Assessment of Energy and Environmental Impacts of Decarbonization Scenarios in Aviation

Samir Nahuel Narvaez Maloof

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Supervisors: Prof. Patrícia de Carvalho Baptista
Dr. Rui Pedro da Costa Neto

Examination Committee

Chairperson: Prof. Luís Filipe Moreira Mendes

Supervisor: Prof. Patrícia de Carvalho Baptista

Member of the Committee: Dr. Ana Filipa da Silva Ferreira

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

Abstract

This thesis assesses the potential of decarbonising the aviation sector via the use of Sustainable Aviation Fuels (SAF), hydrogen propulsion, and direct electrification in major European airports. The case study builds an emissions inventory following European emissions reporting methods and a later, following an LCA approach, emissions analysis in which GHG emissions avoidance is compared to the baseline considering the assumptions and limitations. The analysis of different decarbonization pathways using electrification, hydrogen, and SAFs as main decarbonization drivers revealed that SAF are currently the best solution for reducing emissions from long-haul flights, with an average emission avoidance of 65%, reducing the average emission intensity from 89 g CO_2e/Pk to 31 g CO_2e/Pk. However, for regional and short-medium haul flights, hydrogen and electrification show higher emissions avoidance, up to 98% of emission avoidance with average emission intensities of 4 g CO_2e/Pk but may take longer to deploy. The study also found that the emission factors of different production methods could compromise the sustainability of both SAFs and hydrogen. Electrification's emissions are highly connected to how electricity is produced, with renewable energy yielding the highest GHG emission avoidance. These findings provide a robust foundation for future research in this area.

Keywords

Decarbonization, Sustainability, Aviation, SAF, Hydrogen, Electrification

Resumo

Esta tese avalia o potencial de descarbonização do sector da aviação através da utilização de combustíveis sustentáveis para a aviação (SAF), da propulsão a hidrogénio e da eletrificação direta nos principais aeroportos europeus. O estudo de caso constrói um inventário de emissões de acordo com os métodos europeus de comunicação de emissões e, posteriormente, seguindo uma abordagem LCA, uma análise de emissões em que a prevenção das emissões de GEE é comparada com a linha de base, tendo em conta os pressupostos e as limitações. A análise de diferentes vias de descarbonização utilizando a eletrificação, o hidrogénio e os SAFs como principais motores de descarbonização revelou que os SAF são atualmente a melhor solução para reduzir as emissões dos voos de longo curso, com uma prevenção média de emissões de 65%, reduzindo a intensidade média de emissões de 89 g CO_2e/Pk para 31 g CO_2e/Pk. No entanto, para os voos regionais e de curto e médio curso, o hidrogénio e a eletrificação mostram uma maior prevenção de emissões, até 98% de prevenção de emissões com intensidades médias de emissão de 4 g de CO_2e/Pk, mas podem levar mais tempo a implantar. O estudo concluiu também que os factores de emissão dos diferentes métodos de produção podem comprometer a sustentabilidade tanto dos SAF como do hidrogénio. As emissões da eletrificação estão altamente ligadas à forma como a eletricidade é produzida, com as energias renováveis a produzirem a maior prevenção de emissões de GEE.

Palavras-chave

Descarbonização, Sustentabilidade, Aviação, SAF, Hidrogénio, Eletrificação

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ATAG	Air Transport Action Group
ATJ	Alcohol-to-Jet
CAF	Conventional aviation fuels
CCD	Cruise, Climb, and Descent
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CORSIA	Carbon offsetting and reduction scheme for international aviation
CH_4	Methane
EEA	European Environment Agency
EU	European Union
ETS	Emissions trading scheme
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
GDP	Gross domestic product
GHG	Greenhouse gas
HEFA	Hydro processed Esters and Fatty Acids
IATA	International Air Transport Association
ICCT	International Council on Clean Transportation
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IRA	Inflation Reduction Act
LCA	Life-cycle assessment
LHV	Lower heating value
LTO	Landing and Take-off
Mt	Million tons
MJ	Megajoule
MTOW	Maximum Take-Off Weight
OECD	Organization for Economic Cooperation and Development
SAF	Sustainable Aviation Fuels
SIP	Synthesizing iso-paraffins
Pk	Passenger-kilometre
UCO	Used Cooking Oil

Chapter 1

Introduction

This chapter provides an overview of the current situation of our aviation industry, the need for decarbonization and main objectives of the thesis. It begins by outlining the scope and motivations that motivates the work, before looking into the established state-of-the-art within the studies in decarbonization of the aviation sector. At the end of the chapter, a comprehensive structure of the dissertation is presented, providing a clear layout to the reader.

1.1 Motivation

Aviation is one of the most important economic activities in the modern world. Aviation plays a key role in the global economy accounting for $3.5 trillion, which is about 4.1% of the global GDP [1]. It has helped accelerate globalization, and the exchange of culture, goods, and services, the world would not be what it is today if it were not thanks to the aviation sector.

Aviation is also responsible for around 3% of the world's carbon dioxide (CO_2) emissions [2], and as the world economy expands in the upcoming years and more people enter the middle class, aircraft volumes will rise and so will emissions produced by this [1]. The global air transport sector emitted more than nine hundred million tonnes (Mt) of CO_2 in 2019 plus an unreported quantity of other emissions including nitrogen oxides, sulphur oxides, and carbon particulates [3].

Aviation in the last 20 years is responsible for almost half of the total cumulative emissions in the aviation sector, this is given to the rising developing economies and the appetite for having next summer vacations on the coast of Spain or Thailand or meeting an important business meeting on the other side of the world. This has happened, even though aviation has been developing substantial efficiency increases throughout the years, and the latest aircraft are more efficient than the ones from earlier years.

