life-cycle steps. Table A.1 shows the list of default values currently used within CORSIA. The values indicate a large variability in default life-cycle emissions between pathways, with some pathways (especially energy grass-based and residue/waste-based pathways) providing the opportunity for zero, or close to zero, fossil life-cycle emissions. The CORSIA list of default values is a living document extended with additional pathways once the technical analyses are completed and agreement is reached on the corresponding default value. No values, to date, exist for power to SAF pathways, for example, but existing research indicates emissions savings can be up to 100 percent with the use of renewable electricity and waste CO_2 or CO_2 air capture and a fully decarbonized supply chain (Schmidt et al. 2016).

A study by Staples et al. (2018) analyzes SAF feedstock availability as a function of policy emphasis on SAF-usage to calculate a range of emissions reduction from the use of SAF in the year 2050 at a global level, and provides a first-order estimate of the capital cost required to achieve the projected SAF volumes. The authors find that with sufficiently strong policy support, up to 100 percent of conventional jet fuel could be replaced by SAF in the year 2050, leading to an approximately two-thirds reduction in life-cycle carbon dioxide equivalent (CO_2e) emissions from aviation. The same study also finds the necessary annual capital investment in order to reach such emissions reductions in 2050 ranges from US$(2015)22 billion to US$(2015)88 billion.

De Jong et al. (2018) analyzed SAF availability from nonfood based biomaterials in 2030 for the European Union (EU). The authors find that with sufficiently strong policy support and advancements in SAF conversion technology, SAF could satisfy 6 to 9 percent of the (not adjusted for the COVID-19 pandemic) jet fuel demand in the EU for 2030. We note this study has a relatively narrow feedstock scope compared to other studies listed in this report, as, for example, SAF production potential from municipal solid waste (MSW) is not accounted for. The study estimates the additional costs for the production of SAF compared to the production of conventional jet fuel are equal to €1.00 to €1.40 per passenger and flight, if allocated to intra-EU passengers.

A recent report published by WEF (2020) focuses on feedstock availability constraints in the medium term (out to 2030). The study estimates waste, residue, lignocellulosic, and cover crop availability to be equivalent to 500 million metric tons SAF in 2030, which is significantly higher than total jet fuel demand projections for 2030 from ATAG (2020). Note that first-generation feedstocks (that is, traditional oil crops and edible sugars) are not included in the estimate due to sustainability concerns.

