Sustainable Aviation Fuel Production in Colombia: Opportunities and Challenges

This report was funded by the US Federal Aviation Administration (FAA) Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 93 through FAA Award Number 13-C-AJFE-WaSU-037 under the supervision of Prem Lobo. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

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Sustainable Aviation Fuel Working Group Participants

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Executive summary

The sustainable aviation fuel (SAF) working group in Colombia was convened under the SAF Global Supply Chain Development project (Project A93) led by the Federal Aviation Administration's (FAA) Center of Excellence for Alternative Jet Fuels and Environment, also termed the Aviation Sustainability Center of Excellence (ASCENT) and executed by Washington State University. The working group includes stakeholders across aviation, biofuel production, agriculture, government agencies, academic research, and technical consultancies. A complete list of stakeholders is included after the cover page. This group recognizes that developing SAF requires gathering knowledge and insights across multiple sectors, such as academia, private enterprise, local and federal governments, as well as multilateral, environmental, and energy advocates. This report serves as a high-level information identification to be use as starting point for designing and analyzing the supply chain to produce SAF in Colombia.

The SAF working group stresses the importance of developing SAF supplies to ensure a robust aviation industry. Unlike road transportation and electricity generation, aviation has limited "drop-in" fuel alternatives that provide high-energy-density liquid fuels to current aircraft for the next few decades. The report focuses on gathering information on developing SAF options in Colombia that meet rigorous safety and performance standards approved by ASTM International using commercial or near-commercial conversion technologies. The report identifies opportunities and challenges for three pathways: hydroprocessed esters and fatty acids (HEFA), alcohol to jet (ATJ), and gasification with Fischer-Tröpsch (GFT).

Colombia has defined a domestic carbon emission reduction goal for the aviation sector focusing on performance-based navigation but does not include fuels. However, the International Civil Aviation Organization (ICAO) defined a set of mitigation measures to reduce carbon dioxide (CO_2) emissions, including SAF (ICAO, 2016). ICAO adopted the goal of carbon-neutral growth of international aviation in 2020 from a 2019 baseline (ICAO, 2013). The International Air Transportation Association (IATA) aims to reduce CO_2 emissions in the aviation industry by 50%

by 2050 (IATA, 2017). SAF is essential for achieving these goals. ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), adopted in 2016, requires that SAF reduce greenhouse gas (GHG) emissions by at least 10%. Furthermore, the aviation sector has identified sustainability as a critical criterion. CORSIA details 13 criteria themes to ensure the sustainability of SAF (ICAO, 2022d), including GHG reduction and environmental, social, and economic aspects. These criteria are aligned with other renewable energy sustainability schemes. This report provides insights into the sustainability of the pathways discussed in the Colombian context; validation through third-party organizations is still necessary to determine compliance.

Colombia's jet fuel demand in 2022 was 584.821 MM gallons, primarily from commercial aviation. By 2043, this demand is projected to double. An established SAF industry can help meet this need while enabling non-fossil energy security, creating jobs and tax revenues, and adding value to the agricultural industry. Early participation in this new industry can also provide a first-mover advantage in the market, which creates opportunities for companies to take the lead in producing SAF in the region. Additionally, Colombia is ideally situated to become a SAF hub for the region by leveraging its geographical location and port infrastructure. The concentrated supply chain of the aviation market requires an integrated approach to developing a sustainable fuel industry compatible with Colombia's current infrastructure.

Colombian agricultural and urban areas have substantial potential biomass resources. In addition, the country has unutilized land suitable for agricultural, agroforestry, and forestry purposes. Colombia also has tremendous expertise through research universities, government agencies, and existing industrial enterprises.

Key opportunities

The SAF working group specifically analyzed opportunities and challenges, focusing on three commercial or near-commercial conversion technologies and compatible feedstocks. Additional information regarding CO_2 and green energy as feedstock, often called power-to-liquid or e-fuels, is included due to the increasing number of global announcements using this technology.

Conversion technologies and promising feedstocks

- Hydroprocessing: Commercial technology with ASTM approval for an aviation fuel using up to a 50% SAF blend when stand-alone or a 5% blend when produced through co-processing with petroleum. This provides a near-term opportunity to create a Colombian supply chain for SAF utilizing crude palm oil. Palm oil derived SAF must have an induced land use change (ILUC) value provided by the ICAO Committee on Aviation Environmental Protection (CAEP) for its use under the CORSIA scheme.
- Alcohols: near-commercial technology that converts alcohol into aviation fuel by removing the oxygen and linking the molecules to a desired carbon chain length. Currently, two ASTM-certified pathways allow up to 50% blend with petroleum fuel and use ethanol, isobutanol, isobutene, and a mix of alcohols as feedstock. This medium-term alternative requires increasing sugar and/or starch-rich feedstock availability (e.g., sugar cane, cassava, fermentable herbaceous, and woody biomass).
- Lignocellulosic material can be transformed using emerging and near-commercial technologies. This opens the avenue to using forest, agricultural, and urban residue streams. Three technologies have received ASTM approvals for co-processing or stand-alone production. This alternative could be a near-, medium-, or long-term alternative depending on the feedstock. With limited production capacity, a portion of municipal solid waste (MSW) and agricultural residues can be used in the near future. The establishment of designated energy crops is necessary to supply broader conversion capacities.

Feedstock

The report presents a succinct review of the Colombian agriculture sector, classified as permanent crops, rotation crops, herbaceous and woody biomass, and wastes. Residues with high moisture content are not considered feasible feedstock for the technologies analyzed in this report. We acknowledge that the progress made by continuous technology and ASTM certification is not captured in the document.

- Permanent crops: Palm oil and sugar are feasible feedstock if their production comes from yield increments in the current plantation or new plantations are established on suitable land under strict sustainability criteria. For palm oil, methane capture seems to be imperative to reach established emission reductions under CORSIA; however, a Colombian ILUC value must be computed to define the total emissions under this scheme. Sugar cane bagasse is being currently utilized; therefore, a higher market value than current use would be required. Residues from palm oil and the growing cacao agroindustry show high potential as SAF feedstocks.
- Rotation crops: Rice residues are already being utilized in various applications. Corn residues are limited considering the quantities required for commercial-level SAF production.
- Herbaceous and woody biomass: There are not sufficient residues from this sector; however, the development of sustainable energy crops on suitable land is an alternative that requires further research.
- Wastes: MSW at a considerable scale is gathered in the landfills serving the main metropolitan areas, such as Bogotá, Medellin, Cali, Barranquilla, and Cartagena.

Situational analysis

Based on the information summarized in this document, a classification of the strengths, weaknesses, opportunities, and threads (SWOT) to produce SAF in Colombia is provided in the following diagram.

Strengths

Colombia
- Liquid fuel demand growth
- Suitable cropping land availability
- Oil palm, sugarcane, and municipal solid wastes are potential sources of feedstock in the short and medium term
- Experience in developing policy frameworks, agroindustrial supply chains, and biofuel production
- Continuous communication among interested parties
- Skilled and technical labor
- Initiation of technical studies
- Feedstock, biofuel, and fossil-fuel producers, as well as local investors are interested in producing SAF

From SAF
- SAF has a sustainability and technical framework
- Commercial and near commercial technology

Market
- Growth of the domestic aviation sector
- Global customer demand

Weaknesses

Feedstock, conversion, and infrastructure
- Low sustainability perception of palm oil
- No Colombian palm oil or other potential native feedstock default values in CORSIA
- Scarce transportation infrastructure in areas with the highest suitable cropping land availability
- Limited cost-effective transportation between probable SAF production areas and airports
- Limited research on tropical feedstock portfolio for SAF production
- Low yield of the GFT and ATJ feedstock
- Feedstock, technology, and operational risk
- Aggregated residual biomass (e.i., bagasse, rice husk) has a market in agricultural and industrial applications

Regulations and Policies
- Lack of a regulatory framework for SAF
- Low value of Colombian tax credit
- Low availability of goverment funds to generate adequate incentives
- Uncertainty of international policy support
- Dependence on policies and regulations
- Aviation sector emission reduction goals do not include the use of renewable fuels

Market
- Higher SAF cost relative to jet fuel

Opportunities

International
- Support from international entities (e.g., multilateral organizatons, ICAO) and countries
- Corporate interest in SAF acquisition
- Intention of requesting feedstock default values to CORSIA-CAEP as Latin America block

Colombia
- Energy transition climate
- Rural job creation
- Industrial development

Threats
- Limited government cohesion
- Regulatory changes
- Climate change and its impact on agriculture
- Supply chain disruption due to transportation infrastructure limitations

As with any new energy technology, SAF requires strong policy support, especially in the early stages. The impact of such policies will likely vary depending on whether SAF production aims to supply the international or domestic markets, which will dictate the locations that can claim the corresponding emissions reductions. Support for SAF should, at the minimum, be equivalent to policies supporting other transport and energy sectors. However, priority attention is merited because aviation does not have renewable alternatives to high-energy dense liquid fuels like many other sectors. The following are the top recommendations.

- Urge state energy planning efforts to recognize the need for renewable aviation fuels and develop multi-ministerial integrated strategies to ensure a systemic policy framework.
- Urge agencies to provide a regulatory framework for SAF.
- Urge agencies to facilitate the allocation of international cooperation aid to finance policies focused on SAF.
- SAF supply chain development can provide environmental and social services as well as energy. Policymakers should align the country's strategy and needs with the services provided for developing and utilizing SAF (e.g., job creation, air quality, waste reduction, and GHG reduction).
- Ensure coverage of aviation fuels under existing programs.
- Urge stable, long-term, cumulative, feedstock, and technology-neutral government policies for the SAF industry to grow and thrive. Well-integrated, consistent policies will help mitigate critical risks for feedstock growers and producers when undertaking a new feedstock or technology. Dependable, coordinated policies are essential to provide access to capital and feedstock.
- Targeted resources and policies for incentivizing research and development to accelerate advanced biofuels for the aviation sector.
- Urge the inclusion of academic institutions, research centers, and think tanks to provide technical support and tools for the development of regulatory framework and policies, as well as for the configuration, design, and analysis of SAF supply chains.

1. Introduction

In 2019, the aviation sector was responsible for approximately 2.8% of the global anthropogenic carbon emissions mainly associated with petroleum fuel use (Air Transportation Action Group (ATAG), 2020; IEA, 2020). Without considering fortuitous effects, such as those from the COVID-19 pandemic, emissions from the sector are expected to grow rapidly (IEA, 2022). The International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) through which airlines are required to offset CO_2 emissions growth compared with 2019 levels covering all non-exempt international flights from 2027 (ICAO, 2023a). Moreover, the International Air Transport Association (IATA) member airlines have committed to achieving net zero CO_2 emissions from aviation by 2050 (IATA, 2017). To achieve carbon emission reductions in aviation, ICAO and IATA are pursuing a basket of measures, including 1) aircraft technology improvements, 2) infrastructure and operational improvements, 3) sustainable aviation fuel (SAF), and 4) carbon offsets and carbon capture (IATA, 2023a; ICAO Secretariat, 2019). Although new aircraft are up to 20% more efficient than the models they replace, future reductions based on new technologies, infrastructure/operations, and offsetting/carbon capture are expected to be 35% of the abatement by 2050, with SAF being the main contributor to achieve net zero carbon (IATA, 2023a; IEA, 2022). Despite the high demand for SAF, and its growing production and use, it represented only 0.1% of all aviation fuels in 2021 (IATA, 2023a; IEA, 2022; United States Government Accountability Office, 2023). To meet the demand for reducing the remaining 65% of the emissions to reach net zero in 2050, the production of SAF must be increased from 8 million liters in 2016 to approximately 449 billion liters in 2050 (Figure 1)(IATA, 2023a).

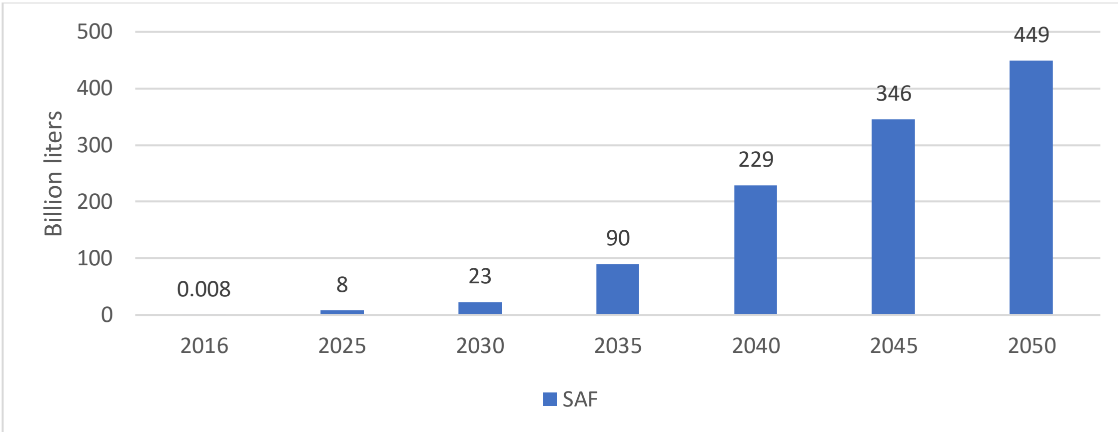


Figure 1. SAF production in 2016 and expected SAF (from 2025) required for net zero aviation emissions by 2050 (IATA, 2023a).

Colombia has a trajectory as a renewable liquid fuels (bioethanol and biodiesel) producer, enhanced in 2005 with the implementation of biofuels blend mandates. Thus, Colombia has a successful experience in consolidating feedstock supply chains, industrial facilities for renewable fuels conversion, distribution systems, and establishing regulatory frameworks and policies. The country also has untapped opportunities for agricultural and industrial development. In 2021, the government passed the Climate Action Law, which indicated that the Ministries of Energy and Mines, and Transport would promote the development and use of SAF. Then, in 2022, the energy transition policy strategy specified that the Ministry of Energy and Mines would work on a biofuels route map including SAF. Clearly, the country's stakeholders are starting along this process.

Recognizing the need to increase worldwide production of SAF and Colombia's potential, the Federal Aviation Administration's (FAA) Aviation Sustainability Center of Excellence (ASCENT) convened stakeholders in Colombia through the SAF Global Supply Chain Development project (Project A93) to assemble a working group, aiming to identify Colombia's assets and challenges facing SAF production. Since July 2022, the working group has conducted regular meetings to gather information and provide insights about specific feedstock and technology pathways, sustainability issues, aviation needs, and private initiatives. The initiative based within a network of similar stakeholder processes in the country.

This report is based on the insights of stakeholder organizations across aviation, biofuel production, agriculture, government agencies, academic research, and technical consultancies, as well as a comprehensive literature review. It includes an overview of Colombia's transportation, energy, and agricultural sectors, as well as the main drivers for SAF production and the work carried out by the stakeholders. Since safety is always paramount in aviation, this report only focuses on "drop-in" fuels, which can meet the rigorous standards set for aviation fuel. From the 11 pathways certified under ASTM D7566 and ASTM D1655 for SAF (ICAO, 2023b), current production is centered on three commercial or near commercial scale pathways: Hydroprocessed esters and fatty acids (HEFA), gasification with Fischer-Tröpsch (GFT), and alcohol to jet (ATJ) (van Dyk & Saddler, 2021). This report focuses on these pathways, and the compatible feedstock with current or potential availability. The report addresses additional opportunities, including a brief review of the use of residual CO_2 to produce liquid fuels. Notably, no single feedstock or technology pathway will likely provide SAF in the near term without a considerable effort on sustainability analysis, energy cropping advancement, yield technology improvement, supply chain design, and policy development.

2. Colombian overview

Colombia's unique topography means that land connectivity across the country is difficult. Figure 2 shows that the country can be divided into five regions: the Caribbean lowlands, Pacific lowlands, Andean highlands, the great plain to the east of the Andes Mountains, and Amazon region (World Facts US, 2008). In addition to the Andean ranges, Colombian's topography is characterized by a group of high mountains northeast of the country, the *Sierra Nevada.* Bogota, the Colombian government and commercial capital, is located in the central-eastern part of the country on the western side of the Eastern Cordillera. The great plains in the country's southeastern part extend from the Eastern Cordillera to the east and southeast of the country to the basins of the Orinoco and Amazon rivers (Bell, 2012).

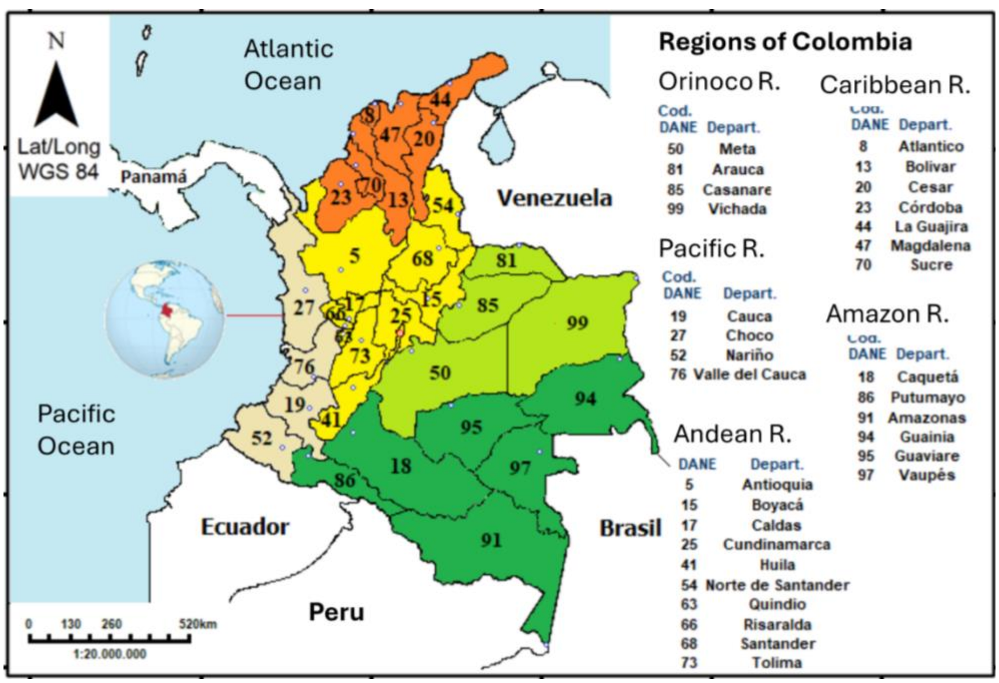


Figure 2. Colombian regions with a list of departments (Depart. as abbreviation) included per region (Avila-Quiñones et al., 2022).

Given this vast geography, air transport plays a critical role in Colombian municipalities in communicating among themselves and with the rest of the world as a fundamental way to promote the country's economic growth. In 2022, air transportation accounted for 48,004,000 passengers, of which 32,742,000 traveled domestically and 15,262,000 internationally. Similarly, 886,606 tons of cargo and mail were transported by plane (MinTransporte Colombia, 2023). In 2022, the aircraft fuel consumptions were 584.821 MM gal (Ministerio de Minas y Energia, 2023).

Besides a market, the establishment of productive chains for SAF production requires the identification of available, sufficient, high-quality, and transportable feedstock; utilities such as electricity, natural gas, and hydrogen for the conversion facilities; and transportation systems for the final product. This section provides a review of the state of these key elements. Since Colombia has a successful case of the development of renewable liquid fuel, this section includes information regarding biodiesel and bioethanol production capacity and policies adopted.

2.1. Transportation

The following subsections present a synopsis of the main transportation modes available in the country, their carrying capacity, and their use. A central focus is the aviation sector, and transportation modes available for feedstock transportation and the associated costs.

2.1.1. Aviation

In Colombia, all modes of transportation are classified as a public service (Law 105 of 1993). The Ministry of Transport is the responsible for regulating and setting transport policies as a public service. However, it delegates some of its functions to affiliated entities (Durán Preciado, 2013; Olivera et al., 2011). The Special Administrative Unit of Civil Aeronautics (Aerocivil) oversees the technical regulations of the aviation sector. The sector is also governed by the rules of the Commercial Code, and by international treaties, agreements, conventions, and practices adopted or applied to Colombia (Law 336 of 1996) (Martínez Ortiz & García Romero, 2016). Indirectly, the sector is influenced by the National Planning Department, and the Energy and Gas Regulation Commission (CREG, by its Spanish acronym). CREG is an entity attached to the Ministry of Energy and Mines that, among other functions, partially regulates the prices of Jet A1 (Decree 4130 of 2011, Law 1450 of 2011). Jet constituted the largest component of airline costs (Martínez Ortiz & García Romero, 2016).

Colombia has 202 airports, including commercial, municipal, military, and private ones (Durán Preciado, 2013). Figure 3Figure illustrates the 14 international and 40 national airports with more than 20,000 annual passengers, representing most of the Colombian commercial airflow. The military operations are centered in 9 military airports.

Figure 3. Main commercial Colombian airports (Aeronáutica Civil, 2022a).

The air transport market for passenger traffic in Colombia has increased over the past 30 years. In recent years, an important driver of air passenger demand has been airfare reduction partially because of a strong competition between airlines (IATA, 2019b). In 2020, due to the COVID-19 pandemic, air passenger traffic dropped by 68.3% compared to 2019, with a slow rebound in 2021 (Figure 4). Domestic passengers lead the air transport market. Approximately 68% of air passengers in the last decade flew domestic routes, with 32% traveling internationally. This suggests a Colombian potential market of 250 MMgal (705.977 tons) for SAF 50% ASTM. This value is considers SAF production through an ASTM D7566-approved pathway and the fuel can be blended up to 50% with jet fuel (BioD, 2023b).

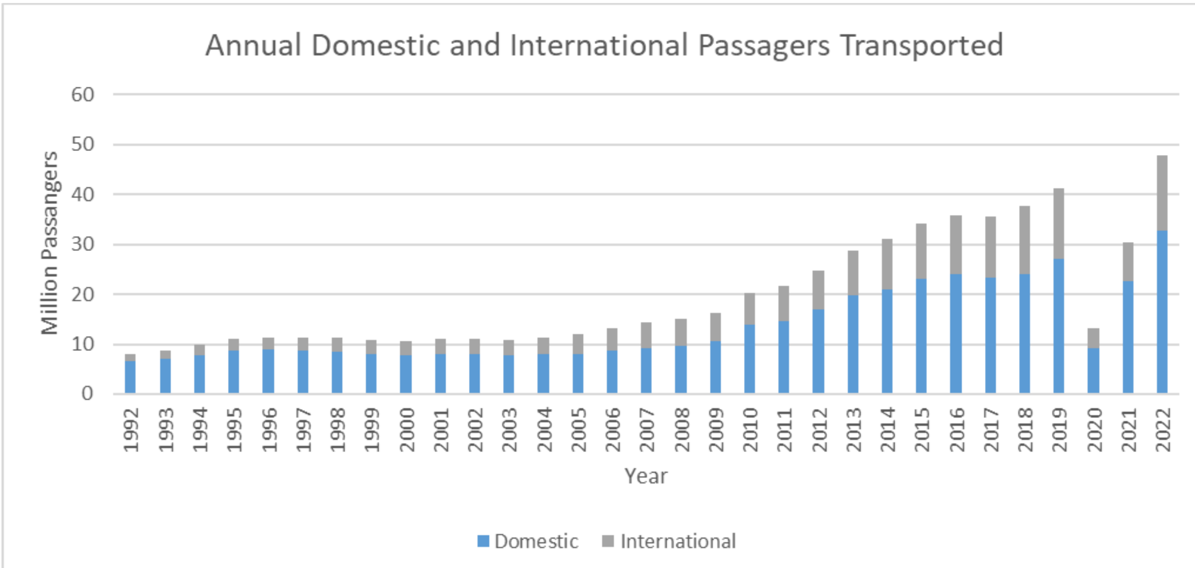


Figure 4. Air transport market in Colombia: Annual domestic and international passengers transported, 1992- 2022 (Aeronáutica Civil, 2022b).

Bogota has the airport with the highest number of international routes, passengers, and cargo traffic, followed by those in Medellin-Rionegro and Cartagena (Aeronáutica Civil, 2022a, 2022b). The main cities of origin and destination of domestic flights are Bogota, Medellin, Cartagena, Cali, and Santa Marta (Figure 5a). However, Colombia has almost 90 domestic connections and Bogota has the major air traffic (Figure 5a). This represents a potential SAF market of 132.5 MM gal (374,168 tons), assuming that it could be blended at a maximum of 50% (BioD, 2023b). In 2022, the leading carriers for domestic flights were Avianca and LATAM-Aires (Figure 5b). Note that Viva Air and Ultra Air ceased operations in 2023.

Figure 5. a) Main domestic origin and destination flights. b) Main carriers in domestic flights by 2022 (Aeronáutica Civil, 2022b).

After Mexico and Brazil, Colombia is the best-connected country in Latin America (IATA, 2019b). Foremost international destinations are the United States, Panama, Mexico, Spain, and Peru (Figure 6a). Avianca, Copa, and American are the top three airlines by the number of passengers (Figure 6b). In 2022, Bogota and the United States were the main destinations, each with approximately 30% domestic and international passengers, respectively. Miami, New York, and Fort Lauderdale were the main destinations in the United States. Aeronautica Civil estimated that Colombian emissions associated with international aviation will be 11.4 million tCO_{2e} by 2030 if no mitigation actions are taken. This estimation is equivalent to 6.7% of the maximum emissions (169.44 million tCO_{2e}) for the country by 2030 (Acción Climática, 2021; Unidad Administrativa Especial de Aeronáutica Civil Colombia, 2021).

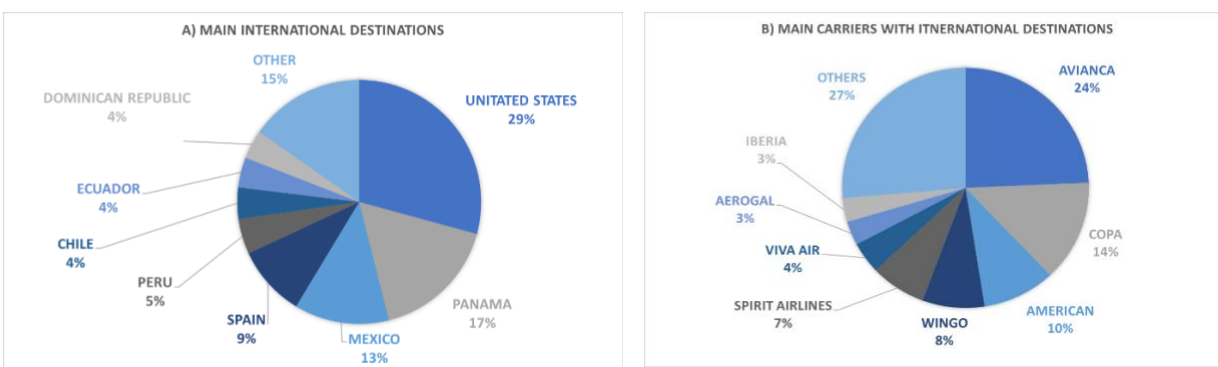


Figure 6. a) Main international destinations. b) Main carriers by 2022 (Aeronáutica Civil, 2022b).

Cargo and mail air transport are approximately 80% international and 20% domestic (Figure 7). In 2022, the United States had 74% of the weight transported, with Miami (FL) as the central destination city (Figure 8a). Tampa Cargo was the leading carrier, with 31% of the weight transported, followed by Linea Aérea Carguera de Colombia (16%) (Figure 8b). Domestically, Aerosucre and Avianca were the primary carriers, with 33% and 27% of the weight transported, respectively (Aeronáutica Civil, 2022b).

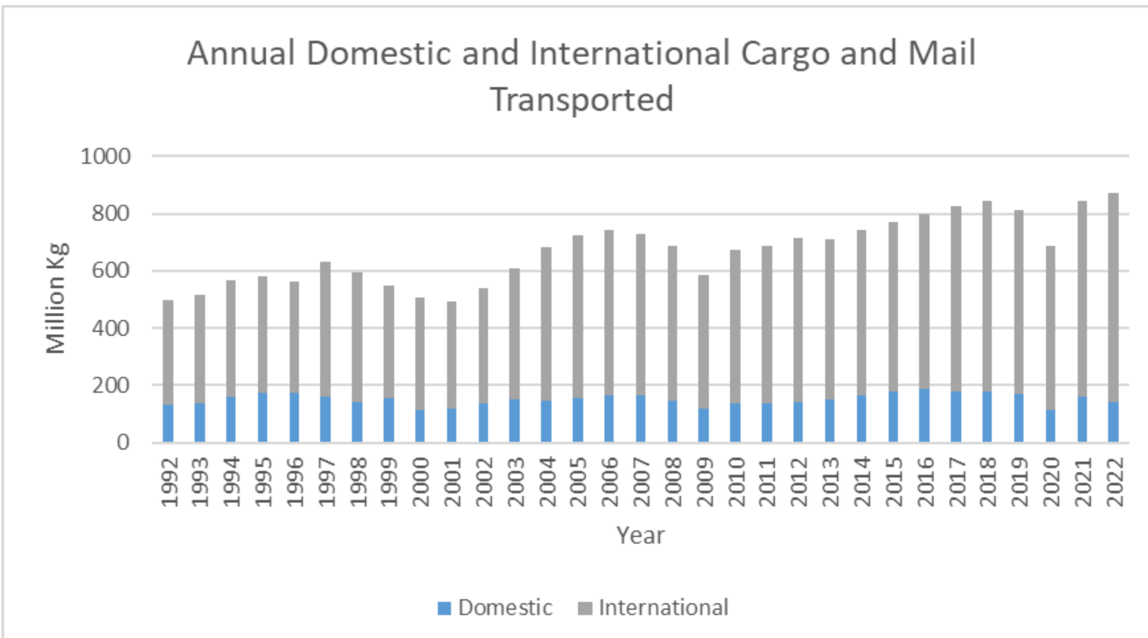


Figure 7. Air transport market in Colombia: Annual domestic and international cargo and mail transported, 1992- 2022 (Aeronáutica Civil, 2022b).

Figure 8. a) Air transport cargo and mail destination countries. b) Main carriers of international cargo and mail by 2022 (Aeronáutica Civil, 2022b).

2.1.2. Road, rail, and waterways

Road transportation is the primary means of freight and passenger transport; thus, there is a need for the freight modal matrix to diversify. The road network integrates the primary production and consumption zones with the marine ports, airports, and neighboring countries (Figure 9). Compared to other countries, Colombia has many urban and production centers in the Andean region, which are far from maritime access. The main roads cross the country in the north-south axis, with a concentration of road infrastructure in the Andean and Caribbean regions. However, the conditions, capacity, and level of road services differ.

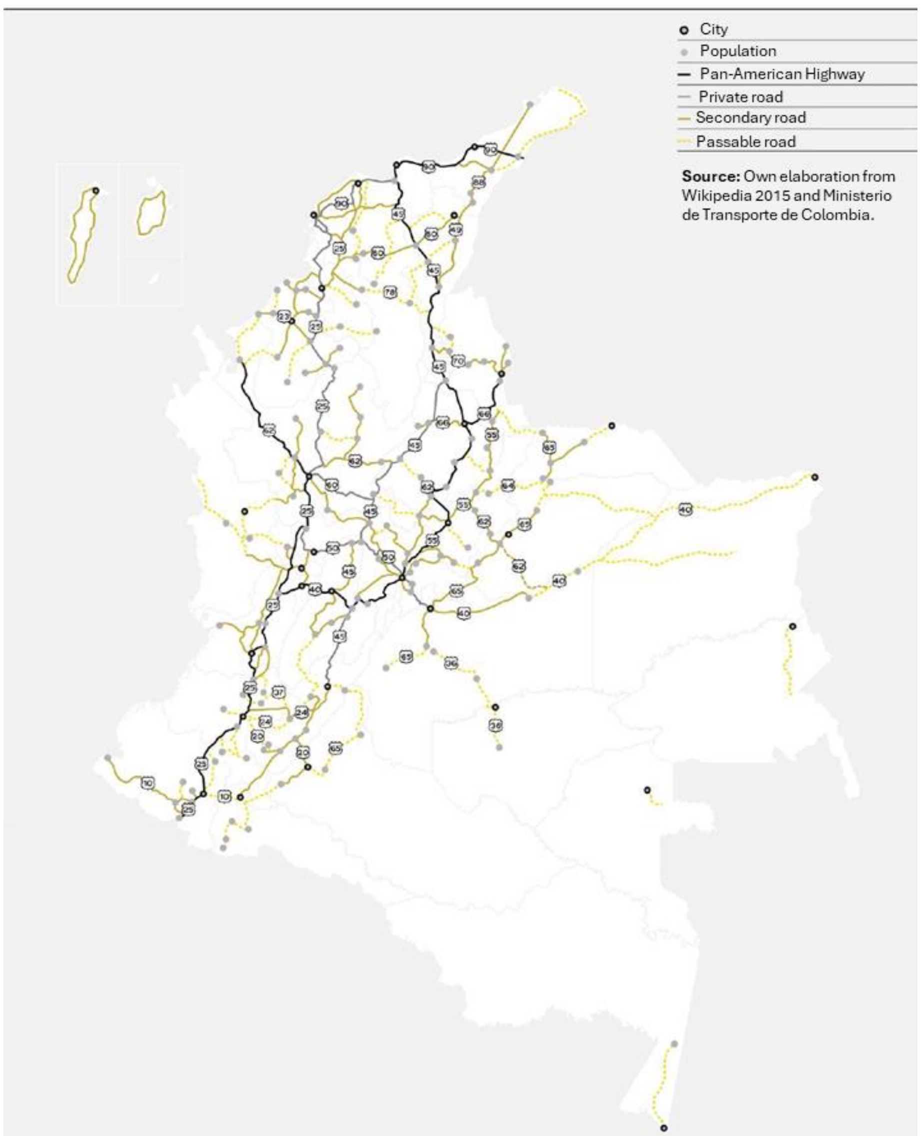


Figure 9. Colombian road network (Kohon et al., 2016).

In 2021, road transportation moved approximately 85% of the freight transport, equivalent to 123,637 million tons and 3,755 million gallons (Ministerio de Transporte, 2022, 2023). The Ministry of Transport has 3,884 authorized companies to provide freight transportation services (Ministerio de Transporte, 2023). Colombia has three types of roads: 1) highways built and maintained by the central government (primary roads), 2) roads built and maintained by state (hereafter, department) governments (secondary roads), and 3) municipal ways (tertiary roads). The road infrastructure is approximately 203,392 km long, with 8% primary (only 1,000 km of multiline highways), 22% secondary, and 70% tertiary roads (Kohon et al., 2016; Ministerio de Transporte, 2019; Ministerio de Transporte et al., 2014). In 2021, 40.84% of the primary roads were concessional. The non-concessional primary network had 80% of the paved roads, of which only 33.4% are in good condition; the remaining 20% are gravel roads (Ministerio de Transporte, 2022). Primary roads in the Andean, Caribbean, and Orinoquia regions are continuously affected by landslides (Ministerio de Transporte et al., 2014).

Biomass transportation uses tertiary roads from the farm to the collection point or pre-processing facility. Road conditions, truck type, and return cargo impact transportation costs (Fontanilla et al., 2015; PROFOR, 2017a). Figure 10 shows transportation costs for three types of trucks as a function of distance. Fontanilla et al. (2015) classified roads condition into five categories (see Table 1), and reported the transportation cost per ton of biomass for four distance ranges in the Colombian north zone (see Table 2). The feedstock transportation for SAF production would likely use tertiary roads based on the geographical availability and quantity.