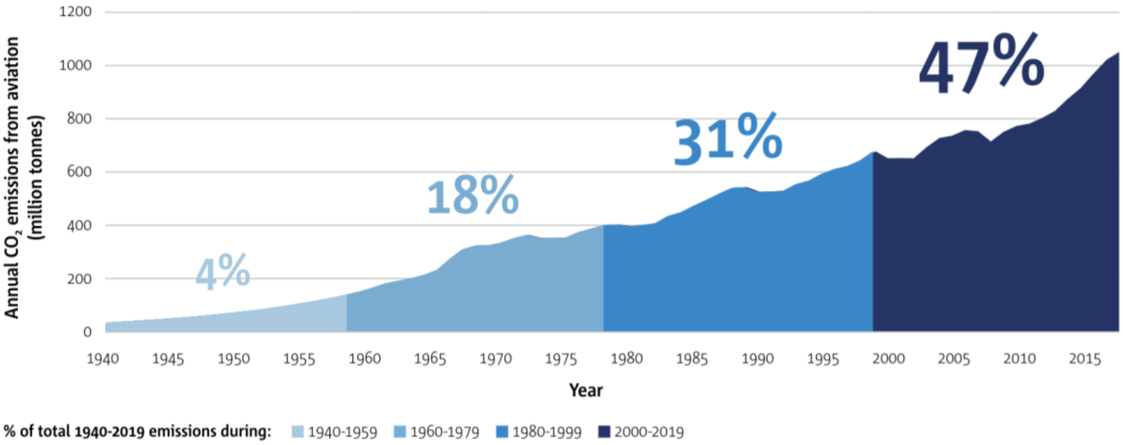


Figure 1. Annual global CO_2 emissions from aviation (1940-2019) with % of total cumulative emissions broken down into 20-year periods [4].

Flights from the European unions and free trade member states were responsible for over 150 million tons of CO_2 in 2019. In 2020 due to the worldwide pandemic, COVID-19 emissions decreased to sixty-five million tons of CO_2, Figure 1. As restrictions over the COVID-19 pandemic finalizes, air traffic is expected to increase. Figure 2 depicts three different air traffic scenarios towards 2050 according to the European Union aviation safety agency and the European Environment Agency. These three scenarios of air traffic are the low traffic scenario (represented in light blue), the base traffic scenario (represented in dark blue) and lastly the high traffic scenario (represented in red). Even more, it includes for each of the traffic scenarios an upper and lower bound. The upper bound of the range reflects fleet renewal with “frozen” technology and the lower bound reflects the “Advanced” technology.

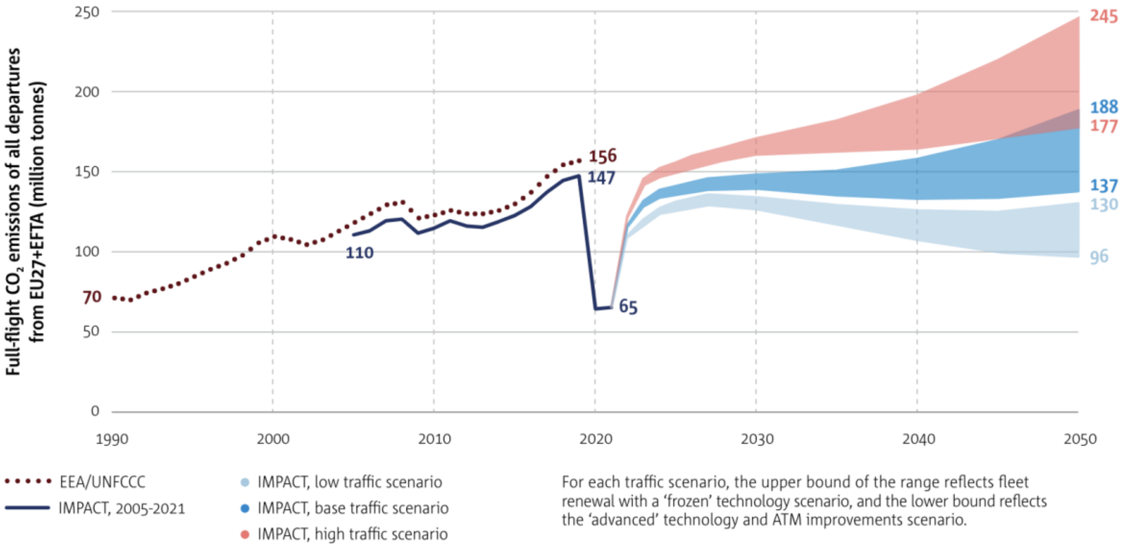


Figure 2. Full-flight CO_2 emissions may grow beyond 2019 levels under the base and high traffic forecast [4]

There are several paths to reduce CO_2 emissions by 2050. Some of this includes air traffic management as if there are less traffic, then less fuel is going to be burnt and therefore fewer CO_2 emissions into the atmosphere. Another path to lowering emissions is the substitution of jet fuel with other alternatives. Sustainable Aviation fuels, or SAFs, are drop-in fuels that can be used in a blend with jet fuel to reduce emissions. Lastly, we have the electrification of aircraft either with direct electrification with the use of batteries or with the use of hydrogen either in fuel cells or with the inclusion of hydrogen jets turbines, in which hydrogen is combusted similarly to how jet fuel nowadays.

