TALLINN UNIVERSITY OF TECHNOLOGY

SCHOOL OF ENGINEERING

Environmental Engineering and Management

COMPARISONS OF FUELS USED IN AVIATION

MASTER THESIS

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Tallinn 2021

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Department of Environmental Engineering and Management

THESIS TASK

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Study programme: EABM03/18, Environmental Engineering and Management

Main speciality: Environmental Engineering

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Thesis topic: "Comparisons of fuels used in aviation" (in English) ;(in Estonian) "Lennunduses kasutatavate kütuste võrdlus"

Thesis main objectives:

1. Get acquainted with the history of air transport and ways to reduce air pollution.
2. Consider various types of biofuels and their production technology.
3. Describe the global requirements for biofuels, as well as the mechanisms for its certification.
4. Analyze the environmental and economic consequences of the massive use of biofuels.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Literature review, formulation of thesis objectives and aims	22.06.2021
2.	Work on text of thesis,	11.10.2021
3.	Methodology, conclusion, and discussion	27.12.2021

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LIST OF ABBREVIATIONS

APU – Auxiliary Power Unit

ASTM – American Society for Testing and Materials

ATJ – Alcohol-to- Jet

CAF – Conventional Aviation Fuel

CORSIA – Carbon Offsetting and Reduction Scheme

Def stan – Defense Standard

FPM – Fine particulate matter

FT – Fisher-Tropsch

GDP – Gross Domestic Product

GHG – Greenhouse gas

GPU – Ground Power Unit

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation

HCT – Human carcinogenic toxicity

HEFA – Hydroprocessed Esters and Fatty Acids

HH – Human Health

HNCT- Human non-carcinogenic toxicity

ICAO – International Civil Aviation Organization

ICCT – International Council on Clean Transport

ISO – International Organization for Standardization

LCA – Life Cycle Analysis

LCIA – Life Cycle Impact Assessment

OPEC – Organization of the Petroleum Exporting Countries

PS – Photochemical smog

RPK – Revenue Passenger Kilometers

SAF – Sustainable Aviation Fuel

SIP – Synthesized Iso-Paraffin

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INTRODUCTION

The life of a modern person is closely connected with transportation. Being the youngest among the types of transportation, air transport is developing dynamically. Nowadays, civil aviation has become one of the factors affecting the environment, manifested mainly in the emission of pollutants into the atmosphere.

CO_2 emissions from aviation in 2010 were about 448Mt and that value was forecasted to reach 778Mt by 2020 and as high as 2700Mt by 2050 if no measure is taken to reduce it[1]. Due to the Covid 19 pandemic CO_2 emissions from aviation fell to about 600Mt in 2020, the lowest level in about a decade. [2]

GHG emissions from aviation namely CO_2 negatively impact the environment. Mitigation of such an impact, namely, reduction of emissions of pollutants into the environment, is an urgent task today, therefore, various scientific studies devoted to this problem are also relevant.

Thus, the purpose of the work is to assess the possibility and prospects of reducing air pollution caused by air transportation through the use of new types of fuel, in particular, biofuels.

To achieve the goal, the following tasks were set:

5. Get acquainted with the history of air transport and ways to reduce air pollution.

6. Consider various types of biofuels and their production technology.

7. Describe the global requirements for biofuels, as well as the mechanisms for its certification.

8. Analyze the environmental and economic consequences of the massive use of biofuels.

The materials for the work were statistical data of international organizations, legislative acts and state standards of the EU, international standards, scientific works, and publications.

This work independently analyzed and processed statistical data, looks at the distribution of pollutant emissions from civil aviation around the world, summarized various information about the biofuel production process, and also showed the possible consequences of the massive introduction of such an alternative type of fuel.

The following provisions were made to defend the final qualifying work:

1. Emission of pollutants into the atmosphere is growing.

2. Issues of reducing emissions require study.

3. Switching to biofuels is a solution to the problem

Chapter 1. AIR TRANSPORT AND AIR POLLUTION

1.1 Aviation history and air traffic trends

The first air vehicles to carry passengers were "lighter than air" crafts. They were balloon structures filled with helium. The most famous being the German Zeppelin patented in 1895.

Then in 1903 the first "heavier than air" flight was made at Kitty Hawk by the Wright brothers.

The first passenger airline service was launched in 1914 in Tampa Florida USA, but commercial jet aviation as we know it today was pioneered by the British company De Havilland Comet and the American company Boeing. The De Havilland DH. 106 was the world's first commercial jet airliner.

Advantages of aircrafts as transportation vehicles:

- High speed of movement
- Ability to deliver passengers and goods to isolated regions
- Lack of dependence on the road and rail networks.

However, air transport is not devoid of disadvantages, among which are the following:

- High cost of transportation compared to other modes of transportation
- Dependence on meteorological conditions.
- The need for infrastructures like airports, Runways, and landing strips.
- A relatively low carrying capacity (compared to Trains and Ships.)

Taken together, these advantages and disadvantages have determined the role of modern aviation as a means of delivery of expensive and perishable goods and one of the priority modes of transport for residents of economically developed countries.

Aviation plays a vital role in the modern world, from transportation of passengers and goods to recreational flights.

Commercial aviation: deals with flight operations for the transportation of passengers and goods for profit generation. There are over 90 airlines registered and operating in Europe alone.

According to data from the International Civil Aviation Organization (ICAO) the volume of both passenger and cargo/freight increased multiple fold from 2008 – 2019.[3]

The five most developed "air transport countries" in the field of cargo and passenger transportation, according to ICAO report, include the United States, China, the United Arab Emirates, the United Kingdom and Germany.[3]

The 2009 -2029 forecasts by Airbus, Europe’s largest aircraft manufacturer predict even greater growth in the market, this growth will be driven by:

The need for replacement of older aircrafts currently in service in mature markets. Forecasted growth in countries in places such as Africa and Latin America. The continued growth of limited liability companies in Asia and increase in traffic on currently existing routes where it will be more efficient to simply increase fleet size than to increase flight frequency.[4]

Other factors that can influence this forecasted growth in air travel include:

Tourism – Majority off international travel is by air trave

Demographics – Population growth affects the overall GDP and the demand for air travel

Economic growth (GDP) – Greater disposable income increases the ability to use air transport.[5] [6]

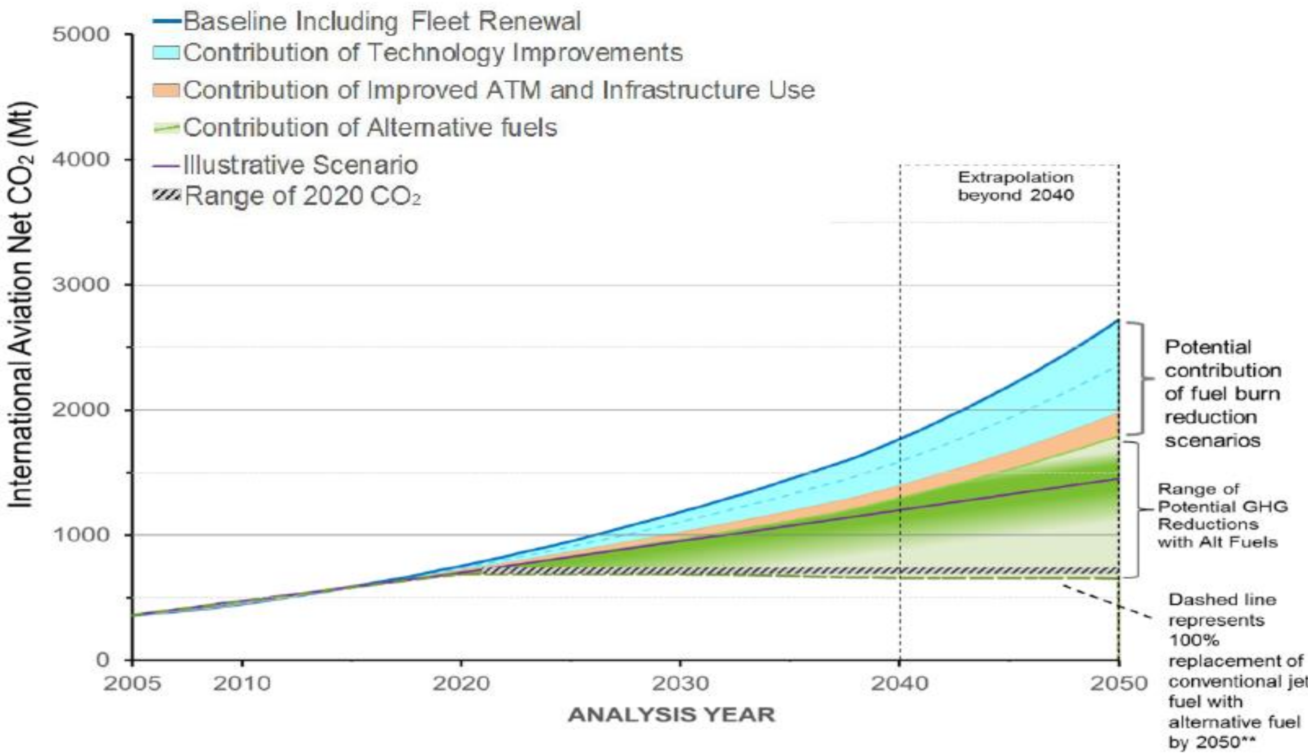

Figure 1. Expected international aviation CO_2 emissions.[6]

