POLITECNICO DI TORINO

Collegio di Ingegneria Elettrica ed Energetica

Corso di Laurea Magistrale
in Ingegneria Energetica e Nucleare

Tesi di Laurea Magistrale

Sustainable Development of Biofuels in Kenya: Opportunities and Constraints

Relatori

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Abstract

The objective of this thesis is to analyse the current sustainable biofuels market in Kenya and to assess the sector's growth potential in the coming years, with particular emphasis on liquid biofuels. Starting from a comprehensive analysis of the national energy balance and the legislative framework, this study analyses potential production capacities across the country, taking into account local resource availability, national production strategies, ongoing investment plans, and existing legislative frameworks. Particular attention is given to variability in biomass resources, technological readiness, and policy commitment to bioenergy development. By integrating these factors, the study provides a realistic estimation of production potentials under different development scenarios.

The large availability of renewable resources in the country enables Kenya to meet over 80% of its electricity demand and roughly 17% of its total energy supply through clean energy sources. However, traditional biomass production and consumption remain critical issues for Kenya, accounting for approximately 62% of the Kenyan's energy mix, primarily serving cooking and heating needs in rural areas. In addition, the entire energy demand of the transport sector relies on imported petroleum products, thereby undermining the country's energy autonomy and requiring substantial financial expenditure and risks as regards country's energy security. Within this context, biofuels can play a significant role in accelerating the energy transition and enhancing national energy independence. Despite significant progress in regulatory frameworks and feedstock assessments, biofuel production and distribution in Kenya remain at an early, largely non-industrialised stage. Scaling up to full commercial deployment requires investments in technologies and green processes, and a detailed understanding of local supply chains and institutional drivers, necessary to develop and support a stable market environment.

In this study, medium- to long-term biofuel production targets are identified, defined in accordance with studies conducted in Kenya and with realistic production capacities. The most suitable feedstocks for achieving the production targets are selected based on the country's geographical characteristics and agricultural experience. Considering typical agricultural yields, the land occupation required to ensure adequate feedstock availability for the targeted biofuel production is estimated. Finally, a comparison is carried out in terms of environmental impact between the energy sources currently used in Kenya and the biomass-based alternatives

presented in this study, assessing the greenhouse gas emissions avoided through the adoption of more sustainable solutions.

This study confirms Kenya's large potential to play a significant role in the production of liquid biofuels, pursuing the dual objective of domestic decarbonization and increased energy independence. Biofuel production in Kenya aligns with the global growth trend observed in recent years, which has been particularly driven by energy transition targets and by the lack of viable alternatives in key sectors, such as aviation. In this way, Kenya can secure a prominent position within international market dynamics, potentially becoming a supplier of liquid biofuels to other African countries and fostering regional sectoral growth, as well as to other continents where the biofuels sector is already well established and demand continues to increase steadily.

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List of Abbreviations

ASAL	Arid and Semi-Arid Land
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2eq	Carbon Dioxide Equivalent
EPRA	Energy and Petroleum Regulatory Authority
FAME	Fatty Acid Methyl Ester
FFA	Free Fatty Acid
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GW	Gigawatt
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HVO	Hydrotreated Vegetable Oil
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LUC	Land Use Change
MW	Megawatt
NDC	Nationally Determined Contributions
NEMA	National Environment Management Authority
REREC	Rural Electrification and Renewable Energy Corporation
SAF	Sustainable Aviation Fuels
TRL	Technology Readiness Level
UCO	Used Cooking Oil
USD	United States Dollar

1. Introduction

Biomass is the oldest energy source known to humanity. Since human beings first learned to ignite fires for cooking and lighting, biomass has been a fundamental component of daily life and has accompanied societal development up to recent centuries. From the industrial revolutions onward, however, the energy paradigm shifted, and fossil fuels gradually took precedence. Coal first, and subsequently oil and then natural gas, proved to be more efficient and economically advantageous sources of energy, ultimately influencing and shaping modern society. Today, fossil fuels account for approximately 80% of total energy supply (IEA, 2023), 95% when considering only the transport sector, while also remaining an essential feedstock base for the chemical and materials industries (IEA, 2025).

Nevertheless, the massive extraction and use of fossil fuels over recent decades have generated significant environmental impacts, which lie at the core of climate change. This has led to the need to limit reliance on fossil sources and to replace them with cleaner forms of energy. Renewable energy sources, such as solar and wind, have emerged in recent years as viable alternatives to natural gas and coal for electricity generation. Technological progress and economies of scale have made renewable technologies competitive not only from an environmental perspective but also from an economic one. Today, in several countries worldwide, electricity generated from renewable sources exceeds that produced from fossil fuels.

However, not every aspect of the energy transition can be addressed by electrification. The hard-to-abate sectors are particularly energy-intensive and require a viable alternative to fossil fuels with similar or identical physical and chemical characteristics. In this context, biofuels can complement the energy transition in those sectors where electrification remains more costly or technically challenging, such as heavy transport and industry. A biofuel is defined as any hydrocarbon fuel produced from organic matter, whether living or recently living, within short timeframes measured in days, weeks, or months. This stands in contrast to fossil fuels, which require millions of years to form.

Global biofuel production expanded rapidly from the mid-1990s onward, driven by government subsidies and mandated blending requirements. This growth responded to concerns regarding fossil fuel supply security and environmental degradation, as well as to the recognition that biofuels could contribute to mitigating GHG emissions and addressing climate change. In 2024, biofuels accounted for approximately 1.3% of global energy consumption and

4% of transport sector demand, led primarily by the United States, Brazil, and European countries (IEA, 2025). According to current estimates of IEA, biofuel consumption is expected to double by 2030 and quadruple by 2035 compared to 2024 levels. By 2035, if previsions will be respected, sustainable fuels, including hydrogen based synthetic fuels, could cover 10% of road transport, 15% of aviation, and 35% of maritime transport (IEA, 2025).

In addition, biofuels hold significant strategic importance, as they reduce dependence on fossil-based products, which in most cases are imported. Approximately 80% of global oil production is concentrated in only ten countries. The limited geographical availability of fossil fuels makes their supply subject to geopolitical agreements with major producing nations. Biofuel production potential, by contrast, has generally a lower variability across countries, thereby reducing petroleum imports and enhancing the valorisation of domestic resources.

Moreover, when biomass, defined as organic material primarily derived from plants, is used to produce alternative fuels, plants absorb carbon dioxide during growth through photosynthesis over relatively short timescales. The carbon emitted during combustion is subsequently reabsorbed by new plant growth, thereby creating a closed carbon cycle. Ideally, under this framework, no additional carbon is introduced into the biosphere. The figure 1.1 shows a simplified comparison between the carbon cycle of biomass and fossil fuels.

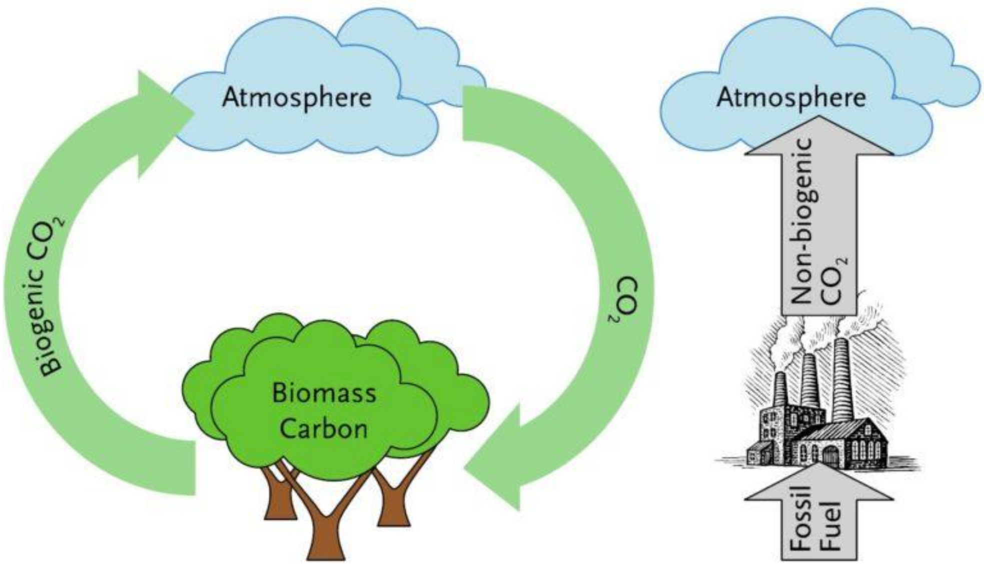

Figure 1.1 – Fossil and biogenic emissions of CO2 (IEA Bioenergy, 2026)

Today, most feedstocks used for biofuel production are food crops, such as maize converted into ethanol and soybean processed into biodiesel. Concerns were therefore raised regarding the potential negative environmental impacts of these first-generation biofuels. Second-generation biofuels are generally derived from non-food sources, including woody crops, agricultural residues, and organic wastes, which are more complex to process and convert into fuel. In this case, land consumption is minimised and food conflicts are avoided since the feedstock is a waste or a secondary product, but advanced conversion technologies are required and the costs increase. In the recent period, a third-generation and a fourth-generation biofuels, related to the production of biofuels from algae and advanced chemical processing, caught the attention of researchers and investors (Devi, et al., 2023).

However, compared with conventional fossil fuels, biofuels are generally more expensive, which limits their widespread adoption. Although thermochemical treatment and biomass conversion processes can be economically viable, feedstock production and collection represent the costliest stages of the supply chain. Due to the length and complexity of the agricultural value chain, feedstock procurement costs can account for up to 70% of the final biofuel price (Machandi, 2021). Conversely, a opposite dynamic is observed when utilizing residues or waste-based feedstocks, such as UCOs and molasses. In these instances, while the collection phase is significantly faster and cost-effective, the conversion process necessitates additional processing stages and higher capital expenditure to ensure compliance with the stringent quality standards required for biofuel production. It therefore becomes necessary to promote the introduction and use of biofuels through stringent regulation and effective policy frameworks capable of bridging the economic gap with fossil fuels. In 2024, approximately 50% of bioenergy demand was supported by blending mandates, GHG emission limits, or financial incentives, reaching up to 80% in the case of liquid biofuels. These mechanisms contribute to narrowing the economic gap with conventional fuels and, importantly, facilitate long term planning of production, consumption, and market adoption (IEA, 2025).

At present, the most widely used biofuels are bioethanol and biodiesel, which, owing to technological development and market diffusion, have nearly reached cost parity with fossil fuels. According to the U.S. Department of Energy, as of October 2025, the average prices for fossil diesel and gasoline were 0.99 USD/litre and 0.83 USD/litre, respectively. In comparison, B100 (100% biodiesel) was priced at 1.14 USD/litre, while E85 blends (85% ethanol and 15% gasoline) stood at 0.70 USD/litre (U.S. DOE, 2025). In several countries, blending mandates are already in force, requiring the incorporation of biofuels into transport fuels. However, due to the physicochemical properties of biodiesel and bioethanol, these fuels cannot be used in high proportions, typically not exceeding 20% to 30%, in conventional internal combustion engines. As a matter of fact, several leading nations in biofuel production, such as Brazil and United States, have already begun to integrate innovative flex-fuel vehicles, which are engineered to operate on any combination of fossil fuels and biofuels, including fuel blends of up to 100% biofuel content. By contrast, other biofuels commonly known as “drop-in” fuels, such as renewable diesel, exhibit physicochemical properties analogous to their fossil counterparts and can be used in blends of up to 100% without any engine modification.

1.1. Objective of the study

The objective of this thesis is to assess the potential for sustainable liquid biofuel production in Kenya. In emerging economies, biofuels may play significant strategic role, stimulating employment generation, industrial growth, and technological advancement.

In Kenya, the energy sector remains heavily dependent on traditional biomass sources, which constitute over 62% of the country’s total energy supply, and on fossil fuels, accounting for approximately 20% of total consumption (IEA, 2026). The intensive use of traditional biomass is systematically depleting the nation's environmental resources, primarily through deforestation for firewood procurement, and severely impacting public health, with over 5000 annual deaths attributed to indoor air pollution (Dalberg, 2018). Simultaneously, the transport sector is entirely dependent on fossil products, generating over 12 million tonnes of CO2eq annually (Republic of Kenya, 2025). Since Kenya lacks active petroleum extraction sites, the country is therefore compelled to import its entire fuel requirement, significantly undermining its energy independence.

The implementation of a national biofuel production program would enable the country to achieve significant environmental improvements and reduce reliance on fossil sources, while gaining a technical advantage in a high-growth sector and stimulating domestic economic growth. However, establishing a functional biofuel value chain requires fundamental considerations, including the physical availability of feedstocks, the evaluation of conversion technologies, and the identification of the sectors best suited to derive maximum benefit from biofuel integration.

According to recent publications by the IEA, the development and adoption of biofuels in emerging markets require robust policy support and appropriate regulatory frameworks. Specifically, it is essential to establish long-term strategies and clearly defined objectives to stimulate both supply and demand. Concurrently, technical and sustainability standards for production processes must be defined, alongside financial mechanisms and incentives designed to attract investment (IEA, 2025).

Within this study, starting from a comprehensive analysis of the Kenyan energy context and the governing policy framework, medium- and long-term biofuel production targets are defined in alignment with national industrial growth ambitions. Diverse biofuel categories are reviewed, ranging from globally established options to advanced fuels with significant growth potential, to evaluate their constraints and opportunities within the Kenyan context. Finally, a strategic integration roadmap is proposed, identifying achievable targets for the medium and long term. This includes an assessment of the resources required for production, with a specific focus on land use and alternative feedstock availability, and a determination of the carbon intensity of these solutions to calculate the net emissions avoided by replacing the energy sources currently utilized in the country.

1.2. Structure of the thesis

The second chapter presents the geographical context of the study, namely Kenya. The first section provides an in-depth analysis of the Kenyan energy system, highlighting both its strengths and its critical challenges, and presenting key data for the various components of the sector. Particular attention is devoted to electricity generation and renewable resource availability, the role and consumption of fossil fuels, the current importance of biomass, and the potential future role of hydrogen. The second section analyses the legislative framework in Kenya, including acts regulating the overall development of the energy sector and climate change mitigation, as well as targeted policies aimed at implementing concrete actions and coordinating sectoral growth. In particular, *Kenya Vision 2030*, the *Climate Change Act*, and the *Energy Act* are presented, together with the main energy and climate policies derived from them, such as the *Nationally Determined Contributions*, the *National Energy Policy*, the *National Climate Change Action Plan*, the *Bioenergy Strategy*, the *National Cooking Transition Strategy* and the *Kenya Energy Transition & Investment Plan*, all of which are highly relevant to this study.

The third chapter shifts to the more technical component of the thesis, focusing on biofuels. It begins with a general overview of global biofuel use, including selected case studies, followed by a detailed analysis of the Kenyan context. The chapter highlights both the main opportunities and the key challenges associated with biofuel production in Kenya, while emphasizing the strategic role that biofuels could play within the national energy economy. Suitable feedstocks for production are then presented, together with their physicochemical characteristics and cultivation requirements. The different biofuels obtainable from these feedstocks are described, along with their properties and potential end uses in which they could provide added value for Kenya.

The fourth chapter builds upon the information presented in the previous sections with the objective of formulating a concrete and operational strategy for biofuel development in Kenya. The biofuels most suitable for production are identified based on the policies and strategies published by the Kenyan government, and realistic production targets are defined in order to meet the country's energy and climate objectives. Drawing on existing literature and publications from international organizations, selected feedstocks considered appropriate for biofuel production in Kenya are proposed, taking into account production yields, land and resource requirements, and farmers' familiarity with specific crops. Based on the defined production targets, the land area required to achieve such volumes is estimated, and the climate impact of this production is assessed in terms of carbon dioxide equivalent emissions.

Finally, Chapter 5 presents the limitations encountered during the study and outlines potential directions for the development and continuation of this work. Considering the diverse themes addressed within this thesis, three factors of uncertainty are identified that would require a deeper system analysis. Specifically, the assumptions adopted regarding the selection of feedstocks in this study are detailed, alongside the logic governing the definition of the end-use sectors. Furthermore, the possibility of including an economic analysis to accompany the technical-climatic assessment conducted in this research is identified, which would provide even greater validity to the results.

2. Kenya

The Republic of Kenya is a country located in the Greater Horn of Africa, bordering Ethiopia, Somalia, South Sudan, the United Republic of Tanzania, and Uganda. The total area of the country is divided into 47 counties, approximately covering 610 thousand square kilometres, of which about 580 thousand consist of terrestrial land and roughly 30 thousand are inland water bodies. In 2023, the total population exceeded 55 million inhabitants, with a large share residing in rural areas, approximately 70%, while 30% live in urban areas, including more than 4 million people in Nairobi alone, the capital of the country (FAO, 2026). A geographical map of Kenya, including its counties and boarder countries, is reported in figure 2.1.

Figure 2.1 - Kenya geographical map (Kenya Revenue Authority, 2026)

In recent years, the population has grown at an average annual rate of 2% to 4%, and around 37% of the population is under the age of 14 and the median age remains below 20 years.

Nairobi, located in the south-central part of the country, is by far the most populous city in Kenya and the centre of most economic activities. Mombasa, the second largest city, has approximately 1.5 million inhabitants and represents the core of commercial activities due to its strategic coastal location and the presence of the country's largest port. Other important urban centres include Nakuru, Kisumu, and Eldoret, all situated in the southwestern part of Kenya near Lake Victoria, where a significant share of agricultural activities is concentrated. In contrast, most of the northeastern region of the country, except for the coastal areas, is sparsely populated due to harsh climatic conditions that render the land largely unsuitable for permanent settlement.

In 2023, Kenya's GDP amounted to approximately USD 108 billion, with a GDP per capita slightly below USD 2000, although steadily increasing on an annual basis (FAO, 2026). The service sector accounts for about 55% of the national GDP, including tourism, finance, and retail activities, while industry contributes around 17%. Agriculture plays a fundamental role in the country's economy, representing approximately 20% of GDP and 43% of total exports. Officially, 12% of the Kenyan population is employed in the agricultural sector, yet some estimates indicate that up to 70% of total informal labour is engaged in rural areas (National Land Commission, 2023). Out of the total population, nearly 8% live in extreme poverty, defined as less than USD 2.15 per day, and more than one third experience overall poverty, characterized by limited access to adequate food and other basic needs (IEA, 2025). Nevertheless, the poverty rate remains lower than the 42.9% estimated in 2020 and has generally been declining since 2015.

Most economic activities in Kenya are strongly influenced by and highly vulnerable to the impacts of climate change. Agricultural production and livestock activities depend on soil conditions and water availability, while tourism is largely linked to natural experiences and wildlife presence. In general, the increasing intensity and frequency of weather-related disasters in Kenya reduce crop and livestock production, undermine livelihoods, exacerbate conflicts primarily over natural resources, displace communities, and contribute to security threats (Government of Kenya, 2023). This also has negative economic repercussions, as some estimates suggest that, in the absence of adequate mitigation and adaptation measures, the cost of climate change could affect up to 8.5% of the country's total GDP (Republic of Kenya, 2025).

Kenya has undertaken considerable efforts to address its core national development objectives, as reflected in its *Vision 2030*, which aims to transform the country into a newly industrializing middle-income nation with a high quality of life by 2030, within a clean and secure environment (Republic of Kenya, 2007). A significant part of the transformations the country has undergone and will undergo in the coming years concerns the energy sector, which also plays a key role in the government's climate change mitigation goals. Below are reported a detailed analysis of the Kenyan energy system and the legislative framework that coordinates and guides its evolution.

2.1. Energy balance

The energy sector in Kenya is undergoing a continuous transformation, largely driven by the modernization and energy transition policies adopted by the country in recent years. The substantial availability of renewable resources allows Kenya to meet more than 80% of its electricity demand through clean energy sources, thereby limiting the consumption of fossil fuels. The country has declared the objective of achieving 100% electricity generation from renewable sources by 2030, primarily driven by geothermal and hydropower (Republic of Kenya, 2025). Despite the growth in electricity consumption and the expansion of national grid coverage, the current installed generation capacity in Kenya remains limited to approximately 4 GW, roughly 4.2% of total energy supply in Kenya. This highlights the country's continued reliance on alternative energy sources to meet daily energy needs, particularly in rural areas. Owing to recent progress, the electrification rate has reached 79%, extending electricity access to remote areas through grid expansion and off-grid generation systems, predominantly based on solar energy (Government of Kenya, 2023).

The most significant share of energy consumption in Kenya originates from the building sector, which accounts for approximately 68% of total final energy use and is mainly associated with cooking and heating needs (IEA, 2025). In this context, traditional biomass, including firewood and charcoal, remains the predominant energy source and is often obtained through illegal or uncontrolled deforestation practices, generating significant tree cover loss. In addition to that, the use of such resources constitutes a serious public health concern, causing thousands of deaths each year due to the inhalation of smoke and particulate matter from the uncontrolled combustion of biomass (Ministry of Energy and Petroleum, 2024). For this reason, one of the key objectives of the national energy strategy is to achieve a full clean cooking transition by 2028 (Ministry of Energy and Petroleum, 2024). The aim is to completely replace traditional biomass through increased use of LPG and the introduction of safer and cleaner energy carriers such as bioethanol and e-cooking solutions. Where immediate substitution is not feasible, or during the early phases of the transition, the strategy promotes the adoption of more modern and energy efficient biomass forms, such as briquettes and pellets, combined with improved cookstoves capable of significantly reducing harmful emissions.

Following households, the transport sector represents the second largest energy consuming sector, accounting for approximately 20% of total energy demand. In this case, energy consumption is entirely fossil based and fully dependent on oil products imported from third countries, primarily through the port of Mombasa, which hosts a major storage hub and serves as the main distribution point to other regions of the country.

The industrial sector, which accounts for 12% of total energy consumption, ranks third. Industrial activity in Kenya remains relatively limited, as the country's GDP is largely driven by agricultural activities and the tertiary sector. To meet industrial energy demand, coal is extensively used (also as a feedstock for industrial processes), together with electricity, biomass, and petroleum products, which contribute to a lesser extent (IEA, 2025).

When considering energy sources, biomass represents the primary source of energy in Kenya, accounting for approximately 62% of total final energy consumption. Fossil fuels follow at 20%, while renewable contribute around 17% (IEA, 2026). A detailed analysis of the main energy sources currently used in Kenya is presented below.

2.1.1. Power Generation

Thanks to concrete efforts and strategic planning by the Government of Kenya, the national energy sector continues to expand. The EPRA (Energy and Petroleum Regulatory Authority) publishes annual statistical reports on national energy data, highlighting progress compared to previous years. In recent years, electricity generation capacity has grown in parallel with GDP, demonstrating the importance and benefits that increased energy access can provide to both the population and the national economy (EPRA, 2025).

Although electricity generation capacity in Kenya remains modest compared to that of economically developed countries, it has expanded significantly in recent years and is now almost entirely renewable installed capacity stands at approximately 3.84 GW and is predominantly based on renewable sources. Geothermal energy accounts for 25.92% of installed capacity, followed by hydropower at 23.97%. Wind and solar represent 14.12% and 11.98%, respectively, while 17.22% of capacity is still based on fossil sources, including 512.8 MW from diesel generators and 52 MW from gas fired plants. Notably, 4.50% of installed capacity is provided by bioenergy, which constitutes the most widely used primary energy source in Kenya, exceeding 60% of total primary energy supply, although it is mainly utilized by households for heating and cooking. Figure 2.2 presents the installed generation capacity in Kenya, disaggregated by energy source.

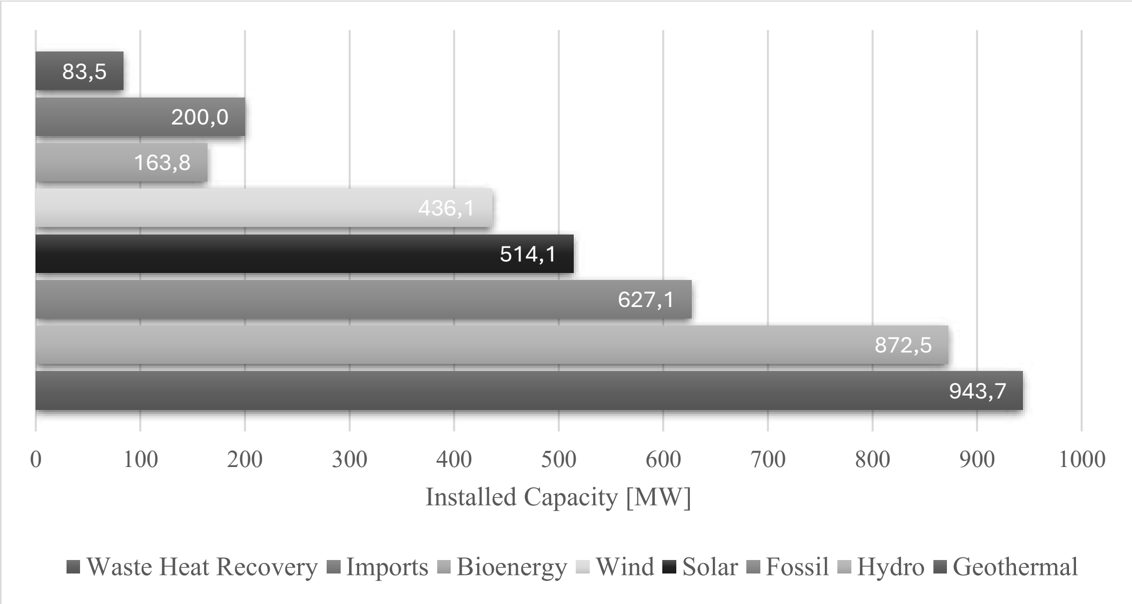

Figure 2.2 - Installed capacity for different energy sources (EPRA, 2025)

The relative contributions of different energy sources change when considering actual electricity generation rather than installed capacity. In the most recent year, locally generated electricity amounted to 14,472 GWh, compared to 13,684 GWh in 2024, confirming an annual growth trend ranging between 4% and 8% (EPRA, 2025).

Geothermal energy becomes even more dominant, accounting for 39.51% of total generation, followed by hydropower at 24.21%. Wind energy contributes 13.18%, while fossil sources and solar decline to 13.18% and 3.27% of the generation mix, respectively. In addition, 10.60% of electricity is imported, mainly from Ethiopia, Uganda, and Tanzania, in order to bridge the demand generation gap (EPRA, 2025). In general, the growth of the power sector and the transition toward renewable energy sources have shown a clear upward trend compared to previous decades. Over the last 25 years, electricity generation in the country has more than tripled from the levels recorded at the turn of the century and the energy mix has also undergone a significant transformation. For instance, in 2000, petroleum-based sources accounted for 53% of total generation, while geothermal energy contributed only 10% (IEA, 2026). The figure 2.3 illustrates the evolution of electricity generation in Kenya over the 2000–2024 period.

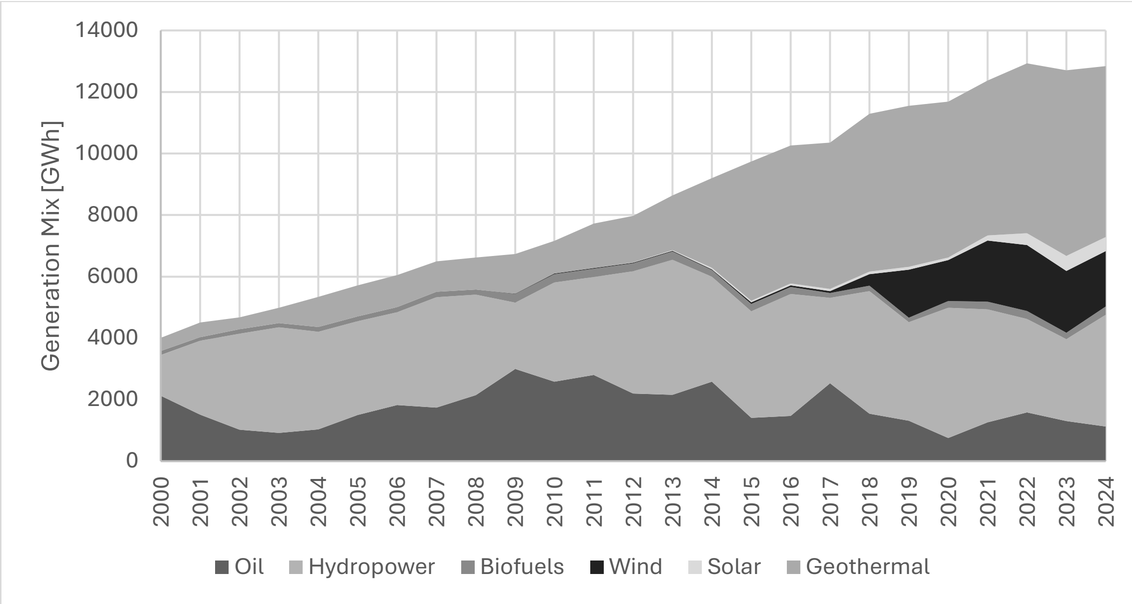

Figure 1.3 - Power generation mix in Kenya under the period 2000-2024 (EPRA, 2025)

It is noteworthy that hydropower has remained relatively stable over time, providing a consistent baseline of renewable generation. In contrast, a rapid expansion of geothermal energy is observed between 2010 and 2015, coinciding with the beginning of the fossil fuel phase-out. While the contributions of other renewables, such as wind and solar, have only become significant in recent years, substantial growth is projected for the near future.

Overall, 80.78% of electricity generated in Kenya originates from renewable sources. Until 2010, fossil fuels accounted for approximately 35% of the electricity mix, but their contribution has steadily declined, primarily due to the expanded use of geothermal and hydropower generation. Geothermal energy is increasingly employed for base load electricity generation, enabling Kenya to maintain and strengthen its reliance on renewable energy while expanding generation capacity to meet the targets of 100% renewable electricity generation and universal electricity access by 2030. As a result of sustained electrification efforts, electricity access has increased from 37% to 79% over the past decade (Government of Kenya, 2023).

Annual electricity consumption in Kenya amounts to 11,330 GWh, of which 66.50% is attributable to the industrial and commercial sector, including commercial enterprises, public infrastructure, and manufacturing facilities. The residential sector, despite continuous growth driven by grid expansion, accounts for 32.13% of electricity consumption. Street lighting and electric mobility represent 1.33% and 0.04%, respectively (EPRA, 2025). From a geographical perspective, the capital city Nairobi alone consumes nearly 5 TWh per year, corresponding to approximately 44% of the total national electricity consumption.

2.1.2. Coal

Although not directly employed for electricity generation, coal plays a significant role as a feedstock for the industrial sector. Approximately 2 million tonnes of coal are imported annually (roughly 11% of total energy imports), mainly from South Africa, Tanzania, and Mozambique, to support cement, steel, and ceramic production (IEA, 2025).

According to certain estimates, Kenya's domestic coal reserves amount to approximately 400 million tonnes, a considerable volume that could reduce reliance on imports and expand local electricity generation. However, the principal constraints are environmental in nature, as coal extraction and combustion generate substantial GHG emissions and other harmful pollutants, including sulphur dioxide and heavy metals, which are incompatible with the country's energy transition and decarbonization ambitions (Republic of Kenya, 2025). For this reason, the country is currently evaluating whether to exploit its domestic mineral resources to stimulate industrial growth or to prioritize alternative and more sustainable energy sources in order to facilitate the gradual phase-out of coal.

2.1.3. Petroleum Sector

The petroleum sector can be divided into three segments along the supply chain, namely upstream, midstream, and downstream, as shown in figure 2.4.