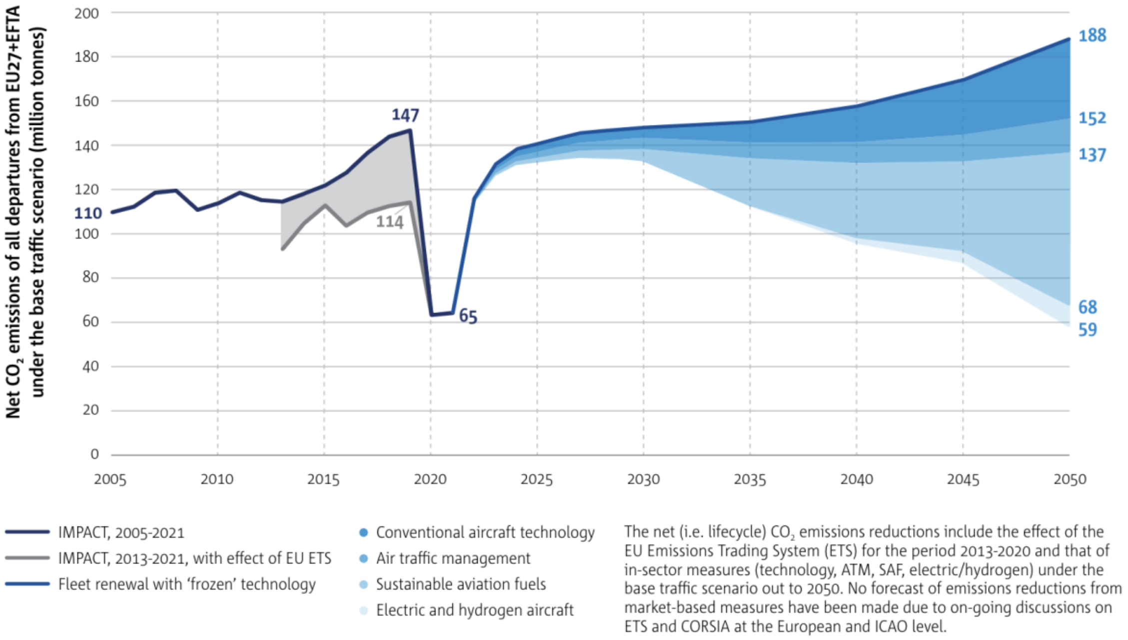


Figure 3. Net CO_2 emissions could be halved by 2050 using sustainable aviation fuels [4]

The European Union aviation safety agency and the European Environment Agency also included in their report how could emissions be further reduced, assuming the base scenario and further evaluating decarbonization options such as Sustainable aviation fuels and electric and hydrogen aircrafts. Figure 3 depicts the different scenarios according to the European environment agency. Upper bound is considered as the fleet renewal with “frozen” technology. Further reductions are considered following conventional aircraft technology, i.e., aerodynamics improvements, and air traffic management. Lastly, even further reductions are included with the inclusion of sustainable aviation fuels which halves emissions through 2050 and the inclusion of electric and hydrogen aircrafts were possible.

In the last years, countries all over the world started to announce pledges to achieve net zero emissions over the coming decades [5]. For these promises to make any sense, a hard-to-abate sector such as the aviation sector needs to be subject of policy makers pushing for the inclusion of decarbonization options into it. Next subsection will further dive into different policy which have been announced in the European union and the world, and what policy makers are further legislating into.

1.2 Regulation on decarbonisation of the aviation industry

The main effort toward pushing decarbonization of the aviation sector into the future is included in some regulatory documents such as the EU Green Deal which created the European emission trading system (EU ETS) and subsequently added aviation into it. Some of the following European efforts toward a more sustainable future include the Fit for 55 and the ReFuelEU aviation initiative. The "Fit for 55" is a package of policies proposed by the European Union to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, Figure 4. The package includes a range of measures across various sectors, including energy, transport, agriculture, and buildings.t

Figure 4. Fit for 55 proposals [6]

One of the key elements of the Fit for 55 packages is the revision of the EU Emissions Trading System (ETS), which is the EU's flagship policy to combat climate change. The revised ETS will have a more ambitious emissions reduction target and include new sectors such as shipping and aviation.

The "Refuel Aviation Initiative" is a part of the Fit for 55 package that aims to accelerate the deployment of sustainable aviation fuels (SAFs). The initiative proposes measures such as blending mandates, tax incentives, and research and development support to increase the production and use of SAFs in the aviation sector, Figure 5.

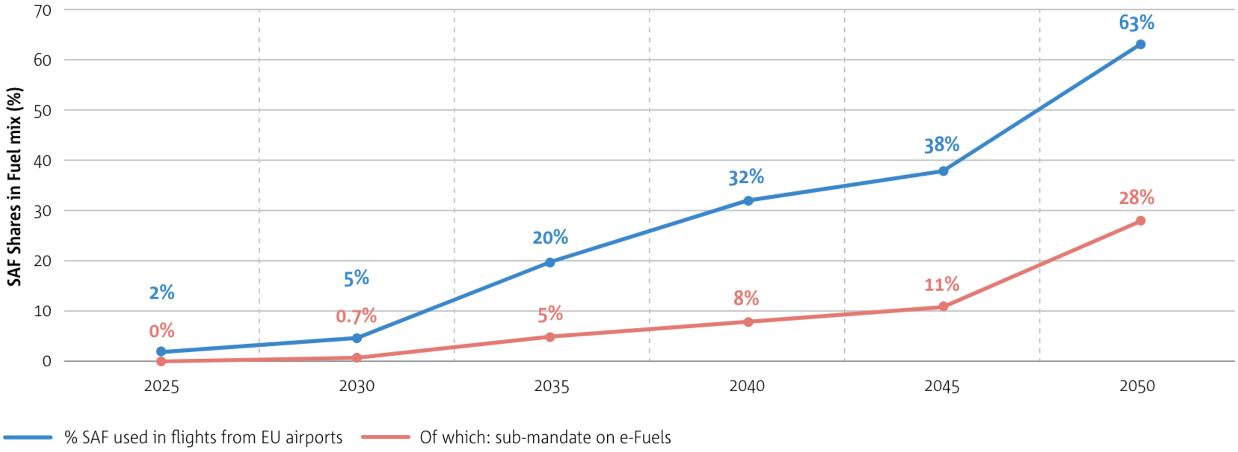


Figure 5. Proposed ‘Fit for 55’ SAF mandate [7]

Other countries such as the United States, have also worked towards policies with decarbonization as part of it. The Inflation Reduction Act (IRA) is a new law approved in 2022. The IRA includes several provisions that are designed to reduce inflation, including tax cuts and increased spending on infrastructure. One of the provisions in the IRA is a new tax credit for the production of clean hydrogen. This tax credit is designed to make it more affordable to produce clean hydrogen, which is a type of hydrogen that is produced without emitting greenhouse gases [8].