Table 1. World air transport growth. The table contains information on passenger air and cargo transportation from 2008 to 2019, it shows a general trend of increase in the volume of passenger traffic carried over the years.[3]

Year	Passengers, million	Annual growth%	Cargo, million tons	Annual growth, %
2008	2500	1.5	39.9	-3.2
2009	2490	-0.4	39.0	-0.8
2010	2708	8.7	48.0	19.2
2011	2873	6.1	49.0	2.2
2012	3007	4.6	48.4	-1.4
2013	3141	4.5	49.5	2.3
2014	3320	5.7	51.1	3.3
2015	3560	7.2	51.3	0.5
2016	3798	6.7	53.2	3.7
2017	4066	7.1	57.0	7.1
2018	4331	6.5	58.8	3.2
2019	4486	3.6	57.6	-2.1

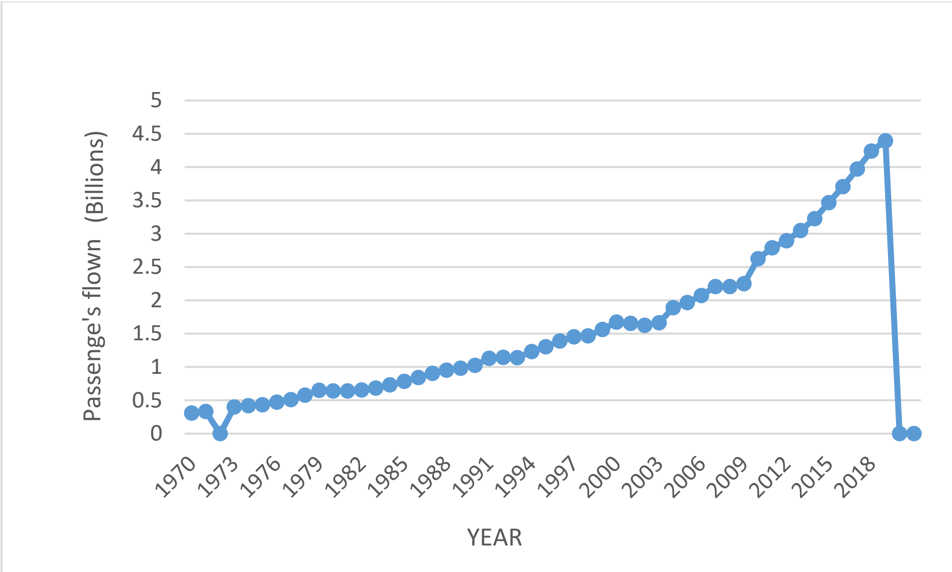

Figure 2. The figure shows the air transport annual passengers carried worldwide from 1970 to 2018 (data collected from International Civil Aviation Organization, Civil Aviation Statistics of the World and ICAO staff estimates.) The sharp drop in passenger volume was due to the Covid-19 pandemic and the subsequent global lockdown.

1.2 Commercial aviation and fuel

The commercial aviation industry depends on aviation fuel for the running of their operations, the operating fuel costs depend on the price of fuel and how fuel efficient the aircraft is (i.e., its fuel consumption).

For some operators, about 12% to more than 40% of overall operating expense is spent on fuel, since this is a significant amount of money, aircraft operators are constantly looking for ways to reduce their overhead costs spent on fuel.[7]

1.2.2 Emission to air from aircrafts

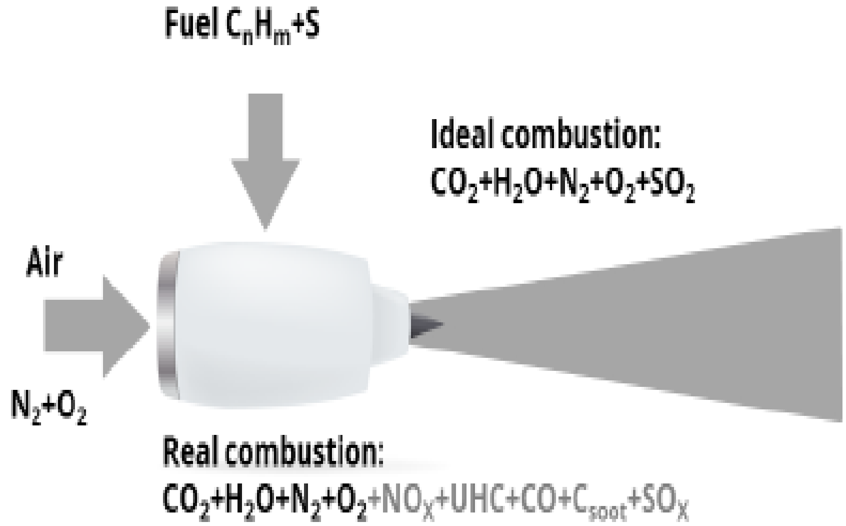

Figure 3. Shows some of the emissions from aircraft fuel combustion [8]

Sources of aircraft emissions are typically comprised of the following:

- Aircraft engine. During the operation of the aircraft engine (from start up to shutdown)
- Auxiliary power unit (APU). A self-contained power unit on an aircraft providing electrical/pneumatic power to aircraft systems during ground operations.

Listed below are some of the emission species produced:

CO_2, NOx, CH_4, SOx (Sulphur oxides), PM(Particulate matter), NMVOCs (non-methane volatile organic compounds), water vapor. [8]

Carbon dioxide (CO_2). Is a gas, it occurs naturally in nature, also as a by-product of burning fossil fuels and biomass, land-use changes, and other industrial processes. Carbon dioxide is the reference gas against which the global warming potential of other greenhouse gases is measured.

Effects: Its contribution to climate change.

Carbon monoxide (CO). Is a colorless, odorless gas formed during incomplete combustion of fuels.

Effects: It causes respiratory problems in humans and animals. It plays a role in the formation of ozone in the troposphere.

Nitrogen oxides ($NOx= NO+NO_2$). Nitrogen oxides encompasses nitrogen dioxide (NO_2) and nitrogen monoxide (NO). Nitrogen Oxide rapidly oxidizes to NO_2, therefore emissions are expressed in terms of nitrogen dioxide (NO_2) equivalents. It is produced during burning of heating and motor fuels at high temperatures.

Characteristics: it is a colorless gas, it is transformed in the atmosphere to NO_2 Effects on humans and ecosystem: respiratory disorders, extensive damage to plants and sensitive ecosystems through the combined action of several pollutants (acidification) and over fertilization of ecosystems.

Particulate matter (PM). Particulate matter is the term used to describe particles with an aerodynamic diameter of 10 micrometers or less. PM2.5 are particles with an aerodynamic diameter of 2.5 micrometer's or less. They are critical in connection with health effects. PM is formed during combustion production processes, combustion processes, mechanical processes (abrasion of surface materials and generation of fugitive dust) and as a secondary formation (from SO_2, NOx, NH_3 and VOC).

Characteristics: it can be solid or liquid particles of varying sizes and composition.

Effects on humans and ecosystem: fine particles and soot can cause respiratory and cardiovascular disorders, increased mortality, and cancer risk; dust deposition can cause contamination of the soil, plants and human exposure to heavy metals that are in dust particles.

