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MIT Center for Sustainability Science and Strategy
MIT Laboratory for Aviation and the Environment

MIT CS3 Special Report

Sustainable Decarbonization of Aviation in Latin America

Assessing emission mitigation policies, aviation demand, and jet fuel consumption up to 2050

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MIT Authors Team:

Sergey Paltsev • Angelo Gurgel • Jennifer Morris • Henry Chen
MIT Center for Sustainability Science and Strategy

Florian Allroggen • Niamh Keogh
MIT Laboratory for Aviation and the Environment

Contact:

Sergey Paltsev (paltsev@mit.edu)

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- **Advance** fundamental understanding of the Earth's complex, interconnected physical and socio-economic systems.
- **Leverage** leading-edge computing and data through the development and dissemination of new knowledge, tools and strategies.
- **Generate** actionable scientific information that mitigates risks to critical life-support systems while supporting equity and justice.

Key Takeaways

- In the scenario of **current policy** approaches and emission trajectories, **aviation demand** in Latin America is expected to **more than triple** between 2019 to 2050, and the corresponding **aviation emissions** are projected to **double**.
- **The aviation sector** is aiming at reaching a **net zero target** by 2050. **Decarbonizing** aviation is a **needed but challenging** task.
- **Sustainable aviation fuels (SAF)** offer a significant decarbonization pathway in Latin America.
- In the **most ambitious economy-wide** emission mitigation scenario considered (1.5°C stabilization pathway with 65% SAF use in Latin America by 2050), we project **aviation emissions to be reduced by about 60%** in 2050 compared to the scenario of current trends considering impacts from SAF use and economy-wide policy (e.g., more efficient aircraft, demand response). To reach net-zero goals, **other measures will be required,** such as improvements in operational and air traffic efficiencies, airplane fleet renewal, alternative forms of propulsion, carbon offsets and removals.
- In Latin America, currently (2024) **jet fuel prices are around $0.70/liter.** It is projected that in the emission mitigation scenario, **carbon prices** by mid-century might be around $200-250/t$CO_2$. This level of carbon pricing might result in **almost doubling jet fuel prices by 2050.** We project the corresponding **reduction in aviation emissions by 22%** (without targeted SAF policies).
- Based on the current **availability of feedstocks**, we project **SAF costs** to range from $1.11–1.77/liter in Brazil, to $1.68–2.53/liter in Chile, $1.51–2.54/liter in Colombia, $1.32–2.15/liter in Ecuador, $1.41–2.40/liter in Mexico, and $1.38–2.86/liter in Peru.
- **Increased fuel prices could affect operating costs** of the aviation sector and could **affect overall aviation demand** in the absence of strategies to **manage price increases**.
- **Sugarcane-based ETJ, palm oil-based HEFA**, and **soybean-based HEFA** offer the most promising near-term opportunities for SAF production in Latin America.
- **Second-generation biofuels** (i.e., based on non-food feedstocks) and **e-fuels** (i.e., power-to-liquids) are more expensive, and expected to **require more R&D** to become economically viable.
- In the most ambitious SAF scenario considered, the total cumulative **capital investments required to build new SAF producing plants** between 2025 and 2050 are estimated at US$204 billion for the six countries studied (US$84 billion in Brazil, US$27 billion in Chile, US$23 billion in Colombia, US$5 billion in Ecuador, $US49 billion in Mexico, US$16 billion in Peru).
- **Government policy and regulatory mechanisms will be required** to create the enabling conditions to attract SAF investments in the region and make **SAF commercially viable**, while **balancing the impact of decarbonization** measures on passenger demand and connectivity.
- For **fuel producers**, **stable policies and regulations** with a long-term vision can create **robust supply chains**, to build a consolidated demand for establishing **economies-of-scale**, and to develop **innovative SAF production pathways.**
- **Unification of decarbonization approaches** between countries will ensure **competitiveness**, economy-of-scale, and **avoidance of leakage** of carbon emissions. Consideration of **international approaches**, such as **CORSIA sustainability criteria**, will help **maintain a level playing field** for aviation in the entire region.
- There is a potential **benefit of international SAF trading.** If the ambitious SAF scenario (65% SAF use by 2050) is applied to the six countries studied (in the global emission mitigation scenario), and they relied solely on domestic SAF production to fulfill this target, aviation demand growth measured in RPK (revenue per passenger kilometer) would be reduced by 5% in 2050. However, if **SAF trading** was introduced, enabling each country to access the **most competitive fuel**, it would **nearly halve the negative impact** on demand growth.
- Because of **different potentials** for the amounts and costs of SAF production, we project that in the case of **regional SAF trading** Brazil, Colombia, Ecuador, and Peru become **SAF exporters**, while Chile and Mexico find it economically attractive to **import SAF**.
- There is a need for **country-specific studies** (on feedstock availability, trading approaches, impacts of policies and regulations) that involve international and **local experts.**

Contents

1 Introduction

The world is facing a serious threat from climate change (IPCC, 2023). Following the goals of the Paris Agreement (UN, 2015), governments, international organizations and companies advocate and explore sustainable pathways to reach net-zero CO_2 and eventually the net-zero overall greenhouse gas (GHG) emissions. In the pursuit of emission reductions, aviation stands out as a hard-to-abate sector because of the relatively limited and expensive mitigation options (ICCT, 2022). According to the International Energy Agency (IEA), aviation accounts for about 2% of global energy related emissions. Without additional policies, aviation emissions are expected to grow from about 0.8 $GtCO_2$ in 2022 to about 1.6-1.8 $GtCO_2$ in 2050 (IEA, 2023; IATA, 2023).

This potential emission growth is driven by the forecasted increase in demand for aviation services. Typically, demand growth is associated with making flying more affordable and efficient for larger segments of the global population. IEA projects an annual growth in aviation demand of about 4% until 2050 (IEA, 2023). Airbus states that air traffic and airline operations are broadly back to pre-Covid levels or higher with few exceptions (Airbus, 2024). In the next three years, Airbus expects traffic to grow at about 8% per year, to catch up lost growth over the pandemic, and then the annual growth is expected to be approximately 3.6% from 2027 onwards (Airbus, 2024). ICCT (2022) provides a range between 2.4% and 3.7%, with a central estimate of 3% of annual growth until 2050.

Projections for Central and South America result in similar trajectories for aviation growth. From 2027 to 2043, domestic passenger traffic is expected to grow at 2.7% per year in Central America and at 4.3% in South America (Airbus, 2024). International routes to and from Central and South America exhibit substantial growth, especially with Africa, The Middle East, India, China and emerging Asia (Airbus, 2024). Air transport is an important component for the economies of Latin America. It is estimated that it contributes 3.5% to regional GDP and helps to support 7.7 million workers, including direct, indirect, and tourism induced jobs (Airbus, 2023). To deliver the increased benefits of air travel to wider segments of the population, aviation services need to be provided in a sustainable manner, with the associated CO_2 emissions being dramatically reduced and eventually eliminated.

To support the Paris Agreement targets, the International Air Transport Association (IATA) member airlines have committed to a goal of reaching net-zero carbon emissions from their operations by 2050 (IATA, 2021). The long-term aspirational goal (LTAG) of net-zero carbon emissions was adopted by the member states of the International Civil Aviation Organization (ICAO, 2022). Achieving the net-zero goals in aviation will require a combination of actions, including low-carbon and zero-carbon sustainable aviation fuels (SAF), new aircraft technology (including more fuel efficient aircraft and potentially battery electric and hydrogen-powered aircraft), improvements in operation and fuel efficiency, and carbon removals using market-based mechanisms (MBM), such as carbon offsets and acquiring negative emission allowances (IATA, 2023). Currently, many advanced technological options still have low technology readiness levels, and the pace of their deployment will depend on the policy instruments that would provide incentives for accelerated actions. SAF has been proposed as a major component for GHG emission mitigation in the aviation industry because it does not require engine or system modification in aircraft or refueling infrastructure so they can largely be used with existing fleet and infrastructure ("drop-in fuels") (ATAG, 2021; IATA, 2023, Prussi et al, 2021).

The goal of this report is to contribute to the existing literature by providing a regional assessment of aviation decarbonization options in selected countries in Latin America. In particular, we focus on the following six countries: Brazil, Chile, Colombia, Ecuador, Mexico, and Peru. For these countries, we provide an assessment of SAF feedstock availability, the costs of the corresponding SAF pathways, and the likely implications of SAF deployment on fuel use, prices, emissions, and aviation demand in these countries. We also explore efficiency improvements and the role for market-based mechanisms in reaching decarbonization targets.

The report is organized in the following way. In Section 2 we provide a summary of the current decarbonization pledges of the countries selected for our analysis. Section 3 discusses policy and technology options for decarbonizing aviation and provides a context for Latin American countries for these options. Section 4 focuses on the results for individual countries and benefits of regional collaboration, and in Section 5 we provide our recommendations for accelerating decarbonization of aviation in Latin America in a sustainable way that considers socioeconomic and environmental implications.

2 Emission reduction pledges of the selected Latin American countries

With an expected growth of air passenger traffic in Latin America at an average annual rate of 3-4% in the upcoming decades, a combination of emission mitigation measures will be needed to reach ambitious decarbonization goals. Furthermore, decarbonization activities in the aviation sector should be integrated with the overall economy-wide emission mitigation. Several Latin American countries declared “net-zero emissions” or “climate neutrality” goals for their economies for mid-century; however, their current decarbonization progress is rather slow (Climate Action Tracker, 2023). To get on track with the declared goals, governments need to accelerate the adoption of regulatory incentives for low-carbon options. The pace of the economy-wide emission mitigation actions will also affect the opportunities for decarbonizing the aviation sector because of its inter-dependence on other sectors of the economy. Hence, we start with a short discussion of the economy-wide goals and actions in the selected countries.

According to the Paris Agreement process, countries submit their emission mitigation “pledges” in the form of their Nationally Determined Contributions (NDCs). These pledges are periodically updated. The current set of NDCs is formulated for 2030, and these NDCs are publicly available at the UN Registry (UNFCCC, 2023). The next round of NDCs is expected to be submitted in 2025 with the emission mitigation targets specified for 2035. International flights and their CO_2 emissions are excluded from the NDC process because they are governed by the international aviation authorities. The International Civil Aviation Organization (ICAO) developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to incentivize the emission reduction from international flights (ICAO, 2023a). Among the six countries of our interest, only Ecuador and Mexico are currently participating in CORSIA. From 2027, Brazil will also be a part of CORSIA due to its mandatory requirement based on international traffic levels (IATA, 2024a). While ICAO in its Third Conference on Aviation and Alternative Fuels (CAAF/3) has set a collective vision that aviation fuel in 2030 should be 5% less carbon intensive than the fossil fuel which makes up nearly all of today’s aviation energy (ICAO, 2023b), it does not stipulate how individual countries will contribute to this goal. It should be noted that CORSIA only applies to international flights. Emissions reductions from domestic flights are subject to country-specific regulations, and they are affected by the mitigation plans for domestic economy-wide emissions.

In Table 1 we provide a summary of national GHG emissions for our selected countries for 2005 and 2019. The reporting is divided into two categories: (1) GHG emissions excluding land use change and forestry (LUC), and (2) emissions (removals) from LUC. According to the UNFCCC (2006), LUC inventories cover emissions and removals of GHG resulting from direct human-induced land use, land use change and forestry activities (LULUCF). For brevity, we denote this emission category as LUC. Note that LUC reporting is different from the indirect land use change (ILUC), a category that is used for calculating emission intensities of aviation fuels. ILUC emissions may occur within and outside national boundaries of a reporting country, while LUC emissions are accounted in national inventories within the reporting country.

As can be seen from Table 1, LUC emissions are sizeable for several Latin American countries, especially for Brazil, Colombia, and Peru. In 2019, the LUC share in total anthropogenic GHG emissions was 33% in Brazil, 36% in Colombia, and 52% in Peru. Ecuador’s LUC emissions contribute a smaller, but still a sizeable share (21%) of its overall GHG emissions. On the contrary, LUC emissions for Chile and Mexico are negative, and they provide a carbon sink to counterbalance GHG emissions from the other sectors of their economies. Land-use change, agriculture and forestry projects can create additional opportunities by providing the emission offsets to CORSIA and other voluntary and mandatory mechanisms if emission reduction is achieved according to the requirements of those regulatory schemes.

Total GHG emissions (excluding LUC) from the six countries (represented in Table 1) grew from about 1,900 $MtCO_2e$ in 2005 to about 2,300 $MtCO_2e$ in 2019. Emissions from these six countries constitute a 4.5% share of the corresponding global emissions. LUC emissions are dramatically reduced from about 1,500 $MtCO_2e$ in 2005 to about 500 $MtCO_2e$ in 2019. These reductions are driven by Brazil (mostly due to its forest law enforcement strategy to combat illegal deforestation (UNFCCC, 2020)), while the other countries have not changed their LUC emissions substantially. **Table 1** provides the numbers for 2005 and 2019 because 2005 is a typical baseyear for the current NDCs.

Table 1. GHG Emissions in selected countries. Data source: Climate Action Tracker (2023).

MT CO2e	2005		2019	
	Excluding LUC	LUC	Excluding LUC	LUC
Brazil	951	1573	1112	561
Chile	81	-73	114	-64
Colombia	124	86	176	99
Ecuador	48	39	59	16
Peru	72	87	100	109
Mexico	624	-199	722	-201

Note: Climate Action Tracker does not report the data for Ecuador. For Ecuador, the data are for 2006 and 2018 from the 4th National Communication of Ecuador to UNFCCC (Ecuador NC4, 2023).

As for the country-specific targets, Brazil's current pledge (Brazil NDC, 2023) is to reduce its 2030 net GHG emissions to 1.2 $GtCO_2e$, which is consistent with a reduction of 53.1% below 2005 levels. While the limit includes land sector emissions, Brazil has not indicated the extent to which it will rely on reducing emissions from its land sector to achieve the NDC goal. Brazil also has a mid-century target to achieve "climate neutrality" by 2050. This target is reiterated in the 2023 NDC submission.

Chile submitted its updated NDC in 2022 (Chile NDC, 2022). For 2030 emissions, it has an unconditional target of 95 $MtCO_2e$ (excluding LUC). It also has a conditional emissions reduction target of up to 45% net GHG emissions from 2016 levels. Achieving this target is provisional on receiving international finance and technology transfers. As reported in Table 1, Chile's GHG emissions in 2019 were 114 $MtCO_2e$. To meet the unconditional target, Chile needs to reduce its emissions by 19 $MtCO_2e$ relative to the 2019 level. Chile also announced a net zero GHG target for 2050. Chile's updated NDC also expands its ecosystem protection by 2030 and commits to reverting the growing trend of methane emission by 2025.

Colombia and Peru have targets for their levels of emissions in 2030. For Colombia it is 169.4 $MtCO_2e$ (excluding LUC). Peru has two targets, which include LUC. The unconditional target for Peru for 2030 is 208.8 $MtCO_2e$. With conditions on international finance, this 2030 target can be lowered to 179 $MtCO_2e$. Colombia and Peru also have their 2050 targets: "carbon-neutrality" for Colombia and "net-zero emissions" for Peru.

Ecuador and Mexico specify their targets relative to a "baseline" or "business-as-usual (BAU)" scenario rather than relative to some historic emission level. Ecuador's targets are for 2025, with the unconditional target of 9% below its 2025 baseline and the conditional target of 20.9% below its 2025 baseline. Mexico's targets are for 2030 with the unconditional target of 35% below 2030 BAU and the conditional target of 40% below 2030 BAU. So far, Ecuador and Mexico have not officially stated emission reduction goals for 2050.

Climate Action Tracker (2023) rates the current NDCs of Brazil, Chile, Colombia and Peru as "insufficient", Mexico as "critically insufficient", and Ecuador is not rated. It is expected that the next round of NDC submissions will be more aggressive in terms of the targets for their GHG emission reductions. Such reductions will have impacts on prices and GDP, which will also affect the domestic aviation sector in these countries. While aviation emissions contribute 1.5-3% to the total national emissions in the six studied countries, emission reductions from all sectors of the economy are needed and these activities will affect all sectors, including aviation.

Domestic policies for decarbonizing aviation in Latin America are still in their early stages of development. Currently, discussions are mostly focused on the SAF deployment component of the overall aviation emission reduction. Separately, there is also a discussion on carbon offset projects through CORSIA. In terms of the current (as of 2024) national regulations, Brazil in 2024 introduced the Fuel of the Future Law that requires a percentage emission reduction relative to a scenario with a conventional jet fuel emission intensity. It starts in 2027 with a 1% reduction and gradually grows to 3% reduction in 2030, 6% in 2033, and 10% in 2037 and thereafter (ProBioQAV, 2024).

Chile announced a roadmap for its SAF, called Vuelo Limpio (Clean Flight), which outlines the steps to reach a goal for 2050 where SAF would contribute 50% of the fuel used in Chile's domestic and international aviation sector (Ministry of Transport and Telecommunications, 2023). Other countries are still exploring the national strategies for SAF deployment and the overall aviation decarbonization. Colombia has the SAF aspiration in development (Aerocivil, 2024). There are active consultations on these issues in Ecuador, Mexico, and Peru, but their proposals are still under development.

3 Policy and technology options for decarbonizing aviation

Policy frameworks are the key to determine a nation's ability to incentivize the deployment of new technologies (such as newer aircraft fleets or low-carbon fuels), attract private capital, internalize externalities (such as the health effects of air pollution and climate change), modernize aviation infrastructure, and expand access to connectivity to wider segments of the society. These policies can range from broader policies like energy price reforms through tax incentives and energy subsidy reduction to technology-specific policies like mandates for biofuel-based or synthetic fuels. Carbon pricing through taxes or quantity controls with tradeable units both leave the allocation of resources to the market and can thereby equalize abatement costs across all covered entities, avoiding technology-picking and offering superior cost-effectiveness over alternative instruments.

Other types of instruments – such as price support measures and fiscal subsidies – can be successful in building coalitions of support, and have also been confirmed through opinion surveys to be more popular with the public (Paltsev et al., 2018). Weak administrative capacities, legal challenges, and unclear mandates can undermine or delay the practical implementation of these instruments which promise to be the most effective and efficient in theory, as shown in the operation of complex policy instruments, such as the European Union Emissions Trading Scheme (EU ETS). Likewise, constitutional or statutory property rights, or state contracts and transparent dispute settlement procedures guaranteeing the rights of investors, are a key factor for determining the ability of countries to attract investments in clean fuels and aviation technologies.

As mentioned, CORSIA is a global measure developed by ICAO. The first mandatory phase of CORSIA – starting in 2027 – will obligate aircraft operators in participating countries to reduce or offset their emissions for international flights beyond 2019 levels (IATA, 2024a). Exemptions are provided to countries with a small share of international traffic, least-developed, small island developing and landlocked developing countries (but they can volunteer to participate). It is expected that Brazil, Ecuador and Mexico will be covered by CORSIA from 2027, while Chile, Colombia, and Peru will have an option to participate if they decide to join.

The European Union included aviation in its emission trading scheme (EU ETS). It implements CORSIA for international flights departing from and arriving to the European Economic Area and applies the EU ETS to the flights within. The EU plans to determine in 2026 if CORSIA provides appropriate emission reduction. Depending on the assessment, the scope of the EU ETS could be expanded (EC, 2024). The EU also introduced the SAF mandates (Official Journal of the European Union, 2023). Beginning in 2025, fuel uplift at the EU airports must contain at least 2% SAF. That percentage will increase over time, with the mandates rising to 6% by 2030, 20% by 2035, and eventually 70% by 2050. From 2030, 1.2% of jet fuels must also be synthetic fuels, rising to 35% in 2050. The EU defines synthetic fuels as renewable fuels of non-biological origin (e.g., e-fuels or power-to-liquids). These fuel requirements will apply to all flights originating in the EU, regardless of destination. For the initial phase (2025-2026), the EU reserved some funds from the EU ETS (20 million ETS allowances, which at a price of 80 Euro is worth 1.6 billion Euro) to support the price difference between conventional jet fuels and SAF.

The legislation calls for the EU Commission to produce a report on feasibility of the "book and claim" system. According to the US International Trade Administration, book and claim would allow airlines flying from an airport without access to SAF to purchase it for use by other operators elsewhere. This way, they are still paying the extra cost of the SAF without having to physically use the fuel in flights where it would be impractical (US ITA, 2024).

In the U.S., the Inflation Reduction Act (IRA) provides fuel producers a tax credit of $1.25 for each gallon of SAF in a qualified mixture. To qualify for the credit, the SAF must have a minimum reduction of 50% in lifecycle GHG emissions. There is also a supplemental credit of one cent for each percent that the reduction exceeds 50%. The maximum value of the SAF credit is $1.75/gallon (IRS, 2024). By 2025, this "SAF tax credit" will be replaced with the Cleaner Fuel Production Credit. In addition, SAFs may qualify for support under the renewable fuel standards (RFS) program. Some states (e.g., California, Oregon, Illinois) provide additional incentives in the form of SAF tax credits, low-carbon fuel standards, and clean fuel programs.

If policy incentives do not fully cover the cost premiums of SAFs, the emission mitigation policies can affect growth rates for aviation demand. In particular, the growth rates for global passenger traffic may be affected because of the increased costs of aviation fuels (from using larger shares of low-carbon and zero-carbon fuels) and associated travel price increase, which can affect travel behavior. In Latin America, fuel costs contribute 30-40% to operating costs of airlines, so that significant fuel price increases have the potential to affect overall costs.

For example, ICCT (2022) estimates that passenger traffic (measured in revenue passenger kilometers, RPK) in 2050 would be 7% lower in the Breakthrough policy scenario (that represents the efforts to reduce carbon emissions in global aviation to zero by 2050) in comparison to their baseline case (that represents a continuation of the status quo). The reduction is due to an estimated 22% increase in ticket prices and 70% increase in fuel costs in 2050 in comparison to the scenario without a strong emission reduction policy. The Mission Possible Partnership (MPP) reports an average fuel cost increase of 75-120% in 2040 compared with fossil jet fuel costs. For 2050, the fuel cost increases are projected to be in the range of 90-190% (MPP, 2022).