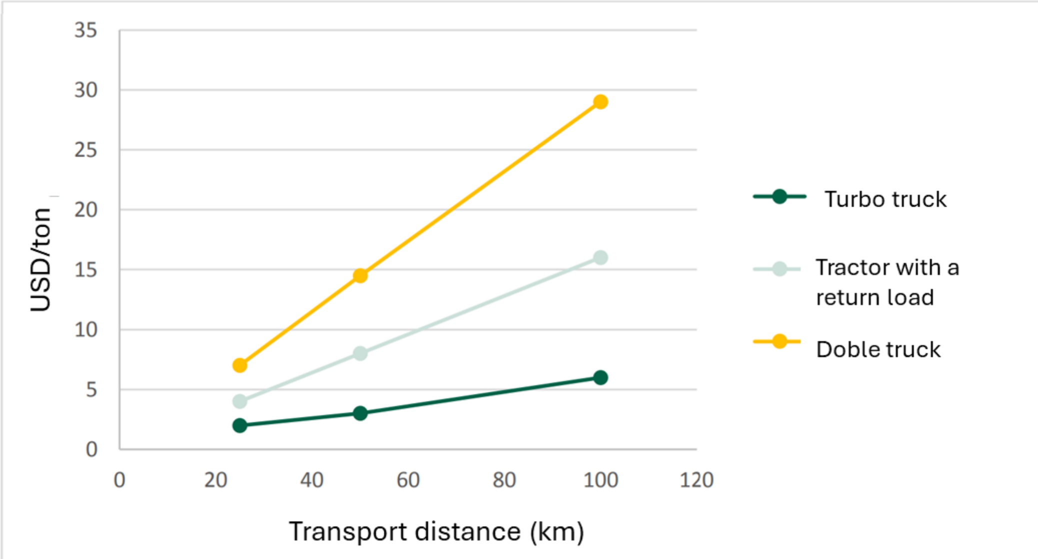


Figure 10. Transportation cost for different types of trucks (PROFOR, 2017a).

Table 1. Road classification and condition (Fontanilla et al., 2015).

Road condition	Description
Excellent	Firm and smooth surface
Good	Smooth surface with few bumps and potholes
Acceptable	Surface with intermittent bumps and potholes
Poor	Surface with frequent bumps and potholes
Very poor	Surface with constant bumps and potholes

Table 2. Transportation cost USD*/ton in the Colombian north zone (Fontanilla et al., 2015).

Road Condition	Distance			
	0 to 10 km	11 to 30 km	30 to 50 km	200 km
Excellent	2.9	6.5	8.0	25.5
Good	2.9	6.5	8.0	NA
Acceptable	3.6	6.5	9.1	NA
Poor	4.3	7.3	9.1	NA
Very poor	NA	NA	NA	NA

* Values converted from COP to USD using the 2015 average exchange rate.

Given the geographical conditions of Colombia, the natural rail corridors are in the south-north direction, and two corresponding to the great valleys of Cauca and Magdalena. The third is the eastern corridor that passes through Bogotá (Kohon et al., 2016). The Colombian railway network has a total length of 3,528 km of 914 mm narrow rail gauge (standard rail gauge is 1,435 mm). Still, only 37% (1,266 km) are in operation, of which 1,077 km are under the National

Infrastructure Agency's management (Figure 11). The sections Chiriguana-Santa Marta (245 km), Bogota-Belencito (273 km), and Dorada-Chiriguana (525 km) are in commercial operation (Kohon et al., 2016; Ministerio de Transporte, 2022). However, railways in Colombia transport coal almost exclusively (Kohon et al., 2016). The railways' low participation in freight movement is related to infrastructure limitations. These limitations make the operation more expensive and complex, only allow the circulation of short trains with low transport capacity, and make them uncompetitive compared to the highways (Kohon et al., 2016). Feedstock or liquid fuel transportation using rail is not currently feasible.

Figure 11. Railroads under the National Infrastructure Agency's management (Ministerio de Transporte, 2022).

The length of the Colombia river network is close to 25,000 kilometers. All-year navigation is possible on 7,000 kilometers for major navigation and 11,000 for minor navigation. Fluvial transportation is vital in the Amazon, Orinoquia, and Choco, where the jungle conditions have not allowed considerable road network development (Kohon et al., 2016). However, the main fluvial ports are on the Magdalena River (Barrancabermeja and Barranquilla) (Ministerio de Transporte, 2022), with limited feedstock or distillates transportation capacity.

In 2013, road transport conveyed 220.3 million tons (73% of total cargo movements), while rail transported just over 25% (76.8 million), of which "non-coal" only represented 97,000 tons. The other modes are equally insignificant. Fluvial transport conveyed, at under 3 million tons (less than 1% of the total), predominantly hydrocarbons through the Magdalena River (Kohon et al., 2016).

2.1.3. Marine

Colombia has 10 seaports, with 8 in the Caribbean (San Andres, Guajira, Santa Marta, Cienaga, Barranquilla, Cartagena, Golfo de Morrosquillo, and Turbo), and 2 in the Pacific (Buenaventura and Tumaco). There are 62 port companies, of which 41 provide public service and 13 provide private services (Ministerio de Transporte, 2022). In 2021, 168.6 million tons were mobilized, of which 138.2 million tons were mobilized foreign trade operations. As shown in Figure 12, Cartagena had 27% of the cargo movement in 2021, followed by Cienaga (15%), Golfo de Morrosquillo (15%), and Guajira (14%).

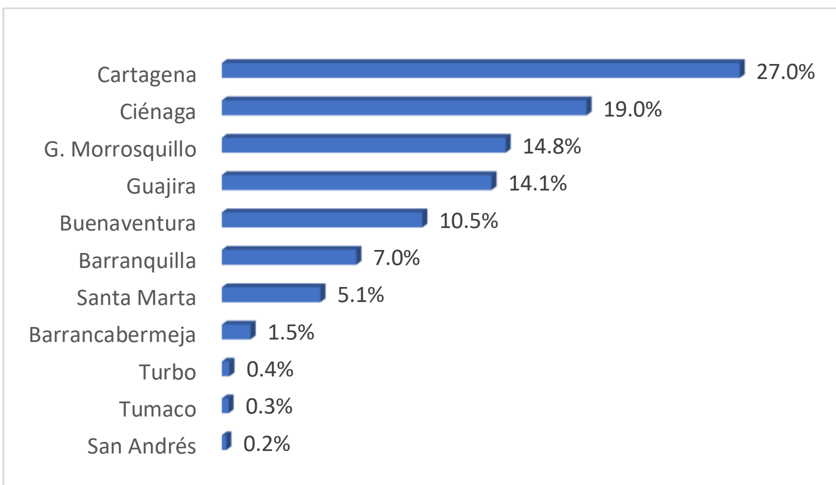


Figure 12. Distribution of cargo movement by port area (Ministerio de Transporte, 2022).

2.2. Energy sector

This subsection summarizes energy production and consumption, zooming in on the liquids fuel refining and transportation networks. Since natural gas, electricity, and hydrogen are imperative utilities for SAF production, a review of these sectors is presented, including sourcing, networks, and costs.

2.2.1. Production and consumption

The energy sector classifies energy in stages as primary, secondary, and final energy. The first stage is energy production, while the second corresponds to energy storage and transportation. Generation and consumption of energy is the final stage. Primary energy sources are wind, sun, water, geothermal, biomass, fossil fuels, and radioactive minerals (REPSOL, 2022). Colombia's primary energy sources are fossil fuels (petroleum, natural gas, and coal), hydroelectric power, and other sources such as biomass and wind (OLADE, 2022).

In 2021, the primary energy extraction was 4,342 PJ, of which 60% was exported, and 40% was used for domestic transformation and consumption (**Error! Reference source not found.**) (Unidad de Planeación Minero Energética, 2022). Table 3 shows the primary energy extraction, secondary energy production, and imports necessary to guarantee the supply of the domestic demand of 74,116.91 GWh in 2021 (Unidad de Planeación Minero Energética, 2021). This demand increased by 5.51% from 2020 (PORTAFOLIO, 2022) because of economic resurgence after the end of the COVID-19 pandemic.

Ecopetrol S.A. is the national, publicly joint-stock petroleum company that extracts 60% of the country’s petroleum (Ecopetrol S.A., 2014a). This extraction represents 37.7% of the total primary energy extraction (Unidad de Planeación Minero Energética, 2021). This petroleum is processed either in the Cartagena (north of the country) or Barracabermeja refineries (northeast of the country) (Global Energy Monitor, 2023). In 2021, approximately 51% (839,000 TJ) of petroleum was used to fulfill the needs of the transport sector. The second primary energy extraction was from coal (36.6%), which is exported (Unidad de Planeación Minero Energética, 2021) principally to the Netherlands, Spain, France, Germany, Poland, Croatia, Italy, and United Kingdom, among other countries. These exports represented 13.7% of Colombian exports, 58.1% of mining exports, and 56% of Colombian mining GDP in 2021 (Bnamericas, 2022).

Diesel (28.42%), electricity (23.72%), and gasoline (16.73%) lead the secondary energy production. The fuel import aims to meet the demand and address quality improvement to comply with Colombian environmental regulations of a maximum sulfur content of 300 ppm for gasoline and 50 ppm for diesel (Unidad de Planeación Minero Energética, 2021).

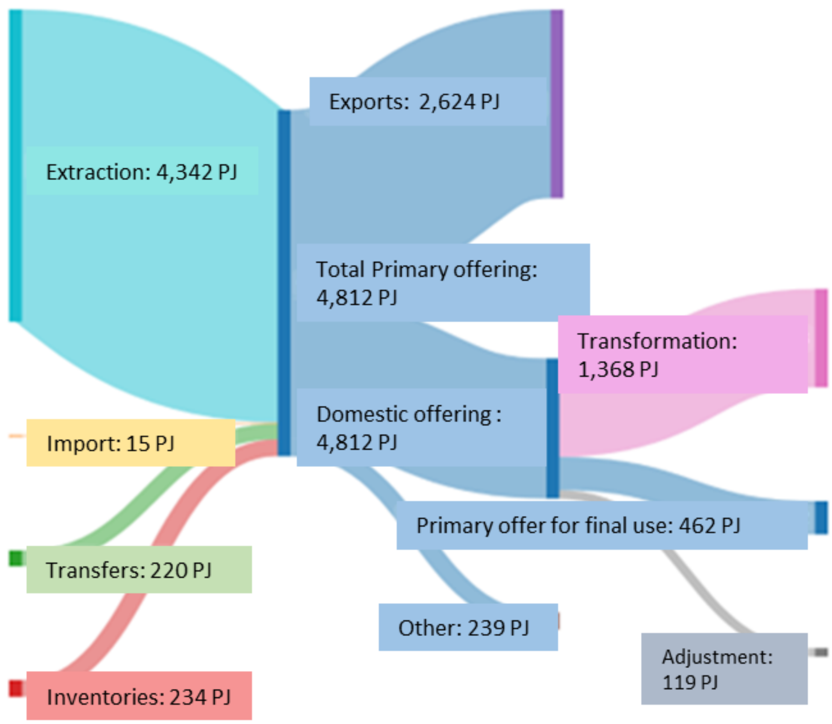


Figure 13. Colombian primary energy distribution for 2021 (Unidad de Planeación Minero Energética, 2022).

Table 3. Colombia primary energy extraction, secondary energy production, and imports in 2021 (Unidad de Planeación Minero Energética, 2022).

	Extraction (TJ)	Imports (TJ)
Primary fuel		
Bagasse	87,674	-
Coal	1,590,126	-
Gas	674,108	1,734
Hydropower	217,786	-
Wood	101,191	-
Oil	1,636,050	13,675
Residues/recoverable	764	-
Other renewable	34,081	-
Total primary fuel	**4,341,780**	**15,409**

Secondary fuels		
Alcohol	8,078	-
Biodiesel	24,581	-
Wood coal	301	-
Coke	81,942	-
Diesel	318,898	50,112
Electricity	266,161	1,726
Auto generation	43,481	-
Fuel oil	109,191	-
LPG	35,622	740
Gasoline	187,696	107,541
Kerosene - Jet	48,998	752
Total secondary fuels	**1,121,949**	**160,871**

The final energy consumption for 2021 was 1,402.5 PJ (Unidad de Planeación Minero Energética, 2022). Energy demand was concentrated in the transport sector, with 42% of the consumption, followed by the industrial (22%) and residential sectors (15%) (Figure 14). The transportation sector uses blends of fossil diesel-biodiesel and gasoline-bioethanol. These blends must fulfill the Law 693 of 2001, which established the policy for the use of alcohol as fuel, and created incentives for its production, sale, and consumption as a component of gasoline in oxygenated blends (Ley 693 de 2001, 2001). In 2021, aquatic transportation used 15,566 TJ of marine diesel, with public administration and defense being the main consumers (DANE, 2022a). In 2020, Resolution 40111 of 2021 established the blending of gasoline-bioethanol at 90% gasoline–10% bioetanol (Resolución 40111, 2021). Similarly, law 939 of 2004 established the use of a blend of biofuels from vegetable or animal sources, and fossil diesel in diesel engines (Ley 939 DE 2004, 2004). Decree 2629 of 2007 established a blend 90% fossil diesel and 10% biodiesel (Decreto 2629 de 2007, 2007).

Diesel and gasoline constitute approximately 43.8% and 49.6% of the energy consumed in the transportation sector, respectively; jet fuel constitutes only 6.6%. The industrial and residential sectors draw energy from various sources, with the main ones being electricity, gas, coal, and wood (from forest areas) (Unidad de Planeación Minero Energética, 2022).

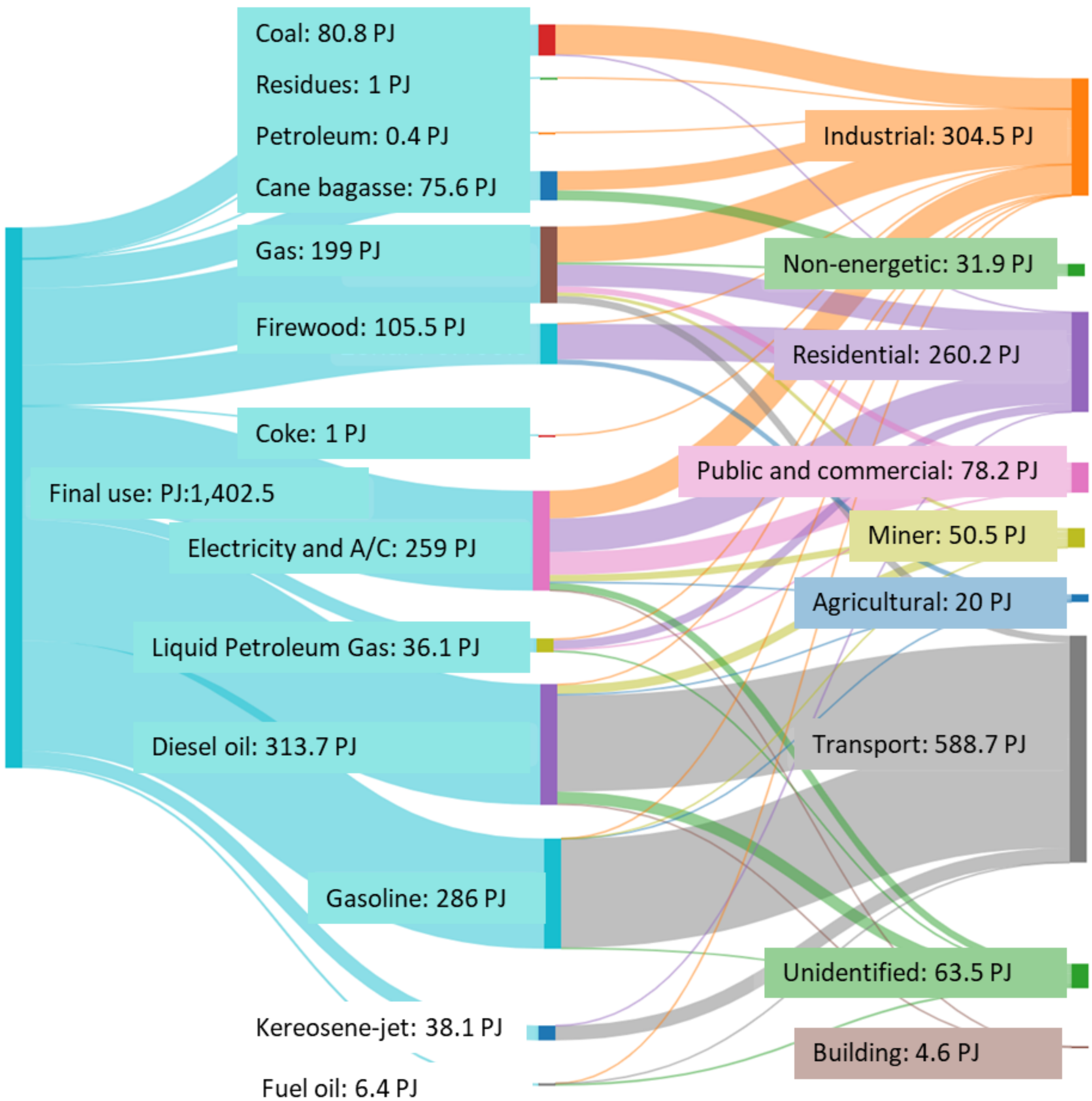


Figure 14. Final energy consumption (Unidad de Planeación Minero Energética, 2022).

2.2.2. Liquid fuels

2.2.2.1. Refining

Liquid fuels are obtained by refining crude oil (petroleum). Crude oil is a blend of paraffin (straight-chain and branched-chain compounds), naphthenes (cyclo paraffins), and aromatics (benzene and its derivatives) (Pisupadti, 2003). In Colombia, crude oil refining is carried out principally in the refineries owned by Ecopetrol S.A., and located in Barrancabermeja and

Cartagena. There are three other auxiliary refineries with limited processing capacity: Apiay, Orito, and Hydrocasanare. Figure 15 shows the location of this complex in the country (CRUDOTRANSPARENTE, 2021).

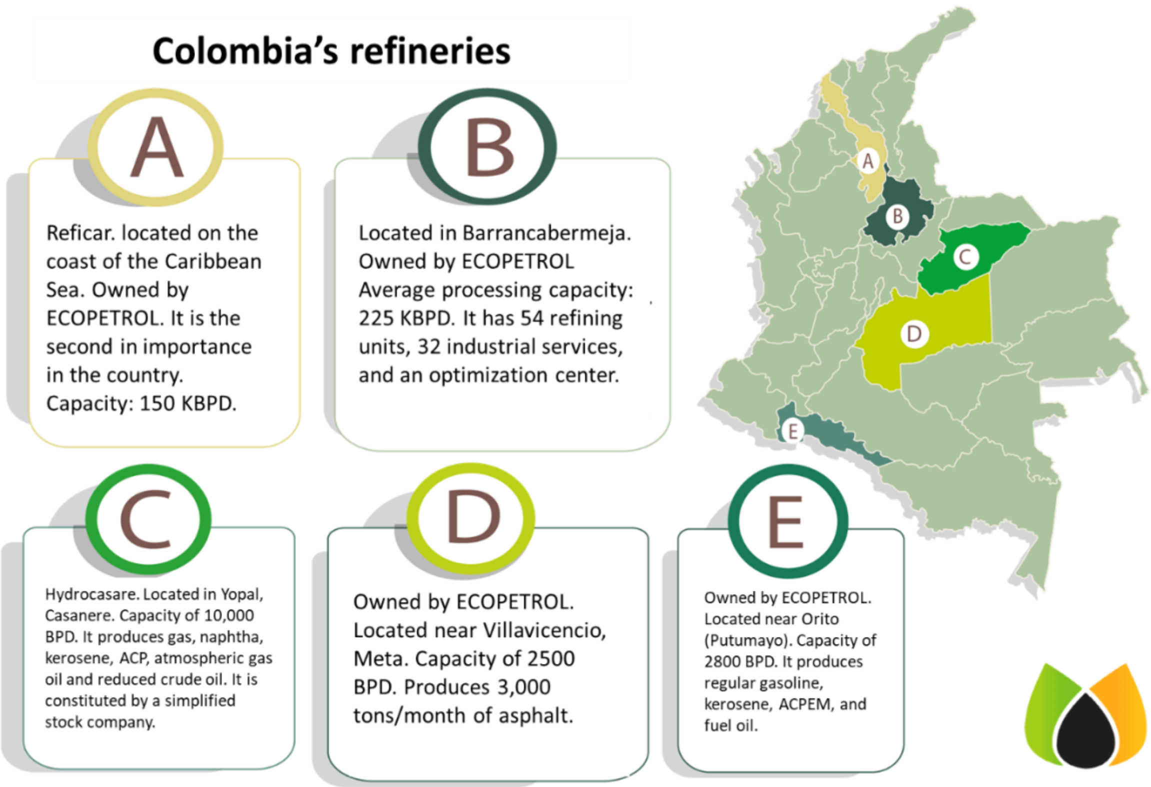


Figure 15. Refineries in Colombia (CRUDOTRANSPARENTE, 2021).

Barrancabermeja refinery is located on the banks of the Magdalena, and has the highest capacity for transforming crude oil and petrochemistry (Ecopetrol S.A., 2014b). The plant processes a nominal load volume of 250,000 barrels per day, supplying approximately 59.6% of national demand. Its configuration allows light crude processing with a medium conversion level, transforming 76% of the crude into light products and limiting the processing of heavy crudes (most of Colombian production). Typical yields by mid-2021 were 1% for liquified petroleum gas (LPG), 24% for gasoline, 9% for jet, and 29% for diesel. This complex produces approximately 60.3% of gasoline, 57.8% of diesel, and 64% of jet required domestically (Unidad de Planeación Minero Energética, 2021).

Cartagena´s refinery (REFICAR), located on the Caribbean coast, is the second-largest refinery. It has a capacity of 165,000 BPD, a conversion yield of approximately 95%, and port infrastructure for loading and unloading products (CRUDOTRANSPARENTE, 2021)(Unidad de Planeación Minero Energética, 2021). REFICAR can process heavy crudes with high sulfur content. Typical yields are 1% LPG, 19% gasoline, 7% jet, and 52% for diesel. This refinery produces marine diesel, a fuel distributed exclusively for river and sea vessels on both coasts, and electricity generation in San Andres and Providencia (Arrieta et al., 2016). One of the distributors of marine diesel is Terpel, serving 15 ports with 23 marine terminals (Terpel, 2021).

Apiay, Orito, and Hydrocasanare are small complexes, with a total refinery capacity of 15,300 barrels per day, which produce asphalt and medium distillates. Apiay and Orito are owned by Ecopetrol S.A. (Unidad de Planeación Minero Energética, 2021).

For the upcoming decades, the Mining and Energy Planning Unit in Colombia (UPME) projects an increasing demand for liquid fuels in Colombia (Figure 16), which will be satisfied primarily by domestic production. However, it will need to import gasoline, jet, and LPG (Figure 17). The imports entry point would be mainly Pozos Colorados (see section 2.2.2.2). UPME also estimates the availability of surplus diesel for exports (Figure 17). For the following decades, the share of jet fuel is expected to remain lower than diesel and gasoline. However, a progressive increase is anticipated.

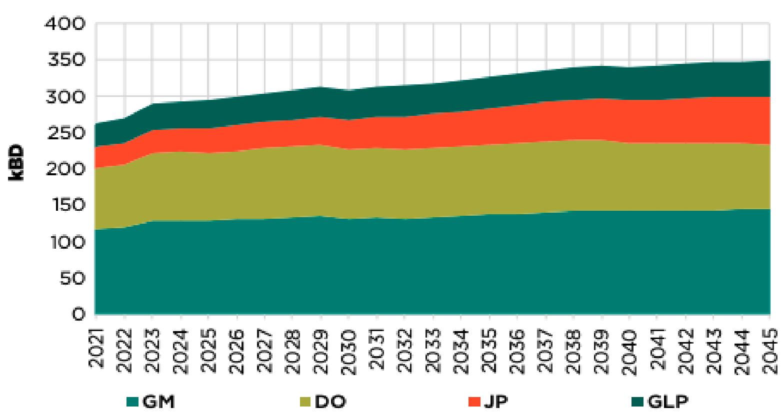


Figure 16. Expected demand for liquid fuels in Colombia (Unidad de Planeación Minero Energética, 2021).

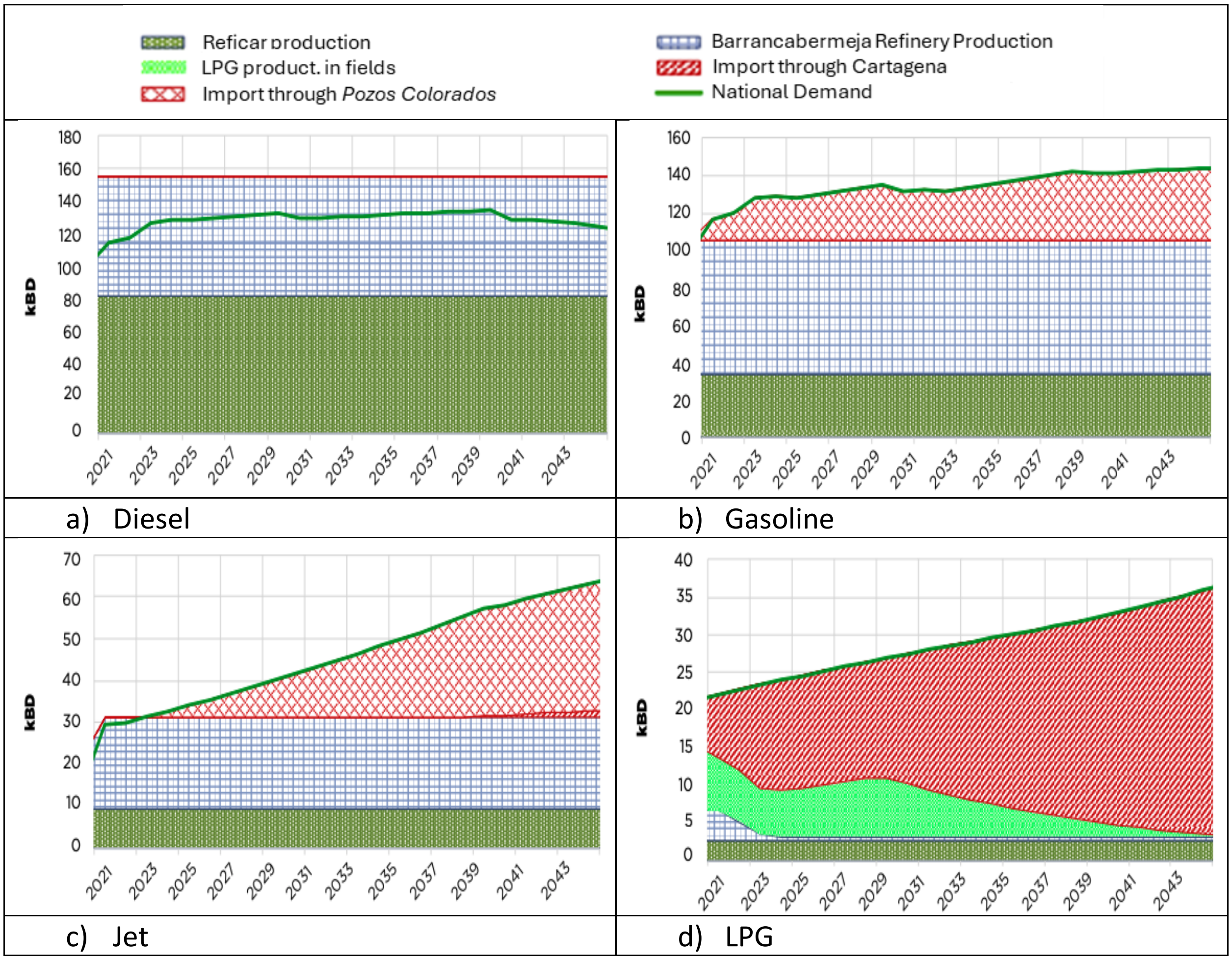


Figure 17. Projected national balance: a) diesel, b) gasoline, c) jet, and d) LPG (Unidad de Planeación Minero Energética, 2021).

2.2.2.2. Transporting

The transportation activity follows the exploitation of a deposit to move the crude oil to the refineries or ports, providing added value to the crude oil (Unidad de Planeación Minero Energética, 2021). In Colombia, most crude oil is transported through pipelines (Superintendencia de industria y comercio, 2013). The system of pipelines in Colombia covers the main production, conversion, consumption, and export centers (Figure 18). Cenit, a company of the Ecopetrol S.A. group; Ecopetrol itself; and third parties own the system of pipelines.

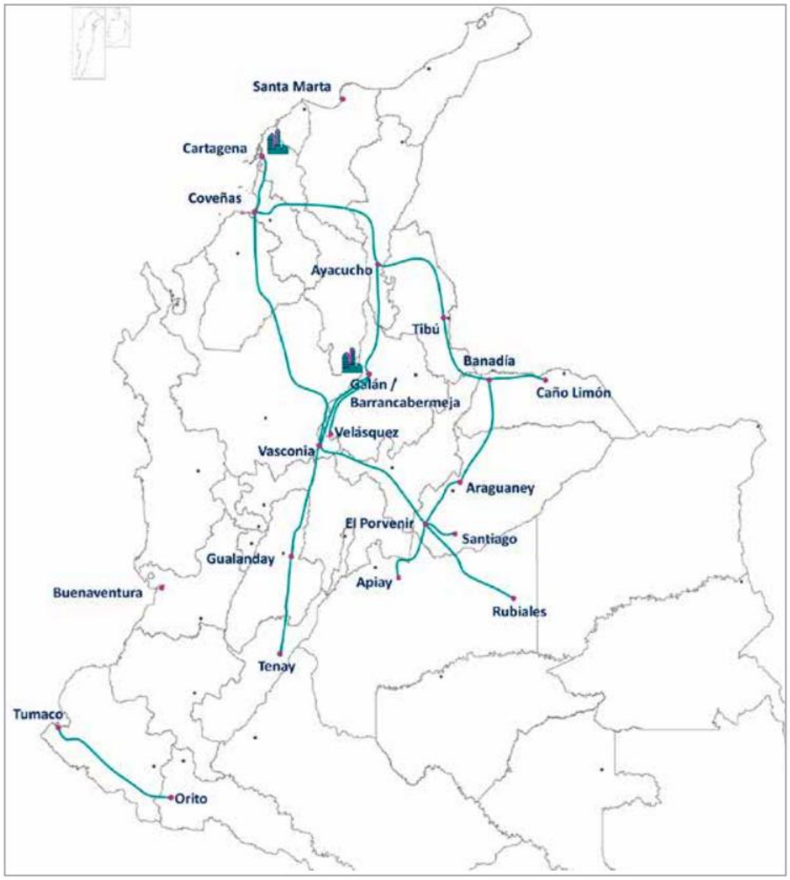


Figure 18. Colombian crude oil pipeline system (Unidad de Planeación Minero Energética, 2021).

The network moves two or more products to transport refined products, with physical separation between them under the "batch" modality. Cenit owns most of the refined products pipeline system, which is the line starting in Pozos Colorados, and ending in Buenaventura, Neiva, and Puente Aranda (Figure 19). The transport of refined products between the Cartagena Refinery and Andean region, as well as the imports required to supply the demand are carried out via the pipeline between the port of Pozos Colorados and Galán (Barrancabermeja). Only one line is owned by third parties, and moves refined products between Medellin and Rionegro (Unidad de Planeación Minero Energética, 2021). Refined products supplied to the center of the country are concentrated in Mancilla (Facatativá). Mancilla station connects to Puente Aranda (43 km, 10” diameter) and supplies Bogota. Puente Aranda has an extension (10 km, 6” diameter) that provides fuel to Bogota Airport. Figure 20 shows the current infrastructure for Jet A1 transportation by polyducts. By 2021, this line was insufficient to satisfy the demand, a deficit which is expected to increase. An analysis of alternatives to expand transportation capacity to the Bogota Airport has been conducted (Unidad de Planeación Minero Energética, 2021).

Colombia has terminals for the movement of hydrocarbons in the seaports of Tumaco and Buenaventura in the Pacific; and Coveñas, Cartagena, Barranquilla, Santa Marta, Puerto Bolívar, and San Andrés in the Caribbean. Tumaco and Coveñas are experts in the shipment of crude oil and reception of refined products from abroad (Unidad de Planeación Minero Energética, 2021).

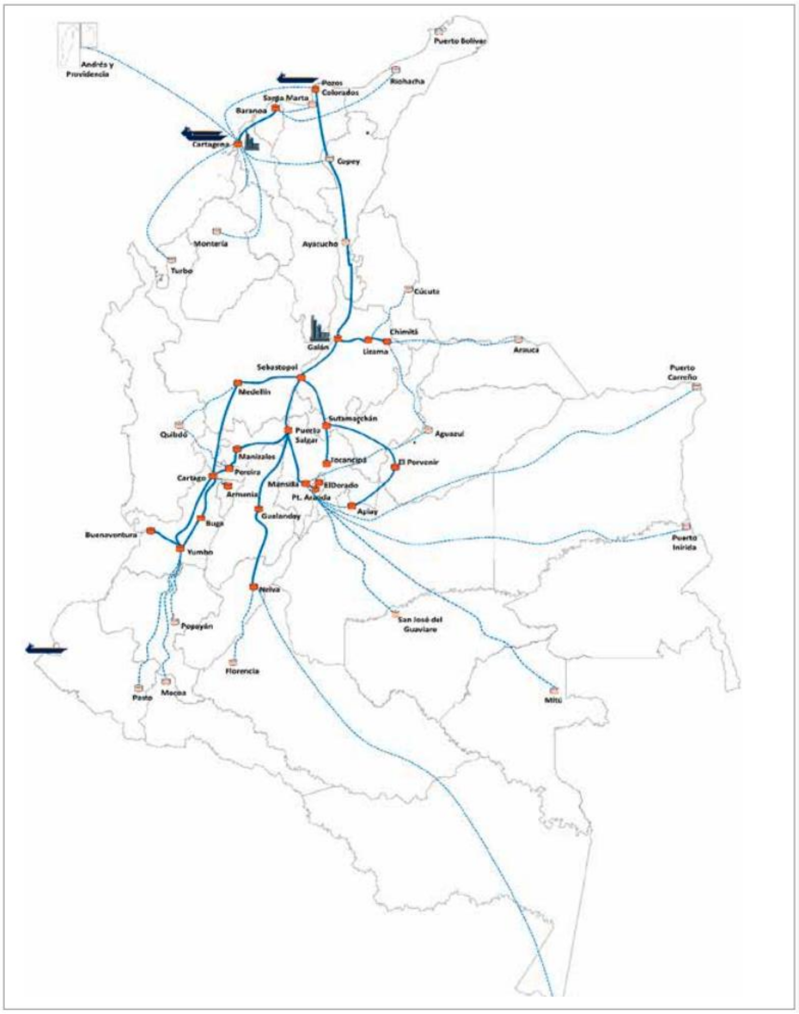


Figure 19. Colombian refined product pipeline system (Unidad de Planeación Minero Energética, 2021).

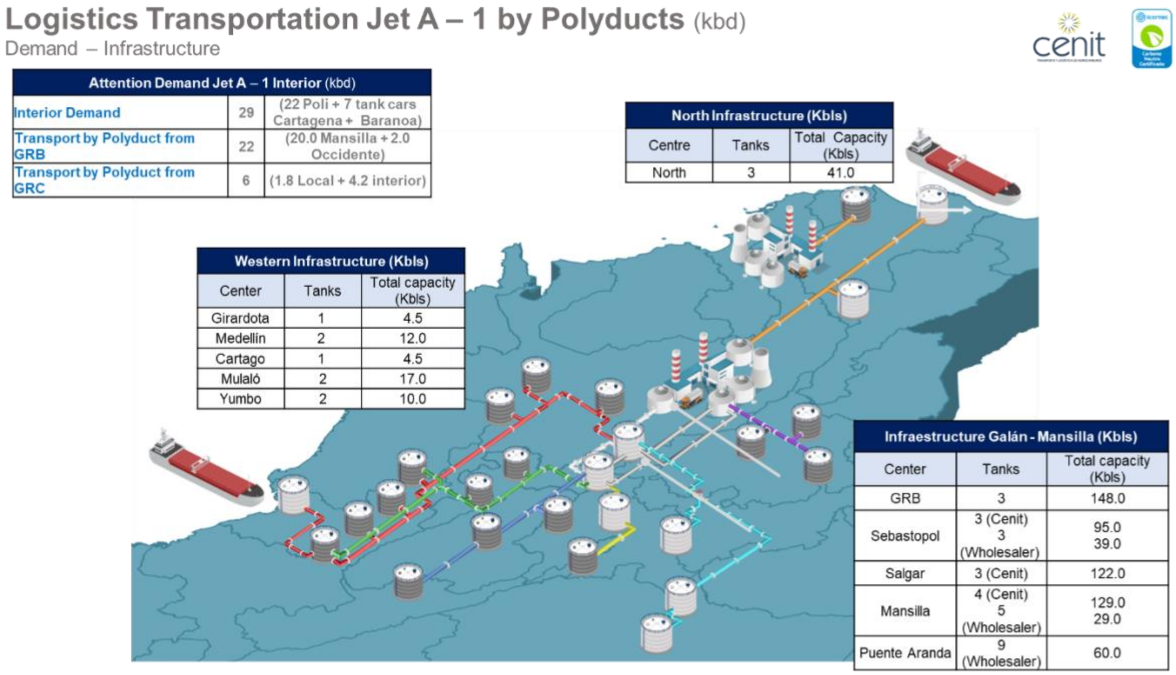


Figure 20. Logistic transportation Jet A-1 by polyducts (CENIT, 2023).