Volatile organic compounds and Sulphur oxides are also part of harmful emissions from aviation. [9]

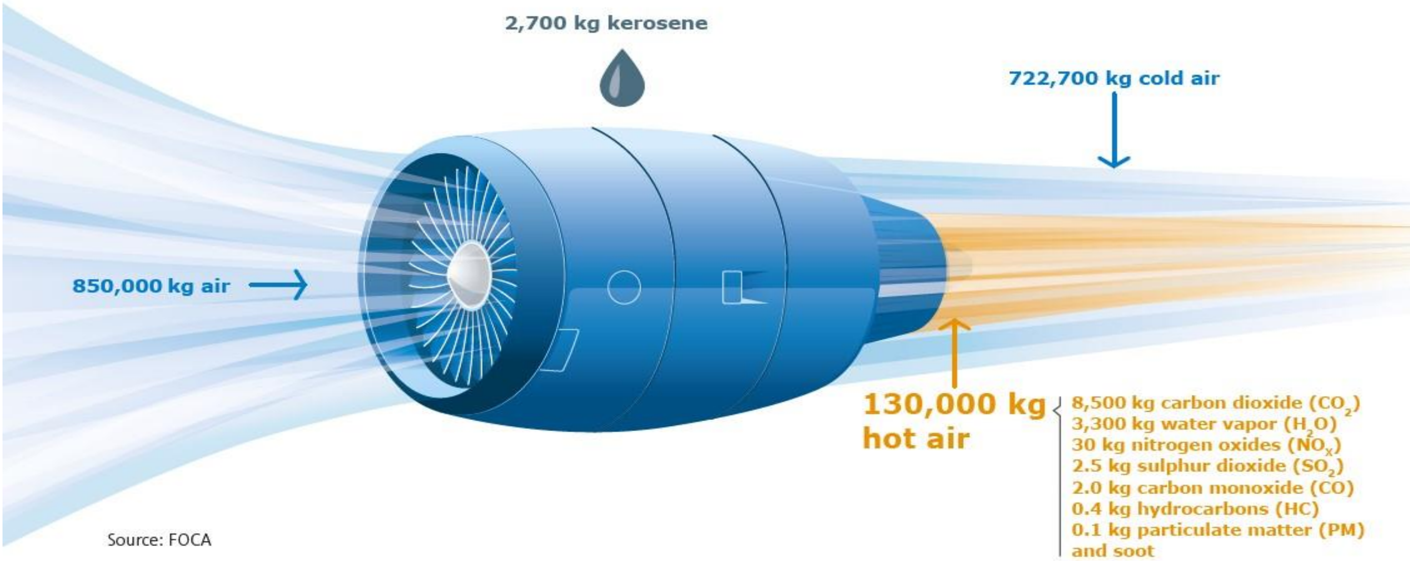

Figure 4. Emissions from 1 hour twin jet engine flight.[10] [11]

1.3 Measures taken to reduce aviation air pollution

The ICAO introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to reduce and prevent growth of pollutant emissions and to achieve its ultimate goal of carbon neutrality.

CORSIA looks at climate change as a global problem, and as such takes a global market-based measure in order to achieve carbon neutrality in civil aviation.

Measures taken include the tracking, reporting, and estimating CO_2 emissions. Realizing and acknowledging potential environmental benefits and the need for deployment of economically feasible and sustainable aviation fuels, lower carbon aviation fuels and research into hybrid, electric, and hydrogen) [12]

Aircraft operators and airports implemented and took steps to improve efficiency and reduce fuel burn, these measures were initially driven by the need to increase profits, reduce expenditures and usually not by the need to be environmentally friendly which is why there is a need for policies to be implemented.

Lower weight: since the amount of weight carried is one of the factors that affect fuel burn operators have switched to installing Lighter seats, galleys/interior, and less reserve fuel taken on board down from 5% to 3%

Use of newer aircrafts: Advances in aerodynamics, materials, airframe, and engine design make newer fleets of aircrafts are more efficient than older ones. Also retrofitting older aircrafts with newer engines aerodynamic aids such as winglets, sharklets, wingtip fences which reduce drag thus saving on fuel use.

The single European sky initiative aims to increase flight efficiency by defragmenting EU air traffic management thus more efficient routes can be flown saving fuel burn also by spending less time taxying [13]

A report by the ICCT on commercial aviation emissions which studied air transport emissions between the years 2013 and 2019 showed that despite a 50% increase in RPK’s in the period there was a 12% reduction in CO_2 emissions per RPK over the study period.[14]

Airports using electric aircraft tugs and other electric, hybrid electric vehicles for ground handling activities.

In order to reduce emissions during the boarding ie while on ground the aircraft is powered by a GPU instead of running on the APU, and in order to reduce the time spent idling the engines/APU while waiting for “pushback” (Pushback is a procedure that results in an aircraft being pushed back from the airport gate by a tractor or tug) aircraft operators are adding electric nose wheel modifications (like ”wheel tug”) to their aircrafts so that they can “pushback” on their own without the need to wait for a tractor thus reducing the time spent idling the engines.

1.4 Aviation fuels

Jet fuel Jet A1: is a type of kerosene which is a refined light petroleum.

Conventional aviation fuel, also known as Jet A1, or aviation kerosene originates and is derived from the fractional distillation of crude oil which is a fossil fuel.

During the distillation process the crude oil is heated in a column, the bottom of the column is heated, and the top of the column is cool, and since crude oil is a mixture of hydrocarbons and as it is heated it separates into separate fractions.

Fractions with lower boiling points rise higher in the column and condense on the way up, and the heavier fractions with higher boiling points condense closer to the bottom of the column.[15]

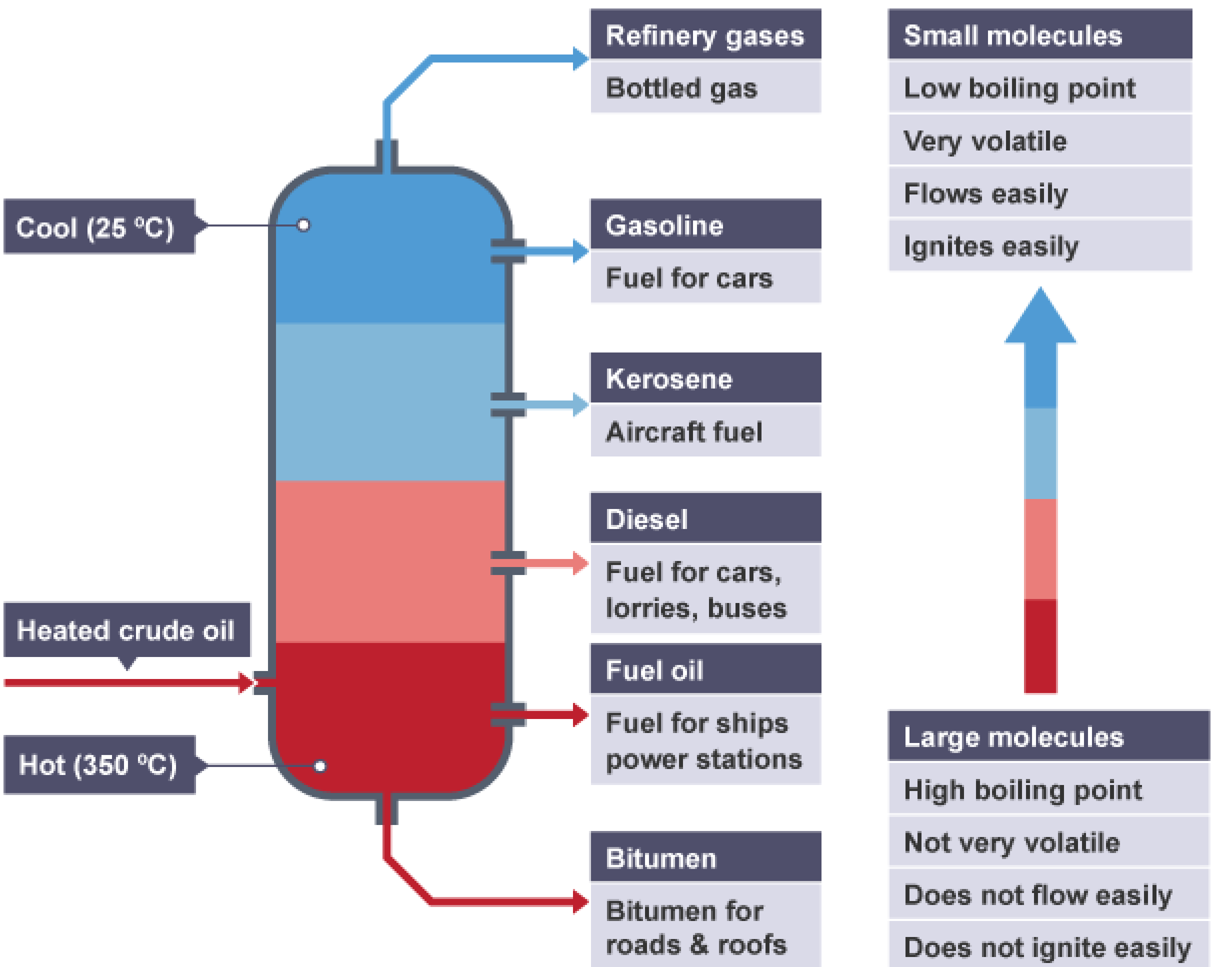

Figure 5. Fractional distillation column: fractional distillation of crude oil. [16]

The closer you get to the top of the column; the hydrocarbons are more:

Lower boiling point

Lower viscosity

Increased flammability

CHAPTER 2. BIOFUELS – AS A WAY TO REDUCE EMISSIONS

Historically, the main fuel for air transport was precisely its mineral variety, produced from crude oil. Unlike other types of transport, aviation is extremely dependent on this type of fuel due to its high specific energy. Jet fuel obtained from crude oil contains the greatest amount of energy per unit of mass and per unit of volume[17] , which promotes its use in the aviation sector, where the carrying capacity of an aircraft are extremely limited.