Correspondingly, fuel cost increases can also affect the fuel consumption by aviation. According to ICCT (2022), global aviation is projected to consume about 25 EJ in 2050 in the baseline case, but this number is reduced to about 16 EJ in their aggressive policy scenario. IEA (2023) reports similar estimates: 24 EJ of aviation fuel in 2050 in the Stated Policies Scenario (STEPS) and 15 EJ in 2050 in the Net-Zero Emission (NZE) scenario, a reduction of 35% between the scenarios in 2050. A major contributor in the IEA-projected reduction of aviation activity is driven by behavioral changes due to such factors as switching from flying to trains or videoconferencing, reduction in business travel, introducing frequent-flyer levies, individual choices, and others (IEA, 2023).

Fuel efficiency improvements throughout the past years were substantial, but they are outpaced by an increasing demand for air travel (Airbus, 2024). An aggregate aviation fuel efficiency is a combination of several components: efficiency of aircraft fuel burn (i.e., technical efficiency), improved aircraft utilization (i.e., payload efficiency), and operational efficiency (i.e., traffic efficiency). From 1990 to 2019, Airbus reports a 2.6% annual improvement in the aggregate fuel efficiency of global aviation (Airbus, 2023).

These improvements may also vary by region. For example, Graver (2022) estimated fuel efficiency improvements for the U.S. commercial flights between 2005 and 2019, and he concluded that the average annual aggregate fuel efficiency improvements were 1.5%, of which 0.4% attributed to aircraft fuel burn, 1% to payload efficiency, and 0.1% to traffic efficiency.

For future projections, ICCT (2022) assumes 1.08% annual improvements in technical efficiency (based on the near-term product mix of airplanes), 0.2% annual improvements in payload efficiency, and 0.1% annual improvements in traffic efficiency. In more aggressive scenarios after 2035, these numbers increase to 2.16%, 0.5%, and 0.7%, respectively (ICCT, 2022). IEA (2023) for its 2019-2050 projections uses 1.3% annual aggregate improvement rate in the STEPS scenario, and in the NZE scenario this number is assumed to increase to 2%. Of course, the larger efficiency improvements result in the lower projected fuel use and the corresponding lower CO_2 emissions. Since these efficiency improvements cannot offset the market growth, additional contribution to decarbonization needs to come from other options, such as SAF.

Figure 1 provides an illustration of potential magnitudes for different actions for aviation decarbonization by 2050 as envisioned by IATA (2023). While efficiency improvements and alternative aircraft technology are important contributors, it is clear that SAF will play a major role in reaching the net-zero goals. It also should be noted that some carbon removal offsets (either nature-based or technological) will be needed to cover the residual emissions. These IATA results are consistent with the findings from IEA (2023), ICCT (2022), and ICAO (2022).

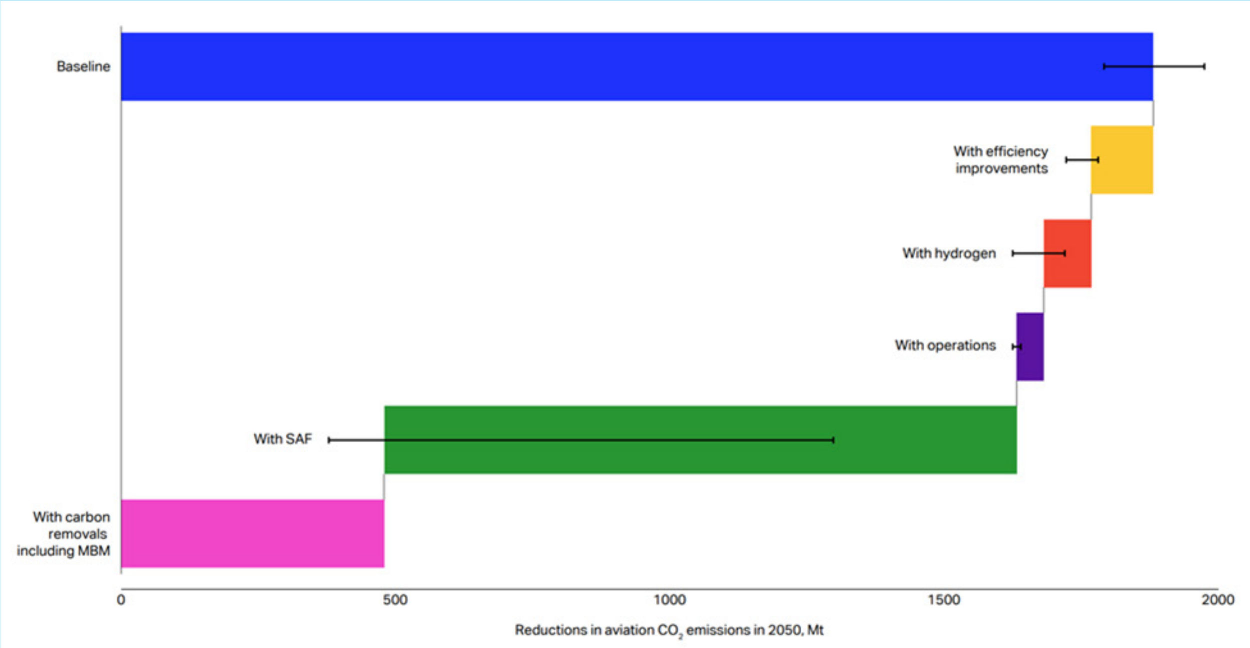

Figure 1. IATA illustrative roadmap for reduction in global aviation by 2050. Black horizontal lines represent a range of scenarios for different options. MBM – market-based measures, such as levies, emission trading, and offsetting; SAF – sustainable aviation fuels; “with operations” refers to better traffic management. Source: IATA (2023).

Note that the range for a potential SAF contribution to decarbonization is rather wide. For example, Air Transport Action Group (ATAG) explored several decarbonization scenarios and concluded that SAF can contribute from 53% to 71% towards the aviation emission reductions in 2050 (ATAG, 2021). The total capital investments required to build SAF plants might be significant. IATA (2024b) estimates that in a net-zero CO_2 transition scenario, the cumulative investments in new

SAF plants are in the range of US$ 4-8 trillion over the period of 2024-2050. All these studies are focused on global results based on global averages, and there is a need for detailed evaluations of region-specific policy mechanisms to inform decision makers at different regional levels and to achieve emission reduction goals in aviation while being sensitive to local circumstances and capacities.

Different technologies exist for making SAFs, which can be broadly divided into bio-based SAFs and power-to-liquids (PTL). Bio-based SAFs use renewable and waste biomass feedstocks as carbon sources. There is a wide range of potential feedstocks, such as sugarcane, soybean oil, rapeseed oil, corn, used cooking oil, animal fat, and many others. To qualify under CORSIA, such feedstocks are required to meet a set of sustainability criteria (Prussi et al., 2022). PTL fuels do not depend on biomass. They are also referred to as “e-fuels” (this term is popular in Europe) or “synthetic fuels” (this term is somewhat mis-leading as all SAFs are based on a synthetic blend component).

There are several conversion processes that can be used for converting biomass feedstocks into SAFs. They include ethanol to jet (ETJ), hydroprocessed esters and fatty acids (HEFA), synthesized iso-paraffins (SIP), Fischer-Tropsch (FT) and others (see Figure A1 in Appendix A). A fundamental characteristic of SAFs is compliance with the standards developed by ASTM, an organization that defines the technical international standards for a wide range of materials, products, systems, and services. It must be noted that for a fuel to be eligible for use in commercial aircraft, the conversion process must be approved by ASTM.

PTL SAFs are produced from a syngas mixture of carbon (carbon monoxide) and hydrogen, where both carbon and hydrogen are obtained from zero- and/or low-emitting sources. These inputs can be converted to SAFs using a variety of processes, including, for example, FT processes. Methanol conversion offers a viable pathway as well, but is not currently ASTM certified. For carbon sources of PTL SAFs, the pathways need to ensure net carbon-neutrality and include direct air capture (DAC) and/or biomass with carbon capture (Desport et al., 2024). Electricity input for DAC needs to be carbon-free. While it is possible to run DAC on fossil fuels, a DAC process using, for example, coal-based electricity would generate 1.2 tonnes of CO_2 for every tonne of CO_2 captured, which would result in net emission increasing (Herzog et al., 2024). For low carbon intensity hydrogen, it can be produced through electrolytic routes (“green hydrogen”) or natural gas reforming with carbon capture and storage (“blue hydrogen”). If green hydrogen is used, a significant amount of electricity input is needed – which is why these fuels are sometimes referred to as power-to-liquid (PTL) fuels.

Another pathway for SAF is co-processing of bio-based feedstocks in existing petroleum refineries. A part of the output is declared as bio-based and that part could be assigned to SAF output. Co-processing can be done with lipids (i.e., fats, oil greases and numerous bio-based oils (e.g., soybean oil)). However, the current ASTM standard does not allow blending of more than 5% of lipids into the crude input stream of the refinery. Current efforts are under way in ASTM to allow higher shares of biogenic input. While IATA (2024b) concludes that co-processing might be useful to reduce the need for initial capital investments for SAF, co-processing is not consistent with the long-term decarbonization targets as it relies on the continued refining of crude oil in refineries.

Under CORSIA, there is also an option to produce the lower carbon aviation fuels (LCAF) from fossil sources. To qualify, LCAFs need to provide at least a 10% reduction in lifecycle GHG emissions relative to the petroleum jet fuel baseline, which is currently set at 89 gCO_2e/MJ (ICAO, 2024). While LCAFs are CORSIA-eligible fuels and all emission reductions are embraced, they offer only limited emissions mitigation (Chiaramonti et al., 2021), and LCAFs do not suit well the ultimate goal of reaching net-zero GHG emissions.

It is important to stress that different pathways and feedstocks have different implications for carbon intensity of the resulting fuel. **Figure 2** provides a schematic of different options for SAF production. It shows that the pathways to produce SAF can have vastly different emissions (and cost, as we discuss later) implications. For bio-based SAFs, lignocellulosic pathways, such as FT on switchgrass, miscanthus, or poplar, offer a large emission reduction potential. PTL SAFs can also offer a very low-carbon option. These fuels require significant electricity inputs and thus a large-scale deployment of renewable electricity infrastructure. Once electricity and supply chains are decarbonized, PTL SAFs can be net-zero carbon.

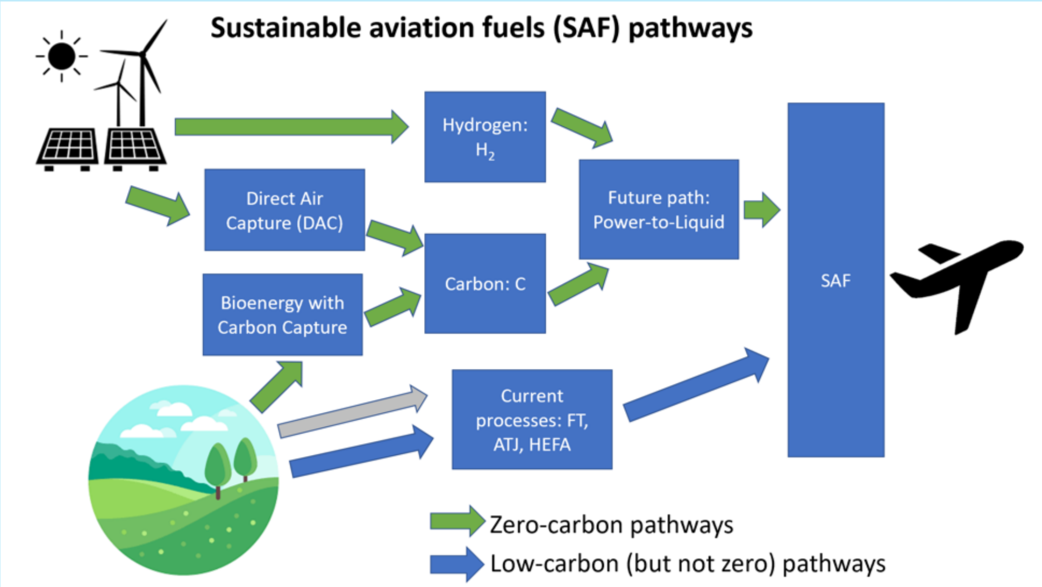

Figure 2. Schematic of SAF pathways outlining various feedstocks and conversion processes. Green arrows illustrate potential zero-carbon pathways (accounting for carbon use and storage). Blue arrows illustrate low-carbon pathways. Grey arrow illustrates pathways that do not provide an improvement in emission intensity relative to conventional jet fuels and cannot be labeled as SAF. FT=Fischer-Tropsch process, ATJ=Alcohol-to-Jet, HEFA=hydroprocessed esters and fatty acids.

Under CORSIA, the GHG emission reductions associated with SAF are based on the life-cycle accounting of emissions associated with the feedstock production and conversion technology. The emissions include all “well-to-wake” emissions, inclusive of the core lifecycle emissions and induced land use change (ILUC) emissions. The core lifecycle emissions cover all emissions associated with feedstock cultivation and collection, feedstock transportation, feedstock-to-fuel conversion, fuel transportation, and fuel combustion. When SAFs (and other biofuels) are produced, they may lead to more food and feed production somewhere else to satisfy the demand for food and feed crops. This can lead to induced land use changes (e.g., by converting grassland or forest to cropland) and the associated ILUC emissions. The ILUC values in CORSIA are based on two models that in some cases produced substantially different results and the assigned values were obtained by the current consensus among the experts (Prussi et al., 2021). A typical value for CO_2 emissions from combusting a conventional jet fuel is 73 gCO_2/MJ (based on 3.16 $kgCO_2$/kg fuel (ICAO ISRP, 2023)). Inclusion of life-cycle components increases the value associated with a conventional petroleum-based jet fuel to 89 gCO_2e/MJ.

As for carbon intensities of different SAF pathways, they vary based on the conversion process, type of feedstock, and region. For example, according to CORSIA-estimated values when ILUC is included (ICAO, 2024), sugarcane ETJ in Brazil results in about 30 gCO_2e/MJ (which reduces emissions by about two-thirds relative to conventional jet fuel), while corn grain ETJ in USA is about 90 gCO_2e/MJ (which does not reduce emissions in comparison to the petroleum baseline). Some pathways, such as open-pond palm oil-based HEFA in Malaysia and Indonesia, result in higher emission intensities (of around 100 gCO_2e/MJ) than conventional jet fuel. As mentioned before, lifecycle GHG emissions for lignocellulosic pathways can get close to zero. With ILUC accounting, the net emissions can be even negative. However, these pathways are currently at low technology readiness levels.

The results for lifecycle emission intensities for SAF production from a range of feedstocks are shown in **Figure 3**, where the min and max variation for a particular pathway is due to different carbon intensity of electricity sources in Latin America. These values are derived from existing input and energy balances in the literature. For the DAC FT PTL pathway, we include embodied emissions assuming that wind electricity is used for hydrogen production and direct air capture. The resulting core carbon intensities differ between feedstocks and SAF production pathways. They vary from about 20 gCO_2e/MJ for sugarcane ETJ (integrated) to about 60 gCO_2e/MJ for corn ETJ and sorghum ETJ. The results for palm oil HEFA (30 gCO_2e/MJ) and soybean HEFA (38 gCO_2e/MJ) are between these values. These are baseline lifecycle emissions considering average agriculture practices and energy sources used in the region. We recognize that some countries may adopt technologies which can substantially reduce emissions intensities, such as those employed in double-cropped corn biofuel in Brazil (Moreira et al., 2021).

For regional and country-specific SAF impacts (discussed in Section 4), we also consider ILUC values that are based on land use changes calculated by the EPPA model (see Appendix B). The core lifecycle emission values represented in Figure 3 can be improved over time with technological progress and the overall decarbonization of the economy (that will affect inputs to SAF production and the corresponding lifecycle emissions).

Currently, no SAF can be blended at more than 50% for use in commercial aircraft, according to ASTM specifications. While it has been proven by test flights that flying on 100% SAF is technically possible, it is not expected that 100% blends will be allowable before 2030. In addition to fuel-based decarbonization options for aviation, innovative propulsion technologies could contribute to reaching the net-zero goals. These options include battery-electric aircraft. Instead of combustion engines, electric motors would drive conventional propellers or sets of multiple fans. CO_2 emissions during operations are zero. However, battery weight is currently a major obstacle for these options, and airliner-sized electric aircraft are currently infeasible (Gnadt et al., 2019). The prospects for small electric aircraft are better. According to IATA (2023), small electric test aircrafts with up to 9 seats are already designed and tested. IATA expects that small regional electric aircraft might be arriving in the 2030s-2040s (IATA, 2023).

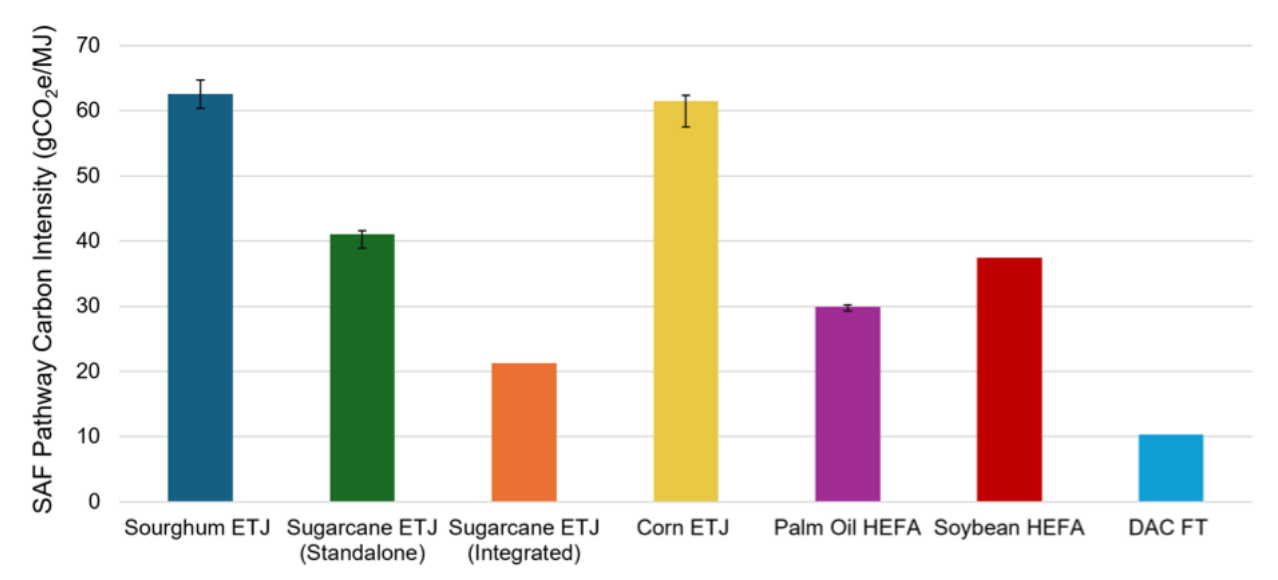

Figure 3. Medium-term values for core lifecycle carbon intensities of SAF pathways in Latin America. Indirect land use change emissions are excluded. Ranges at the top of the bars represent country-specific variations. For the DAC FT PTL pathway, we assume the energy requirements for DAC are met by wind electricity. Embodied emissions are excluded from the system boundary for this analysis making DAC a zero-emissions carbon source. However, we note that significant infrastructure manufacture and construction will be required to scale up wind electricity, resulting in embodied emission of ~10 gCO_2e/MJ.

Another advanced aviation option is hydrogen, which can be used as a propulsion fuel for combustion in conventional engines or in fuel cells. For airliner-sized hydrogen-powered airplanes, cryogenic liquid hydrogen storage tanks and changes in the aircraft fuel system are needed. There are technology programs (e.g., at Airbus) that develop the concepts to overcome the challenges associated with hydrogen use onboard aircraft. Airbus expects that a first hydrogen-powered aircraft could become available by 2035 (Airbus, 2024). Improvements in infrastructure and operational efficiency (e.g., improvements in air traffic navigation, decarbonizing on-ground operations) also play an important role in contributing to achieving net-zero targets (IATA, 2023).

As shown in Figure 1, even if all technological options for aviation decarbonization are deployed, some remaining emissions might be needed to be eliminated by carbon removals, such as nature-based carbon offsets, emission trading mechanisms, direct air capture (DAC), or bioenergy with carbon capture and storage (BECCS). Carbon from DAC and BECCS (the carbon part that is not stored) could also be needed as an input for PTL fuel production. Currently, all these options experience substantial challenges.

Carbon offsets, which are investments in sustainability projects around the globe that conserve emissions, recently received a considerable amount of negative press because of the problem with some projects that overestimated the real benefits. To regain its credibility, the carbon offset market needs uniform verification standards, thorough vetting of projects and a focus on high-integrity offsets (Waring et al., 2023). CORSIA activities are moving into that direction, but additional efforts are desperately needed to ensure the integrity of the crediting system.

DAC and BECCS have a large potential for deployment (Fajardy et al., 2021; Desport et al., 2024), depending on estimates for their costs, which vary widely, especially for

DAC. Some DAC cost estimates fall within the range of 100-300 $/tCO_2$ (IPCC, 2023; IEA, 2023). However, these estimates have been criticized for relying on optimistic assumptions related to capital and energy requirements, siting, and scaling up (Herzog et al., 2024). Studies accounting for those realities propose that a more realistic cost range for DAC is $600-1,000 $/tCO_2$ (Herzog et al., 2024; Desport et al., 2024) – and under very ambitious considerations no lower than $250/$CO_2$ (Sievert et al., 2024). Such cost ranges make the plans that depend on carbon removals or PTL fuels more risky (see Section 4.2 for the impacts of different input assumptions on PTL SAF costs).