2.2.2.3. Biofuels

In addition to liquid fossil fuels, Colombia produces bioethanol and biodiesel in facilities nationwide (Figure 21). The Ministries of Agriculture, Environment, and Energy and Mines regulate the biofuel blend. Bioethanol and biodiesel production have been regulated and promoted through various policies. Law 693 of 2001 established the policy for using bioethanol as fuel and created incentives for its production, sale, and consumption as a blending component for gasoline in oxygenating conditions. It also established the mandatory use of bioethanol in urban centers with more than 500,000 people.

Law 1111 of 2006, Decree 383 of 2007 (and its modifications), and Law 1715 of 2014 defined: 1) exemptions of income tax from capital investments in agro-industrial projects, 2) tax incentives for the development of duty-free zones for biofuel projects, and 3) taxes incentives for investments in projects using unconventional sources of energy.

Law 939 of 2004 promoted the blending program for biodiesel. It declared 10 years (from production start) of net income tax exemption for using of new late-yield crops, including oil palm, cocoa, rubber, citrus, and fruit trees. Decree 2629 of 2007 established a mandatory 10% blend of biodiesel and fossil diesel.

Sugar cane is the primary feedstock for bioethanol. Bioethanol is produced in seven plants, with a nominal capacity of 2,150,000 liters per day. Table 4 shows the contribution of each existing plant. Despite the increase in installed capacity for bioethanol production, the plants' operation have not been operating at their optimum (Table 5) for various reasons, including weather and technical conditions (Asocaña, 2022; Unidad de Planeación Minero Energética, 2021). Thus, since 2013, Colombia has imported corn ethanol from the United States (Unidad de Planeación Minero Energética, 2021). Imported ethanol is used to supply the Colombian north coast mainly because it is costly and inefficient for Colombia's domestic ethanol industry to supply this region due to geographic and logistical issues (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022). Most Colombian ethanol plants are energy self-sufficient and generate surplus power that is sold to the national electric grid. The sugar sector capacity for electric power generation is 316 MW, of which 140 MW supports self-sufficient plant operations (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022). One ethanol facility, Bioenergy, located in the Meta department is not linked to the sugar industry. Bioenergy sources sugarcane from a 20,000 ha area near it (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022). Although Bioenergy started a liquidation process in 2020, a new company took its ownership and obtained resources to continuing operations (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022).

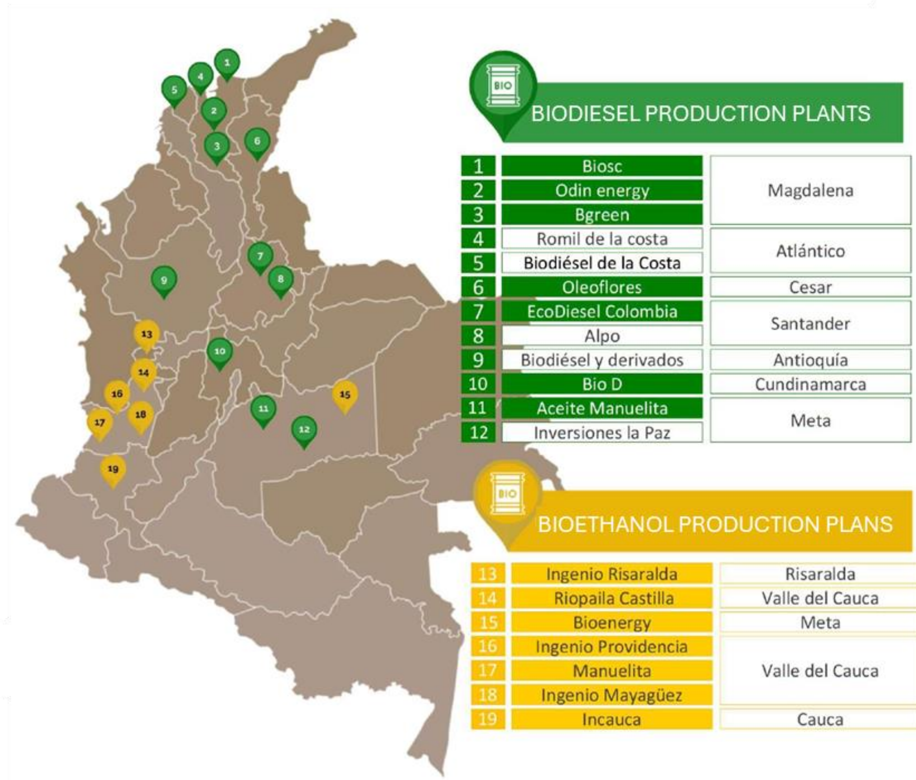


Figure 21. Colombian bioethanol and biodiesel plants (Fedebiocombustibles, 2023).

Table 4. Bioethanol production plants with installed capacity.

Plant (location)	Ethanol production (l/day)
Incauca (Cauca)	350,000
Riopaila-Castilla (Valle del Cauca)	400,000
Risaralda (Risaralda)	100,000
Providencia (Valle del Cauca)	300,000
Mayaguez (Valle del Cauca)	250,000
Manuelita (Valle del Cauca)	250,000
Bioenergy (Meta)*	500,000

*No taking into account harvest season average

Table 5. Increase in installed capacity and balance of bioethanol used for blending with gasoline from 2012-2021 (Asocaña, 2022).

Year	Installed capacity (l/day)	Production (thousands of liters)	National sales (thousands of liters)	Program coverage and mixing	Imports (thousands of liters)
2012	1,250,000	369,722	368,446	8% national blend	0
2013	1,250,000	387,859	339,782	10% blend in Bogota, and center, southwest, and south of the county from November 1	14,999
2014	1,250,000	406,468	418,527	8% national blend from February	12,322

2015	1,650,000	456,403	468,040	10% blend in the southwest from October	1,871
2016	1,650,000	434,431	439,301	7% average blend	18,555
2017	2,150,000	402,753	386,533	7% average blend	67,974
2018	2,150,000	466,613	481,705	8% blend from January and February. From March, 10% national blend	196,420
2019	2,150,000	443,570	449,084	10% national blend	269,492
2020	2,150,000	394,172	354,528	10% national blend	252,205
2021	2,150,000	396,795	376,423	6% average national blend	61,363

Seven plants in the north and center of the country produce biodiesel using palm oil as the primary feedstock. In 2022, the total installed capacity of biodiesel production in the country was 697,200 ton/year (see Table 6) (Fedebiocombustibles, 2023). Diesel for the industrial sector does not have a blending mandate since 2020 (Unidad de Planeación Minero Energética, 2021). The palm oil sector capacity for electric power is estimated at 340 MW (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022).

Table 6. Biodiesel production plants, installed capacity by 2023 (Fedebiocombustibles, 2023).

Plant (location)	Producer	Biodiesel production (ton/year)
San Carlos de Guaroa, Meta	Aceites Manuelita	120,000
Facatativá, Cundinamarca	BioD	240,000
Barrancabermeja, Santander	Ecodiesel Colombia	154,123
Santa Marta, Magdalena	Biocosta Green Energy	76,820
Santa Marta, Magdalena	Biocombustibles Sostenibles del Caribe	150,000
San Carlos de Guaroa, Meta	Inversiones La Paz	75,000
Barrancabermeja, Santander	ALPO	12,000
Total		827,943

2.2.2.4. Commercialization

Figure 22 shows Colombia's operative model of liquid fuels' commercialization. The interaction between parties is established in the regulations (Unidad de Planeación Minero Energética, 2021). The final consumer can only acquire the products via fuel stations up to specific volumes. Wholesale distributors blend all the bioethanol. Refineries blend the diesel delivered to the wholesale distributor up to 2% of biodiesel, which is transported through the pipeline system. Wholesale distributors receive biodiesel (via tanker trucks) and blend up to the required mix.

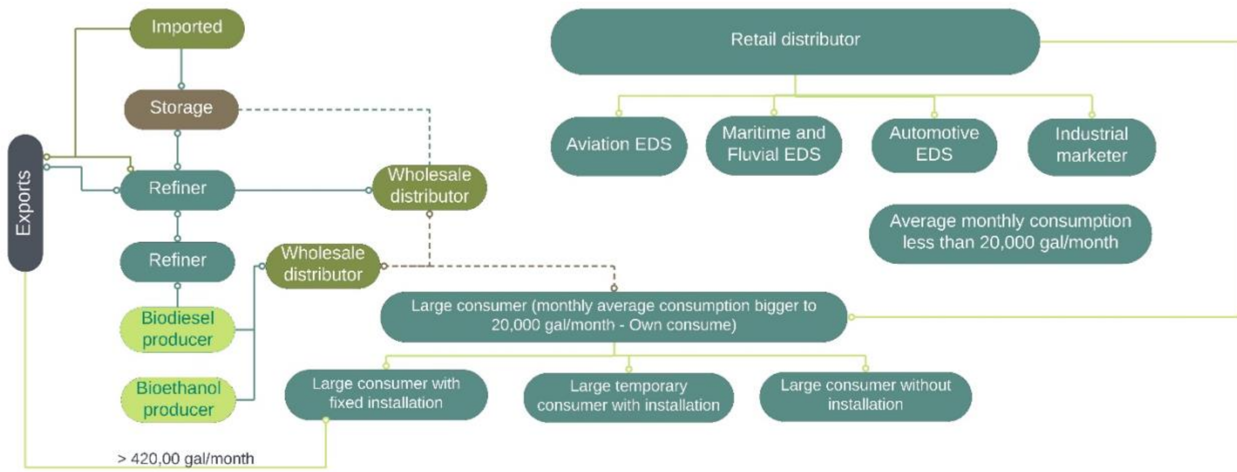


Figure 22. Interactions of liquid fuels commercialization in Colombia (Unidad de Planeación Minero Energética, 2021).

2.2.2.5. Liquid fuel prices

Decree 2119 of 1992 grants the Ministry of Energy and Mines power to set the prices of oil derivatives and natural gas at the refinery, plant, and wholesale distribution. This function was ratified in Decree 07 of 2001. Law 681 of 2001 established that the sale price to the wholesale distributor is the result of adding the income to the producer, the charges for transportation through the pipeline system, and taxes. This law tied the income of the jet fuel producer in Colombia to Platt's US Gulf Coast Wb (Low) index, reference Jet 54 (Martínez Ortiz & García Romero, 2016).

Later, Law 1450 of 2011 stated that the formula to determine the structural components of the jet fuel price will become effective when the national government assigns the functions to a regulatory entity. This entity would determine the price of liquid fuels, biofuels, and natural gas for vehicles. Through resolution 40193, the ministries of energy and finance delegated the function to CREG. Thus, CREG oversees establishing the methodologies for determining the rates and margins associated with the remuneration of the entire supply chain of liquid fuels, except for the income to the producer.

Jet fuel production is a monopoly of Ecopetrol S.A. Its distribution in Colombia depends on a few companies, which justifies the CREG's intervention (Olivera et al., 2011). Jet A1 price setting to the wholesale distributor uses a formula established in Law 681 of 2001. The law includes an income to the producer (with an international parity price), a transportation fee from the refinery to the airport, and some taxes (Martínez Ortiz & García Romero, 2016). The transportation fee varies according to the distance from the refineries or port of import. Thus, the cities farthest from the refineries have higher transportation costs.

Airports influence the fuel cost for the airlines. Fuel distributors require leasing space in the airport to locate the necessary equipment. Fuel dealers need authorization not only to distribute the fuel to the airlines but also to access the airport apron and supply fuel to the plane's wing (Durán Preciado, 2013). For airlines, fuel is the highest direct cost at 30% on average between 2005 and 2014 (Martínez Ortiz & García Romero, 2016).

2.2.2.6. Tax policy

Since 2002, to promote biofuel use and production, the government eliminated the value-added tax (VAT) for biofuels and exempted them from a global carbon tax on fossil fuels. Ethanol blended with gasoline is exempt from the local surcharge fee. A tax on the carbon content (or carbon tax) of all fossil fuels, including all oil derivatives and types of fossil gas used for energy purposes, was introduced in 2016. The rate is based on the release of CO_2 factor for each fuel, expressed as the volume or weight of the fuel. In 2022, Colombia increased the carbon tax rate to approximately USD 4.43/tCO_2e. The tax rate applied for coal will be 25% of the total value in 2025 and 100% in 2028. The percentage of allowable offset is 50% (The World Bank, 2022). However, this value is low compared to similar policies worldwide (Figure 24).

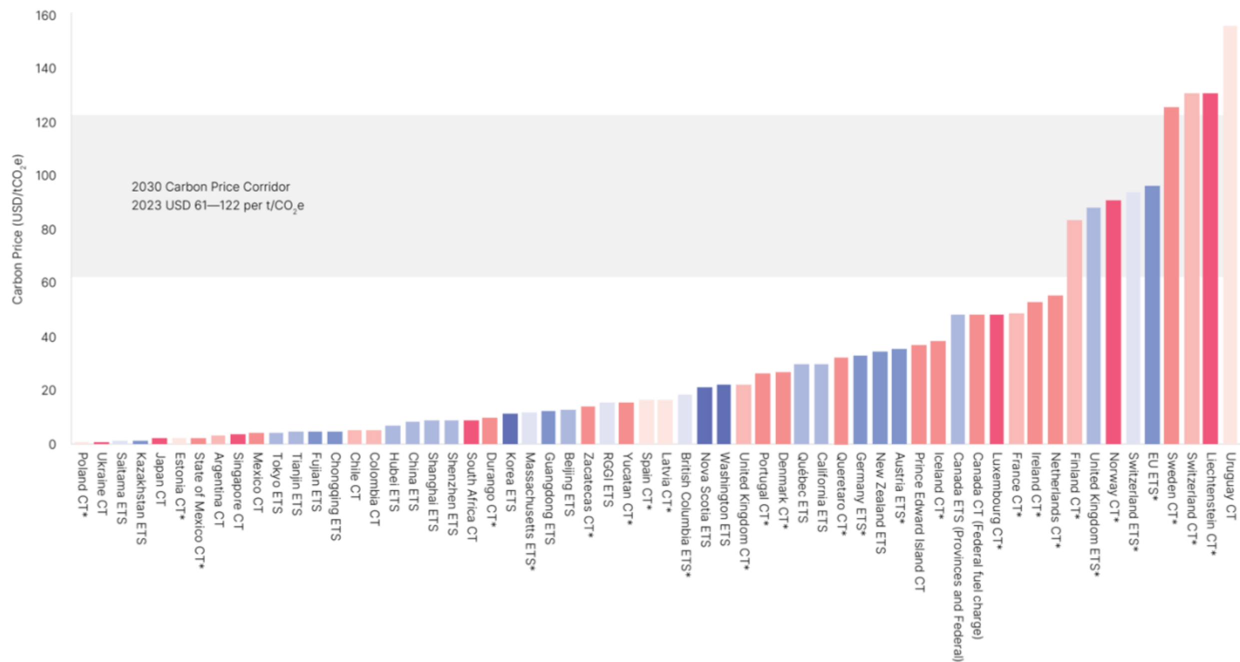


Figure 23. Prices and coverage across emission trading systems (ETS) and carbon taxes (The World Bank, 2022).

Table 7. Current fuel and biofuel tax rates in Colombia (in Colombian pesos)

Tax	Gasoline	Diesel	Biofuels	Regulation
Global tax	$724.70 per gallon on regular gasoline (~USD $0.18)	$693.65 per gallon (~USD $0.17)	Exempt	Art. 167, 168, 173 – Law 1607 of 2012 Art. 218, 219, 220 – Law 1819 of 2019 DIAN- Res. 000007 01/31/2004
Value added tax (VAT)	5% producer income 19% retail distributor	5% producer income 19% retail distributor	Exempt	Art. 183 – Law 1819 of 2016 Art 74 – Law 1955 of 2019 Art. 477 – Estatuto tributario (Biofuels exempt)
Carbon tax	$186 per gallon (~USD $0.04)	$210 per gallon (~USD $0.05)	Exempt	Dec. 926 of 2017 Art. 221, 222, 223 – Law 1819 of 2016 DIAN- Res. 000007 01/31/2004
Local surcharge fee	25% of the reference price.	6% of the reference price	Exempt ethanol blended with gasoline.	Art. 117 to 121 – Law 488 of 1998

	There is no surcharge tax relief on biodiesel	

Note: Values are in COP. Specific tariffs are valid for 2024 and updated annually. Exchange rate used 1 USD = 3,930 COP, average exchange rate in Feb 2024.

2.2.3. Natural gas

The development of the natural gas industry in Colombia began in the mid-1970s with the discovery of this fuel in *La Guajira* in the northern part of the country. Since then, through various government programs, national interconnections have been established, as well as strategies for searching for and discovering new reserves (Comisión de Regulación de Energía y Gas, n.d.). Today, there are more than 10 million users, representing 21% of Colombia's energy basket. In addition, the country has the fifth largest natural gas production in Latin America (Naturgas, 2023; Promigas, 2022).

In December 2020, Colombia had seven years of self-sufficiency available in its proven natural gas reserves. These proven reserves have increased by 7%, and as of January 2022, Colombia has proven natural gas reserves of nearly 3 Tft3 (trillion cubic feet). This represents eight years of self-sufficiency (U.S. Energy Information Administration (EIA), 2022; Naturgas, 2023). The reserves are distributed in 15 departments, and concentrated primarily in Casanare (52%) and La Guajira (18%) (Figure 24) (Promigas, 2022).

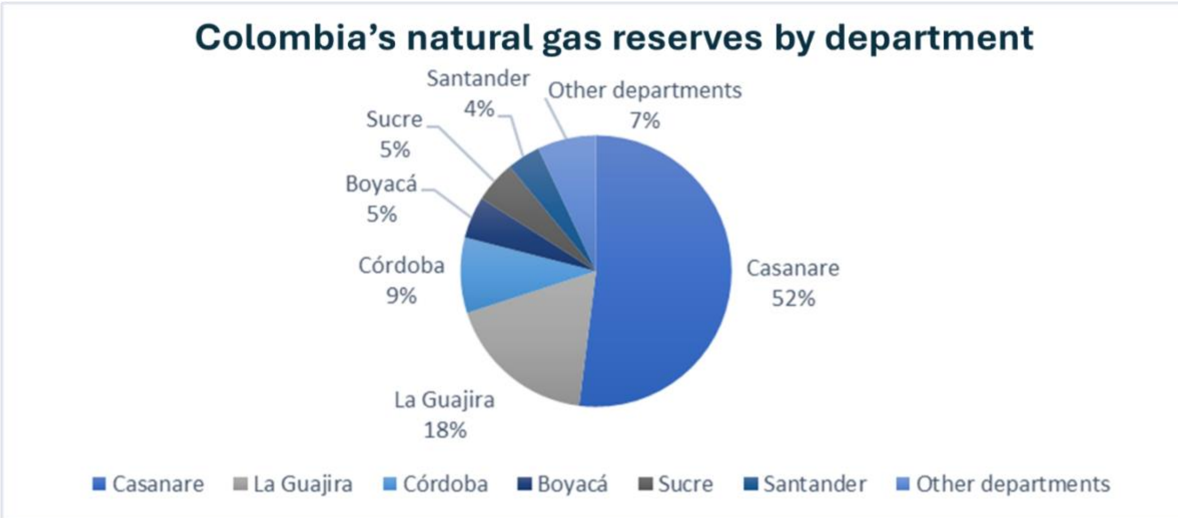


Figure 24. Natural gas proved reserves in Colombia (Promigas, 2022).

2.2.3.1 Production and consumption

Natural gas in Colombia is classified according to whether the extraction sites are in onshore and offshore fields. Cusiana, Cupiagua, and Pauto Sur are onshore fields, while Chuchupa field is an offshore field (EIA, 2022). Natural gas extraction is carried out by both national (majority of production) and foreign companies (principally CNE OIL & GAS, and Canacol, both of which are Canadian companies. Figure 25 shows that Ecopetrol S.A. was the primary producer (72%) in 2022, followed by Ecopetrol's subsidiary Hocol with 12%, CNE OIL & GAS S.A.S with 6%, and Canacol Energy Ltd with 5%. Finally, the remaining 6% was produced principally for foreign companies with operations in Colombia (Agencia nacional de hidrocarburos, 2023).

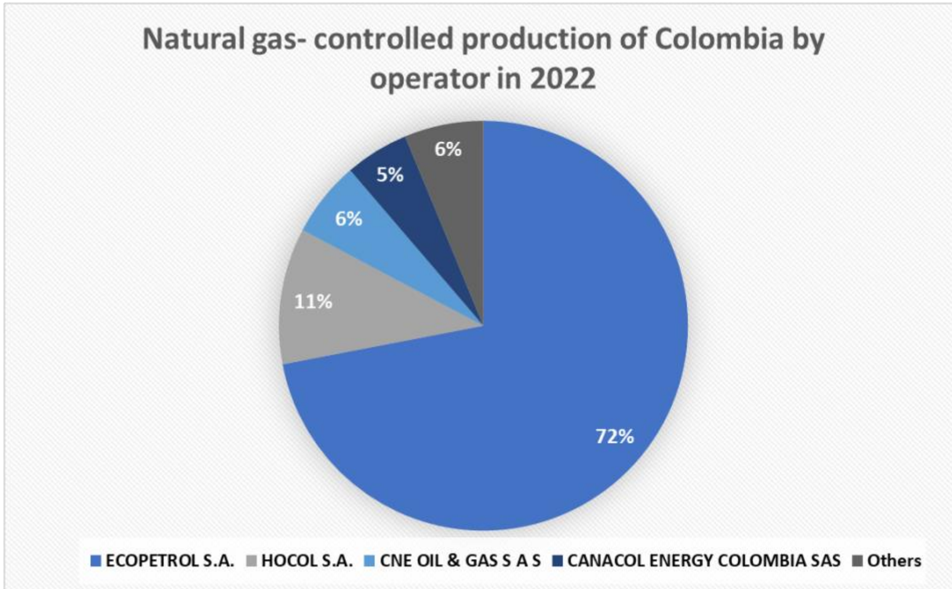


Figure 25. Natural gas-controlled production in Colombia by operator (Agencia nacional de hidrocarburos, 2023).

Natural gas-controlled production decreased by a 181 Gft^3 in the last five years (Figure 26). The decrease of 145 Gft^3 was due to the lower use of reinjection gas for oil extraction in the Eastern Plains. Additionally, Figure 27 shows that the production of the Guajira fields declined (54 Gft^3). This production reduction is due to the depletion of reserves (Promigas, 2022)

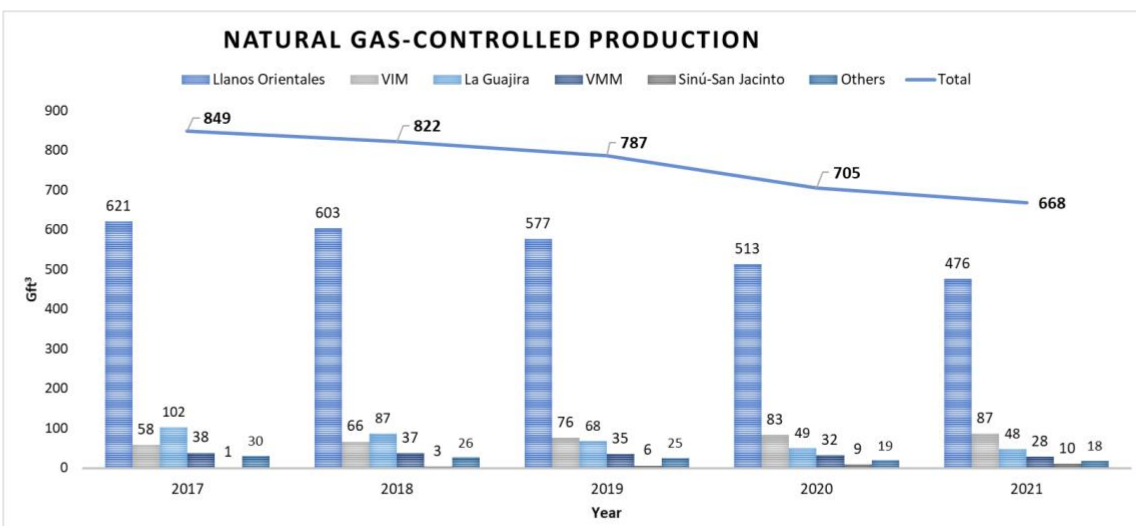


Figure 26. Natural gas-controlled production in Colombia from 2017 to 2021. LMV and MMV refer to the Lower and Middle Magdalena Valleys, respectively (Promigas, 2022).

In Colombia, natural gas consumption is divided into six sectors: commercial and industrial, thermoelectric power generation, petroleum and others, residential, natural gas vehicle (NGV), and petrochemical. Figure 28Figure summarizes the consumption of these sectors between 2017 – 2021. The highest consumer was the industrial and commercial sector throughout the period, with a maximum of 304 Mcfd in 2019. In 2021, the post-pandemic rebound hit consumption of 59 Mcfd (Promigas, 2022).

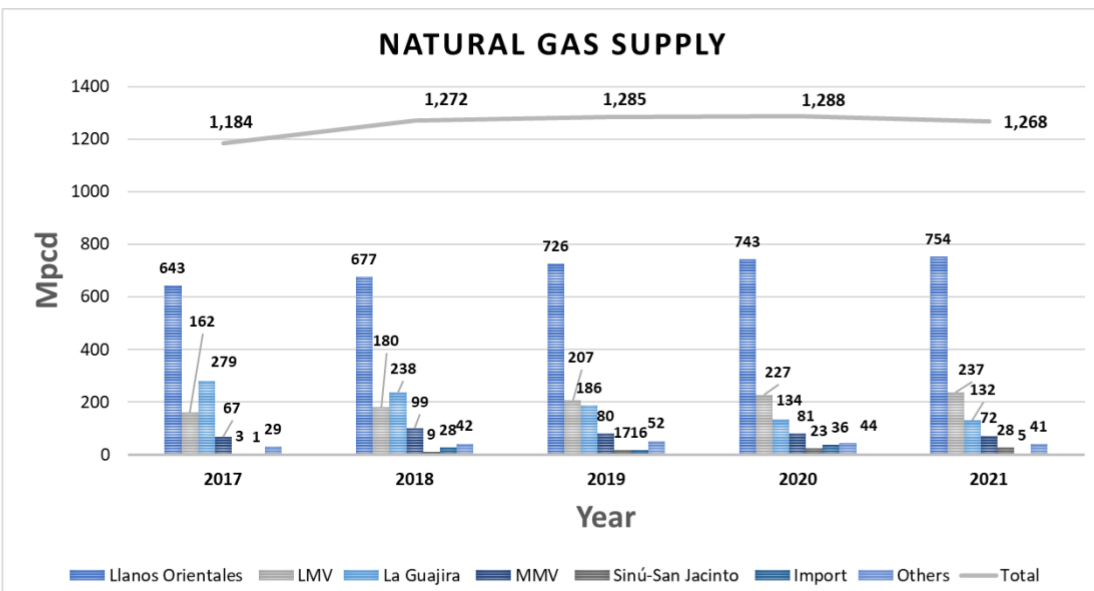


Figure 27. Natural gas supply. LMV and MMV denote the Lower and Middle Magdalena Valleys, respectively (Promigas, 2022).

The petroleum industry uses natural gas for enhanced oil recovery. Both refineries use natural gas-fired plants to power their daily operations. Ecopetrol committed to stopping routine flaring at its operations to reduce 20% of their emission by 2030 (EIA, 2022).

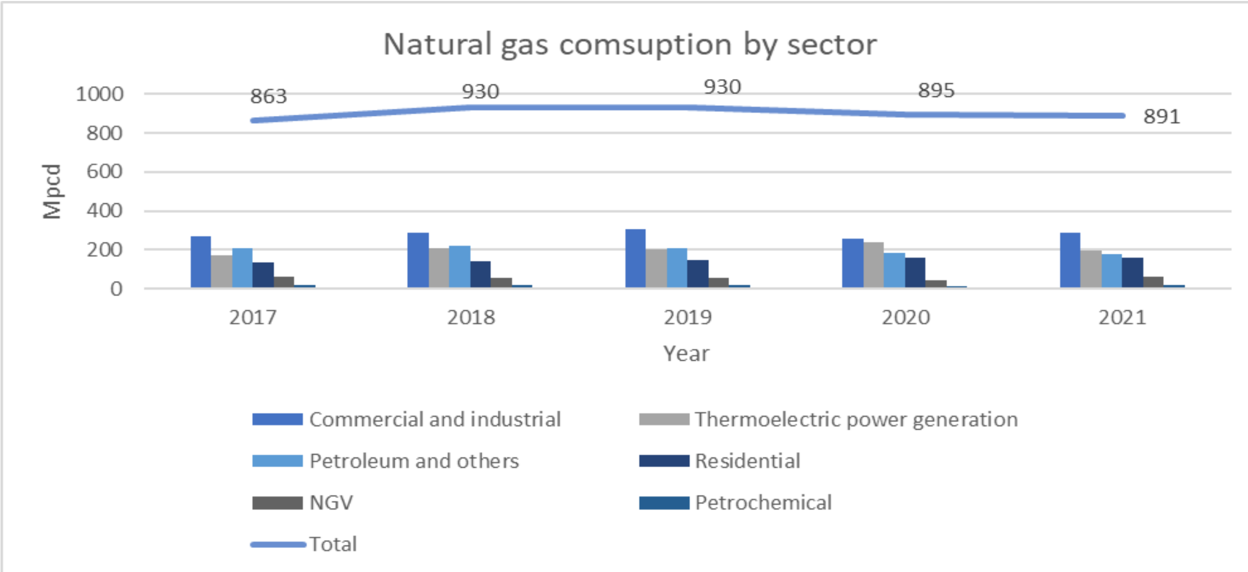


Figure 28. Colombia's natural gas consumption by sector, 2017-2021 (Promigas, 2022).

2.2.3.2 Transportation and supply

The national transportation system of natural gas comprises pipelines that link natural gas production centers to the cities, distribution systems, non-controlled users, international interconnections, and storage systems. As a solution to distribute natural gas to remote areas, modular systems allow the compression of natural gas for storage and then transporting it by road (Superintendencia de Servicios Públicos Domiciliarios, 2023).

Seven companies provide natural gas transportation services (Figure 29), with TGI and Promigas being the main ones. TGI has the highest coverage, with 52% of the pipeline. Promigas focuses on the northern region, representing 35% of Colombia’s pipelines (Promigas, 2022).

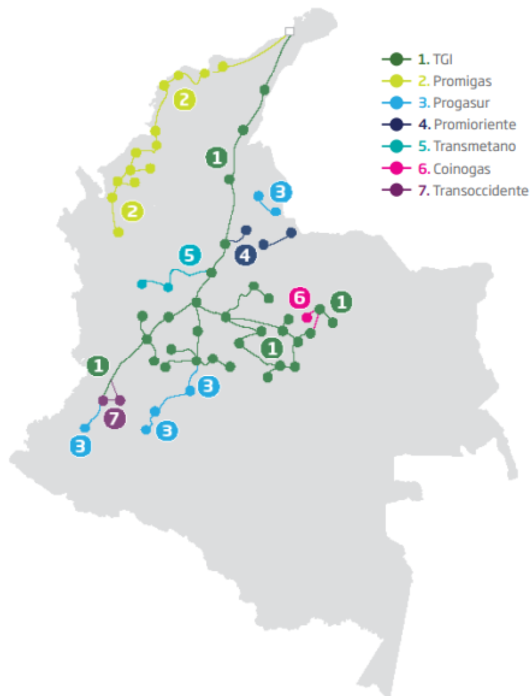


Figure 29. Natural gas transport pipelines in Colombia in 2021 (Promigas, 2022).

2.2.3.3 Prices

The natural gas market has agents and users. Agents make it possible to bring the gas to the end user (producers, transporters, distributors, and marketers). Based on the daily consumption of natural gas, it is classified by user: controlled and non-controlled. The first corresponds to users of less than 100 thousand cubic feet per day (ft^3d). Gas-based electricity generation plants, and large industrial and commercial users are examples of non-controlled users, with daily consumption of more than 100 thousand cubic feet (ft^3d) (Comisión de Regulación de Energia y Gas, 2021).

In 2022, the average price of natural gas was USD22/million British thermal units (mmBTU), including transportation costs of imported natural gas (Fitch Ratings, 2022). The price of domestically produced natural gas was USD 13/mmBTU (Fitch Ratings, 2022), and natural gas used in Barrancabermeja’s refinery was approximately of USD5.7/mmBTU (É. Yáñez et al., 2021).

Table 8 and 9 show the prices for controlled and non-controlled industrial sectors, respectively, reported by the distributor (Promigas, 2022).

Table 8. Prices in the controlled industrial sector (Promigas, 2022)[1].

	Unit	2017	2018	2019	2020	2021
Alcanos	USD	15	15	17	16	18
Efigas	USD	15	15	15	14	14
EPM	USD	12	13	12	12	12
Gases de la Guajira	USD	8	7	9	10	13
Gases del Caribe	USD	14	13	14	12	13
Gasoriente	USD	9	10	10	9	12
GdO	USD	15	16	16	16	15
Surtigas	USD	9	12	12	12	12
Vanti	USD	14	14	13	12	13
Average	USD	12	13	13	12	14

[1] The dollar prices were calculated from the average exchange rates for Colombian pesos for each year.

Table 9. Prices in the non-controlled industrial sector (Promigas, 2022)[1].

	Unit	2017	2018	2019	2020	2021
Efigas	USD	176.74	178.67	179.33	159.82	160.00
EPM	USD	84.54	148.44	133.78	146.72	147.11
Gases del Caribe	USD	144.04	136.46	131.21	123.22	139.70
Gasoriente	USD	109.87	104.92	118.74	102.96	149.89
GdO	USD	175.55	185.26	193.88	182.41	185.58
Surtigas	USD	84.67	118.22	118.87	138.71	141.85
Vanti	USD	159.72	167.11	153.09	138.78	16.75
Average	USD	133.59	148.44	146.98	141.80	130.15

[1] The dollar prices were calculated from the average exchange rates for Colombian pesos for each year.

2.2.4. Electricity

The Colombian electricity sector is fundamentally governed by Laws 142 and 143 of 1994 (Ley 142 de 1994, 1994). These laws define the regime for the provision of electricity, establishing the wholesale electricity market in the country. The regulation of this market was developed by CREG (Ministerio de minas y energía, 2021). Additionally, Law 1715 of 2014 promotes the offering diversification through the incorporation of renewable energies to complement the Colombian energy matrix, as well as achieve a greater supply of energy in favor of market competition and better cost for the final user (Energía Estratégica, 2014).

In Colombia, the coverage of electric power is classified in two zones: the National Interconnected System (NIS) and the Non-Interconnected Zones (NIZ) (Figure 30). The NIS comprises generation plants dispatched to the national territory and transmission networks connected. In this way, they carry the energy produced to a large part of the national territory. Meanwhile, the NIZs are characterized by a low population density with places with complex access. These places are classified as natural reserve territories with indigenous or Afro-descendant populations (Universidad Distrital Francisco José de Caldas & Region Central RAP-E, 2020).