The IRA tax credit for clean hydrogen is a production tax credit, which means that it is a percentage of the cost of producing clean hydrogen. The credit is available for up to 10 years and is phased out over time. The amount of the credit depends on the type of clean hydrogen that is produced. For example, the credit is higher for clean hydrogen that is produced from renewable energy sources, such as solar and wind power.

The IRA tax credit for clean hydrogen is expected to have a significant impact on the development of the clean hydrogen industry. The credit is expected to make it more affordable to produce clean hydrogen, which will make it more competitive with other forms of energy carriers, such as natural gas and gasoline. This is expected to lead to increased investment in the clean hydrogen industry, and it is expected to create new jobs in the sector.

The European Union has also set ambitious goals for the development of hydrogen. The EU Hydrogen Strategy, which was published in 2020, aims to produce ten million tonnes of renewable hydrogen by 2030. The strategy also includes a number of measures to support the development of the hydrogen industry, such as investment incentives and regulatory reforms.

The EU Hydrogen Strategy is similar to the IRA tax credit in that it aims to make it more affordable to produce clean hydrogen. However, there are some key differences between the two approaches. The EU Hydrogen Strategy is more comprehensive, as it includes a number of measures to support the development of the hydrogen industry beyond just investment incentives. Additionally, the EU Hydrogen Strategy is more ambitious, as it aims to produce a much larger amount of hydrogen by 2030.

Overall, both the IRA tax credit and the EU Hydrogen Strategy are positive steps for the development of the clean hydrogen industry. The tax credit is expected to make it more affordable to produce clean hydrogen in the United States, while the EU Hydrogen Strategy is expected to make it more affordable to produce clean hydrogen in Europe. Both measures are expected to accelerate the transition to a clean energy economy.

In addition to the IRA tax credit and the EU Hydrogen Strategy, there are several other factors that are expected to drive the development of the clean hydrogen industry. These factors include: (1) The falling cost of renewable energy, such as solar and wind power. (2) The increasing demand for clean energy, as governments and businesses around the world seek to reduce their emissions of greenhouse gases and (3) The development of new technologies for producing and storing hydrogen.

The clean hydrogen industry is still in its early stages, but it has the potential to play a major role in the transition to a clean energy economy. The IRA tax credit and the EU Hydrogen Strategy are two positive steps that are expected to accelerate the development of the clean hydrogen industry.

1.3 Decarbonization Options in terms of energy carriers

Decarbonizing the aviation sector is a pressing concern, given the industry's significant contribution to global greenhouse gas emissions. Some of the available options for decarbonizing aviation is using different energy carriers such as sustainable aviation fuels (SAFs), electricity, and hydrogen.

Sustainable aviation fuels (SAFs) are synthesized from renewable resources, such as waste oils, agricultural residues, and non-food crops. They can be blended with conventional jet fuel and used in existing aircraft engines without modifications. SAFs have the potential to reduce lifecycle carbon emissions by up to 80% compared to fossil-based jet fuels. Major airlines have already begun incorporating SAFs into their fuel mix, signalling a promising shift towards greener aviation. However, the scalability of SAF production remain a challenge given the availability of feedstocks of the different feedstocks in a sustainable way.

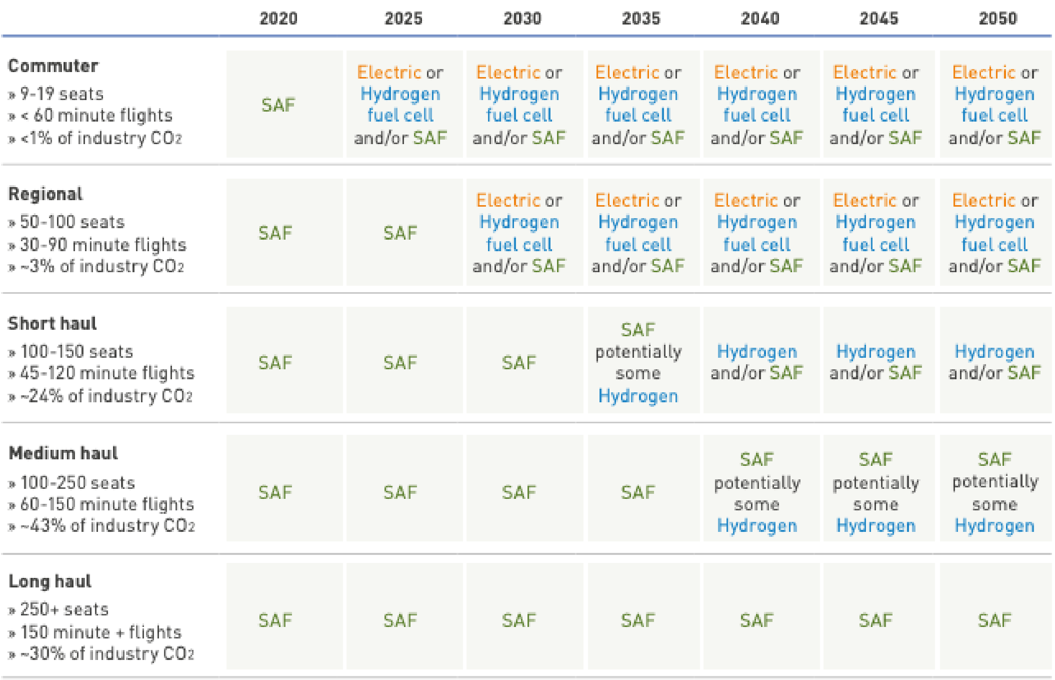
Electric aviation relies on batteries to store and supply power to electric motors. While electric aircraft are currently limited to short-haul flights due to battery weight and energy density constraints, advancements in battery technology could extend their range in the future. Electric planes produce zero emissions at the point of use and can significantly reduce the carbon footprint of regional air travel.