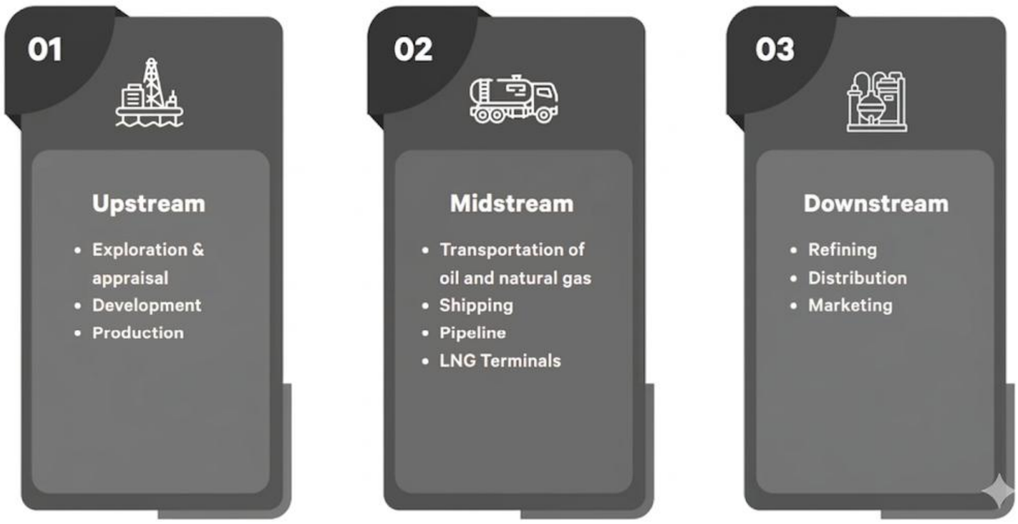

Figure 2.4 - Petroleum subsectors (EPRA, 2025)

The upstream segment includes exploration, extraction, production, and storage activities. Kenya currently hosts 94 exploration sites distributed across four major basins, one of which is partially offshore, but no active extraction sites are yet operational. Nevertheless, significant crude oil reserves have been identified, including approximately 560 million barrels in the Turkana region. Discussions are ongoing within the Government of Kenya regarding the valorisation of these resources. A plan proposed by Gulf Oil, and approved by the government, foresees the extraction of 433 million barrels of crude oil over a 25-year period, primarily for export purposes, as no active refinery currently operates in Kenya. Production is expected to commence at the end of 2026, with a projected capacity ranging between 60,000 and 100,000 barrels per day (Boscagli, 2025).

In addition, the LAPSSET Corridor Development Authority is overseeing the LAPSSET project, which aims to establish a transport and economic corridor linking Kenya with Ethiopia and South Sudan. Within this framework, the port of Lamu has been identified as a strategic hub for the storage and export of petroleum products transported through the corridor (LAPSSET Corridor Development Authority, 2016).

The midstream segment encompasses the transport and distribution of petroleum products, including crude oil, natural gas, LNG, and LPG, by sea and land. As no extraction wells are currently operational, the entirety of fossil fuel demand is met through imports. Between 2005 and 2023, oil consumption in Kenya more than doubled, driven primarily by increased gasoline and diesel demand in the transport sector, as well as rising household consumption of LPG. All oil products are imported mainly from the United Arab Emirates, Saudi Arabia, Malaysia, and India through the port of Mombasa, which functions as a regional hub for East Africa.

The downstream segment comprises distribution activities to final consumers. During the most recent year, approximately 7.4 million tons of petroleum products were imported, including around 936 thousand tonnes of jet fuel, nearly 3.8 million tonnes of diesel, and approximately 2.7 million tonnes of gasoline (EPRA, 2025). Overall petroleum imports increased by 7.7% compared to the previous year, although only a lower share of imported volumes are used to meet domestic demand. Owing to its port and logistics infrastructure, Kenya also serves as a distribution hub for neighbouring countries, including Uganda and South Sudan.

Until 2013, Mombasa was not only a major storage and distribution centre for petroleum products in Kenya and much of East Africa but also hosted a refinery with a processing capacity of 11,000 tonnes per day. Following a temporary suspension of operations for economic reasons, refining activities were never resumed, and the facility currently operates exclusively as a storage and distribution terminal. Although inactive, the refinery has not been dismantled and retains extensive distribution infrastructure across the country. For this reason, its potential conversion into a biorefinery for the production of SAF is currently under evaluation (Boscagli, 2025).

Domestic demand for petroleum products continues to grow, increasing by 6.94% compared to 2024 and approaching 4.6 million tonnes. This demand consists primarily of jet fuel, approximately 722 thousand tonnes, diesel, approximately 2.2 million tonnes, and gasoline, approximately 1.65 million tonnes (EPRA, 2025). In 2024, demand for LPG increased by 15% compared to the previous year, up to 415 thousand tonnes, largely driven by the cooking sector, which relies increasingly on LPG to achieve the clean cooking target by 2028.

2.1.4. Bioenergy

Despite the sustained growth in electricity generation and consumption in Kenya, biomass remains by far the most widely used energy source in the country. When considering total final energy demand, including imports such as petroleum products, biomass still ranks first, covering 62% of national energy needs (IEA, 2026), of which approximately 45% is biomass originating from the uncontrolled deforestation of forests (Ministry of Energy and Petroleum, 2020).

The high level of biomass consumption is primarily driven by the substantial energy demand of the household sector. The majority of dwellings in Kenya are located in rural areas, where access to electricity is limited and modern cooking and heating technologies are often unavailable. This results in the widespread use of inefficient stoves and cooking methods, mainly based on firewood and charcoal, which not only exert significant environmental pressure but are also highly detrimental to human health. Furthermore, dependence on these energy sources poses a serious social challenge, as biomass collection is predominantly carried out by women and children, thereby reducing the time available for income generating and educational activities, respectively (Government of Kenya, 2023).

Between 2001 and 2024, Kenya experienced a loss of approximately 400,000 hectares of tree cover, representing a 12% reduction in its total extent. This decline includes nearly 54,000 hectares of primary forests, which accounts for 8% of the country’s total forested area (Global Forest Watch, 2024). Approximately one million people are engaged in the production and trade of charcoal for energy purposes, generating an estimated annual turnover of 1.6 billion USD. In line with the national objective of maintaining forest cover at 10% of total land area, a transformation in cooking and heating practices has become increasingly necessary. At present, approximately 52% of households rely on wood as their primary fuel, while 12% continue to use charcoal (Ministry of Energy and Petroleum, 2024). In recent years, the use of LPG in the residential sector has increased and is now present in approximately 31% of households, mainly in urban areas, as a result of the clean cooking transition strategy adopted by the Government of Kenya (Ministry of Energy and Petroleum, 2024).

Beyond the dominant use of biomass in the household sector, other biomass-based energy carriers are present in Kenya, including biogas, bioethanol, and biodiesel. However, the absence of clear targets, economic incentives, and blending mandates has hindered the development of a domestic biofuels market, slowing investment in alternatives to fossil fuels. In 2020, the Ministry of Energy and Petroleum published a *Bioenergy Strategy* providing an overview of biomass utilization in the country and outlining high-level strategies and objectives to harness national biomass potential (Ministry of Energy and Petroleum, 2020). In 2023, an action plan was released to assess progress and define targeted measures to achieve the planned objectives by 2028 (Ministry of Energy and Petroleum, 2023). In addition to environmental benefits, domestic biofuel production would enable the valorisation of local resources, including by products and residues, while creating new income streams and employment opportunities that could contribute to national economic growth.

According to estimates by the IEA, approximately 21,000 biogas digesters are currently installed in Kenya, mostly using animal and organic waste as feedstocks (Ministry of Energy and Petroleum, 2020). These are mainly small-scale units used at household level for electricity generation, with an installed capacity estimated between 29 and 131 MW in total, corresponding to an average of 1 to 6 kW per unit. The sole exception is the Biojule plant in Naivasha, which generates 2 MW of power for the national grid utilizing floral waste as its primary feedstock (Ministry of Energy and Petroleum, 2020). Although this contribution remains limited at national scale, biogas represents a strategic solution in rural and remote areas, where municipal, agricultural, and livestock waste can be transformed into a valuable source of clean energy. To support this objective, Kenya launched the National Domestic Biogas Programme in alignment with the broader African Biogas Partnership Programme, promoting the dissemination of small-scale digesters to reduce reliance on firewood and charcoal (IEA, 2025).

Bioethanol is not used for electricity generation but serves a dual function as a feedstock for alcoholic beverage production and as a biofuel within the energy sector. At present, the vast majority of ethanol is allocated to beverage production, for which Kenya still experiences a significant deficit covered through imports. However, national plans foresee a substantial expansion of bioethanol production, positioning it as a key driver for the clean cooking transition and potentially for the transport sector, where it could be blended with gasoline to reduce fossil fuel dependence. Supported by governmental clean cooking policies, the private sector involved in bioethanol production and ethanol stove distribution is expanding, including companies such as KOKO Networks. Nevertheless, ethanol use in the cooking sector remains largely confined to urban areas and accounts for only 1% of total sectoral energy consumption, compared to a final target of 30% (IEA, 2025).

Biodiesel utilization is currently almost negligible. Its main potential application lies in the transport sector, similarly to bioethanol, through blending with conventional diesel to mitigate environmental impacts and reduce import dependence. Although a B2 blend (98% fossil diesel and 2% biodiesel) was considered technically feasible within the Kenyan context, no binding mandate for biodiesel use has been established (Ministry of Energy and Petroleum, 2020). A limited number of domestic biodiesel producers operate in the country, including Zijani and Giloil, yet production capacity remains constrained due to the absence of long-term planning and weak domestic demand. Biodiesel remains more expensive and less competitive than fossil diesel, and a structural market shift is unlikely without decisive state intervention (GTZ, 2009). It is noteworthy that several international biofuel companies operate in Kenya, including Muenzer and Eni. In Kenya, these companies focus primarily on feedstock production and collection, while conversion and commercialization activities are carried out in Europe, where regulatory frameworks and market demand are more developed. In the case of Eni, vegetable oil is sourced from crops grown on degraded lands in Kenya, primarily castor and croton, and subsequently exported to the company's biorefineries in Italy. There, the feedstock undergoes conversion into various biofuels, including the production of SAF (Eni, 2024). This dynamic illustrates that the absence of domestic demand and the lack of a clear regulatory framework and a structured supply chain may result in lost economic opportunities for the country.

Since 2011, Kenya has collaborated within the framework of CORSIA, through carbon offsetting programs that reward the implementation of effective GHG mitigation measures. CORSIA is a global market-based mechanism established by the ICAO to reduce emissions from international aviation. Through participation in ICAO and adherence to the CORSIA framework, Kenya has benefited from dedicated programs supporting the development of SAF strategies and from technical assistance aimed at establishing a robust industrial network capable of ensuring long term decarbonization of the aviation sector.

2.1.5. Hydrogen

For several years now, hydrogen has been at the centre of investment and research plans due to the key role it could play in the energy transition. Owing to its versatility, hydrogen can be used directly as a fuel, as an energy carrier, or as a feedstock for the production of synthetic fuels and in the chemical industry. The main challenges associated with hydrogen are often related to its relatively high production costs and to production pathways that remain largely dependent on fossil fuels.

Kenya, leveraging its availability of renewable energy sources and its strong commitment to pursuing energy transition objectives, has the potential to become a hydrogen production hub in East Africa. Hydrogen could play a significant role across several sectors of the Kenyan economy, starting with the chemical industry for fertilizer production, such as ammonia, and extending to the transport sector, where it would generate substantial environmental benefits. As previously noted, the agricultural sector accounts for a considerable share of Kenya's GDP, yet it remains entirely dependent on imported fertilizers. Domestic hydrogen production would enable the country to partially or fully meet its fertilizer demand, thereby strengthening industrial independence and fostering techno economic development.

A similar consideration applies to the transport sector, which is still entirely reliant on imported fossil products. While several viable alternatives to fossil fuels exist for road transport, such as electrification and biofuels, the options for aviation and maritime transport are more limited, and hydrogen could assume a pivotal role. Kenya is strongly committed to establishing a SAF production chain based on HEFA technology, which requires hydrogen as a process input. Looking ahead to the maritime sector, the leading green fuel solutions are expected to be hydrogen-based, including methanol and ammonia.

By 2030, Kenya aims to install between 150 and 250 MW of electrolyzer capacity, supported by 500 to 600 MW of renewable capacity dedicated exclusively to green hydrogen production (Ministry of Energy and Petroleum , 2023). According to the roadmap published by the Kenyan government, this production volume would make it possible to reduce fertilizer imports by 50%, corresponding to approximately 400 thousand tonnes per year, eliminate methanol imports entirely, initiate new hydrogen based projects in the transport sector, assess regional export opportunities, and avoid overall emissions of approximately 250 thousand tonnes of CO2eq per year.

2.2. Policy framework

In order to achieve the ambitious industrialization and development objectives it has set, Kenya requires a comprehensive and well-structured policy framework capable of safeguarding and guiding its progress over time. An integral component of the country's economic and industrial evolution is the management of climate change impacts, to which Kenya is particularly vulnerable, given that most of its economic activities are based on or strongly dependent upon natural resources.

In 2022, total national emissions amounted to approximately 113 million tonnes of CO2eq, increasing compared to previous years at an average annual rate of around 4%. However, the demographic and economic expansion that the country aims to achieve in the coming years will likely result in a further rise in emissions, reaching an estimated 143 million tonnes of CO2eq by 2030 (Republic of Kenya, 2025).

The sectors with the greatest environmental impact are those related to land use, classified under LULUCF (Land Use, Land-Use Change and Forestry), mainly due to deforestation activities, fertilizer application, and the growing number of grazing areas. Emissions from LUC account for approximately 41% of the total, corresponding to nearly 47 million tonnes of CO2eq, while emissions associated with agricultural activities contribute 32%, equal to around 36 million tonnes of CO2eq (Ministry of Environment, Climate Change and Forestry, 2024). These are followed by the energy sector, with 21.5 million tonnes of CO2eq, representing about 20% of total emissions, then the waste sector with 5 million tonnes of CO2eq, and finally the industrial sector, which accounts for only 3% of total emissions, approximately 3.7 million tonnes of CO2eq. In the figure 2.5, the evolution of GHG emissions per sector is reported from 1990 to 2022.

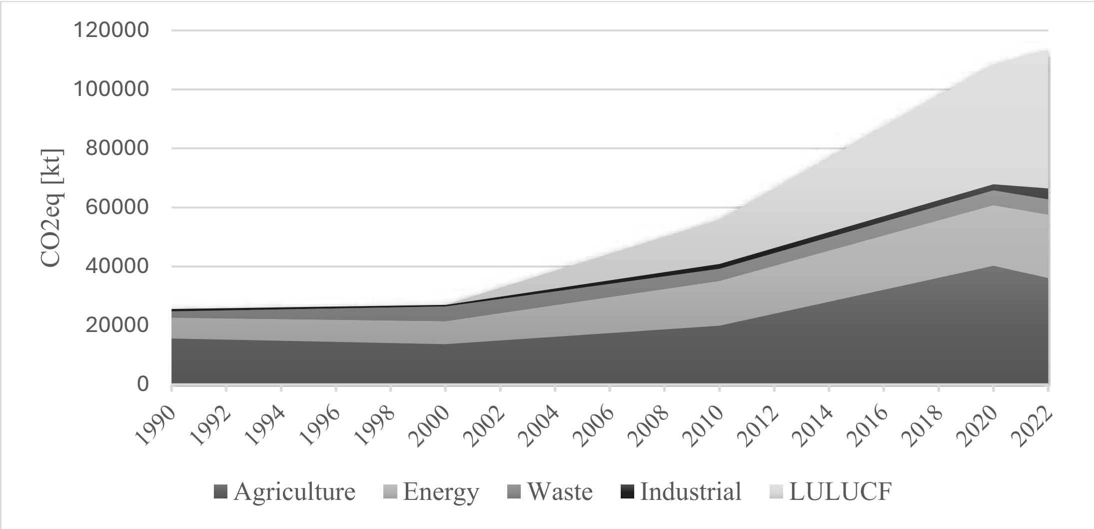

Figure 2.5 - GHG emissions trend per sector from 1990 to 2022 (Ministry of Environment, Climate Change and Forestry, 2024)

With regard to emissions arising from energy consumption, despite an electricity generation mix that is almost entirely renewable, the environmental balance is significantly affected by the widespread practice of deforestation and fossil fuels utilization in the transport sector. Focusing exclusively on energy consumption, the transport sector is the primary contributor to GHG emissions, accounting for approximately 10 million tonnes of CO2eq in 2022. This is followed by the industrial sector, which exceeds 4 million tonnes of CO2eq, while power generation and the residential sector both remain below 2 million tonnes of CO2eq (IEA, 2026). The temporal evolution of GHG emissions by sector for the 2000-2023 period is illustrated in the figure 2.6.

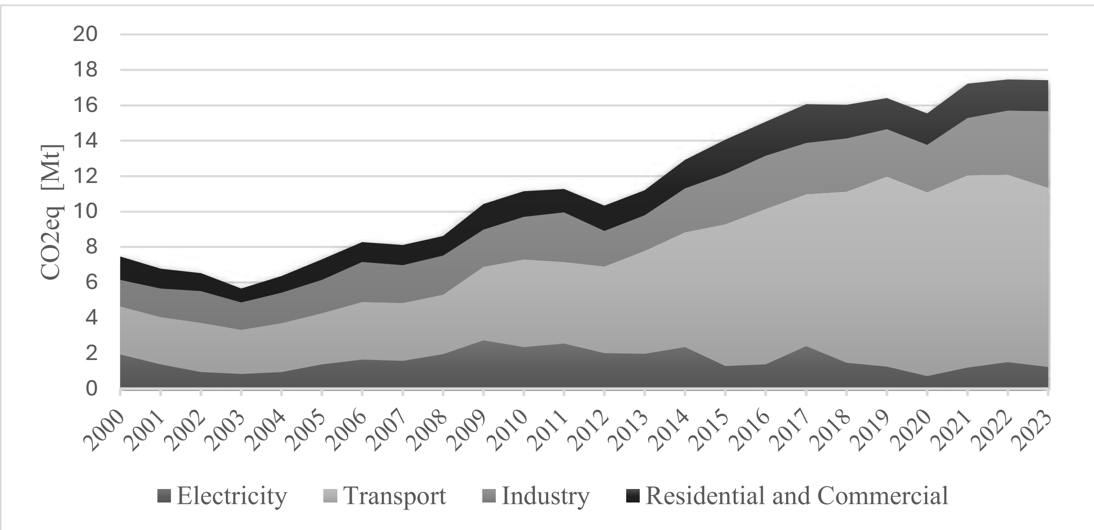

Figure 2.6 - GHG emissions by sectors due to energy consumption (IEA, 2026)

Even considering the recent economic and industrial growth experienced by Kenya, the country's total emissions remain markedly limited when compared to global levels. Kenya contributes less than 0.1% to total global emissions, and its per capita emissions are more than three times lower than the global average, amounting to 0.32 tonnes of CO2eq per person compared to an average of 6.76 tonnes worldwide (IEA, 2026). Nevertheless, due to its geographical location near the tropics, Kenya is particularly exposed to the effects of climate change, including rising average temperatures and increasing rainfall variability, which has led to prolonged dry seasons and a higher frequency of flooding events.

The Kenyan legislative framework is grounded in the Constitution adopted in 2010, which explicitly states that every citizen has the right to live in a clean and healthy environment. In order to pursue these objectives, the *Climate Change Act* was enacted in 2016, establishing the legislative framework for climate related action, followed by the *Energy Act in 2019*, which sets out the regulations governing the energy sector. These acts provide the foundation for the creation of dedicated state entities and institutions responsible for overseeing climate and energy activities, as well as for the development of policies and strategies targeting specific sectors, such as the *National Climate Change Action Plan* and the *National Energy Policy*.

Alongside these institutions, and in support of their implementation, stand the relevant ministries of the Kenyan government. In particular, the Ministry of Energy and Petroleum is responsible for the development of strategic directions and the implementation of key policies related to energy transition and energy security, while the Ministry of Environment, Climate Change and Forestry provides analytical support and technical assistance in the coordination and implementation of climate related measures, in collaboration with the NEMA (National Environment Management Authority).

The presence of numerous institutions and governmental bodies, together with a comprehensive legislative framework and the approval of several climate and energy related policies, underscores Kenya's commitment to a technically and environmentally sustainable development pathway, with the ambition of becoming a regional leader in the energy transition. However, the implementation of the identified strategies remains partial and progresses at a slower pace than the timelines set by the country. The involvement of multiple institutions in pursuing similar objectives has, in some cases, led to overlaps and insufficient communication and coordination. Governmental studies and policy documents occasionally present objectives that are not fully aligned or appear inconsistent with one another. The result is the existence of a wide range of strategies and targets that often fail to translate into concrete action and remain confined to the planning stage. It is therefore necessary to review and further refine the identified objectives, clearly defining the actors involved, both at the public and private levels, and establishing concrete targets within well-defined time horizons. The following sections outlines the legislative acts and primary energy and climate policies that have shaped, and will continue to drive, Kenya's long-term economic and industrial growth in a sustainable way.

2.2.1. Kenya Vision 2030

Kenya Vision 2030 is the national industrial development program launched in 2008 with the objective of transforming the country into a "middle-income nation providing a high quality life to all its citizens by the year 2030" (Republic of Kenya, 2007). *Kenya Vision 2030* is structured around three pillars, namely economic, social, and political.

The economic pillar aims to achieve sustained and geographically inclusive economic growth, translating into an annual GDP growth rate of 10%, through targeted investment in key sectors such as agriculture, industry, and services. The social pillar seeks to create a secure and clean environment capable of fostering an equitable and cohesive society, through the strengthening of the education and healthcare systems, the implementation of housing and urban development programs, and the promotion of environmental protection. The political pillar is oriented toward ensuring long term political stability based on a democratic system that guarantees freedom and respect for the rights of all Kenyan citizens, through the reinforcement of laws and institutions and increased transparency.

The evolution and progress of *Kenya Vision 2030* are monitored through the publication of five-year medium-term plans, which are designed to assess and ensure the achievement of the final objectives. The success of *Vision 2030* depends, among other factors, on the industrialization of the country and on significant improvements in infrastructure. Within this framework, energy development plays a central role, as it is expected to grow in line with economic progress and population increase, and must be supported by strong regulatory frameworks, the exploration of new energy sources, and active participation from the private sector.

2.2.2. Climate Change Act 2016

In order to limit the impact of climate change on a highly vulnerable territory such as Kenya, the *Climate Change Act* was enacted in 2016. The ultimate objective of this Act is the development, management, implementation, and regulation of mechanisms aimed at enhancing climate resilience and promoting low carbon development for the sustainable development of Kenya (Republic of Kenya, 2016). In particular, the Act was conceived to facilitate the formulation of national programs focused on climate resilience and adaptation, as well as on the reduction of environmental risks and disasters.

These objectives can be pursued through the promotion of low carbon technologies and the reduction of GHG emissions, including through the mobilization of domestic financial resources and the introduction of incentives and or obligations for the private sector. The Act establishes specific governmental entities responsible for climate governance, including the National Climate Change Council, which acts as the main coordinating body for all approved climate related actions and measures, among which the five-year publication of the National Climate Change Action Plan. Within the National Climate Change Action Plan, strategies and targets are defined to ensure sustainable national development capable of limiting the impacts of climate change through the promotion of low carbon activities.

In 2023, the *Climate Change Act* was updated to introduce a dedicated regulatory framework for the carbon market and the definition of carbon credits, with the aim of aligning domestic legislation with evolving global policy frameworks (Republic of Kenya, 2023). Through certified activities and low carbon technologies that remove or sequester carbon dioxide from the atmosphere, it is possible to generate a quantified amount of carbon credits, proportional to the volume of avoided or removed emissions, which can then be traded at both national and international levels through carbon offsetting mechanisms.

2.2.3. Energy Act of 2019

In support of national energy policies, in 2019 the Parliament of Kenya enacted the *Energy Act* with the objective of strengthening the legislative framework governing the energy sector, defining key bodies and institutions responsible for monitoring and achieving established targets, including the EPRA and the REREC (Rural Electrification and Renewable Energy Corporation) (Republic of Kenya, 2019).

The EPRA is the entity responsible for regulating the generation, transmission, distribution, and use of electrical energy, as well as the import and export, storage, and transportation of petroleum products. All regulations, tariffs, and conditions related to the use of electricity and petroleum fall under its jurisdiction. The REREC, on the other hand, focuses specifically on renewable energy sources, including biofuels, and on electrification operations across the country.

The primary purpose of the *Energy Act* is to provide a comprehensive legal framework for the regulation, production, supply, and use of all forms of energy in Kenya, including electricity, petroleum, coal, and renewable energy sources. Among its key provisions, the Act mandates the publication of an updated National Energy Policy every five years, outlining the main objectives to be achieved within the energy sector. The National Energy Policy serves as a guiding instrument for energy related infrastructure investments, as a review and assessment of all energy sources currently in use, and as a reference for the selection of energy technologies to be adopted in the subsequent years.

2.2.4. Kenya's Nationally Determined Contributions 2031-2035 (NDCs)

Kenya is a signatory to the Paris Agreement, adopted during COP21, aimed at mitigating the effects of climate change. Pursuant to Article 4, paragraph 2 of the Paris Agreement, each signatory country is required to communicate its national climate mitigation targets every five years through a document known as the Nationally Determined Contributions, which is submitted to the Secretariat of the United Nations Framework Convention on Climate Change.

Kenya has recently submitted its second NDC, covering the period 2031 to 2035, which represents a natural continuation of the first NDC, valid for the period 2026 to 2030. Kenya’s NDCs are structured around two fundamental components, mitigation, aimed at limiting the future impacts of climate change through the reduction of GHG emissions, and adaptation, which seeks to identify concrete solutions to address current climate related challenges.

The primary objective of the mitigation strategy is to reduce total GHG emissions by 35% relative to the projected 2035 levels under the Business-As-Usual scenario, corresponding to approximately 215 million tonnes of CO2eq, whereas the previous NDC had set a 32% target. Consequently, the total reduction target by 2035 amounts to roughly 75 million tonnes of CO2eq. However, Kenya commits to unconditionally achieving only 20% of this target, equivalent to about 15 million tonnes of CO2eq, while the remaining 80% is conditional upon international support, both technical and financial (Republic of Kenya, 2025).

A significant share of this objective is expected to be achieved through the transformation of the energy sector, with the goal of reaching 100% renewable electricity generation by 2035. In addition, more efficient and cleaner forms of energy are to be deployed across other key sectors of the Kenyan economy, including transport, industry, agriculture, and cooking. The transport sector in Kenya is currently entirely dependent on fossil fuels, representing a major source of emissions for Kenya and a huge expenditure in foreign currency. However, strengthening road and railway infrastructure and improving freight logistics are the key priorities for the government to date. In this context, expansion of paved roads, railway electrification, increased use of public transport, and the modal shift of freight transport from road to rail constitute the main initiatives promoted in this document. Furthermore, a substantial contribution in the reduction of carbon emissions is expected from limiting deforestation activities and promoting reforestation, as well as from the effective implementation of sustainable waste collection and valorisation systems.

The objective of the adaptation strategy is to build a climate resilient society in which human life is not endangered, and socio-economic activities can prosper despite the impacts of climate change. In this regard, it is crucial to anticipate and manage environmental disasters, such as prolonged droughts and sudden floods, which threaten large portions of Kenyan territory, through adequate preventive measures. To address food insecurity and crop losses, it is necessary to implement an advanced agricultural system capable of improving crop and livestock productivity, including through the adoption of innovative practices and more modern technologies. Moreover, it is essential to strengthen and construct infrastructure and housing capable of withstanding climate related events, ensure adequate water resource management and supply, implement more efficient healthcare programs, and promote greater awareness of the causes and consequences of climate change.

According to estimates conducted by the Kenyan government, the full implementation of mitigation and adaptation measures would require approximately USD 56 billion. However, also in this case, Kenya commits to financing only a limited share of this amount, approximately 19%, while the remaining portion is expected to be mobilized through international development programs and external investments.

2.2.5. National Energy Policy 2025-2034

The *National Energy Policy 2025-2034* is a document published every five years, as established by the *Energy Act* of 2019, with the purpose of guiding infrastructure investments and technological progress toward the achievement of Kenya’s energy transition objectives, in line with the Paris Agreement and the attainment of Sustainable Development Goal 7. The most recent version of the National Energy Policy was released in 2025 and outlines strategic objectives up to the year 2034. It articulates the country’s commitment to providing affordable, reliable, and sustainable energy capable of driving national development, economic growth, and climate resilience, with the ultimate objective of fully decarbonizing the energy sector by 2050 (Ministry of Energy and Petroleum, 2025).

The fundamental pillars of this strategy include, first and foremost, the transition to clean cooking solutions and the achievement of universal access to electricity by 2030. The transition to clean cooking requires the identification and deployment of alternative energy sources to traditional biomass, including biofuels and electric solutions, in order to reduce both environmental impacts and health related risks. Another key objective concerns the improvement of energy efficiency through the adoption of more modern and technologically advanced equipment, which would make it possible to reduce overall energy consumption and limit emissions harmful to human health. Energy efficiency remains a critical aspect for the country as a whole, considering that even within the electricity generation system losses exceed 23% of the energy produced (EPRA, 2025). Through this policy, Kenya aims to double annual energy efficiency improvement rates and to invest substantially in renewable energy sources.

To ensure the successful implementation of these measures, close collaboration between the public and private sectors will be essential. According to the government's vision, the private sector is expected to play a leading role in facilitating the energy transition. In order to attract both domestic and international investments, the creation of a supportive economic environment, including incentives and favourable taxation schemes, as well as a coherent legislative framework, including blending mandates and minimum targets, is envisaged to promote innovation and the deployment of renewable energy sources.

With specific regard to biomass, the policy identifies a dual role in both the clean cooking and transport sectors. In both cases, the measures refer to the establishment of a comprehensive legal, fiscal, and regulatory framework within five years of the publication of the document, aimed at fostering the diffusion of biofuels. In the cooking sector, the focus is placed on bioethanol and biogas, for which resource mapping and the definition of quality standards are also foreseen. In the transport sector, the scope is broader and includes road, aviation, and maritime applications. For road transport, the most relevant biofuels are bioethanol and biodiesel, for whose production Kenya already possesses the necessary technological capabilities. However, the policy highlights the need to introduce blending mandates, which are currently absent and whose lack hinders market penetration. As for SAFs and marine fuels, these represent more technologically advanced solutions that require dedicated investments in research and development, as well as international partnerships to remain aligned with global targets.

In addition to identifying the aforementioned objectives, the policy also defines the roles that various institutions are expected to assume in its implementation. Among the entities involved are the Ministry of Energy and Petroleum, which will perform coordination and supervisory functions, as well as the EPRA and the REREC, in addition to research and academic institutions and the private sector.

2.2.6. National Climate Change Action Plan III 2023-2027

The *National Climate Change Action Plan 2023-2027*, published in accordance with the Climate Change Act of 2016, serves as the country's central planning document for the implementation of its enhanced NDC and for steering Kenya onto a low carbon, climate resilient development pathway. The *National Climate Change Action Plan 2023-2027* represents the third iteration of this document and has been released with the objective of achieving sustainable development characterized by a low environmental impact, aligned with other national industrial development strategies, including Vision 2030, and inclusive of the entire Kenyan population, from the private sector to civil society, with particular attention to vulnerable and marginalized groups (Government of Kenya, 2023). Special emphasis is placed on adaptation measures, as in recent years Kenya has experienced the severe consequences of climate related disasters, including droughts and floods.

The action plan is structured around eight main intervention areas, for each of which both mitigation and adaptation measures are defined, collectively expected to result in a reduction of 79 million tonnes of CO2eq by 2027. The identified areas include Disaster Risk Management; Food and Nutrition Security; Water, Fisheries and the Blue Economy; Forests, Wildlife and Tourism; Health, Sanitation and Human Settlements; Manufacturing; Energy and Transport; and Children and the Youth.

Projections indicate that under a Business-As-Usual scenario, by 2030 the most emission intensive activities will be electricity generation, accounting for approximately 41 million tonnes of CO2eq, and agricultural production, with 39 million tonnes of CO2eq, followed by deforestation at 22 million tonnes and the transport sector at 21 million tonnes. The reduction of deforestation activities could potentially offset nearly all emissions generated within that category, while afforestation efforts could provide an additional carbon sink with an estimated potential of approximately 41 million tonnes of CO2eq. By 2030, the main share of avoided emissions is expected to derive from halting deforestation and increasing the share of renewable electricity generation, corresponding respectively to around 20 and 9 million tonnes of CO2eq avoided. However, projections to 2050 suggest that emissions from agriculture and transport will become increasingly significant, reaching approximately 87 million tonnes and 76 million tonnes of CO2eq respectively, thus underscoring the need for decisive investments in these sectors as well.