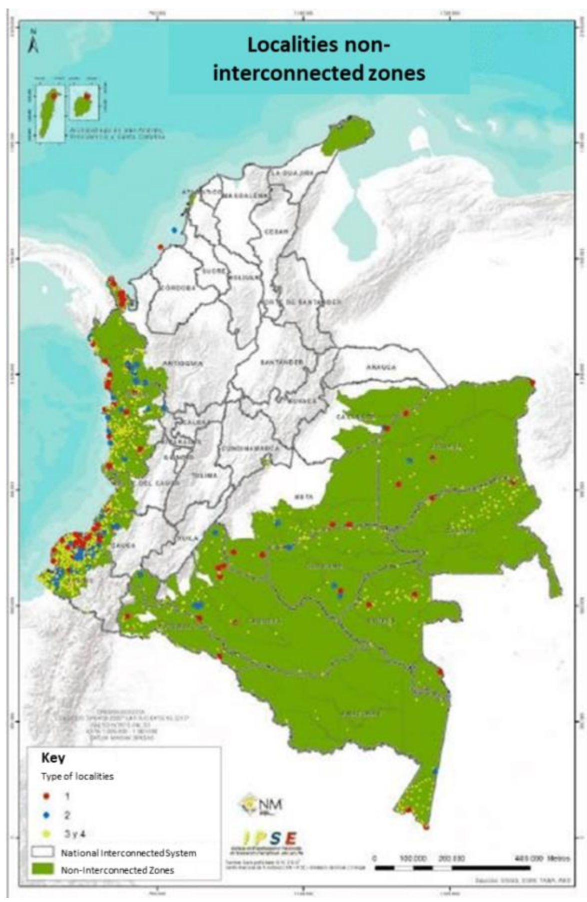


Figure 30. National interconnected system (in white) and non-interconnected zones in green (Forero-Quintero et al., 2014)

The electricity market has four distinct successive activities: generation, transmission, distribution, and commercialization (Enel Colombia, 2018). Each activity is independent and defines a component of the cost of electricity (EPM, 2023). Generation involves the process of electricity production. Colombia has hydraulic, thermal, wind, and solar power generation plants (XM, 2022). Next, regarding transmission, the country's electric grid spans over 200,000 km of high- and extra-high-voltage lines with a frequency of 60Hz across media-Guajira along the Andes down to Ecuador; the last branch of the grid was to the Rubiales oil field in Meta (Burdack et al., 2023). Once the energy is produced, it needs to move to the cities and consumption centers. The transport of energy or transmission is carried out through high voltage lines that are part of the NIS. The high voltage energy is converted to medium and low voltages using substations, which are adequate to supply industrial and domestic consumption. The distribution (medium and low voltage) network is supervised and maintained by distribution agents (AES Colombia, 2023). Trading agents are the companies that broker energy in the wholesale market and sell it to end users.

2.2.4.1 Generation

In 2020, the installed capacity for electricity generation was 17 gigawatts (GW), produced mainly through hydropower (69%), and gas- and coal-fired power plants (30%). The remaining electricity is produced by auto- and co-generation, wind, and solar units. The Colombian energy matrix is clean but highly dependent on climatic conditions due to the dependence on hydropower (International Trade Administration, 2022; Montes, 2019). The non-hydropower renewables sector of Colombia is not as extensive as its hydropower sector, but UPME expects non-hydropower renewables to grow through 2030 because of significant opportunities in solar and wind power. Colombia has committed to reach 4 GW of renewable electricity generation capacity and to derive 74% of total electricity consumption from renewables by 2030 (EIA, 2022).

2.2.4.1.1 Hydropower

Currently, 28 centrally dispatched (Figure 31) and 115 non-centrally dispatched hydropower plants are operating. Centrally dispatched facilities have a net capacity of up to 10,974 MW, while non-centrally dispatched facilities reach 860.57 MW. Centrally dispatched plants typically have a net capacity greater than or equal to 20 MW, while non-centrally dispatched plants have less than 20 MW (Montes, 2019).

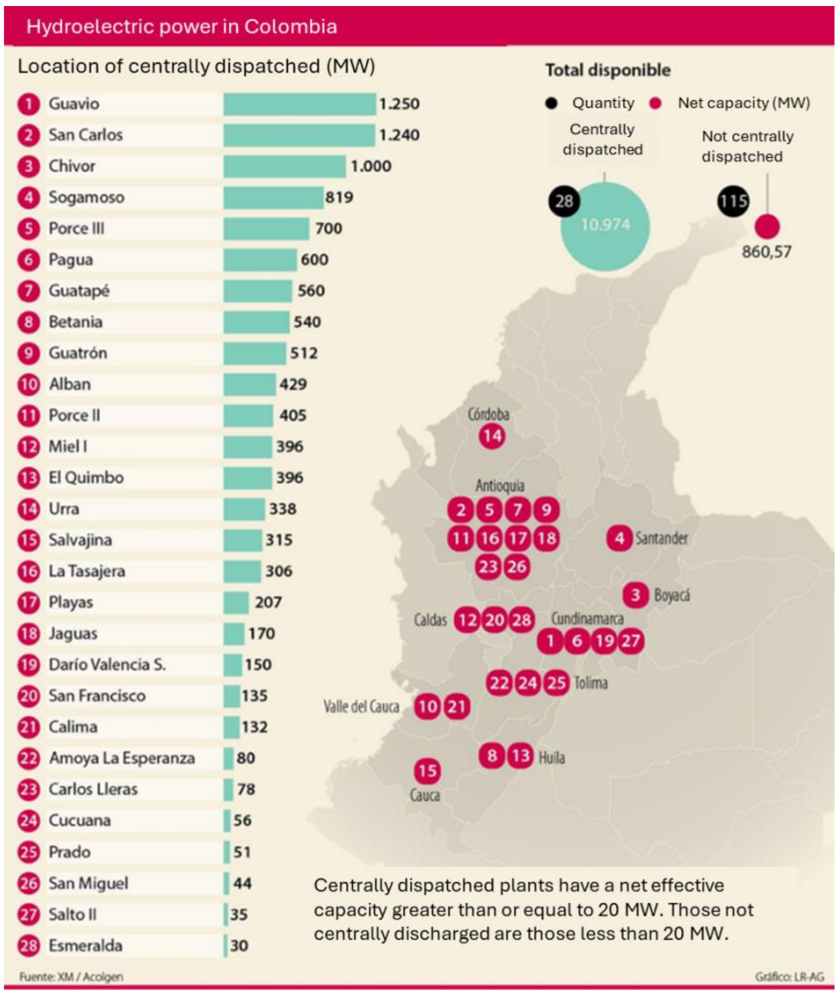


Figure 31. Hydroelectric supply in Colombia (Montes, 2019).

The upcoming hydroelectric plant "Hidroituango" is expected to be the primary electricity generator in Colombia, producing up to 2.4 GW in 2025 (Alcaldía de Medellín, 2022). In 2022, its first power-generation unit came into operation, generating 600 MW of electricity (EIA, 2022).

2.2.4.1.2 Non-hydropower

Colombia currently does not have enough transmission infrastructure to develop non-hydropower renewables in rural areas where renewable power potential is highest. Transmission and distribution infrastructure is a priority under the government's 2031 expansion plan, mainly focusing on increasing power supply and improving the ability to develop new clean power capacity in regions that have not been connected to the national grid (EIA, 2022).

Solar and wind potential have been assessed by dividing the country in eight climatic areas (see Figure 32. a and b) (Ministerio de Minas y Energía, 2021). La Guajira holds the largest wind and solar power potential in the country, estimated at 3.5 GW of wind and 2.5 GW of solar (EIA, 2022). In this department alone, there are already 16 wind energy projects which generate a total of 2.502 MW (Energía Estratégica, 2023) and two transmission lines under construction (Monsalves, 2023) (Figure 33). Without these lines, the area is isolated from the country's main power grid. Additionally, in Cauca Valley (western Colombia), there is a solar panel farm called *La Paila,* which is expected to generate 18,201 megawatts per hour (OLADE, 2022).

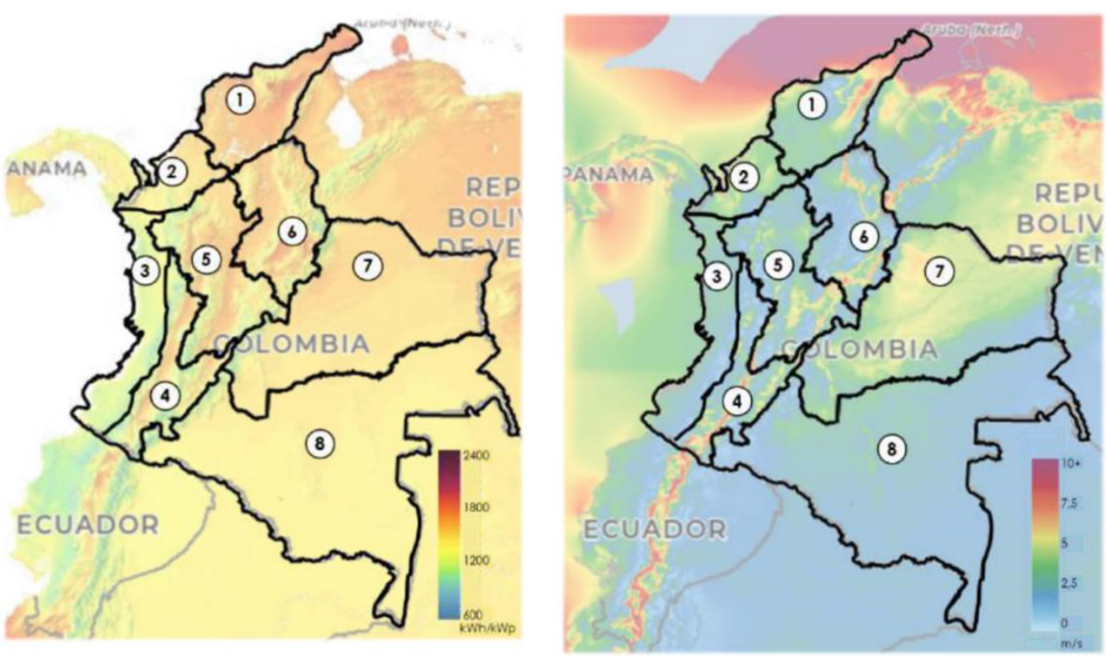


Figure 32. Renewable energy production potential by climatic areas. a) Photovoltaic power potential. b) Mean wind speed (Ministerio de Minas y Energía, 2021).

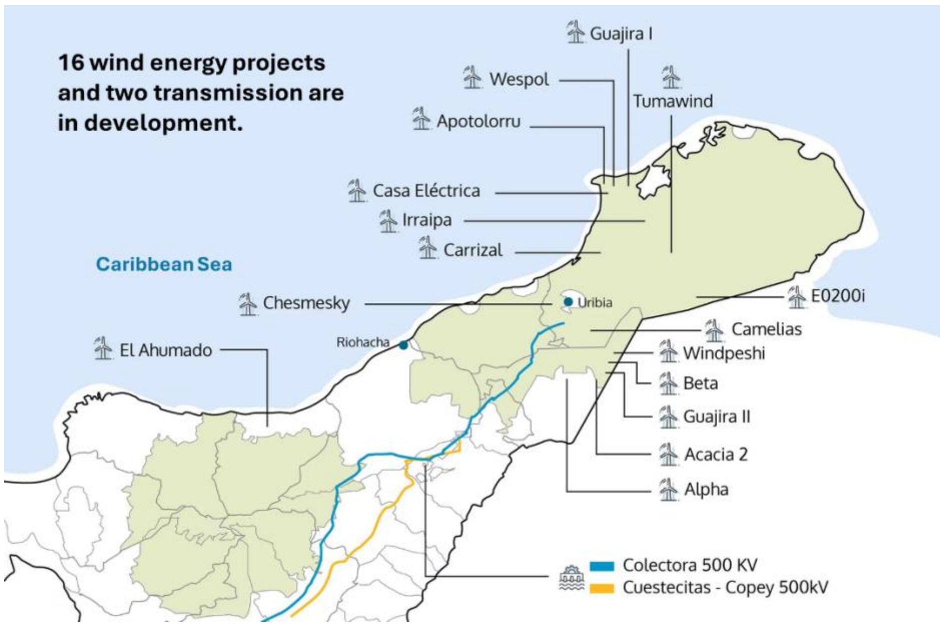


Figure 33. Wind energy projects in development in La Guajira (Monsalves, 2023).

In 2021, the first pilot for geothermal energy generation began in the Maracas Field of San Luis de Palenque in Casanare. The project seeks the co-production of hydrocarbons and electricity, taking advantage of the high temperatures and volumes of water produced in the extraction of hydrocarbons. The project, developed in coordination between the National University (UNAL) and Parex Resources, will produce up to 72,000 kWh/month, equivalent to the monthly electricity consumption of 480 families (OLADE, 2022).

2.2.4.1 Trade

Colombia both imports and exports electricity. The main import source of electricity is Ecuador. In 2020, Colombia imported 1.3-gigawatt hours of electricity. Colombia's and Ecuador's electrical grids are linked by dual 230-kilovolt power lines spanning 132 miles (EIA, 2022). Although

Colombia exports electricity to Panama, Peru, and Venezuela, the largest buyer of national electricity is Ecuador (PORTAFOLIO, 2021) at 250 MWh in 2020 (EIA, 2022).

2.2.4.2 Price

The unit cost of service provision (UC) is the efficient economic cost of providing the service to the regulated end user. The UC of electrical comprises the components of generation, transmission, distribution, commercialization, losses, and system restrictions. Each of these obeys regulated conditions for determining its value. The tariff is the value of applying the legally authorized subsidy or contributing factor to the UC. Table 9 shows the average electricity cost by zone in 2022 (Superservicios, 2023).

Table 10. Colombia's average cost by zone in 2022 (Superservicios, 2023)[1].

Zone	Average Cost 2022 (USD/kWh)
West	0.189
Center	0.205
East	0.211
South	0.213
North	0.217

[1] The dollar prices were calculated from the average exchange rates from Colombian's pesos for 2022.

Colombia's first renewable energy auction in February 2019 assigned bids between buyers and sellers but did not award contracts. At 28.4 USD/MWH for solar and 27.7 USD/MWh for wind, Colombia's weighted average process was significantly lower than the global average for auctions in 2018 (IRENA & USAID, 2021).

2.2.5. Hydrogen

Hydrogen is increasingly a component of the energy transition towards decarbonization and de-fossilization in various sectors (Hren et al., 2023) because it has the potential to replace natural gas (e.g., heat supply to industry and transport fuels). Hydrogen is used in industrial processes in sectors such as oil refining (33%), ammonia manufacturing (27%), methanol (11%) and steel production (3%), and its demand is projected to increase almost sixfold in 2050 driven mainly by the steel and ammonia industries (Cho et al., 2023).

Colombian's estimated hydrogen demand is 150kt from petroleum refineries, fertilizers production, and other minor industrial uses, and is currently supplied by reforming natural gas (Ministerio de Minas y Energía, 2021). The leading consumers are REFICAR with 88.4 kt of H_2/year and Barrancabermeja refinery with 41.5 kt of H_2/year. In 2019, Colombian hydrogen demand for fertilizer production was 43kt, focused mainly on the Caribbean and Valle del Cauca regions (Castañeda et al., 2022).

Nevertheless, although hydrogen is a zero-carbon emissions fuel, its production can generate considerable CO_{2e} ($CO_{2\text{-equivalent}}$) emissions depending on the method used for its production. Table 11 shows the classification of hydrogen by colors, some of which are associated with the initial energy sources and production technologies used to produce this element (Ajanovic et al., 2022).

Table 11. Hydrogen production classification by colors.

Color	Fuel	Process
Black	Coal	Steam reforming or gasification
White	N/A	Natural occurring
Grey	Natural Gas	Steam reforming
Blue	Natural Gas	Steam reforming and carbon capture and storage/repurpose
Turquoise	Natural Gas	Pyrolysis (instead of CO_2, solid carbon is produced)
Red	Nuclear Power	Catalytic splitting
Purple/Pink	Nuclear Power	Electrolysis
Yellow	Solar Power	Electrolysis
Green	Renewable Electricity (e.g., wind and solar)	Electrolysis (Zero emissions are produced)

According to Colombia's Hydrogen roadmap (Ministerio de Minas y Energía, 2021), low-carbon hydrogen produced from natural gas and coal in a production process that uses CO_2 capture and storage technology could supply the national demand for hydrogen. Information regarding natural gas reserves is in section 2.2.3 of this document. Colombia is the largest producer of coal in Latin America and one of the leading exporters worldwide (Oei & Mendelevitch, 2019). Proven coal reserves in 2020 were 5 trillion short tons of mostly bituminous coal (EIA, 2022). These reserves are in La Guajira, Cesar, and some areas in the country's center (Ministerio de Minas y Energía, 2021). There are also explorations underway for natural hydrogen reservoirs, although determining their location and potential is in the early stage.

As described in section 2.2.4, Colombia has substantial wind and solar energy that could be used for the production of green hydrogen. The Caribbean and Andian regions have the capacity to generate solar and wind energy, and adequate biomass availability. Both regions account for 22 hydrogen generation projects (Asociación Hidrógeno Colombia, 2023).

The energy transition law (Law 2099 of July 10, 2021) extended the benefits from the Law 1715 of 2014 (see section 2.2.2.3) to the production of blue and green hydrogen (Ministerio de Minas y Energía, 2021). The four points of tax benefits are (Castañeda et al., 2022):

1. Income tax deductions equivalent to 50% of the investment made in unconventional sources to generate energy. The deduction is up to 15 years from the start of the project. The deduction cannot exceed 50% of the taxpayer's net income.
2. Accelerated depreciation of 33.33% (initially 20%) in machinery, equipment and civil works that have an exclusive destination for activities related to renewable resources.
3. VAT exemption for local and foreign goods and services for projects, including efficient energy management projects, in the investment and pre-investment phase.
4. Exemption from customs duties to import equipment, goods, and machinery is used exclusively during the reinvestment and investment stage of projects from non-conventional renewable energy sources.

The levelized cost of hydrogen (LCOH) forecast for gray and blue hydrogen is shown in Figure 34.a depending on the fuel, considering only the development of new projects, and including the incentives of Law 2099 of 2021. Grey hydrogen production using natural gas is currently the cheapest option at \$1.9/khH_2, while the blue counterpart starts at \$2.4/kgH_2.Figure 34. b shows the evolution of LCOH in different regions considering the incentives from Law 2099 of 2021. In 2020, green hydrogen's price was estimated at 2.8 USD/kgH_2 as the cheapest option in northern Colombia; however, by 2050, it is expected to decrease to 1.5 USD/kgH_2. Despite green hydrogen from solar energy almost being double of the wind-green H_2 cost in 2020, it almost achieves price parity by 2050. The northern Caribbean region has wind resource reaching plant factors of up to 63%, which might reduce the cost by up to 25% (Ministerio de Minas y Energía, 2021).

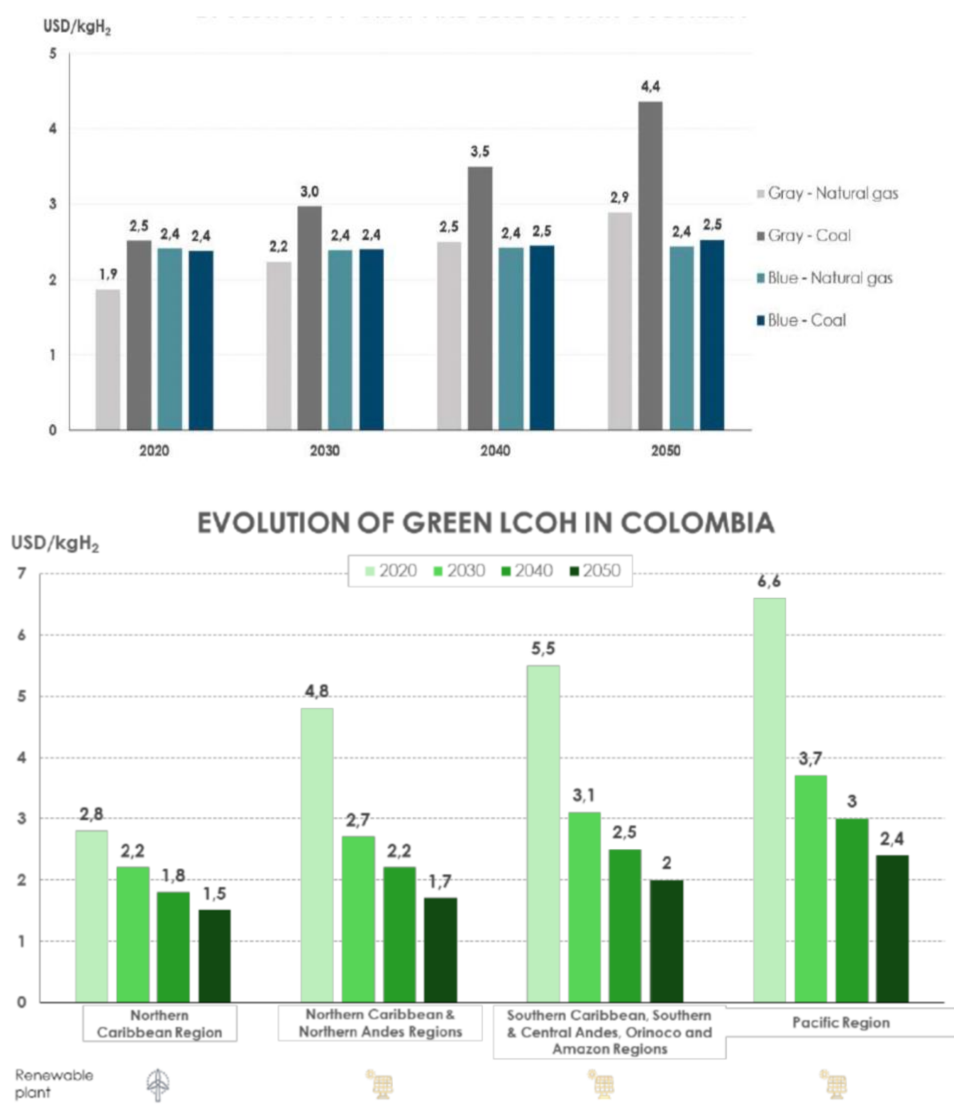


Figure 34. a) Evolution of gray and blue LCOH from natural gas and coal. b) Evolution of green LCOH with renewable mode capacity factor by region (Ministerio de Minas y Energía, 2021).

According to Colombia's hydrogen roadmap (Ministerio de Minas y Energía, 2021), it is expected that 40% of the total hydrogen demand by 2050 (i.e., 740 kt of hydrogen) would be used to supply the production of low-carbon derivatives, such as ammonia and aviation fuel.

The industrial center of Mamonal in Cartagena has hydrogen demand industries as presented in Table . In addition, it has a consolidated gas infrastructure, close to coal extraction, and areas with high potential for solar and wind energy production, sufficient water supply, as well as a potential viable cluster for CCS (Castañeda et al., 2022; E. Yáñez et al., 2020). The existing hydrogen demand of REFICAR can be supplied by green hydrogen produced through current commercial electrolyzers (Castañeda et al., 2022).

Table 12. Potential companies demanding hydrogen and its uses in Cartagena (Castañeda et al., 2022).

Company	Sector	Potential use of H_2
Ecopetrol	Oil & Gas	CCUS
Cartagena refinery	Petroleum refinery	Heat and refining
Argos S.A.	Cement	Heat
Essentia S.A.	Plastics	Heat
Resinas Mexichem Colombia	Plastics	Heat
Yara Colombia	Fertilizers	Catalyst
Cotecmar	Shipbuilding	Heat
Cabot Colombiano	Oil and coal products	Heat
Polybol SAS	Plastics	Heat
Nouvelle Colombia UE	Plastics	Heat
Inversiones Cascabel	Metals	Catalyst and Heat

2.3. Agriculture

Table 13 shows the land classification based on land suitability and recommended use, and Figure 35 illustrates the land suitability in Colombia. The principal classifications are forestry (56.2%), agroforestry (17.7%), and agriculture (13.2%). Notably, the agroforestry and silvopasture subcategories can increase the agriculture and livestock areas up to 19.3% and 13.3%, respectively. The 2012 land surfaces and use map shows that approximately 30% of the land is used for livestock and 4.7-7% for agriculture. Thus, the agricultural sector uses at most 24% of the suitable land (Delgado et al., 2019; Parra-Peña et al., 2021).

Table 13. Land classification according to land suitability and recommended use (Delgado et al., 2019).

Suitability	Main recommended use	Area (ha)	%
Agriculture	Intensive rotation crops	2,019,299	1.8
	Semi-intensive rotation crop	6,797,790	6.0
	Intensive permanent crop	1,720,509	1.5
	Semi-intensive permanent crop	4,478,330	3.9
	Total agriculture	**15,015,927**	**13.2**
Agroforestry	Agroforestry	7,061,698	6.2
	Agro-silvo-pasture	4,057,776	3.6
	Silvopasture	9,101,192	8
	Total agroforestry	**20,220,666**	**17.7**
Livestock	Intensive grazing	64,157	0.1
	Semi-intensive grazing	1,560,588	1.4
	Extensive grazing	4,466,801	3.9
	Total livestock	**6,091,546**	**5.3**
Forestry	Forestry production	3,916,806	3.4
	Forestry protection-production	44,428,762	38.9
	Forestry protection	15,858,726	13.9
	Total forestry	**64,204,294**	**56.2**
Conservation/ Recovery	Conservation of water resources	4,717,083	4.1
	Conservation and recovery	1,586,421	1.4
	Total conservation and recovery	**6,303,503**	**5.5**
Others		2,339,863	2
Total		**114,174,800**	**100**

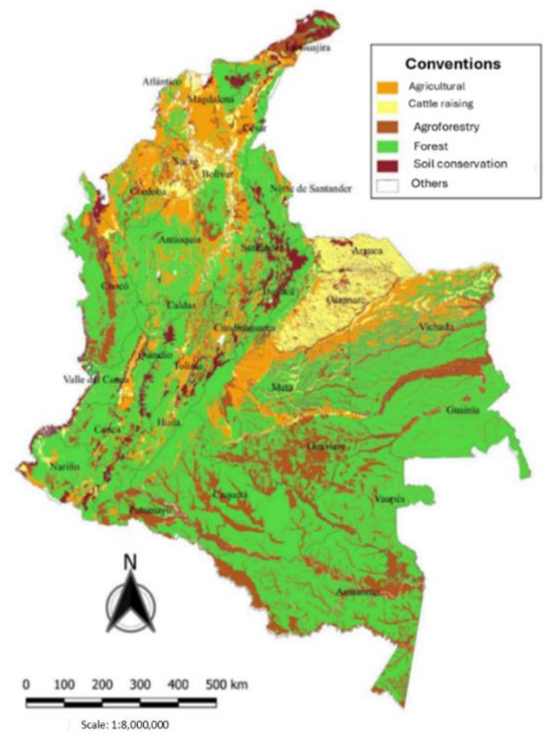
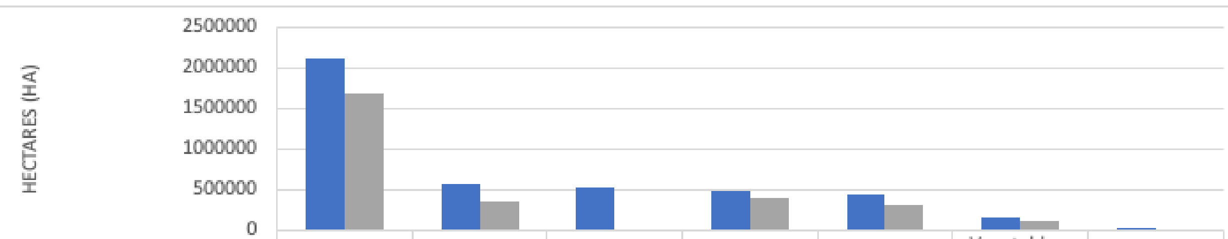


Figure 35. Map of land classification according to land suitability and recommended use (Delgado et al., 2019).

The Colombian agricultural sector mainly comprises small producers. However, the land distribution shows high rural property concentration (Parra-Peña et al., 2021). The agricultural production unit (UPA) is the area that produces farming, forestry, livestock, or aquaculture goods; is owned by a single producer (person or company); and uses at least one means of production (DANE, 2014). According to the 2014 National Agricultural Census, 70.4% of UPAs had less than 5 ha, 55.3% of which had less than 1 ha (DANE, 2014). Some UPAs belong to associative schemes (14.7%), such as coops (35.9%), producer associations (30.4%), community organizations (29.4%), research centers (9%), or federations (2.4%). Further, 9% of the census area belongs to UPAs with less than 10 ha, 27% to UPAs between 10 and 100 ha, and 65% to UPAs with more than 100 ha.

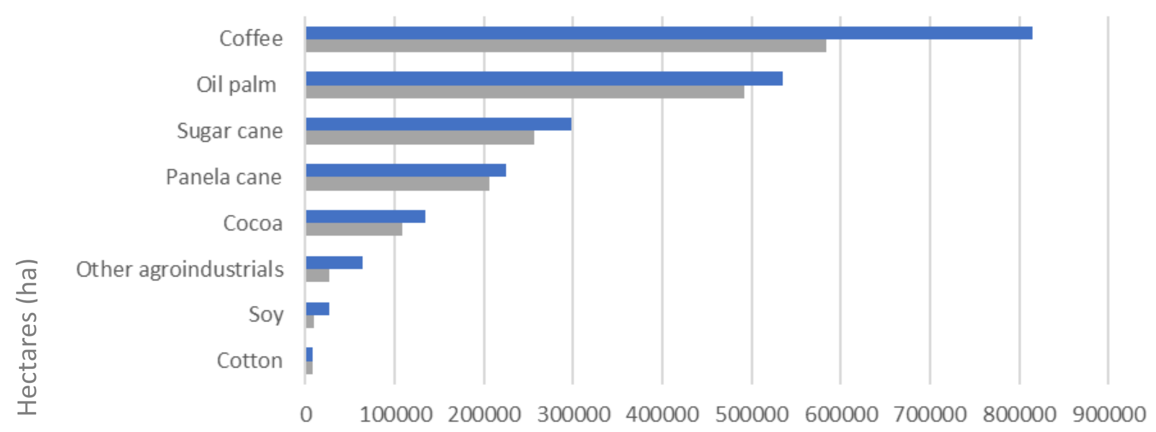
In the first semester of 2019, the total planted area was approximately 4,329,016 ha. Only some of the cultivated area was available for harvesting or in production age due to the normal development of the crop or the establishment of new areas (Figure 36) (DANE, 2020a). The agro-industrial sector represented 48.7% of the planted area, distantly followed by cereals (13.4%), forest plantations (12.2%), tubers and plantains (11.2%), and fruit trees (10.2%).

Within the agro-industrial sector, the most prominent participants of planted areas are coffee (38.7%), oil palm (25.4%), and sugar cane (14.2%). Other crops are panela cane, cocoa, soy, cotton, rubber, and tobacco (Figure 37). The main planted crops in the cereal group are mechanized rice (60.7%), yellow corn (28.3%), and white corn (8.4%). Among the tubers and plantain group, the largest by planted area are plantains (65.0%), followed by cassava (16.3%), and potatoes (15.4%). The fruit trees group has the widest variety; however, bananas and avocados stand out with 22.7% and 19.4% of the planted area, respectively (DANE, 2020a). Permanent crops include avocado, banana, cocoa, coffee, sugar and panela cane, oil palm, and plantain. In contrast, the others are considered transitory crops.



	Agro-industrial	Cereals	Forest plantations	Tubers and plantain	Fruit trees	Vegetables, greens, and legumes	Others
Planted	2108128	580986	529400	486295	441267	146318	36622
Harvested/Productive age	1690861	349844		389658	319672	109825	

Figure 36. Total area planted, and area harvested or in productive age by groups of crops in the first semester of 2019 (DANE, 2020a).



	Cotton	Soy	Other agroindustrials	Cocoa	Panela cane	Sugar cane	Oil palm	Coffee
Planted	8142	26842	64676	134575	225064	298357	535280	815192
Harvested/Productive age	7484	10097	27435	108234	205614	255818	492057	584122

Figure 37. Total area planted, and area harvested or in productive age of the group of agro-industrial crops (DANE, 2020a).

According to the 2014 national agricultural census and Fedesarrollo (Table 14) (Delgado et al., 2019), the Andean region uses 58% of the land with agricultural potential and 30% is used for livestock, around eight times more of the land suitable for ranching. The Caribbean zone has a large area for ranching. It uses only 19% of the land suitable for agriculture, despite having the largest proportion of land for this purpose, favorable road infrastructure, and proximity to ports. The Pacific is the region with the greatest coincidence between its use and suitability. Orinoquia has the second largest area with agriculture suitability, but its use for this purpose is only approximately 14%. In the Amazon region, forestry use surpasses its suitability.

Table 14. Land classification by region in percentage (Delgado et al., 2019).

Land Classification	**Andean**	**Pacific**	**Caribbean**	**Orinoquia**	**Amazon**	**Total**
Forestry	58.1	61.8	32.3	38.1	63.3	53.0
Agroforestry	7.6	19.0	13.6	16.7	33.5	21.0
Agriculture	22.2	7.1	37.7	20.3	0.4	13.8
Livestock	1.6	2.6	11.0	19.8	0.1	6.5
Conservation	8.1	8.1	3.4	4.9	0.1	4.0
Other	1.4	1.4	2.5	0.2	2.6	1.7

Using the information from the agricultural sector in 2006 as a base, the biomass atlas (UPME et al., 2011) shows the annual production of residues, gross energy potential, and net energy yield for eight crops: rice, corn, banana, coffee, sugar and panela cane, oil palm, and plantain. These crops remain relevant in the country; however, production areas have varied. Figure 38. a. shows the annual agricultural residues from the eight crops, identifying the areas in Magdalena, Urabá, and Valle del Cauca for their high annual residues production. Coffee, banana, and plantain have a humidity of approximately 94%, considerably reducing the energy potential in regions such as Urabá (Figure 38.b.)(UPME et al., 2011).

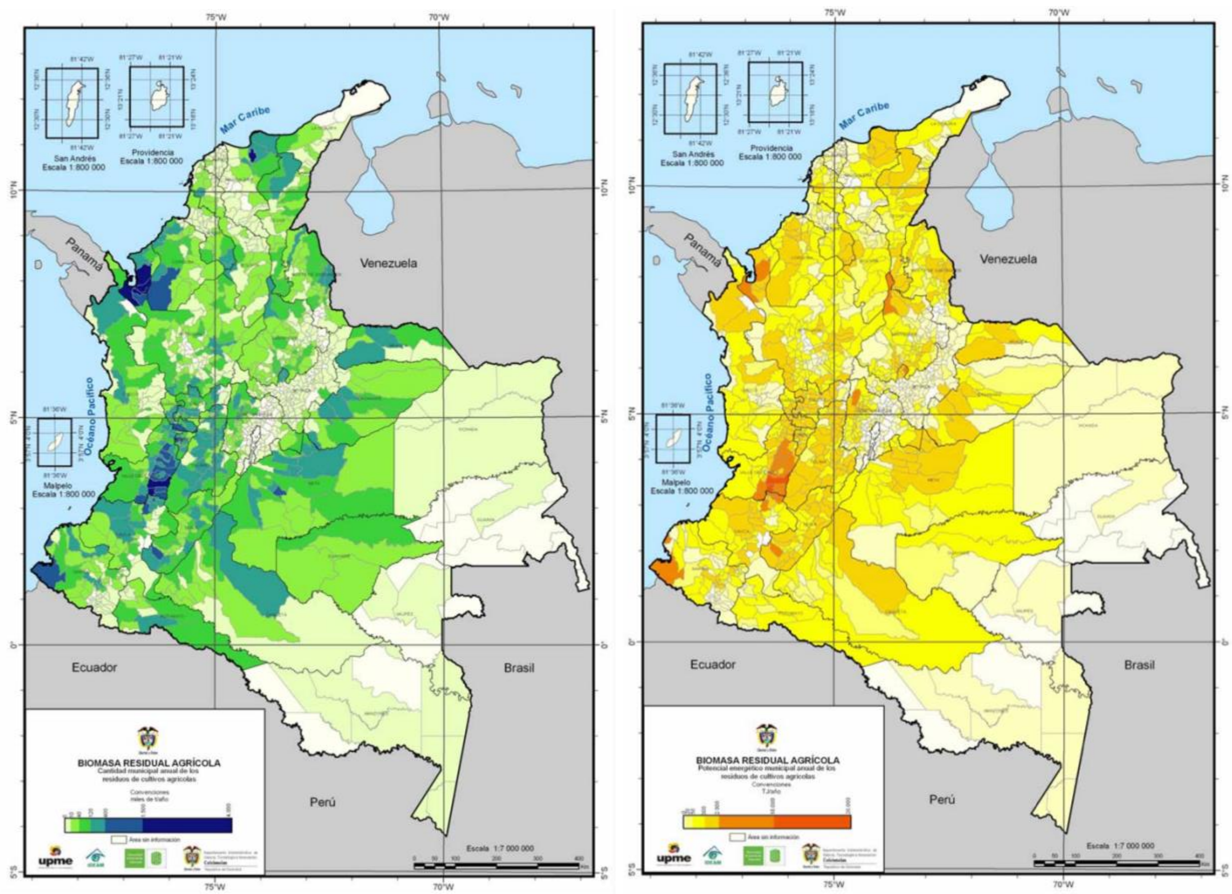


Figure 38. a) Agricultural residues in thousand ton per year. b) Energy potential of agricultural residues in TJ per year (UPME et al., 2011).