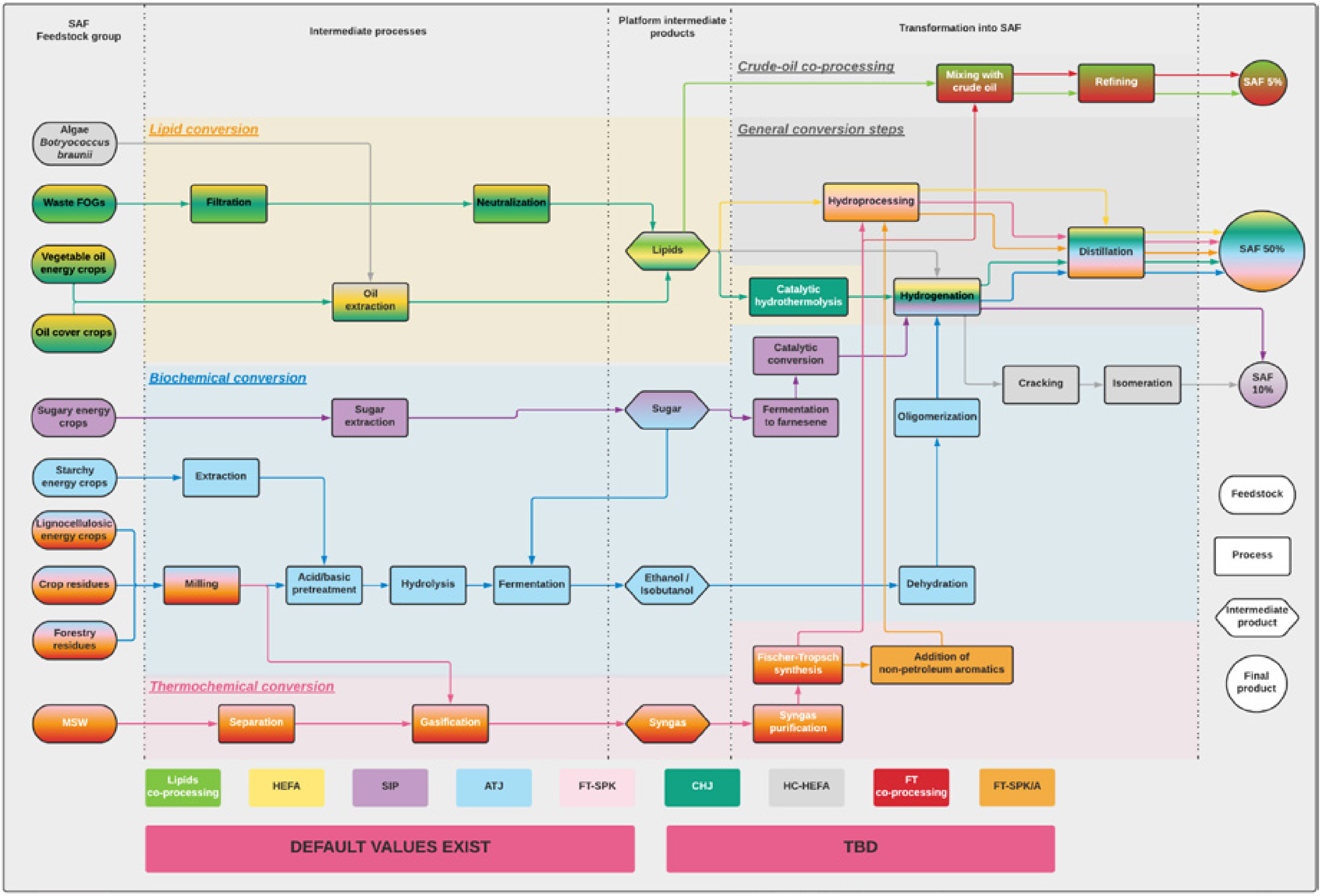
Table A.1. CORSIA Default Life-Cycle Assessment Values, March 2021

Pathway	Feedstock	Region	Core value without LUC	ILUC LCA value	Core LCA value
Conventional fuel	Jet fuel	Global	89.00	0.00	89.00
Ethanol to jet – ATJ	Agricultural residues – standalone	Global	39.70	0.00	39.70
Ethanol to jet – ATJ	Agricultural residues – integrated	Global	24.60	0.00	24.60
Ethanol to jet – ATJ	Forest residues – standalone	Global	40.00	0.00	40.00
Ethanol to jet – ATJ	Forest residues – integrated	Global	24.90	0.00	24.90
Ethanol to jet – ATJ	Sugarcane	Brazil	24.10	8.70	32.80
Ethanol to jet – ATJ	Corn grain	USA	65.7	25.1	90.8
Ethanol to jet – ATJ	Miscanthus (herbaceous energy crops) – standalone	USA	43.3	–42.6	0.7
Ethanol to jet – ATJ	Miscanthus (herbaceous energy crops) – integrated	USA	28.3	–42.6	–14.3
Ethanol to jet – ATJ	Miscanthus (herbaceous energy crops) – standalone	EU	43.3	–23.3	20.0
Ethanol to jet – ATJ	Miscanthus (herbaceous energy crops) – integrated	EU	28.3	–23-3	5.0
Ethanol to jet – ATJ	Switchgrass (herbaceous energy crops) – standalone	USA	43.9	–10.7	33.2
Ethanol to jet – ATJ	Switchgrass (herbaceous energy crops) – integrated	USA	28.9	–10.7	18.2