Nevertheless, the first attempts to find an alternative to mineral aviation fuel began a long time ago.

There are several reasons for them:

- The gains vs. expense that could me made from the technological advancements in aircraft and engine designs was minimal (because the technology is already cutting edge) compared to the gains vs. expense of developing more technologically advanced and efficient types of fuel.
- Politics: dependence of oil supplies on the geopolitical situation (an example of this is the OPEC embargo in 1973-1974).
- Fears of the imminent achievement of the "peak of oil", which could sharply increase the price of fuel.

Taken together, these reasons have become a powerful incentive for further research.

Work in this direction was carried out in the USA and some European countries.

The end of the second energy crisis in the early 1980's led to a decrease and stabilization of oil prices, as a result of which the interest of governments in the search for alternative fuels began to fade.

The aviation industry is now facing a new problem, a fundamentally new environmental problem associated with air pollution, the release of GHG's (1kg of jet fuel releases 3.2kg CO_2 when burned) carbon dioxide is a major GHG and aviation accounts for about 2.5% of global emissions of CO_2, and with a forecasted growth of the aviation industry means further pollution of the atmosphere with GHG. [17]

A renewed revival in the interest and search for alternatives was the result of the Paris Agreement that the United Nations Framework Convention concluded in 2015 between 197 countries.

The successful commercialization of biodiesel in road transportation served as a blueprint for the starting point for the search for alternative fuels.

The emerging interest in biomass fuels that do not require changes to the existing infrastructure and can act as a complement to traditional jet fuel, ushered in a qualitatively new era of research in the field of alternative fuels.

2.1 Generations and classification of biofuels

Biofuels: they are energy sources derived from plant and animal biomass, and this encompasses a fairly wide range of possible raw materials (feedstock) and technologies for the production of this type of fuel.

There are four generations of biofuels. [18], [19]

2.1.1 First generation

First generation biofuels are produced from food crops such as corn (maize), sugarcane, barley, wheat. The raw material is the starch, sugars or oils contained in the crops. Fermentation, transesterification, and esterification are the processing technologies used [20]

The disadvantage of the first generation is the competition with food to produce fuel resulting in higher food prices use of arable land to produce crops for fuel.

Advantage: reduced CO_2 emissions

2.1.2 Second generation

Are produced from non-food biomass. The raw material is the lignocellulose in the biomass. Crops such as Jatropha, Camelina, Straw (cereal waste), corn stalks and forest residue are used in the production of second-generation fuels.

The main disadvantage is complex processing technology (physical, chemical, biological, fermentation and thermochemical treatment)

2.1.3 Third generation

“Third generation biofuels” refers to biofuels obtained by processing algae. Algae represent a large group of photosynthetic organisms that live, depending on the species, in fresh, brackish, or salt water.

One of the main advantages of algae as a raw material for fuel production is a wide range of possible end products of their processing. For example, it is possible to produce biodiesel, butanol, methanol, ethanol from this type of raw material, depending on the genetic modifications of a particular type of algae. [21]

2.1.4 Fourth generation

Is an offshoot of the third generation, it focuses on search for high yielding algae species through cultivation and genetic modification, to increase their carbon entrapment and lipid yields.

2.2 Sustainable aviation fuels

According to ICAO, SAF are fuels that can be used as a drop-in alternative to fossil fuels without need for infrastructural changes nor changes to the aircraft design and structure while at the same time also reducing the carbon footprint of the fuel. [22]

Operators and airlines can use SAF that meet the ASTM D7566, DefStan 91-91 technical certification criteria.

Key requirements of sustainable aviation fuels are

- They must comply with technical and certification requirements
- They need to be approved
- Lower the level of greenhouse gas emissions during life cycle than traditional aviation fuels
- Produced from non-mineral raw materials
- Produced from renewable raw materials that do not contribute to the depletion of natural resources, climate change and do not have negative social impacts.
- Must be made from nonfood energy crops
- Are produced from biomass or recycled carbon.
- Meet stringent sustainability standards with respect to land, water, and energy use.
- Avoid Direct and Indirect Land Use Change (ILUC) impacts
- Do not displace or compete with food crops.
- Provide a positive socio-economic impact.
- Exhibit minimal impact on biodiversity and conservation values.
- Have been assessed and certified by an appropriate sustainability standard. [23], [24]

The use of SAF does not reduce the overall carbon emissions, but a SAF needs to achieve an overall net reduction in carbon emissions through its life cycle.

There are 3 key requirements needed to be met by SAF properties and they are:

1. Performance
2. Operability
3. Drop in (compatible with current hardware without need for modification or change of hardware or fueling infrastructure). [25]

2.2.1 Renewable feedstock for the production of SAF

2.2.2 Camelina

Is an annual herb, predominantly industrial crop with a high seed oil content (30 - 40%) used for biofuel production. The main use of Camelina oil is the production of sustainable fuels, in addition the parts unused during processing can be used as feed for farm animals.

It is worth noting that Camelina is often planted in rotation with other crops throughout the year. Thus, this plant makes it possible to diversify agricultural production and not to exert high and constant loads on the soil and also increase the farmer's profit. [20]

2.2.3 Algae

Algae represent a large group of photosynthetic organisms that live, depending on the species, in fresh, brackish, or salt water, they have a high rate of growth, low land use, high CO_2 absorption, relatively high lipid content and the leftover after lipid extraction can be used as animal feed. They also produce more yields than energy crops, they are not a food crop and do not compete for land use. [26]

2.2.4 Residues and wastes

Wastes from different sources can be a potential reliable source of feedstock for SAF production, waste sources such as municipal waste, forest residues, sawmill residues, animal, and agricultural wastes. This will help with waste treatment and management.

2.2.5 Halophytes

Are plants that grow in brine water, they can be grown in coastal marshes. They are a non-food crops and do not compete with food crops for land and water. [20]

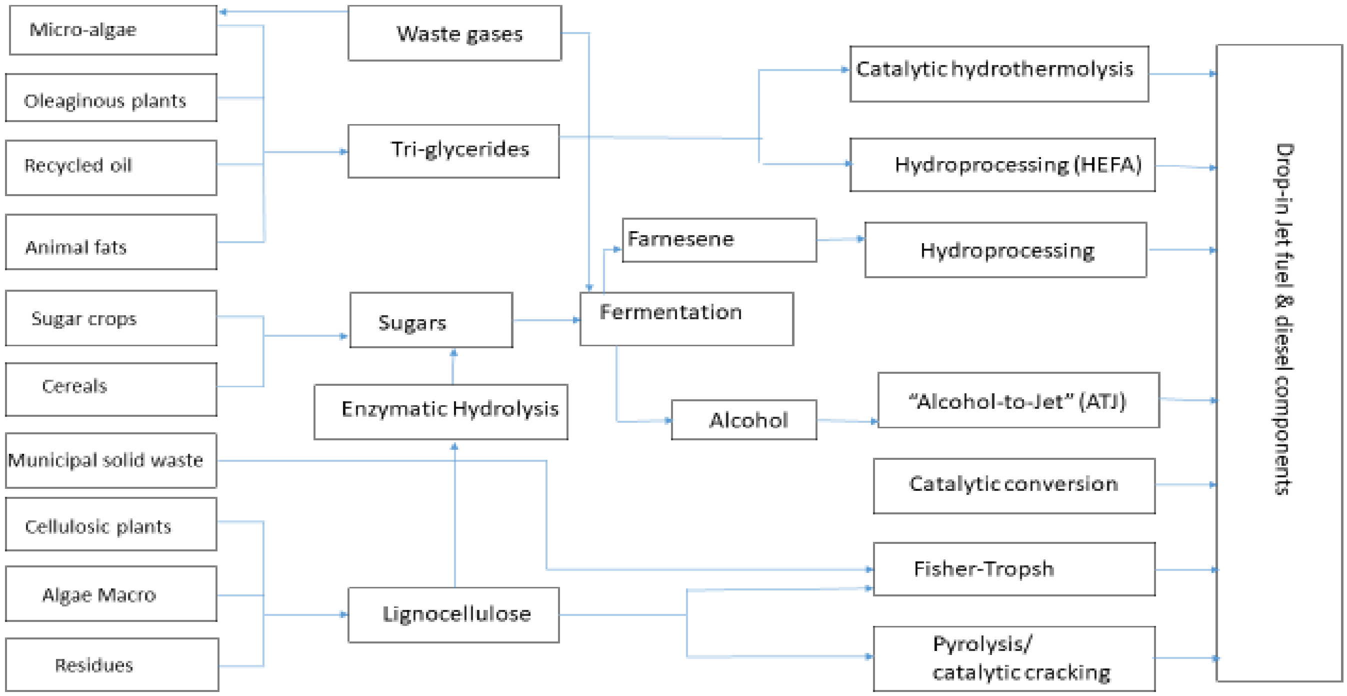

Figure 6. Pathways to sustainable fuels.[27], [28]