Challenges include battery weight, charging infrastructure, and ensuring safety standards.

Hydrogen can be used as a zero-emission fuel for aviation when combusted or used in fuel cells. Hydrogen fuel cells convert hydrogen and oxygen into electricity, powering electric motors that drive the aircraft. The only by-product is water vapour, making it an environmentally friendly option. The effect of water vapour on the creation of contrails and its global warming potential has been mentioned in several papers and won't be included in this work. However, hydrogen storage, distribution, and the production of green hydrogen (hydrogen produced using renewable energy) are areas that need further development.

The Air Transport Action Group (ATAG) is a non-profit association that promotes collaboration on aviation and society issues, one of these being shaping the sustainable future of air transport. In their last report, Waypoint 2050 [9], an overview of where low- and zero-carbon energy could be deployed in commercial aviation. Table 1 better exhibits when certain decarbonization options are expected to be available and for which of the different flight types it is expected to be more suitable. Smaller and shorter flight types, such as the commuter and the regional flights are expected to be able to have a direct electrification with batteries or the use of hydrogen with fuel cells. On the next flight types, short and medium haul, it shows how sustainable aviation fuels (SAFs) are the early in time decarbonization option, with other options coming later such as hydrogen. Lastly, for long haul flights, it is expected that the only decarbonization option is the use of sustainable aviation fuels. This table is further used throughout the work, as the backbone of which decarbonization options are better suitable for each of the subcategories of commercial aviation.

Table 1. Overview of where low- and zero-carbon energy deployment in commercial aviation [9]



	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1% of industry CO_2	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

1.4 Objective

The main objective of the present study is to assess the potential of decarbonisation of the aviation sector via direct electrification where feasible, in-direct electrification through hydrogen propulsion and lastly with the use of sustainable aviation fuels, commonly known as SAFs in the main airports in Europe. This will include the use of three different case studies such as the decarbonization of three different countries such as Portugal, the Netherlands, and Norway. These countries are chosen given what they represent in the European Unions. Norway being forerunner in the decarbonization of their aviation sector, Netherlands being one of the major hubs regarding aviation traffic in Europe, and Portugal being a European country which is considered average in their efforts on decarbonization of its aviation sector.

To achieve this objective, I will conduct the following task. First a Literature review will be done to gain a better understanding of the topic, current methodologies developed and data sources available. Next, following one of these methodologies an emission inventory will be executed for the countries in study, from these different features will be further understood as the amount of fuel currently consumed and the emissions that result from it. At the last stage, an analysis of the different decarbonization pathways using different energy carriers such as electrification, hydrogen, and sustainable aviation fuel as the main decarbonization drivers will be done.

1.5 Structure of the thesis

This work analyses the different decarbonization options available for commercial aviation in their different flight types, such as Commuter, regional, short-haul, medium-haul and long-haul flights and compares it using three different case studies of countries inside the European Union, such as The Netherlands, Norway, and Portugal.

Chapter 1 – Introduction: This chapter offers an overview of the present state of our aviation industry, emphasizing the urgency for decarbonization and the primary goals of this work. It commences by defining the scope and motivation behind this work, then transitions into a review of the existing advancements in the field of aviation decarbonization.

Chapter 2 – Background: This chapter presents the background or state of the art of different energy carriers which are suitable for the decarbonization of the aviation industry. In this section, an overview of the main energy carriers, their production methods, and their overall emissions from an LCA perspective is studied.

Chapter 3 – Methodology: This section presents the background and the step-by-step of how the thesis is developed. Here, the different steps carried throughout the thesis are explained starting from the literature review, to selecting the different case studies and building their emissions inventory to be able to understand the effect of different decarbonization options on each of these case studies. Main assumptions used for the decarbonization scenarios are also included and explained.

Chapter 4 – Results and discussion: This chapter presents the characterization of the current situation which is derived from using the EEA methodology to determine the emissions inventory of the commercial aviation industry for the selected countries for the case study, The Netherlands, Norway, and Portugal. Following, a comprehensive analysis of the best performing energy carriers which are able to help decarbonize the hard to abate industry such as the aviation industry.

Chapter 5 – Conclusions: In this section, main findings are presented displaying a critical analysis of the limitations encountered. Lastly, future work directions are mentioned.

Chapter 6 – References: This section includes a detailed list of all the sources cited in the dissertation and ensures the accuracy and credibility of the information presented here. Also, serve as valuable information for the reader and future work.

Chapter 2

State-of-the-art

As previously discussed in Chapter 1, the aviation industry is one of the most emission-intensive industries accounting for about 2-3% of global CO_2 emissions. Decarbonizing such a sector will require a combination of innovation in fuels, technology, policy changes, and operational improvements.

This section explores the state-of-the-art of different approaches that can be used for decarbonizing the aviation industry. In this approach it focuses on the technology that can be used for the propulsion system, the fuel which they use and the lifecycle emissions for each of the options.

The aviation industry has a diverse types of propulsion systems that can be used to power aircrafts. The most common ones are jet engines, turboprops, piston engines, electric propulsion, and hybrid propulsion. Currently most of them run mostly on kerosene or conventional aviation fuels (CAFs), but in the near future several developments will include engines running on sustainable aviation fuels (SAFs), hydrogen or batteries.