Pathway	Feedstock	Region	Core value without LUC	ILUC LCA value	Core LCA value
FT	Agricultural residues	Global	7.70	0.00	7.70
FT	Forestry residues	Global	8.30	0.00	8.30
FT	Miscanthus (herbaceous energy crops)	USA	10.40	–32.90	–22.50
FT	Miscanthus (herbaceous energy crops)	EU	10.40	–22.00	–11.60
FT	Switchgrass (herbaceous energy crops)	USA	10.40	–3.80	6.60
FT	MSW	Global	5.20	0.00	5.20
FT	MSW	Global	80.20	0.00	80.20
FT	MSW	Global	42.70	0.00	42.70
SIP	Sugarcane	Brazil	32.80	11.30	44.10
SIP	Sugarbeet	EU	32.40	20.20	52.60
HEFA	Soybean oil	USA	40.40	24.50	64.90
HEFA	Soybean oil	Brazil	40.40	27.00	67.40
HEFA	Rapeseed oil	EU	47.40	24.10	71.50
HEFA	Palm oil - closed pond	Malaysia & Indonesia	37.40	39.10	76.50
HEFA	Palm oil – open pond	Malaysia & Indonesia	60.0	39.1	99.1
HEFA	Brassica carinata (grown as secondary crop)	Brazil	34.40	–20.4	14.0
HEFA	Brassica carinata (grown as secondary crop)	USA	34.40	–21.4	13.0
HEFA	Corn oil	Global	17.20	0.00	17.20
HEFA	Tallow	Global	22.50	0.00	22.50
HEFA	Used cooking oil	Global	13.90	0.00	13.90
HEFA	Palm fatty acid distillate	Global	20.70	0.00	20.70
Isobutanol to jet – ATJ	Agricultural residues	Global	29.30	0.00	29.30
Isobutanol to jet – ATJ	Forestry residues	Global	23.80	0.00	23.80
Isobutanol to jet – ATJ	Miscanthus (herbaceous energy crops)	USA	43.40	–54.10	–10.70
Isobutanol to jet – ATJ	Miscanthus (herbaceous energy crops)	EU	43.40	–31.00	12.40
Isobutanol to jet – ATJ	Switchgrass (herbaceous energy crops)	USA	43.40	–14.50	28.90
Isobutanol to jet – ATJ	Corn grain	USA	55.80	22.10	77.90
Isobutanol to jet – ATJ	Sugarcane	Brazil	24.00	7.30	31.30

Source: ICAO 2021.

Figure A.1. SAF Production Pathways



Source: Original figure produced for this publication.

Appendix B: Feedstock Availability Modeling

In order to gain insight into the *availability of sustainable feedstocks*, we build upon detailed bottom-up modeling of sustainable aviation fuel (SAF) feedstock potential conducted to inform the Committee for Aviation Environmental Protection of the International Civil Aviation Organization (ICAO), as published in Staples et al. (2018). For details on the modeling we, therefore, refer to this publication. In this modeling approach, biomass and waste feedstock availability is estimated for the year 2050 as a function of physical limits (such as future arable land area, yields, residue generation) and socioeconomic factors, such as population and gross domestic product (GDP) development, and sustainability constraints. The analysis includes cultivated food crops as well as nonfood crops, agricultural residues from food and feedstock crop production, municipal solid waste (MSW), waste fats, oils, and greases (FOGs) as well as forest and wood processing residues; however, the analysis will distinguish between food crops and nonfood biomass.