With regard to the energy and transport sectors, the objectives set for 2030 primarily concern the transition to clean cooking solutions, the expansion of renewable electricity generation, and the introduction of cleaner alternatives to fossil fuels. By 2030, the policy envisages the installation of an additional 589 MW of renewable capacity, including 208 MW of geothermal, 174 MW of solar, and 161 MW of wind power, and aims to ensure access to modern clean cooking energy services, such as LPG, bioethanol, biogas, and electric cooking, for 75% of the population, while the remaining 25% will continue to rely on traditional biomass used in improved cookstoves designed to reduce health impacts. Furthermore, the plan foresees the construction of two new biofuel production plants, although the specific capacity and type of biofuel are not detailed.

In the transport sector, the expansion and improvement of public road and rail transport systems are planned, alongside the development of electrical infrastructure and the implementation of an e-mobility policy to enable a gradual transition toward electric mobility. In addition, for the decarbonization of the aviation sector, the plan reiterates the importance of participating in international programs, such as CORSIA, and of developing domestic SAF production.

2.2.7. Bioenergy Strategy 2020-2027

Bioenergy in Kenya still accounts for 62% of total energy supply in the country. A significant share of this consumption derives from the unsustainable use of biomass for heating and cooking activities, particularly in rural areas, leading each year to a very high number of deaths from respiratory diseases, which represent approximately 25% of all reported illnesses in Kenya (Ministry of Energy and Petroleum, 2020). For this reason, the Kenyan government, and particularly the Ministry of Energy, has developed a dedicated strategy to manage and guide the use of biomass for energy purposes over the period 2020 to 2027.

The policy was not conceived with the primary objective of setting quantitative targets in terms of biomass production and or utilization, but rather as a supporting framework to advance sustainable development goals related to bioenergy in the short to medium term. Its overarching objective is to achieve Sustainable Bioenergy for All by 2028, encompassing within this vision the full transition to clean cooking solutions. More specifically, the strategy defines four macro-objectives for the 2020 to 2027 period: promoting the sustainable production and consumption of bioenergy; accelerating the transition to clean cooking technologies and fuels; providing essential information to potential investors on viable development opportunities; and serving as a framework for regional and international cooperation and trade in bioenergy and related feedstocks (Ministry of Energy and Petroleum, 2020).

In the short term, namely by 2022, the identified objectives were primarily organizational and focused on assessing the country's biomass production potential. For example, a comprehensive mapping of all feedstocks suitable for bioenergy production was envisaged, taking into account appropriate cultivation areas, agricultural yields, and energy conversion efficiencies. In addition, the strategy promoted the sustainable production of bioenergy feedstocks through the cultivation of energy crops and fast-growing tree species, consistent with climate mitigation and reforestation objectives. Particular attention was devoted to ethanol as a blending fuel in the transport sector, for which domestic production potential was assessed through diversified feedstocks not limited to molasses-based sources, and also regional supply opportunities from Uganda and Tanzania were evaluated.

In the longer term, namely by 2027, the objectives become more implementation oriented and focus on the deployment of concrete bioenergy solutions. Research is identified as a key enabler to enhance awareness, stimulate the formulation of new policies, and valorise currently underutilized resources, such as municipal solid waste. A clear emphasis is placed on clean cooking, including the proposal of fiscal incentives to support the adoption of clean cooking technologies, such as zero value added tax and import duties on clean cooking solutions, capacity development initiatives, and the active involvement of women and youth in strategic activities for the development of the bioenergy sector. The expansion of the bioenergy industry is also linked to the establishment of international partnerships, the engagement of the private sector, and increased public awareness regarding the health and social consequences of unsustainable biomass use.

In 2023, the *Bioenergy Strategy Action Plan* was published, translating the objectives of the Bioenergy Strategy into concrete actions with quantified outputs over a defined time horizon. Examples include the annual distribution of 100 thousand clean cookstoves to vulnerable social groups and the publication of assessment reports on key clean fuels for the energy transition, such as bioethanol and SAF. For each macro-objective, the Action Plan specifies the corresponding measures to be implemented by 2027, identifying the responsible institutions and the allocated budget for each intervention (Ministry of Energy and Petroleum, 2023).

2.2.8. Kenya National Cooking Transition Strategy 2024-2028

The *Kenya National Cooking Transition Strategy 2024-2028* was developed with the objective of achieving universal access to clean cooking across the country by 2028 (Ministry of Energy and Petroleum, 2024). The cooking sector remains heavily dependent on traditional fuels, such as firewood, charcoal, and kerosene. At present, approximately 9 million households, corresponding to about 68.5% of the Kenyan population, lack access to clean cooking technologies, particularly in rural areas.

This situation generates severe environmental, health, and social challenges. From an environmental perspective, large quantities of firewood for cooking are obtained through uncontrolled deforestation activities, progressively reducing Kenya's forest cover. From a health standpoint, the use of traditional fuels in rudimentary stoves and devices produces harmful emissions that lead to severe respiratory diseases and, in many cases, premature death. From a social perspective, firewood collection requires several hours per day and is predominantly undertaken by women and children, thereby limiting their participation in income generating activities and formal education.

The main barriers to the widespread diffusion of clean cooking technologies are primarily economic and logistical in nature. For households living in rural areas and facing economic hardship, traditional fuels represent a practical and low-cost solution. By contrast, the production of modern stoves and the importation of clean fuels, such as LPG, make the transition to clean cooking financially burdensome and often prohibitive for the most vulnerable households. Nevertheless, a full transition to clean cooking could prevent more than 26 thousand deaths annually and avoid approximately 622 thousand Disability Adjusted Life Years, while also reducing GHG emissions by about 16 million tonnes of CO2eq thanks to the avoided unsustainable wood harvest of about 466 thousand hectares, and saving nearly 790 hours per household per year otherwise devoted to firewood collection (Ministry of Energy and Petroleum, 2024).

The strategy commits to achieving by 2028 a cooking energy mix composed of at least 50% LPG stoves, 30% bioethanol, 10% electric cooking, 7% improved biomass solutions, namely pellets and briquettes used in modern stoves, and 3% biogas. According to the analysis conducted by the Ministry of Energy, the implementation of this scenario could require annual government expenditures of approximately 210 million USD, largely allocated to fuel procurement and production, estimated at around 178 million USD, and to stove deployment, estimated at approximately 10 million dollars. These costs, however, could be almost entirely financed through the trading of clean cooking related benefits. On the other hand, the transition is projected to generate benefits primarily associated with the economic value of avoided illnesses and GHG emissions, resulting overall in health, environmental, and time saving benefits exceeding 240 million USD annually (Ministry of Energy and Petroleum, 2024).

The strategy establishes an action plan structured around five core pillars: bridging the supply gap for clean cooking solutions; addressing the affordability gap on the demand side; promoting local manufacturing and fuel production for domestic use and export; reframing and raising awareness of the role of clean cooking; and instituting accountability, planning, and continuous progress tracking mechanisms. Each pillar identifies specific objectives to be achieved by 2028 in order to ensure a successful transition. These include the mandatory adoption of clean cooking solutions in all Kenyan public buildings, financial incentives for economically disadvantaged households to purchase clean fuels and modern stoves, measures to facilitate domestic production of clean stoves and modern fuels, awareness raising campaigns on clean cooking related issues, and the establishment of monitoring and evaluation systems to track progress in the transition.

2.2.9. Kenya Energy Transition & Investment Plan 2023-2050

While not strictly a binding policy, the *Kenya Energy Transition and Investment Plan 2023-2050* serves as a comprehensive long-term developmental framework for the national energy sector. Developed by the Ministry of Energy and Petroleum in collaboration with Sustainable Energy for All and the United Nations, the plan seeks to transform the energy transition from a necessity into a strategic economic opportunity. By leveraging domestic resources through industrial and technological expansion, the ETIP aims to enhance Kenya's energy autonomy and independence.

Achieving a net-zero trajectory by 2050 would potentially create nearly 500,000 new jobs, albeit requiring an estimated investment of 600 billion USD. Conversely, under the Business-As-Usual (BAU) scenario, costs would remain substantial (approximately 435 billion USD), while energy-related emissions could escalate to nearly 130 million tonnes of CO_2 per year, up from the current 20 million tonnes of CO_2, primarily driven by significant economic and demographic growth. Projections indicate that by 2050, Kenya's population will increase by a factor of 1.7, exceeding 85 million, while GDP per capita is expected to more than quadruple (Ministry of Energy and Petroleum, 2023).

The majority of CO_2eq emission reductions are projected to stem from the transition to clean cooking and the cessation of deforestation (accounting for approximately 28% of avoided emissions). This is followed by the complete displacement of fossil fuels through renewable power generation and the integration of biofuels in heavy-duty transport (24%), and the electrification of light-duty transport (22%) (Ministry of Energy and Petroleum, 2023). Additionally, the adoption of low-carbon hydrogen and carbon capture technologies is expected to contribute 15% and 9% to avoided emissions, respectively, particularly within the industrial sector.

3. Biofuels

Biofuels represent a critical component of the global transition towards sustainable energy systems, offering a viable alternative to conventional fossil fuels in the transport sector. As fuels derived from organic matter, they are increasingly recognized for their potential to mitigate GHG emissions and enhance energy security. In the context of emerging economies, biofuels can serve as a tool for reducing dependence on imported petroleum products and fostering rural development.

In 2022, global biofuel consumption reached 170 billion litres per year, primarily in the form of bioethanol and biodiesel, which account for 52% and 44% of total consumption, respectively (IEA, 2023). The growth of the sector over the 1990–2024 period is illustrated in the figure 3.1.

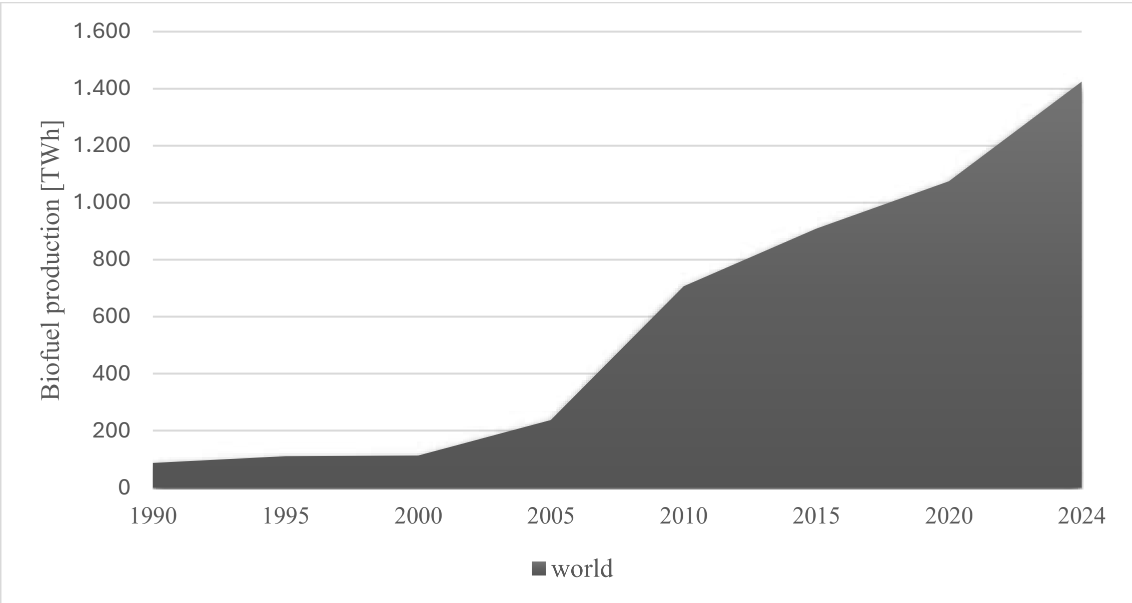

Figure 3.1 - Global biofuel production under the period 1990-2024 (Energy Institute, 2025)

Currently, the primary consumers are the United States, Brazil, Europe, and Indonesia, which collectively account for approximately 85% of total global demand. However, demand growth is increasingly driven by developing economies, which view biofuels as an effective tool for replacing petroleum products (IEA, 2023). While in more economically developed countries fuel demand has largely stabilized over time, and at the same time electric mobility in the transport sector is growing rapidly, in developing countries fuel demand in transport continues to increase steadily, making the search for sustainable alternatives increasingly urgent

(OECD/FAO, 2025). Consequently, if specific policies and economic support is provided by the governments, biofuel production is likely to continue growing in the coming years in order to at least partially meet the rising demand for transport fuels. A clear example of this trend is India, which in a relatively short period has become the third largest producer of bioethanol worldwide, achieving a 10% ethanol blend in 2022 and targeting a 20% blending rate by 2025 (IEA, 2023). As a matter of fact, by 2030, biofuel demand under the IEA Net-Zero Scenario could more than double, driven largely by the increasing requirements of the international aviation sector, reaching nearly 400 billion litres per year (IEA, 2023). However, meeting this target would necessitate an annual growth rate of 11%, a significant acceleration compared to the 6% average annual growth recorded between 2016 and 2022 (IEA, 2023). To satisfy this escalating demand, it is essential to strengthen and expand production chains based on waste, residues, and non-edible feedstocks. While current biofuel production is almost entirely derived from conventional food crops, by 2030, 40% of biofuels could be produced from feedstocks that do not compete with the food supply chain (IEA, 2023). Furthermore, the integration of advanced production technologies, including lignocellulosic bioethanol and biomass-based Fischer-Tropsch, will broaden the range of viable feedstocks for biofuel production.

Considering the Kenyan energy context, it is evident that biomass currently plays a fundamental role in the country's energy supply, although it also presents significant environmental and health related drawbacks. At the same time, as reflected in existing policies and in the objectives declared by the government of Kenya, bioenergy is expected to play a key role in the country's energy transition, particularly in the residential and transport sectors. In the coming years, however, production strategies will need to change significantly, moving towards more advanced biofuels with improved technical performance that can support a more sustainable development pathway for the country.

Beyond this aspect, several sectors in Kenya remain strongly dependent on petroleum products. The transport sector, for example, requires the annual import of almost ten million cubic metres of crude oil and refined petroleum products (EPRA, 2025). Road transport is dominated by second hand vehicles imported from abroad, which represent one of the main sources of air pollution in the country. This is largely due to the fact that many imported vehicles are several years old and exhibit relatively low energy efficiency, thereby contributing further to petroleum consumption and GHG emissions.

Moreover, following the country's projected economic growth in the coming years, both the tourism sector and commercial activities are expected to expand significantly. This expansion is projected to drive a nearly 5% annual increase in jet fuel demand to accommodate rising national and international air traffic within the country (Boscagli, 2025). In the maritime sector, the ports of Mombasa and Lamu serve as critical infrastructure for commercial trade, supporting not only Kenya but the broader East African region, whose economic expansion will lead to the intensification of maritime traffic. Consequently, Kenya has joined the GreenVoyage2050 programme, an initiative aimed at decarbonizing the maritime sector, reflecting the country's commitment to addressing the escalating demand for marine fuel through the implementation of sustainable production pathways (IMO, 2026).

As previously discussed, Kenya currently does not have active oil extraction sites, despite the confirmed presence of several reserves within its national territory. As a result, the country is forced to import virtually all of its petroleum requirements. Within this context, biofuels represent a concrete opportunity to reduce dependence on imported fossil fuels, increase national energy security, and at the same time lower emissions associated with fuel consumption.

At present, however, only a very small share of biomass is used for the production of biofuels, mainly bioethanol and biodiesel, which still play a marginal role in the national energy system. Domestic bioethanol production amounts to approximately 26 million litres per year and is used almost entirely by the food industry. In Kenya, bioethanol is produced exclusively from molasses, a by-product of sugarcane processing, often directly by sugar-producing companies themselves. Despite the widespread experience in molasses processing, the limited availability of feedstock and the strong dependence on the sugar industry currently make bioethanol production both variable and constrained. Although increasing bioethanol production from molasses would also increase sugar production, which Kenya currently imports in large quantities each year, it is unrealistic to assume that the entire national bioethanol supply could be derived solely from molasses. The solution, which applies equally to the production of other biofuels, lies in integrating the cultivation of energy crops into existing agricultural activities.

The agricultural sector plays a crucial role in Kenya's economy and employs by far the largest share of the population, yet the country still possesses large areas of land that remain unused. However, only a limited portion of this land is suitable for conventional food crop cultivation. About 17% of Kenya's territory presents the climatic and soil conditions required for agricultural production, and these areas are already largely dedicated to meeting domestic food demand (National Land Commission, 2023). Most of the remaining unused land falls into the category of ASAL, which are generally unsuitable for food crop cultivation and are therefore often left uncultivated. Nevertheless, several energy crops have been identified as suitable for cultivation in ASAL regions due to their resistance to drought conditions. Biofuel production could therefore exploit the cultivation of energy crops in these areas or alternatively utilize agricultural by products from already established cultivation fields as feedstocks. This approach could create additional income streams for farmers, generate employment opportunities, and contribute to national economic growth.

Several studies conducted by international organizations, including the World Bank and the ICAO, identify Kenya as a potential regional hub for the development of sustainable fuels. Compared with other countries in Sub-Saharan Africa, Kenya benefits from a relatively strong regulatory environment and a more developed economic infrastructure, making it an attractive destination for foreign investment. In particular, significant attention is directed towards the development of SAF, for which ambitious international targets have been established. Despite these opportunities, several challenges remain for the widespread development of biofuels in Kenya, particularly those related to land use and the potential conflict between the food and energy sectors. Although energy crops can be cultivated in ASAL regions, agricultural yields in these areas tend to be relatively low and unpredictable, which may negatively affect both the technical and economic viability of production (GTZ, 2009)

At the global level, most biofuel production still relies on crops that are also used in the food sector, such as soybean and maize. In a context such as Kenya, where fertile land is limited and food security remains a critical issue, this matter becomes particularly relevant. Furthermore, most agricultural activities are carried out on a small scale by individual farmers, which complicates the organization of large-scale feedstock supply chains. At the same time, however, this structure could potentially generate economic and social benefits for farming households (National Land Commission, 2023). For biofuels to be considered sustainable, they must be produced and used in an environmentally, socially, and economically responsible manner. Strong regulation and careful planning are therefore necessary to prevent conflicts between the food and energy markets that could generate social or economic disruption. The use of domestic by products that do not affect land or water use and that do not compete with food production should be prioritized wherever possible. In addition, both domestic and international private investors frequently highlight the absence of a clear and comprehensive policy framework for biofuels in Kenya. Although several policies addressing the broader energy sector have been introduced, concrete numerical targets for biofuel production remain largely undefined. Even within the cooking sector, where bioethanol is expected to play an important role, the different policy documents present adoption targets that are not always aligned, generally ranging between 20% and 30% of total cooking energy consumption.

While the government has clearly expressed its intention to promote biofuels in the coming years, the absence of clear guidelines and long-term targets continues to discourage large scale private investment. It therefore remains essential to identify suitable feedstocks and land areas for biofuel production, to regulate their integration into domestic energy markets through binding production and blending mandates, and to introduce economic incentives or fiscal measures capable of reducing the existing cost gap between biofuels and conventional fossil fuels.

3.1. Feedstocks

The agricultural sector in Kenya plays a primary role in the national economy, accounting for approximately 20% of national GDP and 43% of total exports (National Land Commission, 2023). Agricultural production can be divided into several subcategories depending on the final use of the cultivated products, namely food crops, industrial crops, and horticultural crops. The category of food crops includes staple foods that form the basis of the Kenyan diet, such as maize, rice, wheat, sorghum, potatoes, cassava, vegetables, and beans. Industrial crops include tea, coffee, sugar cane, pyrethrum, barley, tobacco, sisal, cotton, sunflower, coconut, and bixa, which hold considerable economic value beyond their use in the food sector. Finally, horticultural crops include flowers as well as certain types of fruits and vegetables, which are often produced almost entirely for export markets (National Land Commission, 2023).

According to the National Land Commission, only 17% of Kenya's territory can be considered to have high agricultural potential due to favourable climatic conditions and soil mineral composition, while more than 83% of the land falls within the category of ASAL. Despite this limitation, high potential agricultural lands produce approximately 80% of Kenya's total agricultural output, whereas ASAL areas account for the remaining 20% and are frequently used for pastoral activities, hosting around 60% of the country's livestock (National Land Commission, 2023). In addition, it is important to consider that agricultural production in Kenya is highly fragmented and is largely composed of smallholder farmers, with an average landholding size ranging between 0.2 and 3 hectares. These farmers often face limited access to water resources and fertilizers, and approximately 96% of cultivated land relies exclusively on rainfall for irrigation, factors that frequently constrain overall productivity (National Land Commission, 2023).

The main parameters used to evaluate the fertility and productivity of a geographical area are soil properties and climatic conditions. Due to its proximity to the equator, Kenya is located within a tropical climate zone characterized by two rainy seasons each year, from March to May and from October to December, followed by dry and hot seasons. The most humid areas, which receive more than 2000 mm of rainfall annually, are located in the western part of the country near Lake Victoria along the borders with Uganda and Tanzania. The central and coastal regions are characterized by moderate rainfall levels between 1000 and 2000 mm per year, while the northeastern part of the country is predominantly arid, receiving between 200 mm and 600 mm of rainfall annually. The figure 3.2 illustrates the geographic distribution of the main agro-climatic zones across Kenya.

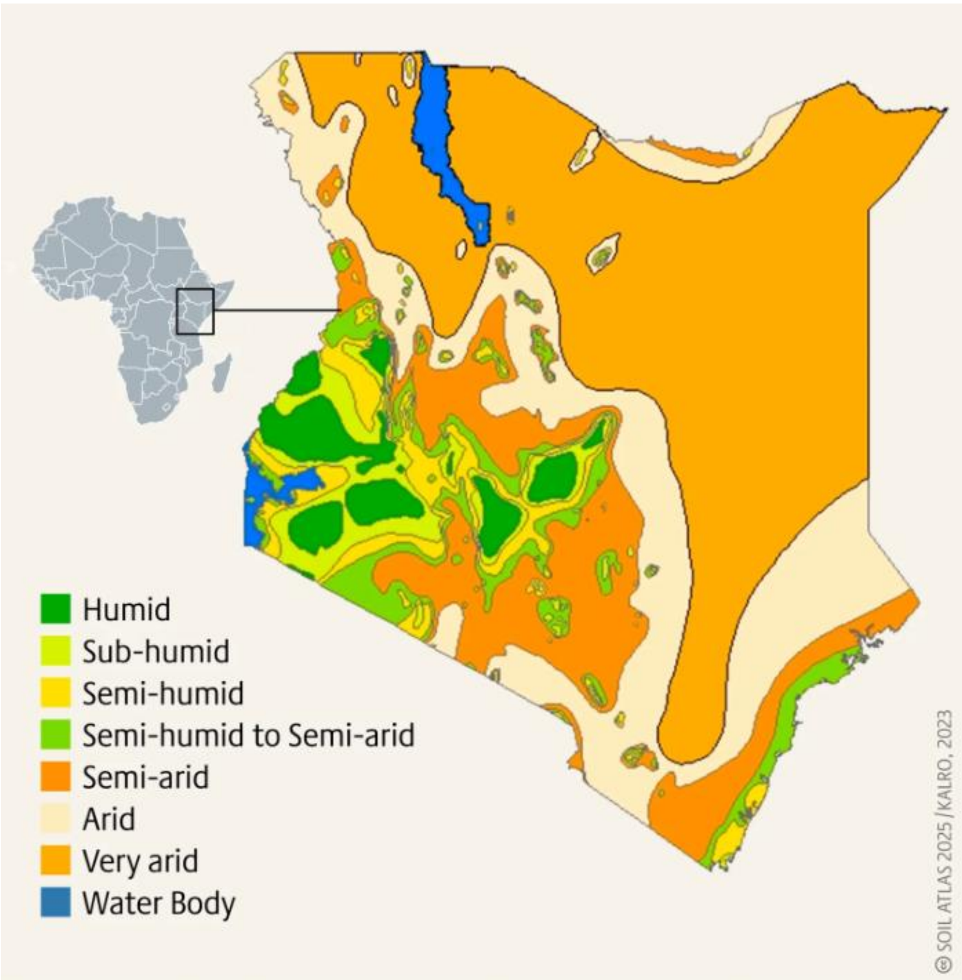

Figure 3.2 - Kenya agro-climatic zones (Heinrich-Böll-Stiftung, 2025)

Another equally important factor is soil quality, namely the presence of the nutrients required for the growth and survival of crops. The primary macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur, while the most important micronutrients include iron, manganese, zinc, and copper. In addition, a high carbon content and a neutral pH contribute to improving soil fertility. In this respect as well, the most suitable areas for cultivation are concentrated in western Kenya near the border regions, and to a lesser extent in the central and coastal zones. By contrast, the northeastern region is characterized by very limited nutrient concentrations and is therefore considered largely unsuitable for cultivation. Within the Kenya Vision 2030 strategy, one of the objectives established by the Kenyan government is precisely to enhance the productivity of ASAL areas through irrigation programs that could involve up to 1.2 million hectares of land (World Bank, 2018).

Biofuels are often categorized according to the type of feedstock used for their production. Different types of feedstocks exist, each requiring specific treatment methods and conversion technologies in order to produce biofuels. It is therefore possible to distinguish biofuels into four generations (Devi, et al., 2023). An overview of the different feedstock generation for biofuel production is reported in the figure 3.3.

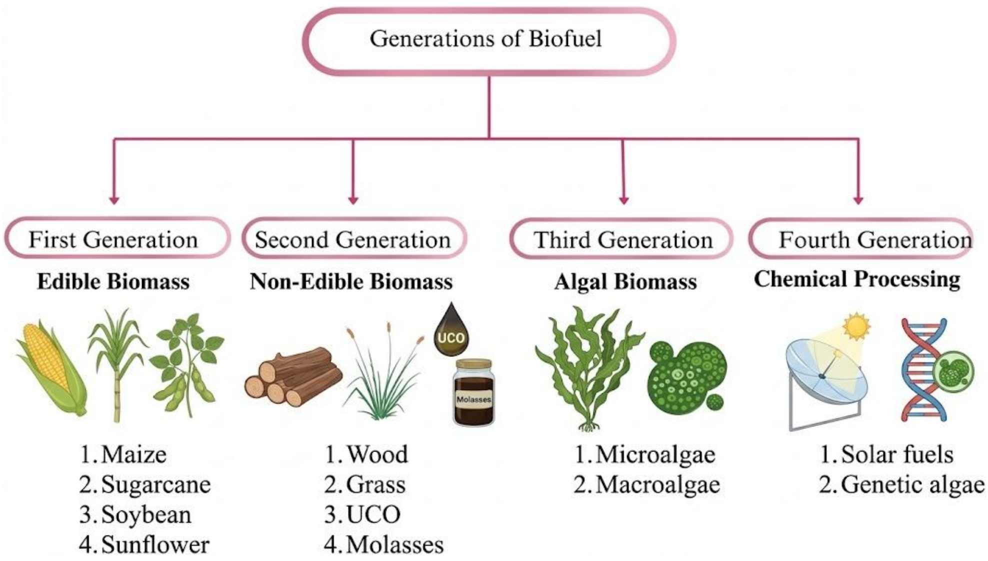

Figure 3.3 - Feedstock generations for biofuels production. Adapted from (Dharani, et al., 2024)

The first generation of biofuels, which has been present for the longest time and remains the most widely used today, relies on food crops as feedstock, namely the same products that are cultivated for the food industry. This type of feedstock is particularly widespread because of its practicality, since the crops are often already well known and widely cultivated, and the conversion of these feedstocks into biofuels is relatively simple both from a technical and an economic perspective. At the global level, ethanol production occurs predominantly from sugarcane and maize, while biodiesel is frequently produced from rapeseed and sunflower oil (OECD/FAO, 2025). The main drawback of these feedstocks, and the reason why subsequent generations have been developed, lies precisely in the competition that arises between the energy and the food sectors. Prices may become unstable and supply shortages can emerge, potentially failing to meet demand. This situation can lead to economic and social crises, particularly in countries where agricultural production is already constrained by climatic and geographical factors.

In order to avoid food security concerns, the second generation of feedstock is often considered, as it relies on products that do not compete with the food chain. This category includes non-edible plants (e.g., jatropha and croton), lignocellulosic biomass (e.g., agricultural residues), and production residues or waste streams (e.g., molasses and used cooking oil). In addition to reducing the conflict between the energy and food sectors, the environmental impact associated with these feedstocks is often lower, as many of them consist of waste materials, compared with feedstocks derived from intensive agricultural production that require substantial inputs of water, land, and fertilizers. The main limitation of this generation of feedstocks often concerns the pre-treatment and production processes, which in some cases require advanced technologies that are more complex and costly. In the case of waste-based feedstocks, production would also depend directly on the sectors or industries from which the waste or by product originates, making long term expansion of production more uncertain and difficult to plan.

The third generation includes algae as feedstock. Algae represent a highly versatile feedstock both in terms of chemical composition, which is suitable for the production of multiple biofuels due to their high lipid and carbohydrate content, and in terms of cultivation conditions, as algae can adapt even to extreme environments such as seawater or wastewater. However, in order to ensure yields suitable for biofuel production, the supply of nutrients and energy is essential, together with careful monitoring during the growth phase. Although algae cultivation can theoretically be replicated almost anywhere, including through intensive laboratory-based systems, the subsequent treatment and conversion stages remain complex and economically demanding. While the first two categories of feedstock are already widely adopted for biofuel production, algae-based biofuels remain largely at the experimental stage. Several studies and research initiatives are currently underway with the aim of unlocking the potential of algae-based biofuels and reducing their operational costs, which at present render their production economically uncompetitive compared with alternative fuels.

Finally, the fourth generation includes genetically modified feedstocks designed to improve both the characteristics and the productivity of biomass. Certain plants and algae can be genetically modified to enhance crop yields and to improve their carbon dioxide absorption capacity during growth, thereby potentially enabling carbon negative processes, meaning that more emissions are absorbed than emitted. However, this category remains in the early stages of research and requires significant investments to advance experimental activities (Devi, et al., 2023).

From an energy perspective, the most effective way to valorise biomass is to convert it into products with high energy content and optimized physicochemical properties. The conversion of biomass into biofuels can occur through different chemical processes, although the specific conversion pathway always depends on the characteristics of the feedstock. The selection of feedstock for biofuel production depends not only on technical and economic considerations but also on local availability and climatic conditions. Based on the chemical composition of biomass, it is possible to distinguish three main categories: sugary and starchy biomass, lipid biomass and lignocellulosic biomass.

3.1.1. Sugars and Starches

The category of sugary and starchy feedstocks includes all feedstocks characterized by a high content of simple sugars (e.g., glucose) and complex carbohydrates (e.g., starch). This category includes feedstocks such as sugarcane, sugar beet, sweet sorghum, cassava, maize, and wheat, as well as certain processing by products such as molasses. The molecular structure of simple sugars, namely monosaccharides, is illustrated in the figure 3.4.

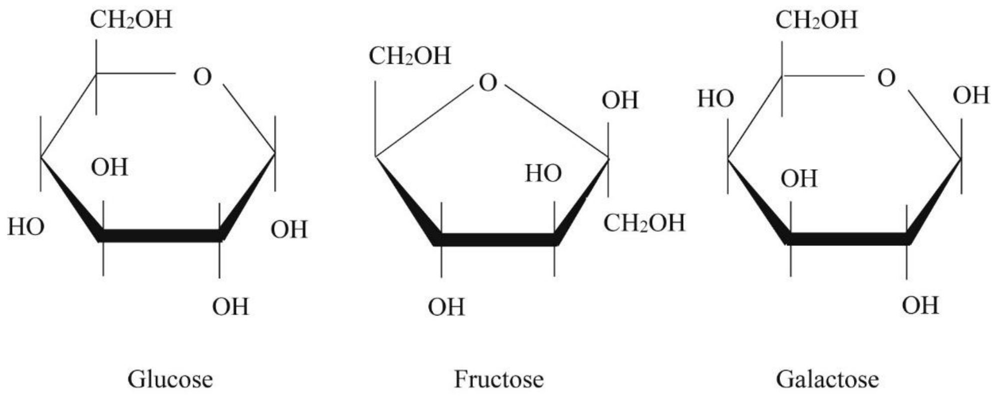

Figure 3.4 - Molecular structure of the main monosaccharides (Qi & Tester, 2019)

At present, the cultivation of sugarcane, maize, and cassava is widespread in Kenya, although these crops play a particularly important role in the food industry. In order to avoid competition over raw materials, as well as potential economic risks and food security crises, it is essential to carefully plan and identify which crops, and in what quantities, could be allocated to the energy sector.