2.3 Biofuel production technologies

2.3.1 Alcohol to jet fuel (ATJ-fuel)

Alcohol to jet fuel (ATJ-fuel) - Is a biofuel obtained by processing alcohols such as methanol, ethanol, and butanol [21]

The alcohols required for the production of aviation fuel can be obtained in a variety of ways. The choice of raw materials can influence many factors, in particular, the specific processing methods used during production, the volume and efficiency of the process as a whole

ATJ feedstocks can be of the first-generation type (Sugar and starch plants) or of the second-generation type (lignocellulosic biomass of plants)

The first process towards the production of ATJ-fuel is the fermentation process to obtain alcohol.

Fermentation – Enzymes split organic substances mainly carbohydrates and biochemical reactions carried out by microorganisms on the carbohydrates (glucose) is converted into molecules of ethanol, butanol, and carbon dioxide. The ethanol produced can be further processed in a different pathway (Hydroprocessing)

Hydroprocessing: The ethanol obtained from fermentation is processed further by dehydration, oligomerization and hydrotreating. [29], [30]

Dehydration: is a chemical process which involves the elimination of water from molecules of a compound, this is carried out thermally in the presence of catalysts or substances that bind water. The result of dehydrating alcohol (Ethanol or Butanol) is an ethylene alkene(olefin) is formed which is already oligomerized.

Oligomerization is a chemical process of formation of oligomers, molecules in the form of a chain of a small number of identical constituent units. The mixture of oligomerized olefins is further hydrotreated.

Hydrotreating is a chemical process carried out to obtain gasolines, diesel, and jet fuels. The main purpose of hydrotreating is the removal of sulfur and nitrogen compounds and the destruction of organometallic compounds.

2.3.2 Synthetic isoparaffin (SIP)

Is also obtained from sugars as a result of fermentation, the resultant product is farnesenes, further processing of which produces SIP fuel. SIP fuel belongs to the first-generation biofuels due to the raw materials used in its production.

2.3.3 Fisher-Tropsch process (FT -fuel)

Fischer-Tropsch synthesis is a conversion technology capable of converting carbonaceous material into a petroleum product, which can then be processed into transportation fuel and petrochemicals [31]

The creation of FT-fuel includes three sequential stages: conversion of the used biomass into synthesis gas or syngas (a mixture of CO, H_2 and CO_2)

Through gasification at elevated temperatures, conversion of synthesis gas to oil using the actual Fischer-Tropsch process, the oil is then further refined using hydrotreating.

Gasification: is the thermochemical oxidation of carbon containing raw materials resulting in a mixture of gasses including hydrogen, CO, and other compounds.

The Fischer-Tropsch process is the catalytic hydrogenation of carbon monoxide with the formation of a mixture of hydrocarbons. This produces synthetic hydrocarbons suitable for further use as synthetic fuel.

2.3.4 Hydroprocessed Esters and Fatty Acids (HEFA - fuel)

HEFA-fuel (Hydroprocessed Esters and Fatty Acids) - biofuel obtained by hydrotreating vegetable fats and oils [32]

Extracted from various types of raw materials (rapeseed, soybeans, camelina, jatropha, algae), the oil is hydrotreated, during which the oil is decomposed. Then unwanted chemical compounds are removed from it, such as sulfur, nitrogen, some others, saturation of double carbon bonds and removal of water.

2.4 Aviation fuel requirements

The feedstock for the production of aviation jet fuel is crude oil. As a result of a wide range of refining processes, jet fuel is a complex mixture of various hydrocarbons. Jet A-1 is a kerosine grade of fuel suitable for most turbine engine aircraft. It has a flash point minimum of 38°C and a freeze point maximum of -47°C. The main specifications for Jet A-1 grade are listed in ASTM specification D1655 (Jet A-1), DEF STAN 91-91 (Jet A-1) Nato code F-35. These standards include comprehensive descriptions of various qualitative and quantitative characteristics of aviation fuel, as well as methods for their determination.

Some of the major characteristics to that are relevant when considering the introduction of biofuels are listed below.

Table 2. Characteristics and performance Properties of Jet fuel.[33]

Calorific value	42.8MJ/kg
Viscosity	8.0mm
Crystallization (Temperature)	-47°C
Flash point	38°C
Thermal oxidative stability	25mm Hg @ 260°C
Ash content	18mm
Corrosiveness	24mg/l

Table 3. Desirable characteristics of aviation fuel. [25], [34], [35]

Desirable characteristics		Why it's needed
1.	High energy content	Turbine engine depends on chemical energy stored in the fuel. The maximum range of a flight depends to some extent on the amount of energy contained in the fuel.
2.	Good combustion characteristics	During combustion certain classes of hydrocarbons present in jet fuel are capable of forming fine carbonaceous particles during combustion. These particles have several negative effects on engine performance.
3.	High storage and thermal stability	Important that the fuel remains stable and does not pre-ignite under different temperatures and pressures.
4.	Good lubricity	It should lubricate and reduce amount of friction between surfaces in the fuel pumps
5.	Good fluidity	It should be fluid under different atmospheric and temperature conditions to be able to move from fuel tanks through the fuel system to the engine.
6.	Viscosity	Affects fuel droplet size and affects the pressure drops across the fuel system all of which affect the performance of the engine
7.	Freezing point	Fuel should remain fluid and pumpable till 4°C to 15°C below its freezing point.
8.	Volatility	Needs to be vaporized first before combustion, however this results in evaporative losses if the fuel is too volatile.
9.	Non-Corrosivity	Should not corrode contact surfaces during transportation, storage, and use.
10.	Cleanliness	Free from solid particulates, water and microbial growth which can damage fuel system parts.

2.5 Fuel Certification

ASTM D7566 is a certification standard that lays down the standards required for aviation turbine fuel containing synthesized hydrocarbons[25]. There are currently six production processes for the production of synthesized hydrocarbons that are certified by the American Society for Testing and Materials (ATSM) at the moment.

Table 4. ASTM D7566- approved SAF's certification standard and feedstock.[36]

Annex	Fuel type	Abbreviation	Year of certification	Feedstock
A1	Fisher – Tropsch Syntetic Paraffinic Kerosine	(FT-SPK)	2009	MSW, Forest wastes, Energy crops, grass
A2	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene	(HEFA-SPK)	2011	Fatty acids, plant & animal lipids(oils), algae, jatropha, camelina
A3	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	(HFS-SIP)	2014	Sugars (bacterial conversion of sugars into hydrocarbon)
A4	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	(FT-SPK/A)	2015	MSW, Forest wastes, Energy crops, cellulosic biomass, agricultural waste (grass, straw, corn shoots)
A5	Alcohol to Jet Synthetic Paraffinic Kerosene	(ATJ-SPK)	2016	starches/sugars
A6	Catalytic Hydrothermolysis Synthesized Kerosene	(CH-SK, or CHJ)	2020	fatty acids, fatty acid esters, plant, and animal lipids

2.5.1 Fuel blending/ Blended fuels

Aromatics, n-Alkanes, iso-Alkanes, and cycloalkanes are the 4 chemical families which make up the molecules of typical fuels.

Fuels are made up of blends of molecules including inorganics and metals. The blending of these molecules must comply with the requirements put forth by the ASTM. The finished blended fuel needs to meet the ASTM fuel specifications. Blending is carried out in order for the fuel to have the same characteristics and meet the same specification as fossil jet fuel.

Aromatics: Is believed to be responsible for majority (about 90%) of particulate emissions due to their lower heats of combustion which results in their not being able to cleanly burn. They are also known to improve seal swell characteristics of nitrile rubber.

n-Alkanes and iso-Alkanes usually have:

- Higher thermal stability than the other 2 remaining molecular families.
- Lower density
- Usually, higher specific energy

Cycloalkanes (strained molecules, monocyclic and fused bicyclic) can have positive attributes towards:

- Density,
- freeze point
- flash point
- and specific energy of the fuel.