2.1 Literature review

Initially, a comprehensive literature review is conducted as the first important step in the research process. This involves a thorough assessment of the existing literature related to the research topic, with the aim of gaining a deeper understanding of the subject matter. This includes, among others, analysing previous findings, exploring the different methodologies that have been used, and identifying the data that is currently available and the granularity of it. During the literature review conducted, both scientific papers and grey literature were included. Literature review was limited to no more than five years old, with few exceptions where literature within this range followed older literature.

On one hand, Scientific papers are extensive resources of knowledge and previous research work done by researchers. Scopus from Elsevier and google scholar were used are main source of information regarding scientific papers. The research queries used were “Aviation AND Decarbonization” which yielded over 13,000. Afterwards, the abstracts are skimmed and the ones relative for the research are selected to be used.

On the other hand, as scientific papers lack a broader perspective of the strategy used by different agencies into the decarbonisation of the aviation sector. For this reason, grey literature from different institutions were used to gauge the possibility of different energy carriers of being adopted into the perspective of decarbonization of the commercial aviation industry. Some of this included important reports from specialized agencies, consulting companies and other corporations such as the ICCT [2], DNV [32], [33], OECD [34], Shell [35], Deloitte [1] and the IEA [5], [36] among others.

2.2 Commercial aviation

Commercial aviation has revolutionized the world. Since its early beginnings until now, a lot of advancement has occurred. Commercial aviation can be further divided into subcategories such as their flight types. These flight types include such as commuter, regional, short-haul, medium-haul, and long-haul flights. Each of these diverse types of fights may include one or several types of engines.

Engines have been developed, starting from piston and turboprop engines to newer, more powerful, and fuel-efficient jet engines. Also, different sizes of aircrafts have been developed, carrying more passengers over a longer period of time for longer distances without the need to refuel halfway. Below, a brief introduction to different flight types and the engines that are being currently used and those who most probably will be the next low carbon generation engines that will help decarbonize the aviation sector.

2.2.1 Commuter flights and regional flights

A commuter flight is a short haul plane that people typically use to commute between work and home.

These flights usually travel from a small regional airport to a main airport and are often domestic flights. They operate on smaller aircrafts which can have from 9 to 19 seats and are often less than 60-minute flights.

Regional flights are covered with small airliners that are designed to fly up to one hundred passengers on short-haul flights, usually feeding larger carriers airline hubs from small markets. Regional airliners are used for short trips between smaller towns or from a larger city to a smaller city [10].

Regional aircrafts normally refer to aircrafts such as the ATR 42 [11], produced in France and Italy, is another turboprop that can accommodate between 40 and 52 passengers. Lastly in Figure 6, The De Havilland Canada Dash 8 [12], a Canadian turboprop, has a seating capacity ranging from 37 to 90. These aircrafts play a crucial role in the hub and spoke model of passenger and cargo distribution as well as taking part in point-to-point transit.

Figure 6. Dash 8 Q200 aircraft

Commuter and regional aircrafts are normally equipped with turboprop engines, which are used on smaller aircraft and work by using a gas turbine to power a propeller. They are generally more fuel-efficient than jet engines at lower speeds and altitudes.

2.2.2 Short-haul and medium-haul flights

Short haul and medium-haul flights can be defined as flights with between 100 to 250 seats, which can be as short as an hour flight, up to 2.5 hours flight. Short and medium haul aircrafts normally regard to aircrafts such as the Boeing 737 family, produced in the state of Washington and the airbus A320 family which is produced in Europe.

Short and medium haul aircrafts are normally equipped with jet engines, which are the most common propulsion system in the aviation industry. They work by compressing air and mixing it with fuel, which is then ignited to produce a high-velocity exhaust stream that propels the aircraft forward. There are two main types of jet engines: turbojets and turbofans.

2.2.3 Long-haul flights

Long haul flights can be defined as flights with 250+ seats, which normally are longer than 2.5 hours. Long-haul aircraft are engineered for flights that traverse vast distances, often spanning continents and oceans. These aircraft are typically larger and equipped with more amenities than their short-haul or medium-haul counterparts, as they need to cater to passengers for extended durations. Examples of such aircraft include the Airbus A340-300, known for its range of approximately 11,000 kilometres and several long-distance records, and the Boeing 787 Dreamliner, a lighter and more efficient plane in demand for ultra-long routes. The Airbus A350-900ULR is another efficient aircraft popular for ultra-long routes, similar to the Dreamliner in its lightness. The Airbus A380 and Boeing 777-200LR have been serving ultra-long routes for over a decade and are often used by airlines for their longest and most popular routes.

2.3 Energy carriers

As described in the section above, decarbonizing aviation through different propulsion systems requires using different energy carriers, which in the end involves various sources and methods of production. Each of the possible energy carriers will be addressed regarding its production method, and emissions compared to conventional aviation fuels (CAFs).

2.3.1 Jet fuel- Conventional Aviation fuels (CAF)

Conventional aviation fuels, or most known as Kerosine jet fuel, have been developed from the illuminating kerosine used in the early gas turbine engines. Jet A-1 is the most used worldwide kerosene-type fuel. It is compatible with most jet aircraft, helicopters, turboprops, and compressions-ignition piston engines. It is characterised to meet international standards such as the ASTM D1655 among others, with a boiling point of 150 °C - 250 °C, a flashpoint over 38.0 ºC (100 ºF), and a maximum melting point of -47.0 ºC [13].

Most jet fuels are petroleum-based products, relying on the crude oil that has been forming underground for millions of years. The crude oil is a mixture of several different hydrocarbons. These compounds are separated from each other through atmospheric and vacuum fractional distillation, which is a process where the crude oil is heated, and the different products boil off and are recovered at different temperatures, Figure 7.