The sugar content of these feedstocks is crucial because their fermentation produces bioethanol. It is important to clarify that there is no chemical difference between ethanol and bioethanol, although the latter term is commonly used to emphasize its origin from biomass. Since bioethanol is produced through the fermentation of simple sugars, in the case of complex carbohydrates such as starch it is first necessary to carry out a hydrolysis process in order to break them down into their constituent simple sugars. Ethanol can be used directly as a fuel, or it can be further processed through hydroprocessing in order to obtain ATJ-SPK, a drop in biofuel belonging to the category of SAF. The figure 3.5 presents a simplified scheme of the main conversion pathways involving feedstocks rich in sugars and starch.

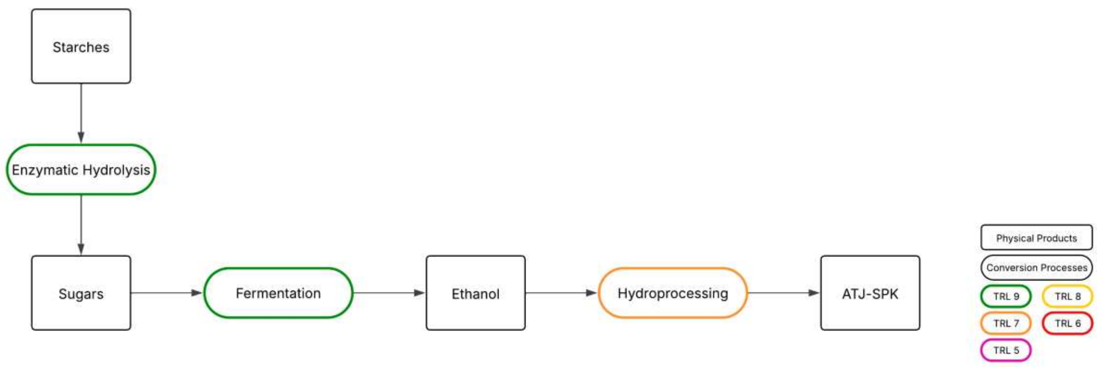

Figure 3.5 - Conversion process of starch and sugars into biofuels

In the case of complex sugars, such as starches, an initial enzymatic hydrolysis phase is required to break down polysaccharides into monosaccharides, which are then fermented to produce ethanol. Although bioethanol is one of the most widely used biofuels globally and can be utilized in its pure form, it can be further upgraded into ATJ-SPK through hydroprocessing to enable its use in the aviation sector. The primary distinction lies in the cost and complexity of the process; while bioethanol production is relatively simple, cost-effective, and globally established at scale, the conversion into ATJ-SPK is not yet commercially stable and remains at a TRL of 7 (IEA, 2025). However, several ATJ-SPK production facilities have already been announced and are expected to become operational in the coming years, particularly across Europe and the United States (IEA Bioenergy, 2024).

3.1.2. Lipids

From oleaginous crops that produce oil rich seeds containing high concentrations of triglycerides, it is possible to obtain vegetable oils, as in the case of those commonly used in the food supply chain (e.g., sunflower, palm, and soybean oil) through extraction in press mills. Alternatively, other types of non-edible vegetable oils that are sometimes used in the chemical and cosmetic industries (e.g., jatropha, castor, croton, and algae). The lipid category also includes certain waste products such as UCO and animal fats, which can be recovered and valorised by taking advantage of the availability of semi processed products that do not require additional land use and have a very limited environmental impact. In addition to these sources, recent years have seen an expansion in research regarding biofuel production from algae, which can be cultivated even under adverse environmental conditions and possess a high lipid content, but currently remain at an experimental stage of development.

In all cases, this type of feedstock is characterized by the high presence of fatty acids, primarily in the form of triglycerides. Triglycerides are molecules composed of one glycerol molecule bound to three fatty acid molecules, typically linear chains containing between 12 and 24 carbon atoms. Fatty acid chains can be classified as saturated, unsaturated, or polyunsaturated depending on the degree of saturation of the molecule, namely the number of double bonds present in the chain. The chemical properties of the molecule depend precisely on the length of the carbon chain and on the degree of saturation (Caltzontzin-Rabell, et al., 2022).

The figure 3.6 illustrates the chemical structure of the main fatty acids present in triglycerides.

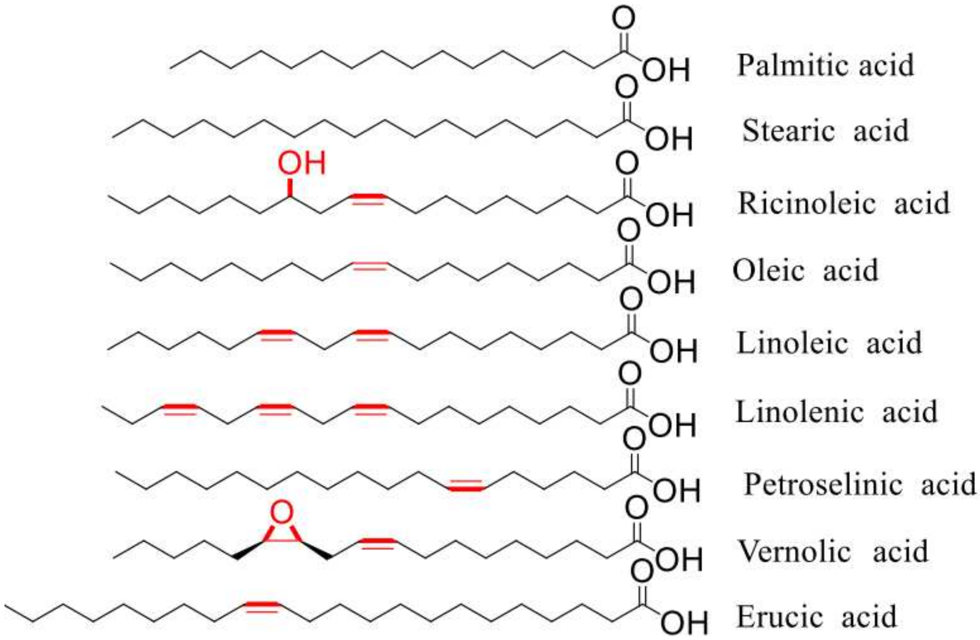

Figure 3.6 -– Molecular structure of the most common fatty acids in triglycerides (Rajput, et al., 2023)

Starting from triglycerides, it is possible to produce different types of biofuels. The figure 3.7 presents a simplified scheme of the biofuels that can be produced from lipid-based biomass and their relative TRL.

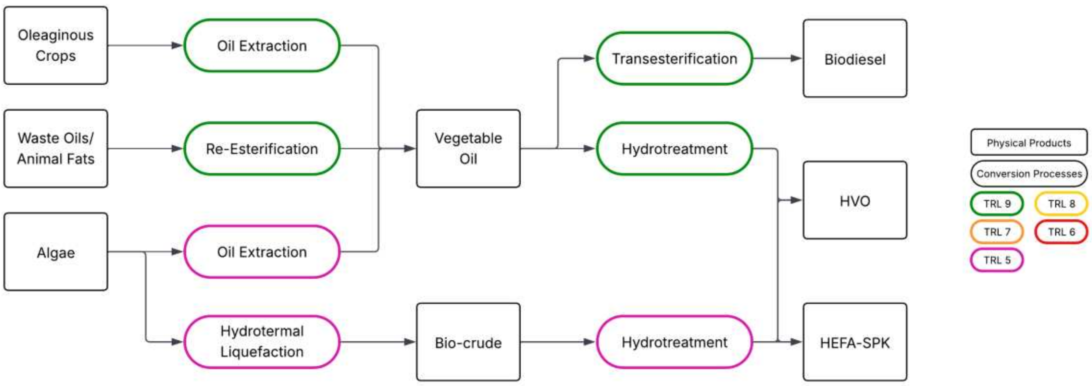

Figure 3.7 - Conversion process of lipids into biofuels

The most common product, and currently the most widely produced, is biodiesel, for which several blending mandates already exist in Europe and North America. Through the transesterification reaction, triglycerides are converted into a mixture of FAME, with physicochemical properties similar to those of conventional diesel. The production of FAME biodiesel through transesterification is a mature technology that has reached TRL 9, as it is currently widely deployed and commercially established on a global scale (IEA Bioenergy, 2020).

In addition to biodiesel production, the production of a higher quality fuel has become increasingly widespread, obtained through the hydrotreatment of triglycerides with hydrogen. This process allows the production of HVO, commonly referred to as green diesel or renewable diesel, a compound that is chemically equivalent to fossil diesel and can therefore be blended with it up to 100%. Green diesel can be further refined through hydrocracking and isomerization processes in order to produce HEFA-SPK, commonly known as biojet fuel, which belongs to the category of SAF. Although both HVO and HEFA-SPK are classified as advanced biofuels involving technologically complex conversion processes, their production has already reached TRL 9. Driven by stringent energy regulations, such as the Renewable Energy Directives (RED), which mandate the progressive integration of advanced biofuels into the energy mix, Europe has emerged as a global leader in production, with several commercial-scale facilities already in operation (Joint Research Centre, 2024).

Regarding algae, although they exhibit exceptionally high lipid content, reaching up to 70% in certain species, the oil extraction process remains complex and prohibitively expensive. Since algae grow in aquatic environments where they constitute only 0.1-1% of the total solid mass, they require extensive dewatering and drying operations prior to oil extraction, which is then realized through mechanical or chemical processes. Conversely, Hydrothermal Liquefaction (HTL) is a thermochemical conversion process that transforms biomass into a liquid intermediate by processing it in a hot, pressurized aqueous environment (IEA Bioenergy, 2020). Because HTL occurs in water, it eliminates the need for intensive algae dewatering. Nevertheless, biofuel production from algae remains in both cases at the pilot phase, currently at a TRL of 5 (IEA Bioenergy, 2020).

3.1.3. Lignocellulose

Lignocellulosic biomass represents the most abundant type of biomass on Earth, as it constitutes a fundamental structural component of all plants. This category includes woody and fibrous biomass such as wood and sawdust, as well as agricultural residues including husks, straw, and bagasse. Lignocellulosic biomass is defined as such because it is mainly composed of cellulose, typically ranging between 35% and 55%, hemicellulose, between 20% and 40%, and lignin, between 15% and 30% (Mupondwa, et al., 2022). The molecular structure of cellulose is illustrated in the figure 3.8.

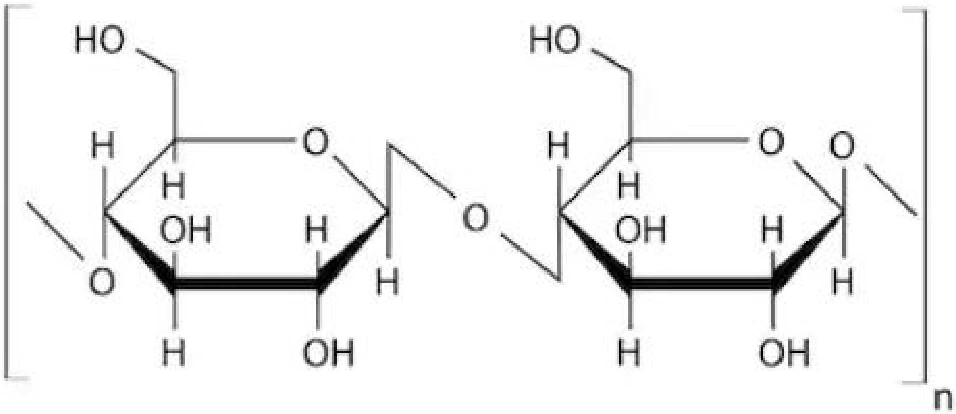

Figure 3.8 - Molecular structure of cellulose (Mupondwa, et al., 2022)

Although lignocellulosic biomass is the most widely available form of biomass in nature, it is generally less utilized than lipid and sugar-based biomass because it requires more complex and often more expensive processing technologies. The chemical composition of lignocellulosic biomass makes it possible to produce a wide variety of products, including several energy carriers, depending on the conversion pathways applied to the biomass. In Kenya, lignocellulosic biomass currently represents the most widely used source of biomass, particularly in the form of wood. However, its use is in most cases rather rudimentary, as wood is frequently burned directly as a fuel. In some cases, in order to increase the energy content of the biomass, wood is carbonized to produce charcoal, which is also widely used in the residential sector. In a limited number of cases, where cooking technologies allow it, wood can be converted into pellets and briquettes, thereby improving the physicochemical characteristics of the biomass during the combustion phase.

However, lignocellulosic biomass could be used for the production of a wide range of additional biofuels, although these pathways require more advanced processing technologies. The figure 3.9 summarizes the main conversion pathways of lignocellulosic biomass with their related TRL.

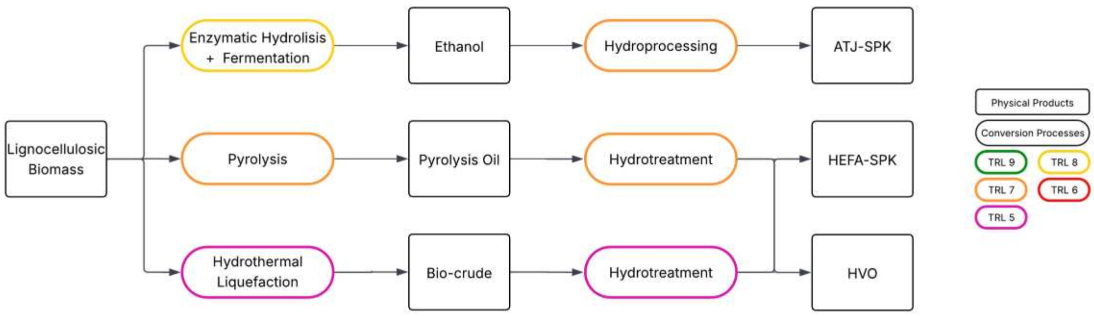

Figure 3.9 - Conversion process of lignocellulose into biofuels

For instance, it is possible to break down the cellulose and hemicellulose present in lignocellulosic biomass in order to obtain simple sugars from which ethanol, and eventually ATJ-SPK, can be produced (Mupondwa, et al., 2022). After the fermentation phase, it is possible to obtain an average ethanol yield of 300 litres per tonne of lignocellulosic biomass (IEA Bioenergy, 2020). Despite the fact that lignocellulosic bioethanol production remains limited on a global scale, significant industrial milestones have been achieved in recent years, and the technology has now achieved a TRL of 8 (IEA, 2025). As a matter of fact, six commercial-scale facilities, with annual capacities ranging from 25,000 to 90,000 tonnes, have been established across Europe, the United States, and Brazil in the last decade (IEA Bioenergy, 2020).

Through the pyrolysis process it is possible to produce a liquid fuel commonly referred to as pyrolysis oil, which can be used directly as a fuel or further upgraded through hydroprocessing in order to obtain HVO and HEFA-SPK. Pyrolysis is the chemical decomposition of organic matter of biomass by heating in the absence of oxygen which leads to the formation of char, oil and gases (IEA Bioenergy, 2020). Depending on the heating rate and temperature, the distribution of pyrolysis outputs varies significantly. To maximize the yield of the liquid fraction, typically accounting for 40–60% of the total output, the reaction is conducted within seconds at temperatures between 450°C and 550°C (Joint Research Centre, 2024). However, the resulting pyrolysis oil is characterized by high impurity levels and a substantial oxygen content, ranging from 30% to 40%. Consequently, upgrading processes are mandatory to convert it into viable biofuels. Through hydrotreatment, a process similar to that utilized for lipid biomass, the oxygen content is minimized, enabling the production of advanced biofuels such as HVO and HEFA-SPK (IEA Bioenergy, 2020). To date, the technology for the production and upgrading of lignocellulosic biomass into advanced biofuels remains at a TRL of 5–7, primarily because existing facilities are still at the demonstration stage, with maximum production capacities reaching approximately 200 tonnes per day (Joint Research Centre, 2024).

3.2. Fuels

Following the analysis of various feedstock categories, the focus now shifts to the final fuel products. This section provides a detailed discussion of their production processes, as well as their specific utilization in Kenya and globally. The conversion pathway determines the final characteristics of the biofuel and consequently the applications for which it can be used. In particular, the following section outlines the main transformation processes required for the production of biodiesel, bioethanol, HVO, HEFA-SPK, and ATJ-SPK fuels.

3.2.1. Biodiesel

The use of vegetable oil as an alternative to diesel dates back to the early twentieth century, when peanut oil was first used as a fuel in a diesel engine (Salaheldeen, et al., 2021). Although several types of biofuels exhibit properties similar to diesel, the term biodiesel usually refers specifically to FAME, which are produced through the transesterification of virgin vegetable oils, UCO, or animal fats.

The United States is currently the largest global producer of biodiesel, accounting for approximately 27% of total production, although in recent years the production of HVO has also grown significantly. In Europe, where the sector is regulated by the Renewable Energy Directive (RED), biodiesel consumption accounts for around 10% of total diesel consumption, with a modest increase to approximately 11% expected by 2034. The RED framework also foresees an increase in the use of advanced biofuels up to 5.5% of total fuel consumption by 2030. Brazil, in addition to being one of the largest producers of bioethanol, currently enforces biodiesel blending mandates of up to 14% in diesel vehicles. Indonesia has also implemented a national program to promote biodiesel as an alternative to fossil fuels, which has resulted in announced blending mandates of 35% and potentially 40% biodiesel. In order to meet these mandates, Indonesia could reach an annual production of approximately 15 billion litres of biodiesel by 2034 (OECD/FAO, 2025).

In contrast, biodiesel consumption in Kenya remains limited. While the *Bioenergy Strategy* acknowledges the potential for implementing a national B2 blend with fossil diesel, no formal regulations have yet come into force (Ministry of Energy and Petroleum, 2020). Currently, a few biodiesel refineries operate within the country, notably those managed by Giloil and Zijani, which utilize waste oils as feedstock, though their specific production volumes are not transparently reported. Ultimately, the sector's expansion is contingent upon the publication of clear regulations regarding feedstock management and production, as well as the introduction of incentives or mandatory blending mandates.

Biodiesel is produced from vegetable oil through the transesterification reaction, which improves the physicochemical properties of the oil and enables its blending with fossil diesel. Although vegetable oil already possesses a relatively high calorific value, it also exhibits very high viscosity and poor cold flow properties, which negatively affect engine performance (Salaheldeen, et al., 2021). Due to its biological origin, however, biodiesel has a significantly lower environmental impact and today represents an economically viable alternative to fossil diesel.

During the transesterification reaction, one mole of triglyceride reacts with three moles of alcohol to produce three moles of esters and one mole of glycerol. Methanol is typically used as the alcohol because of its low cost, although other alcohols can also be employed, including bioethanol produced from biomass, which in that case could further reduce the environmental impact of the resulting biodiesel. Each mole of alcohol reacts with the triglyceride molecule and progressively breaks it down first into diglyceride and then into monoglyceride, forming one ester molecule at each step (in the case of methanol, a methyl ester), and finally producing one mole of glycerol. The overall reaction is illustrated in the figure 3.10.

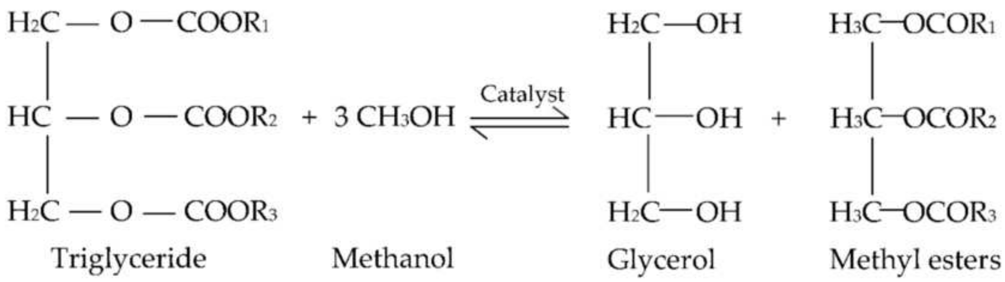

Figure 3.10 – Transesterification reaction diagram (Miyuranga, et al., 2022)

One of the most critical factors determining the effectiveness of the transesterification reaction is the choice of catalyst. The quality of the reaction is evaluated by the final percentage of methyl esters in the biodiesel mixture. Homogeneous basic catalysts such as sodium hydroxide or potassium hydroxide are commonly used because they are inexpensive, ensure relatively fast reaction rates, and typically yield conversion efficiencies above 99%

(Salaheldeen, et al., 2021). However, a high concentration of FFAs in the feedstock, combined with a basic catalyst, may favour saponification rather than transesterification. In such cases, an additional treatment step would be required to convert the soaps back into alkyl esters, which would increase production costs.

The concentration of FFAs depends strongly on the type of feedstock used and is often particularly high in UCO. This parameter can significantly affect the success of the transesterification process. To ensure optimal yields, the FFA content should ideally remain below 0.5%. For higher concentrations, the use of an acid catalyst becomes preferable, as it is less affected by the presence of FFAs. When the FFA content exceeds 5%, a dedicated pretreatment step is generally required (Gomez-Castro, et al., 2022). For this reason, when utilizing waste oils or animal fats, after a preliminary purification phase to remove impurities, a re-esterification reaction must follow. This process is essential to reduce the concentration of FFAs by converting them back into triglycerides, thereby ensuring the feedstock is suitable for subsequent conversion stages (IEA Bioenergy, 2020).

In recent years, heterogeneous catalysts have gained increasing attention. Although they typically provide slightly lower yields, generally between 92% and 99%, they offer important operational and environmental advantages. Unlike homogeneous catalysts, heterogeneous catalysts can be recovered and reused after the reaction, and they enable continuous biodiesel production processes without the need to treat large volumes of wastewater (Salaheldeen, et al., 2021).

3.2.2. Bioethanol

Bioethanol is a liquid biofuel produced from feedstocks with a high sugar content, such as sugarcane, sweet sorghum, and molasses, or with high starch content, such as cassava, maize, and wheat. Bioethanol has been used in the transport sector since the early twentieth century, although its use declined for several decades due to higher costs compared with petroleum-based fuels.

The United States is currently the largest producer of ethanol globally, accounting for approximately 46% of total production, almost entirely derived from maize, which represents about 99% of national output. Brazil ranks second in global bioethanol production, supported by government blending mandates requiring ethanol to be blended with gasoline up to 27%. The widespread presence of flex fuel vehicles in Brazil, namely vehicles capable of operating with blends containing up to 100% ethanol, has facilitated the implementation of these mandates and stimulated ethanol demand, which is expected to increase further in order to meet a blending target of up to 40% in the coming years. At present, most Brazilian ethanol production relies on sugarcane, although maize is expected to become an increasingly important feedstock in order to meet rising demand.

In Europe, bioethanol accounts for approximately 6.5% of gasoline consumption and is expected to remain relatively stable in the near future. India has also significantly expanded its ethanol production in recent years with the objective of reaching an E20 blending mandate. According to current estimates, thanks to its large domestic agricultural resources, India could reach and potentially exceed annual ethanol production levels of 15 billion liters and may explore even more ambitious blending mandates in the future (OECD/FAO, 2025).

Kenya has identified ethanol as a key component for achieving national clean cooking access by 2028. Approximately 30% of total energy consumption in the cooking sector is expected to come from bioethanol (Ministry of Energy and Petroleum, 2024). According to the *National Energy Policy 2025–2034*, bioethanol production in Kenya currently amounts to approximately 26.5 million litres per year, primarily derived from molasses, although the installed production capacity is around 83 million litres annually (Ministry of Energy and Petroleum, 2025). National ethanol demand is considerably higher than current domestic production, over 40 million litres per year, since ethanol is also widely used in the food and beverage industry for the production of alcoholic drinks. As a result, the majority of ethanol consumed in Kenya is currently imported. In order to achieve the ambitious targets set by the government for the clean cooking sector, and potentially also for the transport sector in order to reduce gasoline imports, domestic ethanol production is expected to increase significantly. This expansion will likely require the allocation of additional agricultural land for ethanol feedstock production, which at present relies heavily on by products from the sugar industry.

When derived from biomass, ethanol is produced through the fermentation of sugars present in the feedstock. Under anaerobic conditions and in the presence of yeast, biological reactions convert simple sugars into ethanol, carbon dioxide, and other by products. When polysaccharides are present in the feedstock, as in the case of starchy or lignocellulosic biomass, it is first necessary to break down these complex carbohydrates through hydrolysis in order to obtain fermentable monosaccharides. In the case of lignocellulosic biomass, a pretreatment step is also required prior to hydrolysis in order to increase the surface area of the feedstock and facilitate the breakdown of cellulose and hemicellulose into simple sugars. Pretreatment methods can be biological, through the use of fungi, physical, through processes such as extrusion or mechanical milling, or chemical, through decomposition reactions. This pretreatment stage often represents the most expensive part of the entire bioethanol production process (Otieno & Ogutu, 2020). After pretreatment and hydrolysis, the fermentation phase converts sugars into ethanol as reported below:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

During the first stage of fermentation, known as glycolysis, sugars are broken down by yeast to form pyruvate molecules. These pyruvate molecules are subsequently converted into acetaldehyde and finally into ethanol (Behera, et al., 2022). At the end of the fermentation process, ethanol remains highly diluted and must therefore be dehydrated before it can be used as a fuel. The ethanol content in the fermentation broth typically varies between 5% and 12%, requiring distillation and dehydration operations to achieve a concentration exceeding 99%. The distillation phase exploits the lower boiling point of ethanol relative to water to separate the two compounds, followed by the condensation of the gaseous ethanol. At the conclusion of this process, ethanol purity reaches 95.6%, which corresponds to the ethanol-water azeotropic limit (Hanchate, et al., 2019). To further reduce the water content, dehydration must be performed using techniques such as azeotropic distillation, extractive distillation, or membrane technologies, which enable an ethanol concentration of up to 99.8% (Hanchate, et al., 2019).

3.2.3. HVO

HVO is an advanced biofuel produced through the hydrotreatment of vegetable oils. The feedstocks used are the same as those employed in the FAME biodiesel production, but in this case the final product is a hydrocarbon rather than an oxygenated fuel. To date, FAME biodiesel production remains the most significant in terms of volume, even if HVO production technology has reached full maturity in recent years, as several commercial plants already are in operation, such as those managed by Neste in Finland and Eni in Italy. Driven by superior fuel properties and regulatory support, HVO production is projected to expand substantially in the coming years (IEA, 2025). It is essential to note that the production of HVO is closely linked to that of HEFA-SPK, as they utilize the same feedstocks and undergo the same core conversion processes. Consequently, both are high-value outputs of the same production plant. The primary technical distinction arises during the final separation phase following hydrotreatment. Specifically, HEFA-SPK requires additional processing to enhance its cold flow properties, a critical requirement for its application in the aviation sector. It is also worth noticing that the average capacity of HVO/HEFA biorefineries is significantly higher than that of FAME biodiesel plants. While FAME facilities typically have an average capacity of 110,000 tonnes per year, with many operating below the 100,000-tonne threshold, HVO/HEFA plants maintain an average capacity of approximately 280,000 tonnes per year (Bockey, 2019). Although this requirement did not impede growth in Europe, where the number of HVO plants increased from 4 to 12 between 2012 and 2017, the necessity for large-scale infrastructure may hinder adoption in developing economies. In Kenya, the substantial capital investment required, coupled with uncertainties regarding biofuel demand and the logistical challenge of securing large feedstock volumes, represents a significant barrier to the widespread deployment of HVO technology.

The crucial difference lies in the oxygen content, which in the case of HVO is completely removed through hydrotreatment in order to obtain physicochemical properties that closely resemble those of fossil diesel (Resta, 2024). For this reason, HVO belongs to the category of drop in fuels, meaning fuels that can be blended up to 100% in existing internal combustion engines designed for fossil fuels. HVO, due to its characteristics, can be used either in blends or as a full substitute for conventional diesel and is therefore often referred to as green diesel.

The production process of HVO begins with the hydrotreatment of the feedstock, with the objective of converting triglycerides and unsaturated fatty acids into pure hydrocarbon chains. In the first stage, known as hydrogenation, hydrogen is added in the presence of a metallic catalyst such as platinum or nickel in order to eliminate all double and triple bonds present in the fatty acids. In the second stage, decarboxylation reactions occur, removing the carboxyl group typical of fatty acids and fully deoxygenating the molecules. At the end of the hydrotreatment process, which typically occurs at temperatures around 400°C and pressures close to 92 bar, only saturated hydrocarbon chains composed exclusively of carbon and hydrogen atoms remain.

The removal of oxygen from fatty acid molecules is essential to increase the calorific value of the fuel and to comply with the chemical composition requirements defined by ASTM standards (Mupondwa, et al., 2022). The final product is a high-quality paraffinic mixture containing hydrocarbons with chain lengths typically ranging between 10 and 24 carbon atoms, which corresponds to the typical range of fossil diesel. At this stage, a portion of the produced distillate, typically ranging between 10% and 20%, falls within the carbon chain length of kerosene. However, to achieve effective HEFA production, subsequent hydrocracking and isomerization steps are mandatory to refine the fuel to the necessary technical specifications required by the aviation sector.

3.2.4. HEFA-SPK

HEFA fuels are also produced through the hydrotreatment of vegetable oils in order to obtain high quality hydrocarbons with physicochemical properties similar to conventional kerosene-based jet fuel. HEFA fuels, also known as biojet fuels, belong to the category of SAF and currently represent the most widely adopted SAF production pathway globally.

Although HEFA and HVO are used in different sectors, aviation and road transport respectively, they are closely related and follow essentially the same conversion pathway. The only significant difference occurs in the final stage of chemical processing. HEFA fuels are essentially HVO that undergo additional hydrocracking and isomerization reactions. Hydrocracking is a thermal decomposition process used to reduce the length of hydrocarbon chains until they fall within the range typical of jet fuel. Isomerization, by contrast, modifies the chemical structure of the hydrocarbons in order to optimize cold flow properties.

Compared with conventional fossil jet fuel, which typically consists of a mixture of alkanes, cycloalkanes, and aromatic hydrocarbons, HEFA fuels contain a similar mixture of hydrocarbons but lack aromatic compounds. Due to this absence, and in order to comply with ASTM fuel standards, biojet fuels produced through the HEFA pathway can currently be blended with conventional jet fuel only up to 50%, unless additional aromatic compounds are added to compensate for this deficiency (Mupondwa, et al., 2022).

At the global level, approximately 83% of the SAF production projects announced by 2025 rely on the HEFA pathway. HEFA biorefineries are highly flexible and allow producers to adjust output according to market demand. Since HVO and HEFA are closely related products, it is theoretically possible to configure production processes to maximize either HVO or HEFA output depending on market conditions and economic considerations. Nevertheless, it is essential to specify that the total conversion of feedstock into a 100% HVO or 100% HEFA distillate is technically impossible. Even when optimizing for HVO output, the actual distillate yield ranges between 50% and 80% depending on the feedstock utilized, while varying proportions of HEFA, LPG, and water are generated as by-products. Similarly, when maximizing HEFA production, the net distillate yield is approximately 60–80%, with a significant share of the feedstock being converted into naphtha, LPG, and water (Boscagli, 2025). In general, the substantial share of by-products generated during the conversion process acts as a constraint on total distillate output. Given these limitations, the majority of operational biorefineries currently opt for a production split of 70% HEFA and 30% HVO for their distillate fraction, while the resulting by-products are frequently repurposed to provide process energy for the facility's internal operations (Boscagli, 2025).However, significant cost reductions in HEFA production technologies are unlikely in the coming years due to the technological maturity of the process and the increasing cost of feedstocks driven by rising demand.

3.2.5. ATJ-SPK

ATJ-SPK is an advanced biofuel produced through the hydroprocessing of alcohols. It belongs to the category of SAF and can be blended with fossil jet fuel up to a maximum of 50%. Although ATJ-SPK can theoretically be produced from different types of alcohols, the technology was originally developed to utilize alcohols derived from renewable biomass in order to reduce the environmental impact of aviation fuels. Bioethanol, discussed earlier, can therefore be used as a feedstock for ATJ SPK production.