When considering the implications of SAF deployment, it is important to note that fuel refining processes produce numerous output products rather than just SAF. There always exist co-products, such as diesel, gasoline, naphtha, and others. The shares of co-products in the total output can vary by production technology and feedstock (see **Figure 4**). The minimum selling price of SAF will depend on prices for these co-products that refining companies will be able to receive. Neglecting the representation of the output slate may lead to an incorrect estimation of the SAF production volumes (and costs). SAF production will be substantially lower (or equal to zero) if other product outputs are maximized. We will illustrate later (in Section 4) the impacts of different pricing for co-products in different countries on the overall SAF production costs in these countries.

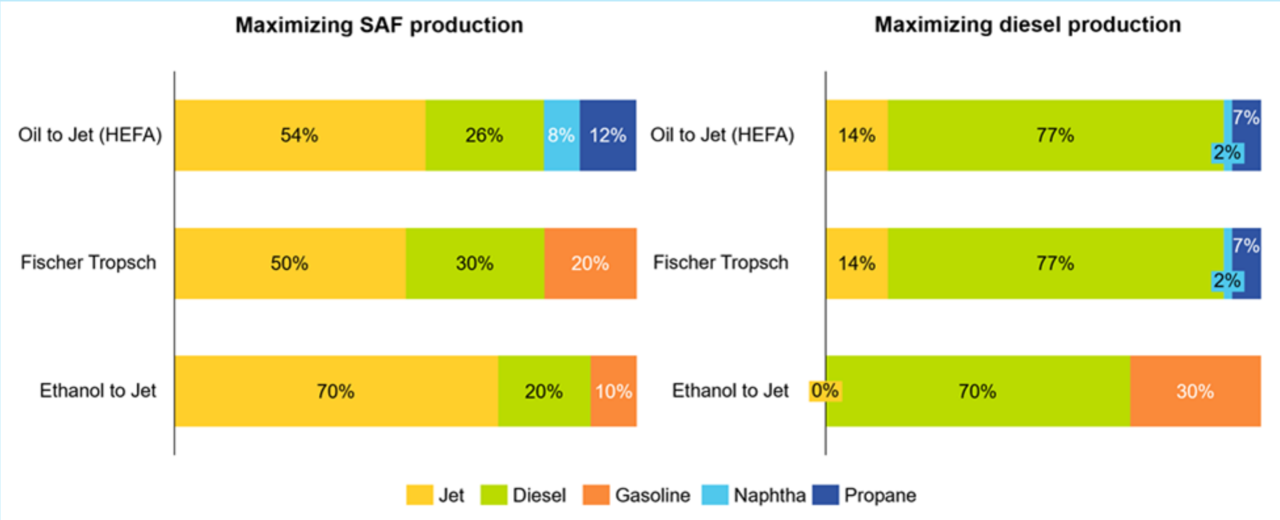

Figure 4. Notional production output slate based on current refinery technology (Note: future technology may allow for a larger share of SAF output).

Turning to specific characteristics of the countries in Latin America, we note that the region is well suited to play an important role for SAF production for domestic and global fuel markets. Due to its competitive advantage in productivity of crops that can be used as feedstocks for SAF production, selected countries can become substantial contributors to the global SAF supply. Winchester and Reilly (2015) explored the feasibility and costs of large-scale bioenergy production and determined that bioenergy crop yields in Brazil and other Latin American countries provide advantages in comparison to other regions of the world. With proper incentives and carefully crafted policies, this could make Latin America a major player in SAF production.

Figure 5 shows conversion efficiency (i.e., how many liters of SAF can be produced per hectare of land) for different SAF feedstocks in selected countries. This information can be useful for exploring the potential for different SAF pathways and their land implications. The crop productivity for feedstocks in individual counties are based on the data from the UN Food and Agriculture Organization (FAO). Note that conversion efficiency is defined per unit of land, but these countries have substantially different land areas that are currently dedicated to these crops. For example, even if the conversion efficiency for sugarcane-based alcohol-to-jet (ATJ) pathway in Brazil is lower than in Peru, the area of sugarcane production in Brazil is substantially larger than in Peru.

When a country has a smaller land area for agriculture (and its land is constrained), such a country can be better positioned to apply intensification methods for its agriculture, such as more efficient irrigation, fertilization, and others, to improve its crop yields. An example of corn-based ATJ in Chile reflects this phenomenon, where crop productivity in Chile is higher than in the other countries, but on a relatively small area of production in comparison to the main corn producers. Substantial increases in the area of production may bring challenges to keeping high crop yields on the larger areas.

To demonstrate the potential of Latin American countries for bio-based SAF production, we constructed a simple illustrative calculation where we start with the data for the current (2022) crop production volumes in the selected countries. Then we increased the corresponding crop areas by 20% and calculated the amounts of SAF that can be produced in these new areas. In the case of sugarcane bagasse, we consider that 0.14 kg bagasse/kg of sugarcane is produced as a residue. Obviously, this illustrative calculation is not related to the likely crop production increases, but it can be used to understand the amount of land and crop production that would be required to provide the substantial SAF volumes from these countries.

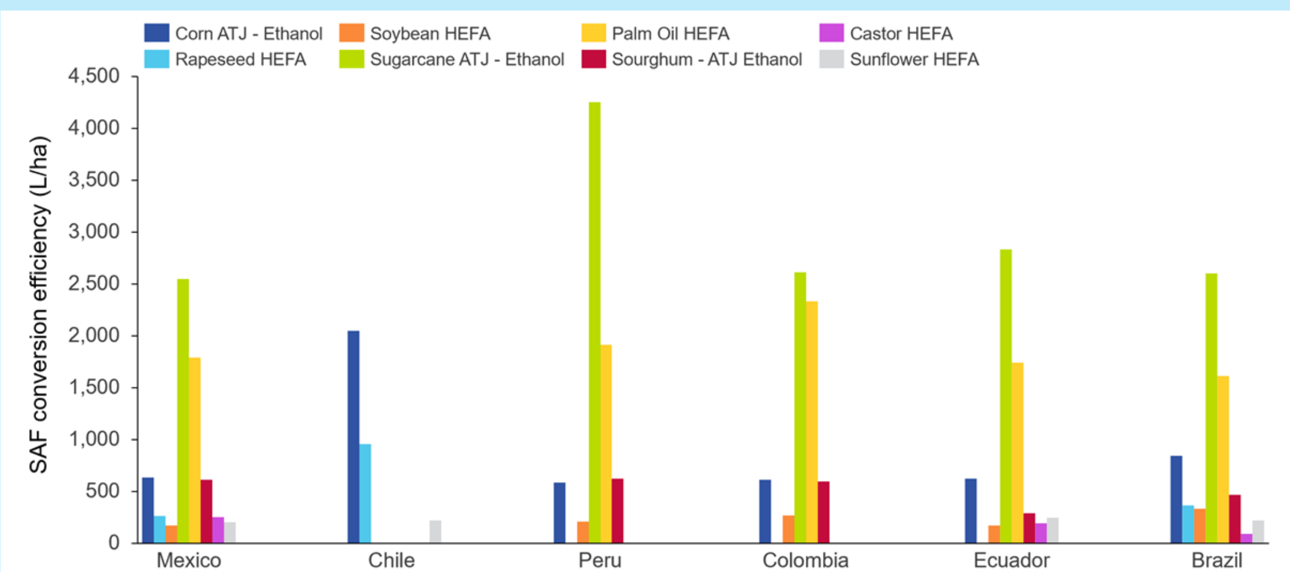

Figure 5. Conversion efficiency by area per country.

Figure 6 shows the results of our calculations in terms of liters of SAF production from individual crop feedstocks. It shows the amount of SAF produced from a 20% expansion in agricultural land as percentage of 2019 jet fuel consumption in six countries. Because Brazil is a large producer of agricultural commodities, a 20% increase in the area for a particular crop leads to substantial volumes of SAF production.

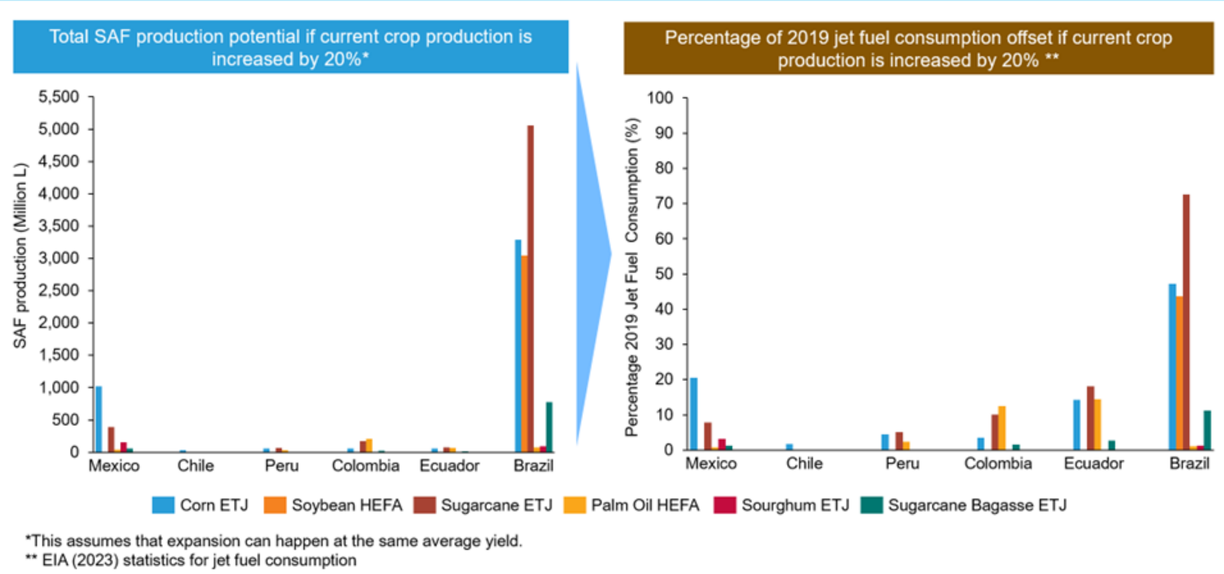

Figure 6. Potential SAF production (in million liters and as percentage of 2019 jet fuel consumption) if the current crop production is increased by 20% per country

Aviation fuel consumption differs by country with the size of each country's aviation sector. According to EIA (2023), in 2021 Brazil's jet fuel consumption was about 4,400 million liters per year (ML), Chile consumed about 1,000 ML, Colombia's consumption was about 1,100 ML, Ecuador consumed about 200 ML, Mexico consumed 3,500 ML, and Peru's consumption was about 400 ML. Since 2021, these volumes increased because the aviation sector in 2021 was still experiencing the impacts of the Covid-related restrictions.

Before the pandemic, in 2019 jet fuel consumption in Brazil, Chile, Colombia, Ecuador, Mexico and Peru was about 7,000 ML, 1,700 ML, 1,700 ML, 400 ML, 5,000 ML and 1,300 ML, respectively. However, the after-Covid data from EIA are either incomplete or still preliminary and for illustration we focus on the 2019 data for the regional fuel consumption.

Figure 6 also shows the results of the same increase by 20% of domestic crop production, but this time it is reported as a percentage of the 2019 aviation fuel consumption in the corresponding countries. Recall that this calculation is for illustrative purposes, and it is unlikely that a country would increase its production of all crops by 20%, but Figure 6 provides a useful indication of the potential SAF shares that can be domestically produced. Similarly to the previous outcome, Brazil is in a position to cover substantial shares of SAF.

To narrow down the viable bio-based SAF pathways in different countries, we calculated the number of small-scale biofuel plants (with a capacity of 100ML/year) that can be supported if 100% of country crop production in 2021 (for a particular feedstock) is dedicated to SAF. Countries differ by their potential for supporting bio-based SAF production. We consider only feedstocks which can support at least one conversion plant. **Table 2** presents the resulting data, where the number of viable pathways in Ecuador and Peru is reduced to corn ETJ, sugarcane ETJ, and palm oil HEFA. For Chile, corn ETJ becomes the only viable option. On the other side, Brazil and Mexico have a sizeable agriculture sector, and these countries can support sizeable SAF production.

While relatively large crop yields have implications for bio-based SAF pathways, selected Latin American regions might also be well-suited for producing PTL SAF. We explore this in Section 4.2, where we consider the SAF pathways for Chile, because it has a comparative advantage for producing PTL SAF due to its abundant solar and wind resources. Note that Table 2 does not include PTL SAF facilities because they are not constrained by crop production, but rather by their access to economically competitive CO_2 sources (from DAC) and H_2 production.

Table 2. Number of 100ML/year biofuel plants that can be supported by the current (2021) crop production in each country.

	Brazil	Chile	Colombia	Peru	Ecuador	Mexico
Corn ETJ	234	2	4	4	4	73
Sugarcane ETJ	361		12	4	5	27
Sugarcane Bagasse ETJ	55		1			4
Sorghum ETJ	6					11
Palm Oil HEFA	7		19	2	5	3
Soybean HEFA	281					

4 Regional and country-level analysis

In this section we focus on the results for the selected countries in Latin America: Brazil, Chile, Colombia, Ecuador, Mexico, and Peru. For each country of interest, we estimate the cost of SAF production from its major feedstocks. A description of techno-economic analysis for evaluating the SAF production costs is provided in Appendix A. We then use that information as an input to an enhanced version of the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev et al., 2005; Chen et al., 2022). The EPPA model calculates the impacts on economy, aviation sector, fuel use, and the resulting aviation and economy-wide emissions. The EPPA model is described in Appendix B.

To evaluate the impacts of emission mitigation, we consider two scenarios for all regions of the world: *Current Trends (CT)* and *Accelerated Actions (AA)*. In the Current Trends scenario, we assume continuation of current policy approaches and emission trajectories. In the Accelerated Actions scenario, the world is on a path to a 1.5°C stabilization. This scenario abates global CO_2 emissions by about 75% in 2050 relative to 2015. The details of the scenarios are described in the MIT Global Change Outlook (Paltsev et al., 2023). While economies are growing over time, economy-wide GHG emission constraints result in the endogenously determined implicit carbon prices that rise over time (due to increasing stringency of emission constraints). They also affect the prices of fossil-based fuels, including jet fuel. This, in turn, affects the costs of goods and services that use fossil-fuels. Changes in prices and incomes also affect demands for good and services (including aviation demand).

We expanded the set of scenarios to explore the impacts of different SAF ambitions (see **Table 3**). We term the corresponding SAF scenarios *A1, A2, A3*. Note that these scenarios are selected for exploration purposes, and we are not advocating for any particular trajectory for SAF regulations.

For Brazil, we evaluate the impacts of its current requirement for emission reduction in aviation (*CT+Mandate* and *AA+Mandate*). We convert the emission reductions into the required SAF shares (see Section 4.1 for details). For Chile, we evaluate the impacts of its current SAF proposal (*CT+Ambition* and *AA+Ambition*). For Brazil and Chile, we impose the SAF requirements both in the CT and AA emission mitigation scenarios because of their publicly stated SAF goals. For Chile, in the A2 and A3 scenarios we also impose PTL SAF requirements (hence, they are denoted as A2* and A3*) as described in Section 4.2.

For Colombia, Ecuador, Mexico, and Peru (where policies are still under development), we impose SAF requirements in the AA emission mitigation scenario only. While Colombia's SAF roadmap is not published yet at the time of writing this report, we evaluate Colombia's ambitions as being similar to the SAF shares in Chile, reaching 50% of SAF by 2050 in the A2 scenario. For Ecuador, Mexico, and Peru, we assume milder SAF ambitions. In the A1 scenario, these countries follow Brazil's path but are delayed by 10 years. In the A2 scenario, Brazil reaches 30% by 2050, and these countries also reach 30% SAF by 2050, but they start implementing the mandates 5 years later than Brazil.

In the most ambitious SAF scenario considered in this study (A3), all countries follow the same trajectory for the SAF share in their total jet fuel consumption. This scenario is inspired by the global SAF contribution of 65% of emission reduction to the net-zero goal, as evaluated by IATA (2024c), and the EU SAF mandates of 70% by 2050. Considering lower income per capita in Latin American countries in comparison to the EU, we assume that the SAF shares in the A3 scenario being slightly lower (65%), but still comparable, to the targets imposed in the EU countries.

Table 3. Assumed trajectories for the SAF share in total jet consumption (%).

	Setting	2025	2030	2035	2040	2045	2050
Brazil	CT	0	0	0	0	0	0
	CT+Mandate	0	6	9	12	12	12
	AA	0	0	0	0	0	0
	A1 (AA+Mandate)	0	6	9	12	12	12
	A2	0	6	9	15	22	30
	A3	0	6	14	25	42	65
Chile	CT	0	0	0	0	0	0
	CT+Ambition	0	5	10	17	30	50
	AA	0	0	0	0	0	0
	A1	0	5	10	15	20	25
	A2* (AA+Ambition)	0	5	10	17	30	50
	A3*	0	6	14	25	42	65
Colombia	CT	0	0	0	0	0	0
	AA	0	0	0	0	0	0
	A1	0	5	10	15	20	25
	A2	0	5	10	17	30	50
	A3	0	6	14	25	42	65
Ecuador	CT	0	0	0	0	0	0
	AA	0	0	0	0	0	0
	A1	0	0	0	6	9	12
	A2	0	0	5	10	20	30
	A3	0	6	14	25	42	65
Mexico	CT	0	0	0	0	0	0
	AA	0	0	0	0	0	0
	A1	0	0	0	6	9	12
	A2	0	0	5	10	20	30
	A3	0	6	14	25	42	65
Peru	CT	0	0	0	0	0	0
	AA	0	0	0	0	0	0
	A1	0	0	0	6	9	12
	A2	0	0	5	10	20	30
	A3	0	6	14	25	42	65

In the main setting, we assume that SAF targets are satisfied by domestic SAF production and there is no international trade of SAF. We also explored scenarios when SAF is regionally traded between all six countries of our study. In all scenarios we impose annual average efficiency improvements of 1% in aviation. In addition, consumers endogenously react to the changing prices by adjusting their demand for aviation, and the aviation sector is engaging in additional price-driven efficiency improvements (where prices are impacted by economy-wide emissions mitigation activities). Note that in these scenarios we do not impose the net-zero emission targets on the aviation sector. To reach net-zero, the remaining emissions need to be addressed with other efficiency improvements, technological advances (new propulsion technologies), regulatory and market-based mechanisms (such as those described in Section 3). The costs of these options are highly uncertain at this point. Depending on their costs, these options may put additional pressure on the aviation demand.

4.1 Brazil

Brazil's pre-Covid aviation CO_2 emissions were about 15-17 $MtCO_2$ (**Figure 7**). In 2019, emissions from domestic aviation were 55% of the total aviation emissions (OECD, 2023), reflecting the large share of domestic flights. The pandemic impacted the international flight segments more than domestic, although both were severely affected. Both segments are recovering now. As discussed in Section 3, carbon emissions from Brazil's international flights will be subject to CORSIA regulation from 2027.

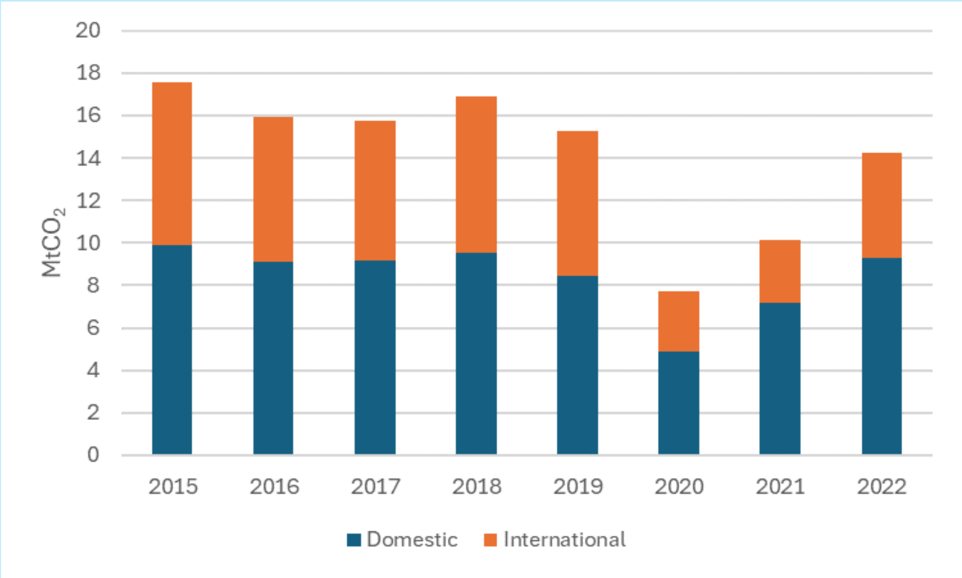

Figure 7. Aviation CO_2 emissions in Brazil. Data source: OECD (2023).

To address the aviation emissions, Brazil in its 2024 Fuel of the Future Law introduced the requirements for aviation fuel emission intensity reductions that are specified relative to a conventional jet fuel emission intensity (ProBioQAV, 2024). It starts in 2027 with a 1% reduction and gradually grows to a 3% reduction in 2030, 6% in 2033, and 10% in 2037 and thereafter. Because the target is specified in terms of emission intensity, the resulting emission levels (and the amount of SAF) will depend on the growth of the aviation sector over time. Using the growth trajectory from the EPPA model, we calculated the needed SAF quantities to satisfy the emission intensity requirements. For 2030-2050, they translate to the following SAF shares in the total jet fuel consumption: 6% in 2030, 9% in 2035, and 12% in 2040 and thereafter.

To assess the impacts of the requirements, we start with estimating the costs of different SAF pathways in Brazil. **Figure 8** shows the results of techno-economic analysis for the minimum selling price for SAF production in Brazil. For the major ETJ pathways (sugarcane-, sorghum-, corn-based), the costs are in the range of \$1.10-\$1.40/liter. Using sugarcane bagasse reduces competition for land and food products, but this pathway is more expensive at about \$1.80/liter. The costs of HEFA SAF pathways (palm oil and soybean) in Brazil are about \$1.60/liter.