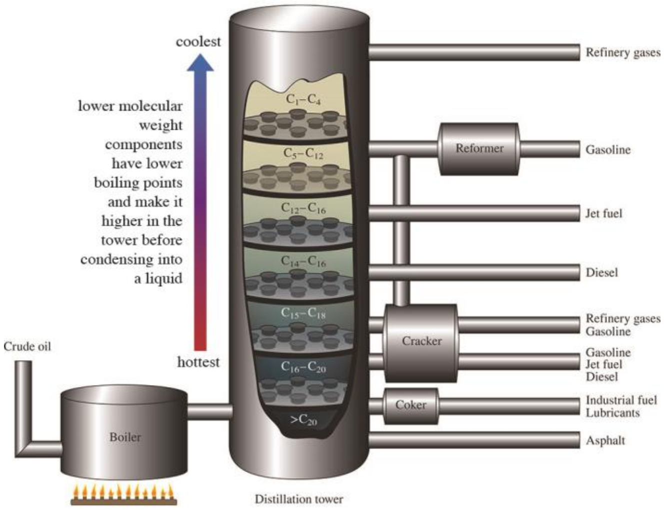


Figure 7. Crude oil refining [14]

2.3.2 Sustainable aviation fuels (SAF)

Sustainable aviation fuel (SAF) is a term that generally refers to non-fossil-derived aviation fuel. SAFs are characterised by three key elements:

- Sustainable as must be something that can be continually and repeatedly resourced in a manner consistent with economic, social, and environmental aims, and conserves an ecological balance by avoiding the depletion of natural resources [9].
- Alternate feedstock to crude oil as in this case non-conventional or advanced fuels and includes any materials or substances that can be used as fuels, other than conventional, fossil-sources. It is also processed to jet fuel in an alternative manner. Feedstocks for SAF are varied, ranging from cooking oil, plant oils, municipal waste, waste gases, and agricultural residues.
- Fuel as it must meet the technical and certification requirements for use in commercial aircraft.

There are currently seven different approved pathways and 2 co-processing pathways. Each pathway broadens the opportunity to produce more SAF over time. Each ASTM reference also includes the blending limit, which for most of the alternatives is 50% SAF mixed with fossil fuel. This is primarily due to the lack of aromatics in sustainable aviation fuel, which are the particles that help the seals to swell inside of older engines and prevent fuel leaks. Hence, newer engines do not have these concerns and have been assessed with 100% SAF.

For a pathway to be considered approved, the new pathway candidate should pass the ASTM D4054 specifications as specified in Figure 8, afterwards, it would be added to the ASTM D7566 which is the standard specification for aviation turbine fuel containing synthesized hydrocarbons. Afterward, it can be blended with Jet A-1, which follows the standard ASTM D 1655, ensuring the blending limits ratio for each of the pathways is respected according to [7].

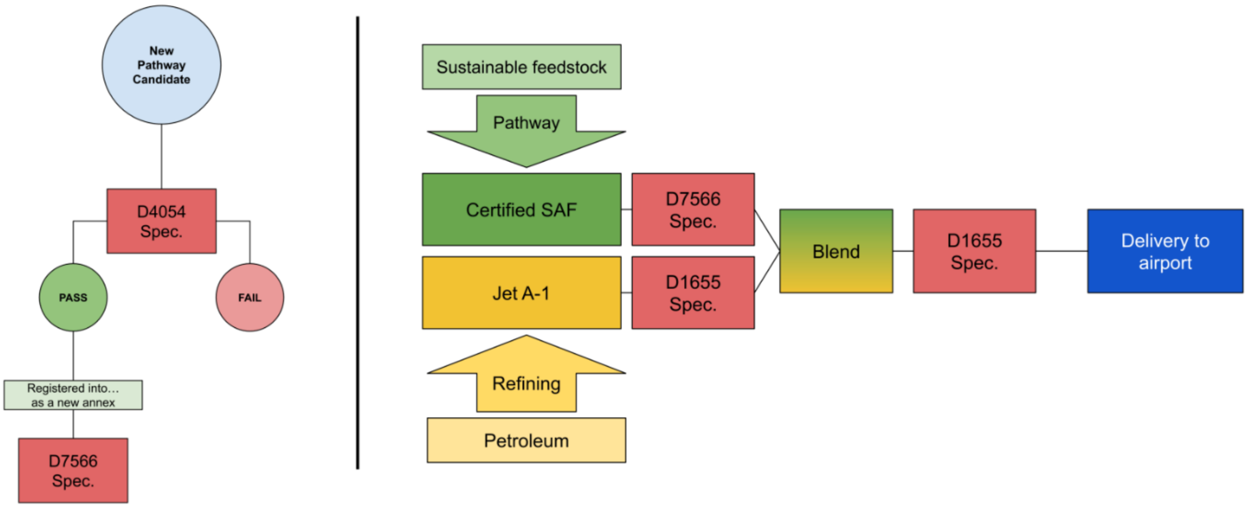


Figure 8. Relationship between value chain and specifications [15]

Table 2. Conversion pathways approved by ASTM [7]