2.3.1. Permanent crops

2.3.1.1 Coffee

In 2020, coffee production was 863,317.07 tons (Agronet, 2021), where 9.5% of the harvested grain weight from coffee crops is used as a raw material for industrial purposes and the remainder is discarded (Duarte et al., 2014). Furthermore, the crop must be renewed every four years by cutting the coffee tree 15 - 20 cm above the soil, which transforms it into a residue that is used as a natural fertilizer, or power source for the ovens and stoves on farm (Duarte et al., 2014). Table 15 shows the waste type, waste rate (tons per tons of main product), waste calculated for 2020 coffee production, and energy potential of coffee residual biomass (Escalante Hernández et al., 2010).

Table 15. Coffee waste for 2020 coffee production, waste rate, waste type, and energy potential of coffee residual biomass.

Harvest	Waste	Waste rate[1] (t waste/t main product)	Waste[2] (Mton/year 2020)	Energy potential[3] (TJ/year)
Coffee	Pulp	2.13	1.84	6,602.04
	Husk	0.21	0.18	3,058.42
	Stem	3.02	2.61	35,325.68

[1] (Escalante Hernández et al., 2010).
[2] Waste was calculated considering the coffee production in 2020 multiply by waste rate.
[3] The energy potential was calculated considering the biomass waste for 2020 and the rate of energy potential showed in (Escalante Hernández et al., 2010).

Colombia produces approximately 2.3 tons/ha/year of coffee pulp, and 768 kg/ha/year of coffee mucilage used for animal feed, mushroom substrate, compost, and biogas at the farm scale (Rodríguez Valencia, 2011; Ruiz-Colorado et al., 2014). The coffee mucilage is generated in the demucilage stage; on a wet basis, it represents approximately 15% of the weight of the fresh fruit (Ruiz-Colorado et al., 2014). A portion of the coffee husk is used for co- and auto-generation (DANE, 2020b). The coffee stems from the practice of *zoqueo* (renovation of coffee plantations) are generated close to 0.6 kg/kg of processed cherry coffee (Ruiz-Colorado et al., 2014).

2.3.1.2 Palm oil

Colombia is the fourth largest producer of palm oil in the world, and the largest in the Americas (Peña González et al., 2021). Oil palm cultivation has a productive presence in approximately 70% of the country (155 municipalities in 21 departments) (Fedepalma, 2022b). In 2021, Colombia had 595,722 ha of oil palm, which represent 7% of the total cultivated area in the country (Fedepalma, 2023). The cultivated area is split into four zones: west (47%), central (31%), north (19%), and southwestern (4%) (Fedepalma, 2022a). Figure 39 shows the main producer zones of palm oil (Ministerio de Agricultura y Desarrollo Rural, 2020). The west zone grew approximately 26% between 2017-2021, being the zone with the most considerable growth.

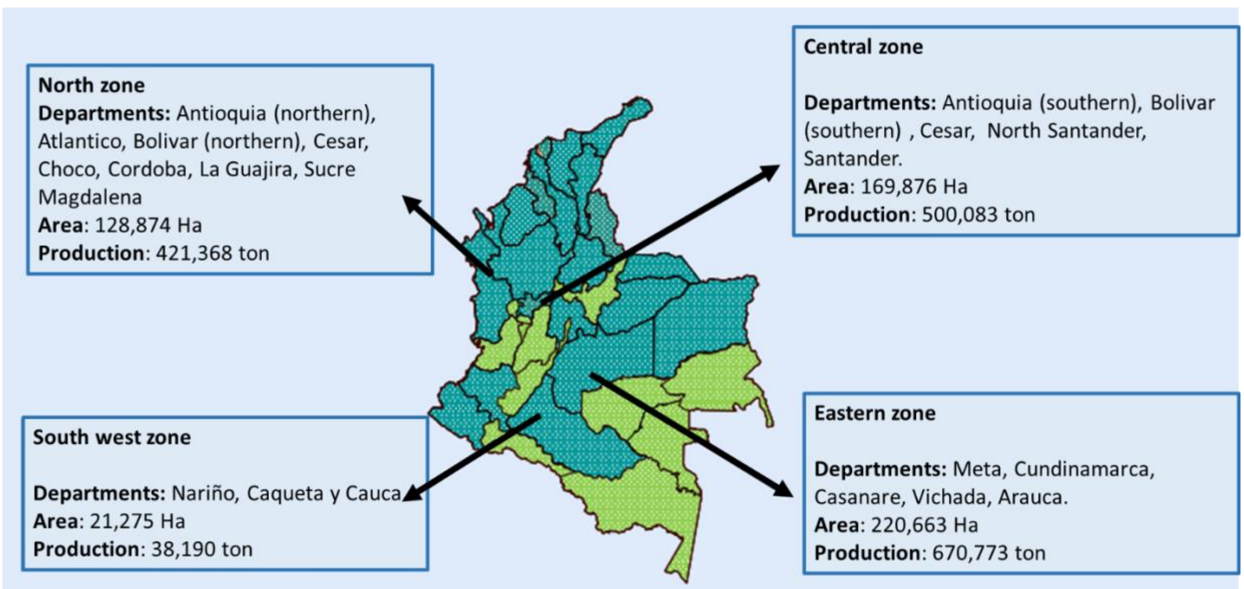


Figure 39. Main producer zones of palm oil (Ministerio de Agricultura y Desarrollo Rural, 2020).

The fresh fruit bunches (FFB) of palm oil are processed to obtain oil and almonds. These products represent 21% and 5% by weight of the FFB, respectively. In 2021, 1,747,377 tons of crude palm oil (3.5-ton crude oil/ha on average) and 122,915 tons of palm kernel oil were produced, commercializing 71.1% of the crude palm oil in the domestic market (Fedepalma, 2022a). Biodiesel consumed 558,174 tons (32.8%). Brazil (20.2%), the Netherlands (13.9%), Spain (11.9%), Italy (11.2%), and Mexico (10.6%) are the leading destinations for exports. These countries have free access conditions for Colombian palm oils due to the free trade (FTA) and MERCOSUR agreements (Fedepalma, 2022a).

Approximately 41% weight of FFB biomass is generated during the extraction process. In the renewal of oil palm cultivation, approximately 75 t/ha of dry biomass is produced. The total production of dry matter of leaves, stems, and bunches is approximately of the order of 20-30 t/ha-year, which represents 96% of the total accumulation of biomass by the palm. The leaves provide 56% of the total dry matter, resulting in approximately 11-16 t/ha of organic matter into the soil when degraded in the field (García et al., 2010).

Fiber and biomethane are used for co- and auto-generation. Depending on the plant's needs and efficiency of the boilers, the shells are used as fuel or sold. Since 2018, eight (out of 70) plants have closed ponds (Fedepalma, 2022a). In 2018, 87 kW was auto generated and 259 kW co-generated (DANE, 2020b). Empty fruit bunches, fiber and shell surplus, and pond sediments partially replace traditional fertilizers through direct application to the soil. By late 2021, 25 plants had composting systems (Fedepalma, 2022a). Table 16 shows the total biomass produced and estimated quantity potential in Colombia for other uses. Fiber is the by-product that is most used in processing plants, especially as fuel in boilers, leaving a residue of 1.57%/FFB (44,953 tons/year) available for other uses. The empty fruit bunch is one of the by-products with the highest production per processed fruit generated, of which 17.36% (496,225 tons) is available for use in other alternatives. Table 17shows the uses of the residual biomass generated in palm fruit processing plants.

Table 16. Total biomass produced and estimated quantity potential in Colombia for other uses.

Processed fruit	**Produced biomass**			**Potential biomass**	
(ton)	**Biomass**	**%/FFB**	**Mass (ton)**	**%/FFB**	**Mass (ton)**
2,858,868.00	Empty fruit bunch	20.94	598,758.00	17.36	496,225.00
	Fiber	13.02	369,745.00	1.57	44,953.00
	Palm shell	5.35	152,988.00	3.07	87,719.00

Table 17. Uses of the residual biomass generated in palm fruit processing plants (García et al., 2010).

Central, Northern and Eastern Zone			%/FFB
% total utilization	Palm shell	Road	0.40
		Sale	0.86
		Compost	0.26
		Boiler	3.58
	Fiber	Press	0.24
		Boiler	10.5
		Field	1.78
		Compost	0.75
	Empty fruit bunch	Boiler	0.41
		Field	17.36
		Compost	3.07
		Bedding for pigs	0.10

2.3.1.3 Sugar and panela cane

The primary sugarcane production is in Valle del Cauca and Cauca, while panela cane production is highly dispersed (29 departments) (DANE, 2014; Fedepanela, 2022). In 2021, the planted area of sugarcane was 244,644 ha (yield of 120 ton/ha), of which 69.7% was harvested with productivity of 13.6 tons of sugarcane/ha (Asocaña, 2022; Canabarro et al., 2023). For the same year, 206,785 ha of panela cane were planted and 171,190 ha harvested, with an average yield of 6.26 tons/ha of panela (Fedepanela, 2022). While in Valle del Causa and Cauca, sugarcane mills and ethanol distilleries are able to produce almost year-around, in the Meta Department, climate conditions only allow sugarcane harvesting during eight months per year (USDA Foreign Agricultural Service & Global Agricultural Information Network, 2022).

Sugarcane is harvested from 12 to 24 months (Yara Colombia, 2023). The green top or sugarcane tops are usually cut, and the stem is sent to the sugar mills. From the harvest to the final processing, there are four main sugarcane wastes produced: (i) sugarcane bagasse, (ii) dry leaves and sugarcane tops, (iii) sugarcane press mud, and (iv) molasses (Singh et al., 2021).

Agricultural sugarcane cut residues, or RAC, are leaves, tops, and roots that remain after removing the stem during the sugarcane harvest. During this process, 0.25-ton RAC is obtained for every ton of cane cultivated. RAC is used in a proportion close to 50% to adapt the soil where the sugar cane is planted again (CENICAÑA, 2022). The rest of the cut waste is discarded because of its low density (70-100 kg/m^3), which makes the transportation costs to the mill boilers or the thermal energy generation plants very high (Agencia de Noticias Univalle, 2020).

The sector produced 2,099,941 tons of sugar (80.7% domestic consumption), 170,991 tons of molasses, 396,795 thousand liters of ethanol, and 1,825 GWh of electricity (Asocaña, 2022). The area planted with sugarcane increased by 7.3% between 2012 and 2022 (Asocaña, 2022). Bagasse is widely used for co-generation, auto-generation, and paper and cardboard production (Figure 14). In Colombia, bagasse is the third largest source (12.42%) of feedstock for the paper and paperboard industry after recycling (60.81%) and forestry (26.7%) (ANDI, 2018). Vinasses, molasses, ashes, and crop residues from the sugarcane industry are used in compost and other nitrogen-enriched organic fertilizers, which partially replace the use of traditional fertilizers (Asocaña, 2010). Table 18 shows the waste, waste rate in tons per tons of main product, and energy potential of sugarcane and panela cane.

Table 18. Waste rate from oil palm, sugarcane, and panela cane (Escalante Hernández et al., 2010).

Harvest	**Waste**	**Waste rate (t waste/t main product)**	**Energy potential (TJ/year)**
Sugarcane	Leaves - top	3.26	41,707.22
	Bagasse	2.68	76,871.65
Panela cane	Leaves - top	3.75	18,749.01
	Bagasse	2.53	62,305.56

2.3.1.4 Cacao

In 2020, Colombia ranked tenth in the world in annual cocoa production. In 2021, Colombia produced 65,174 MT of cocoa with a planted area of 194,428 ha. The main region for cocoa production in Colombia is Santander at 41.7% of national production. Other regions include

Antioquia, Arauca, Huila, Nariño, and Tolima (Figure 40). Colombia harvests cacao year-round, with the production year starting in October and ending in September of the next calendar year. Broadly, there are two cacao harvest seasons: the main one (called "Principal") runs from October to January, and the minor one (called "Mitaca") runs from May to June. Most producers are smallholder farmers who farm an average of three hectares of cacao (FAS Bogota, 2022).

Region	Cocoa production (MT) in 2020	Total cocoa production in 2020
1.Santander	26,315	41.7%
2.Antioquia	5,947	9.5%
3. Arauca	5.082	8.1%
4. Tolima	4,312	6.8%
5. Huila	4,197	6.7%
6. Nariño	2,980	4.7%
7. Meta	1,949	3.1%
8. Cesar	1,543	2.4%
Other regions	4,722	17%
Total	57,074	100%

Figure 40. Main Colombian cocoa producing departments (FAS Bogota, 2022).

From 2014 to 2021, Colombia increased cocoa production by 36.5%, as shown in Figure 41. During the same period, Colombia increased growing area by 21.3% to 194,428 ha. In total, 12.8 million ha is available with medium or high aptitude for commercial cacao growing. The cost of planting one cacao hectare under an agroforestry system (i.e., cacao as a short-term crop and timber trees as long term) is approximately USD 3,252, with 53% of the total cost going into inputs including seeds and or plantlets, 41% into labor, and 6% into tools and equipment (FAS Bogota, 2022). The price Colombian farmers are paid for cocoa varies depending on the market; however, the gap between the national and international market has reduced. The price has remained stable since 2018 at above USD 2 per kg (Figure 42) (FAS Bogota, 2022).

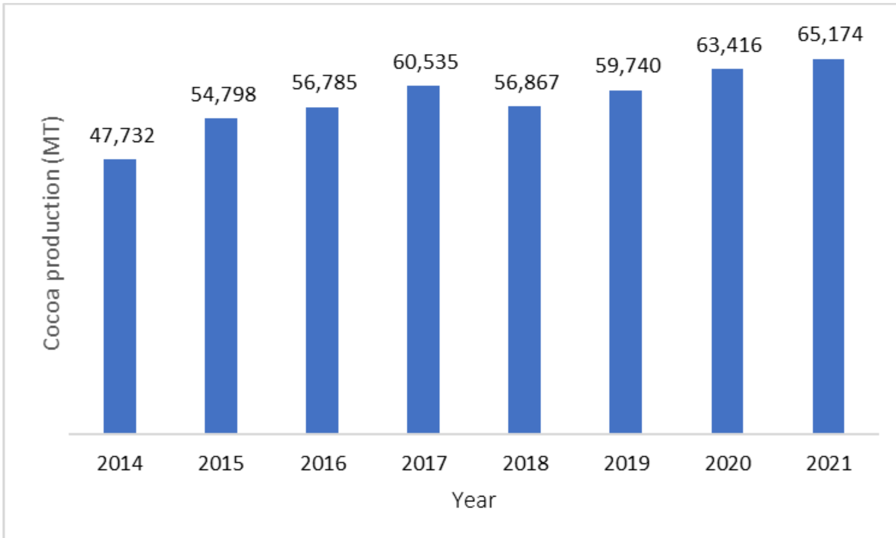


Figure 41. Colombian cocoa production, 2014–2021 (MT) (FAS Bogota, 2022).

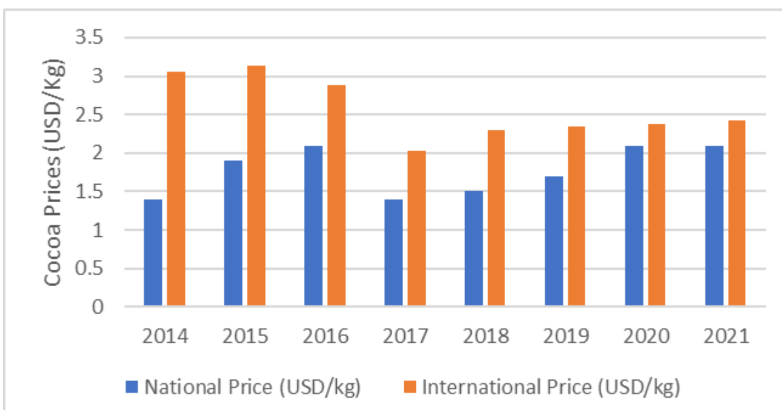


Figure 42. Cocoa prices (USD/kg), national price paid to farmer versus international price (FAS Bogota, 2022).

The cacao supply chain includes producers, commercialization, processing, and chocolate manufacturing. Around half of the cacao manufactured is for drinking chocolate preparation, sale on the domestic market (Abbott et al., 2018). Small and medium producer farms produce 95% of the cacao. According to Abbott et al. (2018), farmers deliver or arrange transport of dried and fermented cacao to aggregation points. Some small producers, especially in remote areas, rely on agents to sell their cacao. The aggregation centers are either independently owned buying centers or facilities belonging to producer groups. Two firms, Casa Luker and Nutresa, purchase between 80-90% of cacao production. Contracts are not used, although agreements to purchase may be in place. The firms buy between 30-55% of the cacao directly from farmers' organizations and the rest from independent buyers who are typically affiliated with one of the two firms. The cacao is transported via truck to regionally located company warehouses and transported to factories in urban areas when needed. Fedecaco has begun to purchase cacao from farmers and producer groups for exporting.

The Colombian armed conflict has affected virtually all the potential cacao-producing regions of the country (Abbott et al., 2018). According to 2015 data, 46.1% of the area planted with cacao was in conflict areas (Table 19), having a lower average yield than the non-conflict areas and Santander (department not included due to its ambiguous conflict situation). This affects the technical assistance and marketing channels, especially for smallholder farmers (Abbott et al., 2018).

Table 19. Comparing cacao area planted, production, and yield by conflict/non-conflict areas, and Santander (Abbott et al., 2018).

Zone	Item	Area planted (ha)	Production (MT)	Yield (kg/ha)
Non-Conflict Areas	Quantity	37,505	13,651	364
	Share	22.7%	24.9%	
Conflict Areas	Quantity	76,001	18,720	246
	Share	46.1%	34.2%	
Santander	Quantity	51,500	22,424	435
	Share	31.2%	40.9%	

In 2021, Colombia exported 11,689 tons of dry cocoa beans and 14,647 tons of derivatives or transformed product (Fedecacao, 2022) to at least 70 countries. The country is a major exporter of cocoa related products such as cocoa butter, cocoa paste, chocolate, and cocoa powder. However, cocoa related products exports increased by just 1% from 2011 to 2021 in volume terms. Meanwhile, cacao bean exports increased by 400% in volume terms during the same period (FAS Bogota, 2022).

2.3.1.4.2 Cacao waste

At present, the cocoa industry has concentrated on the processing of almonds, which is the seed of this fruit and almost 80% of the output is not used efficiently. Traditionally, the seeds are used to produce powder, liquor, butter, and cocoa coating. The other parts, such as the cob, mucilage and husk, are wasted throughout the entire production chain (Lozano Moreno, 2020). The husk is mainly discarded; in some cases, it is used to feed livestock. The placenta is removed and discarded in the process prior to drying. Finally, there is the pod and cocoa that, as seen in Figure 43, makes up the largest part of the cocoa fruit (Lozano Moreno, 2020). With the Colombian production of cocoa beans of 62,158 ton in 2022 (Federación Nacional de Cacaoteros, 2023), this indicates 49,726.4 ton of waste from the cocoa fruit.

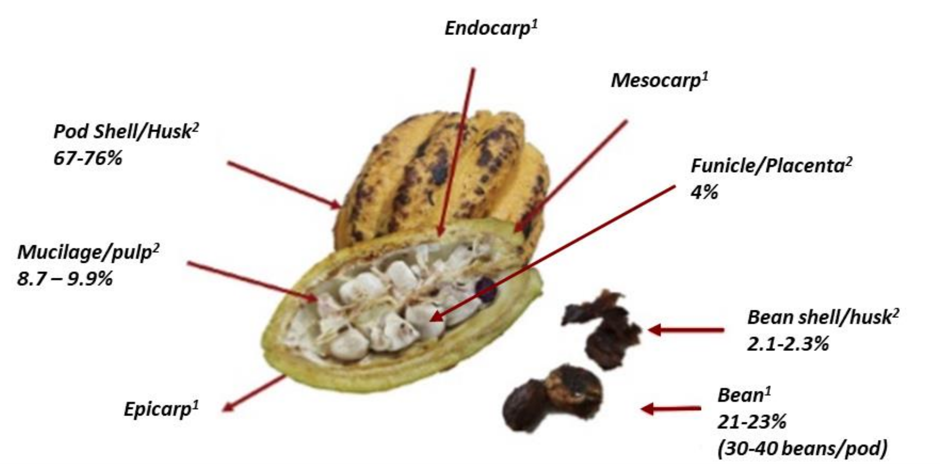


Figure 43. The cocoa fruit's structure[1] and waste[2] (Campos-Vega et al., 2018; Lozano Moreno, 2020).

2.3.1.5 Banana and plantain industry

Colombia is considered an important producer and exporter of bananas worldwide (Quintero et al., 2022). In 2019, a total of 51,227 ha was planted in Colombia. In 2019, banana production reached 2.1 million tons, of which 1.8 million tons were allocated for export and 300,000 tons for national consumption (Quintero et al., 2022).

In Antioquia and Magdalena, 46,752 ha are cultivated. This area represents more than 80% of the national production (Ruiz-Colorado et al., 2014). Banana rachis and stem residues amount to 11,269,162 ton/year, or 20% of the total residual mass (Escalante Hernández et al., 2010). Meanwhile, 40% of the banana residues that remain in the field are considered cover and organic matter for soil maintenance (Ruiz-Colorado et al., 2014).

In Colombia, the most cultivated plantain varieties are Dominico-Hartón, Hartón, Dominico, and Africa. They are mainly cultivated in the departments of Caldas, Quindío, and Risaralda, demonstrating a good adaptation to their agroecological conditions (Ruiz-Colorado et al., 2014). The plantain crop is cut off with the idea of allowing another crop to grow. This agronomic practice leads to substantial waste being discarded near the banks of rivers, streams, and on roads, which causes a significant environmental problem (Ruiz-Colorado et al., 2014). A maximum of 50% can be left in the field for soil amendment, or nutrient recirculation of the banana and plantain harvest residues. Of the remainder, 7% is used for animal feed, 5% for other crop fertilization, and 38% is not used (Meneses et al., 2010).

2.3.2. Rotation crops

Rotation crops (corn and rice) are produced in various region around the country, with considerable variation in the area planted annually (DANE, 2022b; Ministerio de Agricultura y Desarrollo Rural, 2022). Meta, Casanare, Tolima, and Huila are the departments with more area in mechanized rice production, while Cordoba stands out in the production of corn (DANE, 2020b).

2.3.2.1 Rice

In Colombia, rice ranks first among short-cycle crops. Colombia is the second largest rice producing country in Latin America and the Caribbean. Mechanized rice represents 98% of the National production and at least 95% of the total area planted in the country. This area is between 400 to 500 thousand hectares planted per year. Rice is planted in two systems: dry with an average production of 4.7 ton/ha; and irrigation with production reaching up to 6.5 ton/ha. Total national production reached 2.2 million tons (Agro Bayer Colombia, 2022).

Colombia has approximately 490,000 ha for sowed rice with a yield of 5.8 tons/ha (Ruiz-Colorado et al., 2014). Approximately 400,000 ton of rice husk are produced annually to be used in other agricultural and industrial sectors (DANE, 2020b). Although part of the husk is marketed for use in stables, poultry farming, and gardening, this market does not have the capacity to consume all the available biomass. The amount of husk consumed in these uses is not known; still, estimates a priori establish that it is not more than 5% of the total husk produced. The largest use is controlled semi-burning in the open air, which guarantees the commercialization of the final product (semi-burned husk) used as a substrate in flower crops (Ruiz-Colorado et al., 2014). Table 20 shows the waste rate and its energy potential in 2010 (Escalante Hernández et al., 2010).

Table 20. Waste rate from rice harvest (Escalante Hernández et al., 2010).

Harvest	Waste	Waste rate (t waste/t main product)	Energy potential (TJ/year)
Rice	Straw	2.35	20,699.41
	Husk	0.20	7,136.53

2.3.2.2 Corn

Colombia harvests yellow and white corn, mechanized or traditional. In 2022, 1,921,177 tons of corn were produced (yellow and white) and 462,625 ha was harvested in total. Meta Piedemonte had the major yield of corn harvest per ha (6.98 ton/ha). Table 21 shows the harvest area and total of corn production by department in 2022 (Fenalce, 2022). Table 22 shows the corn crop waste, waste rate, and energy potential (Escalante Hernández et al., 2010).

Table 21. Total corn production and harvest area in 2022 (Fenalce, 2022).

Department	Area (ha)	Production (ton)	Yield (ton/ha)
Antioquia	22,320	41,698	2.84
Atlantico	3,135	10,167	3.30
Bolivar	54,350	133,780	3.60
Boyaca	11,530	26,585	2.32
Caldas	1,842	10,815	4.63
Casanare	3,500	17,640	3.60
North Cesar	16,420	38,356	3.40
South Cesar	15,800	64,520	3.69
Cordoba	43,492	196,901	3.58
Cundinamarca	22,300	53,900	2.75
Huila	38,850	125,625	3.60
La Guajira	16,980	38,727	3.41
Meta Altillanura	53,271	359,979	6.64
Meta Piedemonte	21,800	151,270	6.94
Nariño	12,482	30,196	3.17
Putumayo	2,150	4,604	2.15
Quindio	1,590	9,722	4.76
Risaralda	2,124	15,172	5.25
Santander	19,700	90,810	3.87
Sucre	46,976	133,038	2.81
Tolima	34,704	235,704	6.83
Valle del Cauca	17,309	131,969	6.55

Table 22. Waste rate from corn harvest.

Harvest	Waste	Waste rate [1] (t waste/t main product)	Waste [2] (Mton/year 2022)	Energy potential [3] (TJ/year)
Corn	Stover	0.93	1.79	17,457.49
	Cob	0.27	0.52	5,339.89
	Husk (Capacho)	0.20	0.38	6,086.68

[1] Escalante Hernández et al. (2010).

[2] Waste was calculated considering the coffee production in 2022 (Fenalce, 2022) and multiplied by waste rate.

[3] The energy potential was calculated considering the biomass waste for 2022 and the rate of energy potential showed in prior work (Escalante Hernández et al., 2010).

2.3.3. Herbaceous and woody biomass

In Colombia, there are herbaceous and woody biomasses with different species in each region (Table 23) which differs in yield and density. However, there is a deficit of commercial forest plantations for wood production to satisfy the national demand (PROFOR, 2017b). Due to the long distances from the transformation centers and low prices of wood, few commercial forest plantations in Colombia are subject to management that includes thinning practices. Hence, the volumes of wood available from these practices are very limited (PROFOR, 2017a). The volume of forest residues throughout the country is estimated at 0.6 million m³ (20% of the volume of harvested standing timber), which is sold in local markets, or is left in situ in or near the plantations (PROFOR, 2017a).

Table 23. Commercial species established in some regions of Colombia (Ruiz-Colorado et al., 2014).

Species	Shifts (Optimal time for the use of the plantation)	Density (g/cm^3)	Yield (m^3/ha*year)	Location
Alnus jorullensis	20	0.40 – 0.60	10-20	Antioquia, Boyacá, Caldas, Risaralda, and Cundinamarca
Cedrela odorata	18-25	0.44	11-22	Antioquia, Caquetá, Cauca, and Valle del Cauca
Cordia alliodora	20-30	0.46	5-20	Antioquia
Eucalyptus camaldulensis	6-8	0.815	20-35	Antioquia, Cauca, and Valle del Cauca
Eucalyptus globulus	10-15	0.70	15-20	Antioquia, Boyacá, Caldas, Nariño, and Cundinamarca
Eucalyptus grandis	6-8	0.45	25	Antioquia, Cauca, and Valle del Cauca
Eucalyptus tereticornis	6-8	0.66 - 1.06	18	Antioquia, Casanare, and Valle del Cauca y Vichada
Pinus patula	30	0.43	27	Antioquia, Cauca, Santanderes, Cundinamarca, and Valle del Cauca
Pinus radiata	20-25	0.39	10-25	Cundinamarca

2.3.4. Wastes

In 2020, 32,580 tons/day of solid waste were disposed of, increasing 0.89% compared to 2019. Of this, 96.6% were disposed of in landfills (Secretaria distrital de Ambiente, 2022). The eight cities of Bogotá, Medellín, Cali, Barranquilla, Cartagena, Cúcuta, Soacha, and Soledad, accounted for 45.23% of the solid waste (Ministerio de ambiente y desarrollo sostenible, 2022).

2.3.4.1. Final waste disposal systems

In Colombia, the systems for the final disposal of waste are classified into authorized and unauthorized systems. Authorized systems are landfills and contingency cells (Superintendencia de Servicios Públicos Domiciliarios, 2021). These have the environmental permits corresponding to the environmental license (Sector Ambiente y Desarrollo Sostenible, 2015), Environmental Management Plan (Ley General Ambiental de Colombia, 1993), or administrative act through which the operation of the site is allowed. Meanwhile, the unauthorized systems are transitory cell and open-air dumps. Figure 44 shows the types of final disposal sites nationally. Table 24 shows the ratio of tons disposed versus the useful life of the disposal site. Authorized systems received 11,465,555.37 ton/year of waste, while 135,293.84 ton/year of waste were disposed in unauthorized systems (Superintendencia de Servicios Públicos Domiciliarios, 2021).

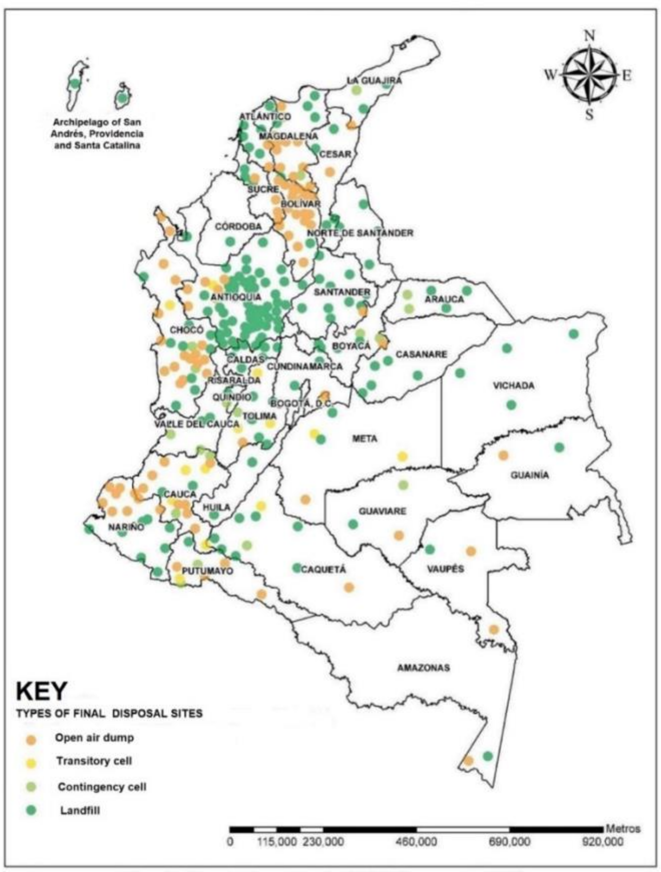


Figure 44. Types of final disposal sites (Superintendencia de Servicios Públicos Domiciliarios, 2021).

Table 24. Ratio of tons disposed versus the useful life of the disposal site (Superintendencia de Servicios Públicos Domiciliarios, 2021).

Time	ton/year	Percentage
Permit expired	397,520.90	3.43%
0-3 years	585,513.03	5.05%
3-10 years	6,358,343.13	54.81%
More than 10 years	4,124,141.19	35.55%
No information registred	37.12	0.0003%
Unauthorized system	135,293.84	1.17%
Total	11,600,849.21	100%

Doña Juana landfill receives the municipal solid waste (MSW) of the Bogotá metropolitan area. In 2021, 2,924,997 tons of waste were disposed in this landfill (Secretaria distrital de Ambiente, 2022). Table 25 shows the characterization of waste disposed in Doña Juana landfill with the percentage of waste composition according to Alcaldía de Bogotá(2012) and total amount of waste generated in 2021 (Secretaria distrital de Ambiente, 2022).

Table 25. Waste characterization in Doña Juana landfill (total/year al final).

N°	Category	Subcategory	Weighted average (%)[1]	Annual waste acceptance rate (ton/year) (2021)[2]
1	Food	Cooked food	8.56	250,379.74
		No-cooked food	52.00	1,520,998.44
2	Garden waste		0.87	25,447.47
3	Paper and cardboard waste		7.10	207,674.79
4	Plastic waste	Polyethylene	6.20	181,349.81
		Polycarbonate	0.04	1,170.00
		Rigid polystyrene	0.34	9,944.99
		Polyvinylchloride	0.04	1,170.00
		Transparent PET	1.33	38,902.46
		Amber PET	0.09	2,632.50
		Green PET	0.07	2,047.50
		Rigid polypropylene	0.31	9,067.49
		High density polyethylene	0.70	20,474.98
		Flexible polypropylene	0.87	25,447.47
		Styrofoam	0.30	8,774.99
		Others	0.16	4,680.00
5	Rubber and leather waste		0.42	12,284.99
6	Textile waste		1.89	55,282.44

7	Wood waste		0.32	9,359.99
8	Metallic waste	Ferrous	0.67	19,597.48
		Aluminum	0.14	4,095.00
		Lead	0.02	585.00
		Copper	0.02	585.00
		Others	0.00	0.00
9	Glass waste	Amber	0.22	6,434.99
		Transparent	1.46	42,704.96
		Green and colored	0.40	11,699.99
10	Ceramic production wastes, ash, rocks and debris		1.19	34,807.46
11	Domestic generation hazardous waste	Automotive maintenance packaging	0.00	0.00
		Home maintenance and cleaning products	0.28	8,189.99
		Biocides (pesticides and garden items)	0.01	292.50
		Medicines and drugs	0.21	6,142.49
		Hygienic and sanitary waste	11.62	339,884.65
		Beauty and personal care products	0.42	12,284.99
		Batteries, electrical and electronic	0.20	5,849.99
		lamps (Bulbs)	0.06	1,755.00
		Other dangerous products	0.14	4,095.00
12	Other waste not included in this listing		1.32	38,609.96

1 Alcaldía de Bogotá (2012)
2 Secretaria distrital de Ambiente (2022)

The Aburra Valley, located in the center-south of the department of Antioquia, hosts a metropolitan area made of ten municipalities: Caldas, La Estrella, Sabaneta, Envigado, Itagüí in the south, Medellín in the center of the valley, and Bello, Copacabana, Girardota and Barbosa in the north (Área Metropolitana del Valle de Aburrá, 2019; Medellín Cómo Vamos, 2021). In 2020, 1,157,163 ton/year of solid waste were generated in this region (Superintendencia de Servicios Públicos Domiciliarios, 2021). Table 26 shows the solid waste distribution in Aburra Valley, where 66.66% of the solid waste is generated by the residential sector, 13.17% commercial, 11.29% industrial, 5.90% institutional, and 2.98% swept.

Table 26. Amount of solid waste generated in the Aburra Valley by sector.