In order to avoid potential conflicts of SAF feedstocks with competing land usages for feed, food, or urban dwelling purposes, current crop and urban land areas are assumed to be unavailable for SAF feedstock cultivation. Primary forests and protected areas are equally assumed to be unavailable for SAF production for sustainability reasons. As an additional sustainability safeguard for feedstocks that require dedicated arable land, we only include those lands from the Staples et al. (2018) analysis, whose conversion leads to emissions from land-use change less than 60 percent of the SAF emissions benefit from the other life-cycle steps. Land-use projections are taken from the land-use harmonization project.[1] For available arable land, a certain patch of land is assumed to be used for the feedstock type with the highest areal feedstock yield, and these yields are modeled by specific location from the global agroecological zones (GAEZ) model, that accounts for agroclimatic attainable yields of different feedstock types at a particular location (IIASA/FAO 2012). MSW quantities are estimated by using the relationships between GDP per capita and MSW generation from the Hoornweg and Bhada-Tata (2012) analysis to extrapolate MSW availability out to 2050.

Waste FOG availability is modeled as a function of future livestock production using Alexandratos and Bruinsma (2012) projections, and residue availability is modeled as a function of crop and forest product availability and assumptions on sustainable residue removal rates as discussed in greater detail in Staples et al. (2018). The estimated biomass availability per feedstock type is converted into SAF-equivalent quantities using feedstock-specific distillate conversion efficiency assumptions and SAF production shares in the finished fuel. Tables B.1 and B.2 provide an overview of core assumptions. The scope of the analysis is global, and we can break out the results by world region. For countries outside the Organisation for Economic Co-operation and Development (OECD), we can distinguish between three regions: the Middle East and Africa (MAF); Latin America and the Caribbean (LAM); Asia and the former reforming economies of Eastern Europe and the former Soviet Union (ASIA/REF), as shown in appendix S1 in Staples et al. (2018).

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[1] Data, documentation, and project description are available online at: https://luh.umd.edu.

Table B.1. Core Assumption for the Feedstock Availability Modeling

No.	Feedstock		Assumed Parameters
1.	Cultivated feedstock crops	Representative concentration pathway (RCP) Land Use Harmonization (LUH) scenario	RCP 6.0
		Hadley climate change scenario for global agroecological zone (GAEZ) yields	B2
		Inclusion of secondary forested land	Yes
		Protected areas	Not touched
		Land use change (LUC) emissions threshold	Good
		Pastureland availability	10.0%
		Shared socioeconomic pathway (SSP) scenario	SSP4
		Per annum assumed yield growth rate by region	
		MAF	1.50%
		ASIA	1.50%
		LAM	1.50%
		REF	0.25%
		OECD	0.25%
2.	Agricultural residues	Net available fraction	28.9%
3.	MSW		Dependent on assumed SSP
4.	Waste FOG	Net available fraction	50.0%
5.	Wood & forestry products	Wood fuel & roundwood availability (EJ/year)	14.0
		Net available fraction of residues	Primary: 19.8% Secondary: 8.1%

Source: Adapted from Staples et al. 2018.

Note: Scenario used and shown here is the S2 scenario from that source. MAF = Middle East and Africa; LAM = Latin America and the Caribbean; REF = former reforming economies of Eastern Europe and the former Soviet Union; OECD = Organisation for Economic Co-operation and Development; MSW = municipal solid waste; FOG = fats, oils, and grease; EJ = exajoule.

Table B.2. Distillate Output and SAF Output Assumptions Used in the SAF Feedstock Potential Analysis

Feedstock	Technology assumed	Distillate output	SAF output
Vegetable oil crops	HEFA	90%	50%
Lignocellulosic energy crops	FT	20%	70%
Starchy crops	ATJ	13%	77%
Sugary crops	ATJ	13%	77%
Lignocellulosic (LC) residues	FT	20%	70%
Food crop residues	FT	20%	70%
Municipal solid waste (MSW)	FT	20%	70%
Waste fats, oils, and greases (FOGs)	HEFA	90%	50%

Source: Adapted from Staples et al. 2018.
Note: ATJ = alcohol-to-jet; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids.