Table 5. SAF qualified for use in aviation with blended percentage in mixture.[23], [37]

Type of fuel	Certification year	SAF blended percentage
FT-SPK	2009	50%
FT-SPK/A	2015	50%
HEFA	2011	50%
HFS-SIP	2014	10%
ATJ-SPK	2016	30 to 50%
Co-processing	2018	5%
Catalytic Hydrothermolysis Synthetic Kerosine (CH-SK)	2020	50%

(ASTM D1655-20b allows coprocessing of up to 5% mono-, di-, and triglycerides, free fatty acids, and fatty acid esters or up to 5% of FT hydrocarbons. Hydrocracking/hydrotreating and fractionation are required. No other coprocessing in refineries is allowed for jet fuel.)

Table 6. ASTM D7566 standard Physiochemical properties [23], [37]

	Property	Unit	ASTM Requirement
1	Density at 15 ºC	Kg/m3	775 to 840
2	Viscosity at -20 ºC	mm^2/s	Max 8.0
3	Calorific value	MJ/kg	Min 42.8
4	Aroma content	%	Min 8, man 25
5	Napthalene content	%	Max 3.0
6	Flash point	ºC	Min 38
7	Crystallization temp	ºC	Max -47
8	Lubricity	mm	Max 0.85
9	10% distillation temp	ºC	Max 205
10	End distillation temp	ºC	Max 300
11	Loss	%	Max 1.5
12	Residue	%	Max 1.5
13	Viscosity at -40 ºC	mm^2/s	Max 12

Table 7. Physiochemical properties of some SAF pathways. In the table note that the fuels have the same energy content as traditional aviation kerosine, this means that the duration and range of flight of the aircraft is not adversely affected. [23], [37]

Characteristic	Value		
	FT and HEFA	SIP	ATJ
Calorific value, MJ / kg	42.8		
Minimum flash point, °C	38	100	38
Density range at 15 °C, kg / m^3	730-770	765-780	755-800
Maximum freezing temperature, °C	-40	-60	- 40
Thermal oxidative stability, mm Hg at 325 °C	25		

Maximum viscosity at -40 °C, mm^2	12.0
Minimum aromatic content	8.4
Lubricity mm	0.85

CHAPTER 3. METHODOLOGY

In the previous chapters we have looked at the biofuels intended for use, the raw materials(feedstock), the production process, the required physiochemical properties, and characteristics of the resulting fuel mixtures, and the certification process was described in general.

In this chapter we shall be looking at the environmental and economic impacts of SAF using Life Cycle Assessment (LCA) approach.

We shall focus on and analyze the lifetime GHG emissions of SAF using data from six LCA studies conducted by various researchers and then using descriptive statistics to compare the results from the studies against the baseline GHG emissions of conventional jet fuel.

Statistical analysis is used to analyze lifecycle GHG emissions data collected from the studies and used to find a correlation between lifetime GHG emissions of three different SAF production technologies namely, FT, HEFA, ATJ and feedstock used. This is done by calculating the Mean value (m) of the collected data on the GHG lifecycle emissions on each of the three chosen production technologies, then the resulting data is compared with conventional aviation fuels lifecycle GHG emissions to draw conclusion on whether SAF are more beneficial i.e., generate lower emissions when compared to conventional jet fuel.

GHG emissions analyzed include CO_2, CH_4 and NO_2 using 100-year global warming potential and it is measured in g/CO_2eq/MJ. This study is conducted using a quantitative/mixed method approach.

The studies used were chosen based on their relevance to LCA of SAF.

I chose the literature review approach rather than conducting my own LCA study for its simplicity and convenience, as there were already multiple LCA studies on SAF’s already performed.

3.1 Environmental assessment

In order to provide a complete understanding of the environmental impacts and consequences of using a product in this case such as biofuels/aviation biofuel/ sustainable aviation fuels, an analysis of the products entire life cycle should be performed this approach is called Life Cycle Assessment (LCA).

LCA is the collection of information, assessment and comparison of input flows, output flows and as well as the possible impacts on the environment through the entire life cycle of the product[38], [39]. It is the analysis of a product throughout its existence from production to transportation to packaging use and waste management.

It is a standardized methodology, and the standards are provided and set forth by the International Organization for Standardization in ISO 1440 and 14044.

The table below shows result of study caried out by Brooks et al. and shows the life cycle emissions for several generations of alternative fuels, different feedstocks, and different types of alternative fuels.

Table 8. Life cycle emissions for different types of alternative fuels.[40]

Generation	Raw materials	Fuel	Life Cycle Assessment, g CO_2 eq / MJ
First	Sugarcane	ATJ	48.1
	Corn		113.8
Second	Cereals	ATJ	40.3
		FT	from -2 to 17.7
	Waste corn and logging wastes	FT	from 9 to 13.6
	Soya	HEFA	From 29.9 to 50.8 (in the case of deforestation from 90.4 to 600.4)
	Camelina		20 to 46
	Jatropha		33 to 40 (up to 141 in case of deforestation)
Third	Seaweed	HEFA	14.1 to 193.2

Table 9. Greenhouse gas emissions savings of SAF, excluding carbon emissions from land use change. The study shows several conversion technologies, feedstocks and the percentage emission savings compared to conventional aviation fuel emissions. It shows that all conversion technologies studied have greater emissions savings when compared to conventional aviation fuel emissions. [11]

Conversion technology	Fuel feedstock	% Direct emissions savings compared to fossil-based aviation baseline of 89 gCO_2eq/MJ
Fisher-Tropsch (FT)	Agricultural residues Forestry residues Municipal solid waste (MSW) Short rotation woody crops Herbaceous energy crops	89-94% 88% 68% 81% 87%
Hydroprocessed esters and fatty acids (HEFA)	Tallow Used cooking oil Palm fatty acid distillate Soybean Rapeseed/Canola Camelina	78% 85% 76% 53% 48% 54%
Synthesized iso-paraffins (SIP)	Sugarcane Sugarbeet	62% 68%
Alcohol(iso-butanol) to jet (ATJ)	Agricultural residues Forest residues Sugarcane Corn grain Herbaceous energy crops	71% 74% 69% 54% 66%
Alcohol(ethanol) to jet (ATJ)	Sugarcane Corn grain	69% 26%

Table 10. Shows some LCA studies performed over the years and their results.

LCA Study	Results	Title
FT jet fuel from natural gas, coal, and biomass; bio-jet fuels from fast pyrolysis of biomass; and hydroprocessed renewable jet fuel from vegetable and algal oil	Well to wake analysis showed life cycle GHG emissions reduction by 55-85%	Life-cycle analysis of alternative aviation fuels in GREET.[41]
Tropsch (F-T) fuels and Hydroprocessed Renewable Jet (HRJ) fuel	10-50% reductions in emissions that contribute to climate change	Life cycle greenhouse gas emissions from alternative jet fuels.[42]
FT pathways, Hydrothermal liquefaction, Pyrolysis, HEFA and ATJ	FT pathway showed GHG emission savings (86–104) Hydrothermal Liquefaction (77–80%), Pyrolysis (54–75%), UCO-based HEFA (68%), sugarcane- (71–75%) and corn stover-based ATJ (60–75%)	Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production.[43]
Gasification-FT of lignocellulosic byproducts wastes and residues	Have low well to wake emissions. GHG savings, ranging from 58% to 140%	ICCT WORKING PAPER 2021. ASSESSING THE SUSTAINABILITY IMPLICATIONS OF ALTERNATIVE AVIATION FUELS. [36]

Fischer-Tropsch (FT) fuels and Hydroprocessed Renewable Jet (HRJ) fuel	could provide aviation with modest (~10%) to large (~50%) reductions in emissions that contribute to global climate change.	COMPARISON OF LIFE CYCLE GHG EMISSIONS FROM SELECT ALTERNATIVE JET FUELS.[44]
LCIA human health impacts	biomass conversion into aviation biofuel is a major contributor to all impact categories; namely HCT (by 28–52%), HNCT (by 19–45%), FPM (by 27–45%), PS (by 12–48%), and HH (by 25–57%),	Human Health Impacts of Aviation Biofuel Production: Exploring the Application of Different Life Cycle Impact Assessment (LCIA) Methods for Biofuel Supply Chains.[45]
Determine the comparative GHG impacts of bioenergy,	GHG emissions reduction by between 18% and 128% compared to their fossil counterpart reference systems.	Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy.[46]

3.2 Economic assessment

Jet fuel accounts for about 40% of an airlines operating cost[7] therefore for wide adoption of SAF their production costs should be comparable or preferably lower than that of conventional aviation fuel.