The objective of the ATJ process is to upgrade the properties of alcohols, which can be relatively easily produced from renewable resources, in order to make them suitable for use in the aviation sector. The conversion process consists of three main reactions: alcohol dehydration, olefin oligomerization, and hydrogenation. The dehydration reaction removes hydroxyl groups from the alcohol molecules, converting them into the corresponding alkenes. The oligomerization reaction then combines the short hydrocarbon chains produced during dehydration, which in the case of ethanol contain two carbon atoms, in order to form longer chains within the typical kerosene range of approximately eight to sixteen carbon atoms. Finally, hydrogenation saturates the remaining double bonds in the hydrocarbon chains through the addition of gaseous hydrogen (Geleynse, et al., 2018). The figure 3.11 shows the conversion process of a generic alcohol into ATJ-SPK.

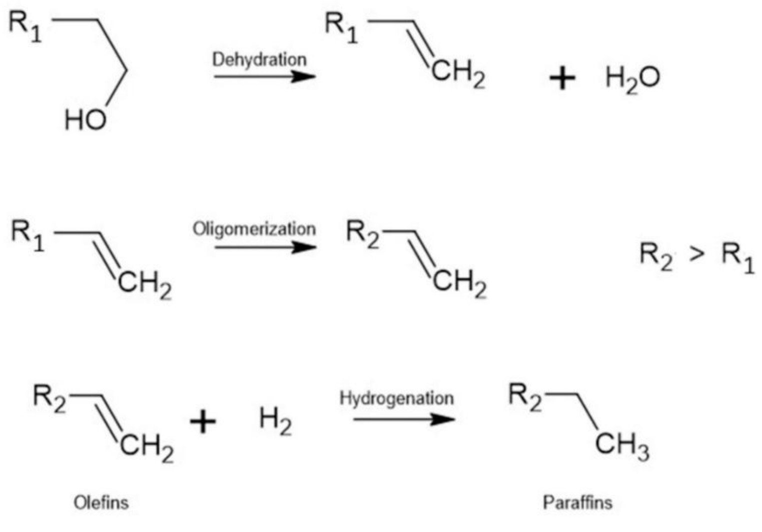

Figure 3.11 - ATJ conversion pathway (Teixeira, et al., 2024)

According to a study conducted by ICAO in Kenya, the production of 200,000 tonnes per year of ATJ SPK would require approximately 385,000 tonnes of ethanol, corresponding to a conversion yield of around 52%, which is significantly lower than that of the HEFA pathway (Boscagli, 2025). In addition, both investment and operational costs associated with ATJ SPK production remain considerably higher than those required for HEFA production. According to a study published by the World Economic Forum, the capital investment required for the construction of a SAF production facility with an annual capacity of 500,000 tonnes is estimated at approximately 0.7 billion USD for the HEFA pathway, rising to 2.2 billion USD for the ATJ pathway (WEF, 2025). Consequently, HEFA currently remains the dominant SAF production pathway.

Nevertheless, considering the large availability of lignocellulosic biomass, including agricultural residues that could be used for ethanol production, it is possible that ATJ-SPK production will increase significantly in the coming years, if the production will become economically feasible. In Kenya as well, if the targets for the penetration of electric technologies are achieved in the coming years, part of the bioethanol initially intended for the cooking sector and for road transport could potentially be redirected toward the production of ATJ-SPK.

3.3. End-use sectors

Depending on their specific characteristics, each biofuel can be employed in a particular sector or as a substitute for a specific conventional fuel. Some biofuels are highly versatile and can be used across multiple sectors, as is the case for bioethanol in both the residential and transport sectors. The following section describes and analyses the main sectors in which biofuels could find application and play a significant role, taking into account the investment strategies and transition targets identified by Kenya.

3.3.1. Cooking Sector

The Kenyan government aims to complete the transition to clean cooking by 2028, in line with the decarbonization targets presented in the second version of the NDC (Republic of Kenya, 2025)

In 2022, more than 68% of the population, corresponding to approximately 9 million households, still relied on traditional fuels as their primary energy source for cooking. Around 52% of the population used firewood as their main cooking fuel, a figure that rises to approximately 81% in rural areas. LPG accounted for roughly 31% of the total and was used primarily in urban areas, while charcoal represented about 12% of the total. Other modern and cleaner energy sources, such as ethanol and electricity, remained marginal and accounted for less than 1% of total consumption (Ministry of Energy and Petroleum, 2024).

According to the study published by the Kenyan Ministry of Energy, the transition to clean cooking is necessary for three main reasons: health, environmental, and social considerations. Achieving universal clean cooking access by 2028 would make it possible to avoid approximately 27,000 premature deaths caused by household air pollution. In addition, emissions related to the cooking sector could be reduced by around 16 million tonnes of CO2eq per year, mainly from preventing the deforestation of nearly 470,000 hectares of forest, equivalent to approximately 11% of the total forested area, which has already been significantly reduced over the years (Ministry of Energy and Petroleum, 2024).

Furthermore, it is estimated that collecting firewood for cooking requires on average around 790 hours per year per household. This implies that more than two hours per day are typically spent collecting wood, most often by women and children, rather than being devoted to productive or educational activities that could improve the social and economic status of households (Ministry of Energy and Petroleum, 2024).

According to projections from the Ministry of Energy, achieving universal access to clean cooking in Kenya by 2028 will require LPG to become the most widely used energy source, accounting for approximately 50% of total consumption. Bioethanol is expected to represent around 30%, while electric cooking and biogas would account for approximately 10% and 3% respectively (Ministry of Energy and Petroleum, 2024). In order to ensure a realistic transition in the short term, solid biomass such as firewood and charcoal will not be completely eliminated but will continue to represent around 7% of total consumption, used through improved cookstoves that reduce health impacts and GHG emissions. In the long term, the ultimate objective is to completely eliminate the use of solid biomass and reduce reliance on LPG, while maximizing the use of bioethanol, biogas, and electric cooking solutions.

Between 2018 and 2022, approximately 33 million litres of ethanol were imported solely for cooking purposes. According to the *Ethanol Cooking Fuel Masterplan* published by the Kenyan government, meeting ethanol demand for cooking fuel by 2030 would require the construction of between two and seven new production facilities (Ministry of Energy and Petroleum, 2021). Under this scenario, approximately 78% of the total investment would be allocated to the construction of new biorefineries, while only 15% and 7% would be required for feedstock production and ethanol distribution across the country.

Considering the expected growth trajectory and the central role of bioethanol in the clean cooking transition, the same study estimates that ethanol production by 2030 could range between 115 and 268 million litres per year, with a baseline scenario of approximately 192 million litres annually. This volume would correspond to the consumption of roughly 760,000 households, still significantly below the target of covering 30% of total cooking energy demand, which would correspond to approximately 4.3 million households in 2030 (Ministry of Energy and Petroleum, 2021).

3.3.2. Road Transport

Road transport is by far the most widely used mode of transportation in Kenya. According to the *Integrated National Transport Policy*, approximately 90% of all domestic passenger and freight movements occur via road. The domestic transport sector is responsible for more than 12.6 million tonnes of CO2eq of emissions, of which approximately 98%, corresponding to 12.4 million tonnes CO2eq, originates from road transport (Ministry of Roads and Transport, 2023). This is largely because only about 5% of aviation sector emissions are associated with domestic flights, while the majority of aviation emissions, roughly 95%, arise from international air traffic (Ministry of Roads and Transport, 2023).

The Kenyan road fleet largely consists of about 2 million second-hand vehicles, of which approximately 85% are imported, including motorcycles, cars and trucks, that are fuel-inefficient and powered almost exclusively by gasoline and diesel, with only a few thousand electric vehicles in circulation (Ministry of Energy and Petroleum, 2023). As a result, the efficiency of the national vehicle fleet is relatively low, leading to higher fuel consumption and increased emissions. As a member of the Global Fuel Economy Initiative, Kenya has committed to doubling the fuel efficiency of its road vehicle fleet, reaching approximately 3.75 L per 100 km, and to reducing vehicle emissions by 90% by 2050 (GIZ, 2025).

Part of these objectives may be achieved through the expansion of electric vehicle adoption. At present, the uptake of electric vehicles is constrained by high costs and the incomplete electrification of the country. However, the large availability of renewable energy resources could significantly change this situation in the coming years. Starting from approximately 5,000 electric vehicles in 2024, the Kenyan government has set the ambitious objective that at least 5% of newly registered vehicles will be electric from 2025 onwards (GIZ, 2025).

Rail transport, which currently remains limited to a few strategic routes, generates approximately 0.06 million tonnes of CO2eq per year due to its reliance on fossil fuels. In the coming years, however, one of the main priorities of the Kenyan government will be the modernization of the railway system, including its electrification, as well as the reorganization of logistics routes in order to maximize the share of freight and passenger transport carried by rail (Ministry of Roads and Transport, 2023).

A few years ago, an E10 ethanol blending mandate, corresponding to a 10% ethanol blend in gasoline, was approved. However, it was never effectively implemented due to insufficient ethanol availability (Ministry of Energy and Petroleum, 2020). According to a study conducted by GTZ, the introduction of a B2 blending mandate, corresponding to a 2% biodiesel blend in diesel engines, would be technically feasible (GTZ, 2009). Nevertheless, these projections remain purely indicative and are not supported by any regulation currently in force.

In recent years, the electrification of road transport has also gained increasing attention. Although this option cannot represent an immediate solution, due to the limited grid capacity and lack of universal electricity access in the country, it could become more widespread in the coming years due to the country's significant renewable energy potential. At present, the installed grid capacity in Kenya would not be sufficient to sustain a large-scale transition to electric mobility. Consequently, the use of alternative fuels, such as bioethanol, biodiesel and renewable diesel, remains essential in the short to medium term in order to gradually reduce the environmental impact generated by the sector.

3.3.3. Aviation Sector

The global CORSIA aims to reduce GHG emissions from aviation by 50% by 2050 compared with 2005 levels and to avoid approximately 2.5 billion tonnes of CO_2 emissions by 2035 (Mupondwa, et al., 2022).

At present, SAFs represent the only low carbon fuel technology available for air transport and are therefore essential for the sector to achieve its climate objectives. This is particularly relevant for long haul flights, which account for the majority of aviation fuel consumption. Several governments have already introduced policies to promote the deployment of SAF, often building upon previous policy frameworks that successfully integrated biofuels into the road transport sector, particularly through targeted mechanisms designed to reduce production costs.

The aviation industry expects SAF to provide the majority of the emission reductions required to meet climate targets. Many airlines have begun to adopt SAF, although current volumes remain limited, while fuel producers have invested in additional production capacity. Scaling up SAF production will require coordinated efforts between governments and companies operating within the aviation sector, and such efforts must begin immediately in order to achieve the necessary rate of deployment for the sector's decarbonization pathway.

The aviation sector is generally classified as a hard-to-abate sector because of the extremely stringent physicochemical requirements that aviation fuels must satisfy in order to ensure safe and reliable aircraft operation.

At the global level, international aviation currently accounts for approximately 1.3% of total GHG emissions, corresponding to around 700 million tonnes of CO2eq per year, although this figure is expected to increase significantly as the sector expands in the coming decades, potentially exceeding 1600 million tonnes of CO2eq by 2040. Partial emission reductions can be achieved through technological improvements, increased fleet efficiency, and operational optimization. However, without the introduction of cleaner fuels, aviation emissions could still reach approximately 1200 million tonnes of CO2eq by 2040 (White, 2018).

In Kenya, the aviation sector contributes approximately 1.1% to national GDP and is expected to grow further in order to support tourism and trade activities. The country currently has 55 airports, although only four operate international routes. Despite this limited number, these international routes account for approximately 88% of total jet fuel consumption, corresponding to about 722,000 tonnes per year (Boscagli, 2025).

Within the context of the energy transition, the international aviation sector has set ambitious targets, aiming to fully decarbonize aviation by 2050. Achieving this objective will only be possible through the adoption of alternative fuels with a significantly lower environmental impact compared with conventional kerosene-based fuels. The main challenges are both technical and economic. Research on SAF is progressing rapidly in order to identify technically viable alternatives to fossil fuels and to ensure the economic viability required to scale up production.

The alternative fuels considered technically viable are the so-called drop-in fuels, meaning fuels that possess physicochemical properties similar to those of conventional jet fuels and can therefore be used in blends with petroleum-based fuels or potentially replace them entirely. In this context, neither biodiesel nor bioethanol belong to this category. Although their properties allow them to be blended with diesel and gasoline for road transport applications, the requirements for aviation fuels are significantly more stringent. In addition to having an energy density comparable to conventional jet fuel, SAF must maintain optimal performance under extreme conditions of temperature and pressure that extend well beyond the operational range typical of road transport fuels.

Despite the significant technological progress achieved in recent years, only a limited number of solutions are currently considered technologically mature for partial blending with conventional jet fuel, and none of them are yet economically competitive with fossil fuels. In 2024, total SAF consumption reached approximately 0.5 million tonnes, corresponding to around 0.5% of global jet fuel consumption, still far from the targets required for international aviation decarbonization. To date, eleven conversion pathways have been approved by ICAO for SAF production, with an additional eleven utilizing alternative feedstocks and conversion processes currently under evaluation (ICAO, 2023). The table 3.1 outlines the primary SAF production technologies and their respective maximum blending limits with conventional jet fuel.

Table 3.1 - Main conversion processes for SAF production (ICAO, 2023)

ASTM reference	Conversion Process	Fuel Abbreviation	Possible Feedstocks	Maximum Blend Ratio
ASTM D7566 Annex A1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	FT	Coal, natural gas, biomass	50%
ASTM D7566 Annex A2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A3	Synthesized iso-paraffins from hydroprocessed fermented sugars	SIP	Biomass used for sugar production	10%
ASTM D7566 Annex A4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%
ASTM D7566 Annex A5	Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	Ethanol, isobutanol and isobutene from biomass	50%
ASTM D7566 Annex A6	Catalytic hydrothermolysis jet fuel	CHJ	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A7	Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids	HC-HEFA-SPK	Algae	10%

A study conducted by the World Bank identifies Africa as a region with significant growth potential for SAF production, not only to serve local markets but also to supply international aviation (Abate, et al., 2025). The large availability of feedstocks could enable African countries to enter the global market for sustainable fuels. Nevertheless, high investment costs and the absence of adequate regulatory frameworks currently limit the development of the sector. According to World Bank estimates, Kenya could install production capacity equivalent to approximately 4,000 barrels per day of HEFA fuel, corresponding roughly to 200 thousand tonnes per year, primarily using UCO and castor oil as feedstocks, with an estimated investment of around 235 million USD (Abate, et al., 2025). Significant cost reductions, amounting to approximately 35% of the total capital investment, could be realized through brownfield development, specifically by repurposing existing refinery infrastructure. However, the business implementation study published by ICAO regarding the conversion of the Mombasa refinery into a 250 thousand tonnes per year HEFA production facility estimated the required capital investment to be between 407 and 535 million USD (Boscagli, 2025).With such production volumes, Kenya could cover approximately 25% of its current jet fuel demand and around 20% of projected demand by 2030 (Boscagli, 2025).

3.3.4. Maritime sector

The maritime sector in Kenya is highly developed and holds considerable strategic importance. In 2024, goods worth approximately 28 million USD were traded through maritime imports and exports, representing around 23% of the country's total GDP (United Nations Trade and Development, 2025). In addition, the Port of Mombasa is one of the most important ports in East Africa and serves as a major import hub not only for Kenya but also for several neighbouring countries.

Similarly to road transport and aviation, the maritime sector remains entirely dependent on fossil fuels. Beyond its significant environmental impact, the reliance on fossil fuels, which must be imported by sea, requires substantial foreign currency reserves, exposes the country to volatile international fuel markets, and limits national energy independence.

In 2023, the IMO updated its strategy for the decarbonization of international maritime transport, identifying concrete actions and targets required to achieve net zero emissions by 2050. Green and low carbon fuels are expected to play a central role in reducing GHG emissions within the maritime sector. By 2030, at least 5% of total emission reductions, with an aspirational target of 10%, should come from the adoption of low emission marine fuels (International Maritime Organization , 2023). Kenya, as a member of the IMO and a participant in the IMO GreenVoyage 2050 initiative, is currently working on the decarbonization of its maritime sector through the development of a National Action Plan aimed at reducing emissions from domestic shipping and port operations (IMO, 2026). In particular, following the publication of the *Green Hydrogen Strategy* in 2023, Kenya aims to position itself as a regional hub for the production of low carbon hydrogen-based fuels such as e-ammonia and e-methanol (Ministry of Energy and Petroleum , 2023).

A study conducted by the Global Maritime Forum highlights that large scale hydrogen production could be feasible in Kenya due to the country's abundant renewable energy resources, particularly geothermal, wind, and solar energy. The estimated production costs of ammonia and methanol in Kenya are comparable to global average production costs but remain approximately four times higher than those of conventional fossil fuels (Global Maritime Forum, 2025). In order to facilitate the energy transition in the maritime sector, coordinated action will therefore be required, including binding government policies and clear strategic targets, international support through capacity building and financing mechanisms, and strong engagement from the private sector to integrate low carbon fuels into shipping operations (Global Maritime Forum, 2025).

4. Analysis

In 2022, Kenya's total emissions amounted to approximately 113 million tonnes of CO_2eq, representing a marked increase from the 1995 levels of 56.8 million tonnes of CO_2eq. According to the Business-As-Usual scenario developed by the government, these figures are projected to rise further, reaching 215 million tonnes of CO_2eq by 2035 (Republic of Kenya, 2025). Although Kenya is a marginal contributor to global emissions, accounting for only 0.1% of world cumulative emissions as of 2019, the country has established ambitious mitigation targets within its NDCs. Within the second and most recent NDC, covering the period 2031–2035, Kenya commits to reducing its emissions by 35% relative to the 2035 projections, corresponding to a reduction of approximately 75 million tonnes of CO_2eq compared to an estimated total of 215 million tonnes (Republic of Kenya, 2025).

The availability of renewable resources in the country enables Kenya to meet over 80% of its electricity demand through clean energy sources. Geothermal and hydropower alone account for approximately 64% of total electricity generation, while solar and wind currently play a secondary role (at present around 16% of total generation) (EPRA, 2025). Nevertheless, their contribution is expected to grow exponentially in the coming years, driven by Kenyan energy policies and by the country's substantial untapped generation potential. The electrification process is advancing rapidly, with more than 79% of the Kenyan population now having access to electricity through either national grid connections or off-grid systems (Government of Kenya, 2023). However, electricity consumption still accounts for a small share of the total primary energy supply, with generation capacity currently standing at approximately 3,200 MW, including off-grid solutions which contribute a modest 46 MW (EPRA, 2025).

To date, sustainable renewable energy sources account for approximately 17% of Kenya's total energy supply (IEA, 2026). As a matter of fact, the country remains heavily reliant on traditional biomass (e.g., firewood, charcoal), which meets nearly the entire demand of the building sector, representing about 62% of the Kenyan energy mix. Furthermore, fossil fuels constitute over 20% of the energy supply, dominating the transport sector where they account for almost the totality of consumption (IEA, 2026). In 2024, Kenya's aggregate consumption of petroleum products reached approximately 4.5 million tonnes, all coming from external imports. This total included 720 thousand tonnes of aviation jet fuel, 2200 thousand tonnes of diesel, and 1650 thousand tonnes of motor gasoline. As a reference, Italian jet fuel consumption stands 5 million tonnes per year only considering jet fuel demand, while United States require more than 80 million tonnes per year (U.S. EIA, 2025).

In this context, sustainable alternatives such as biofuels could play a pivotal role as a fundamental driver in the national energy transition. These fuels can facilitate the decarbonization of key sectors while reducing dependence on unsustainable energy sources that deplete national environmental resources (0.3% of Kenya's forest area is lost annually due to fuel production) and severely limit the country's energy independence. As evidenced by the analysis of Kenya's primary energy policies, the country has devoted considerable attention to liquid biofuels, both in relation to the clean cooking transition, where bioethanol is recognized as a key solution, and in the transport sector, where SAFs are viewed as a potential pathway to decarbonize Kenyan aviation. This commitment is further demonstrated by Kenya's participation in international frameworks, such as ICAO CORSIA and COP agreements, which promote the production and deployment of sustainable alternatives to fossil fuels.

The objective of this chapter is to review the targets set by Kenya regarding the deployment of sustainable liquid biofuels, evaluate their future potential, and assess the environmental benefits generated by their adoption. Specifically, the analysis focuses on estimating short-term production volumes and long-term penetration targets for bioethanol and HEFA-SPK within the cooking and aviation sectors, respectively. Under convenient technological and economic conditions, the repurposing of bioethanol upgrading to SAF through ATJ conversion process is also discussed and evaluated. Based on the findings of previous chapters, these fuels are identified as having high strategic potential in the country's future energy dynamics. Although fossil fuels are utilized significantly in road and maritime transport, as previously discussed in Chapter 3, Kenya appears inclined toward alternative solutions to decarbonize these sectors. Specifically, the progressive electrification of the country is expected to lead to the electrification of the road fleet in the long term. For the maritime sector, the adoption of green hydrogen-based fuels (e.g., methanol, ammonia) is emerging as the most viable solution. Following the definition of production objectives, the most suitable feedstocks for sustainable biofuel production in Kenya will be evaluated, alongside their respective barriers and opportunities. Once targets and feedstocks are established, the analysis will proceed estimating the resources and land occupancy required to achieve these production goals, as well as the carbon emissions arising from biofuel production compared to the fossil alternatives currently utilized in Kenya.

4.1. Target Definition

The definition of quantitative production targets is complex and requires an in-depth understanding of the Kenyan energy system, the country's industrial structure, and the availability of human and material resources necessary to achieve such targets. In recent years, Kenya has published several policy documents outlining its projected energy development, including the role of sustainable biofuels in the future energy landscape. The projected evolution and possible outcomes are now described in relation to the cooking and aviation sectors.

4.1.1. Cooking Sector

The universal clean cooking transition has been prioritized by the government with the aim of enabling the gradual phase out of traditional biomass energy sources (e.g., firewood, charcoal) in favour of cleaner and healthier alternatives (e.g., LPG, electric cooking, bioethanol), by 2028. However, traditional biomass production and consumption remain critical issues for Kenya, accounting approximately 62% of the country's total energy supply, primarily to meet cooking and heating needs in rural areas (IEA, 2026). In relation to the cooking sector, where traditional biomass is mostly used, about 52% of cooking demand is met by firewood and about 12% by charcoal. At the same time, LPG utilization increased steadily in the last few years with the purpose of reducing health-issues related to indoor pollution. Consequently, LPG now covers about 31% of total cooking consumption and required the import of more than 330 thousand tonnes in 2022 (Ministry of Energy and Petroleum, 2024). In addition to that, kerosene still covers almost 4% of the cooking demand, contributing to increase Kenyan reliance on fossil fuels and dependence on energy imports.

However, in the long-term the transition to cleaner and healthier energy sources, such as bioethanol and e-cooking, is expected to take the lead and completely replace traditional biomass and fossil fuels. Several studies related to universal clean cooking access have been published by the government, including the Ethanol Cooking Fuel Masterplan (Ministry of Energy and Petroleum, 2021) and the Kenya National Cooking Transition Strategy (Ministry of Energy and Petroleum, 2024), emphasizing the importance of the role that bioethanol is expected to play in the cooking sector. Currently, bioethanol adoption for cooking purposes remains marginal, accounting for approximately 1% of the sector's total energy consumption. However, national strategic frameworks aim to scale this share to 30% by 2028 (Ministry of Energy and Petroleum, 2024). In contrast, various policy documents and technical studies issued by the Kenyan Ministry of Energy present fluctuating projections, typically ranging between 10% and 30% of total cooking energy demand (Ministry of Energy and Petroleum, 2023; Ministry of Energy and Petroleum, 2021). For instance, under the base scenario outlined by the *Ethanol Cooking Fuel Masterplan*, bioethanol demand is projected to reach approximately 192 million litres by 2030, which would represent a share significantly lower than the 30% of the cooking energy mix (Ministry of Energy and Petroleum, 2021).

In the absence of clearly defined short-term targets, the present study adopts as intermediate 2030 benchmark the production of 192 million litres of ethanol, as estimated in the previously cited study. However, this study aims to envision a long-term sustainable development pathway for biofuel production and to evaluate its penetration within the Kenyan energy sector. Accordingly, energy consumption volumes for the cooking sector are estimated up to 2050, also including 2040 as intermediate milestone, factoring in projected population growth and economic expansion. According to United Nations estimates, Kenya's population is expected to exceed 83 million by 2050, representing an average annual growth rate of approximately 1.5% from 2020 levels (United Nations, 2024). Following the strategic direction of the Kenyan government and global climate transition goals, it is anticipated that the building sector will undergo extensive electrification, with most demand, including cooking, met by electricity. Consequently, this study hypothesizes that bioethanol production capacity will reach the target of 30% cooking energy mix by 2040 and finally be able to cover 50% of the demand by 2050. Based on an average household size of four persons (Kenya National Bureau of Statistics, 2020), utilizing a reference value of 275 litres of bioethanol per household per year (Ministry of Energy and Petroleum, 2021), achieving this objective would necessitate approximately 1,528 and 2,874 million litres of ethanol, by 2040 and 2050, respectively. The table 4.1 shows the ethanol production targets across the three milestone years identified.

Table 4.1 – Bioethanol production targets

Years	Definition	Output	Target
2030	Achieving bioethanol production capacity estimated by the ECF Masterplan	Bioethanol	192 Ml
2040	Achieving 30% bioethanol consumption in the cooking energy mix	Bioethanol	1528 Ml
2050	Achieving 50% bioethanol consumption in the cooking energy mix	Bioethanol	2874 Ml

4.1.2. Aviation Sector

The aviation sector is classified as a hard-to-abate sector, representing those industries that are particularly challenging to decarbonize due to stringent technical and performance requirements. In the case of aviation, aircraft operating conditions necessitate fuels capable of performing under pressure and temperature ranges far beyond those of standard road transport, requiring higher fluidity and optimal cold flow properties. To meet these specifications, conventional biofuels must undergo specific upgrading processes, as detailed in Chapter 3. Despite rapid technological progress in recent years leading to the development of several sustainable alternatives, global SAF production remained limited to 1 million tonnes in 2024, accounting for just 0.3% of total jet fuel demand and 11% of global renewable fuel production (IATA, 2024), with approximately 90% of this output currently generated via HEFA conversion technology (IATA, 2025). However, according to IATA projections, SAF production could reach 400 million tonnes by 2050, against a total projected demand of 500 million tonnes (IATA, 2025).

In Kenya, as previously noted, the aviation sector is currently entirely fossil-based, with a net demand of approximately 722 thousand tonnes of jet fuel per year, encompassing domestic, regional, and international jet fuel consumption, which account for 7%, 5%, and 88% of total demand, respectively (Boscagli, 2025). However, according to ICAO estimates, the sector is expected to undergo robust growth in the coming years to support national economic and tourism activities, with fuel demand projected to increase at an average annual rate of 5% (Boscagli, 2025), potentially approaching 2.4 million tonnes by 2050, more than triple current figures.

To date, no clearly defined targets currently exist for SAF production in Kenya. Even though Kenya is a member of ICAO, whose final target is to achieve net-zero aviation sector by 2050, no binding mandates, financial incentives, or formally established targets have yet been introduced for the upcoming period. However, several studies published by ICAO, World Bank, and the Kenyan government highlight that domestic SAF production could increase substantially in the coming years. Kenya is identified as a suitable country for large-scale SAF production due to its political and economic organization, which makes it one of the most stable and reliable countries in the Sub-Saharan region (Abate, et al., 2025). Its strategic geographical position would enable Kenya to act both as a producer and as a regional distribution hub, particularly toward Ethiopia, which has a significant demand for jet fuel, and toward other continents where the SAF market is already more established and actively seeking suppliers, such as Europe.

A recent study published by the ICAO estimates the potential for SAF production through the conversion of the former Mombasa refinery, whose operations ceased in 2013, into a dedicated SAF biorefinery (Boscagli, 2025). According to the study, the Mombasa biorefinery would be capable of processing approximately 250,000 tonnes of feedstock for SAF production using HEFA technology. The product outputs of the biorefinery remain flexible in response to market dynamics, since HEFA refining also generates co-products, such as HVO, which could be re-employed as a substitute for diesel in road or maritime transport. From the same amount of feedstock, it would therefore be possible to produce approximately 210,000 tonnes of HVO or 180,000 tonnes of HEFA-SPK, or an intermediate configuration depending on market conditions. However, a crucial aspect that remains to be verified concerns the availability of 250,000 tonnes of feedstock, in the form of vegetable oil, in order to supply the refinery (Boscagli, 2025). According to ICAO, a diverse range of feedstocks is suitable for HEFA production in Kenya, encompassing castor, yellow oleander, croton, jatropha, Brassica Carinata, cottonseed, canola, and coconut, as well as UCO. However, the agro-economic feasibility of large-scale cultivation and collection must be rigorously evaluated to ensure the consistent availability of the vegetable oil volumes required for industrial-scale processing (Boscagli, 2025).

In the absence of clearly defined short-term targets, the present study adopts as intermediate 2030 benchmark the supply of 250,000 tonnes of vegetable oil required as input for the Mombasa biorefinery. As for the long-term targets, given the inherent uncertainties in forecasting the evolution of a sector that currently maintains a marginal role in Kenya's market dynamics, the following analysis hypothesizes a progressive penetration level of HEFA-SPK in the aviation sector.

Although both ICAO and the Kenyan government aim for a net-zero aviation sector by 2050, achieving total SAF penetration appears unlikely under current conditions. The IATA suggests that while HEFA-SPK production will likely remain the most prevalent pathway in the near term due to technical and economic advantages, long-term feedstock constraints will necessitate the integration of alternative SAF pathways, such as ATJ-SPK and e-SAF (IATA, 2025). Europe's ambitions, within the world's most developed SAF market, under the ReFuelEU Aviation initiative, highlight a target of achieving at least a 70% SAF share of total jet fuel consumption by 2050, with approximately 35% from synthetic e-fuels (EASA, 2026).

In the Kenyan context, despite the need for significant logistical and technical advancements, HEFA remains the most mature technology for SAF production. Consequently, feasible long-term production targets are established, with the aim of achieving 15% and 30% of total jet fuel demand, by 2040 and 2050, respectively, as reported in the table 4.2.

Table 4.2 – HEFA-SPK production scenarios by 2050

Years	Definition	Output	Target
2030	Achieving required input for the Mombasa biorefinery	Vegetable Oil	250 ktons
2040	Achieving 15% HEFA-SPK in jet fuel demand	HEFA-SPK	367 ktons
2050	Achieving 30% HEFA-SPK in jet fuel demand	HEFA-SPK	733 ktons

In addition, in the long-term, the Kenyan expertise in the production and the existence of a robust ethanol supply chain may support SAF production under the ATJ conversion technology. In the case of intensive electrification of the buildings and cooking sector, as projected by the Kenyan government itself (Ministry of Energy and Petroleum, 2023), bioethanol production could be reallocated toward the transport sector, specifically aviation. Consequently, bioethanol would find a strategic application in the aviation sector, complementing HEFA production (and potentially e-SAF in the future) to fully displace fossil-based fuels. Currently, ATJ-SPK production in Kenya, and globally, is primarily hindered by economic barriers, but projections suggest a significant output increase in the coming years (IATA, 2025). According to the 2050 bioethanol production estimates already discussed, 2,874 million litres, this study hypothesizes the repurposing of bioethanol for aviation based on various electrification levels in the cooking sector. Starting from a "Zero-Aviation" base scenario where bioethanol production is still fully required by the cooking sector, two further scenarios are evaluated. Namely, under the "Half-Aviation" scenario, half of the total bioethanol is repurposed for ATJ-SPK production, while under the "Full-Aviation" scenario, a complete shift of bioethanol from the cooking to the aviation sector is assumed by 2050. The abovementioned scenarios, with their related bioethanol allocation, is therefore presented in the 4.3.