Appendix C: SAF Abatement Costs Construction

In order to shed light on the costs of emissions reductions from the use of sustainable aviation fuel (SAF), we construct a marginal abatement cost curve (MACC), in which the greenhouse gas (GHG) emissions reduction potential from the use of SAF is contrasted with the costs of reducing a metric ton of emissions. The curve is built by estimating for each SAF type the GHG abatement costs and GHG reduction potential and by stacking them up according to the merit order. Given that some feedstock types (for example agricultural and forest residues) can be converted into SAF using both thermochemical and biochemical conversion technologies, GHG emission reduction potentials are estimated for each feedstock type for the specific feedstock-conversion pathway that minimizes the GHG abatement costs.

The GHG abatement costs for each SAF pathway can be calculated according to equation 2:

$$GHGAC_i = \frac{C_{SAF,i} - C_{JF}}{EF_{JF} - EF_{SAF,i}}$$

where *GHGAC* depicts the GHG abatement cost for a SAF pathway *i* (with a pathway defined as a combination of specific feedstock type and conversion technology ,$C_{SAF,i}$ and $EF_{SAF,i}$ the costs and life-cycle GHG emission factor per SAF pathway, respectively, and C_{JF} and EF_{JF} the costs and life-cycle GHG emission factor of conventional jet fuel respectively.

In order to calculate SAF pathway-specific abatement costs we need to make assumptions about (1) the feedstock and technology scope; (2) the SAF pathway-specific GHG emission factors; and (3) the SAF pathway-specific costs; (4) an emission factors for conventional jet fuel; and (5) the costs of conventional jet fuel.

We constrain the *SAF feedstock scope* to sustainable feedstocks as defined in WEF (2020): Feedstock groups, therefore, include waste fats, oils, and greases (FOGs), oil cover crops, oily feedstock grown on degraded lands, municipal solid waste (MSW), crop residues, forestry residues, and lignocellulosic energy crops. In other words, in our analysis, no food or feed crops grown as a first crop on arable lands are taken into account for sustainability reasons. Three different *SAF conversion technologies*—ATJ (alcohol-to-jet), FT (Fischer-Tropsch), and HEFA (hydroprocessed esters and fatty acids)—are considered to cover the three major conversion technology options (lipid conversion, thermochemical conversion, and biochemical conversion). *SAF pathway-specific emission factors* are derived from the default values available within CORSIA. For *conventional jet fuel*, the CORSIA baseline *emissions factor* of 89 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) was used. The *SAF costs* data for the different feedstock groups and conversion pathways were obtained from the available literature. Costs were harmonized by augmenting the discount rate and analysis year, where needed. *Conventional jet fuel costs* are taken from data available from the U.S. Energy Information Agency (EIA 2021).

Given the immaturity of the current SAF market, we model SAF abatement costs for the year 2030. We augment the SAF cost estimates derived for our base year (2019) to the year 2030 by accounting for pathway-specific cost-reduction factors from the expert assessment presented in WEF (2020), where available, or directly from the original reference. The year 2030 conventional jet fuel costs are modeled using the range of price forecasts for that year from EIA (2021). Finally, feedstock availability estimates for the year 2030 are taken from WEF (2020). We also model first-order estimates for abatement cost per SAF pathway out to 2050 by using the expert judgement from WEF (2020) in combination with EIA (2021)'s forecast for year 2050 jet fuel prices. Note that for the year 2050 analysis, no changes were made with regard to feedstock availability assumptions in this report. Tables C.1 to C.4 depict the full data used in the abatement cost analysis for each of the SAF pathways. We use the estimates on feedstock type-specific SAF costs per metric ton of carbon dioxide equivalent (tCO_2e) abatement in combination with the feedstock availability estimates to develop marginal abatement cost curves (MACC) for the use of SAF (table C.5).