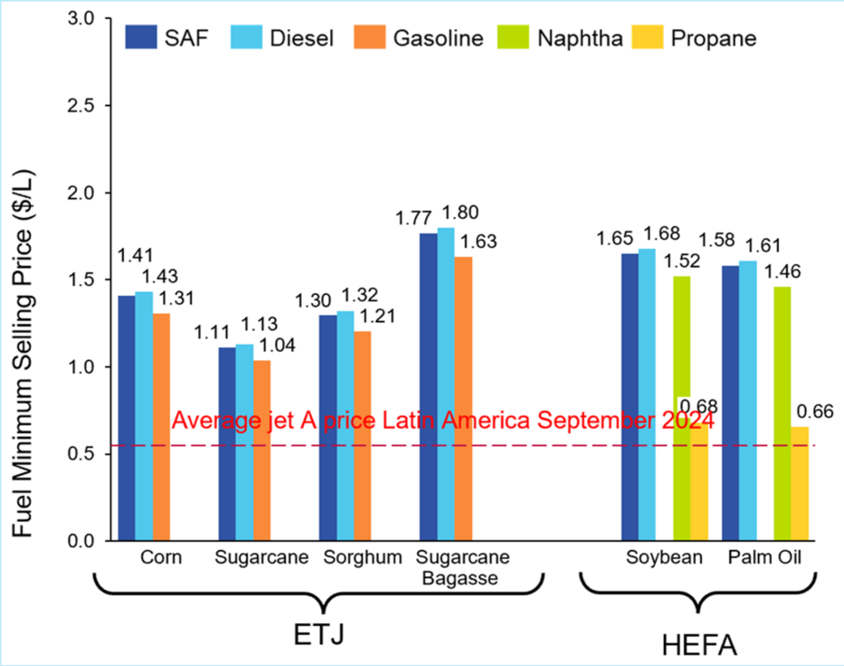

Figure 8. SAF production costs in Brazil for selected pathways for the n-th plant.

We also explored the FT pathway based on agricultural residues (not shown on the figure), but excluded this pathway from further analysis due given its estimated high costs (around $2.50/liter). All SAF costs are reported for the "n-th of the kind" plant (i.e., for mature technology). According to the IATA Jet Fuel Price Monitor, the prices for conventional jet fuel in Latin America in September of 2024 were around $0.60/liter (which is even lower than the current average for 2024 of $0.70/liter). Our analysis indicates that SAF prices are higher than the current prices for fossil-based jet fuel.

The costs represented in Figure 8 reflect the scenario setting, where the refinery configuration is optimized for SAF production. Production costs are proportionally distributed to all refinery products. However, the SAF costs would be higher if the other refinery products cannot be sold at a "green premium" (i.e., at prices higher than the prices for the corresponding fossil-based products). This connection to the market prices of the co-products emphasizes the importance of integrating domestic policies in all sectors of the economy, because if there are no regulations for "green gasoline" or "green diesel", then prices at which co-products can be sold would be lower (determined by the prices of their fossil-based counterparts), thereby increasing the SAF costs.

To illustrate this issue, we can calculate SAF costs when the co-products can be sold only at the current prices of the fossil-based products. For example, sugarcane ETJ SAF costs $1.11/liter when a green premium can be charged for all output products. However, as shown in **Figure 9**, if co-products are sold at the historic prices observed in 2022, then the SAF cost would be $1.20/liter, about 10% higher than the previous setting of "green premium". Of course, this calculation depends on the price levels. For example, in 2021 fossil fuel prices were lower than in 2022. Using 2021 price levels for the co-products, the sugarcane ETJ SAF production cost would be $1.32/liter, about 20% increase. For different SAFs the magnitudes of increases might be different, but the message is the same: policies in different sectors of the economy (such as road transportation, power generation, industry, agriculture) should be integrated.

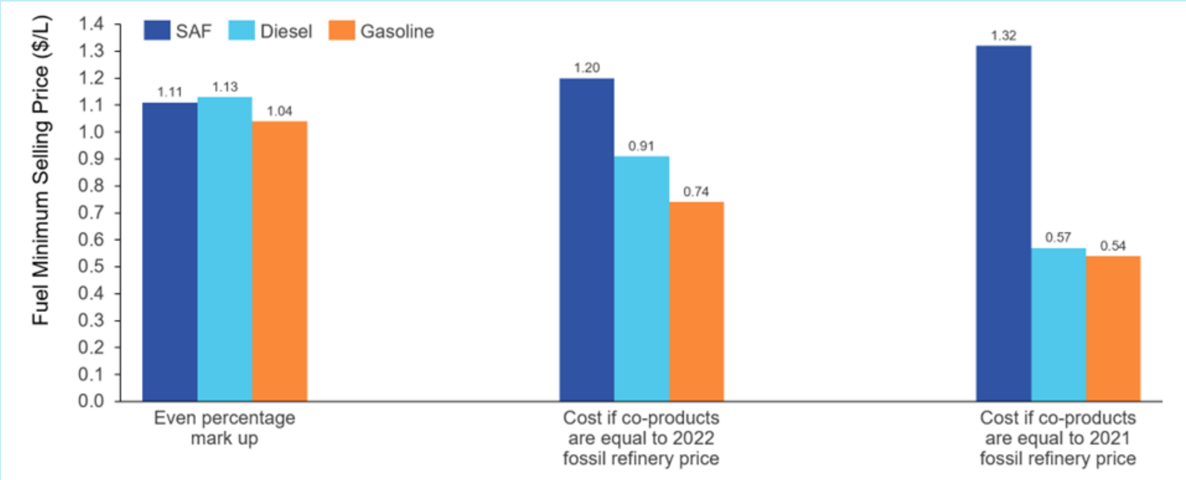

Figure 9. Sugarcane ETF SAF production costs in Brazil if green premium is paid by SAF only and co-products are sold at market prices.

Using the SAF cost estimates derived by our techno-economic analysis, we apply the EPPA model to estimate the aviation fuel consumption in Brazil. **Figure 10** provides the results for fuel use by type (for the scenarios presented in Table 3). In the CT scenario without the aviation emission reduction requirement (which we convert to SAF mandate), aviation fuel consumption in Brazil grows from about 7,000 ML in 2019 to about 9,000 ML in 2030, and to about 15,000 ML in 2050.

A SAF mandate without additional policies to cover the green premium increases the prices of jet fuel and the corresponding operational expenses of the aviation sector, which in turn increases the cost of air travel. Individual airlines may decide to seek options to mitigate the impacts of the increased costs on their customers. We estimate that the SAF mandate leads to a reduction in the overall jet fuel consumption, as shown in Figure 10 for the series labelled *CT+Mandate*. In 2030-2050, the total amount of aviation fuel is about 3% lower than without the mandate (due to higher fuel costs).

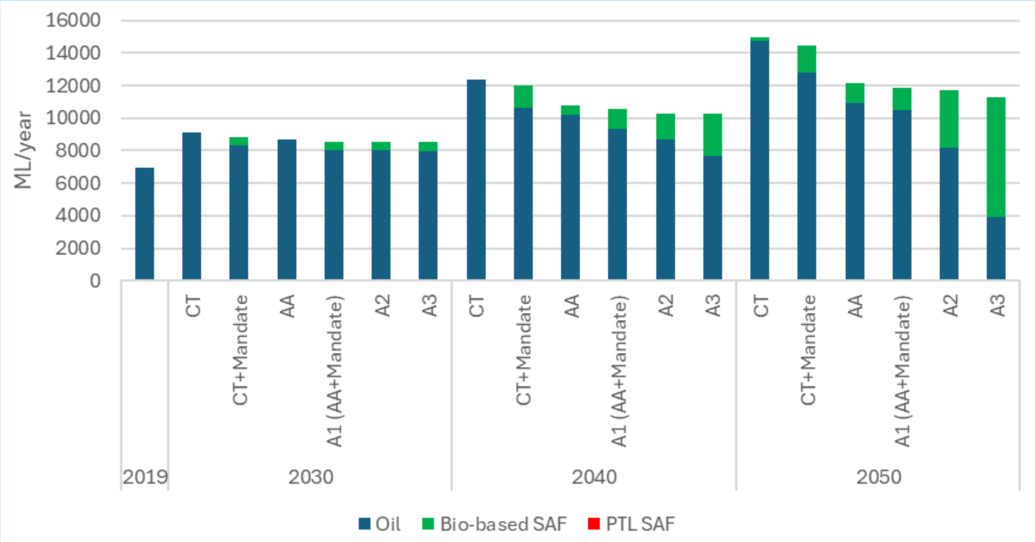

Figure 10. Aviation fuel consumption in Brazil under the current SAF regulations and alternative scenarios.

The volumes of SAF are projected to increase from about 510 ML in 2030 to about 1,700 ML in 2050. Note that if the SAF mandate is not accompanied by aggressive emission reductions in other sectors of the economy, then aviation emissions are reduced but the economy-wide emissions in Brazil are not decreasing. In the AA scenario, fossil fuels in all sectors of the economy are affected by their emission mitigation activities, which results in the response by fuel producers and aviation consumers. In this scenario, economy-wide CO_2 emissions in 2050 are reduced by 75% relative to the 2020 level, and Brazil's fuel consumption is projected to be lower than in the CT scenario. In 2030, it is reduced from about 9,000 ML to about 8,800 ML, and in 2050 the reduction is from about 15,000 ML in CT to about 12,000 ML in AA. These declines are driven by price-induced efficiency improvements and demand-side responses.

Imposing SAF mandates in the AA scenario leads to lower impacts on aviation fuel use than imposing the same mandates in the CT scenario. Jet fuel consumption in the *AA+Mandate* scenario is reduced by about 2% relative to AA scenario in 2030-2050 (in comparison to about 3% reduction on the *CT+Mandate* scenario relative to the CT scenario). This result is driven by the economy-wide emission constraint that changes relative prices in the economy and makes SAF more competitive.

In the AA scenario, even when the mandate is not imposed, about 5% of jet fuel in 2040 is provided by SAF. By 2050, the SAF share in this scenario reaches about 10%. The mandate requirement leads to a further increase in SAF (recall that by 2050 the SAF share is 12% in the *AA+Mandate* scenario). As a result, the AA and *AA+Mandate* settings achieve similar outcomes for SAF by 2050 by imposing different regulatory instruments. The mandate becomes less binding because of the overall emission constraints and the corresponding price-induced mitigation activities. But the AA scenario alone does not achieve substantial emission reductions in the aviation sector because it is a relatively expensive sector for abatement, and most emission reductions occur in the other sectors of the economy.

Figure 10 also shows the results for the SAF requirements of different stringency. For Brazil, the A1 setting corresponds to *AA+Mandate*. The resulting impacts on aviation demand (and the corresponding fuel use) are growing over time and with the stringency of the SAF mandates. In the A2 setting, the total fuel consumption in Brazil is about 11,700 ML in 2050. In the A3 settings, it decreases to about 11,250 ML. At the same time, the amount of SAF production in 2050 grows from about 3,500 ML in the A2 setting to about 7,300 ML in A3.

Note that in 2019 Brazil used about 7,000 ML in aviation fuel, so by mid-century the required volumes of the SAF in the stringent scenarios are comparable to the current conventional jet fuel consumption. Relative to a no-policy CT scenario, emission reductions in Brazil's aviation sector in 2050 are 24% in AA, 27% in A1, 38% in A2, and 60% in the A3 scenario. These results are reported for the case where all SAF is produced domestically. Without strategies to manage price increases, SAF requirements can affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Brazil is 3.82% per year. The most ambitious SAF scenario (A3) will reduce the growth to 3.75% per year. We also explore the benefits to Brazil from regional collaboration. The results for aggregate aviation demand are provided in Section 4.7.

A ramp-up of SAF production will require substantial capital investments. **Figure 11** shows our estimates for the cumulative SAF investments to build new production plants in different scenarios. In the A1 scenario, capital investments total up to US$ 28 billion. In the A2 and A3 scenario, the required Brazil's investments in SAF plants are US$ 46 billion and US$ 84 billion, correspondingly. According to IATA (2024b), the capital investment needed to build new renewable fuel facilities for SAF production is a prerequisite for making any net zero transition plan possible. These costs can eventually be passed on to airlines as a part of the SAF price, as well as to other customers of the resulting refined output (renewable diesel for road transport, for instance), but the upfront costs will need to be shouldered by fuel producers (IATA, 2024b).

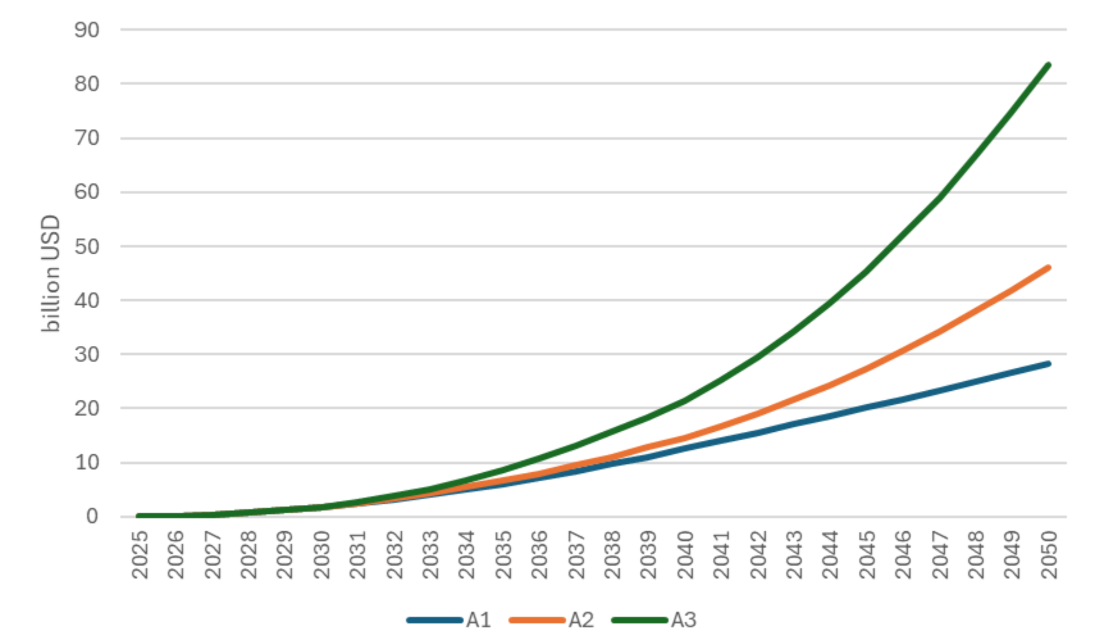

Figure 11. Cumulative capital investment in new SAF plants in Brazil in different scenarios.

As mentioned earlier, Brazil is well positioned to be an important producer of SAF either for domestic, Latin American, or global markets because Brazil has a substantial expertise in large-scale agricultural activities. In particular, it currently produces many potential feedstocks for ETJ and HEFA pathways for SAF. We evaluated the land requirements in Brazil to scale up to large volumes of SAF feedstock production. **Figure 12** shows an illustration of land-use requirements for SAF production in Brazil. To allocate where feedstocks can be potentially grown, we use a downscaling and change detection model, Demeter (Vernon et al., 2018; Chen et al., 2019), driven by the results from the EPPA model. While the Demeter model does not distinguish crop changes by its drivers, most of the changes in sugarcane production projected by EPPA are due to the SAF expansion. Hence, we can attribute the land changes represented in **Figure 12** to SAF feedstock production, where between 2020 and 2050 the crop areas are expanding and the number of green-color cells that represent larger shares of land dedicated to sugarcane are increasing.

By 2050, the land area required to grow SAF feedstocks is estimated to be 0.6% of total cropland in Brazil in the A1 scenario. In the A2 and A3 scenarios, the 2050 areas are 1.6% and 3.3%, respectively. Latin America has large areas of degraded land that can be partially and/or potentially improved to accommodate agricultural expansion. Gibbs and Salmon (2015) report degraded land areas ranging from 56 Mha to 306 Mha in Latin America. Brazil, in particular, has detailed mapping of degraded pastures available to livestock intensification and crop expansion. Around 57% of the total 173 Mha of pasturelands were degraded by 2018, and approximately 40 Mha of them suffer from a severe level of degradation (Feltran-Barbieri and Feres, 2021; LAPIG, 2020).

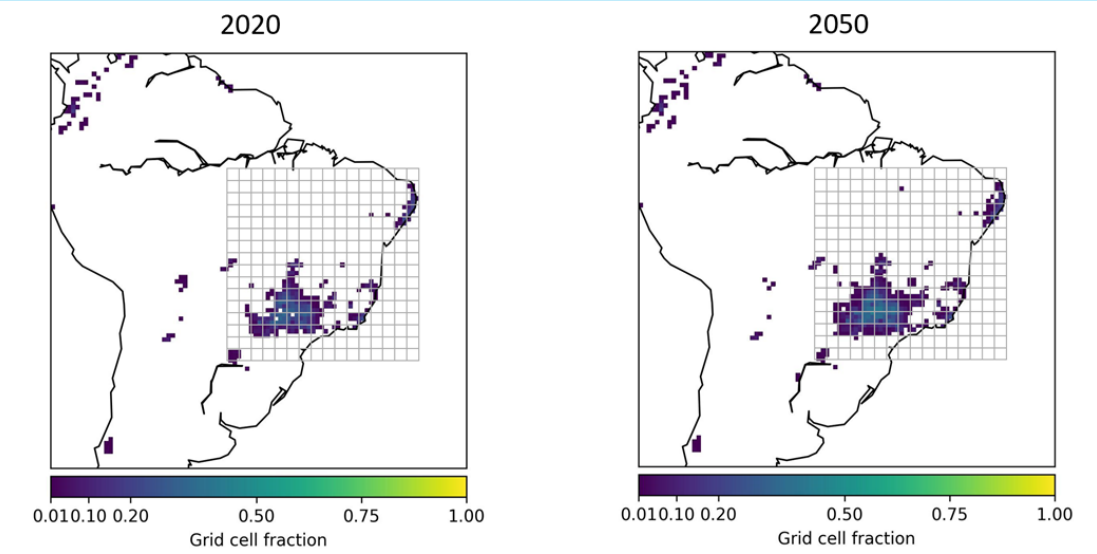

Figure 12. Land use distribution of sugarcane production in Brazil in the A3 scenario.

The relevance of degraded pasture as a potential source of agricultural and bioenergy expansion may be illustrated by the sugarcane expansion in Brazil in the 2000's. Accordingly to Nassar et al. (2008), 77% of the 1.03 Mha increase in harvested sugarcane area between 2000 to 2006 was due to conversion from pastureland, while satellite images show the planted sugarcane area has increased by 0.99 Mha on former pasture areas from 2007 to 2008 in Brazil. To put these numbers in perspective, we estimate that in the A3 scenario the feedstock area for SAF in 2050 would be around 3.6 Mha, while the total cropland area in Brazil is about 100 Mha, and the area of degraded land that has a potential for agricultural expansion is estimated to be about 80 Mha.

Brazil is in the process of developing additional feedstocks for SAF production. For example, some companies began domestication of Macauba as a potential pathway for SAF production (BNDES, 2024). While it is too early to assess the full potential and likely costs of the SAF production process based on Macauba, it offers another possible option for SAF feedstock cultivation on degraded lands.

It is worth mentioning an important caveat to our estimates. If there are no domestic incentives for producing SAF, then Brazil may focus on ethanol and/or bio-based feedstock production, ship feedstocks and ethanol to export to the countries with substantial SAF incentives (e.g., to the EU with its mandates or to USA with IRA incentives) and the fuel would be produced there. Economic decisions of producing SAF domestically or focusing on the feedstock production for SAF production abroad will depend on the integration of aviation policies worldwide.

4.2 Chile

Historic CO_2 emissions for 2015-2022 for Chile's aviation are provided in **Figure 13**. The pre-Covid levels were about 3 $MtCO_2$. In 2019, emissions from domestic aviation were 33% of the total aviation emissions in Chile (OECD, 2023), reflecting the large share of international flights. The pandemic impacts on the international flight were larger than on domestic segments. Both domestic and international flight volumes are gradually recovering, leading to an increase in aviation emissions.

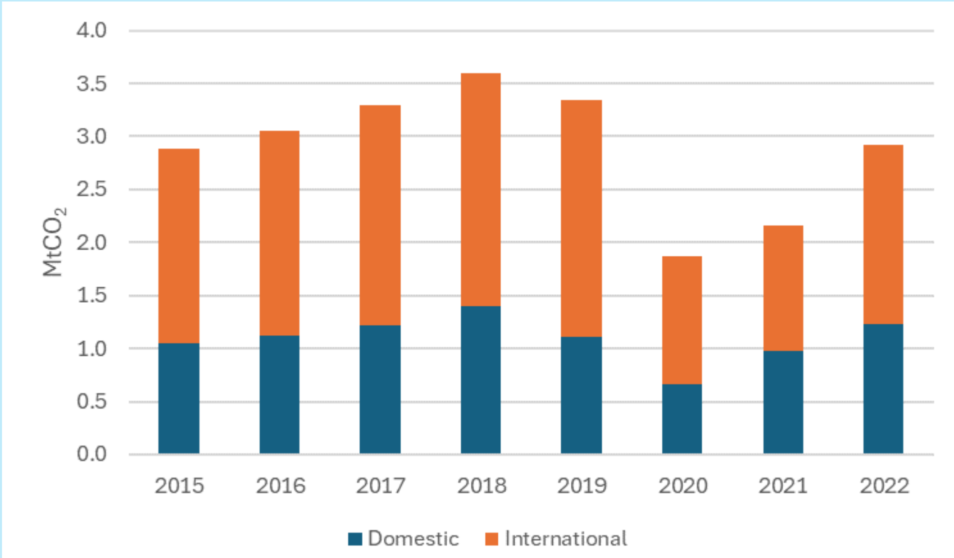

Figure 13. Aviation CO_2 emissions in Chile. Data source: OECD (2023).