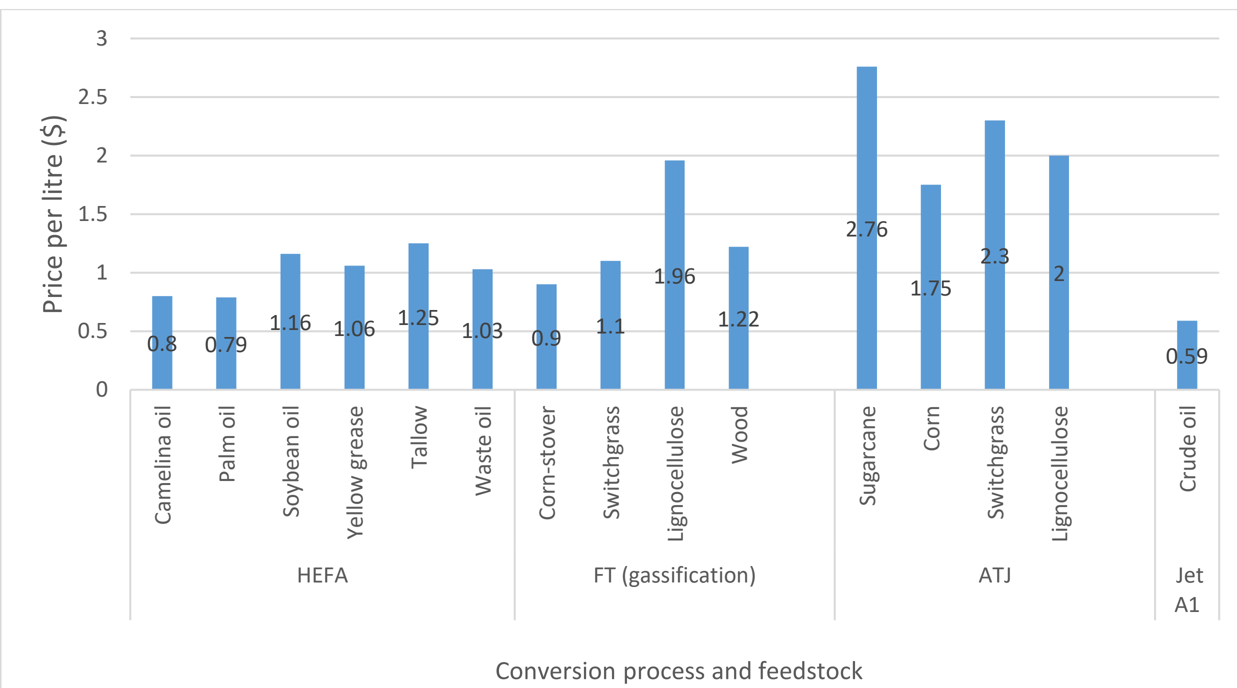

Figure 7. Shows the relative price of production of SAF using different conversion processes, and the table shows that they cost relatively more to produce than conventional aviation fuel.[6]

Table 11. Shows the studies used for data analysis in this study.

Title	Author	Study number	
CORSIA Eligible Fuels - Life Cycle Assessment Methodology.	ICAO	S1	[47]
Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production.	Jong et al.	S2	[43]
Review of Jet Fuel Life Cycle Assessment Methods and Sustainability Metrics.	Unnasch et al.	S3	[48]
Life cycle analysis of alternative aviation fuels in GREET.	Elgowainy. A et al.	S4	[49]
Life cycle greenhouse gas emissions from alternative jet fuels.	Stratton W. Russel et al.	S5	[42]
Comparison of life cycle GHG emissions from select alternative jet fuels.	ICAO	S6	[44]

The GHG life cycle emissions data of FT fuels, HEFA fuels and ATJ fuels using different types of feedstocks which was selected from the studies.

CHAPTER 4. RESULTS

The data represented in the figure below, was compiled using data for FT fuels from the studies and it shows the importance of the choice of feedstock used in production of the fuel.

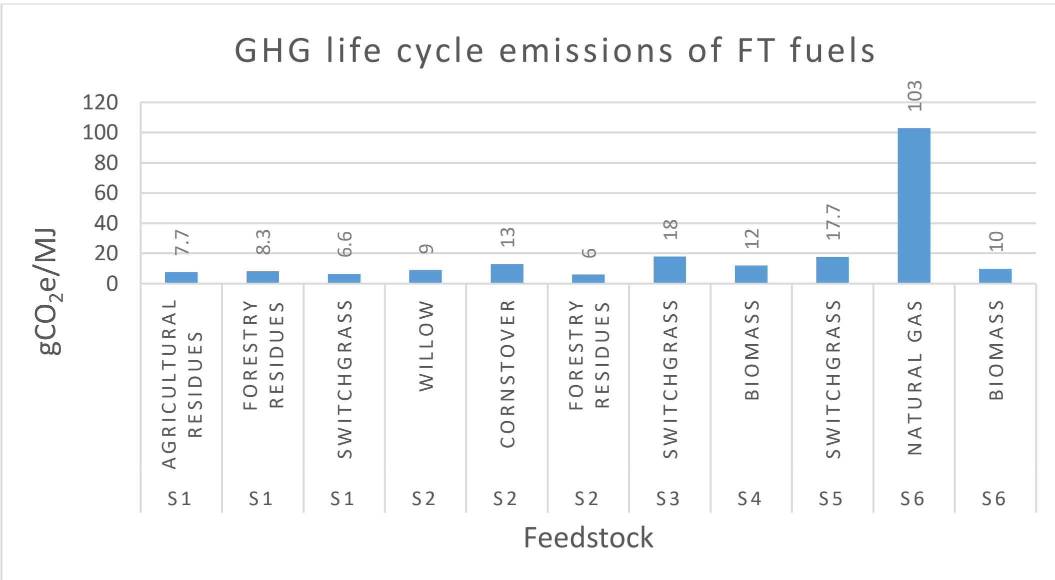

Figure 8. GHG life cycle emissions of FT fuels. Illustrates the important role that type of feedstock used in production plays in overall GHG lifecycle emissions of a fuel, in the case of FT conversion process using natural gas as a feedstock to produce fuel results in a fuel that has a greater GHG lifecycle emission than conventional jet fuel made using crude oil.

GHG lifecycle emissions of HEFA fuels produced using different feedstocks is then compared using data collected from the studies.

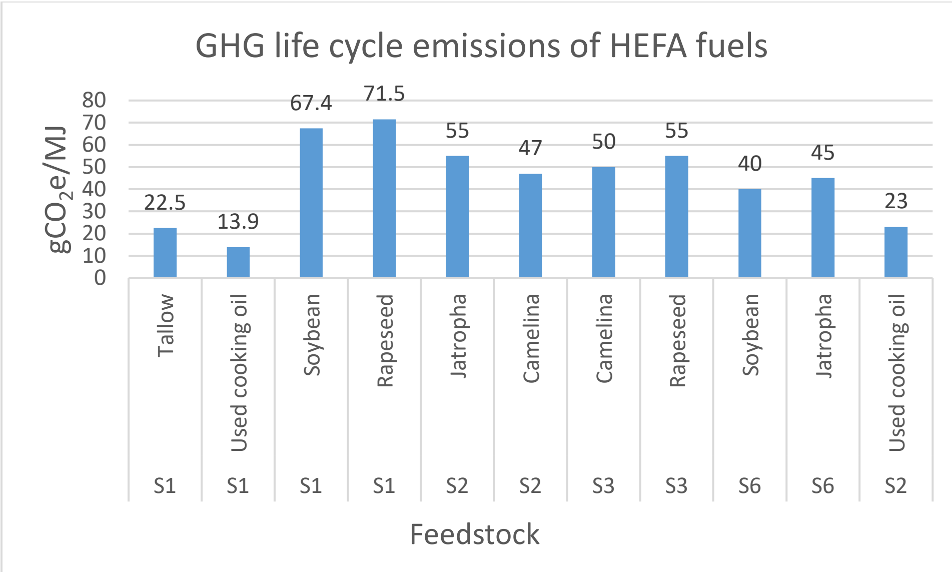

Figure 9. GHG life cycle emissions of HEFA fuels. It shows that used cooking oils and animal fats have lower overall GHG life cycle emissions when compared to cultivated feedstocks.

GHG life cycle emissions of ATJ fuels using different feedstocks are also compiled using data from the studies selected.