	Solid waste in Aburra Valley	
Sector	**Percentage (%)[1]**	**Aburra Valley waste (ton/year)[2]**
Residential	66.66%	771,365.09
Commercial	13.17%	152,398.41
Industrial	11.29%	130,643.74

Intitutional	5.90%	68,272.64
Swept	2.98%	34,483.47
Total	100.00%	1,157,163.35

[1]Área metropolitana Valle de Aburrá (2020)
[2] Superintendencia de Servicios Públicos Domiciliarios (2021)

Table 27 shows that organic matter (451,793 ton/year) and paper (112,740 ton/year) are the two major solid waste generated by the residential and institutional sectors in the Aburra Valley.

Table 27. Generation by type of waste in residential and industrial sectors in Aburra Valley.

Waste	Residential sector waste		Institutional sector waste	
	Percentage (%)[1]	ton/year[2]	Percentage (%)[1]	ton/year
Organic material	55.11%	425,099.30	39.10%	26,694.60
Paper	12.58%	97,037.73	23.00%	15,702.71
Other	9.34%	72,045.50	8.09%	5,523.26
Plastic	9.04%	69,731.40	17.20%	11,742.89
Glass	3.61%	27,846.28	2.01%	1,372.28
Textiles	3.15%	24,298.00	3.93%	2,683.11
Cardboard	3.13%	24,143.73	1.90%	1,297.18
Hazardous	2.23%	17,201.44	1.93%	1,317.66
Metal	1.20%	9,256.38	1.30%	887.54
Specials	0.51%	3,933.96	1.43%	976.30
Rubber	0.06%	462.82	-	-
Leather	0.03%	231.41	-	-

[1]Área metropolitana Valle de Aburrá (2020)
[2] Superintendencia de Servicios Públicos Domiciliarios (2021)

Table 28 shows the tons of waste per year for other six principal cities in Colombia. However, detailed waste types of generation were not found in the public information.

Table 28. Annual tons disposed – six main cities (Superintendencia de Servicios Públicos Domiciliarios, 2021).

City	Tons of waste/year 2020
Cali	609,433.20
Barranquilla	534,662.89
Cartagena	418,721.53
Bucaramanga	188,230.01
Santa Marta	192,359.59

Pasto	118,561.36

3. Sustainable aviation fuel

SAF refers to renewable or waste-derived liquid fuels that meet technical and safety requirements as laid out in ASTM D7566 and ASTM D1655, with reduced greenhouse gas (GHG) emissions. SAFs are drop-in fuels that are renewable hydrocarbons functionally equivalent and compatible with fossil products (Karatzos et al., 2017). Currently, these fuels can only be used in commercial flights when blended with conventional fuel (International Civil Aviation Organisation, 2018). Fossil-based aviation fuels produced using technologies such as Carbon, Capture, Utilization, and Storage (CCUS) and the use of renewable energy in oil refineries thus have a smaller carbon footprint, and are defined as Lower Carbon Aviation Fuels (LCAF) (ICAO, 2022c).

A key aspect of the production of renewable fuels, specifically for SAF and LCAF, is the demonstration of long-term sustainability of its production. ICAO's Committee on Aviation Environmental Protection (CAEP) defined the sustainability criteria applicable for CORSIA to be considered when defining SAF and LCAF. CORSIA's sustainability criteria include carbon reduction, environmental, and socio-economic themes. Table 29 summarized the themes and criteria applicable for batches of CORSIA-SAF and LCAF.

Table 29. CORSIA sustainability criteria. Adapted from prior work (ICAO, 2022d).

Theme	Criteria
1. Greenhouse gases (GHGs)	Reduction of at least 10% compared to the baseline life cycle emissions for aviation fuel (89 gCO_2/MJ).
2. Carbon stock	Biomass cannot be obtained/extracted from land or aquatic ecosystems with high carbon stocks converted after January 1, 2008. In the event of land used conversion after January 1, 2008, direct land use change (DLUC) will be calculated. The greater value between DLUC and the default indirect land use change (ILUC) value will be use.
3. GHG emission reduction permanence	Implementation of operational practice to monitor, mitigate, and compensate any material incidence of non-permanence from carbon capture and storage activities. For LCAF: implementation of operational practices and financial measures to monitor, mitigate, and compensate any material incidence of GHG emissions resulting from closure and post-closure period of oil ang gas wells.
4. Water	Implementation of operational practices to:

		a. maintain or enhance water quality, b. use water efficiently, and c. avoid depletion of surface or groundwater resources beyond replenishment capacities.
5.	Soil	Implementation of agricultural and forestry best management practices for feedstock production or residue collection to maintain or enhance soil health (e.g., physical, chemical, and biological conditions).
6.	Air	Limited air pollution emissions
7.	Conservation	Areas protected by the state due to biodiversity, conservation value, or ecosystem services cannot be used to obtain biomass unless evidence showing no interference with the protection purposes is provided. Selection of low-invasive risk feedstock for cultivation and appropriate control to prevent uncontrolled spread of cultivated alien species and modified microorganisms. Implementation of operational practices to avoid adverse effects on areas protected by the state due to biodiversity, conservation value, or ecosystem services.
8.	Waste and chemicals	Implementation of operational practices to ensure responsible storage, handling, and disposal of chemicals and operational wastewater. Implementation of responsible and science-based operational practices to limit or reduce pesticide use. Implementation of operational practices to prevent, minimize, and mitigate any damage from unintentional release of fossil resources, fuel products, and/or other chemicals.
9.	Seismic and vibrational impacts	For LCAF: Implementation of operational practices to minimize seismic, acoustic energy and vibrational impacts related to surface, subsurface, and underwater activities.
10.	Human and labor rights	Respect human and labor rights
11.	Land use rights and land use	Respect existing land and land use rights, including indigenous peoples' rights, both formal and informal.
12.	Water use rights	Respect existing water and use rights of local and indigenous communities.
13.	Local and social development	In regions of poverty, strive to improve the socioeconomic conditions of the communities affected by the operation
14.	Food security	In food insecure regions, strive to enhance the local food security of directly affected stakeholders.

SAF production and use has increased in recent years. However, from a production capacity perspective, the industry is still at a nascent stage. The current volumes of SAF are below 0.1% of the EU and United States annual jet fuel consumption (Surgenor, 2021; United States

Government Accountability Office, 2023). Table 30 shows the evolution of SAF production in the United States from 2016 to 2022 compared to the jet fuel consumption by major airlines.

Table 30. Comparison of SAF produced and jet fuel consumed by major United States airlines by year in millions of gallons (United States Government Accountability Office, 2023).

Millions of gallons		
Year	**SAF Produced**	**Jet fuel consumption by major United States airlines**
2016	1.9	17,138
2017	1.7	17,662
2018	1.8	18,325
2019	2.4	18,746
2020	4.6	11,067
2021	5.1	14,617
2022	15.8	17,510

3.1. Drivers

Governments, airlines, and other aviation stakeholders have identified SAF as the most promising technology for the greatest near-term reduction of GHG emissions within the aviation sector (United States Government Accountability Office, 2023).

3.1.1. Domestic drivers

Colombia is responsible for 0.54% of the global GHG emissions (UNDP, 2019). In December 2020, Colombia updated its Nationally Determined Contribution (NDC) and, within the framework of COP 26, its Long-Term Climate Strategy E2050, which together outline the roadmap for climate action in the country to achieve the objectives established in the medium and long term: a 51% reduction in emissions compared to the reference scenario by 2030, and carbon neutrality by 2050 (IDEAM et al., 2021). Renewable energy production and use, electric mobility (road transportation), performance-based navigation (air transport), road cargo transportation modernization, and multimodal transportation are some of the proposed mitigation mechanisms (Gobierno de Colombia, 2020).

The Third Biennial Update Report (BUR3), which contains the National Inventory of Greenhouse Gases in 2018, includes the emissions associated with civil aviation, calculated using the default emission factor for CO_2 proposed by the IPCC 2006 for Landing/Take-off (LTO) cycles (IDEAM et al., 2021). The breakdown of civil aviation emissions into national and international components responds to the emission accounting rules for national inventories, according to which emissions from international activities are estimated and reported but are not added to the national inventory emissions (Pelgrims et al., 2020). According to BUR3 (IDEAM et al., 2021), the total emission of domestic civil aviation in 2018 was 4,107.11 Gg CO_{2e}, or 11% of the transport sector emission, while the international civil aviation emissions for the same year were estimated at 453 Gg CO_{2e}.

In 2021, Aeronáutica Civil presented a voluntary CO_2 emissions reduction action plan to ICAO (Unidad Administrativa Especial de Aeronáutica Civil Colombia, 2021). The CO_2 emission baseline was calculated following ICAO methodology and using secondary information sources, specifically Avianca's 2018 sustainability report. For 2015 (baseline), the emissions calculated were 7,412.56 Gg CO_2, and the emissions projected in 2030 were 11,434.29 Gg CO_2. Six mitigation measures were included: 1) fleet renewal, 2) air infrastructure improvements, 3) energy efficiency, 4) air traffic optimization and management, 5) emission compensation using CORSIA emission units, and 6) SAF.

Colombia does not have a SAF mandate, aviation emission reduction target, or policies that spur SAF production. However, a legal framework for the production and use of SAF is now being built. Further details are available in section 3.4.2.

3.1.2. CORSIA

In 2016, ICAO adopted a global market-based measure scheme to address CO_2 emissions from international aviation, which aims to stabilize net CO_2 emissions from international civil aviation at 2020 levels (Bauen et al., 2020a). CORSIA is implemented in three phases: pilot (2021-2023), first (2024-2026), and second phases (2027-2035). The first two phases are voluntary. From 2027, offsetting requirements will apply to all international flights, except flights to or from states that are 1) least development countries, small island developing states, and landlocked developing countries; and 2) states that represent a small share of international aviation activities (in Revenue Tone Kilometer-RTK) (IATA, 2019a; ICAO, 2023a).

CORSIA allows aircraft operators to reduce their offsetting requirements by using CORSIA eligible fuels, including SAF and LCAF, compliant with the sustainability criteria (Table 29) and certified under the ASTM D7566 (Table 32). The emissions reductions that an airplane operator can claim from CORSIA eligible fuels will be proportional to the life cycle emissions benefit of the fuels used, compared to the reference value of aviation fuel, which is 89 gCO_{2e}/MJ for jet fuel and 95 gCO_{2e}/MJ for AvGas (ICAO, 2018). Default life cycle emission values for CORSIA eligible fuels are published by ICAO, and detailed information is provided elsewhere (ICAO, 2022a). However, an operator may decide to use the actual life cycle emission if a fuel producer can demonstrate lower emissions than the default value or if a fuel producer uses a pathway that does not have a default value (IATA, 2019a). To do so, an approved sustainability scheme (ICAO, 2020), will ensure that the methodology applied follows the one approved for CORSIA and described in (ICAO, 2022c).

Airplane operators (airlines and cargo carriers) have signaled their interest in SAF by signing off-take agreements with producers. Under these agreements, airline operators agree to a future purchase of specified amounts of SAF if certain conditions are met, such as a specific price (United States Government Accountability Office, 2023).

3.1.3. Private mitigation of CO_2

Corporations are seeking to address climate risk, reduce their carbon footprint, and achieve environmental, social, and governance (ESG) pledges; thus, the demand for carbon reduction solutions has been growing rapidly and is likely to evolve further as voluntary commitments strengthen (Badri et al., 2023; Ghatala et al., 2023; United States Government Accountability Office, 2023). High-quality carbon reductions are necessary to make credible reduction claims. Carbon credit quality is driven by eight environmental integrity drivers: 1) permanence, 2) additionality, 3) no leakage, 4) monitoring, reporting, and verification, 5) baselines, 6) counted only once, 7) no net harm, and 8) co-benefits. Further information is available (Badri et al., 2023).

SAF is considered a high-quality carbon reduction; therefore, SAF acquisition and its production catalysis is one strategy to reduce emissions associated with corporate business travel (Martinez-Valencia et al., 2023). For example, United Airlines has 30 corporate customers that agreed to fund the price premium associated with purchasing 7 million gallons of SAF (United States Government Accountability Office, 2023).

3.1.4. Book and Claim

Book and Claim is a chain of custody method that allows the separation and differentiated tracking of the sustainable attributes (e.g., CO_{2e} reductions) from the sustainable fuel molecule. Currently, various initiatives are developing SAF accounting and reporting systems based on book and claim that include scopes 1 and/or 3 emissions, and have been applied to the voluntary market (Avelia solutions, 2022; RSB, 2023; World Economic Forum, 2021). The Sustainable Aviation Buyers Alliance (SABA) announced the first collective purchase of GHG emission certificates for nearly 850,000 gallons of SAF produced by World Energy and helping JetBlue flights reduce an estimated 8,500 tons of CO_2 on a lifecycle basis (SABA, 2023). Furthermore, Etihad Airlines powered the first net-zero flight, displacing approximately 26,000 gallons of fossil jet using net-zero equivalent gallons at Los Angeles International Airport, thereby eliminating approximately 250 tons of CO_{2e} related to Etihad's regular routing flight from Washington Dulles to Abu Dhabi during COP27 (Etihad, 2022). The emission accounting and reporting systems involving regulated schemes, NDCs, and other systems involving various national/states accounting systems, and book and claim are yet to be determined. The benefits and challenges of book and claim are shown in Table 31.

Table 31. Benefits and challenges of initiatives based on the book and claim chain of custody method.

Benefits	Challenges

Operators with or without access the actual molecules may have facilitated access to SAF benefits.	Definition and widespread use of a protocol for emission reporting.
Expands the potential market for SAF producers.	Geographically dependent incentive, regulatory, and/or accounting of the fuel booking with sustainability certification claim.
Facilitates logistical efficiency for reducing cost and emissions.	Potential overlap when complying with different schemes.

3.2. Pathways

There are three leading categories of conversion technologies for SAF production: oleochemical, biochemical, and thermo-chemical (Bauen et al., 2020b; Paris et al., 2021). In addition to SAF, the pathways produce other hydrocarbon fuels, such as propane, naphtha, diesel, and bunker fuel, partially targeted based on the producers' criteria (Mawhood et al., 2016; Serrano-Ruiz & Dumesic, 2011; Surgenor, 2019). Oleochemical pathways convert various fatty acids using physicochemical methods. Biochemical conversion transforms carbohydrate-rich feedstock into an intermediate product using microorganisms. Meanwhile, thermochemical routes deconstruct macro-molecules of solid biomass using high temperature and oxygen deficiency. Table 32 summarizes ASTM certified pathways from 2009 to 2020 and the technology readiness. Additional conversion technologies at the prototype or demonstration readiness levels, such as aqueous phase reforming (APR), pyrolysis-Fischer-Tröpsch (FT), and hydrothermal liquefaction (HTL), have not yet been certified (Bauen et al., 2020b).

Table 32. ASTM certified pathways for SAF production (ASTM International, 2020a, 2020b; Eni, 2021; Fulcrum, 2022; ICAO, 2018b, 2023c, 2023b; IRENA, 2021; Mawhood et al., 2016; Susan van Dyk, 2022).

Conversion technology	Feedstock	Pretreatment	Conversion process	Technology status	Blend ratio
Oleochemical	Vegetable oils Bio-derived lipids Waste fats, oils, and greases	Oil extraction and refining/degumming	Hydroprocessed esters and fatty acids (HEFA)	Commercial	≤50%
			Catalytic hidrothermolysis (CH)	Prototype	≤50%
			Hydrocarbon-HEFA (HC-HEFA-SPK)	Prototype	≤10%
			Co-Processed HEFA (with petroleum)	Commercial	≤5%

Biochemical	Sugar and starch	Sugar extraction or sugar production	Alcohol to jet (ATJ) -Isobuthanol -Ethanol -Mixed alcohols	Demonstration	≤50%
			Hydroprocess fermented sugars	Prototype	≤10%
			Fischer-Tröpsch synthetic paraffinic kerosene (FT-SPK)	Demonstration	≤50%
Thermochemical	Lignocellulosic	Syngas production	Fischer-Tröpsch synthetic paraffinic kerosene with aromatics (FT- SKA)	Demonstration	≤50%
			Co-Processed FT (with petroleum) Co-Processing of biomass	Commercial	≤5%

The electrochemical route is a more recent conversion pathway, which uses hydrogen produced by electrolysis of water and a concentrated source of CO_2, methane, methanol, or short carbon chains molecules (Bauen et al., 2020b; J. E. Holladay et al., 2020; Kaltschmitt & Neuling, 2017; Paris et al., 2021). This conversion process, also known as power-to-liquid (PtL) or e-fuels, requires renewable or zero-carbon electricity input, and renewable waste carbon sources or CO_2 from direct air capture (DAC) (Isaacs et al., 2021; World Economic Forum, 2020). Currently, the capital and operating costs of this conversion path are high due to the early stage of the technology and the cost of electricity (Bauen et al., 2020b; Isaacs et al., 2021). The increasing interest in the electrochemical pathway lies in the potential to produce fuels with very low GHG emissions (Bauen et al., 2020b).

Technologies to power aircraft such as hydrogen and electricity have attracted attention as clean energy sources; however, they require major aircraft and infrastructure changes that limit their use in the near future for long-distance flight. Hydrogen has the potential to reduce noise pollution, increase efficiency, and reduce GHG emissions as long as the hydrogen is produced from a renewable, low carbon energy source, or fossil sources with carbon capture and storage (Bauen et al., 2020b). Electrically assisted propulsion relies on electric energy storage, hybrid energy, or turboelectric (IRENA, 2021). Current challenges for long-distance commercial aircraft are the low energy density of batteries and range limitations (Thapa et al., 2021).

3.3. Building supply chains

No single feedstock has the capacity to replace petroleum fuels on its own. Biomass feedstocks are limited by factors such as land area, water supplies, sustainability concerns, and cost. Moreover, no single feedstock or technology pathway would be likely to provide SAF at sufficient scale (Macfarlane et al., 2011a).

The renewable fuel's supply chain comprises a series of sequential steps that include production, logistics and preprocessing of feedstock, conversion of the feedstock-to-renewable fuel, and subsequent distribution and end-use of the fuel (Figure 45). The feedstock supply chain focuses on the upstream processes before the biomass reaches the preprocessing facility. Upstream processes are critical because biorefineries require substantial quantities of biomass feedstock, which is often spatially distributed across a region with a low density, and requires many supply chain participants to collect and process (Martinez-Valencia, Camenzind, et al., 2021). Chemical characteristics and desired yields of alternative fuels are largely influenced during the growing and harvesting phase. The physical characteristics of biomass are controlled in the preprocessing stage (van Loo & Koppejan, 2008).

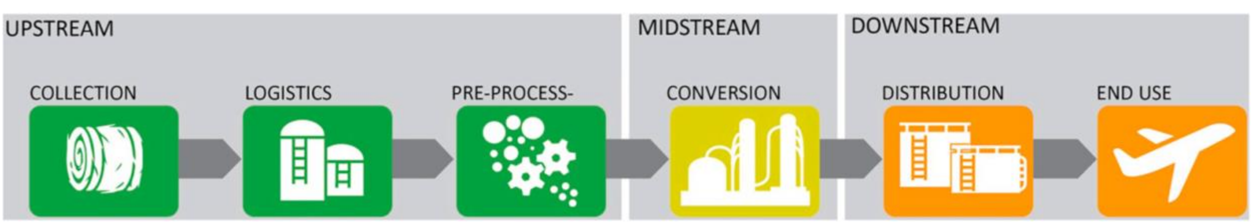


Figure 45. SAF supply chain (Martinez-Valencia, Garcia-Perez, et al., 2021).

The main goals for configuring a feedstock supply chain are to: 1) supply homogeneous feedstock to reduce the investment, maintenance, and personnel costs; 2) establish clear quality standards (moisture content (MC), particle size, and impurities) for the raw material that is received at the pretreatment plant; and 3) increase energy density to reduce transportation, handling, and storage costs (van Loo & Koppejan, 2008).

Following harvest or collection, each commodity requires a reliable and cost-effective delivery system. Such a system may incorporate storage at the point of production, intermediate storage facilities, pre-processing facilities, conversion facilities, and transportation between each stage. The configuration of the supply chain depends on the feedstock type, location, weather conditions, seasonality and reliability of feedstock sources, and the available transportation network. Feedstock processing, handling, and transporting constrains the production of advance biofuels (United States Government Accountability Office, 2023).

The storage system is critical to guarantee biomass quality, ensure that facilities are not idle during any part of the year, and reduce operation and transportation costs because there is a close relationship between storage facilities and wait times for trucks (Ebadian et al., 2013; Gold & Seuring, 2011; Kaltschmitt & Neuling, 2017; Ko et al., 2018). Storage of biomass is a non-value-added process with a high cost due to the infrastructure and space requirements, and losses of feedstock quality (Sahoo & Mani, 2017). The type of storage used mainly depends on the climate and the stage of the feedstock. It requires attention and control because improper storage leads to fire risk and high biomass loss by microbial degradation, which causes changes in the physical structure, and thus, increased material losses and energy consumption in grinding and chipping (Ebadian et al., 2013; Wendt et al., 2018).

The number of storage units needed as buffer capacity depends on the length of the harvesting season and geographical distribution of the feedstock (Gold & Seuring, 2011; Uslu et al., 2008), which substantially impacts the feedstock delivery cost (Ebadian et al., 2013). The storage costs are determined by the location, type of the stores, volume stored, and storage time (weeks, months, or year) (Gold & Seuring, 2011; Marjolein & Romijn, 2008). Outdoor storage requires little capital investment with high flexibility to change locations, while indoor storage requires a permanent structure with substantial capital investment (Sahoo & Mani, 2017).

The storage location can be close to the harvest or forest site at the roadside; at further-off hubs, characterized for higher capacity and close to the main transportation systems, and also known as intermediate storage (Gold & Seuring, 2011); or near the pre-processing facilities (Zhang et al., 2016). Storage location selection criteria includes, in addition to the transportation access, the workforce (Zhang et al., 2016).

A major consideration of the design process is determining how pre-processing/treatment, intermediates storage, and conversion/upgrading facilities should be organized within a supply chain. Research has focused on two types of configurations: the centralized or integrated biorefinery (IBR) configuration, which converts feedstock to fuel at one facility, and the distributed configuration, which uses a network of depots to start the conversion process before finishing the fuel at an upgrading refinery (Camenzind et al., 2023).

SAF production facilities are often new, stand-alone, and capital-intensive projects that involve a laborious process of development, planning, and construction, which could result in a “Valley of Death” where financing runs out before the project generates revenue (United States Government Accountability Office, 2023). Limited engineering and operational experience, immature supply chains, and technology risk could result in extended project installation periods and process instability (IRENA, 2019). Besides HEFA, more nascent SAF production pathways seem stuck in early stages because the technologies are too expensive or risky to attract traditional investors (United States Government Accountability Office, 2023). Various types of integration, such as co-location, retrofitting, repurposing, and co-processing in petroleum refineries, explained in detail elsewhere (K. Brandt et al., 2022; De Jong et al., 2015; Tanzil et al., 2021), have been analyzed as an alternative for costs reduction. In Colombia, these integrations could include the oil refineries; as well as the ethanol and biodiesel biorefineries.

Siting fuel production facilities requires identifying locations that are the most compatible with the needs of processing facilities. The data required includes feedstock location, transportation networks with associated costs, geospatially distinct electricity and natural gas costs, local workforce, and destination of the product (Port of Seattle & Washington State University, 2020). An initial overview of this information is available in section 2 of this document; however, data layers with this information is require for analysis using geographical information systems, some of which are not currently available (e.i., electricity and natural gas).

The transportation of SAF from the refineries to the airports has its own concerns due to the ability to access existing transportation infrastructure (United States Government Accountability Office, 2023). Initial SAF delivery methods relied on fuel trucks to place fuel directly into the aircraft. Airports with ongoing SAF supply utilize the same delivery approach as Jet A/A1, which is via the co-mingle hydrant fuel supply system (Ghatala et al., 2023). Sites that can support the receipt, blending, storage, and delivery infrastructure might need to be identified on a case-by-case basis (WSP et al., 20161).

Colombian opportunities for SAF supply chain were discussed from the actors' perspectives in the roundtables leads by the Inter-American Development Bank and the Civil Aeronautics of Colombia (Aerocivil, 2023). Ecopetrol analyzed two alternatives for SAF distribution depending on the production site: Barrancabermeja Refinery - GRB (dedicated plant) or Cartagena Refinery - GRC (co-processing). In the first case, SAF's distribution would be by polyduct and tank trucks. Furthermore, pure or premixed product delivery options were considered in percentages defined by regulation. In the second alternative in GRC, SAF distribution would be by polyduct and local delivery. The option of delivery of co-processed products was considered in percentage defined by regulation, preliminarily 5%. For both cases, storage tanks (Refineries/Transporter/Wholesaler/Airport) are required for the premix batch; quality assurance body certification in the different points in the chain and fleet of tank trucks dedicated to handling of the product would also be required (Ecopetrol, 2023a).

El Dorado Airport’s SAF pilot plan aims to offer SAF in the medium term for the different aircrafts operating at the airport. As a main challenge, this pilot plan has identified the need to define a regulatory framework for the supply chain, market incentives, and define the Jet/SAF mixing point. Defining the mixing point is essential because depending on the site, the infrastructure needs and quality controls to be carried out (certification/recertification) vary. This can impact the cost of the process and need to advance a supply chain regulatory framework and market incentives (EL DORADO, 2023).

There are three possible mixing points: at the refinery, a fuel terminal, or the airport. Table 33 shows the advantages, disadvantages, and limitations of each. Oil refineries are the sites that handle the most significant volumes of fuel, and therefore, are ideal for large quantities of SAF. Fuel terminals generally have more capacity and space than airports. However, 100% of the SAF must be transported to the terminal via dedicated SAF infrastructure (ship, truck, or pipeline). Trucks would be suitable for smaller volumes, but this needs to change to more efficient modes for larger volumes. Unloading platforms for trucks or vessels must accept 100% SAF, and tanks to store and mix it. Mixing is not recommended at the airport and would only allow smaller quantities of fuel to be handled (IATA, 2023b).

Table 33. Advantages, disadvantages, and constraints of possible mixing points in Colombia (IATA, 2023b).

Possible mixing point	Refineries	Fuel terminal	Airport
Advantages	- Expertise in handling different hydrocarbons, including biofuels - Expertise in driving jet fuel flexible transportation infrastructure (multiple pipelines, ports, and highways)	- More fuel volume can be handled than at airports - Experience in handling biofuels - Infrastructure for loading and unloading fuel - It could keep airport infrastructure intact - The industrial operation makes the site more viable than the airport. - The same terminal can supply many airports - Some terminals may have experience with fuel mixtures.	- Fewer trucks are needed for SAF. (1 truck with 100% SAF versus 3 trucks with 33% SAF) - Potentially reduced transportation costs - Increases the visibility and presence of SAF to the airport workforce.
Disadvantages	- Only viable for large quantities	- Requires SAF specific fuel supply infrastructure	- Requires additional airport infrastructure to receive, store, and mix the fuel.

			- Requires duplication of fuel supply chains to the airport - Fuel certification must be carried out on site - Land traffic congestion increases
Constrains	- Optimized for large quantities - They may be far from SAF production sites - Large quantities of SAF could have to be transported, requiring more infrastructure	- An efficient and transparent accounting system is needed to track fuel to different airports	- Trucks are needed to transport SAF if 100% SAF is not allowed in the pipeline (this is currently the case), which restricts delivery volumes - The airport's tank storage capacity is small compared to other locations - Regulations would be required for on-site mixing - Lack of experience in certification requirements. - Limited quantities of fuel can be discharged through existing discharge racks. - Lack of legal framework to transport 100% SAF

3.4. Options for SAF production in Colombia

This section focusses on the production of SAF through commercial or closed to commercial scale technological pathways 1) HEFA, 2) ATJ, and 3) GFT. Pathways such as pyrolysis FT and PtL were included due to the increasing number of facility’s announcements using such technology (ICAO, 2023c).

The economic information in this section is based on the ICAO Rules of Thumb (International Civil Aviation Organization (ICAO), 2023), which were calculated using the United States costs and financial assumptions (Table 34). Note that “The SAF rules of Thumb were intended to provide a big picture trend for cost and processing technology/feedstock comparisons and could be utilized to make an order of magnitude estimations. They do not provide precise cost or price information. As such, investment or policy decisions should be based on a dedicated analysis that captures specific details related to the investment or policy” (International Civil Aviation Organization (ICAO), 2023). Thus, the values may change for Colombian-specific conditions.

Table 34. Financial parameters used in all economic calculations (K. L.Brandt et al., 2020; Port of Seattle & Washington State University, 2020).

Economic Parameter	Assumed Value
Cost year	2017
Plant financing	30% equity
Plant life	20 years + 3 years for construction
Real discount rate	10%
Income tax rate	17.2%
Inflation	2%
Working capital	20% annual operation costs
Depreciation schedule	7 years, double declining balance to straight line
Construction schedule	3 years (8% fist year, 60% second year, and 32% third year)
Maintenance	6% total delivered equipment cost (TDEC)

Hydrogen is a reagent required for all routes (hydrocracking large molecules, building up small molecules, or saturating direct fermentation molecules) (J. Holladay et al., 2020). The economical information includes hydrogen purchase under United States assumptions.

The feedstock availability is based on available public information on Colombian's biomass resources and potential feedstock. Greater detail of the feedstock inventories would be required for further analysis. When possible, information regarding the sustainability of the feedstock is included; however, there is no consistent information for all the pathways or the CORSIA sustainability criteria.

3.4.1. Hydroprocessed esters and fatty acids

The HEFA route uses catalysts and heat, the same process as hydrotreated vegetable oil (HVO). The hydroprocessing removes oxygen, adds hydrogen, and rearranges carbon molecules to create a drop-in petroleum substitute that requires no engine modifications in a 50% blend; a general process flow for HEFA pathway is shown in Figure 46. Hydroprocessing produces mostly renewable diesel and can produce 50-70% jet fuel with an additional isomerization step (Bauen et al., 2020c). The remaining products would be propane and naphtha.

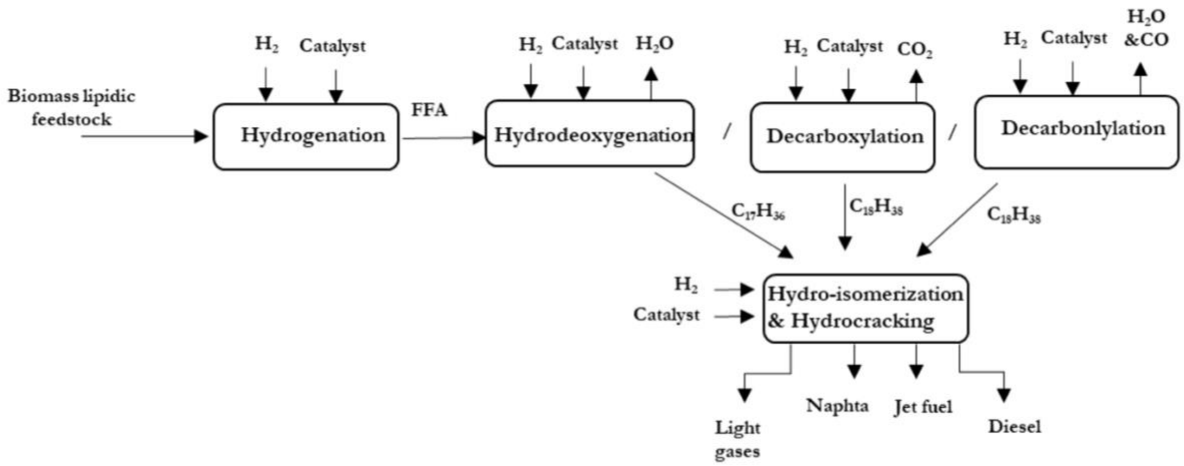


Figure 46. General process flow for the HEFA pathway (ICAO, 2022b).

In co-processing, biologically derived fats and oils are refined with petroleum fractions to produce refinery products that include renewable carbons (Herbertson & Wheeler, 2022; ICAO, 2022c, 2022b). Co-processing can occur in existing infrastructure. The chemical composition of lipid feedstocks presents challenges in co-processing operations, limiting the volumes that can be co-processed(Canada's Biojet Supply Chain Initiative, 2019). The oxygen content of lipids (~11%) requires higher volumes of hydrogen during processing but does not interfere with the desulfurization reaction of petroleum feed (Canada's Biojet Supply Chain Initiative, 2019). Lipid feedstocks also contain contaminants such as metals, including phosphorus, which may inhibit hydrotreating catalysts. Pre-treatment, such as acid-degumming, can be carried out to remove these contaminants. The ASTM specification for co-processing limits the proportion of renewable feedstock to 5%, restricted to triglycerides and fatty acids.

There are five commercial HEFA technologies available: Ecofining from Honneywell UOP, Neste's proprietary process -NExBTL, Hydroflex from Haldor-Topsoe, Axen, and Biosynfining from Syntroleum (Canada's Biojet Supply Chain Initiative, 2019). A comparison of three technologies is presented in Table 35. Honeywell UOP is the largest commercial provider of HEFA processing technology.

Table 35. Comparison of the three commercial HEFA technologies. Adapted from prior work (Canada's Biojet Supply Chain Initiative, 2019).

Item	Ecofining	NExBTL	Hydroflex
Licensed to	World Energy, Diamond Green Diesel, Eni Italy, Emerald Biofuels, Petrixo, and SG Preston	Neste Rotterdam, Singapore, and Porvoo	UPM Lapeenranta, Pree, and Gothenburg (co-processing)
Annual capacity (planned)	1.6 BL (3.0 BL)	3.0 BL	1 BL
Feedstock approved	Tallow, pretreated vegetable oils (canola, soy, palm, and jatropha)	Palm oil, palm fatty acid distillate, fish oil, tallow, used cooking oil (UCO), rapeseed, and camelina	Tall oil, tall oil biodiesel, and canola
Input/output (wt%)			
Crude lipid feedstock	100	100	100
Hydrogen	1.5 – 3.8	3.2	2.5
Production yield (HEFA Diesel)	75-85	82.6	94 (precursor, uncracked fatty acids C17 – C22)
Naphtha	<1 – 7	0.43	-
Butane	0 - 2	-	-
Propane	5	5	5.2
Other gases (CO, CO_2, and CH_4)	Not specified	Not specified	1.8

3.4.1.1. Economics

HEFA is expected to play a pivotal role as a primary, short-term accelerator for SAF due to its maturity (low capital expenditure (CAPEX)). However, the availability of sustainable oil-based raw materials poses a limitations. Feedstock costs vary depending on the source. More sustainable, less carbon-intensive "waste" oils, such as used cooking oil, animal fat, vegetable oil from processing waste and residues (e.g., palm fatty acid distillate, spent bleaching earth oil, and palm effluent sludge), fish fat from fish processing waste, and technical corn oil (a residue from ethanol production), are only available in limited quantities. Moreover, their cost might increase due to competition(IRENA, 2021). Lipid feedstocks are already used extensively in the chemical industry, and for biofuels in the road transport sector, with SAF likely competing with renewable diesel (IRENA, 2021). Renewable diesel is a fraction of the fuel output of HEFA/HVO biorefineries, which have more favorable policies and incentives; thus, producers do not invest in the equipment necessary to separate the SAF fraction from the renewable diesel (K. L. Brandt et al., 2022; IRENA, 2021). The cost of fuels produced via the HEFA/HVO route varies based on the lipid feedstock used (feedstock cost is approximately 80% of the total cost of the biofuel) and plant size (K. L.

Brandt et al., 2022; IRENA, 2021; Port of Seattle & Washington State University, 2020). Table 36 summarizes economic information for the HEFA pathway using fat, oil, and greases (FOGs), and soybean oil as feedstock, assuming a yield of 0.83-ton distillate/ton feedstock, total capacity of 1000 million L/year, and SAF production of 550 million L/year.

Table 36. Summary HEFA economic data using FOGs and soybean oil as feedstock, and default LCA values (ICAO, 2023d).

Feedstock	Feedstock price	Total capital investment (million $)	Capital cost ($/L total distillate)	Minimum Selling Price (MSP) ($/L)	Life cycle emissions (gCO_{2e}/MJ) **	Abatement cost ($/$tCO_{2e}$)
FOGs	$580/ton	448	0.40	0.80	18.20	130
Soybean oil*	$809/ton	456	0.50	1.00	64.90	640

* 2013-2019 average price of soybean oil
** Based on default life cycle emission provided in the ICAO document “CORSIA Default life cycle emissions values for CORSIA eligible fuels".