For SAF deployment, Chile announced a 2050 roadmap (Ministry of Transport and Telecommunications of Chile, 2024), where it is envisioned that SAF will be used starting from 2030 and by 2050 SAF would contribute 50% of the fuel used in Chile's domestic and international aviation. **Figure 14** provides the results of our technoeconomic assessment for the major SAF production pathways in Chile. The corn-based ETJ pathway is estimated to result in a minimum selling price of $1.68/liter. SAF from the forest residue-based FT pathway costs $2.53/liter. While HEFA pathways are also possible, we estimate that domestic feedstocks for these pathways are not sufficient to produce large volumes of SAF in Chile.

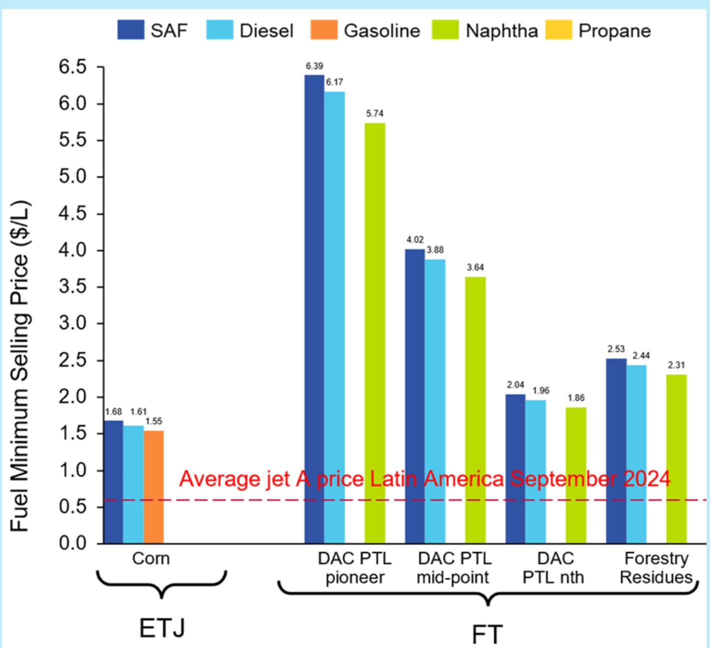

Figure 14. SAF production costs in Chile for the selected pathways (for the n-th plant for corn ETJ and forestry residues FT, and for plants of different maturity for DAC PTL).

A distinctive feature of Chile is its good potential for green hydrogen production, which can be used for PTL SAF pathways. While hydrogen production costs might be relatively lower in Chile than in other parts of the world, the resulting cost of synthetic fuels would depend on the maturity of direct air capture technology and/or availability of CO_2 from the sources that would not deteriorate the lifecycle carbon intensity of the fuel. The costs of PTL fuels are expected to decrease substantially. Figure 14 shows the results for a pioneer direct air capture-based power-to-liquid (Fischer-Tropsch) pathway (DAC PTL FT), a "mid-point" maturity plant, and a "n-th plant" where the potential for the technological maturity is achieved.

For these levels of maturity, we assume the following input costs for H_2 from electrolysis and CO_2 from DAC. For the pioneer plant, H_2 cost is $3.10/kg and DAC CO_2 cost is $600/t$CO_2$. For the mid-point maturity plant, H_2 cost is $2/kg and DAC CO_2 cost is $375/t$CO_2$. For the n-th plant, these costs are $1.70/kg$H_2$ and $150/t$CO_2$. As discussed in Section 3, these are optimistic cost assumptions. SAF production cost levels in Chile can be compared with the current jet fuel prices in Latin America, where IATA reports about $0.70/liter in March 2024 and about $0.60/liter in August 2024. This comparison indicates substantial cost differences both for bio-based and PTL SAF pathways in Chile. Even extremely hopeful assumptions for PTL fuels make them a very expensive option. As a result, for Chile it might be worth considering not only domestic SAF production, but also lower-cost SAF imports (see Section 4.7).

Similarly to the discussion in the previous section for Brazil, SAF production costs would be higher if co-products can be sold only at the current prices of the fossil-based products. For example, DAC PTL production cost for the n-th plant is $2.04/liter considering equivalent green premiums for all co-products. However, if co-products are sold at the historic prices observed in 2022, then the DAC PTL SAF cost would be $2.93/liter, a 40% increase relative to the previous setting. Using 2021 price levels for co-products would lead to the DAC PTL SAF production cost of $3.25/liter, a 60% increase.

The overall consumption of aviation fuel in Chile is growing over time in all scenarios, as shown in Figures 15. In the Current Trends (CT) scenario, the use of jet fuel in Chile increases from about 1,650 ML in 2019 to about 2,200 ML in 2030, and to about 3,500 ML in 2050. Considering the proposed SAF requirements (*CT+Ambition*), we estimate that the overall consumption of jet fuel (relative to the CT scenario) is reduced by 2.5% in 2030, 7% in 2040, and 15% in 2050. As discussed earlier, an imposition of SAF requirements increases the operational expenses of the aviation sector. Our study is not intended to consider how individual airlines may respond to the potential cost increases because our modeling is done at the level of the overall aviation sector.

To incentivize economy-wide emission reductions (as in the AA scenario), fossil fuels are facing carbon penalties (either explicitly or implicitly), and it results in the supply and demand responses. In the AA scenario, economy-wide CO_2 emissions in Chile in 2050 are reduced by about 70% relative to the 2020 level. Jet fuel consumption in this scenario is projected to be lower than in the CT scenario. In 2030, it is reduced from about 2,200 ML to about 2,150 ML, and by 2050 the difference will grow to a change from about 3,500 ML in CT scenario to about 3,000 ML in the AA scenario. These reductions in volume are driven by price-induced efficiency improvements and demand-side responses to higher costs.

Imposing SAF requirements in the AA scenario also leads to impacts on aviation fuel use, but these impacts are lower than in the case of the corresponding SAF targets imposed on the CT scenario. The overall reduction of jet fuel consumption in the *AA+Ambition* scenario relative to the AA scenario is 1.5% in 2030, 5% in 2040, and 8% in 2050. The change in relative prices in the AA scenario reduces the price differences between fossil-based fuels and SAF.

In the AA scenario where the mandate is not imposed, SAF becomes economically viable (without subsidies or targeted support) by mid-century and its share in 2050 is about 14%. The *AA+Ambition* has a requirement that leads to a 50% share of SAF in 2050. As discussed earlier, the AA scenario alone does not achieve substantial emission reductions in the aviation sector because it is a relatively expensive sector for abatement, and emission reductions occur in the other sectors of the economy. It is up to policymakers to decide if the ultimate objective is to achieve economy-wide reductions at the lowest cost, or to ensure that the aviation sector faces substantial emission reductions. While the end goal is net-zero emissions for the economy, contributions from different sectors to mitigation activities may vary.

Figure 15 also shows the results for Chile for the scenarios of different SAF mandate stringency (A1-A3 as defined in Table 3). For Chile, the A2 scenario corresponds to the *AA+Ambition* setting described above in terms of the SAF share. For the A2 scenario, we also consider an addition of a portion of SAF from the power-to-liquids (PTL) pathway. Because PTL SAF in Chile gets a substantial attention from experts and policymakers, in the A2 and A3 setting we included an additional requirement that PTL SAF (hence, they are labeled A2* and A3*). In the A2* scenario, PTL SAF contributes 1% in 2040 and 5% in 2050. In the A3* scenario, the share of PTL SAF is 5% in 2040 and 10% in 2050.

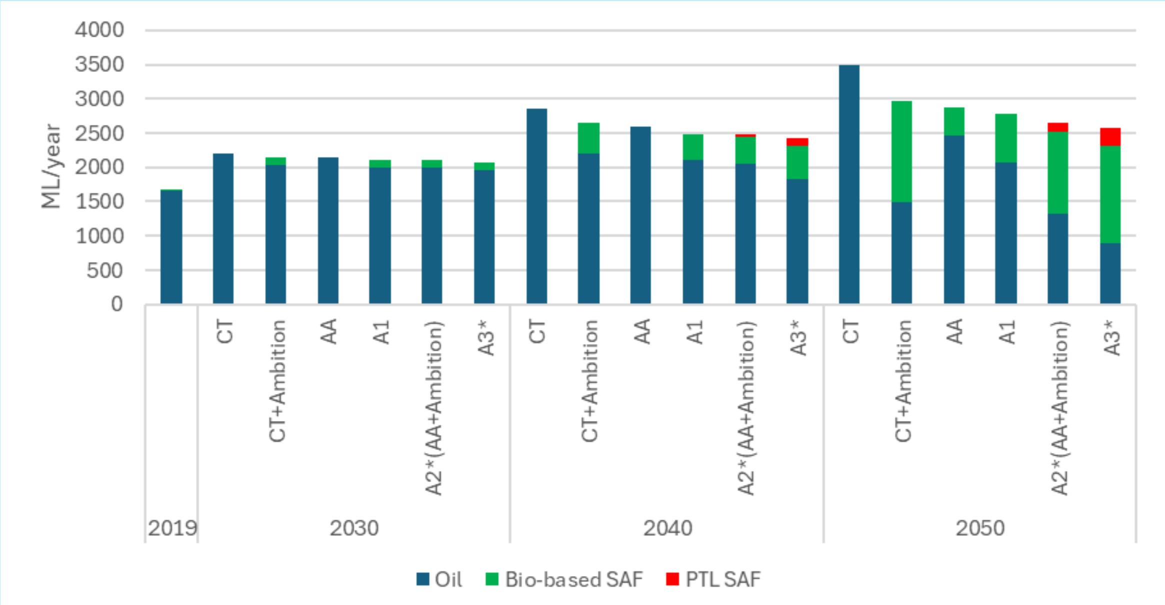

Figure 15. Aviation fuel consumption in Chile in different scenarios.

The resulting impacts on aviation fuel consumption are growing over time and with the stringency of the SAF mandates. In the AA scenario, the total aviation fuel consumption in Chile is about 2,900 ML in 2050. In the A2* and A3* settings, it decreases to about 2,650 ML, 2,550 ML, correspondingly. As a result, fuel consumption in the A3* setting in 2050 is 11% lower than in the AA scenario.

At the same time, the total amount of SAF production in 2050 grows from about 400 ML in the AA setting to about 700 ML in A1, 1,300 ML in A2*, and 1,700 ML in A3*. Note that in 2019 Chile consumed about 1,700 ML in aviation fuel, and by mid-century the required volumes of SAF in the stringent scenarios are comparable to the current conventional jet fuel consumption in Chile. Without strategies to manage price increases, SAF requirements can affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Chile is 3.8% per year. The most ambitious SAF scenario (A3) will reduce the growth to 3.54% per year.

Cumulative capital investments needed for SAF deployment are shown in **Figure 16**. In the A1 scenario, the cumulative investments for 2025-2050 are US$ 10 billion. In the A2* scenario, they grow to the amount of US$ 17.5 billion. In the A3* scenario, the required Chile's investments in the new SAF plants are US$ 27 billion.

Mitigation policies lead to emission reduction in Chile's aviation sector. By 2050, emissions will decrease by 35% in A1, 52% in A2, and 63% in the A3 scenario, all relative to 2050 emissions in the no-policy CT scenario. These results are reported for the case where all SAF is produced domestically. In Section 4.7 we also discuss the benefits to Chile from regional collaboration.

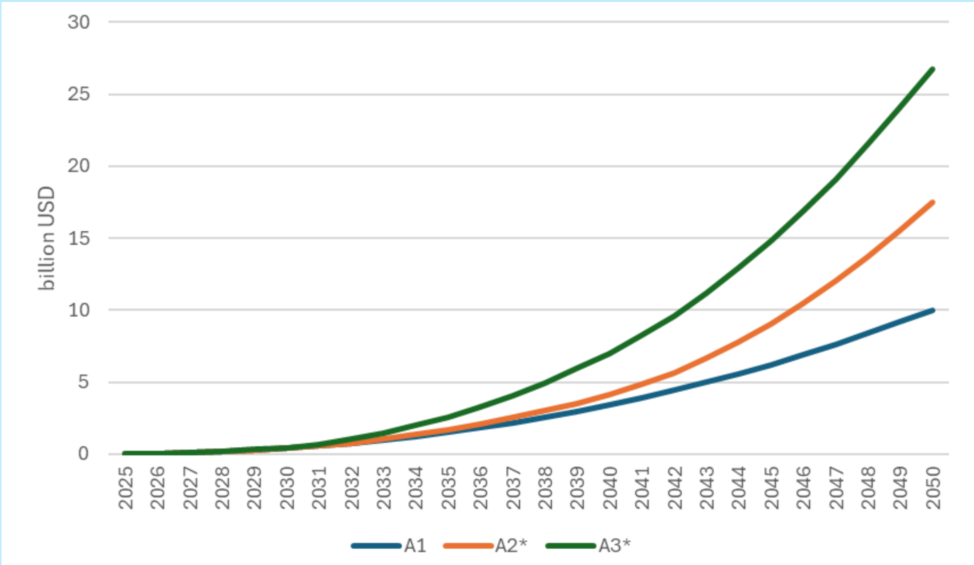

Figure 16. Cumulative capital investment in new SAF plants in Chile in different scenarios.

4.3 Colombia

For Colombia, aviation CO_2 emissions for 2015-2022 are provided in **Figure 17**. The pre-Covid levels were about 4 $MtCO_2$. In 2019, emissions from domestic aviation were 40% of the total aviation emissions in Colombia (OECD, 2023). The pandemics severely impacted both domestic and international flights. The flight volumes recovered, leading to an increase in Colombia's aviation emissions.

The results of our techno-economic analysis for the minimum selling price for SAF production in Colombia are presented in **Figure 18**. The most attractive pathways are palm oil-based HEFA (recall from a discussion in Section 3 that the estimated carbon intensity for this pathway in Colombia is lower than in Malaysia and Indonesia) and sugarcane-based ETJ. They both cost about $1.50/liter. Using sugarcane bagasse reduces competition for land and food products, but this pathway in Colombia is more expensive at about $2.30/liter. The cost of corn-based ETJ is about $2.50/liter. All SAF costs are reported for the "n-th of the kind" plant (i.e., for mature technology). According to the IATA Jet Fuel Price Monitor, the prices for conventional jet fuel in Latin America in September of 2024 were about $0.60/liter, while for the 2023-2024 period the prices were around $0.70/liter. Our analysis indicates that potential prices of SAF are higher than the current prices for fossil-based jet fuel.

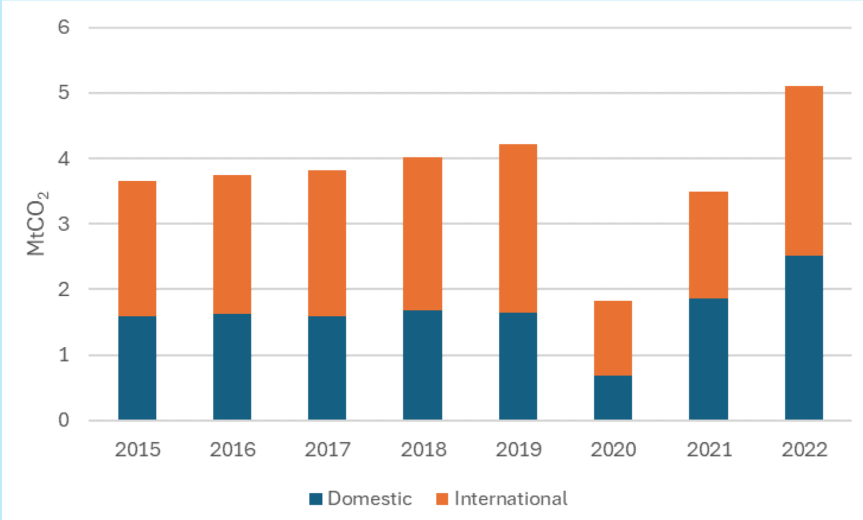

Figure 17. Aviation CO_2 emissions in Colombia. Data source: OECD (2023).

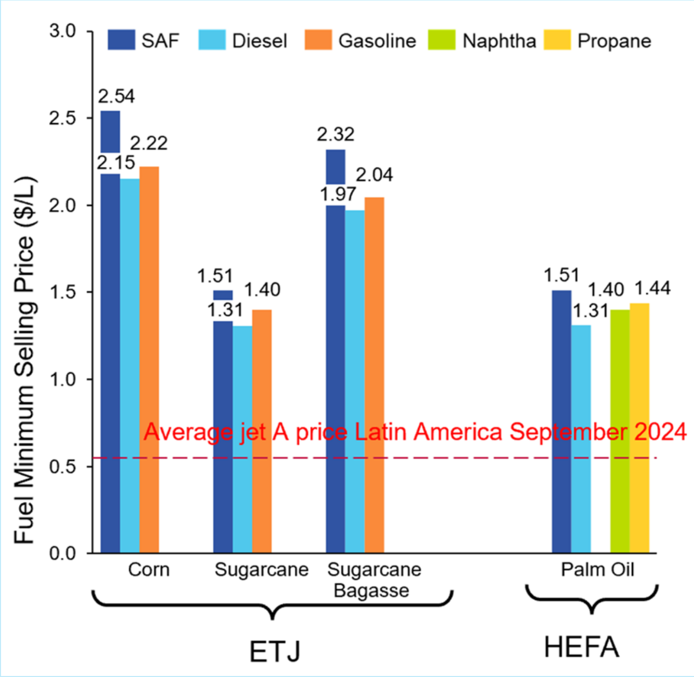

Figure 18. SAF production costs in Colombia for selected pathways for the n-th plant.

Our discussions in Colombia reveal the importance to assess the impacts of the biorefinery size on the SAF costs. To provide the context, Colombia currently has two large refineries (Cartagena and Barrancebermeja) with a capacity of around 9,000-12,000 ML/year each. There are also two small refineries in Colombia (Apiay and Orito), each with a capacity of around 150 ML/year. Our base calculations in this report consider a small-sized refinery with a capacity of 100 ML/year. For a comparison, currently the largest U.S. biodiesel refinery has a capacity of around 500 ML/year.

We explored how the changes in a refinery size affect the cost of SAF production. **Figure 19** shows the extent of the economies-of-scale, where SAF costs decrease as the refinery size increases. Recall that for our base setting of 100 ML/year, the minimum selling price for palm oil HEFA in Colombia is $1.51/liter. Increasing the size to 500 ML/year leads to a decrease in cost to $1.26/liter. However, the further cost reductions are less substantial. Increasing the refinery size to 1,000 ML/year results in the SAF cost of $1.26/liter. There is another consideration to keep in mind. Theoretically, Colombia could supply palm oil for a 1,000 ML/year plant, but it would require a little more than 50% of the total palm grown in Colombia in 2021 (FAO, 2023). The plant sizes need to be considered based on the availability of feedstocks.

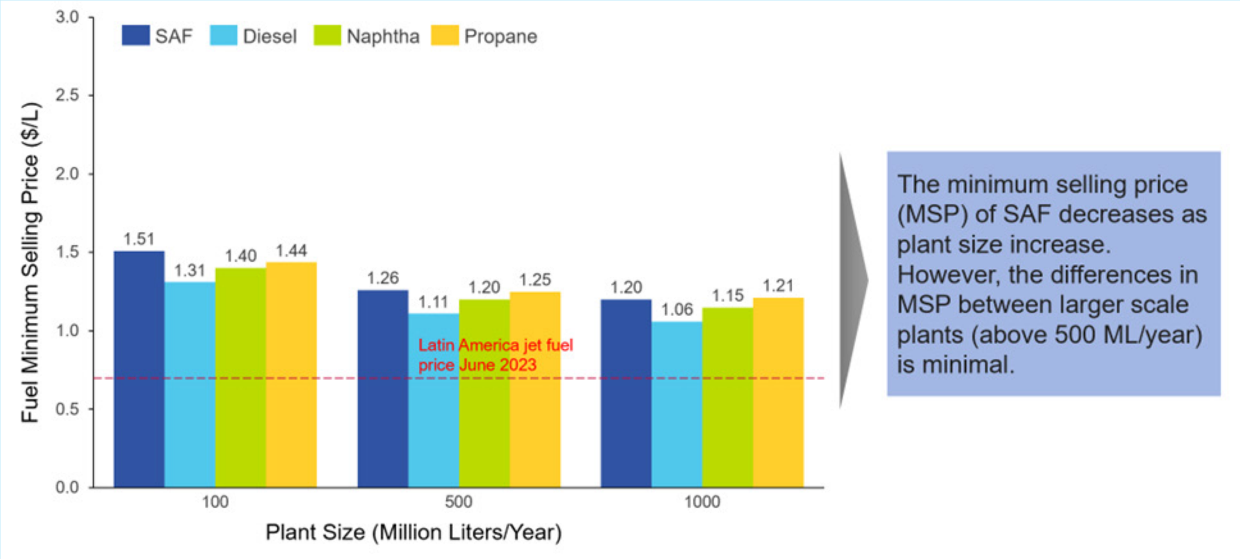

Figure 19. SAF production costs in Colombia for palm oil HEFA for various plant sizes.

While the government of Colombia is actively seeking ways to introduce SAF, there are no public SAF announcements yet. For SAF scenarios in Colombia, we impose the same overall percentages as in Chile (see Table 3). The results for aviation fuel consumption are presented in **Figure 20**, where the trajectories exhibit the similar behavior as in Brazil and Chile. Consumption of aviation fuel is growing over time in all scenarios, but it grows less in emission mitigation scenarios. In the CT scenario, aviation fuel consumption in Colombia grows from about 1,700 ML in 2019 to about 2,350 ML in 2030, and to about 3,900 ML in 2050.

As described earlier, fuel consumption in the AA scenario declined due to economy-wide emission reduction policies and the resulting price-induced efficiency improvements and demand-side responses. In this scenario, economy-wide CO_2 emissions in Colombia in 2050 are reduced by about 70% relative to the 2020 level. Aviation fuel consumption in the AA scenario is about 2,300 ML in 2030 and about 3,500 ML in 2050, which are reductions of 1.5% in 2030 and 9% in 2050 relative to the CT scenario.