Table C.1. Assumed SAF Price Ranges under Different Feedstock-Production Process Combinations

US$ (2020) per gigajoule of sustainable aviation fuel (GJ_{SAF})

Pathway	Feedstock group	Year	Min	Midpoint	Max	Reference
ATJ	Crop residues	2030	$56.61	$79.74	$102.86	(Doliente et al. 2020)[a]
ATJ	Forestry residues	2030	$32.11	$45.75	$59.39	(Capaz et al. 2021)
ATJ	Starchy energy crops	2030	$33.18	$43.39	$53.60	(Bann et al. 2017)
ATJ	Sugary energy crops	2030	$23.86	$34.65	$45.44	(Capaz et al. 2021)
ATJ	Lignocellulosic energy crops	2030	$49.67	$63.26	$76.85	(Bann et al. 2017)
FT	Crop residues	2030	$53.12	$58.67	$64.22	(Capaz et al. 2021; Doliente et al. 2020)
FT	Forestry residues	2030	$44.20	$48.66	$53.12	(Capaz et al. 2021; Doliente et al. 2020)
FT	Municipal solid waste (MSW)	2030	$34.36	$42.32	$50.28	(Bann et al. 2017)
HEFA	Oil-bearing trees on degraded lands	2030	$28.58	$35.76	$42.95	(Tao et al. 2017; Wang and Tao 2016; Zech et al. 2018)
HEFA	Waste from fats, oils, and greases (FOGs)	2030	$24.51	$28.09	$31.67	(Capaz et al. 2021)
HEFA	Oil cover crops	2030	$23.16	$29.02	$34.88	(Alam et al. 2021; Capaz et al. 2021)
ATJ	Crop residues	2050	$52.65	$74.15	$95.66	(Doliente et al. 2020)[a]
ATJ	Forestry residues	2050	$29.87	$42.55	$55.24	(Capaz et al. 2021)
ATJ	Starchy energy crops	2050	$30.87	$40.36	$49.86	(Bann et al. 2017)
ATJ	Sugary energy crops	2050	$22.20	$32.23	$42.27	(Capaz et al. 2021)
ATJ	Lignocellulosic energy crops	2050	$46.20	$58.85	$71.49	(Bann et al. 2017)
FT	Crop residues	2050	$45.70	$50.47	$55.24	(Capaz et al. 2021; Doliente et al. 2020)
FT	Forestry residues	2050	$35.58	$41.81	$48.04	(Capaz et al. 2021; Doliente et al. 2020)

Pathway	Feedstock group	Year	Min	Midpoint	Max	Reference
FT	MSW	2050	$29.56	$36.41	$43.25	(Bann et al. 2017)
HEFA	Oil-bearing trees on degraded lands	2050	$26.99	$33.78	$40.57	(Tao et al. 2017; Wang and Tao 2016; Zech et al. 2018)
HEFA	Waste FOGs	2050	$23.15	$26.53	$29.91	(Capaz et al. 2021)
HEFA	Oil cover crops	2050	$21.87	$27.41	$32.94	(Alam et al. 2021; Capaz et al. 2021)

Source: Original table produced for this publication.

Note: a. The minimum selling price (MSP) in original reference does not include variation in MSP. Variation was added here by taking the variation of the alcohol-to-jet forestry residues pathway in percentage change from the mid-point. ATJ = alcohol-to-jet; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids.

Table C.2. Projected Conventional Jet Fuel Price, 2020

US$ per gallon

Year	High prices	Low prices	Business-as-usual
2022	$2.48	$1.00	$1.54
2023	$2.82	$1.09	$1.71
2024	$3.05	$1.16	$1.85
2025	$3.22	$1.23	$1.93
2026	$3.32	$1.26	$2.01
2027	$3.44	$1.28	$2.05
2028	$3.54	$1.28	$2.12
2029	$3.63	$1.29	$2.16
2030	$3.70	$1.31	$2.22
2031	$3.72	$1.33	$2.27
2032	$3.81	$1.37	$2.32
2033	$3.88	$1.39	$2.35
2034	$3.93	$1.39	$2.37
2035	$3.98	$1.42	$2.39
2036	$4.05	$1.43	$2.41
2037	$4.10	$1.45	$2.45
2038	$4.18	$1.45	$2.49
2039	$4.21	$1.47	$2.50
2040	$4.27	$1.46	$2.56
2041	$4.28	$1.47	$2.59
2042	$4.32	$1.48	$2.62
2043	$4.35	$1.49	$2.67