Table 4.3 - Bioethanol use in cooking and aviation sector under different electrification scenarios

	Zero-Aviation	Half-Aviation	Full-Aviation
Bioethanol Cooking [%]	100%	50%	0%
Bioethanol Cooking [Ml]	2874	1437	0
Bioethanol Aviation [%]	0%	50%	100%
Bioethanol Aviation [Ml]	0	1437	2874

4.2. Feedstock Identification

In Chapter 3, the different types of feedstocks commonly used for biofuel production worldwide were presented. As previously stated, numerous viable alternatives currently exist and are employed to produce bioethanol and HEFA-SPK. Hence, the selection of feedstocks for biofuel production depends on the geographical, technical, and economic context of the country. The choice of a single feedstock generally simplifies the production process, which can be optimized according to the physicochemical characteristics of the selected feedstock and may result in higher yields. Conversely, a more flexible production configuration that allows for the interchangeability of certain feedstocks, such as different types of vegetable oil, requires additional technical adjustments due to variations in chemical composition. However, it reduces pressure on the supply chain, as different feedstocks can be used to produce the same final product (Boscagli, 2025). This approach makes it possible to compensate for unexpected shortages or underproduction of one feedstock by relying on another, while also ensuring greater adaptability to market dynamics.

In this study, four suitable feedstocks are therefore identified for the production of each biofuel, namely four for bioethanol and four for HEFA-SPK. The feedstocks were selected based on the country's climatic conditions, prioritizing crops that are already cultivated domestically and are familiar to local farmers, as well as on the basis of recommendations contained in the main policy documents and studies published for Kenya. Table 4.4 summarizes the selected feedstocks.

Table 4.4 - Proposed feedstocks to produce bioethanol and HEFA in Kenya

Bioethanol	**HEFA-SPK**
Molasses	Jatropha
Sugarcane	Castor
Cassava	Croton
Sweet Sorghum	UCO

4.2.1. Sugars and Starches

At present, all bioethanol produced in Kenya is derived from molasses, a by-product of sugarcane processing. This implies that bioethanol production is strictly linked to the sugar industry. On the one hand, this allows ethanol to be produced from a residual product, resulting in relatively low environmental impact and favourable economic conditions. On the other hand, it constrains the potential expansion of production. Molasses accounts for approximately 4.8% by weight of sugarcane, and around 300 litres of ethanol can be produced per tonne of molasses. Consequently, producing 1,000 litres of ethanol would require approximately 70 tonnes of sugarcane (Kabeyi & Olanrewaju, 2022). If the same 70 tonnes of sugarcane were instead used directly for ethanol production, approximately 4,900 litres could be obtained, corresponding to nearly five times higher output. Molasses therefore remains a valuable resource that can generate additional economic value through ethanol production, but it cannot be considered the primary feedstock for achieving the country’s production targets.

Sugarcane production between 2020 and 2023 fluctuated between 5 and 9 million tonnes, with an average of 7.2 million tonnes per year harvested over approximately 95,000 hectares (FAO, 2026). The main driver for sugarcane cultivation is sugar production for the food industry, which still does not fully satisfy domestic demand and often requires imports. Molasses is mainly used for the production of ethanol destined for alcoholic beverages, while only a limited share is currently used as fuel in the cooking sector. However, sugarcane production is expected to increase in the coming years in order to reduce sugar imports and to expand bioethanol output.

Similar figures characterize cassava production. In 2024, cassava has been harvested on approximately 82,000 hectares, with production exceeding 1 million tonnes (AFA, 2025). Cassava is currently considered a staple food in the Kenyan diet, hence requiring careful planification and clear regulation to avoid potential conflicts related to food security when its use is destinated for energy purposes. Approximately 170 litres of ethanol can be produced from one tonne of cassava (White, 2018). Compared to sugarcane, cassava exhibits strong growth performance in arid areas with limited water availability, a crucial characteristic in the Kenyan context where large areas of land remain underutilized due to low rainfall. However, cassava is highly susceptible to viral diseases and pests, which can render entire harvests unusable.

Sorghum is already widely cultivated in Kenya, mainly for the production of edible grains intended for human consumption. The cultivated area exceeds 220,000 hectares, with an annual production of approximately 200,000 tonnes (AFA, 2025). However, the sugar-rich variety known as sweet sorghum, which would enable ethanol production, is not currently cultivated in Kenya. Nevertheless, according to a report published by ICAO, replacing conventional sorghum with sweet sorghum would be feasible (White, 2018). This transition could increase sugar and ethanol production while maintaining partial edible grain output, thereby limiting competition between the food and energy sectors. Average sweet sorghum yields are approximately 35 tonnes per hectare, enabling the production of around 40 litres of ethanol per tonne of harvested crop (White, 2018). Table 4.5 presents the agricultural yields and production potentials of the feedstocks described above.

Table 4.5 - Theoretical yields for the selected bioethanol feedstocks

Feedstock	Crop Yield [t/ha]	Ethanol Yield [l/t]	Land Use [ha/1000 l ethanol]	Source
Molasses	2,9	300	1,15	(Kabeyi & Olanrewaju, 2022)
Sugarcane	60,2	70	0,24	(KNBS, 2024; White, 2018),
Cassava	13,7	170	0,43	(AFA, 2025; White, 2018)
Sweet Sorghum	35	40	0,71	(White, 2018)

4.2.2. Lipids

On the other side, HEFA production is based on the hydrotreatment of vegetable oil. Hence, oleaginous crops with high lipid content are the ones targeted to produce HEFA.

For several years, Jatropha Curcas was promoted as a potential global solution for biodiesel production due to its strong resistance to drought and its ability to grow on semi-arid and low-fertility soils. Jatropha originates from Central America, but it can be readily cultivated in tropical and subtropical regions, including Sub-Saharan Africa and Asia. Jatropha fruits are toxic and unsuitable for human consumption, yet their oil content ranges between 30% and 50%, making them attractive for biofuel production. Moreover, the production residues are rich in nitrogen and can be used as fertilizer. Nevertheless, although Jatropha grows on marginal lands, several obstacles can emerge from its cultivation and yields are highly dependent on soil quality and fertilizer availability (GTZ, 2009). According to data reported by the ICAO, Jatopha Curcas yields approximately 2.5 tonnes of seeds per hectare, with a potential oil production of 336 litres per tonne of seeds (White, 2018).

Another possible feedstock for HEFA production is identified in the Castor tree (Ricinus Communis), a perennial plant native to Eastern Africa that produces seeds with high oil content. Castor oil is not suitable for food consumption and is traditionally used in industrial and pharmaceutical applications, although its use as a biofuel feedstock is increasing. Eni has established a vegetable oil production facility in Kenya based on castor cultivation, with the oil exported to Italy for SAF production. Its capacity to grow on semi-arid land could enable planners to prioritize production on marginal and underutilized areas. However, castor cultivation is known to rapidly deplete soil nutrients and requires fertilizer application or intercropping practices to maintain soil fertility. On average, castor seed yields range between 1.8 and 2 tonnes per hectare, characterized by an exceptionally high oil content varying from 35% to 65% (Cafaro, et al., 2025).

Lastly, Croton Megalocarpus, an indigenous tree original to Eastern and Southern Africa, is a drought-resistant species which yields nuts with high oil content, but inedible for both humans and animals (Diaz-Chavez, 2020). It is a fast-growing canopy tree that can reach heights of up to 36 meters, matures after five to seven years, and has a lifespan of up to 70 years. Croton trees grow naturally in forested areas of Kenya and are commonly used in the timber industry, but for many years croton nuts were considered waste due to their lack of value in the food sector. However, they may represent a promising resource for vegetable oil production for energy purposes. Assuming an average yield of approximately 25 kg of seeds per mature croton tree (Takase & Danish, 2022) and a planting density of 100 trees per hectare, the estimated average yield for Croton nut production is approximately 2.5 tonnes per hectare. Table 4.6 presents the agricultural yields and oil production potentials for the selected crops.

Table 4.6 - Crop and Vegetable oil yield for the selected crops

Feedstock	Crop Yield [t/ha]	Oil Yield [l/t]	Land Use [ha/1000 l vegetable oil]	Source
Jatropha	2,5	336	1,19	(White, 2018)
Castor	1,8	500	1,11	(Cafaro, et al., 2025)
Croton	2,5	320	1,25	(Takase & Danish, 2022; White, 2018)

Despite the current limited production of oilseeds in Kenya, particularly when compared to the more established sugar and starchy crop sectors, there is significant momentum regarding their potential as primary feedstocks for biofuel production. For instance, the International Finance Corporation and the Italian Climate Fund have invested USD 210 million in Eni's Kenyan biofuel initiative. This project aims to scale oilseed production, including castor, croton, and cottonseed, to reach 500,000 tonnes annually and to expand domestic processing infrastructure (International Finance Corporation, 2024). To date, the declared production capacity from Eni's agri-hubs is approximately 70,000 tonnes of oilseeds per year, primarily castor.

However, official national data present a more fragmented picture. The Kenyan Agriculture and Food Authority recorded only 7,400 tonnes of exported castor oil in the most recent reporting periods. This discrepancy suggests potential challenges in production scaling, supply chain inefficiencies, or gaps in official reporting. The values selected for this study represent global average benchmarks that are considered replicable within the Kenyan agro-ecological context. Nevertheless, it is important to note that agricultural yields and oil content vary according to the specific cultivar, soil conditions, including the presence of micro and macronutrients, as well as water and fertilizer availability. It is therefore not possible to determine precise oil production yields a priori for the crops considered, as numerous studies conducted in different regions of Kenya, across different time periods and using diverse agricultural practices, have reported heterogeneous results. For instance, a study published by GTZ compared Jatropha yields in Kenya under marginal land conditions with yields reported in international literature, finding significant differences between yields in Kenya, ranging from 0.2 to 0.9 kg per tree, and yields reported in other studies, between 1.5 and 2.0 kg per tree (GTZ, 2009). Similarly, the Kenyan Agricultural Food Authority (AFA) provides only partial data about these crops. For instance, reported castor yields for 2024 were significantly low, at approximately 0.14 tonnes per hectare, while data for jatropha and croton remain entirely unavailable (AFA, 2025). Therefore, verifying the field feasibility of these yields is critical, since the biological adaptability of these species to ASALs does not automatically guarantee theoretical production yields. Performance may fall short of expectations in the absence of adequate fertilizers or sufficient water supply, and neglecting proper agricultural management could result in yields that are too low to sustain viable oil production, thereby hindering the scalability of the biofuel industry and compromising the economic sustainability of the entire value chain (Von Maltitz, et al., 2014).

In this context, UCO also is expected to play an increasingly important role in biofuel production. Kenya is a major consumer of vegetable oil for food purposes, with an annual demand exceeding 900,000 tonnes, of which nearly 830,000 tonnes are imported (AFA, 2025). At present, the collection and reuse of waste cooking oil are not centrally managed by the state but are handled by a limited number of specialized companies (e.g., Zijani, GilOil, Muenzer) which collect UCO from large production centres such as hotels and major restaurants. Currently, approximately 8,000 tonnes of UCO are collected and recovered annually, although the potential HEFA production from UCO could reach up to 160 thousand tonnes by 2030 (Boscagli, 2025).

According to a study analysing vegetable oil consumption and collection in 23 countries worldwide, approximately 32% of cooking oil can be recovered after use (Teixeira, et al., 2018). Applied to the Kenyan context, this corresponds to more than 300 million litres of potentially recoverable oil, although the actual reusable volume depends on the efficiency of collection systems. In high-income countries, collection systems can recover on average 75% of used oil, compared to approximately 23% in low-income countries (Teixeira, et al., 2018). Based on these estimates, Kenya could potentially recover between 67 and 216 thousand tonnes of UCO. Considering the projected population growth and the likely increase in vegetable oil consumption, enhanced UCO collection could represent a key strategy to ensure a stable supply of vegetable oil while limiting additional land use for energy crops. Accounting for population growth projections through 2050, and assuming per capita demand remains constant, the total demand for edible vegetable oil could reach 1,200 thousand tonnes by 2050. Figure 4.1 reports the theoretical UCO availability volumes under the two collection scenarios considered, namely “Low-UCO” and “High-UCO”, from 2030 to 2050.

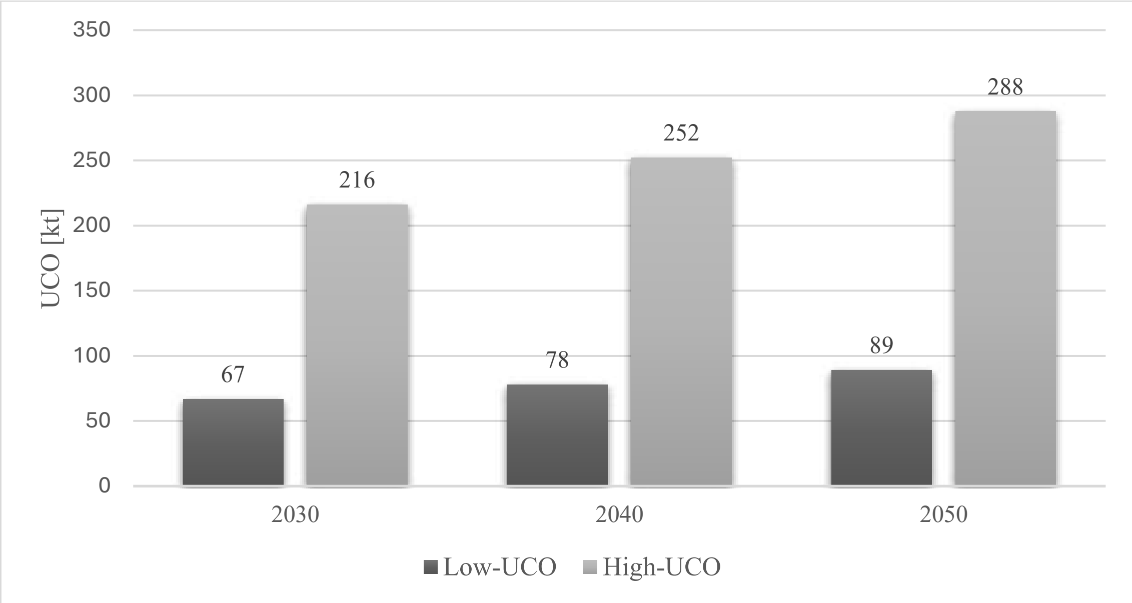

Figure 4.1 - UCO availability for biofuels production

4.3. Land Use

The availability of arable land for energy crop production has long been at the centre of the debate on biofuel development in Kenya. One of the main constraints to expanding biofuel production is the limited availability of cultivable land and the difficulty of identifying areas that can be allocated to energy feedstock cultivation without compromising the balance of the food sector.

Food security remains a highly relevant and priority issue in Kenya, taking precedence over energy production. Domestic food production is insufficient to meet internal demand, which is partially satisfied through imports of key commodities such as cereals, vegetable oil and sugar. It is therefore essential to safeguard land currently dedicated to food production and to ensure that a share of underutilized agricultural land is directed toward food cultivation in order to reduce dependence on imports and meet the increasing food demand associated with the projected population growth.

This already fragile situation is further compounded by the country's territorial characteristics, as most of the Kenyan land surface consists of ASALs that are poorly suited to the cultivation of major food crops. A study published by the National Land Commission indicates that approximately 83% of the national territory falls within the ASAL category, with 68% of the total land characterized by low to very low agricultural potential, while only 32%

exhibits medium-to-high cultivation potential, primarily located in the western part of the country and along the coast (National Land Commission, 2023). Most ASALs are suitable for ranching and pastoral activities, which do not require particularly fertile or humid soils, while approximately 15% of these lands could support crops that do not require high soil moisture (National Land Commission, 2023). Table 4.7 reports the main findings of the cited study.

Table 4.7 - Agricultural classification according to Kenya Natural Resource Atlas. Adapted from (National Land Commission, 2023)

Land type	Area [1000 ha]	Annual rainfall [mm/year]	Agricultural potential	Share of total land
Humid/Sub-humid/Semi-humid	6,970	800-2700	Very High/ High	12%
Semi-humid/Semi-arid	2,900	600-1000	Medium	5%
Semi-arid	8,710	450-900	Medium/Low	15%
Arid	12,800	350-550	Low	22%
Very Arid	26,720	150-350	Very low	46%

According to FAOSTAT, approximately 50% of Kenya's total land area is used for agricultural activities. Of this share, nearly 13% is devoted to crop cultivation, while the remaining portion is allocated to livestock activities. Excluding forested areas, which account for approximately 6.5% of the territory, and inland water bodies, which represent around 2%, the remaining 41% of land is currently classified as abandoned or unused (FAO, 2026). However, it is important to note that Kenya has launched a reforestation program within the framework of its NDC, with the objective of restoring and maintaining forest cover equivalent to 10% of the national territory as part of its climate change mitigation strategy (Republic of Kenya, 2025).

By cross-referencing the information from these sources, it can be inferred that approximately 23% of medium-to-high fertility land is currently allocated to forests and food production. In addition, reducing current food imports and meeting future food demand in line with demographic growth will require increased domestic agricultural production. Even under a scenario of significant improvements in crop yields, approaching the standards observed in more industrialized countries, additional land use would likely be necessary to ensure adequate food supply.

4.3.1. Sugars and Starches

In light of these considerations, land characterized by high agricultural potential, which is already limited in the country, should be prioritized for sectors considered more strategic than energy production. A more suitable approach would consist of valorising medium- and low-potential land, especially through the cultivation of drought-resistant species capable of growing in less fertile environments. However, this reasoning could hinder the spread of sugarcane, cassava, and sweet sorghum, which require more fertile soils, higher nutrient availability, and greater water supply. In the case of these crops, it is therefore essential to meticulously and efficiently plan land utilization, clearly defining the proportion to be allocated for food consumption and the fraction potentially dedicated to energy production.

The figure 4.2 reports the land requirements associated with achieving the previously defined targets of bioethanol production.

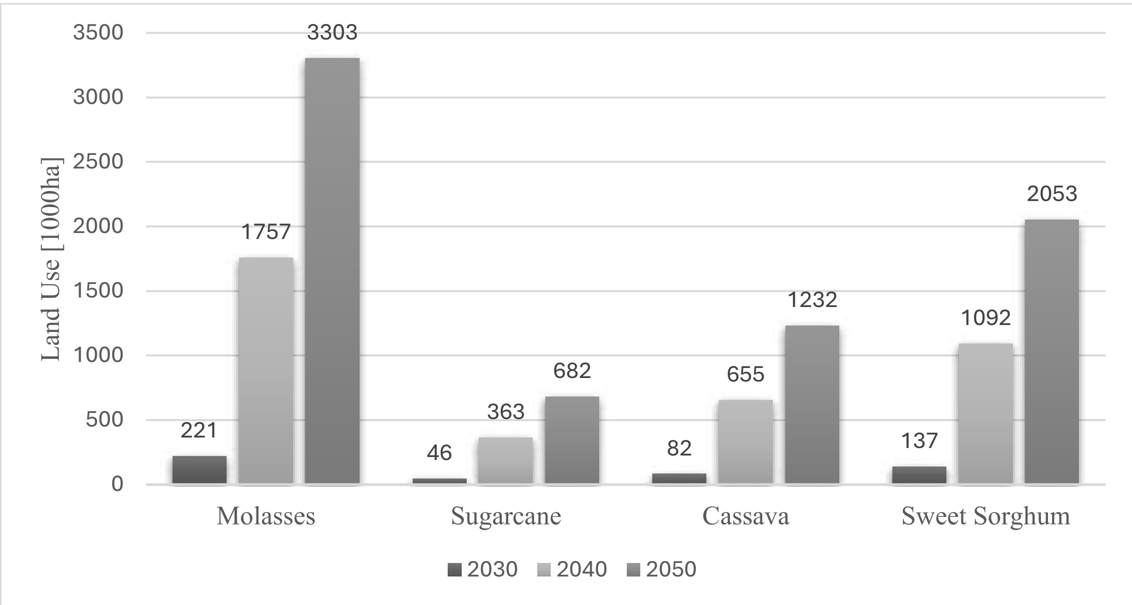

Figure 4.2 - Land requirements for bioethanol production

As shown in the figure above, a moderate land use is required to meet the 2030 production targets, never exceeding 0.4% of the total land area. For instance, in the most demanding scenario, meeting the entire ethanol demand through molasses would require approximately 221,000 hectares of sugarcane cultivation. However, this land could simultaneously support increased sugar production, while processing residues, such as molasses and bagasse, could be used for ethanol production and electricity generation. If sugarcane cultivation were instead fully dedicated to ethanol production, only 46,000 hectares would be required, approximately corresponding to 0.08% of the total land. Cassava and sweet sorghum occupy an intermediate position, respectively requiring 82,000 and 137,000 hectares of land, yet still demonstrating higher overall productivity compared to molasses-based ethanol pathways.

However, the land requirements to meet 2040 and 2050 production targets increase sharply. To achieve a 30% penetration target for bioethanol in the cooking energy mix, the required land would range between 363,000 and 1,757,000 hectares, depending on the selected feedstock. Aiming for a strong decarbonization of the cooking sector, with bioethanol reaching a 50% share of the energy mix by 2050, land requirements could rise to more than 3 million hectares in the case of molasses. Even with more performative crops, the surface area dedicated to sugarcane harvesting would need to increase approximately sevenfold compared to current levels, resulting in a land footprint equivalent to 1.17% of Kenya's total land area. Nevertheless, sugarcane, thanks to its lower soil consumption, represent a great solution compared to the alternatives and remains the primary feedstock for ethanol in other major producing nations like Brazil and India. On the other side, sugarcane demands highly fertile soil and significant water inputs, whereas cassava and sweet sorghum require fewer resources, a decisive factor within the Kenyan agricultural context.

The future landscape will likely involve a mix of these three crops, with their respective shares determined by economic strategies and land availability. Much will depend on Kenya's future sugar production, since sugar remains a major import, exceeding 600,000 tonnes in 2023 (KNBS, 2024). Given an average yield of 110 kg of sugar per tonne of sugarcane (Shelar, et al., 2023), satisfying domestic demand would require approximately 5.5 million tonnes of sugarcane, occupying roughly 90,000 hectares based on the last five year average yields (KNBS, 2024). In this scenario, utilizing molasses residues could yield about 78 million litres of ethanol annually, nearly half of the 2030 target.

In the long term, however, a significant share of ethanol production could derive from lignocellulosic biomass, leveraging the vast availability of agricultural residues and wood waste. Nevertheless, this second-generation technology has yet to reach commercial maturity and remains prohibitively expensive compared to conventional bioethanol production (IEA, 2024).

4.3.2. Lipids

A different consideration applies to vegetable oil production. The 2030 target reflects the feedstock requirement of vegetable oil necessary to supply the potential retrofitting of the Mombasa refinery, as identified in the ICAO study (Boscagli, 2025). The 2040 and 2050 targets, conversely, outline a progressive penetration of HEFA technology within total jet fuel consumption. To calculate land use for these scenarios, it is crucial to determine the production outputs of a HEFA refinery, accounting for the varying chemical compositions of the identified feedstocks. Below are explanatory figures detailing the product shares of HEFA conversion, assuming a production setting of 70% HEFA-SPK and 30% HVO, which, as previously discussed, represents the most common operational configuration. Figure 4.3 represents the output shares from the HEFA conversion process when UCO, croton, castor and jatropha oil are used as input of the process.

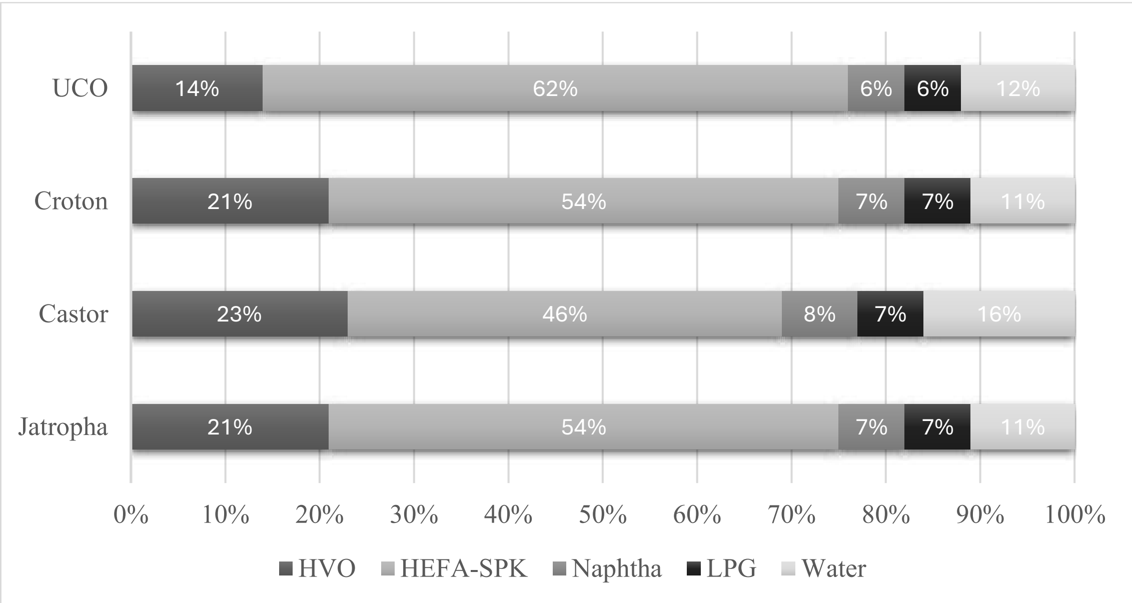

Figure 4.3 - Output shares of HEFA conversion process. Adapted from (Boscagli, 2025)

The chemical composition of the feedstock, specifically the profile of its fatty acids, directly influences the final output of the conversion process. This effect is particularly evident in the case of UCO, where HVO yields are restricted relative to HEFA-SPK production, and castor oil, which exhibits a significantly higher water production during processing compared to other feedstocks. Assuming a standard average oil density across all vegetable oils, the figure 4.4 details the land use requirements necessary to achieve the previously identified production targets.

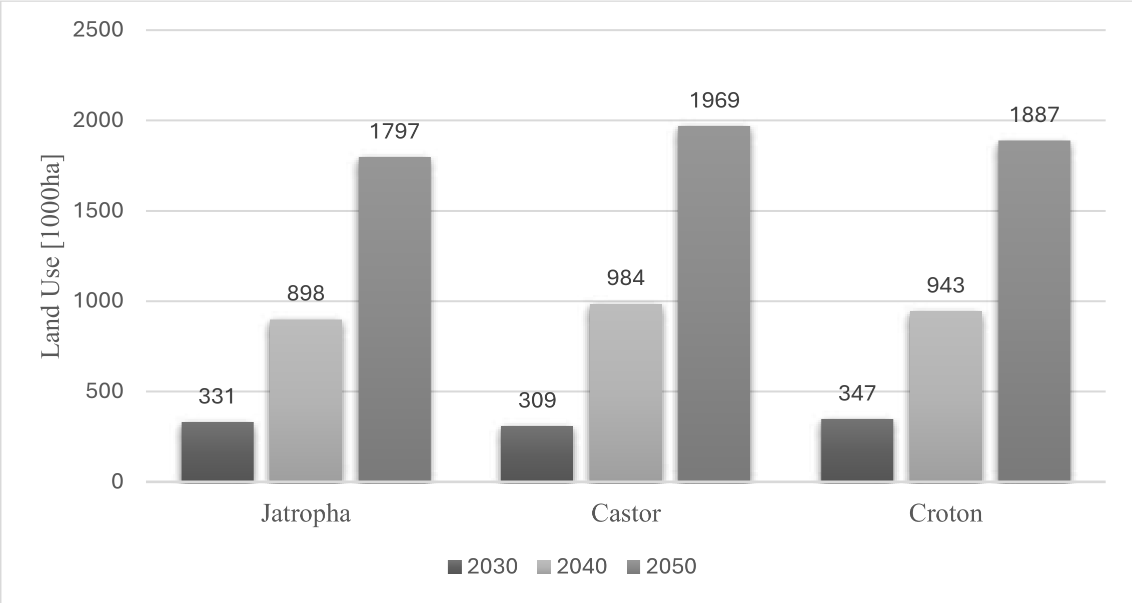

Figure 4.4 - Land requirements for HEFA-SPK production

The land requirements to achieve the 2030 intermediate targets remain within an limited, ranging between 309,000 and 347,000 and never exceeding 0.6% of Kenya's total land area. Since the three analysed crops exhibit similar yields and lipid profiles, the differences in land occupancy are relatively limited, with castor theoretically offering superior performance due to its high oil content. Conversely, in the long term, as the focus shifts toward HEFA-SPK production rather than raw vegetable oil, castor's performance slightly declines, as only 46% of its weight is effectively converted into bio-jet fuel. Nevertheless, when castor oil is used as feedstock, a significant share of HVO is generated as a co-product, the impact of which will be detailed subsequently.

To achieve 2040 HEFA-SPK production targets, land consumption increases on average three times compared to the 2030 requirements. By 2050, the increment is about 6 times, and final land requirements range from 1,797,000 to 1,969,000 hectares, corresponding to more than 3% of Kenya's total land. However, the crops analysed for this purpose would primarily be introduced on currently unused or abandoned land, theoretically enabling its valorisation. Castor cultivation represents the most land-intensive option, requiring nearly 2 million hectares, approximately 3.39% of the national territory. While this share is significantly lower than the 41% of land currently classified as unused, the primary uncertainty lies in the effective productivity of these crops. Although they exhibit strong drought resistance, achieving technically and economically viable yields necessitates irrigation and fertilization. Without these inputs, there is a significant risk that producers may shift energy crop cultivation toward fertile food-grade lands to ensure profitability, thereby triggering land-use change (LUC) and raising social issues. In this context, enhancing the recovery of UCO is essential to mitigate the demand for virgin oils and reduce the associated land footprint.

Taking into account the two distinct UCO collection scenarios presented in the previous chapter, the figure 4.4 is revised to illustrate the reduction in land requirements under the Low-UCO (figure 4.5) and High-UCO (figure 4.6) collection scenarios.

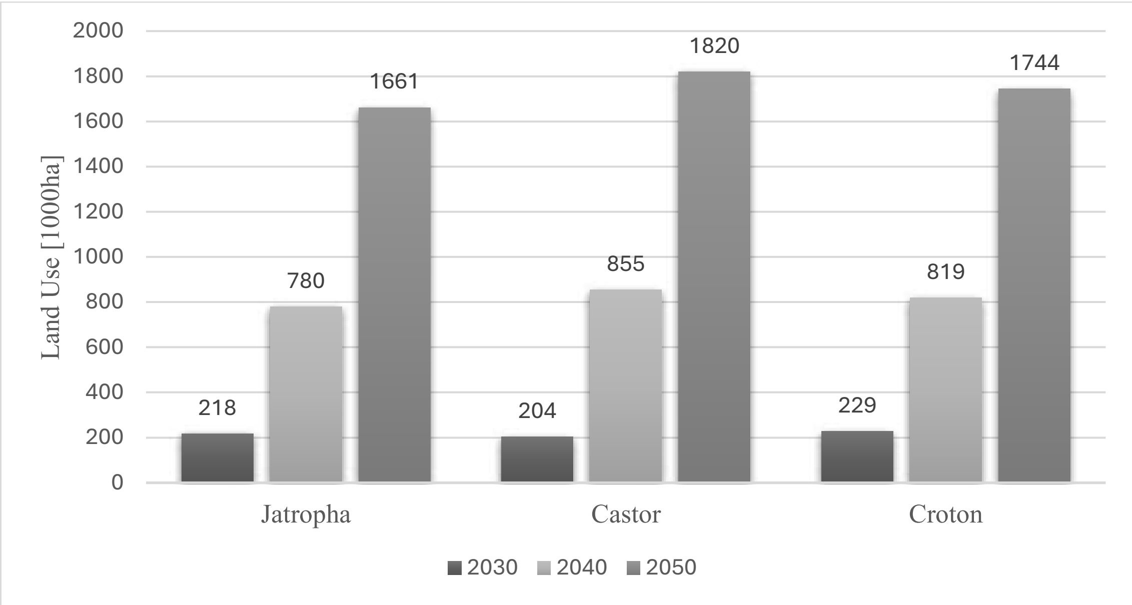

Figure 4.5 - Land requirements for HEFA-SPK production under the Low-UCO collection scenario

The implementation of an efficient UCO collection system could substantially reduce the need for vegetable oil derived from conventional cultivation. In the initial phase of industry development, the immediate availability of UCO could support and accelerate biofuel production while agricultural supply chains are gradually established. To support feedstock production for the Mombasa biorefinery, the integration of UCO would mitigate land demand by approximately 105,000-118,000 hectares in the Low-UCO scenario, and up to 271,000-304,000 hectares in the High-UCO scenario. Under an efficient UCO collection framework, the total land use required to produce 250,000 tonnes of vegetable oil would remain below 0.1% of Kenya's total land area across all three analysed feedstocks.