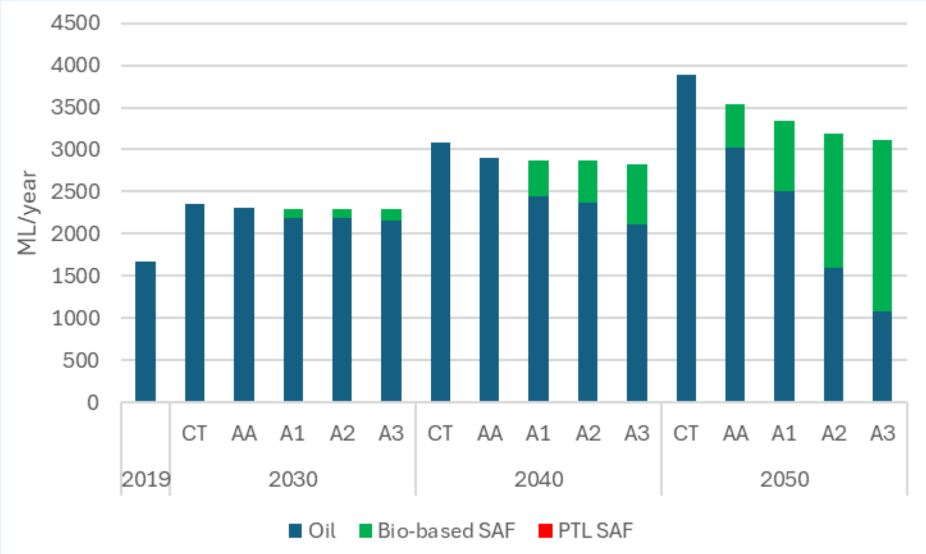

Figure 20. Aviation fuel consumption in Colombia in different scenarios.

As shown in Figure 20, the resulting impacts on aviation fuel consumption are growing with the stringency of the SAF mandates. In the A1 setting, the total aviation fuel consumption in Colombia is about 3,350 ML in 2050. In the A2-A3 settings, it decreases to about 3,200 ML and 3,100 ML, correspondingly. At the same time, the total amount of SAF production in Colombia in 2050 grows from about 500 ML in the AA scenario to about 800 ML in A1, 1,600 ML in A2, and 2,000 ML in A3. Note that in 2019 Colombia consumed about 1,700 ML in aviation fuel, so by mid-century the required volumes of the SAF in the stringent scenarios are comparable to the current conventional jet fuel consumption. Without strategies to manage price increases, SAF requirements can affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Colombia is 4.45% per year. The most ambitious SAF scenario (A3) will reduce the growth to 4.25% per year.

In terms of aviation emission reductions relative to the CT scenario, they will decrease in 2050 by 30% in A1, 48% in A2, and 58% in the A3 scenario. To support these outcomes, capital investments in new SAF plants are needed. As shown in **Figure 21**, the cumulative investments for 2025-2050 are US$ 12 billion in the A1 scenario. In the A2 scenario, they grow to the amount of US$ 17 billion. In the A3 scenario, they are US$ 23 billion.

We note that the current palm production in Colombia could support a 2,000 ML SAF output, but it would need to dedicate a 100% of the current levels of palm output for this purpose. Additional domestic and imported feedstocks would be needed for scaling up SAF in Colombia. Another option is to be involved in the regional and international SAF markets, which are still in need of development. These results are reported for the case where all SAF is produced domestically. In Section 4.7 we discuss the benefits to Colombia from regional collaboration.

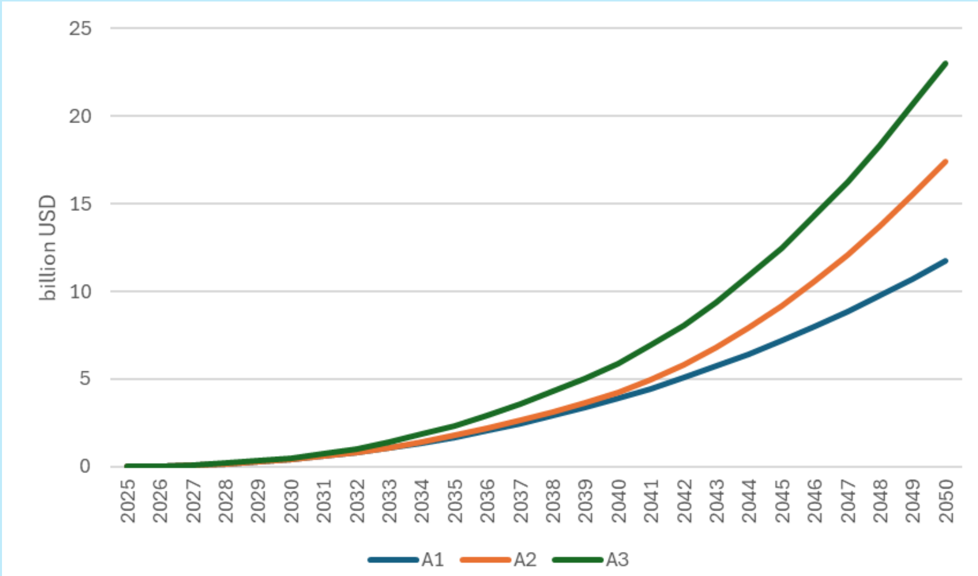

Figure 21. Cumulative capital investment in new SAF plants in Colombia in different scenarios.

4.4 Ecuador

Ecuador's aviation CO_2 emissions for 2015-2022 are reported in **Figure 22**. The pre-Covid levels were about 1 $MtCO_2$. In 2019, emissions from domestic aviation were 20% of the total aviation emissions (OECD, 2023), which reflects the relatively smaller size of the country. The pandemic impacted both domestic and international aviation markets, which have nearly recovered to year 2019-levels.

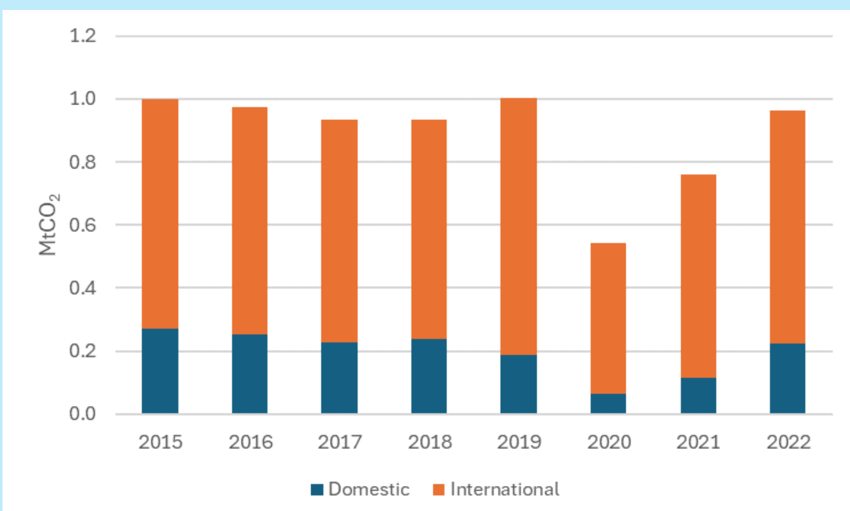

Figure 22. Aviation CO_2 emissions in Ecuador. Data source: OECD (2023).

As with the other countries, we start with the techno-economic analysis for the minimum selling price for SAF. The results for Ecuador are presented in **Figure 23**. The most attractive pathways in Ecuador are sugarcane-based ETJ ($1.32/liter) and palm oil-based HEFA ($1.45/liter). Corn-based ETJ and sugarcane bagasse ETJ are more expensive at about $2.05/liter and $2.15/liter, respectively. All SAF costs are reported for the "n-th of the kind" plant (i.e., for mature technology) and when a green premium is applied to all co-products. As discussed earlier, not being able to charge the green premium results in higher SAF costs. These costs can be compared to the conventional jet fuel prices in Latin America. In September of 2024, they were about $0.60/liter. For the period of 2023-2024, the prices were around $0.70/liter.

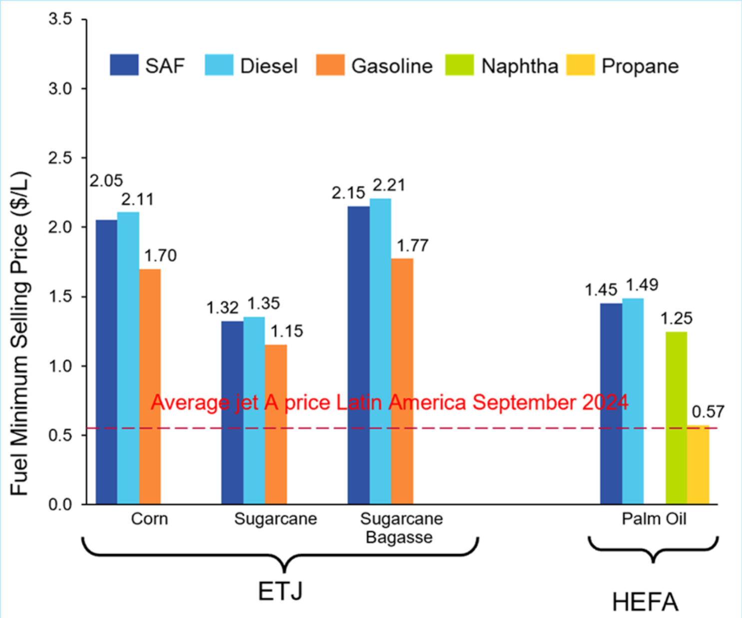

Figure 23. SAF production costs in Ecuador for selected pathways for the n-th plant.

The results for aviation fuel consumption in 2019-2050 in Ecuador are presented in **Figure 24**. In the CT scenario, aviation fuel consumption increases from about 450 ML in 2019 to about 570 ML in 2030, and to about 860 ML in 2050. In the AA scenario, Ecuador's fuel consumption is lower due to economy-wide emission reduction policies and the resulting price-induced efficiency improvements and demand-side responses. In this scenario, economy-wide CO_2 emissions in 2050 are reduced by about 60% relative to the 2020 level. The consumption of aviation fuel in Ecuador in the AA scenario is projected to be about 565 ML in 2030 and about 720 ML in 2050.

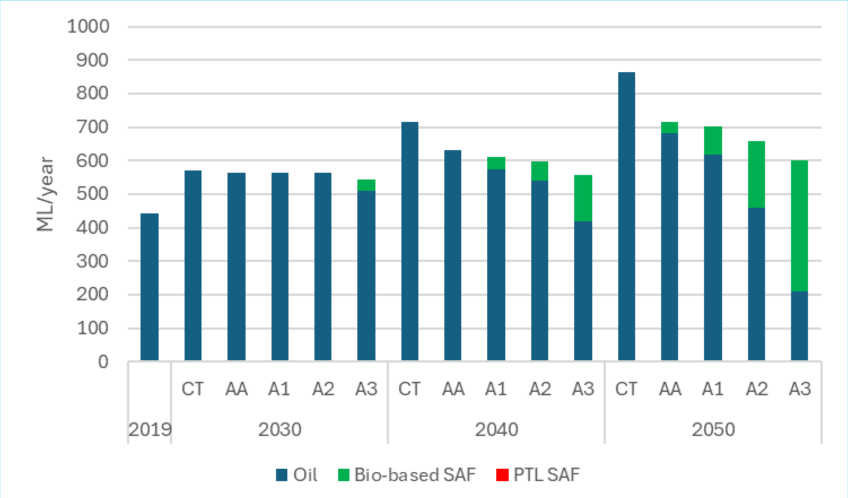

Figure 24. Aviation fuel consumption in Ecuador in different scenarios.

The impacts on aviation fuel consumption are growing over time and with the stringency of the SAF mandates. In 2050, in the A1 setting the total aviation fuel consumption in Ecuador is about 700 ML. In the A3 and A4 settings, consumption decreases to about 650 ML and 600 ML, respectively. The total amount of SAF production in Ecuador is estimated to be in 2050 about 35 ML in the A1 setting, about 80 ML in A2, 200 ML in A3, and 400 ML in A4.

Aviation emissions in Ecuador are reduced in 2050 by 25% in A1, 40% in A2, and 60% in the A3 scenario. Without strategies to manage price increases, SAF requirements can affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Ecuador is 3.56% per year. The most ambitious SAF scenario (A3) will reduce the growth to 3.42% per year. Capital investments in new SAF plants in these scenarios are provided in **Figure 25**. For 2025-2050, Ecuador investments are US$ 1 billion in the A1 scenario, US$ 2 billion in the A2 scenario, and US$ 4.5 billion in the A3 scenario. The benefits to Ecuador from regional collaboration are discussed in Section 4.7.

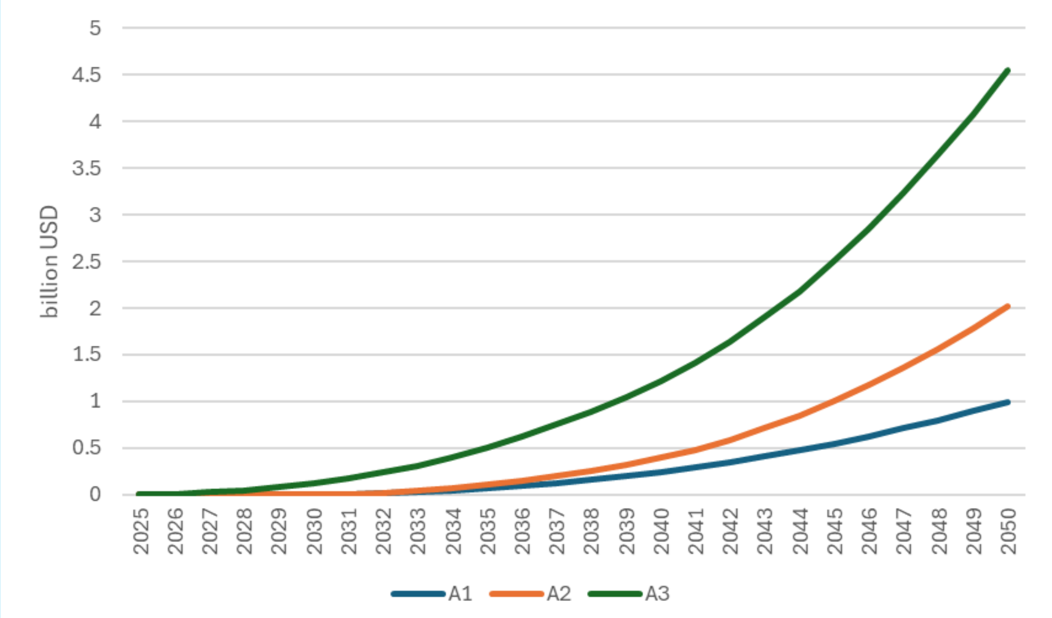

Figure 25. Cumulative capital investment in new SAF plants in Ecuador in different scenarios.

4.5 Mexico

Aviation CO_2 emissions in Mexico for 2015-2022 are shown in **Figure 26**. In the pre-Covid years (2015-2019), emissions were growing from 10 to 13 $MtCO_2$. In 2019, emissions from domestic aviation were 45% of the total aviation emissions (OECD, 2023). The pandemic most strongly impacted international flights. The market recovered from the impacts of the pandemic in 2022.

The results of our techno-economic analysis for the minimum selling price for SAF in Mexico are depicted in **Figure 27**. Several SAF pathway costs are in the range of $1.40 to 1.60/liter. They include corn, sugarcane, sorghum ETJ and palm oil HEFA. Sugarcane bagasse ETJ is more expensive at $2.40/liter. As before, all SAF costs are reported for the “n-th of the kind” plant (i.e., for mature technology) and with a green premium applied to all co-products. These costs can be compared to the conventional jet fuel prices in Latin America in September of 2024 of around $0.60/liter.

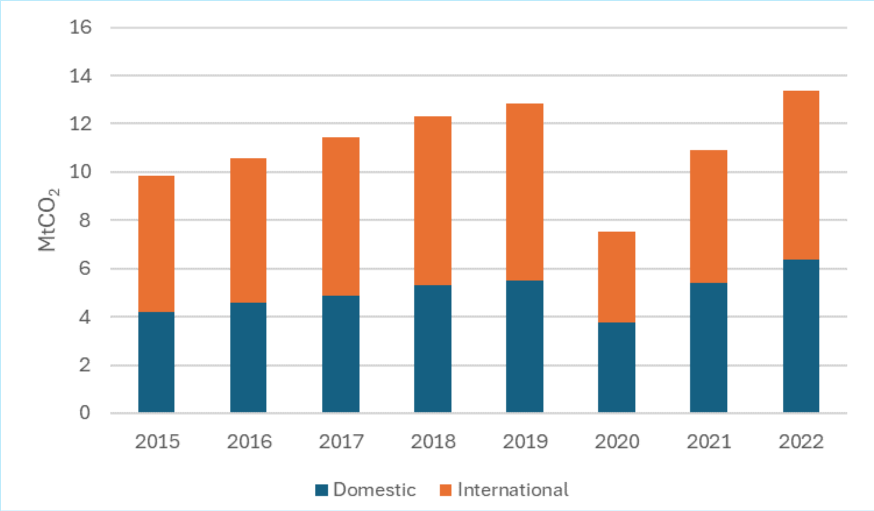

Figure 26. Aviation CO_2 emissions in Mexico. Data source: OECD (2023).

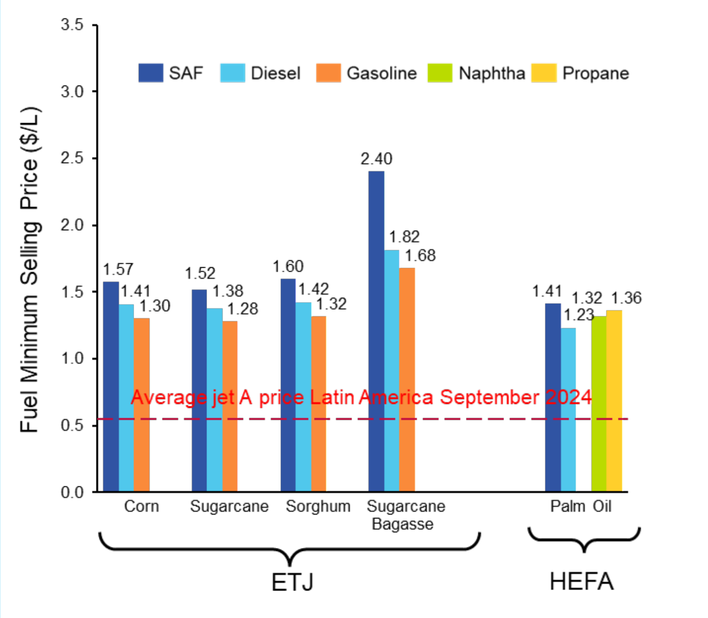

Figure 27. SAF production costs in Mexico for selected pathways for the n-th plant.

The results for aviation fuel consumption in Mexico are presented in **Figure 28**. In the CT scenario, the use of aviation fuel grows from about 5,000 ML in 2019 to about 6,400 ML in 2030, and to about 9,000 ML in 2050. As discussed in earlier sections, fuel consumption in the AA scenario is lower due to economy-wide emission reduction policies and the resulting price-induced efficiency improvements and demand-side responses. In this scenario, economy-wide CO_2 emissions in Mexico in 2050 are reduced by about 60% relative to the 2020 level. Aviation fuel consumption in Mexico in the AA scenario is projected to be about 5,600 ML in 2030 and about 7,500 ML in 2050.

In the SAF scenarios, the impacts are growing over time and with the stringency of the SAF mandates. In 2050, and with the A1 setting the total aviation fuel consumption in Mexico is about 7,100 ML. Under the A2 and A3 settings, consumption decreases to about 6,700

ML and 6,400 ML, respectively. The total amount of 2050 SAF production in Mexico is estimated at about 800 ML in A1, 2,000 ML in A2, and 4,200 ML in A3. In these scenarios, Mexico's aviation emissions are reduced in comparison to emissions in the scenario of current trends. In comparison to the CT scenario, in 2050 they are lower by 27% in A1, 41% in A2, and 62% in the A3 scenario. Without strategies to manage price increases, SAF requirements affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Mexico is 3.32% per year. The most ambitious SAF scenario (A3) will reduce the growth to 3.15% per year. Cumulative capital investments in new SAF plants in Mexico are shown in Figure 29. For 2025-2050, the required investments are US$ 10 billion in the A1 scenario, US$ 21 billion in the A2 scenario, and US$ 49 billion in the A3 scenario. Mexico's benefits from regional collaboration are discussed in Section 4.7.

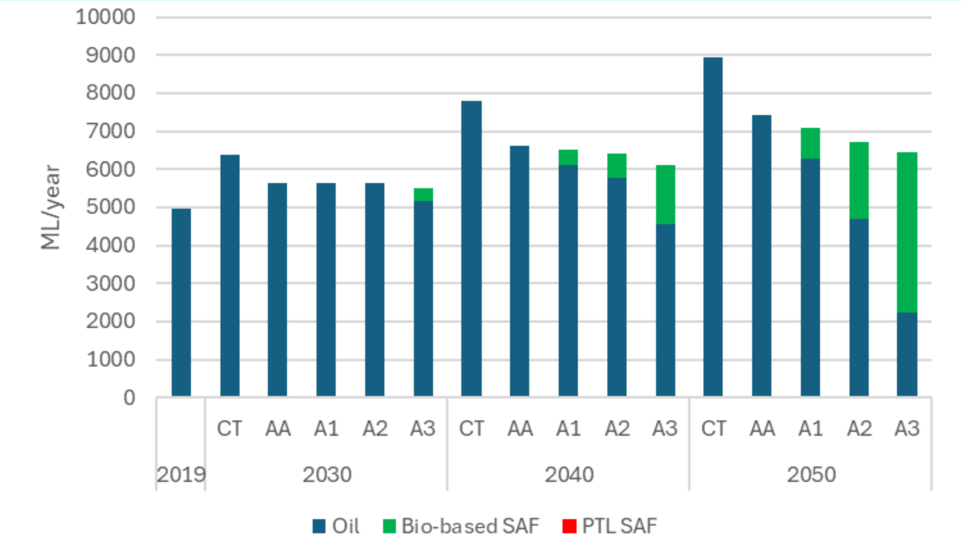

Figure 28. Aviation fuel consumption in Mexico in different scenarios.