Year	High prices	Low prices	Business-as-usual
2044	$4.39	$1.51	$2.68
2045	$4.44	$1.53	$2.69
2046	$4.47	$1.55	$2.73
2047	$4.51	$1.55	$2.75
2048	$4.57	$1.57	$2.75
2049	$4.60	$1.58	$2.77
2050	$4.64	$1.60	$2.77

Source: EIA 2021.

Note: For calculation purposes, a density and low heating value of 757 kilogram per cubic meter (kg/m^3) and 43.2 megajoule per kilogram (MJ/kg) respectively, were assumed for conventional jet fuel.

Table C.3. SAF GHG Emission Factors by Feedstock-Production Process Combination and Scenario

Grams of carbon dioxide equivalent per megajoule (gCO$_2$e/MJ)

Pathway	Feedstock group	Minimum	Midpoint	Maximum
ATJ	Crop residues	24.6	32.15	39.7
ATJ	Forestry residues	23.8	31.9	40
FT	Crop residues	3.3	7.7	12.2
FT	Forestry residues	3.9	8.3	12.8
FT	Municipal solid waste (MSW)[a]	0.8	5.2	9.7
HEFA	Oil-bearing trees on degraded lands	−1.3	10.4	22.1
HEFA	Waste from fats, oils, and greases (FOGs)	13.9	18.2	22.5
HEFA	Oil cover crops	12.9	12.9	12.9

Source: Adapted from ICAO 2021; values derived from the range of results in ICAO CORSIA default values (ICAO 2021).

Note: a. Only a biogenic fraction. Where there was no variation in the default value results, a range was defined for a pathway based on the definition of a pathway in the CORSIA system (up to 8.9 grams of carbon dioxide equivalent per megajoule (gCO$_2$e/MJ) variation in the result are allowed). This range was applied in those cases to establish a minimum and maximum value for a known midpoint value. ATJ = alcohol-to-jet; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids.

Table C.4. Estimated Feedstock Availability for SAF Production

Million metric tons of sustainable aviation fuel (Mt_{SAF})

Pathway	Feedstock	Availability in million metric tons (Mt) of SAF
ATJ	Lignocellulosic energy crops	20
ATJ	Starchy energy crops	37
ATJ	Sugary energy crops	29
ATJ	Crop residues	118
ATJ	Forestry residues	69
FT	Municipal solid waste (MSW)	65
FT	Crop residues	37
FT	Forestry residues	114
HEFA	Oil-bearing trees on degraded lands	118
HEFA	Oil cover crops	69
HEFA	Waste from fats, oils, and greases (FOGs)	65

Source: WEF 2020.

Note: For calculation purposes, a low heating value of 43.2 megajoule per kilogram (MJ/kg) was assumed for SAF. ATJ = alcohol-to-jet; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids.

Table C.5. Marginal Abatement Cost Curve (MACC) Scenarios

Scenario	SAF price	Jet fuel price	SAF GHG emission factor	Reference year for SAF cost decreases
2030 – Moderate ambition	Low	Midpoint	Mid	2030
2030 – SAF emphasis	Low	Min	High	2030
2050 – Moderate ambition	Low	Midpoint	Mid	2050
2050 – SAF emphasis	Low	Min	High	2050

Source: Original table produced for this publication. SAF = sustainable aviation fuel; GHG = greenhouse gas.

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