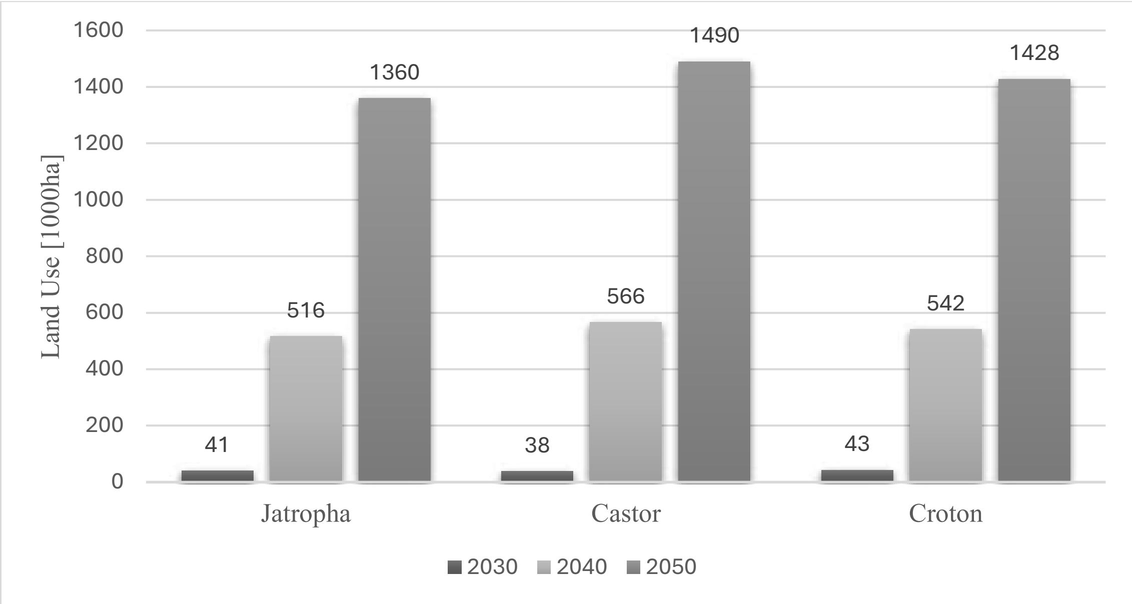

Figure 4.6 - Land requirements for HEFA-SPK production under the High-UCO collection scenario

Over the longer term, assuming a UCO-to-HEFA-SPK conversion rate of 62% (see figure 4.3), an effective recovery strategy could prevent the conversion of 135,000-148,000 hectares under the Low-UCO scenario, and approximately 437,000-479,000 hectares under the High-UCO scenario by 2050. Compared to the land requirements in the base scenario, the utilization of UCO as a feedstock for HEFA-SPK production would reduce soil occupation by almost 25%. These figures suggest that a robust UCO strategy alone could potentially supply the entire feedstock demand for the Mombasa biorefinery in the long term. Nevertheless, to meet the broader national targets for HEFA-SPK generation, agricultural production remains indispensable. Even under the High-UCO scenario, between 1,360,000 and 1,490,000 hectares of land would still need to be dedicated to the cultivation of oleaginous crops to achieve 30% HEFA-SPK in jet fuel consumption in 2050.

In any case, valorising a waste product such as UCO would generate significant economic benefits, as collection costs are lower than those associated with establishing new oilseed plantations, and environmental advantages, since the use of waste-derived feedstock results in net emission savings compared to virgin vegetable oil alternatives.

4.4. Carbon Intensity

The use of biofuels in the energy sector brings multiple and significant benefits. From an economic perspective, it can reduce foreign currency expenditures for the purchase of petroleum products. From a strategic perspective, a greater use of locally produced biofuels increases the country's energy independence. From a social perspective, domestic biofuel production strengthens the industrial sector and expands employment opportunities. In the case of Kenya, biofuel production could also contribute to the recovery of abandoned land and generate substantial health benefits, since thousands of people die each year due to harmful emissions released by rudimentary cooking technologies.

More broadly, one of the key advantages associated with the adoption of biofuels is the reduction of environmental impact compared to fossil fuel use, especially considering GHG emissions. However, estimating the environmental benefits derived from biofuels is not straightforward and depends on several different factors. While the GHG emissions related to the use phase of biofuels (i.e., combustion) are generally considered neutral, because the emissions released during use roughly correspond to those absorbed during feedstock growth and development, a significant share of emissions is nevertheless released during feedstock cultivation, harvesting, transport, and processing. The methods adopted and the resources employed in both feedstock production and its conversion into the final product are responsible for generating GHG emissions that reduce, and in some cases nullify, the benefits associated with a carbon neutral energy source. High fertilizer use, fuel consumption during transport phases, and the origin of certain process inputs (e.g., electricity, steam) can lead to substantial GHG emissions if not properly managed.

4.4.1. Cooking sector

With regard to bioethanol production, most studies in the literature indicate that the cultivation phase of the feedstock represents the most significant source of GHG emissions, often accounting for more than 60% of total emissions, while the actual conversion of feedstock into bioethanol has a comparatively lower impact, slightly above 10% of total emissions (Machandi, 2021). The table 4.8 reports the carbon emission values associated with the whole bioethanol production process, including the cultivation and conversion stage, for each of the previously identified feedstocks.

Table 4.8 - GHG emissions of different ethanol feedstocks

Feedstock	gCO2eq/litre(ethanol)	gCO2eq/MJ	Source
Molasses	270.9	12.8	(Machandi, 2021)
Sugarcane	508.8	24.0	(IEA Bioenergy, 2024)

Cassava	425.1	20.1	(Rathnayake, et al., 2018)
Sweet Sorghum	424.2	20.0	(Machandi, 2021)

Since bioethanol production in Kenya currently relies exclusively on molasses, limited information is available on the environmental impact generated by alternative feedstocks. In order to obtain comparable results, emission values were selected from studies conducted in similar geographical areas with boundary conditions analogous to those identified in Kenyan studies. The figures reported in Table 4.8 do not include the contribution of LUC and ILUC, which can play a relevant role, particularly when feedstock cultivation partially or entirely replaces a previous crop in the same area that already contributed to GHG absorption.

Bioethanol production from molasses shows a lower environmental impact compared to other feedstocks, since molasses is a by-product of sugarcane that is already cultivated for sugar production. Although land occupation is higher in the case of molasses-based bioethanol, total emissions amount to approximately 270.9 gCO2eq per litre of ethanol, whereas producing the same quantity of ethanol from sweet sorghum results in approximately 424.2 gCO2eq per litre (Machandi, 2021). To estimate emissions associated with direct ethanol production from sugarcane, a study published by IEA Bioenergy was used as reference, in which the environmental impact of bioethanol was compared with that of gasoline (IEA Bioenergy, 2024). Specifically, the emission value reported for Ethiopia, approximately 24 gCO2eq/MJ, was adopted and considered representative for Kenya. A similar approach was applied to cassava, for which a study conducted in Thailand, where cassava is commonly used as a bioethanol feedstock, was selected as reference (Rathnayake, et al., 2018).

Based on the specific emission values identified above, it is possible to estimate the total amount of CO2eq emitted upon reaching the established targets. A comparative analysis is conducted with other fossil fuels used in the Kenyan cooking sector (i.e., LPG and kerosene) to evaluate their respective carbon emissions. For ethanol, feedstock-specific emission values are utilized, alongside a standard LHV of 21.2 MJ/litre (EUBIA, 2021). For LPG and kerosene, LHVs of 47.3 MJ/kg and 43.8 MJ/kg (Ogalo & Rop, 2024) are assumed, with WTW emission factors of 75 gCO2eq/MJ (Edwards, et al., 2014) and 89.0 gCO2eq/MJ (Bauen, et al., 2022), respectively. By accounting for the typical efficiencies of bioethanol, LPG, and kerosene stoves, rated at 65%, 55%, and 35% (Ogalo & Rop, 2024), it is possible to estimate the equivalent energy demand for each resource, including required volumes and resulting CO2eq emissions. Assuming an energy demand equivalent to that satisfied by ethanol, the following figures illustrates the comparative CO2eq emissions for the 2030 (figure 4.7) and 2050 (figure 18) production targets.

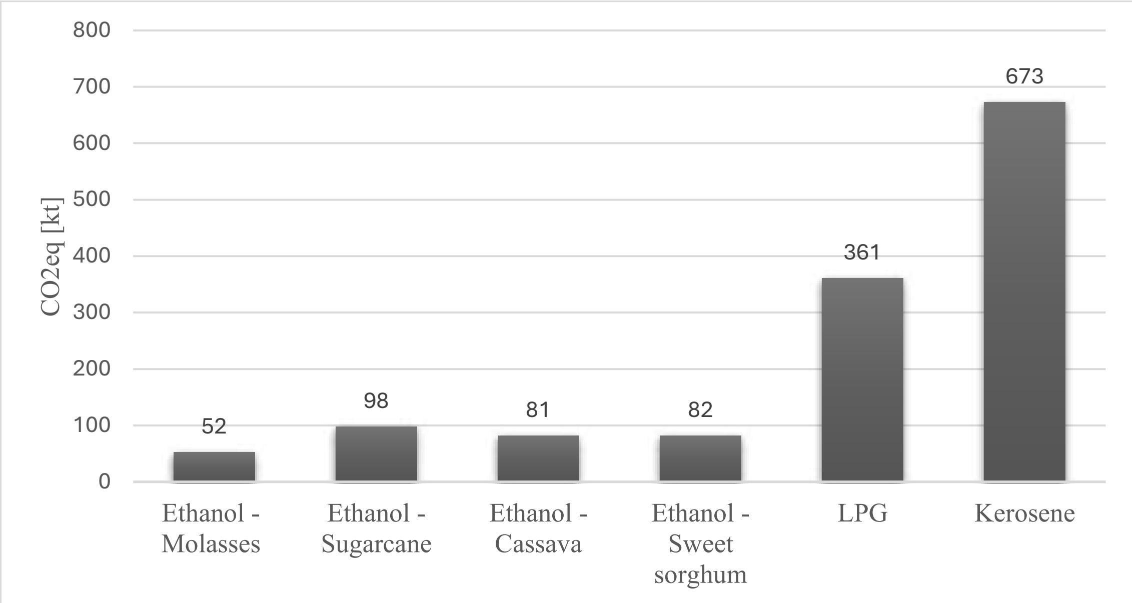

Figure 4.7 - Carbon emissions related to energy demand equivalent to 192 million litres of ethanol

The analysis reveals that bioethanol provides a substantial reduction in total emissions compared to fossil alternatives, even in the case of sugarcane, which exhibits higher emission intensities than other biogenic feedstocks. The carbon footprint of feedstock cultivation and ethanol conversion remains significantly lower than the extraction and combustion cycle of fossil fuels. Furthermore, additional energy benefits are coming from the superior performances offered by bioethanol-based cooking technologies compared to the fossil alternatives. By 2030, emissions from ethanol are projected to be 4 to 7 times lower than LPG and 6 to 13 times lower than kerosene. Kerosene, characterized by a high emission profile and very low conversion efficiency, represents the least sustainable solution, generating over 670 thousand tonnes of CO2eq by 2030 and potentially exceeding 10 million tonnes by 2050. However, it should be noted that, even if kerosene has been intensively used in Kenya in the recent years, its current demand accounts for about 4% of the cooking energy mix and is not part of the government's long-term strategic plans (Ministry of Energy and Petroleum, 2024). For this reason, kerosene is not considered as a viable solution to satisfy cooking demand by 2050 and therefore is not included in the following figures.

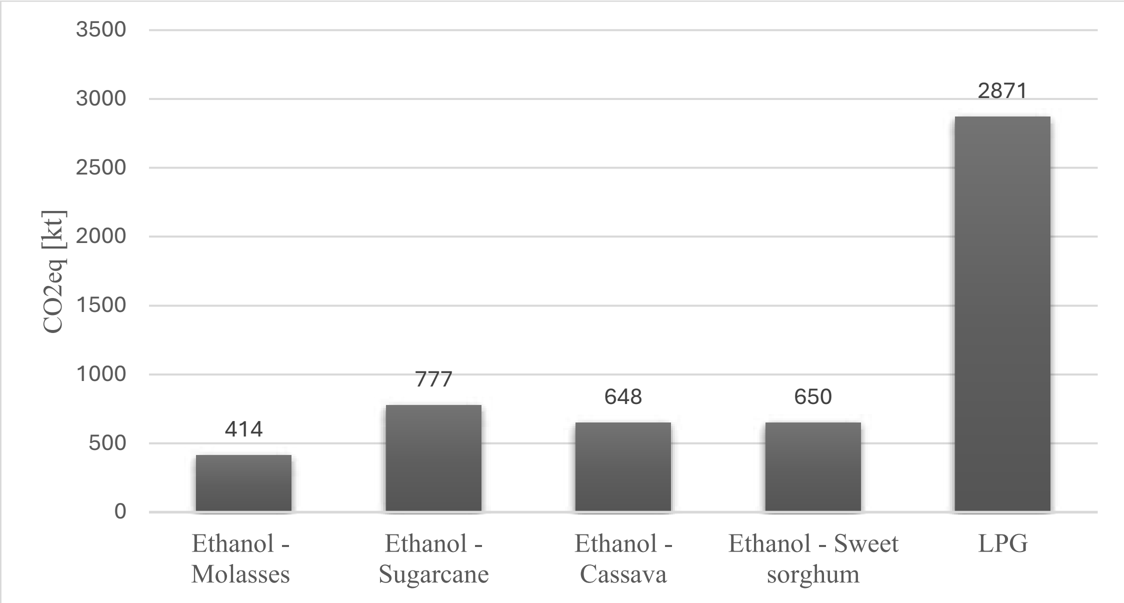

Figure 4.8 - Carbon emissions generated to achieve 30% in the cooking energy mix by 2040

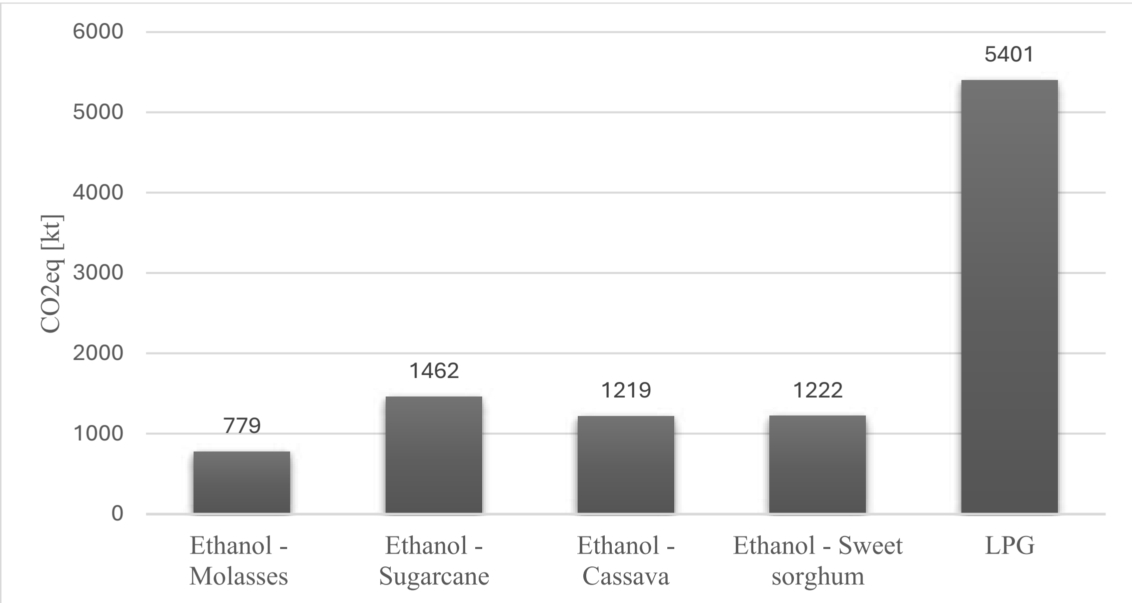

Figure 4.9 - Carbon emissions generated to achieve 50% in the cooking energy mix by 2050

LPG holds a strategic role in the transition to universal clean cooking access, currently representing 31% of the cooking energy mix, with the national target aiming for a 50% share by 2030 (Ministry of Energy and Petroleum, 2024). If the LPG share were to remain at 50% through 2050, due to potential delays in electrification or in the ethanol transition, demand could reach approximately 1500 thousand tonnes, resulting in annual emissions of over 5 million tonnes of CO_2eq. Conversely, if bioethanol achieves a 50% share in the cooking energy mix, annual emissions would range between 779-1462 thousand tonnes of CO_2eq, depending on the feedstock utilized. Even considering a bioethanol production full based on sugarcane, avoided emissions would be roughly around 4 million tonnes.

However, firewood remains the primary energy source for Kenyan households, accounting for 52.4% of total consumption (Ministry of Energy and Petroleum, 2024). Although wood is categorized as carbon-neutral biomass, its intensive use causes significant environmental degradation through deforestation and poses severe risks to human health due to particulate matter released during combustion. Based on an average consumption of 1.78 tonnes of firewood per household (Ogalo & Rop, 2024), transitioning to ethanol could save 1.2 million tonnes of wood by 2030 and over 18 million tonnes by 2050. From a public health perspective, shifting from firewood and charcoal (the latter currently covering 12% of the mix) to cleaner sources like ethanol could prevent at least 5000 deaths and over 400mila DALYs (Disability-Adjusted Life Year) annually caused by indoor air pollution (Dalberg, 2018).

Finally, to provide a comprehensive overview of the emission savings achieved, Table 4.9 details the specific avoided emissions relative to equivalent LPG consumption. These values account for both land occupancy and the quantity of feedstock input required for bioethanol production.

Table 4.9 – Specific avoided emissions per hectare and tonne of crops in bioethanol production

Feedstock	tCO2eq/ha	tCO2eq/t(crops)
Ethanol - Molasses	-	0,482
Ethanol - Sugarcane	5,77	0,096
Ethanol - Cassava	3,39	0,247
Ethanol - Sweet sorghum	2,04	0,058

Considering avoided emissions relative to land use, the best specific results are achieved by sugarcane. Despite having the highest resource requirements among the selected crops, its exceptionally high agricultural yields ensure an excellent return in terms of avoided emissions, reaching approximately 5.77 tonnes of CO_2eq avoided for every hectare cultivated. This is followed by cassava, with 3.39 tonnes of CO_2eq avoided per hectare, and sweet sorghum at 2.04. Molasses is excluded from this specific ranking, as it would be reductive to attribute the land requirements for molasses production solely to bioethanol. Indeed, molasses is a byproduct obtained during sugarcane processing for sugar production. Therefore, to evaluate its specific environmental impact in relation to land use, it would be necessary to include the benefits derived from sugar production within the analysis, a scope that falls outside the present study.

A different perspective emerges when analysing specific emissions per process input in ethanol conversion. In this case, the concentration of fermentable sugars available for ethanol production becomes decisive. Molasses records the highest values here, with a conversion rate of up to 300 litres per tonne, effectively avoiding approximately 0.48 tonnes of CO2eq for every tonne utilized. Cassava, with an average yield of 170 litres of ethanol per tonne, also demonstrates strong performance, avoiding about 0.25 tonnes of CO2eq per tonne. Conversely, sweet sorghum remains at the bottom of the ranking due to one of the lowest conversion efficiencies, only 40 litres per tonne, resulting in just 0.058 tonnes of CO2eq avoided per tonne of input.

4.4.2. Aviation Sector

SAF production enables substantial reductions in GHG emissions through the use of renewable biomass instead of fossil fuels. Although several technologies exist for SAF production, this analysis focuses exclusively on the carbon impact of SAF produced through HEFA technology, which currently represents the most mature and strategically relevant option for Kenya from both a technical and economic perspective, and ATJ technology, which represents a valid alternative in the long-term due to the already established ethanol value chain in the country.

As previously discussed, SAF production via HEFA technology allows for variable co-production of HVO depending on market needs. By adjusting the parameters adopted during the feedstock conversion phase (i.e., hydrotreatment and hydrocracking), it is possible to determine the final production volumes of the two biofuels. During the transformation process, additional by-products are generated, such as naphtha and LPG, and their utilization significantly influences the environmental performance of the final product. For example, it is possible to maximize distillate production, approximately 210 thousand tonnes of distillate from 250 thousand tonnes of feedstock, when production is fully oriented toward HVO, with no HEFA-SPK output (Boscagli, 2025). Conversely, full HEFA production, with no HVO output, results in lower distillate volumes, around 180 thousand tonnes from the same feedstock input, and higher production of naphtha and LPG (Boscagli, 2025). In this second case, the reuse of by products within industrial processes allows overall GHG emissions to be minimized, even though total distillate production is lower than in the full HVO case.

For simplicity, this study reports an indicative scenario with 70% HEFA and 30% HVO production, the configuration which is most adopted in currently operating biorefineries producing SAF via HEFA technology, whose outputs were already presented in figure 4.3 for the different feedstocks. For the HEFA pathway, official CORSIA values were utilized for previously approved feedstocks, namely Jatropha and UCO (Boscagli, 2025). Castor and croton, although characterized by properties similar to approved CORSIA feedstocks, are not currently included among the recognized feedstocks for SAF production. Nevertheless, the environmental impact associated with the use of castor for HEFA production has been estimated by ICAO and is therefore included in this analysis (Boscagli, 2025). However, it was not possible to identify reliable estimates for HEFA-SPK production from croton, which consequently has been excluded from the following analysis.

The table 4.10 shows the emission profiles related to SAF production via different feedstock, including also conventional kerosene-based jet fuel.

Table 4.10 – Carbon emission values for aviation fuels production

Feedstock	**gCO2eq/kg**	**gCO2eq/ MJ**	**Source**
HEFA - Jatropha	950	22.1	(Boscagli, 2025)
HEFA - Castor	1080	25.0	(Boscagli, 2025)
HEFA - UCO	598	13.9	(Boscagli, 2025)
ATJ - Molasses	980	22.8	(Machandi, 2021; Han, et al., 2017)
ATJ - Sugarcane	1460	34.0	(IEA Bioenergy, 2024; Han, et al., 2017)
ATJ - Sweet sorghum	1290	30.0	(Machandi, 2021; Han, et al., 2017)
ATJ - Cassava	1295	30.1	(Rathnayake, et al., 2018; Han, et al., 2017)
Jet Fuel - Kerosene	3830	89.0	(Bauen, et al., 2022)

Regarding the ATJ pathway, to preserve the detailed data gathered on crop cultivation in Kenya, the impact of upgrading ethanol into ATJ-SPK was integrated at this stage. An average conversion impact of 10 gCO2eq/MJ (Han, et al., 2017) was assumed, resulting in total values that align with the ranges identified by CORSIA (ICAO, 2025).

For both categories of feedstock, the solutions with the lowest impact in terms of GHG emissions are those represented by UCO and molasses. These production residues do not require resources for cultivation, but only for the collection, pretreatment and conversion phases. Compared to fossil kerosene, net emission savings are observed in all cases, with values on average 3 to 4 times lower, and HEFA solutions showing slightly better results, as also confirmed by CORSIA publications (ICAO, 2025). In the case of jatropha, although the plant exhibits a relatively high emission profile (46.9 gCO2eq/MJ), the positive impact generated by the cultivation on degraded or abandoned land from an ILUC perspective, compensate the overall carbon intensity of the crop, more than halving the original production emissions. As a matter of fact, the value of 22.1 gCO2eq/MJ is considered for SAF production in Kenya, since jatropha cultivation is mostly expected to occur in ASALs (Boscagli, 2025).

However, to evaluate the total emissions generated for the identified HEFA production targets, it is necessary to consider the total distillate fuel resulting from the conversion process. Even if the conversion rate of vegetable oil into drop-in fuels is comparable across feedstocks, remaining within the 69-76% range, the specific yields of HEFA-SPK and HVO vary significantly. This discrepancy becomes particularly evident when examining HVO production projected for 2040 and 2050. Unlike the 2030 target, which is set to meet the vegetable oil demand for the repurposing of the Mombasa refinery (input-based), the targets defined for 2040 and 2050 focus on net HEFA-SPK production (output-based). Consequently, the required vegetable oil input fluctuates depending on the chemical characteristics of the feedstock, which in turn dictates the final volume of co-produced HVO. To further clarify the dynamics discussed above, the inputs and outputs of the HEFA conversion process are detailed in Figures 4.10, 4.11, and 4.12, corresponding to the years 2030, 2040, and 2050, respectively.

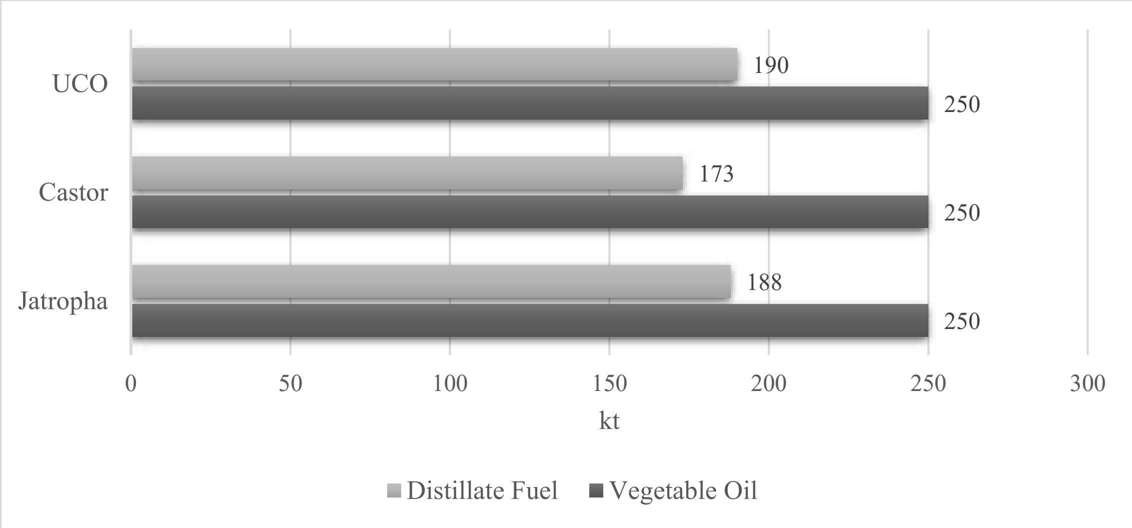

Figure 4.10 - Input/Output of the HEFA conversion process to achieve 2030 targets

In the case of castor oil, the total distillate production is slightly lower due to higher water generation during the conversion process, achieving a 69% conversion rate from vegetable oil to drop-in biofuels. Conversely, UCO shows the best conversion rate, with 76% of total distillate output. While the HEFA/HVO production ratio can be adjusted during refining, certain technical constraints inherent to the feedstock's nature remain a critical factor for planning. By 2050, for example, achieving a 30% share of HEFA-SPK in total jet fuel consumption would require approximately 1183 thousand tonnes of UCO or 1595 of castor oil, a difference of over 400 thousand tonnes.

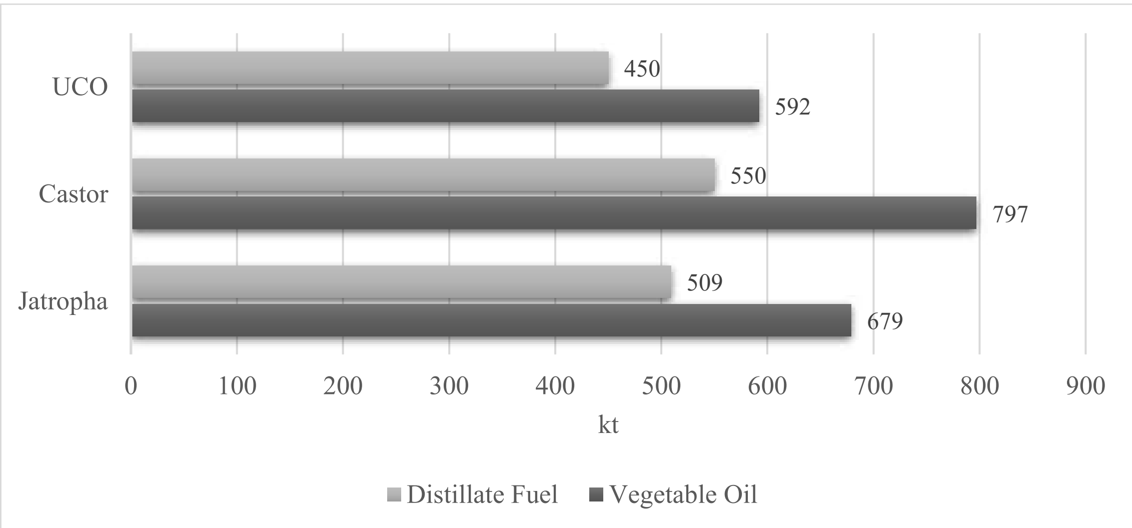

Figure 4.11 - Input/Output of the HEFA conversion process to achieve 2040 targets

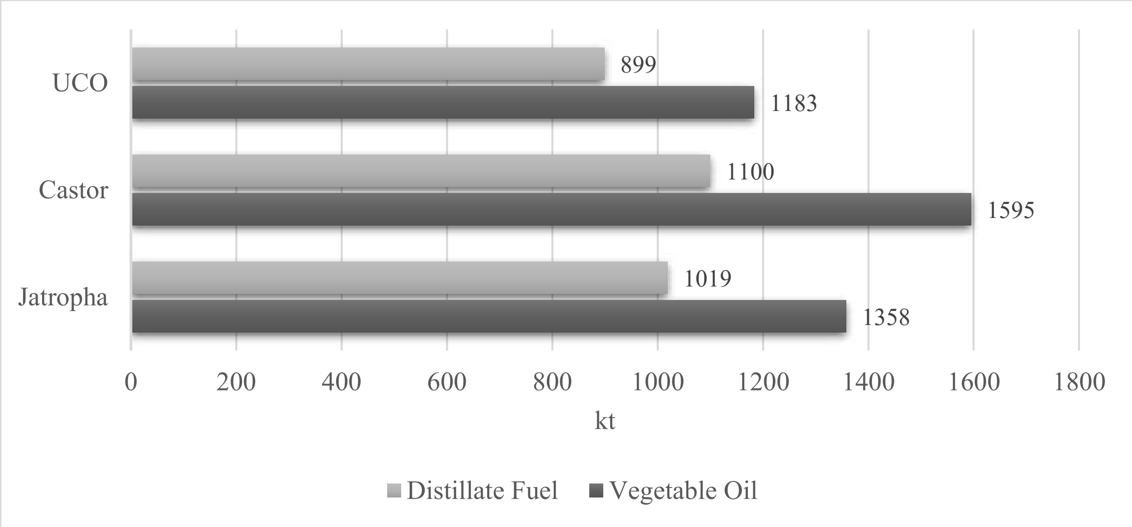

Figure 3.12 – Input/Output of the HEFA conversion process to achieve 2050 targets

However, the higher feedstock demand for castor results in a greater availability of HVO, corresponding to about 33% of total distillate production. HVO, although not suitable for direct application in the aviation sector, represents a high-quality biofuel with properties analogous to conventional diesel. It can be utilized either in blends or as a standalone fuel to reduce fossil fuel consumption in other transport segments, such as road and maritime transport, reducing their carbon footprint. Considering the conventional 70-30 configuration of an HEFA/HVO production plant, the HVO co-produced under the different scenarios is reported in figure 4.13.