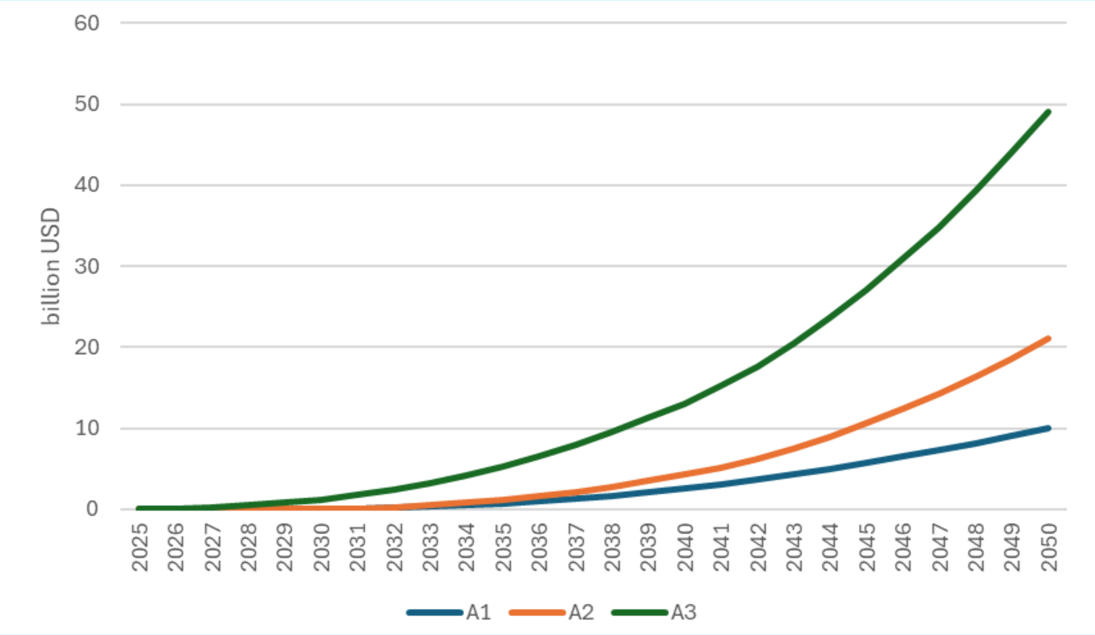

Figure 29. Cumulative capital investment in new SAF plants in Mexico in different scenarios.

4.6 Peru

CO_2 emissions from Peru's aviation for 2015-2022 are provided in **Figure 30**. The pre-Covid levels were about 3 $MtCO_2$. In 2019, emissions from domestic aviation were 30% of the total aviation emissions (OECD, 2023). The pandemic impacted aviation activities in Peru. After the pandemic, aviation emissions gradually increased.

Figure 31 presents the results of our techno-economic analysis for the minimum selling price for SAF in Peru. The most attractive option for SAF in Peru is sugarcane ETJ, with an estimated cost of $1.38/liter. Palm oil HEFA would cost $1.50/liter in Peru. Sugarcane bagasse ETJ and corn ETJ are more expensive pathways with the costs of $2.19/liter and $2.86/liter, correspondingly. As before, all SAF costs are reported for the "n-th of the kind" plant (i.e., for mature technology) and with a green premium applied to all co-products. These costs can be compared to the conventional jet fuel prices in Latin America in September of 2024 of around $0.60/liter.

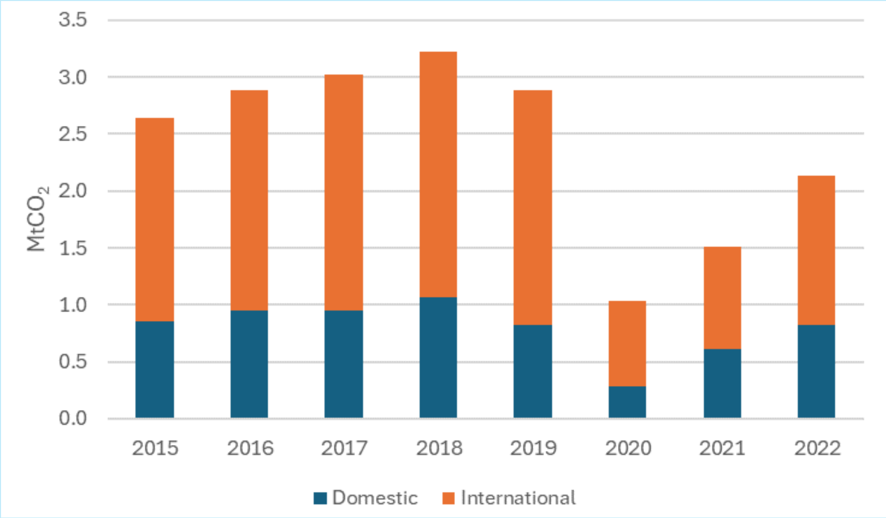

Figure 30. Aviation CO_2 emissions in Peru. Data source: OECD (2023).

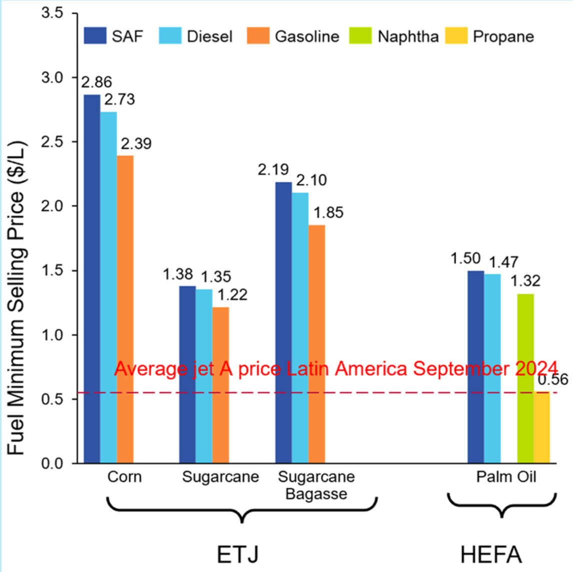

Figure 31. SAF production costs in Peru for selected pathways for the n-th plant.

Figure 32 shows the results for aviation fuel consumption in 2019-2050 in Peru. In the CT scenario, aviation fuel consumption grows from about 1,300 ML in 2019 to about 1,850 ML in 2030, and to about 2,800 ML in 2050. In the AA scenario, fuel consumption in Peru is lower due to economy-wide emission reduction policies and the resulting price-induced efficiency improvements and demand-side responses. In this scenario, Peru's economy-wide CO_2 emissions in 2050 are reduced by about 70% relative to the 2020 level. The level of consumption of aviation fuel in the AA scenario is projected to be about 1,830 ML in 2030 and about 2,450 ML in 2050.

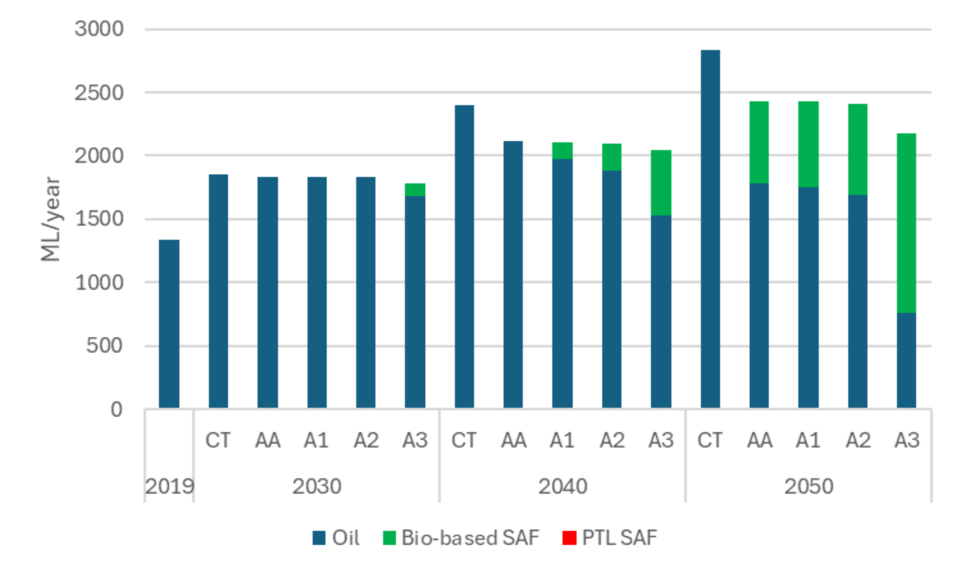

Figure 32. Aviation fuel consumption in Peru in different scenarios.

Under the A1 and A2 settings for the SAF requirements, aviation fuel consumption in 2050 is projected to be slightly lower than in the AA scenario, but still close to 2,400 ML. In the A3 setting, fuel consumption decreases to about 2,200 ML in 2050. The total amount of 2050 production of SAF in Peru is estimated to be about 650 ML in the AA scenario (without any SAF requirements), about 670 ML in A1, 720 ML in A2, and 1,400 ML in A3. In Peru, SAF production amounts in 2050 are similar in the AA, A1, and A2 scenarios. This implies that economy-wide mitigation activities in Peru result in the relative prices that make some SAF production economic by the middle of the century even without mandates.

Aviation emissions in Peru are reduced in the mitigation scenarios. In comparison to the CT scenario, in 2050 they are lower by 32% in A1, 33% in A2, and 59% in the A3 scenario. Without strategies to manage price increases, SAF requirements can affect the resulting aviation demand. The average annual growth of aviation demand in the AA scenario in Peru is 3.95% per year. The most ambitious SAF scenario (A3) will reduce the growth to 3.8% per year. Peru's capital investments in new SAF plants are represented in **Figure 33**. For 2025-2050, the required investments are US$ 6 billion in the A1 scenario, US$ 7 billion in the A2 scenario, and US$ 16 billion in the A3 scenario.

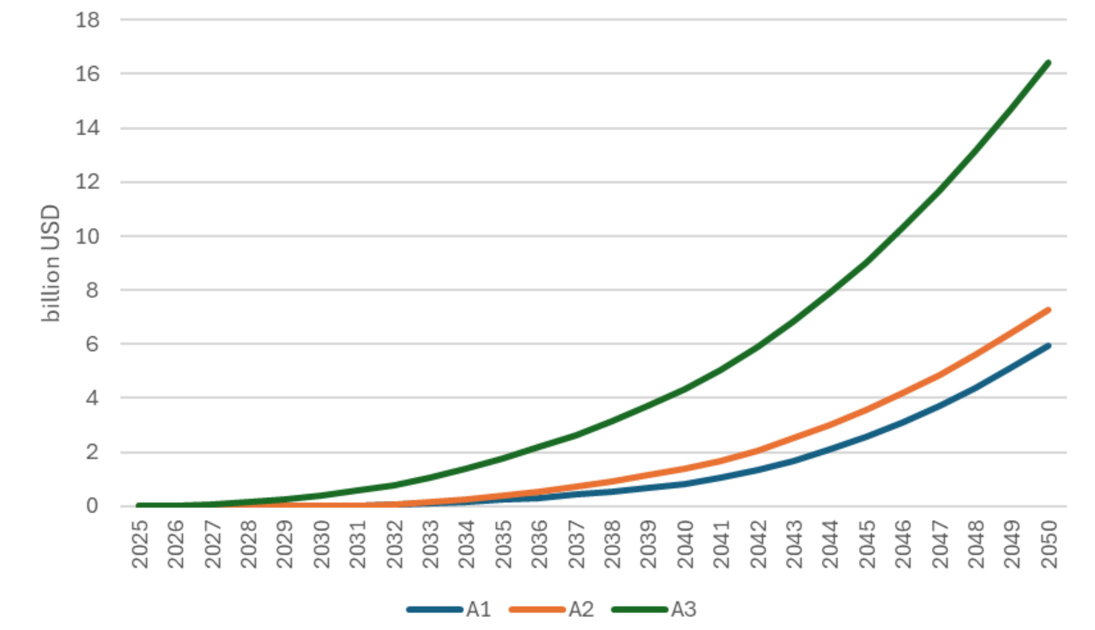

Figure 33. Cumulative capital investment in new SAF plants in Peru in different scenarios.

4.7 Benefits of regional collaboration

When SAF regulations are discussed, policy makers often consider domestic actions to support local farmers and fuel producers. Indeed, supporting domestic SAF production is attractive for political reasons. However, there are several counter-balancing considerations that call for a regional and international collaboration in SAF deployment and the overall emission mitigation from the aviation sector.

First, the availability of feedstocks for bio-based SAF varies significantly among countries. As reported in Table 2, the current (2021) crop production can support about 944 SAF plants in Brazil, 2 plants in Chile, 36 plants in Colombia, 14 plants in Ecuador, 118 plants in Mexico, and 10 plants in Peru. Dedicating all current crop production of the current feedstocks solely for SAF production needs would lead to a potential production of about 115,000 ML of distillate, which could result in 72,340 ML of SAF (when optimizing for SAF slate). In the most ambitious SAF scenario considered (A3, which results in 65% SAF use by 2050), we project that about 17,000 ML will be consumed in six countries of our study.

Obviously, it is impossible to dedicate all crops only for fuel production, which means that either the area of feedstock cultivation needs to be expanded (which may lead to an increase in ILUC emissions), current technologies need to be improved, new technologies for SAF production (like PTL) need to be developed and expanded, and/or greater use of non-food feedstocks (such as switchgrass, miscanthus, sugarcane bagasse, corn stover, etc.) needs to be introduced. Considering the current SAF feedstocks and technologies, we project that in the A3 scenario the share of land dedicated to SAF in 2050 (as a percent of total cropland) would be 3.3% in Brazil, 25% in Chile, 4.6% in Colombia, 5.8% in Ecuador, 3.5% in Mexico, and 2.3% in Peru. These results show that SAF deployment might have non-trivial land use impacts. If land-use changes are not managed properly, this may increase national GHG emissions (as an increase in land-use change emissions might be higher than those reduced by SAF).

Second, SAF production costs differ between countries. As discussed earlier, for the pathways considered in each country, costs for mature bio-jet-fuel plants range from \$1.11 - 1.77/liter in Brazil, to \$1.68 - 2.53/liter in Chile, \$1.51 - 2.54/liter in Colombia, \$1.32 - 2.15/liter in Ecuador, \$1.41 - 2.40/liter in Mexico, and \$1.38 - 2.86/liter in Peru. The PTL pathway was assessed for Chile only, with the costs range from \$2.04/liter (under extremely optimistic assumptions of \$1.70/kgH_2 and \$150/tCO_2) to \$6.39/liter (under more realistic costs for H_2 at \$3.10/kg and DAC at \$600/tCO_2).

These two considerations suggest that access to lower-cost SAF (rather than relying only on domestic SAF production) is beneficial for the cost of fuels and aviation demand. To evaluate the potential benefits from regional collaboration, we explored a scenario where SAF can be traded between the six countries. The results for an aggregate aviation demand in the six countries under consideration (Brazil, Chile, Colombia, Ecuador, Mexico, Peru) are provided in **Figure 34**, where we constructed an index of aviation demand relative to 2019 (when it is set to 100).

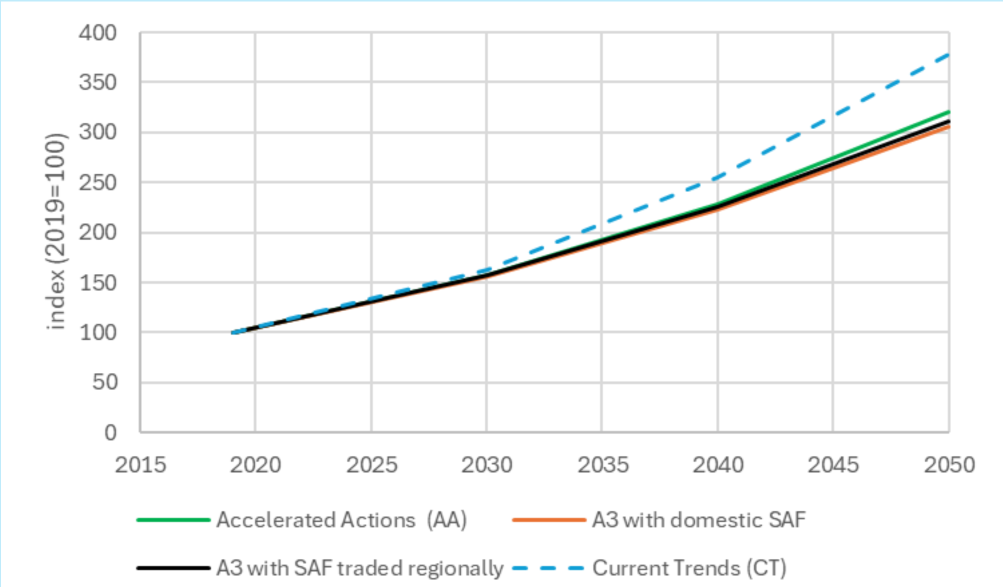

Figure 34. Index of aviation demand in six Latin American countries. Note: 2019=100. For 2019-2025, effects of Covid are averaged

In the CT scenario, an aggregate (in six countries) aviation demand grows at an average annual rate of 4.38%. However, emissions in this scenario are not controlled. In the mitigation scenarios, aviation emissions are lower. By 2050, the AA scenario reduces them by 22%, A1 by 28%, A2 by 41%, and in the A3 scenario emissions are reduced by 61%. Without mitigation of cost premiums, emission reduction activities are expected to affect aviation demand. For example, the average annual growth of aviation demand in the AA scenario is lower. It is 3.83% per year in this scenario, and in the most ambitious SAF scenario (A3) the growth is further reduced to 3.67% per year.

The difference in the *levels* of aviation demand in 2050 between the AA scenario (which does not impose SAF regulations) and A3 scenario (which imposed 65% SAF requirement) is 4.8%. However, if SAF trading was introduced (i.e., removing the requirement that SAF needs to be produced domestically), enabling each country to access the most competitive fuel, it would reduce the negative impact on demand by 40% (i.e., a difference with the level of aviation demand with the AA would be a reduction of 2.9%).

In other words, the estimated impact of allowing full regional trade in SAF among the six countries is an increase in the level of aviation demand in 2050 by 2% relative to the case where the SAF mandate was achieved only by the domestically produced SAFs.

While the exact settings for a such trading regime require further examination, we found that the overall amount of SAF consumption does not change substantially as the volumes are mostly driven by the overall mandates. However, several countries, such as Chile and Mexico, would likely find it economically attractive to switch from the domestic SAF production to imports from Brazil, Colombia, Ecuador, and Peru, whereas some of the latter countries could benefit from increased production volumes for export. These results are driven by SAF production costs, feed-stock availability, land prices, and patterns of agricultural trade (that competes with SAF for resources). Our illustrative calculation shows that Chile and Peru can be the largest beneficiary as a result of SAF trading, but all countries benefit from trade as shown in **Figure 35**.

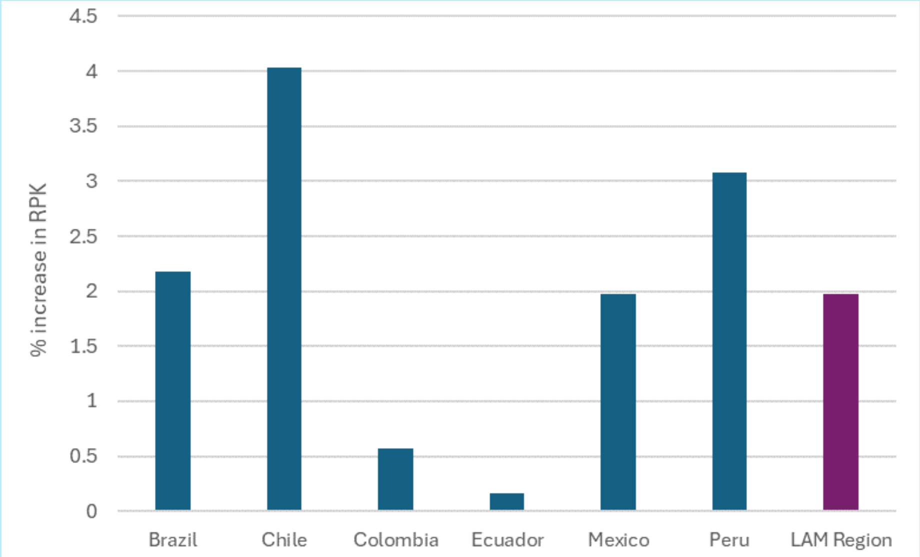

Figure 35. Impacts of regional trade in SAF on aviation demand (% increase in RPK in the A3 scenario with regional SAF trade relative to the A3 scenario without trade).

Chile and Mexico benefit from their access to a cheaper fuel and from an ability to dedicate feedstock to higher-value activities (determined by their agricultural production and trade). Brazil, Colombia, Ecuador and Peru benefit from selling their SAF abroad, where they get higher prices for their products. For fuel producers, it is also beneficial to consolidate demand because it allows creating more robust supply chains for establishing economies-of-scale.

It is worth noting that in the A3 scenario Colombia and Peru initially export SAF in 2030-2040, and in 2050 when SAF requirements are getting more stringent, they become SAF importers. This result underscores the fact that detailed country-specific studies that represent the nuances of feedstocks, transportation costs, and trading approaches are needed for a thorough examination of potential trading patterns.

Without SAF mandates, emission mitigation actions (AA scenario) reduce carbon emissions from aviation in 2050 by 22% relative to the status quo (CT scenario). In the most ambitious SAF scenario considered in this study (65% SAF use by 2050), the use of SAF in combination with an economy-wide mitigation is projected to reduce aviation emissions by about 60% in 2050. To reach the net-zero goals, further improvements in carbon intensity and costs of SAFs will be needed and other measures will be required, such as improvements in operational and air traffic efficiencies, airplane fleet renewal, alternative forms of propulsion technology, and market-based mechanisms (MBM). MBMs include fees and emission allowances, such as those imposed in the AA scenario of this report. They also include credits and offsets that provide flexibility to emitters by giving them alternative methods of reducing emissions.