3.4.1.2. Feedstock

In Colombia, the largest source of lipids comes from palm oil cultivation (section 2.3.1.2), with an established production and logistic system. Companies collecting used cooking oil, primarily in the main cities, adds up a monthly collection capacity of 2,104 ton, some of which is used in biodiesel production (CVC, 2023).

Palm oil production is mostly absorbed by the domestic market (food, fuels, and chemicals); however, approximately 28% which is exported (Fedepalma, 2022a) could be available for SAF production. In addition, hybrid OxG crops cropping is growing, which has a productivity of 27.4-ton FFB/ha according to the 2019 national average or 41-ton FFB/ha for the best agronomic practices, and with an oil extraction of 23.7%. This is higher than that for conventional materials (25.6-ton FFB/ha and 21.2% oil extraction rate) and competitive economically, despite the need of assisted pollination or hormone application (Daza et al., 2021; Mosquera-Montoya et al., 2021). The lipidic profile of the hybrid material might have higher demand in the food market due to the unsaturated fatty acid content (Mozzon et al., 2013).

3.4.1.3. Production potential from crude palm oil with the HEFA-SPK process

The World Bank has developed a model to estimate the regional potential of SAF production from crude palm oil (CPO) and palm residues (empty fruit bunches (EFB), fibers, and shells). The parameters considered in the model were land availability (land area continues to expand at the 2012-2022 average rate), productivity (CPO & FFB yield equals 2012-2022 average), availability for SAF production, and pathway. CPO is assumed to be converted by the HEFA-SPK process. Figure 47 presents HEFA production potential from crude palm oil. Notably, palm production must increase in all regions if CPO is to be available for SAF without impacting existing markets. Further, Orinoquia has the highest potential for HEFA production due to higher land availability. By 2050, 1.1 Mha of land will be cultivated in Orinoquia compared to 0.22 Mha in 2022. Deployment of methane capture is essential to realize SAF potential in all regions. Without methane capture, HEFA produced from CPO is highly unlikely to meet sustainability criteria (e.g., CORSIA) (BANCO MUNDIAL, 2023).

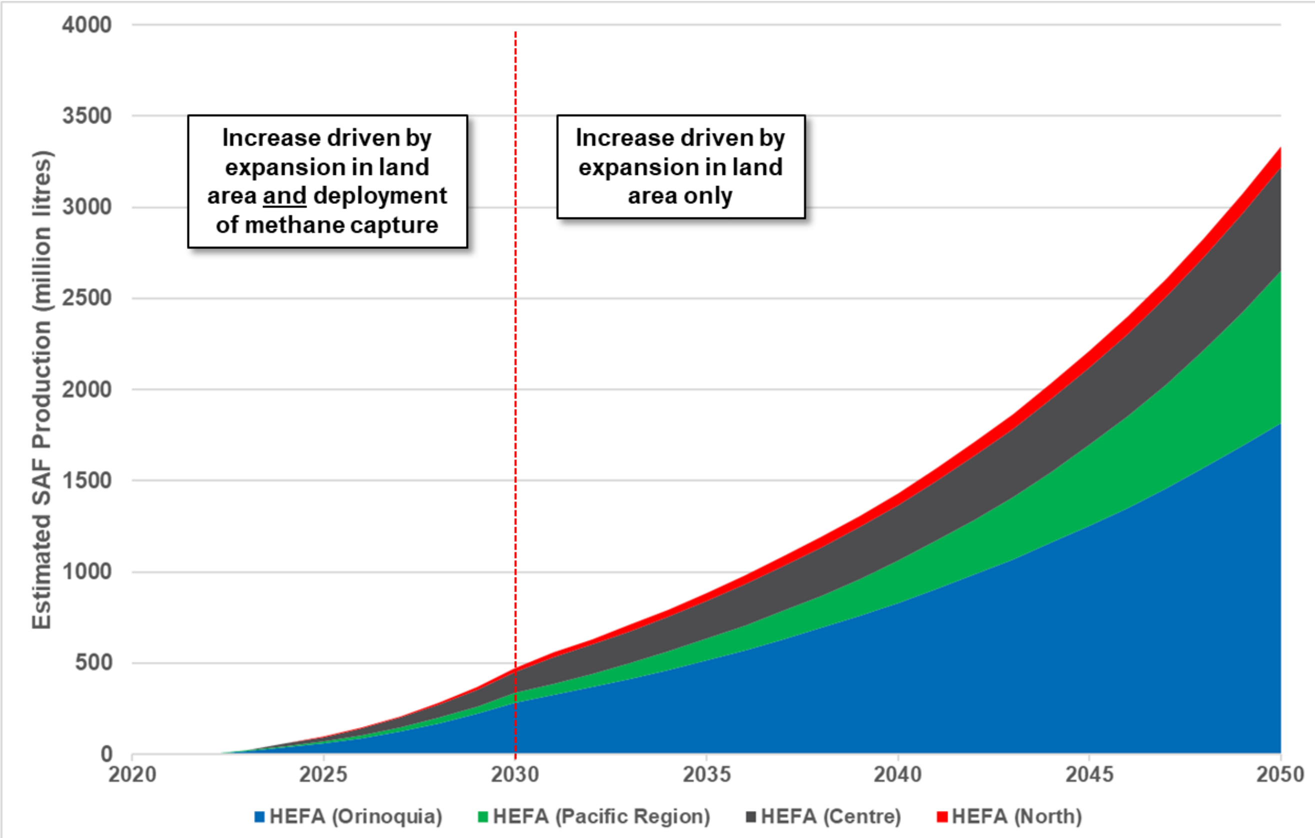


Figure 47. HEFA production potential from crude palm oil (BANCO MUNDIAL, 2023).

3.4.1.4. Logistics

In Colombia, the oil palm value chain is made up of service and input providers (seeds and seedlings, agrochemicals, services, and credits), palm growers, palm oil extractors, palm oil refiners, marketers of final products, and consumers (national and international) (Peña González et al., 2021). The first two processes are fertilization and harvest. The transport of the FFB from the field (producer) to the processing plant (buyer) is the third process and has the highest cost. Transportation contributes 8% of the cost of a ton of fruit and approximately 5% of the cost of a ton of oil (Mosquera & Valenzuela, 2006). The transport logistics of FFB in companies in the Colombia's northern region (Figure 39) are affected by road conditions, vehicle maintenance, vehicle assignment, and FFB production. The selection of transport vehicles for FFB depends on the road conditions (Table 1). The external roads of processing plants located in the department of Magdalena are in poor albeit acceptable conditions. In contrast, the processing plants located in the department of Cesar have better road conditions possibly due to their proximity to primary roads. Depending on the state of the road, the travel speed can vary from 5 km/h to more than 60 km/h. This, of course, added to the distance to travel, affects the offer of vehicle trips and directly impacts the transport rate (longer travel time and fewer trips per day) (Fontanilla et al., 2015). Additionally, in the eastern zone, the transportation cost is approximately 8.54 USD [1]/ton using trucks with a capacity of 30 tons and 50 km as the average distance (BioD S.A., 2023).

3.4.1.5 Sustainability screening

Although the production of vegetable oils contributes significantly to rural jobs and the local economy, there are concerns about the sustainability of potential SAF fuel from feedstocks such as palm oil and soybean. Sustainability, in this case, is complex, as broader concerns around direct (DLUC) and indirect land use change (ILUC) need to be considered (IRENA, 2021).

SAF production from palm oil has key factors that influence GHG emissions, such as palm oil mill effluent (POME) treatment, waste utilization, and ILUC factors[2], which must be quantified. SAF has the same chemistry as Jet A1; therefore, the CO_2e emissions in the engine exhaust are the same. To capture the emissions reductions achievable from SAF requires the use of full lifecycle, or well-to-wake (WTW), emissions analyses. Table 37 summarizes the WTW emission under three scenarios: optimum, base, and worst (BANCO MUNDIAL, 2023).

Table 37. Well-to-wake (WTW) emissions analysis (BANCO MUNDIAL, 2023).

Scenario	**WTW emissions**	**Comments**
Optimum	59.2 gCO_2e/MJ (**-33%**)	Closed pond POME treatment (85% methane recovery); Wastes (fibres, almond shells, and other residual biomass) for heat recovery/energy production

[1] COP $40,000/ton (May 2, 2023)
[2] The results presented in the Aerocivil's roundtable did not specify which criteria were considered for ILUC analysis.

		Lower end of ILUC range (34.6 gCO_2e/MJ); plantation established on non-productive agricultural land
Base	74.5 gCO_2e/MJ (**-16%**)	Closed pond POME treatment (85% methane recovery); No wastes for heat recovery/energy production Mid value of ILUC range (39.1 gCO_2e/MJ); CORSIA recommendations
Worst	118.6 gCO_2e/MJ (**+33%**)	Open pond POME treatment (no methane recovery); Upper value of ILUC range (60.2 gCO_2e/MJ)

Regarding the environmental impacts, the GHG emissions of biodiesel from palm oil in Colombia are 84% lower than those from fossil diesel. Burning biomass for the cogeneration in the system contributes to the terrestrial acidification process. The total contribution to ozone depletion of the biodiesel from palm oil in the Colombian case is 9% of that from fossil diesel (Canabarro et al., 2023).

Ramirez-Contreras et al. (2022) assessed the environmental and economic impacts of land-use change (LUC) in the Orinoquia region by examining agricultural intensification and bioenergy production scenarios in 2030. If inefficient agricultural practices persist, 93% of natural vegetation will be converted to farmland, leading to substantial increases in GHG emissions, biodiversity loss, and water consumption. Despite slight intensification, 29% of natural areas would still be converted. However, medium- and high-intensity scenarios allow for meeting food demand within existing agricultural lands, with surplus land available for bioenergy crops, reducing environmental impacts, and maintaining biodiversity. Positive economic returns are projected for all scenarios. The authors emphasized the need for targeted agricultural investments, particularly in cattle production, and integrated land-use planning considering agroclimatic conditions, soil characteristics, and water supply. They highlighted the importance of conserving natural savanna ecosystems and calls for local planning to exclude certain areas from intensive agriculture. The study suggests sustainable water management practices, and emphasizes the importance of future research and specific spatial assessments. Government policies are recommended to support economic benefits, tax reductions, payment schemes for ecosystem services, incentives for sustainable agricultural practices, and increased investment in agricultural research and development (Ramirez-Contreras et al., 2022).

In collaboration with the World Bank, ISCC, along with MEO and GRAS, has conducted a life cycle analysis (LCA) of SAF and renewable diesel (RD) produced from palm oil and its residues in Colombia. The project aims to assess the impact of oil palm sector development on SAF and RD production, serving as a basis for promoting green market opportunities in the country. The World Bank, through the BioCarbon Fund Initiative for Sustainable Forest Landscapes (ISFL) Program, has actively supported the project, assisting the Colombian government in sustainable land use planning, emission reduction programs, biodiversity integration, and landscape connectivity. The initiative falls under the Advisory Services and Analytics (ASA) activity focusing on climate-smart agricultural supply chains. The analysis indicates a positive outlook for the Colombian palm sector, with minimal deforestation and potential compliance with emission reduction requirements. Key lessons include reducing POME treatment emissions, nitrous oxide (N_2O) field emissions, and energy consumption for significant emission reductions. A strategic roadmap is proposed, emphasizing the need for a Colombia-specific ILUC value for CORSIA certification, raising awareness, training operators, creating an enabling environment for investments, adopting sustainable agricultural practices, and implementing emission reduction measures at the plantation and oil mill levels. While the analysis highlights Colombia's potential for SAF production, certification should be conducted site-specific basis using actual data (ISCC, 2024).

3.4.2. Alcohols

Biomass feedstocks can be used to produce sugars that may be fermented to alcohols such as ethanol or isobutanol for ATJ production, or directly fermented to hydrocarbons such as farnesene (Karatzos et al., 2014). While fermentation of sugars from edible plants is the most common practice to produce alcohol derivatives, fermentation from non-edible plants requires other advanced techniques involving pre-treatment, specific microbes, and additional process units (ICAO, 2022b). In the ATJ process, alkenes are oligomerized from C8 to C16 molecules. The key is controlling the growth regarding carbon length and carbon backbone (i.e., carbon length, branching level, and degree of cyclization/aromatization)(J. Holladay et al., 2020). A general process description is illustrated in Figure 48.

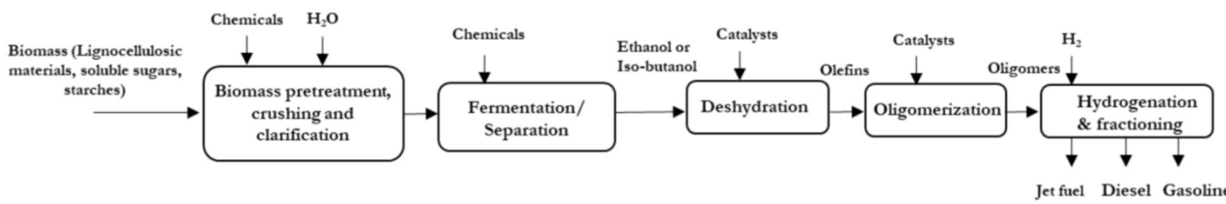


Figure 48. General process flow for the alcohol-to-jet pathway (ICAO, 2022b).

Benefits of the pathway could be the availability of ethanol as a mature biofuel. Further, using the right feedstock and process operation technologies, very high yields (up to 70% of jet) and energy efficiency can be achieved with ethanol production. Finally, ATJ has lower hydrogen demand compared to other pathways (J. Holladay et al., 2020; IRENA, 2021). Currently, various technology developers or licensors are involved in the ATJ pathway as shown in Table 38. ATJ processes have been ASTM approved and the resulting biojet has been successfully used in some flights (IRENA, 2021).

Table 38. ATJ technologies (Csonka et al., 2022; IRENA, 2021).

Technology developer/Licensor	Process details
Gevo	Biojet from isobutanol derived from corn
LanzaJet	Fermentation of waste carbon gases or syngas to make ethanol for the ATJ process
Global Bioenergies	ATJ derivative utilizing biochemical production of isobutene
Swedish Biofuel	ATJ derivative starting with mixed alcohols

3.4.2.1. Economics

Although the yield in ATJ might be considerably higher than that achievable via the HEFA or thermochemical pathways, an ongoing challenge is the value of the alcohol intermediate (ICAO, 2022b; Karatzos et al., 2014). Certain cases, such as advanced fermentation, may have higher costs for additional enzymes or catalysts required for pretreatment and hydrolysis steps (Geleynse et al., 2018; IRENA, 2021). Operating expenses (OPEX) can also increase due to excessive heat requirements for steam distillation and dehydration of the produced alcohols. With the recent fast-paced development towards commercialization, the CAPEX and OPEX for ATJ should decrease over time (IRENA, 2021). As noted before, ATJ processes have been ASTM approved and the resulting biojet has been successfully used in some flights; the relatively high value of the alcohol intermediates and current policy drivers encouraging their use in road transport are ongoing challenges.

Table 39 summarized the economic information for the ATJ pathway using ethanol and isobutanol as feedstock, assuming a yield of 0.60- and 0.75-ton distillate/ton feedstock for ethanol and isobutanol, respectively, a total capacity of 1000 million L/year, and a SAF production of 700 million L/year. The facilities are considered nth plants.

Table 39. Summary ATJ economic data using various sources ethanol and isobutanol as feedstock, and default LCA values (ICAO, 2023d).

Feedstock	**Feedstock price**	**Total capital investment (million $)**	**Capital Cost ($/L total distillate)**	**MSP ($/L)**	**Life cycle emissions (gCO_{2e}/MJ) *****	**Abatement cost ($/t$CO_{2e}$)**
Ethanol*	$0.41/L	328	0.3	0.9	90.85	No CO_2 abatement
Ethanol, agricultural residues, stand alone	$1.20/L	581	0.6	2.2	39.7	1020
Isobutanol-low*	$0.89/L	332	0.3	1.3	77.9 ****	2100
Isobutanol-high*	$1.20/L	410	0.4	1.7	77.9****	3220
Isobutanol-low Sugarcane**	$0.89/L	332	0.3	1.3	33.1****	420
Isobutanol-sugarcane**	$1.20/L	410	0.4	1.7	33.1****	640

* Alcohol feedstock is corn-based

** Same cost structure than corn base isobutanol

*** Based on default life cycle emission provided in the ICAO document “CORSIA Default life cycle emissions values for CORSIA eligible fuels"

**** Includes iLUC values, which can be subtracted with the use of low LUC risk practice as defined in the ICAO document “CORSIA Methodology for Calculating Actual Life Cycle Emissions Values.”

3.4.2.2. Feedstock

Colombia has an established ethanol industry, as presented in section 2.2.2.3., with an installed capacity to produce 2,150,000 L/day to fulfil the national demand as a gasoline oxygenator. Ethanol for SAF production would require additional sugarcane or other sugars/starch-rich crop developments.

Cassava (Manihot esculenta) is a woody bush cultivated annually in tropical and subtropical regions for its edible starchy tuberous root, and is a major source of carbohydrates. In Colombia, 2,249,180.60 ton of cassava was produced in 2021 (Table 40). 90.24% of the produced cassava was destined for human consumption, whereas the remaining 9.76% was used for industrial applications (starch production)(Agronet, 2021). The average yield of cassava production for industrial use is higher (16.92 ha/ton) than the cassava crop for human consumption (9.8 ha/ton) (Agronet, 2021). Cassavas roots and stalks are suitable feedstock for ethanol production (Castaño Peláez et al., 2011; García-Velásquez et al., 2020). In 2009, the Cantaclaro project was announced, which aimed to produce 20,000 L of ethanol (185 L EtOH/ton cassava) (Gomez Cano & Salazar Redondo, 2022); however, it was not completed (Botero Agudelo et al., 2011; Portafolio, 2009).

Table 40. Production and yield of cassava, and cassava for industrial applications in 2021 (Agronet, 2021).

	Cassava		**Cassava for industrial applications**	
Department	**Production (ton)**	**Yield (ha/ton)**	**Production (ton)**	**Yield (ha/ton)**
Antioquia	142,123.35	12.95		
Arauca	117,612.00	19.79		
Atlantico	46,006.30	9.51	2,373.00	14.83
Bolivar	305,580.40	9.42		
Boyaca	20,004.96	8.70		
Caldas	233.00	11.10		
Caqueta	56,645.30	7.09		
Casanare	17,448.00	10.10		
Cauca	81,161.84	14.24	61,278.00	16.92
Cesar	100,066.00	11.20		

Choco	28,456.36	8.82		
Cordoba	174,917.70	10.54	65,992.60	21.18
Cundinamarca	38,997.00	11.06		
Guainia	16,874.00	7.80		
Guaviare	14,904.00	9.57		
Huila	22,752.50	6.93		
La Guajira	31,009.00	9.80		
Magdalena	258,465.30	11.96	180.00	20.00
Meta	127,583.00	16.38		
Nariño	12,594.90	7.18		
Norte De Santander	93,400.66	13.39		
Putumayo	25,295.38	7.11		
Quindio	6,445.00	17.71		
Risaralda	1,439.97	6.47		
San Andres Y Providencia	120.96	10.08		
Santander	90,506.78	13.80		
Sucre	139,789.50	9.41	89,609.40	16.88
Tolima	34,605.86	9.47		
Valle Del Cauca	9,153.78	13.57		
Vaupes	9,241.80	5.38		
Vichada	6,313.00	8.92		

Feedstock for second-generation ethanol has been researched. Table 41 shows some of the woody biomass available in Colombia and its potential for ethanol production based on the fermentable sugars from its cellulose and hemicellulose composition. Each of these fractions can be processed to produce hexoses and pentoses, among other compounds. Hexoses and pentoses are of interest in making sugary syrups for ethanol production (Ruiz-Colorado et al., 2014).

Table 41. Herbaceous and woody biomass, and potential fermentable sugar content (Ruiz-Colorado et al., 2014).

Species	By 100 g of lignocellulosic material		
	Potential sugar fermentable (g)	**Convert to theoretical ethanol (g)**	**Ethanol (L/dry ton)**
Cordia alliodora	69.27	35.37	450.59
Cupresus lisitanica	69.98	35.74	455.23
Eucalyptus camaldulensis	69.25	35.36	450.51
Gmelina arborea	74.90	38.25	487.21
Pinus caribaea	74.88	38.24	487.10
Pinus kesiya	68.26	34.86	444.06
Pinus oocarpa	72.75	37.15	473.28
Pinus patula	91.32	46.64	594.09

Pinus radiata	68.89	35.18	448.11
Tectona grandis	82.08	41.92	533.95

3.4.2.3. Sustainability screening

The production of alcohol from crops requires sustainable sourcing without interfering with food production.

GHG emissions of ethanol from sugar cane in Colombia are 81% lower than fossil gasoline. Burning biomass for cogeneration contributes to the terrestrial acidification process. The share of sugarcane farming in ozone depletion was 68.8% for Colombia. However, the total contribution to ozone depletion is 13% of that from fossil gasoline (Canabarro et al., 2023).

Use of Technology, Inputs, and Management of waste:

- **Carbon footprint of cassava ethanol:** The carbon footprint of cassava ethanol is 0.395 kg CO_{2e} per kg of ethanol. This means 75 gCO_{2eq}/MJ allows a net reduction of 13.5 gCO_{2e}/MJ emissions compared to conventional gasoline (Botero Agudelo et al., 2011).

3.4.3. Lignocellulosic pathways (GFT and pyrolysis)

Lignocellulosic biomass comprises three materials: cellulose, hemicellulose, and lignin. The latter two bind and protect the cellulose. Technologies must break down the material to process biomass into bioenergy and bioproducts. GFT is a high-temperature (700 - 1500 °C) partial oxidation process in which solid biomass is partially oxidized using a gasification agent (air, oxygen, or steam). The product is a combination of gases (CO, CH_4, and H_2) subsequently cleaned, upgraded, and catalytically converted using hydrogen as a reagent, resulting in a mixture of hydrocarbons products with chain length ranges from C_1 to C_{20+}. From this, fuels such as diesel, jet, gasoline, and other chemicals can be extracted. A more detailed description is available elsewhere (Kaltschmitt and Neuling, 2017). A general process flow for a GFT pathway is shown in Figure 49. The FT process is used in the world's largest natural gas-to-liquids facility (Shell's Pearl

GtL facility in Qatar, completed in 2011), which produces 140000 barrels of fuel per day (~22 million litres per day)(IRENA, 2021). The co-processing of FT liquids at 5% blends in existing refineries was approved in 2020 in Colombia.

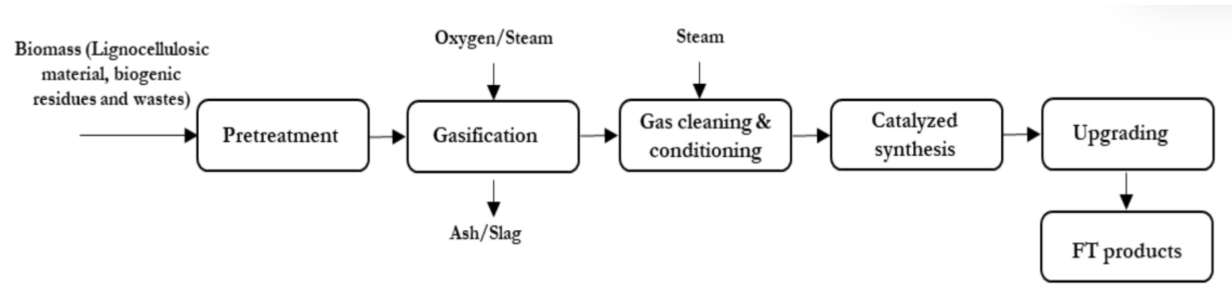


Figure 49. General process flow for Fischer-Tröpsch pathway (ICAO, 2022b).

Gasification of biomass has challenges, such as tar formation which needs to be cleaned up; less energy-dense syngas due to high the oxygen content of biomass, and impurities (IRENA, 2021). Typically, biomass- and MSW-derived syngas needs to be enriched with hydrogen and cleaned of the impurities such as tars, nitrogen, and other heteroatoms that can deactivate the synthesis catalysts (Karatzos et al., 2014; Rhyner, 2016).

Pyrolysis is the thermal decomposition of biomass at elevated temperatures in non-oxidizing conditions with solid, liquid, and gas products (Yogalakshmi et al., 2022). Multifarious pyrolysis parameters should be considered to reach high energy efficiency through biomass pyrolysis system, including biomass type, particle size, reaction conditions, reactor type, transport phenomena within the reactor, variables like catalyst addition, and the mechanism for vapor condensation (Yogalakshmi et al., 2022).

Although companies such as Ensyn in Canada have obtained regulatory approval for their drop-in fuels, RFDiesel and RFGasoline, based on co-processing in oil refineries, it has produced no jet fuel (IRENA, 2021). Biojet fuel produced via the pyrolysis route is still in development because the bio-crudes obtained contain up to 40% oxygen (similar to the biomass itself), needing upgrading via hydroprocessing (Jones et al., 2013). Several technical challenges to co-processing bio-crudes still exist, such as the point of bio-crude insertion, extent of upgrading required before insertion, and different catalysts needed to upgrade bio-crudes. However, coprocessing of pyrolysis bio-crudes in existing petroleum refineries could be a key strategy for producing lower carbon-intensive jet fuels (van Dyk et al., 2019). Table 42 shows some emerging technology companies using gasification or the pyrolysis process.

Table 42. Emerging technology companies (Ensyn, 2020; Fulcrum, 2022; Fulcrum Bioenergy, 2021; Macfarlane et al., 2011b; Wijeyekoon et al., 2020).

Technology	Owner	Process	Facilities
Choren	Daimler and Volkswagen	Gasification/Fischer-Tröpsch	3.9 mgy plant in Germany in 2008
Fulcrum Bioenergy		Plasma gasification	~11 mgy of renewable syncrude from 175,000 ton of landfill waste. Located near Reno, Nevada (US)
Powermax		Bed gasifier	
IH^2	Shell Catalysts & Technologies	Gasification	5 tons dry feedstock/day
Envergent Technologies	Ensyn & Honeywell	Pyrolysis	Facility in development to produce 22 million gallon/year Ensyn biocrude in Brazil
Valmet	Fortum, Valmet	Pyrolysis	50,000 tons/year pyrolysis oil in Finland
Alder Fuels		Pyrolysis	

3.4.3.1. Economics

Notably, gasification technologies typically involve high capital costs to both gasify the biomass and convert the resulting syngas to FT liquids (Swanson et al., 2010). The capital costs for construction of the Fulcrum Bioenergy and Red Rock Biofuels facilities are estimated at USD 4,560-5,560 per kilowatt (kW) (USD 200-355 million)(IRENA and The Methanol Institute, 2021). For FT, the higher OPEX can be due to the costs associated with catalyst development and regeneration, and the use of hydrogen for upgrading (IRENA, 2021). For pyrolysis, the CAPEX and OPEX components are comparable to those of gasification and FT. For a standalone bio-oil upgrading plant, CAPEX is very similar to that of a co-processing unit. However, the OPEX is lower for a co-processing unit since the process can be coupled with an existing petroleum refinery (IRENA, 2021).

Table 43 summarizes economic information for the GFT and pyrolysis process using MSW, and forest and agricultural residues assuming nth plant facilities, based on information available for the US available in the ICAO Rules of Thumb.

Table 43. Summary of thermochemical pathways economic data using various feedstock and default LCA values (ICAO, 2023d).

Feedstock	Yield (tib distillate/ton feedstock)	Feedstock price	Total capacity (million L/year)	SAF production (million L/year)	Total capital investment (million $)	Capital cost ($/L total distillate)	MSP ($/L)	Life cycle emissions (gCO_{2e}/MJ) **	Abatement cost ($\$/tCO_{2e}$)
				FT					
MSW*	0.31	$30/ton	500	200	1428	2.90	0.90	32.50	210
Forest residues*	0.18	$125/ton	400	160	1618	4.00	1.70	8.30	420
Agricultural residues*	0.14	$110/ton	300	120	1509	5.00	2.00	7.70	520
				Pyrolysis* ***					
Forest residues	0.23	$125/ton	400	180	1038	2.60	1.30	25.70****	370
Agricultural residues	0.21	$110/ton	400	180	1084	2.70	1.30	0.20****	270

* Feedstock price is for pre-processed feedstock

** Based on default life cycle emission provided in the ICAO document “CORSIA Default life cycle emissions values for CORSIA eligible fuels"

*** Pyrolysis ASTM approval is pending

**** Life cycle emissions obtained from external references; not CORSIA.

3.4.3.2. Feedstock

As shown in sections 2.3.1 and 2.3.2, residues from cropping systems could be used throughout thermochemical conversion processes to produce SAF after a collection and pre-processing system. As demonstrated by Duarte et al. (2014), for setting up a facility using coffee cut stems as feedstock, the transportation costs (Table 44), even using primary roads, highly influence the decision-making process.

Table 44. Annual biomass transportation cost (USD/t-km)[1] between the five main cities of the coffee-growing region (Duarte et al., 2014).

Source	**Destination**				
	Medellin	Manizales	Pereira	Armenia	Ibague
Medellin	28.40	29.10	29.30	29.80	40.10
Manizales	28.40	-	22.30	22.30	30.80
Pereira	31.80	20.60	-	19.50	31.10
Armenia	34.20	16.70	14.30	-	19.70
Ibague	40.10	30.70	27.90	25.90	-

[1] Cost by 2014

Clustered biomass can provide a competitive advantage as long as the density allows efficient transportation. Studies performed by UNAL grouped palm oil industries in six poles. Figure 50 shows the interconnection between poles I, II, III and IV. Table 45 companies link with distances between 90-160 km and available biomass (Cheje, 2023).

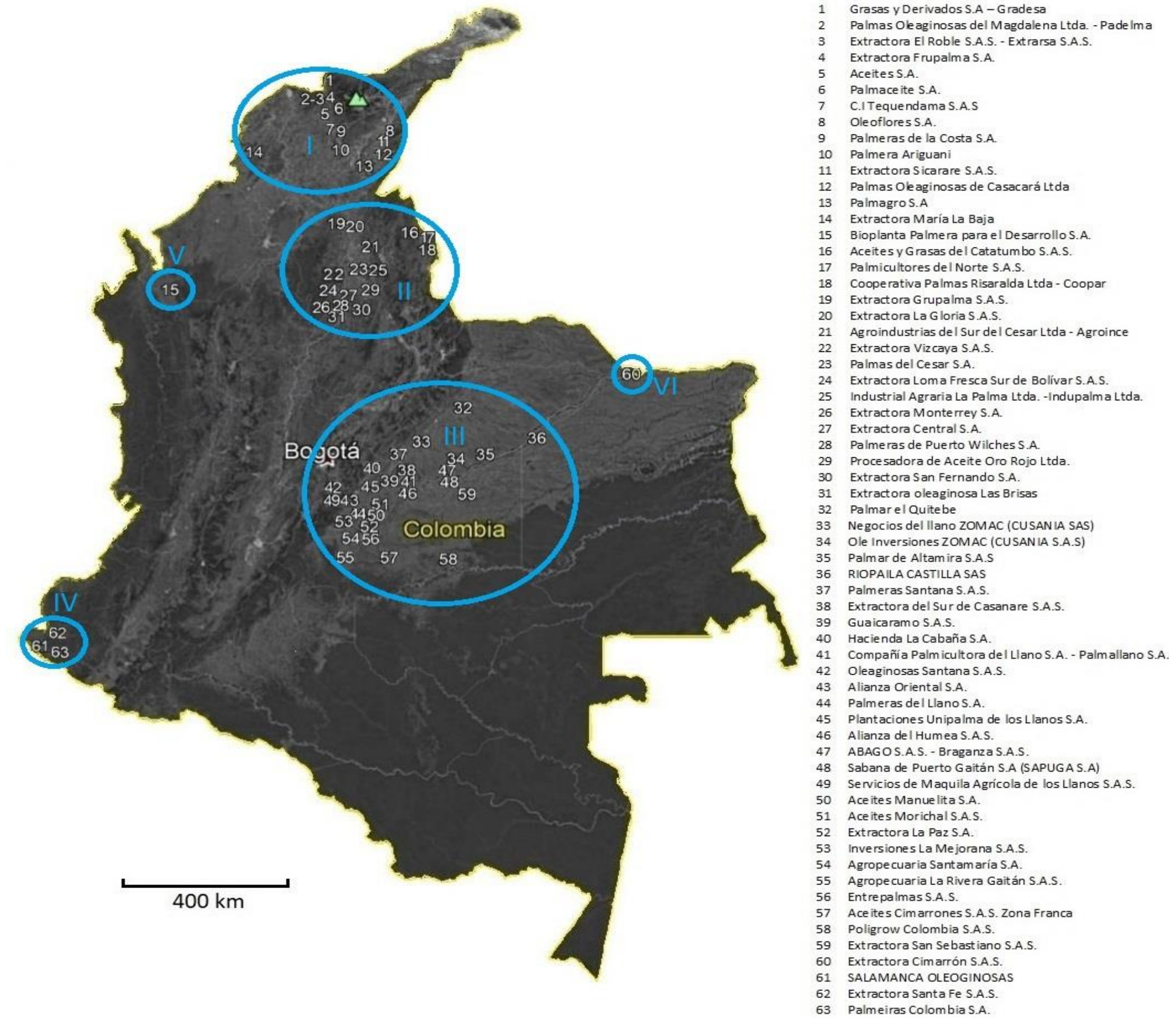


Figure 50. Poles of palm oil industries in Colombia (Cheje, 2023).

Table 45 Companies link with distances between 90-160 km and available biomass (Cheje, 2023).

Pole	Quantity of companies	Distance (km)	Available Biomass (ton/h)			Available biomass (ton/km)		
			Palm husk	Fiber	Kernel	Palm husk	Fiber	Kernel
1	10	120	222,121	52,175	38,645	8,329,546	1,956,560	1,449,180
2	4	90	97,305	22,856	16,929	4,865,242	1,142,816	846,458
3	4	129	138,517	32,537	24,099	4,831,997	1,135,007	840,674
4	9	108	186,630	43,838	32,470	7,776,250	1,826,583	1,352,917
5	10	160	145,633	34,208	25,337	4,095,937	962,111	712,614
6	6	115	118,945	27,939	20,694	4,654,351	1,093,279	809,767

The current supply of wood from the plantations is barely enough to satisfy the demands of the national forestry industry. Therefore, forest plantations for energy purposes should be established exclusively, avoiding affecting plantations to produce wood for the transformation industries (PROFOR, 2017a). An example of this approach is the recent announcement of a partnership between EDF Colombia and Refocosta to develop eucalyptus crop for biomass power generation which will be used by Ecopetrol (Morais, 2023). Some authors (Romero Serrano & Jaime Calvera, 2016) have evaluated the potential of lignocellulosic biomass from fast-growing species in Colombia, identifying 28 lignocellulosic species. Some of these are native or have adapted to the climatic conditions of Colombia. Meanwhile, 10 species do not belong to Colombia but could be adaptable, since they have similar requirements to those established in the country. Table 46 and Table 47 summarize domestic and adaptable fast-growing lignocellulosic biomass with potential as energy crops.

Table 46. Domestic lignocellulosic biomass with potential as energy crops (Romero Serrano & Jaime Calvera, 2016).