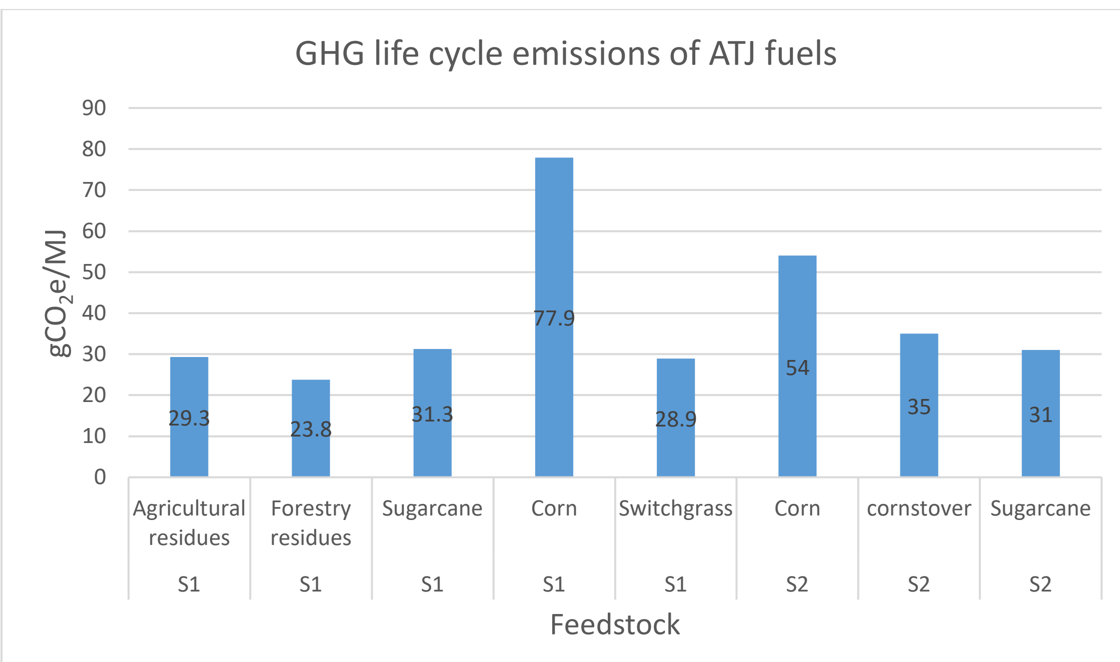

Figure 10. GHG life cycle emissions of ATJ fuels. It shows that forest and agricultural residues have lower GHG lifecycle emissions compared to corn which is cultivated for use as fuel feedstock.

To evaluate and compare the data collected, statistical Mean of each production technologies GHG lifecycle emission value is calculated and then compared with the GHG life cycle emission of conventional jet fuel. Results show that FT fuels have 87% lower GHG life cycle emissions, HEFA fuels have 47% lower GHG lifecycle emissions and ATJ fuels have 53% lower GHG lifecycle emissions when compared to GHG lifecycle emissions of conventional aviation fuels.

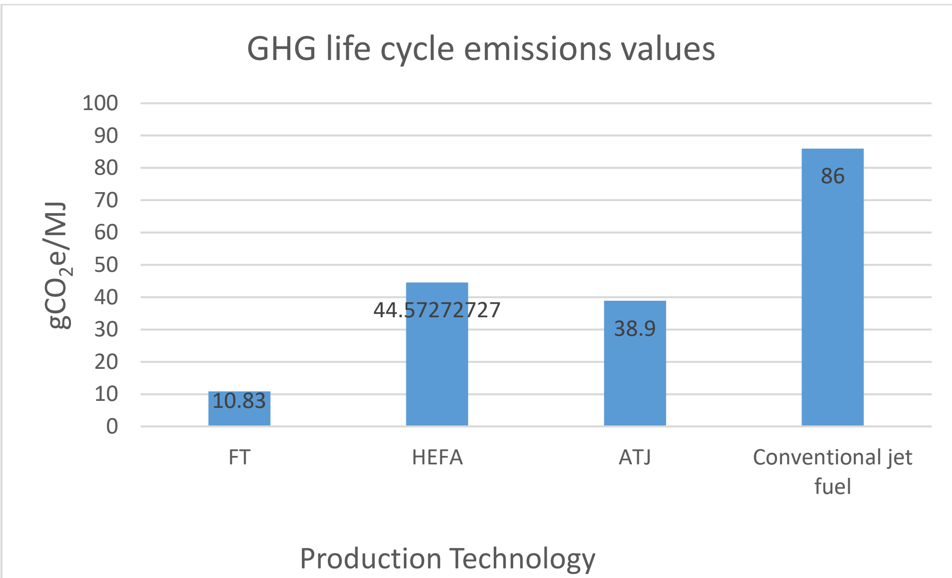

Figure 11. GHG life cycle emissions, using Mean value for FT, HEFA, ATJ vs baseline jet A1 conventional fuel. It shows that all the three evaluated alternative fuel technologies have lower overall GHG lifecycle emissions than GHG lifecycle emissions of conventional aviation fuel.

Discussion

The result of this study shows that SAF can reduce emissions to air from aviation. It shows that FT fuels produce about 86% less overall lifecycle GHG emissions, HEFA fuels produce 47% less overall lifecycle GHG emissions and ATJ fuels have 53% less overall lifecycle GHG emissions when compared to overall life cycle GHG emissions of conventional aviation fuels which falls in line with the results of EASA 2019 study [11]

Economic assessment is very valuable since Jet fuel accounts for about 40% of an airlines operating cost[7] and the study shows that SAF cost more per liter when compared to conventional aviation fuels, therefore, to boost wide adoption and use the production price of SAF has to be comparable to or lower than that of conventional aviation jet fuel.

CONCLUSION

Using the LCA approach to analyze the life cycle emissions of several SAF using different production technologies and feedstocks. This study has not only shown that SAF are better for emission reduction in aviation, but it has also shown that FT fuels produce about 86% less overall lifecycle GHG emissions, HEFA fuels produce 47% less overall lifecycle GHG emissions and ATJ fuels have 53% less overall lifecycle GHG emissions when compared to overall life cycle GHG emissions of conventional aviation fuels shown in Figure 11.

This is very beneficial as they are "drop in" substitutes for conventional aviation fuels and does not require costly modifications or changes to current aircraft, engines or fueling systems.

The cost of production of SAF is an important factor and a major hindrance affecting the rate of adoption shown in Figure 7.

It is of my opinion that the current state of technology is more than adequate, also that the technical know-how is already there and an important factor that's needed to bring down the production price of SAF's is the economics of scale.

SAF's production needs to be scaled up greatly for the production price to be comparable to, or even cheaper than conventional aviation fuels.

There is need for government incentives, investment, and support to bridge the gap between today's supply base and future supply base economically for both SAF provider and airline operators.

Future research is needed into creating better, higher capacity and lighter energy storage systems i.e.., Battery storage, as current day battery technology is too bulky, heavy, expensive, and not efficient enough to be implemented in aviation thus fully electric commercial aviation is not possible now.

With cheaper and cleaner renewable energy sources, clean hydrogen can be produced using electrolysis which emits no CO_2, but further research is needed in engine design and development to create units that can burn hydrogen and into the production of synthetic fuels created from extracting CO_2 from the atmosphere and combining it with the hydrogen.[50]

SUMMARY

In the first chapter we looked at the importance of commercial aviation in everyday life, it showed that aviation is a highly sought-after form of transportation, this is shown by the growth in passenger and cargo traffic data in Table 1, also by its forecasted increase in volume over the coming years. With this growth comes greater emissions of GHG which if left uncontrolled is forecasted to reach 2700Mt by year 2050 shown in Figure 1.
We also looked at the measures taken by aircraft designers, operators, and regulatory bodies to reduce emissions to air from commercial aviation.

In the second chapter we looked at further ways of reducing the emissions from commercial aircraft by implementing the use of biofuels. We looked at the classification of biofuels, feedstocks, and several production technologies used in the production of SAF. In this chapter we also looked at the requirements of aviation fuel and the fuel certification process. We also investigated several types of SAF using different feedstocks, these SAFs have passed the ASTM 7566 certification and can be used as drop-in alternatives in the form of blended fuels.

In the third chapter, we used results of six LCA studies to conduct environmental and economic assessment of SAF, then compared the results to that of conventional aviation fuel and found that SAF lifecycle GHG emissions are far lower than that of conventional aviation fuel shown in figure. 8,9,10. We also showed that the cost of production of SAF is an important factor and a major hindrance affecting the rate of adoption shown in Figure 7.

The results section of this study shows that FT fuels produce about 86% less overall lifecycle GHG emissions, HEFA fuels produce 47% less overall lifecycle GHG emissions and ATJ fuels have 53% less overall lifecycle GHG emissions when compared to overall life cycle GHG emissions of conventional aviation fuels shown in Figure 11.

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