Regional collaboration on the rules and regulations for carbon offsetting and carbon removals can further benefit the overall emission reduction. Latin America is a region with a high potential for high-quality carbon offsets. While the potential is high, the actual supply of offsets is inadequate for the needs of aviation. As discussed, CORSIA-eligible carbon offset credits must meet strict criteria to ensure their integrity. In addition, the countries with the offset projects need to authorize the usage of credits for the purpose of CORSIA and must conduct a corresponding adjustment in the national registry under their NDCs to ensure that the emissions reductions claimed by airlines are not double claimed by the host countries.

Regional collaboration in carbon offsets can increase the supply of CORSIA-eligible projects. Working together on unification of standards for offsets is crucial for proper tracking and verification. The aviation sector can greatly benefit from an increased supply of high-quality credits from Latin America. An example of such development is a recent announcement by the government of Guyana on the authorization of carbon units for the use in CORSIA (Government of Guyana, 2024). The authorization ensures the environmental integrity of these carbon units, emphasizing the prevention of double-claiming between CORSIA and other national environmental purposes. Unification of decarbonization approaches between countries will be beneficial to ensure competitiveness and economy-of-scale.

5 Recommendations

While our analysis is intended to provide a "big picture" regarding the decarbonization options for aviation in Latin America and many aspects of aviation operations are beyond the scope of our modeling (such as details of day-to-day operations, exact routes served, fleet composition, airline behavior, airports infrastructure, etc.) and therefore the exact numerical values should be treated with a great degree of caution, several recommendations can be offered based on our assessment. With all inherent uncertainty about the potential cost reductions for existing technologies and deployment of new technological options, one message is clear: substantial government interaction will incentivize and accelerate decarbonization activities in Latin America. Currently, airlines and SAF producers offer pilot projects, but different forms of government support will enable scaling up sustainable decarbonization pathways.

To reach net-zero goals, several measures will be required, such as the use of sustainable aviation fuels (SAF), improvements in operational and air traffic efficiency, airplane fleet renewal, introducing alternative forms of propulsion technology, and use of market-based mechanisms to offset the remaining emissions.

SAF offers a significant decarbonization pathway, and in the case of combining aggressive SAF ambitions with an economy-wide emission mitigation (i.e., considering impacts from SAF use and economy-wide policy, such as more efficient aircraft, demand response, etc.) we estimate aviation emissions reductions in Latin America up to 60% by 2050 relative to the current trends. To make it a reality, all key stakeholders of the SAF value chain will have to mobilize their efforts to ensure its sustainable deployment in the region. Setting up the ecosystem for SAF deployment might face challenges. Hence, it is important to structure the necessary adjustments through private-public consultations (roundtables, initiatives, alliances) to ensure that shaping policies and regulation at a country level will be the result of mutual agreement that will integrate the relevant design of measures to support the SAF ambitions.

It is important to consider how aviation decarbonization actions fit the economy-wide mitigation at a country level. The current climate actions in Latin America are not sufficient for achieving the stated net-zero emission goals, and it would be challenging for the aviation industry to reach the decarbonization goals without corresponding accelerated actions in all sectors of the economy. Policymakers need to accelerate mitigation actions and integrate aviation emission reduction goals into the overall strategies for the countries.

Different forms of government support (to SAF producers, airlines, and/or passengers) will enable scaling-up of SAF deployment and make it a commercially viable option. Without appropriate policy frameworks, SAF requirements will increase the cost of air travel. Gradual introduction of regulations and market-based mechanisms can incentivize the market participants to prepare their investment strategies. At the same time, market participants need certainty that regulations will not be reversed or changed.

The cumulative capital investments required to build new SAF plants are extensive. In the ambitious SAF scenario (65% SAF use by 2050), we estimate that the investments over the 2025-2050 period will be US$204 billion for the six countries studied: US$84 billion in Brazil, US$27 billion in Chile, US$23 billion in Colombia, US$5 billion in Ecuador, $US49 billion in Mexico, US$16 billion in Peru.

We recommend a gradual implementation of SAF requirements that are combined with government support mechanisms. Such measures can be more successful in building public-private coalitions of support for ambitious actions. To ensure sustainable decarbonization, policymakers need to ensure a comprehensive assessment of impacts, determining the effects on the region's connectivity and the ability to access air transport for disadvantaged communities. The impact of decarbonization measures on passenger traffic and connectivity will likely depend on government incentives (to SAF producers and/or airlines).

Because the aviation industry is a fuel consumer, supply-side regulatory and tax incentives to SAF producers can ensure commercial production, reduce SAF project risks, and decrease the opportunity costs of producing SAF. In anticipation of more stringent requirements for SAF volumes, airlines can establish long-term partnerships with SAF suppliers to provide more certainty both on the SAF supply and demand side. Our findings regarding the potential SAF costs and production volumes show that countries in Latin America have heterogeneous levels of potential and capabilities, although most of them can produce sizeable amounts at costs which are relatively comparable among Latin American countries. While there is technical feasibility to reach sizeable SAF ambitions in the regions, relevant policies are important to support the nascent industry.

Coordination of decarbonization approaches between countries can further be beneficial to avoid non-competitiveness concerns and ensure a level playing field among the countries. Such an approach can also benefit the development of carbon markets in general, including approaches to robust carbon offset mechanisms. Airlines may face substantial challenges to adjust to SAF policies (or aviation decarbonization policies) if such policies differ substantially among Latin American countries, or if they have to rely only on the domestically produced SAFs.

Regional integration can further lead to more competitive SAF options that help fulfill policies in the partnering countries. Regional collaboration on the mechanisms, such as "book-and-claim" would further facilitate an accelerated adoption of SAF. In the Accelerated Actions scenario, the estimated impact of allowing full regional trade in SAF among the six countries is an increase in RPK in 2050 by 2% relative to the case where the SAF mandate was achieved only by the domestically produced SAFs.

We stress that there is a need for detailed evaluations of country-specific and region-specific policy mechanisms (including regulatory incentives, carbon taxes, and carbon offsets) to achieve emission reduction goals in aviation in a sustainable way. Government authorities and industry participants should encourage such studies that involve local and international experts. The results of such studies can provide a valuable framework for understanding the challenges and opportunities ahead, guiding the region toward a sustainable aviation future.

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Appendix A. Inputs to SAF techno-economic analysis

To determine the minimum selling price for SAF, we used a modified version of models developed by Brandt et al. for different jet fuel pathways (Brandt, Geleynse, et al., 2021; Brandt, Tanzil, et al., 2021; Brandt and Wolcott, 2021). The minimum selling price is calculated using a discounted cash flow method that accounts for capital costs, operational costs (e.g., feedstock, electricity, natural gas, maintenance), loan interest payments, and shareholder interest payments. We calculate the cost of SAF and its co-products considering different feedstocks for ethanol-to-jet (ETJ), hydrotreated esters and fatty acids (HEFA) and Fischer-Tropsch (FT) pathways.

These models were modified to make them specific to a particular country by adjusting the equity and debt loan rates, corporate tax rates, utility costs (e.g. electricity, natural gas), and fossil distillate fuel prices. We focused on the ASTM-approved feedstocks and conversion pathways (See Figure A1). Country specific feedstock costs were sourced from FAO data (FAO, 2023). In the case of ETJ, the corn ethanol fermentation process was modelled based on the process described by Kwiatkowski et al. (2006), and the sugarcane ethanol fermentation process was modelled based on the process described by Junqueira et al. (2017). Based on this information, we determine realistic available combinations of feedstocks and conversion technology to produce SAF at scale (as illustrated in Figure A2). Tables A1-A3 provide information for selected input assumptions.

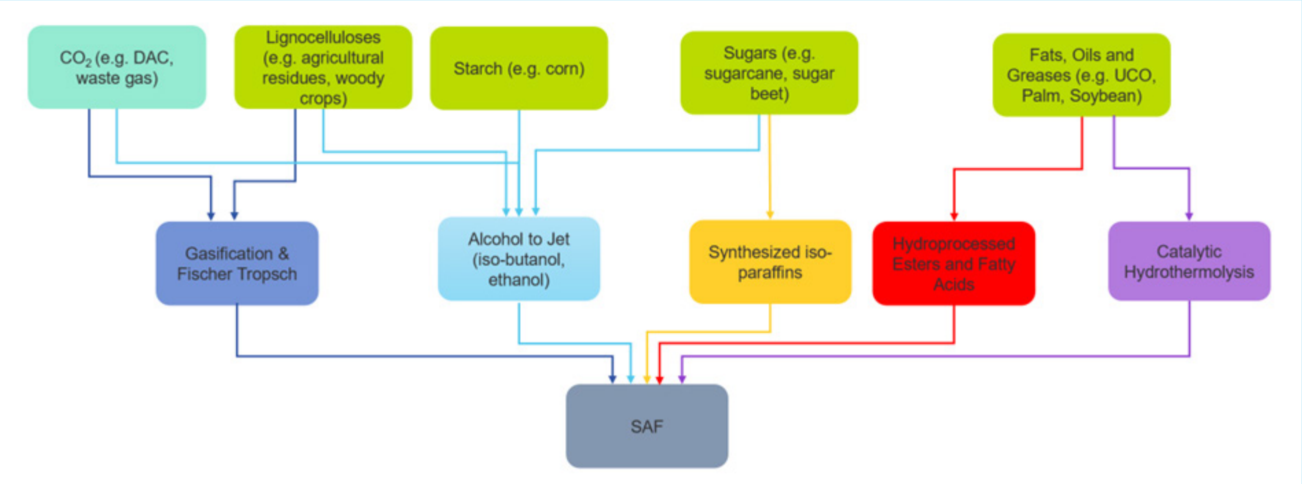

Figure A1. Conversion pathways for SAF approved by ASTM (an international standards organization)

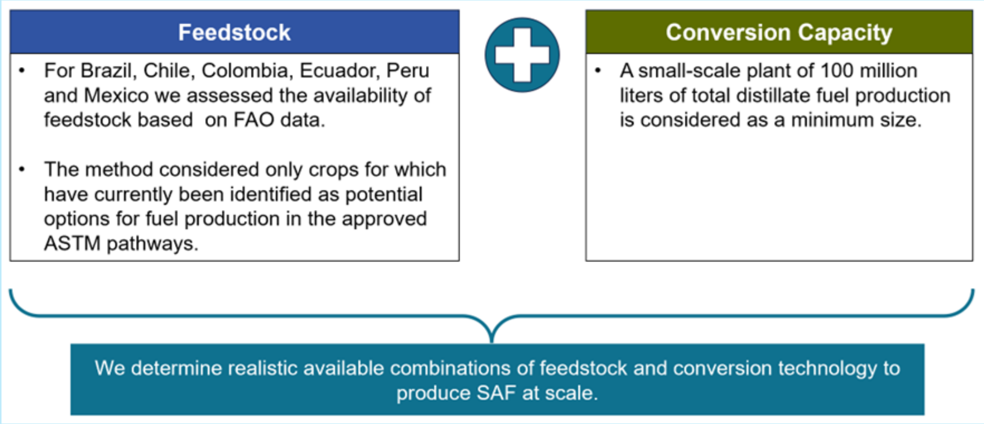

Figure A2. Infographics of our assessment of SAF feedstocks and conversion pathways

	Unit	Brazil	Chile	Colombia	Ecuador	Mexico	Peru
Refinery size	ML/year	100	100	100	100	100	100
Feedstock prices (3 year average 2020 - 2022)							
Sugarcane	$/tonne	20		35.05	30	39	35
Corn	$/tonne	209	388	449	361	244	581
Sorghum	$/tonne	164				227	
Palm oil	$/tonne	910		1003	1198	910	
Soybean oil	$/tonne	977					
Forestry Residue	$/tonne		125				
Energy prices (2022)							
Electricity	$/kWh	0.15	0.14	0.13	0.078	0.086	0.045
Natural Gas	$/MMBtu	10.4	12.11	10.66	4.22	6.36	3.79
Hydrogen	$/kg	1.77	1.77	1.77	1.77	1.77	1.77
Diesel	$/liter	0.91	0.95	1.05	0.84	1.01	0.86
Gasoline	$/liter	0.74	0.92	0.99	0.78	0.94	0.74
Financial Inputs							
Inflation	%	6.09	4.41	4.47	1.93	4.46	3.34
WACC	%	12.61	8.45	9.88	11.59	9.88	9.72
Corporate Tax Rate	%	34	27	35	25	30	29.5
Equity	%	30	30	30	30	30	30
Equity Loan Rate	%	22	12	22	22	20	20
Loan Interest Rate	%	13	9.5	7.2	9.5	7.91	7.54
Loan Term	year	10	10	10	10	10	10
Property Insurance	% of fixed costs	1	1	1	1	1	1
Project life	year	20	20	20	20	20	20
Equity/Debt Ratio	ratio	30/70	30/70	30/70	30/70	30/70	30/70

Table A1. Input assumptions for bio-based SAF pathways

	Unit	Value
Refinery size	ML/year	100
Financial Inputs		
Inflation	%	4.47
Corporate Tax Rate	%	27
Equity	%	30
Equity Loan Rate	%	12
Loan Interest Rate	%	9.5
Loan Terms	year	10
Property Insurance	% of fixed costs	1
Pioneer Plant Input Costs		
Green H2	$/kg	3.1
CO2	$/tCO2	600
Mid-point Plant Input Costs		
Green H2	$/kg	2
CO2	$/tCO2	375
Mature (n-th) Plant Input Costs		
Green H2	$/kg	1.7
CO2	$/tCO2	150

Table A2. Input assumptions for synthetic SAF pathways (direct-air capture Fisher-Tropsch, DAC-FT for different levels of technology maturity).

	Unit	Corn ETJ	Sugar ETJ	Sorghum ETJ	HEFA*	DAC-FT nth	DAC-FT pioneer
Refinery size	ML/year	100	100	100	100	100	100
Capital Costs	Million USD	102	177	134	115	390	1066
Fixed Operation and Maintenance Costs	Million USD/yr	11.3	11.9	11.3	16.4	30.5	77.8
Variable Operating Costs (excluding Hydrogen, Natural Gas, Electricity)	Million USD/yr	12.3	2.8	12.3	2.8	6.7	6.7
Energy Input Requirements							
Hydrogen	t/yr	840	840	840	3658		
Electricty	GWh/yr	40.5	27.0	40.5	1.8	1847.1	2457.2
Natural Gas	TJ/yr	1057.8	712.8	1057.8		11.2	11.2

Table A3. Pathway-specific characteristics. The HEFA pathway only includes the oil to distillate step (oil extraction is not included). In the DAC-FT pathway, electrolyzer and DAC costs are included in costs, and electricity use for electrolytic H2 and DAC are included in electricity use.

Appendix B. EPPA model description

The MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev et al., 2005; Chen et al., 2022) is built on the Global Trade Analysis Project (GTAP) economic dataset (Aguiar et al, 2019) which provides a consistent representation of regional production, bilateral trade flows, and markets. Energy and land markets are supplemented with accounting in physical units. This economic data is augmented with additional information on advanced technologies, greenhouse gases and air pollutants emissions, taxes and details of selected economic sectors. The data are aggregated to 18 regions and multiple sectors, with additional detail in the energy sector added in the form of advanced technology alternatives that are incorporated using bottom-up engineering detail (see infographic on Figure A1). For this work, additional aviation fuel options were added.

The model's production and consumption sectors are represented by nested Constant Elasticity of Substitution (CES) production functions (or the Cobb-Douglas and Leontief special cases of the CES). The model is calibrated to economic and energy data from the IMF (2023) and IEA (2023) for 2015 and 2020 and then it is solved recursively in 5-year time steps from 2020 to 2050. The model is designed for projecting long-term trends, so it does not capture business cycles or short-term shocks such as those that often occur in, for example, commodity markets that play out over periods of less than the 5-year time step of the model.

A model solution must meet three conditions: market clearance conditions (supply must equal demand), zero profits (the cost of inputs should not exceed the price of the output), and income balance (expenditures must equal income, accounting for savings, subsidies and taxes). Production technologies are chosen based on their relative competitiveness given the characterization of input requirements for the technology, which, in turn, determine the cost of the technology given prices for the inputs.

Base year prices for all inputs are in the base economic data of the model, and future technology costs depend on how prices change for inputs used by the technology. Input prices change over time depending on the dynamics of the model, including changes in the labor force, investment and capital availability, resource availability/depletion and existing or new policies or constraints. All technologies require capital and labor inputs, and so capital and labor productivity improvement (a major component of the dynamics of the model) drives down technology costs over time. The model also traces inter-industry and inter-regional demands. These influences combine to determine the resulting technology mix. Additional information about the EPPA model is available at: https://globalchange.mit.edu/research/research-tools/human-system-model

The EPPA version used in this study is expanded to include the aviation sector details (see Figure A1). Among the key parameters related to aviation are air travel demand elasticities relative to the cost of travel and relative to income of travelers. The widely adapted values in aviation studies are from InterVISTAS (2007). For price elasticities for South America, they are -1.1 for short-haul, -1 for long-haul for national level. The corresponding elasticities for pan-national (international) level are -0.83 for short-haul and -0.75 for long-haul. We used -0.8 for price elasticity. For income elasticities, the typical values are between 1 and 2 depending on the level of development of a country (InterVISTAS, 2007). Based on Airbus (2023) and Gillespie (2011), we used the value 1.4 for income demand elasticity. The resulting EPPA modeling outputs for aviation are influenced by numerous channels, including elasticities, relative costs of inputs and outputs, relative shares of aviation in private and industrial consumption, economic growth, policies and regulations. Because elasticities are important for the magnitudes of the impacts, we searched for more recent studies. Our consultations with aviation experts reveal that the comprehensive updates of the InterVISTAS (2007) elasticity estimates are non-existent at this point, and there is a strong need for a thorough assessment of region-specific and segment-specific elasticities, including an appropriate inclusion of the effects of pandemic on aviation demand.

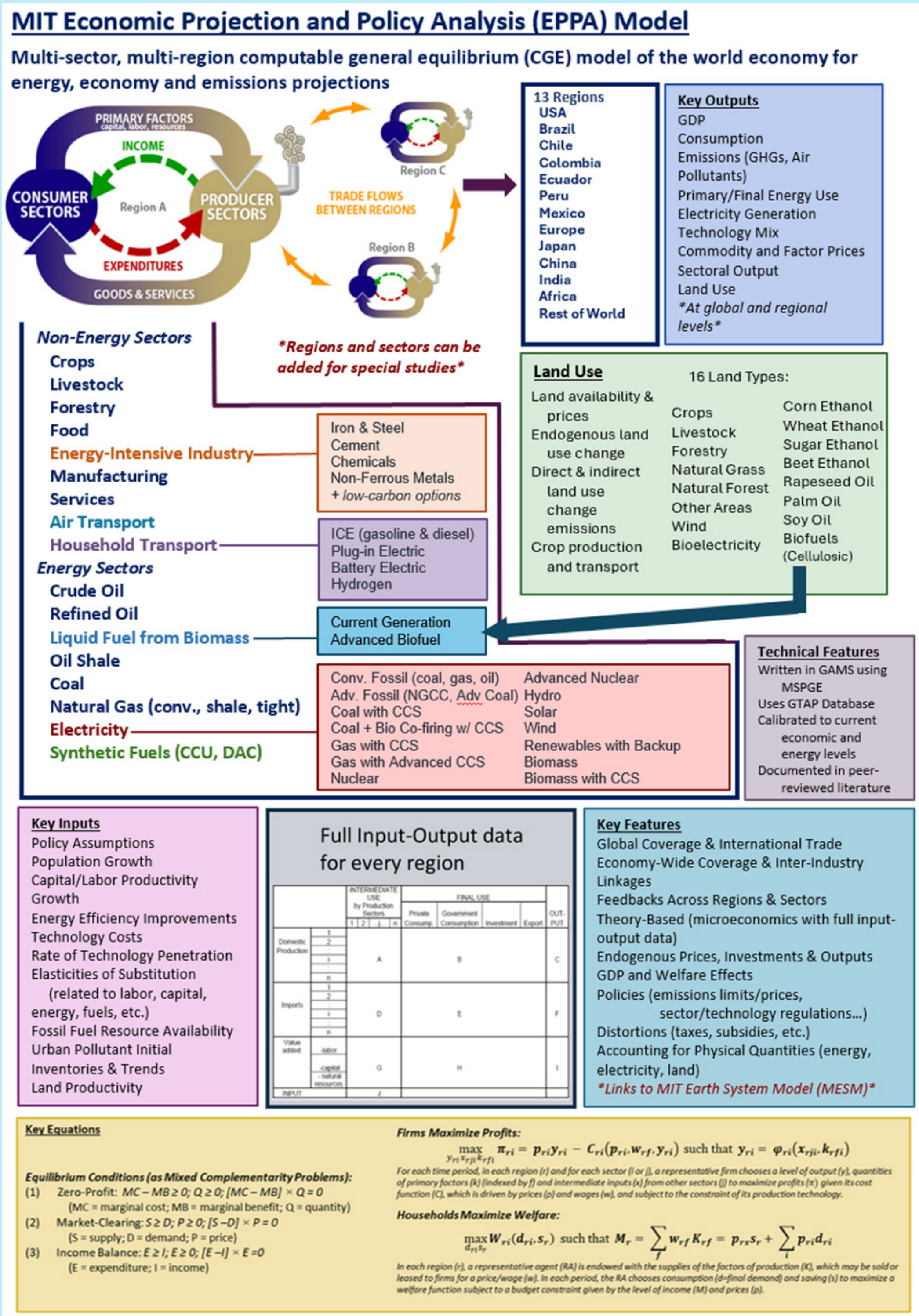

Figure A3. Infographics of the EPPA model