Family	Species	Metabolism	Requirements				Physicochemical characteristics					Division		
			pH	T (°C)	Precipitation (mm)	Height at sea level (m.s.n.m)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Dry matter (%)	Ash (%)	Stem (%)	Leaves (%)	Branches (%)
Asteraceae	Cynara cardunculus	C4	6.75 +/- 0.25	16.5 +/- 1.5	450 +/- 50	1935 +/- 285	42.37	33.43	24.20	39.00	11.23	56 +/- 11	5.5 +/- 0.5	18 +/- 2
Euphorbiaceae	Hura crepitans	C4	6 +/- 1	24.5 +/- 4.75	755 +/- 525	2730+/-1230	41.46	31.33	27.21	61.93	8.43	66.5 +/- 2.5	5.5 +/- 2.5	20.25 +/- 0.25
	Pedilanthus tithymaloides		6.25 +/- 0.25	25.5 +/- 4.25	776 +/- 524		38.44	33.55	28.01	14.05	15.23	56 +/- 1	8.5 +/- 1.5	14 +/- 2
Fabaceae	Gliricidia sepium	C4	6.25 +/- 0.75	25 +/- 2.5	1400 +/- 900	800 +/- 450	29.40	46.20	24.40	66.00	10.74	40.3 +/- 3.7	10 +/- 1.6	-
	Leucaena leucocephala		7 +/- 0.5	26 +/- 2	1325 +/- 975		35.00	43.70	21.30	90.30	10.73	55.35 +/- 4.36	5 +/- 3	15.25 +/- 5.26
	Pueraria phaseoloides	C3	4.5 +/- 1	14 +/- 0.5	1600 +/- 4000		48.70	21.00	30.30	22.00	5.30	52.3 +/- 6.8	5.5 +/- 2	-
Lamiaceae	Tectona grandis	C3	7 +/- 0.5	27 +/-1.5	1750 +/- 750	900 +/- 300	28.00	39.00	33.00	53.00	0.90	52.85 +/- 1.85	4 +/- 1	14.75 +/- 1.75
Myrtaceae	Eucalyptus benthamii	C3	5.75 +/- 0.75	20.5 +/- 3.25	1250 +/- 250	1400 +/- 400	47.00	23.00	30.00	66.00	1.30	60.5 +/- 2.5	3.55 +/- 0.45	14.5 +/- 2.5
	Eucalyptus globulus		6 +/- 1	15 +/- 1.5	1150 +/- 350	2700 +/- 500	48.60	23.40	28.00	40.00	0.10	58 +/- 9	21.5 +/- 1.5	16.65 +/- 2.05
	Eucalyptus grandis		5.25 +/- 0.75	20 +/-	1400 +/- 400	1250 +/- 350	33.89	38.89	20.01	41.10	0.56	57 +/- 1	7.5 +/- 1.5	15 +/- 1
	Eucalyptus spp		6.5 +/- 0.5	18 +/- 2	1200 +/- 400	1100 +/- 100	47.00	32.00	21.00	66.00	1.30	67. 5 +/- 2.5	10.5 +/- 1.5	19.5 +/- 0.5
Pinaceae	Pinus patula	C4	6.25 +/- 1.25	15 +/- 2.5	1500 +/- 500	2300 +/- 500	44.75	30.75	24.50	40.00	0.25	65.5 +/- 7.5	7.05 +/- 1.95	14 +/- 2
	Pinus radiata	C3	7 +/- 1	21.5 +/- 4.25	1125 +/- 475	2250 +/- 750	43.00	21.62	35.38	57.00	0.60	52 +/- 1	8.5 +/- 0.5	19.3 +/- 1.3

Table 47. Adaptable fast-growing lignocellulosic biomass with potential as energy crops (Romero Serrano & Jaime Calvera, 2016).

Family	Species	Metabolism	Requirements				Physicochemical characteristics					Division		
			pH	T (°C)	Precipitation (mm)	Height at sea level (m.s.n.m)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Dry matter (%)	Ash (%)	Stem (%)	Leaves (%)	Branches (%)
Leguminosae	Acacia dealbata	C3	6.70 +/- 0.3	17.50 +/- 11.5	700 +/- 300	500 +/- 500	37.00	16.00	25.70	81.60	14.00	59.79 +/- 4.57	-	-
	Medicago sativa L	C4	7.00 +/- 0.5	35.00 +/- 10	900 +/- 300	3200 +/- 800	22.12	23.55	12.70	19.26	10.80	60.3 +/- 2.9	22.7 +/- 1.6	-
Myrtacea	Eucalyptus urophylla	C4	6.00 +/- 1	14.00 +/- 5	1450 +/-950	2500 +/- 500	19.00	24.00	17.00	97.00	1.52	39.5 +/- 7.5	-	-
Paulowniaceae	Paulownia	C4	6.75 +/- 0.75	21.00 +/- 11	600 +/- 100	1400 +/- 600	44.25	24.79	22.61	30.80	1.10	17.7 +/- 3.8	-	-
Pinaceae	Pinus pinaster	C3	5.35 +/- 1.15	18.50 +/- 4.5	1450 +/- 750	1200 +/- 600	43.00	28.00	32.00	17.00	7.60	26 +/- 6	14.8 +/- 1.6	10 +/- 2
	Pinus silvestris L		5.5 +/- 0.50	22.00 +/- 3	1500 +/- 500	1500 +/- 900	52.38	73.30	32.40	26.00	0.70	36 +/- 11	9 +/- 5	16 +/- 8
Poaceae	Miscanthus giganteus	C4	6.5 +/- 1	32.5 +/- 7.5	1250 +/- 250	1000 +/- 1000	25.00	40.50	2.95	43.46	5.70	-	55 +/- 11	-
	Panicum Virgatum		6.2 +/- 2	25 +/- 5	550 +/- 475	750 +/- 450	28.40	19.30	19.30	89.30	8.00	-	42 +/- 8	-
	Switchgrass		9 +/- 0.1	16.75 +/- 3.25	2050 +/- 250	2400 +/- 600	50.00	35.00	35.00	45.60	5.80	-	61 +/- 8	-
	Tripsacum dactyloides		6.65 +/- 1.15	30 +/- 10	500 +/- 250	550 +/- 450	52.00	45.60	45.60	3.90	11.89	-	45 +/7	-

3.4.3.2.1 SAF production potential from palm residues with the FT-SPK process

As noted before, the World Bank has developed a model to estimate the regional potential of SAF production from crude palm oil (CPO) and palm residues (empty fruit bunches (EFB), fibers and shells). The parameters considered in the model were land availability, productivity, availability for SAF production, and pathway. Here, residues are assumed to be converted by the FT-SPK process. Figure 51 presents estimated SAF production from palm residues, where it is possible to observed that Plam production does not necessarily have to increase for residues to be available for SAF production. Furthermore, residue availability is directly proportional to palm production. Consequently, Orinoquia has the greatest potential for FT-SPK production (BANCO MUNDIAL, 2023).

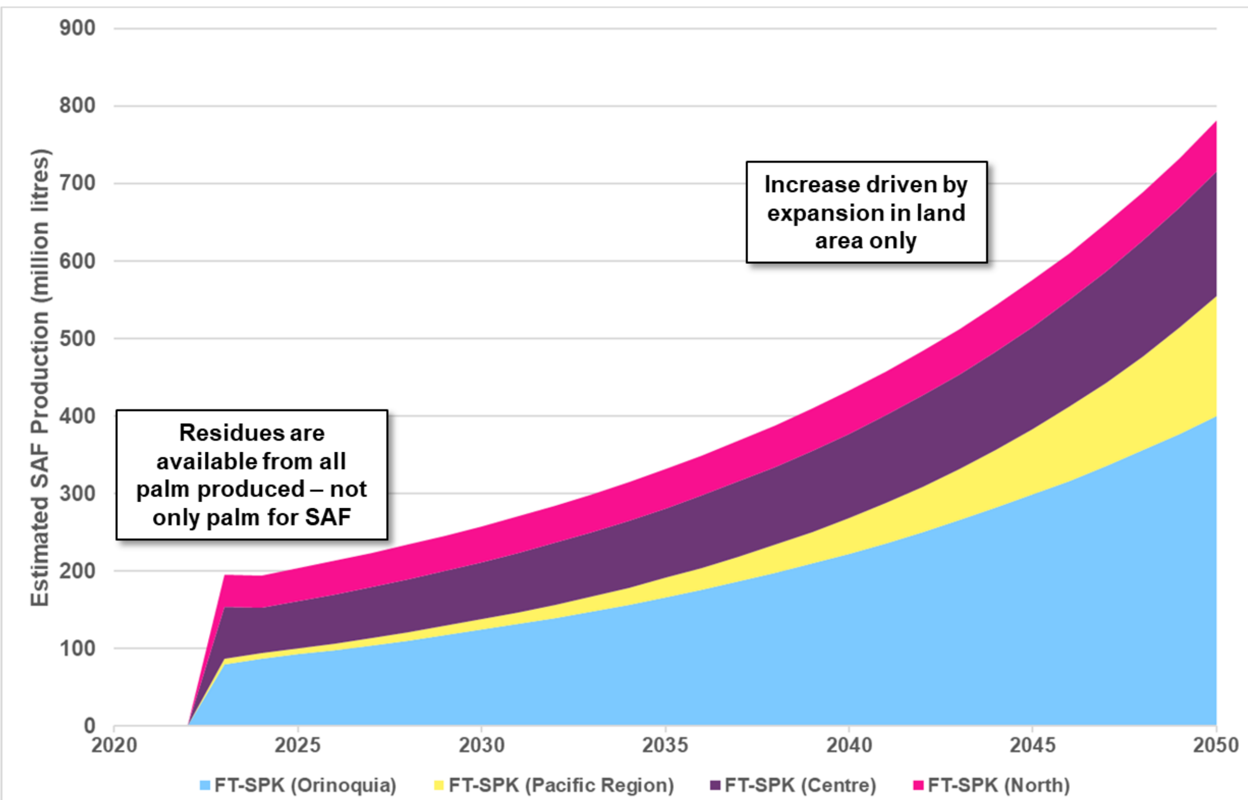


Figure 51. SAF production potential from palm residues with the FT-SPK process (BANCO MUNDIAL, 2023).

3.4.3.3. Sustainability screening

The use of legumes and grasses has the following advantages: they do not compete directly with agriculture for food production; they can be established on marginal soils, degraded soils, or soil unsuitable for agriculture; the production costs of this biomass is lower compared to others; the structure of their tissues is less recalcitrant than that of woody species; and the biomass yields per hectare are very high. Thus, it is possible to cross some of these species to achieve varieties. In addition, a greater production of biomass is possible, are renewable species with several cuts per year, are resistant to stress caused by climatic changes, have high nutritional value, are easy to propagate, have high tolerance to pests and diseases, and can easily adapt to different thermal floors (Ruiz-Colorado et al., 2014).

One study (Ortiz-R et al., 2014) has performed a LCA measuring environmental impacts throughout the life cycle of the cocoa production system using data collected in 2012 from 30 farms between Santander, North Santander, and Antioquia. The LCA considers 1 ha of land planted with cocoa with a projected 25-year life span. Figure 52 shows the global warning potential (GWP, measured in Kg of CO_{2e}) with positive and negative values. The positive values correspond to net CO_2 emissions. The highest environmental impact is from the use of fertilizers, which account for approximately 90-96% of the total life cycle's emissions. Comparing the use of synthetic and organic fertilization, the latter results in negative GWP values. Therefore, the use of organic fertilizer significantly contributes to reducing environmental impacts such as CO_2 emissions. Finally, regarding the phytosanitary management, the total emissions of the 30 farms studied are 932 kgCO_2-Eq, in which herbicides make up 76%, insecticides 22%, and fungicides 1%.

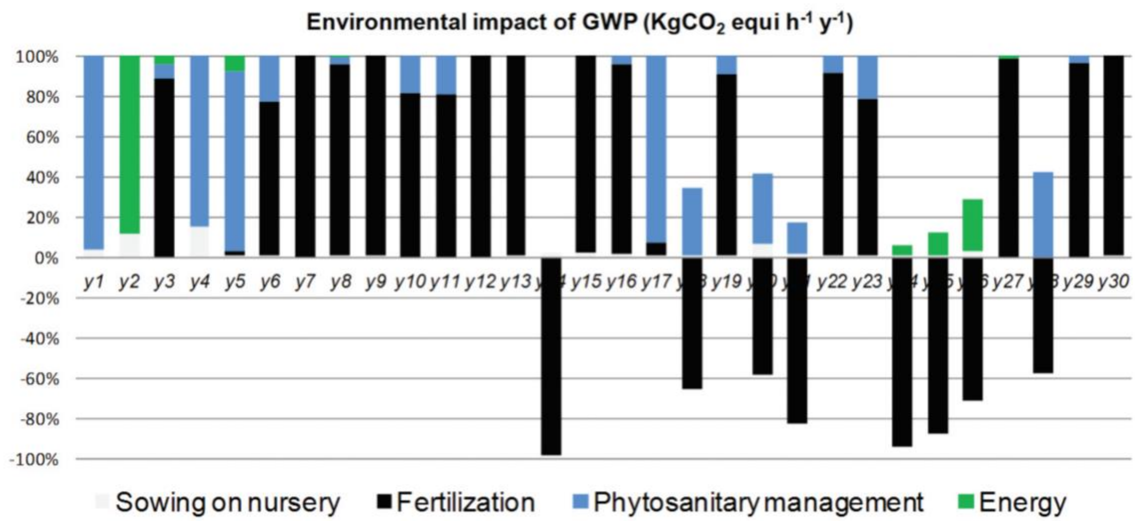


Figure 52. Environmental impact of 30 cocoa's farms in Colombia – a GWP analysis (Ortiz-R et al., 2014).

3.4.4. CO_2 and green energy (PtL)

CCUS have been proposed as an alternative to limiting climate change (IEA, 2021). These technologies include CO_2 capture from point sources. Technologies used for capturing carbon dioxide includes absorption, adsorption, cryogenics, membranes, and microbial/algal systems, and have been described in depth elsewhere (Wilberforce et al., 2019). In some cases, it includes using CO_2 in productive activities such as the food industry, the fertilizer industry, synthetic fuel production, and enhanced oil recovery (EOR). Likewise, these technologies can include bioenergy with capture and storage (BECCS) and DAC, thus reducing CO_2 concentrations in the atmosphere. Table 48 shows the leading carbon capture companies in the world.

Table 48. Leading carbon capture companies (Ahmad, 2023).

Company	Carbon captured per Year (t CO_2)
Global Thermostat	4,000
Climeworks	4,000
CO_2 Solutions by SAIPEM	11,000
LanzaTech	150,000
Carbon Clean	335,745
Aker Carbon Capture	400,000
Carbon Engineering	1,000,000
Quest Carbon Capture & Storage (SHELL)	1,200,000

Carbon Free	800,000,000
CarbFix	1 billion/lifetime

PtL, also known as electrofuels, are drop-in fuels with low-carbon-intensity when produced with hydrogen obtained through the water electrolysis using renewable energy sources (wind, hydro, solar), and waste or DAC carbon sources (CO or CO_2) (IRENA, 2021). The feedstock is processed via FT. Availability of excess renewable electricity is a critical component. PtL has not yet been approved under ASTM D7566. A general process flow for a PtL pathway is shown in Figure 53.

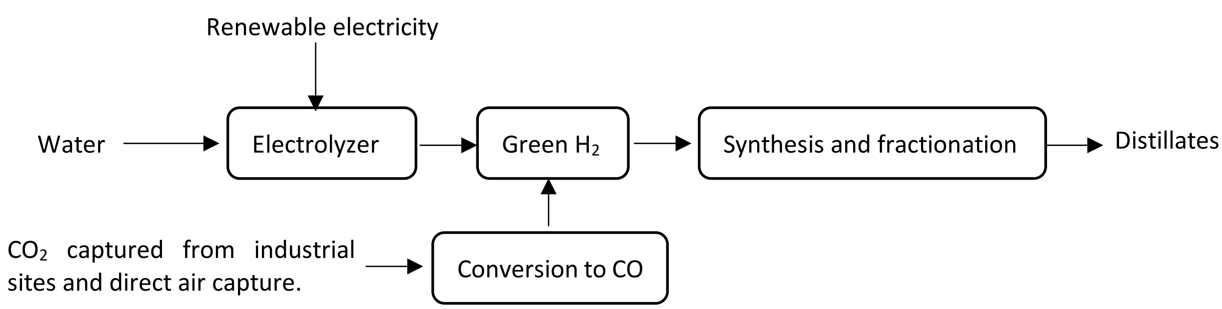


Figure 53. General process flow of the power to liquid pathway.

Companies such as Sunfire GmbH are commercializing this technology and form part of the Norsk e-fuel consortium (IRENA, 2021). Topsoe is commercializing the G2L™ eFuels technology for FT-SPK/eJet (Topsoe, 2022).

3.4.4.1. Economics

Table 49 summarizes the economic information for FT economic data using DAC, and waste CO_2 feedstock and LCA values, assuming nth plant facilities.

Table 49. Summary of Fischer-Tröpsch economic data using various CO_2 feedstock and LCA values(ICAO, 2023d).

Feedstock	**Electricity for H_2 production**	**Yield (tib distillate/ton feedstock)**	**Feedstock price**	**Total capacity (million L/year)**	**SAF production (million L/year)**	**Total Capital investment (million $)**	**Capital cost ($/L total distillate)**	**MSP ($/L)**	**Life cycle emissions (gCO_{2e}/MJ) ***	**Abatement cost ($/$tCO_{2e}$)**
CO_2 from direct air capture (DAC), H_2	Wind	0.24	$300/t, $6/kg	1000	200	3366	3.4	4.4	7	1390
	Solar								25	1780
	Grid								279	No CO_2 abatement
Waste CO_2, H_2	Wind	0.24	$300/t, $6/kg	1000	200	3209	3.2	3.5	31	1510
	Solar								49	2190
	Grid									

* Life cycle emissions obtained from external references; not CORSIA

3.4.4.2. *Feedstock (ethanol plants, refineries, cement plants, others)*

Industries that facilitate equipment installation for carbon capturing and transportation are high-emission fixed sources with centralized activities (Wilberforce et al., 2019). According to some scholars (E. Yáñez et al., 2020), Colombian industrial sectors with concentrated and/or high CO_2 emissions include oil, cement, power generation, and ethanol distilleries. These sources add up a total of 17,810,435 tCO_2/year, equivalent to 356 tons of CO_2 in the lifespan of 20 years (Table 50.). 55% of CO_2 emissions come from the refineries, but the major CO_2 concentration is from the ethanol production (94%) (A. Duarte et al., 2022; E. Yáñez et al., 2020).

Table 50. Inventory of potential CO_2 sources in Colombian industry and CO_2 concentration (A. Duarte et al., 2022; E. Yáñez et al., 2020).

Sector	CO_2 emissions from sources	CO_2 concentration
Refineries[1]	55%	7% -94%
Cement	23%	47%
Power generation	15%	40%
Ethanol	4%	94%
Natural source of CO_2	3%	94%

[1] Emissions from Barrancabermeja and Cartagena refineries.

3.4.4.3. *Sustainability screening*

There are environmental impacts associated with the manufacturing of inputs necessary for carbon capture. For example, the production of amines for CO_2 capture, which is the most mature technology for capture processes, results in the formation of carcinogenic compounds, secondary aerosols that affect the ozone layer, and hazardous waste of amine-based solvents (Escobar Carbonari et al., 2021).

3.5. Colombian approaches to the production and use of SAF

Various organizations must be considered to transfer SAF literacy, identify raw materials, work on regulatory and political frameworks, supply chain design, and market development for SAF production, such as government, airlines, Ecopetrol, Colombian Biofuels Federation (Fedebiocombustibles, representing its abbreviation in Spanish), feedstock producers associations (Fedepalma, Asocana, and Fedecacao), and academia. This section presents a brief overview of efforts, perspectives, and needs expressed for those organizations.

3.5.1. Government

Since 2021, the Colombian government has made efforts related to SAF. Table 51 summarizes advances and developments by the government.

Table 51. Overview of Colombian governmental initiatives, legal framework, and documents.

Year	Initiative/Document	Observation	Reference
2021	Law 2169 of 2021	Climate action law. "The national government, through the Mines and Energy Ministry and the Transportation Ministry, will promote the development and use of sustainable aviation fuels (SAF), to contribute to the reduction of greenhouse gas emissions from the transport sector."	Ley 2169 de 2021 (2021)
2021	MOU- Agriculture ministry and Alder Fuels	The announcement done at the COP26 stated: "Colombia will tap into its agricultural infrastructure and incentivize local farmers to supply biomass feedstock for conversion into sustainable low-carbon crude oil. Alder will then use its refining process to convert forestry and crop residue, as well as regenerative agricultural crops into drop-in replacement 'green' crude used for producing aviation fuel."	MinAgricultura (2021); Moss (2021)
2022	Consejo Nacional de Política Económica y Social (CONPES) 4075 Energy Transition Policy	The Ministry of Energy and Mines "will establish the sectoral road map for the consolidation of the use of first generation biofuels, as well as for the definition, analysis, design, evaluation and formulation of guidelines and regulations for the promotion of the alternative use of biofuels and to carry out pilot projects of biofuels of a temporary nature, in which the requirements or demands of relevant aspects for the use of renewable diesel,	Aerocivil (2023)

		biojet, Sustainable Aviation Fuels (SAF), or other sustainable fuels will be established.”	
2023	National Development Plan for 2022-2026	The document reflects the national government's road map and indicates that it “will promote the development and use of SAF sustainable aviation fuels, as a contribution to the reduction of greenhouse gas emissions from transport.”	Departamento Nacional de Planeación (2023)
2023	Aerocivil – Cielos limpios	Aerocivil is leading a SAF roundtable aiming to build a SAF roadmap	Aerocivil (2023); Aerocivil (2023)

The Ministry of Energy and Mines opened a consultancy for the diagnostic study and roadmap formulation to produce SAF (Camargo, 2023). It identified the regulatory framework to be a key challenge (Camargo, 2023). Some progress has been madel until December 15, 2023, the technical regulation that adopts the requirements and quality parameters of aviation fuels for turbine-type engines was open for public comments (MinEnergia, 2023).

Green taxonomies are understood as a classification system or set of criteria to identify if an asset, economic activity, project, or investment contributes to the fulfillment of environmental objectives prioritized by a country or region and to what extent they do so (Government of Colombia, 2022). Colombia’s taxonomy includes asset-level disclosures in the financial sector to provide a transparent understanding of the financial instruments for green activities and to promote the green bond market. One of the critical issues these jurisdictions tackle by including activity, asset, and entity-based metrics within their taxonomies is the reduction of greenwashing. Colombia is advancing towards linking its national measurement, reporting, and verification (MRV) system for climate finance with its taxonomy to assist with the monitoring, reporting, and verification of sustainability aligned financial flows (Center for Clean Air Policy (CCAP) & Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2022). According to the Colombian green taxonomy, the manufacturing of biomass, biofuels, and biogas is an economic activity and asset in the energy sector with substantial contribution to the climate change mitigation goal. the eligibility criteria and compliance requirements are described elsewhere (Government of Colombia, 2022).

3.5.2. Colombian Air Force

The Colombian Air Force (FAC, its acronym in Spanish) has played integration, research, and leadership roles. Regarding research, FAC and the universities associated with its projects focus on various elements, such as the identification of critical political, economic, social, technological, environmental, and legal aspects for SAF implementation in Colombia and their integration as a business model; supply chain design; and minimum selling price estimation (López Gómez et al., 2023)

3.5.3. Airlines

In 2021, IATA established an industry-wide commitment to achieve net-zero carbon emissions by 2050. This agreement has been echoed by Colombian members of IATA, who have collectively established similar goals considering their individual capacity and future growth plan. However, Colombian airlines recognize that the net-zero objective will be met through a combination of maximum elimination of emissions at source, and the use of approved offsetting and carbon capture technologies. The key elements of the emissions reduction strategy are:

- The use of SAF sourced from feedstocks that do not degrade the environment, or compete with food or water.
- Investment in new aircraft technology, including radical new aerodynamic and alternative propulsion (electric or hydrogen) solutions.
- Continued improvement in infrastructure and operational efficiency, with a particular focus on improved air traffic management.
- The use of approved offsets, including carbon capture and storage technology.

The development and deployment of SAF in Colombia are critical to achieve the industry's climate goal. Policy interventions to leverage activities in research, production, and deployment of a national production capacity to support the commercialization of SAF should be undertaken and ensure:

- Reducing the cost of SAF, as currently the cost differential with conventional jet fuel is higher, making it unfeasible to sustain an accessible and affordable industry for all.
- Adherence to international sustainability criteria adopted by the ICAO to maximize the environmental co-benefits of Colombia’s national SAF production and commercialization to the international markets.
- Expanding SAF supply and end use through support for national feedstock and production levels. This will ensure diversification of production capacities and exploit the country’s potential to produce a wide range of SAF from different sources.

Conversely, the successful deployment of SAF in the country will require the coordinated and combined efforts of the entire industry and significant government support. Airlines cannot do it alone, nor can any other stakeholder within the aviation ecosystem, including governments, who have a critical role in supporting the industry on the road to net zero. This is a challenge that will require collective engagement toward a goal that is greater than the sum of its parts.

3.5.4. Ecopetrol Holdings

Ecopetrol has contemplated SAF production as part of their growing energy transition strategy. They evaluated alternative refining points (GRC in co-processing and GRB as a dedicated plant), technological routes with different raw materials, and the supply chain (Ecopetrol, 2023a, 2023b).

The company has studied the HEFA pathway. This route is a TRL9 technology and is compatible with the current fuel production chain. Palm oil, used cooking oil (UCO) and animal fats are considered as raw materials, and proposed to be co-processed in diesel hydrocracking units to obtain jet + SAF. However, the challenges are asset integrity (corrosion), H2, and renewable traceability (Ecopetrol, 2023b).

Although biomass pyrolysis is a mature technology, the hydro-pretreatment to produce bio-oil is a technology with TRL6. For Ecopetrol, this route presents the advantage of the affinity that exists with hydroprocess units. However, it presents challenges such as its technological maturity, the lack of valorization of byproducts such as biochar, bionaphtha, and HVO, as well as the lack of recognition by ASTM. Regarding biomass gasification, water gas shift (WGS), and FT, it has the advantage that there are synergies of gasification technology with HEFA technologies. However, the technological maturity, availability of raw material, valorization of byproducts such as bionaphtha, HVO, and the requirements of H_2 have been identified as a challenge for Ecopetrol (Ecopetrol, 2023b).

In the ATJ route, Ecopetrol considers two processing routes. The first is thermochemistry and the other is through the enzymatic hydrolysis of biomass pretreated with acid/base. In the first, the gasification of pelletized or torrefied biomass is considered, which is then treated with syngas, and subjected to hydrogenation, and finally, SAF is produced. In the second, after enzymatic hydrolysis, the sugars are fermented until a final fermentation step for the SAF selection. Although the first route has the advantage of being a technology with TRL9, the main challenge of this route is the H2 requirements in the oligomerization and hydrogenation steps. The second fermentation of SAF so far is only with TRL5 (Ecopetrol, 2023b).

Colombia currently has a supply chain for jet fuel. The national jet fuel is sold through refineries in Barrancabermeja and Cartagena, and is transported by pipeline. The imported jet fuel is sold in ports and collected in tank trucks by customers. The supply of fuel at the different airports is carried out by wholesale and retail distributors. In the SAF production alternatives at the Barrancabermeja refinery, it is projected that there will be distribution in a refinery mesh by pipeline and tank trucks. For the Cartagena refinery, distribution in a refinery mesh by pipeline and local delivery is planned (Ecopetrol, 2023a).

3.5.5. Fedebiocombustibles

Fedebiocombustibles represents 90% of the biodiesel and 100% of the bioethanol produced in Colombia(Fedebiocombustibles, 2023). Fedebiocombustibles identified current first-generation feedstock and its residues, agricultural and forestry residues, MSW, and suitable cropping land suitability as assets for SAF production (Fedebiocombustibles, 2023). They have facilitated knowledge transfer by organizing conferences. For them, developing a regulatory and institutional framework is necessary to secure SAF deployment. These frameworks required clear objectives, an agnostic position towards feedstock and technologies, financial incentives, and local certification schemes (Fedebiocombustibles, 2023).

3.5.6. Possible producers

As presented in section 2.2.2.3, Colombia has multiple ethanol and biodiesel producers with the potential of producing SAF. Ecopetrol, BioD and DAABON group have shown a clear interest in expanding their biofuel portfolio, including SAF.

BioD is the largest biodiesel producer in Colombia. In 2023, BioD and LATAM formed a partnership to advance and promote the development SAF, which includes plans to construct a SAF production plant in Colombia, starting in 2025, with an initial investment of USD 700 million and an estimated production of 50 million gallons using agricultural residues, forestry residuals, and energy crops (Diaz, 2023). BioD has identified the following as key elements for SAF deployment in Colombia: the development of regulatory and policy frameworks in the upstream and midstream of the SAF supply chain, domestic GHG goals setting, and a clear GHG accounting system between domestic/international/regulatory/voluntary markets (BioD, 2023a).

3.5.7. Feedstock producers

Colombia has a strong producer association system. For SAF production matters, some relevant associations are the Palm Oil Federation (Fedepalma), the Sugarcane Association (Asocaña), and the Cacao Federation (Fedecacao). While Fedepalma and Asocaña have been participating actively in various SAF stakeholders' roundtables, Fedecacao is yet to be involved. Fedepalma accompanied and shared information for two studies developed by the World Bank regarding SAF (ISCC, 2024), and has been engaged in various academic studies to stablish the sustainability of palm oil production in Colombia (Ramirez-Contreras et al., 2022).

3.5.8. Colombian Hydrogen Association

The Colombian Hydrogen Association, established in 2021, has been participating in the SAF roundtables because hydrogen is a natural component since it is critical for SAF production. As mentioned in section 2.2.5, multiple projects with the potential to produce hydrogen at a competitive price are planned in various regions (Hidrogeno Colombia, 2023).

3.5.9. Academia

A pool of public and private universities has worked independently or in agreement with public and private organizations on renewable liquid fuel production (including feedstock), quality, supply chain, sustainability, economics, and finances, with a strong focus on regional considerations. Some studies are foundational or transferable to SAF; however, SAF-specific projects are nascent. The collaboration between various universities and Colombian aero spatial force (FAC for the Spanish acronym) stands out among SAF-specific projects. The development and deployment of SAF will require robust and multi-disciplinary projects that facilitate knowledge among stakeholders and provide sound answers that could reduce risk at different levels. Furthermore, public and private funding might be required.

4. Situational Analysis

54 summarizes the strengths, weaknesses, opportunities, and threats (SWOT) analysis for the development of SAF in Colombia based on the information gathered and presented in this document. While Colombia has important strengths and opportunities, it also has strong weaknesses, making the production of SAF currently unfeasible. Until now, no single feedstock or technology pathway will likely provide SAF in the near term, complying with CORSIA requirements, without a considerable effort on sustainability analysis, energy cropping advancement, yield technology improvement, supply chain design, and policy development. However, palm oil, sugar cane, and MSW can provided the fastest path. Crucially, government cohesion for developing a strong, sufficient, and long-lasting regulatory and policy framework is imperative. This analysis is in line with the findings of other studies (López Gómez et al., 2023; BANCO MUNDIAL, 2023).

Strengths

Colombia
- Liquid fuel demand growth
- Suitable cropping land availability
- Oil palm, sugarcane, and municipal solid wastes are potential sources of feedstock in the short and medium term
- Experience in developing policy frameworks, agroindustrial supply chains, and biofuel production
- Continuous communication among interested parties
- Skilled and technical labor
- Initiation of technical studies
- Feedstock, biofuel, and fossil-fuel producers, as well as local investors are interested in producing SAF

From SAF
- SAF has a sustainability and technical framework
- Commercial and near commercial technology

Market
- Growth of the domestic aviation sector
- Global customer demand

Weaknesses

Feedstock, conversion, and infrastructure
- Low sustainability perception of palm oil
- No Colombian palm oil or other potential native feedstock default values in CORSIA
- Scarce transportation infrastructure in areas with the highest suitable cropping land availability
- Limited cost-effective transportation between probable SAF production areas and airports
- Limited research on tropical feedstock portfolio for SAF production
- Low yield of the GFT and ATJ feedstock
- Feedstock, technology, and operational risk
- Aggregated residual biomass (e.i., bagasse, rice husk) has a market in agricultural and industrial applications

Regulations and Policies
- Lack of a regulatory framework for SAF
- Low value of Colombian tax credit
- Low availability of goverment funds to generate adequate incentives
- Uncertainty of international policy support
- Dependence on policies and regulations
- Aviation sector emission reduction goals do not include the use of renewable fuels

Market
- Higher SAF cost relative to jet fuel

Opportunities

International
- Support from international entities (e.g., multilateral organizatons, ICAO) and countries
- Corporate interest in SAF acquisition
- Intention of requesting feedstock default values to CORSIA-CAEP as Latin America block

Colombia
- Energy transition climate
- Rural job creation
- Industrial development

Threats

- Limited government cohesion
- Regulatory changes
- Climate change and its impact on agriculture
- Supply chain disruption due to transportation infrastructure limitations

Figure 54. Strengths, weaknesses, opportunities, and threats (SWOT) analysis for the development of SAF in Colombia.

An initial step to overcome current pitfalls is the assessment and adaptation to a Colombian Technical Norm (NTC is the Spanish acronym) of the ASTM 7566 and ASTM 1655, as well as the preparation and certification of laboratories to conduct the physicochemical tests required by such standards (BANCO MUNDIAL, 2023). The Colombian Institute of Technical Standards and Certifications (ICONTEC is the Spanish acronym) established an NTC (6546) for the Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ICONTEC, 2023)

As with any new energy supply, SAF requires strong policy support, especially in the early years. The amount and strength of such policies might vary depending on whether SAF production aims to develop a new industry supplying the international or domestic market, with corresponding emissions reductions. Support for SAF should, at minimum, be equivalent to policies supporting other transport and energy sectors. However, priority attention is merited because aviation does not have renewable alternatives to high-energy dense liquid fuels. The following are the top recommendations.

- Urge state energy planning efforts to recognize the need for renewable aviation fuels and develop multi-ministerial integrated strategies to ensure a systemic policy framework.
- Urge agencies to provide a regulatory framework for SAF.
- Urge agencies to facilitate the allocation of international cooperation aid to finance policies focused on SAF.
- SAF supply chain development can provide environmental and social services, and energy (Martinez-Valencia, Garcia-Perez, et al., 2021). Policymakers should align the country's strategy and needs with the services provided for developing and utilizing SAF (e.g., job creation, air quality, waste reduction, and GHG reduction).
- Ensure coverage of aviation fuels under existing programs.
- Urge stable, long-term, cumulative, feedstock and technology-neutral government policies for the SAF industry to grow and thrive. Well-integrated, consistent policies will help mitigate critical risks for feedstock growers and producers when undertaking a new feedstock or technology. Dependable, coordinated policies are essential to provide access to capital and feedstock.
- Targeted resources and policies for incentivizing research and development to accelerate advanced biofuels for the aviation sector.

Although palm oil could be identified as a feedstock for domestic use, it is advisable to request the default iLUC and CORE LCA values for Colombian palm oil from ICAO. These default values are required to access the CORSIA market. Similarly, any identified promising feedstock not included in CORSIA would require default values.

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
Colombian_overview		

4. Title and Subtitle	5. Report Date
Sustainable Aviation Fuel Production in Colombia: Opportunities and Challenge	2024
	6. Performing Organization Code
7. Author(s) Lina Martinez-Valencia and Claudia Valderrama-Rios,	8. Performing Organization Report No.
9. Performing Organization Name and Address Center of Excellence for: Alternative Jet Fuels and Environment Washington State University, Pullman, WA 99164	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 13-C-AJFE-WaSU-037
12. Sponsoring Agency Name and Address Federal Aviation Administration Office of Environment and Energy	13. Type of Report and Period Covered Report 14. Sponsoring Agency Code

15. Supplementary Notes

DOI: https://doi.org/10.7273/000006281

16. Abstract

The sustainable aviation fuel (SAF) working group in Colombia was convened under the SAF Global Supply Chain Development project (Project A93) led by the Federal Aviation Administration’s (FAA) Center of Excellence for Alternative Jet Fuels and Environment, also termed the Aviation Sustainability Center of Excellence (ASCENT) and executed by Washington State University. The working group includes stakeholders across aviation, biofuel production, agriculture, government agencies, academic research, and technical consultancies. A complete list of stakeholders is included after the cover page. This group recognizes that developing SAF requires gathering knowledge and insights across multiple sectors, such as academia, private enterprise, local and federal governments, as well as multilateral, environmental, and energy advocates. This report serves as a high-level information identification to be use as starting point for designing and analyzing the supply chain to produce SAF in Colombia.

17. Key Words	18. Distribution Statement
ASCENT	Open Access

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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