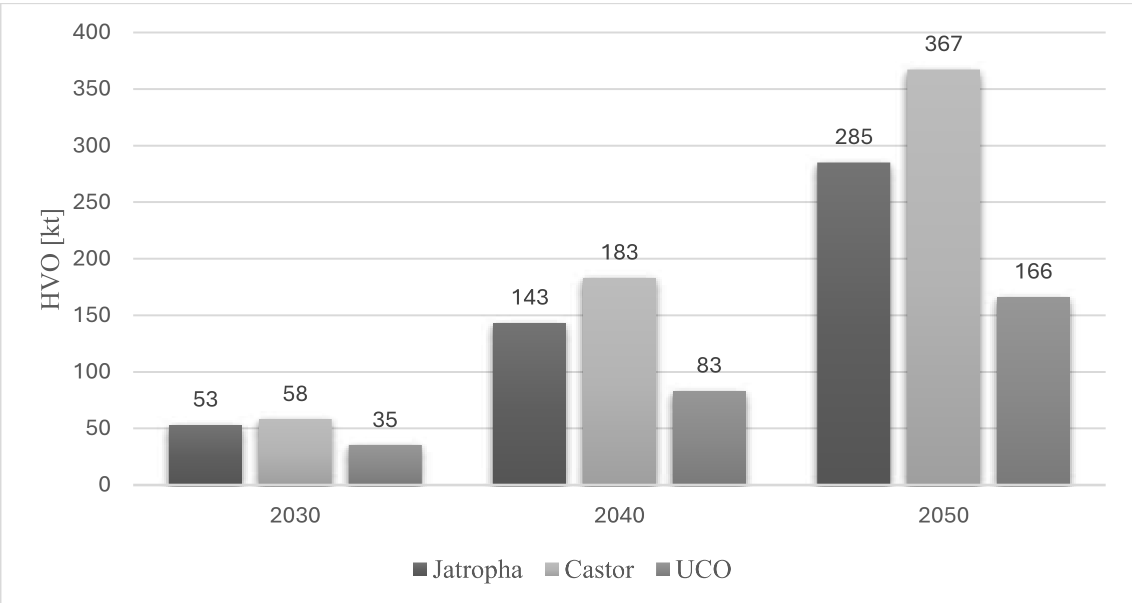

Figure 4.13 - HVO output from HEFA processing

Indeed, the co-production of 367 thousand tonnes of HVO from castor is nearly four times higher than the 99 thousand tonnes recorded for UCO. Nevertheless, if prioritizing HEFA production is the primary goal, UCO and jatropha offer substantial raw material savings and a lower demand in terms of land.

Further insights emerge from analysing the emissions avoided through the use of these distillates. Based on a WTW emission value of 87 gCO2eq/MJ for fossil diesel (Edwards, et al., 2014) and 89 gCO2eq/MJ for kerosene-based jet fuel (Bauen, et al., 2022), it is possible to estimate the emission reductions achieved by substituting fossil fuels with biofuels in the transport sector. The following figures provides a comprehensive comparison of emissions generated by fossil sources versus biofuels, corresponding to the volumes required to achieve the production targets. Respectively, figure 4.14 shows the results relative to jatropha-based biofuels, figure 4.15 shows the results relative to castor-based biofuels and figure 4.16 shows the results relative to UCO-based biofuels.

In the case of Jatropha, the conversion rate of vegetable oil into HEFA-SPK is approximately 54%, increasing to 75% when accounting for total distillate production. This implies that in 2030, from the utilization of 250 thousand tonnes of vegetable oil, a production of approximately 135 thousand tonnes of HEFA-SPK and 53 thousand tonnes of HVO would be achieved, resulting in roughly 553 thousand tonnes of avoided CO2eq.

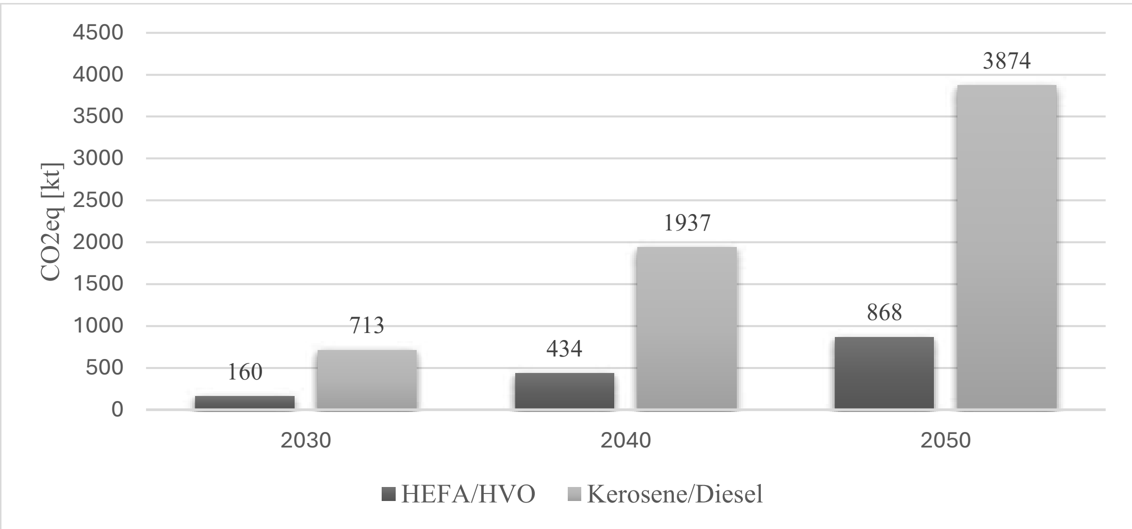

Figure 4.14 - Carbon emissions of jatropha-based drop-in fuels vs fossil fuels

Moreover, by 2050, beyond displacing the consumption of 733 thousand tonnes of kerosene-based jet fuel, HVO production could reach 285 thousand tonnes per year, generating a net saving of approximately 3 million tonnes of CO2eq compared to the full fossil-fuel scenario.

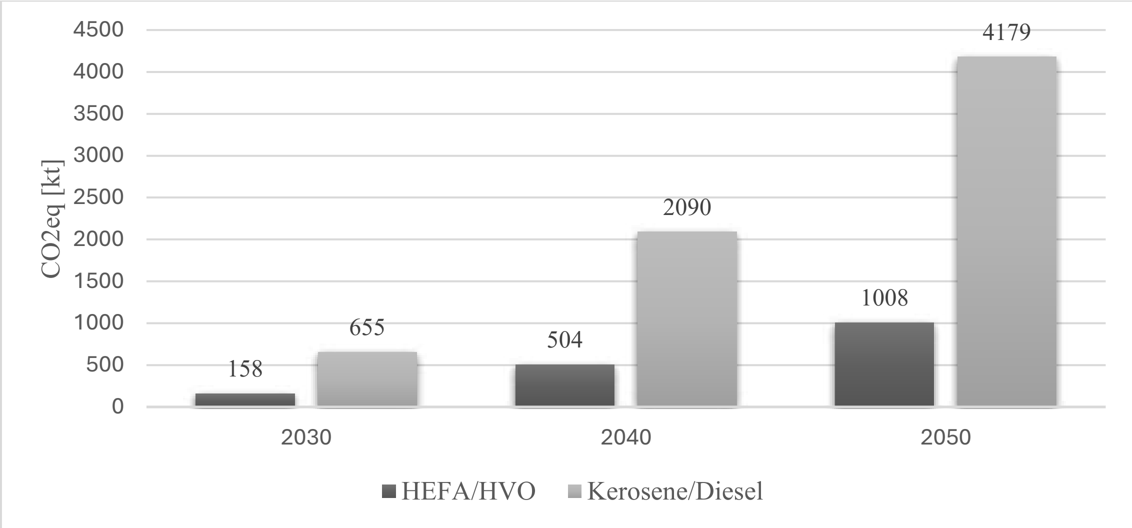

Figure 4.15 - Carbon emissions of castor-based drop-in fuels vs fossil fuels

Considering production via castor oil, due to a lower oil-to-HEFA-SPK conversion rate of only 46%, the avoided emissions by 2030 are lower compared to other alternatives. Looking at long-term objectives, the necessity to meet HEFA-SPK demand requires a greater availability of vegetable oil in the case of castor, and consequently higher land occupancy, for the same volume of HEFA production. Nevertheless, HVO production increases proportionally, ensuring an overall greater reduction in fossil fuel consumption, with 1100 thousand tonnes avoided in 2050 through the deployment of biofuels and over 4 million tonnes of CO2eq saved.

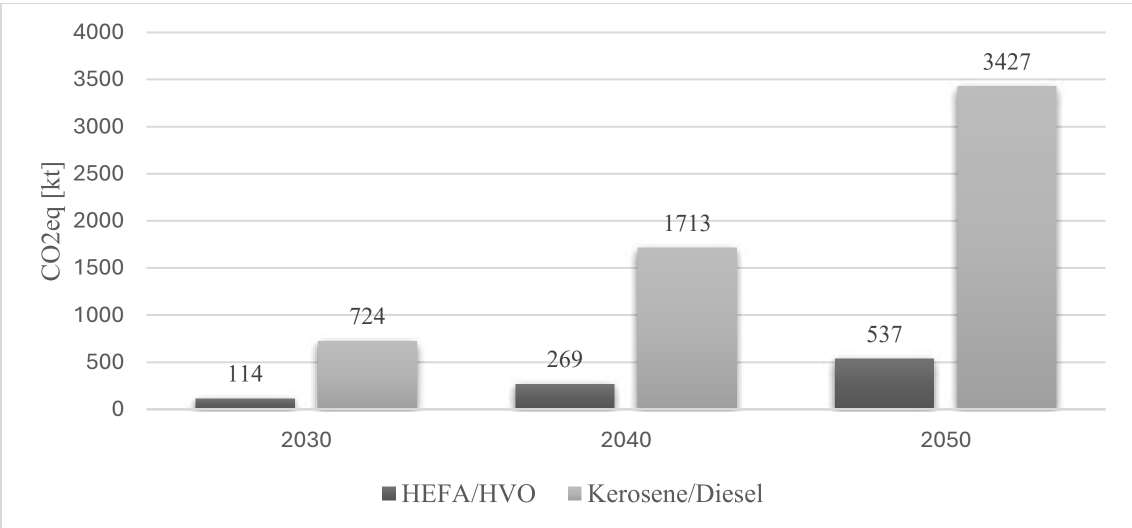

Figure 4.16 - Carbon emissions of UCO-based drop-in fuels vs fossil fuels

Regarding the 2030 targets, UCO guarantees the highest savings with approximately 610 thousand tonnes of CO2eq avoided, followed by jatropha and castor, which achieve 553 and 497 thousand tonnes of CO2eq avoided, respectively. In general, UCO provides excellent results in terms of avoided emissions, reaching nearly 3.5 million tonnes of CO2eq by 2050, while maintaining the most limited resource consumption, at less than 1200 tonnes. On the contrary, HEFA-SPK production via castor, while requiring a higher availability of oil and greater land use, achieves a substantially higher HVO co-production which allows for avoiding a significant share of emissions from diesel consumption. Jatropha represents a middle-ground solution, offering good HEFA-SPK conversion yields and requiring less land than castor, while achieving emission reductions that, in the most optimistic case, exceed 3000 thousand tonnes.

Beyond these results, it remains essential to verify actual production feasibility and the capacity to build a robust, organized supply chain to meet the identified targets. For instance, while UCO offers superior technical, economic, and environmental performance, actual feedstock availability and the implementation of efficient collection systems must be confirmed. As previously discussed, the complete production of SAF from a single feedstock is unlikely, particularly considering current estimates of UCO availability in Kenya and existing collection rates. The final level of emissions associated with SAF production will therefore depend, among other factors, on the mix of feedstocks used. In any case, even by maximizing HEFA-SPK production from UCO, a significant share of SAF would still need to be produced from alternative feedstocks to reach the 30% total target.

As a matter of fact, the collection and repurposing of UCO for HEFA-SPK production would allow for virgin vegetable oil savings of 216 million litres of by 2030, and 288 million litres by 2050, under the most optimistic collection scenarios. This has a positive impact on total avoided emissions, as UCO guarantees a superior ratio of avoided emissions per tonne of vegetable oil input.

Finally, considering ATJ conversion technology, it is possible to estimate the extent to which the repurposing of the ethanol industry could impact the aviation sector.. The figure 4.17 presents the comparison between the emission generated by ATJ-SPK production across the different analysed feedstocks with conventional kerosene-based jet fuel.

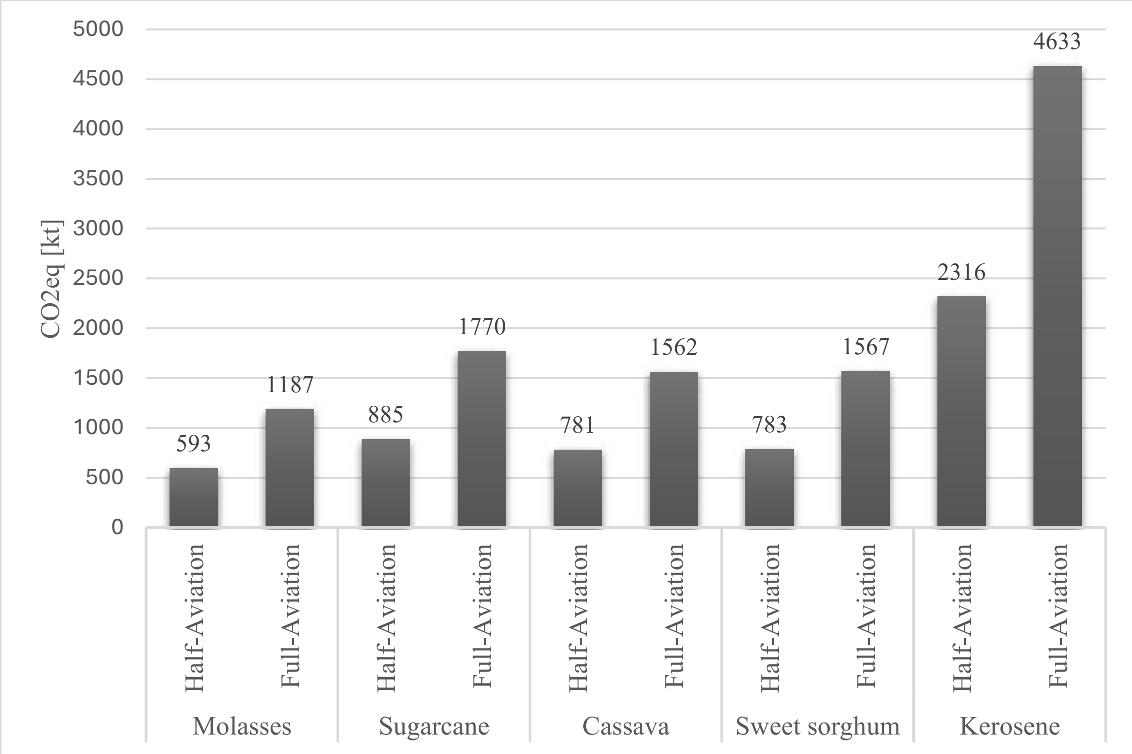

Figure 4.17 - Carbon emissions of bioethanol-based ATJ-SPK vs kerosene-based jet fuel

Assuming an ethanol-to-ATJ-SPK conversion efficiency of 52% (Boscagli, 2025), a total of 605 thousand tonnes and 1211 thousand tonnes of ATJ-SPK could be produced under the Half-Aviation scenario and Full-Aviation scenario, respectively. Consequently, it is possible to estimate the generated CO2eq emissions by 2050 in case of ethanol upgrading via ATJ conversion technology.

Repurposing the ethanol value chain as a feedstock for SAF production could cover a significant share of the country's final jet fuel demand. Given a projected demand of 2.4 million tonnes of jet fuel by 2050, under the Half-Aviation scenario, approximately 24.7% of the demand would be met by ATJ-SPK, while the Full-Aviation scenario could cover nearly 50%. Assuming a parallel HEFA-SPK production targeting 30% of final demand, Kenya's total jet fuel consumption could consist of up to 80% SAF, potentially cutting over 6 million tonnes of CO2eq from the aviation sector.

However, as previously discussed, ATJ conversion technology currently remains at TRL 7 and is not yet commercially widespread due to high production costs. This implies that ATJ-SPK production in Kenya, and globally, remains contingent upon significant technological improvements and clear mandates or incentives at both local and international levels. The ATJ-SPK production estimates in this study are optimistic, as they evaluate theoretical production potential rather than actual market dynamics. Considering that the bioethanol value chain is currently the most developed in Kenya and will continue to grow driven by the transition to clean cooking, it is likely that by 2050 bioethanol will play a prominent role in the country's energy dynamics. Simultaneously, the availability of renewable energy will foster electrification, which is crucial for decarbonizing the buildings and transport sectors. In this context, bioethanol production could be redirected toward hard-to-abate sectors where electrification is not feasible, such as aviation, provided that production becomes economically favourable.

Finally, a comprehensive comparison of the SAF alternatives analysed in this study is presented, considering different feedstocks to provide a clear overview of the associated benefits and requirements. Specifically, the table 4.11 details the benefits in terms of specific avoided emissions in the aviation sector relative to conventional jet fuel, considering land use and process inputs.

Table 4.11 - Specific avoided emissions per hectare, tonne of crops and tonne of input in SAF production

Feedstock	tCO2eq/ha	tCO2eq/t(crops)	tCO2eq/t(input)
ATJ - Molasses	-	0,360	1,20
ATJ - Sugarcane	4,20	0,070	1,00
ATJ - Cassava	2,49	0,182	1,07
ATJ - Sweet sorghum	1,49	0,043	1,07
HEFA - Jatropha	1,67	0,669	2,21
HEFA - Castor	1,61	0,895	1,99
HEFA - UCO	-	-	2,44

Similarly to the previous section, the table above elucidates the emissions avoided through the use of different feedstocks. Regarding land use, the most significant impact is achieved by sugar and starchy crops which demonstrate higher average agricultural yields, thus requiring less land to achieve the same benefits in terms of avoided emissions. In this context, sugarcane shows the best result with 4.2 tonnes of CO2eq avoided per hectare consumed, even with a significant decrease from the 5.77 value obtained for simple ethanol production. This reduction reflects the carbon footprint of the upgrading process from bioethanol to ATJ-SPK, which inherently lowers the net avoided emissions. Oleaginous crops, in both scenarios, remain above 1.60 tonnes of CO2eq avoided per cultivated hectare, performing better than sweet sorghum for ATJ-SPK. Furthermore, it remains essential to note that the oleaginous crops analysed in this study are suitable for cultivation in ASALs, where land-use constraints are typically less stringent. UCO is excluded from this first analysis stage as, being a residue, it requires no land for cultivation.

However, when considering emission reductions per single tonne of crop, oleaginous crops demonstrate superior results, significantly outperforming sugar-based alternatives, due to their high oil content, which maximizes fuel output per tonne of harvest. Even molasses, which shows the best performance within the ATJ pathway, yields approximately 0.36 tonnes of CO2eq avoided per tonne of input, a value two to three times lower than those recorded for jatropha and castor.

Finally, analysing the net conversion of the intermediate liquid into the final fuel (bioethanol to ATJ-SPK and vegetable oil to HEFA-SPK), the best results are obtained from UCO. As previously discussed, UCO possesses the lowest emission profile and a conversion capacity into HEFA-SPK of approximately 62% by weight. Consequently, every tonne of UCO input results in a net reduction of approximately 2.44 tonnes of CO2eq. Overall, the HEFA-SPK pathway records higher values, with jatropha and castor guaranteeing savings of 2.21 and 1.99 tonnes of CO2eq per tonne of input, respectively. In contrast, for bioethanol conversion, the values only slightly exceed one tonne of avoided emissions, even when considering the most performant feedstocks.

5. Limitations and Future Directions

This study provides a critical analysis of the Kenyan energy landscape and a comprehensive review of the primary energy policies published by the government, with the ultimate objective is to estimate the medium- and long-term biofuel production potential and to propose a strategic integration framework within the country's energy mix. However, several obstacles were identified during both the review and analysis phases, which are detailed in the following sections.

5.1. Feedstocks

The definition of feedstocks is the cornerstone of biofuel and bioenergy production. The predictability and availability of these raw materials dictate the success or failure of a production strategy; even with strong market demand, the absence of consistent feedstock supply decisively limits final production volumes. In this regard, Kenya currently lacks comprehensive regulation concerning energy crop production. Although the publication of the *Bioenergy Strategy* has initiated the categorization of land productivity and theoretical yield studies for key feedstocks, there has been no formal stance on which specific territories or crops should be prioritized.

In a country like Kenya, where food requirements are largely met through imports and most fertile land is dedicated to food crops, precise and effective agricultural planning is vital, especially as food demand must scale alongside population growth. Consequently, it remains challenging to estimate with certainty which lands will be allocated for energy crops in the future. This study provides numerical estimates of the land area required to reach specific targets, assuming that each crop is cultivated under its optimal agro-climatic conditions. While production yields are based on reliable studies from Kenya or similar geographic contexts rather than empirical verification, literature suggests that theoretical yields often fall short of expectations, particularly in ASAL regions characterized by limited water resources and degraded soils. Thus, securing land does not automatically guarantee a defined biofuel output. The success of these agricultural activities will depend on available resources, geographical allocation, and technologies, factors that are difficult to predict and lack extensive historical data in the nascent Kenyan biofuel sector.

The feedstocks selected for this study are resources already present at the national level, which Kenya could theoretically scale with relative ease. The identified energy crops are well-known to the local agricultural community, requiring no radical transformation of existing farming practices. Residues, such as molasses and waste oils, currently represent the primary feedstocks for biofuel production, with the main uncertainties involving future volume availability and the establishment of effective collection and recycling systems. However, the future deployment of alternative feedstocks, such as lignocellulosic biomass, should not be ruled out. Although currently limited by high costs and technological complexity, lignocellulosic biomass could become significant due to their versatility and huge availability. Similarly, yellow oleander represents a promising lipid source due to its high oil content and adaptability to ASAL environments, though a comprehensive suitability study for biofuel production is still lacking. Future research should evaluate the role these alternative feedstocks might play, potentially displacing or augmenting conventional ones, and determine the long-term production volumes they could realistically guarantee.

5.2. End-use Sectors

Beyond evaluating theoretical production capacities, this study aims to assess the potential applications and end-uses of biofuels within Kenya. Although the analysed feedstocks offer various conversion pathways, the analysis focuses primarily on bioethanol for the cooking sector and HEFA-SPK for the aviation sector. Following a review of the country's primary energy policies and strategies, these two sectors emerge as focal points of Kenya's energy transition. The shift toward clean cooking is a government priority, with a clearly defined strategy aimed at achieving this goal by 2028. Simultaneously, the development of a SAF production value chain represents a strategic objective at both regional and international levels, as evidenced by Kenya's active participation in programs such as ICAO CORSIA.

Given the resource requirements of these sectors, the limited availability of feedstocks, and the technological challenges of scaling a biofuel industry, this study assumes that biofuels production will predominantly cover the demand arising from these two areas. However, it is plausible that a portion of these resources could be utilized in the short and medium term to support the energy transition in sectors still heavily reliant on fossil fuels, such as road and maritime transport. While the current use of bioethanol and biodiesel in Kenya remains very limited in the vehicle fleet, the establishment of a robust production system could enable these fuels to partially displace fossil consumption in road transport. This development would occur in parallel with the growing demand in the cooking and aviation sectors, where biofuels are expected to play a primary role in the national energy transition. As a matter of fact, the country's declared long-term objective is intensive electrification, aiming to eliminate petroleum consumption in road transport through a predominantly electric vehicle fleet.

Consequently, this research prioritizes sectors that promise constant and growing demand for biofuels in both the short and long term, namely cooking and aviation, rather than evaluating the temporary impact of biofuels in sectors where they are not the ultimate decarbonization solution. For instance, regarding the lipid value chain, the inherent feedstock constraints and the lack of viable alternatives for aviation suggest that the HEFA/HVO pathway will likely supersede FAME biodiesel in the long term. Future research could beneficially evaluate the specific volumes and timelines through which biofuels might facilitate the transition in sectors beyond those considered in this study.

5.3. Economics

To ensure methodological clarity and due to the current lack of sufficient primary data, this study does not include a detailed economic analysis regarding the production costs or commercial value of biofuels. It is evident that during the implementation phase of production projects, economic dynamics will play a preponderant role in investment decisions and feedstock selection. However, the scope of this research is not to provide financial investment advice, but rather to establish the requirements and theoretical feasibility of creating a biofuel supply chain in Kenya, focusing specifically on technical and climatic aspects.

Moving forward, it will be essential to complement this analysis with a comprehensive economic valuation of biofuel production. This should include assessing costs related to feedstock procurement, conversion processes, in terms of both CAPEX and OPEX, and the logistics of national, regional, and international distribution.

6. Conclusions

The present thesis set out to investigate the potential for the sustainable development of liquid biofuels in Kenya, with the dual objective of contributing to national decarbonization efforts and enhancing energy security. To this end, the study combined a comprehensive assessment of the Kenyan energy system and policy framework with a technical evaluation of biofuel production pathways, feedstock availability, and environmental implications. The results obtained provide a structured and realistic perspective on the opportunities and constraints associated with the deployment of biofuels within the Kenyan context.

At the outset, the analysis highlighted the structural characteristics of the Kenyan energy system, which presents a combination of strengths and critical challenges. On the one hand, Kenya stands out for its high penetration of renewable energy in the power sector, where more than 80% of electricity generation is derived from clean sources, primarily geothermal and hydropower. On the other hand, the overall energy mix remains heavily dependent on traditional biomass, which accounts for 62% of total energy supply, particularly in the residential sector, and fossil fuels, which are responsible for an additional 20%. This reliance is associated with severe environmental degradation, including deforestation, as well as significant public health impacts due to indoor air pollution and consistent carbon emissions arising from the energy sector.

The transport sector emerges as a key area of concern, being entirely dependent on imported petroleum products. This condition not only contributes substantially to GHG emissions but also exposes the country to external market volatility and undermines its energy independence. Within this framework, the role of biofuels becomes particularly relevant, as they represent one of the few viable alternatives capable of addressing emissions in hard-to-abate sectors, such as aviation, while leveraging domestic resources.

The policy and regulatory analysis further emphasized that Kenya has established a comprehensive and ambitious framework to guide its energy transition. The *Kenya Vision 2030*, the *Climate Change Act*, and the *Energy Act* provide a solid institutional basis, complemented by sector-specific policies including the *National Energy Policy*, the *Bioenergy Strategy*, and the *National Cooking Transition Strategy*, which demonstrate a clear political commitment to sustainable development, clean energy adoption, and climate change mitigation.

However, the study also identified a persistent gap between policy formulation and effective implementation. The coexistence of multiple institutions and overlapping mandates often results in fragmented governance and limited coordination. Moreover, the absence of binding targets and economic incentives, particularly in the biofuels sector, has hindered the development of a structured and competitive market. This institutional and regulatory context represents a critical constraint that must be addressed in order to unlock the full potential of biofuels in Kenya.

Building upon this contextual framework, the technical chapters provided an in-depth analysis of biofuels, including feedstock characteristics, conversion technologies, and end-use applications. Particular attention was devoted to identifying feedstocks that are compatible with the Kenyan agro-climatic conditions and suitable for a sustainable biofuel production. In this regard, the study emphasized the convenience of relying on traditional biofuels, such as bioethanol, and advanced biofuels, such as HEFA-SPK, exploiting conventional crops and alternative non-edible crops, as well as waste-based resources like UCO and molasses.

The analysis of biofuel pathways highlighted that bioethanol, given its technological maturity and relative ease of integration into existing infrastructure, can play an important role in achieving universal clean cooking access in the short term and full decarbonization of the cooking sector in the longer period. At the same time, advanced biofuels, such as HEFA-SPK, represent a strategic opportunity particularly in the aviation sector where alternatives remain limited.

The core contribution of this thesis lies in the quantitative assessment presented in the analysis chapter, where realistic production targets were defined and evaluated against resource availability and environmental performance. The results indicate that Kenya possesses a substantial potential for biofuel production, supported by robust political institutions, extensive agricultural activity and the availability of underutilized land. Under the scenarios considered, it is possible to achieve meaningful penetration of biofuels in both the cooking and transport sectors, contributing to emission reductions and reduced fossil fuel imports. Considering the proposed implementation strategy, Kenya could lead regional technological development in biofuel production and establish itself as a key reference point for international trade in a fast-growing market.

The study demonstrates that, with appropriate scaling of production and distribution systems, bioethanol could significantly reduce reliance on traditional biomass, thereby alleviating pressure on forest resources and improving public health outcomes. The results show that to meet the projected bioethanol growth for 2030, about 46,000 hectares would be required, approximately 0.08% of the country's total land area, if production is based on sugarcane. While molasses represents the most land-intensive pathway for bioethanol production, as it is a byproduct of sugarcane processing, it maintains the strategic advantage of scaling domestic sugar production. In the case of molasses, approximately 220,000 hectares, equivalent to 0.38% of the total land area, would be necessary to achieve the same 2030 objectives. By 2050, achieving a bioethanol penetration of up to 50% in the cooking sector remains a viable solution, although it necessitates significantly higher land occupancy. In this scenario, ethanol production could reach 2,874 million litres, requiring 682,000 hectares in the most optimistic case. At the same time, bioethanol utilization in the cooking sector could avoid the consumption of 1.5 million tonnes of LPG and consequently saving about 3.9 to 4.6 million tonnes of CO2eq emissions depending on the input feedstock.

While the integration of bioethanol as a clean cooking fuel emerges as a concrete solution to support universal access to clean energy, the implementation of a robust domestic supply chain would potentially enable fossil fuel replacement in other sectors as well, owing to ethanol's inherent flexibility, such as the transport sector. Particularly, the total repurposing of the bioethanol value chain toward the aviation sector could potentially lead to a production of over 1200 thousand tonnes of ATJ-SPK. This volume would account for approximately 50% of Kenya’s jet fuel demand by 2050, ensuring a reduction in emissions ranging between 2.8 and 3.4 million tonnes of avoided CO2eq.

However, as of today, ATJ technology has not yet reached commercial maturity, making its large-scale deployment unlikely in the short term. In contrast, the HEFA conversion pathway can play a prominent role in both the short and long term. The potential conversion of the Mombasa refinery into a biorefinery for HEFA-SPK production would require an annual input of 250 thousand tonnes of vegetable oil. This feedstock could be procured through the cultivation of ASAL-suited crops, requiring a land occupancy slightly exceeding 300,000 hectares, which represents less than 0.6% of the country’s total area. Should an efficient system for the collection and conversion of UCO be implemented, the required land occupancy would drop to approximately 40,000 hectares. Nevertheless, to cover 30% of jet fuel consumption by 2050 via HEFA-SPK, even if a high UCO collection system could reduce land consumption of about 480,000 hectares, at least 1,360,000 hectares of land would be necessary, equivalent to 2.34% of Kenya's surface area. In any case, the adoption of HEFA-SPK would enable the displacement of approximately 733 thousand tonnes of kerosene-based jet fuel, ensuring an emission reduction exceeding 3 million tonnes of CO2eq.

The results indicate that, while significant land areas are needed to achieve large-scale production, these requirements can be managed through the use of degraded lands, the prioritization of non-edible feedstocks and effective recovering of residues and wastes. Even if this approach minimizes competition with food production and aligns with broader sustainability objectives, careful planning and monitoring are essential to avoid unintended environmental and social impacts.

From an environmental perspective, the comparison between current energy sources and biofuel alternatives confirms the potential for substantial GHG emission reductions, which can contribute to lowering the carbon intensity of the energy system and supporting national climate targets. However, the overall environmental performance depends strongly on the entire supply chain, including cultivation, processing, and distribution, underscoring the importance of implementing robust sustainability standards.

In light of these considerations, this thesis suggests that the successful development of the biofuels sector in Kenya will depend on a combination of policy, economic, and technical measures. Key priorities include the definition of clear production targets, the establishment of financial incentives and blending mandates and the strengthening of institutional coordination. Furthermore, the active involvement of the private sector and the attraction of international investments will be essential to scale up production and ensure long-term sustainability.

In conclusion, Kenya possesses the necessary resources and strategic positioning to become a significant player in the global biofuels market. While the sector is currently at an early stage of development, the potential benefits in terms of energy security, environmental sustainability, and economic growth are substantial. By addressing existing constraints and implementing coherent and targeted strategies, biofuels can play a central role in the country’s energy transition, contributing to a more resilient and sustainable energy system.

Ultimately, the development of biofuels in Kenya should not be viewed as an isolated objective, but rather as an integral component of a broader transformation of the energy sector. In this perspective, biofuels can complement other renewable energy sources and emerging technologies, in a diversified and integrated approach to decarbonization.

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