Conversion process	Abbreviation	ASTM reference	Possible Feedstocks	Blending ratio by volume	Commercialization proposals / Projects
Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	FT	ASTM D7566 Annex 1	Coal, natural gas, biomass	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	ASTM D7566 Annex 2	Bio-oils, animal fat, recycled oils	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
Synthesized iso- paraffins from hydroprocessed fermented sugars	SIP	ASTM D7566 Annex 3	Biomass used for sugar production	10%	Amyris, Total
Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	ASTM D7566 Annex 4	Coal, natural gas, biomass	50%	Sasol
Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	ASTM D7566 Annex 5	Biomass from ethanol or isobutanol production	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
Catalytic hydrothermolysis jet fuel	CHJ	ASTM D7566 Annex 6	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%	Applied Research Associates (ARA)
Synthesized paraffinic kerosene from hydrocarbon- hydroprocessed esters and fatty acids	HC-HEFA-SPK	ASTM D7566 Annex 7	Algae	10%	IHI Corporation
FOG Co- processing		ASTM D1655 Annex A1	Fats, oils, and greases (FOG) from petroleum refining	5%	
FT Co- processing		ASTM D1655 Annex A1	Fischer-Tropsch (FT) biocrude as an allowable feedstock for petroleum co-processing	5%	Fulcrum

Each of these pathways is defined as the transformation from the sustainable feedstock to SAF, presented in Table 2. Each pathway is characterized by three points as seen in Figure 9: The intermediate product, the suitable feedstock and the converting technology used to transform the target molecule into SAF.

Figure 9. Definition of the pathways. From Feedstock to Intermediate Product to SAF [15]

2.3.2.1 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

The Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) is a biofuel that consists of Fischer-Tropsch's process of producing a hydrocarbon fuel using biomass resources and then combining it with kerosene to make an aviation fuel. FT-SPK can be blended with fossil kerosene up to 50%, Figure 10.

Feedstocks can include MSW and non-renewable feedstocks like coal and natural gas, as well as renewable biomass such as agricultural and forestry wastes, wood, and energy crops. This thermochemical method creates hydrocarbons from CO and H2 by FT synthesis after gasifying the feedstock [16].

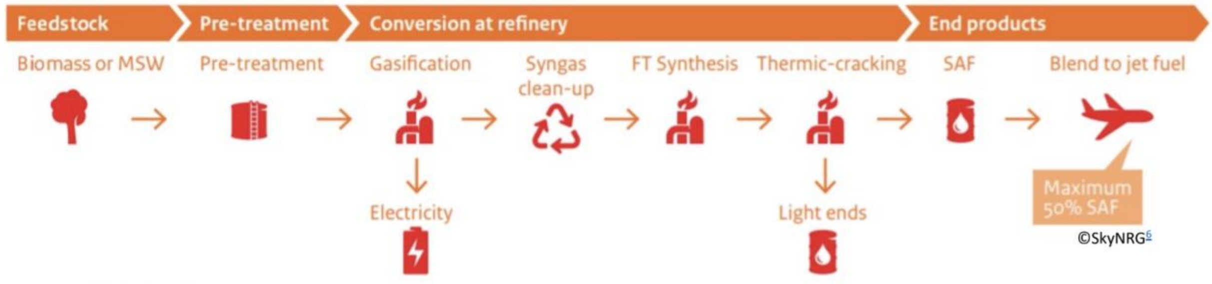


Figure 10. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) [15]

2.3.2.2 Synthesized paraffinic kerosene from Hydro processed Esters and Fatty Acids (HEFA)

Synthesized paraffinic kerosene from Hydro processed Esters and Fatty Acids (HEFA-SPK) is a conversion technology that is used to turn oil-bearing biomass into drop-in jet fuel. This process consists of several catalytic reactions by removing oxygen from the feedstock in the presence of hydrogen, followed by isomerization, Figure 11.

Feedstocks include plant oils and animal FOGs. It should be noted that this annex only covers hydrotreatment processing. Therefore, even when using FOGs as feedstock, processes using other techniques are not currently included [16].

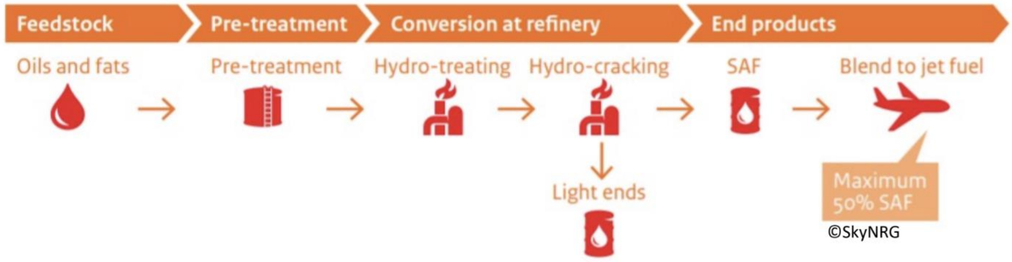


Figure 11. Synthesized paraffinic kerosene from Hydro processed Esters and Fatty Acids (HEFA-SPK) [15]

2.3.2.3 Synthesizing iso-paraffins from hydro processed fermented sugars

The method for synthesizing iso-paraffins from hydro processed fermented sugars (SIP-SPK) was approved in 2014 at blend levels up to 10%. Sugars from all sources are considered feedstocks. Using upgraded yeasts, this metabolic route converts sugars into the C15 hydrocarbon molecules farnesene, which must be further hydrotreated to produce farnesane [16].

2.3.2.4 Synthesized paraffinic kerosene with aromatics

The synthesized paraffinic kerosene with aromatics (SPK/A) pathway involves alkylation of light aromatics from coal feedstock, although it automatically applies to biomass-based feedstocks. The pathway was certified in 2015 for blend levels up to 50%. This is a thermochemical process based on gasification and FT synthesis with the addition of alkylation of light aromatics (primarily benzene) to create a hydrocarbon blend that includes aromatic compounds. This is the only approved process that includes aromatics in the biocomponent, unlike the other processes where only paraffinic hydrocarbons are produced [16].

2.3.2.5 Alcohol-to-Jet

The Alcohol-to-Jet pathway is a set of biochemical processes whose purpose is to generate a sustainable aviation fuel through the usage of alcohol. It is a process that involves two main phases: the production of intermediate alcohol and its further conversion to bio-jet fuel blend stock, Figure 12.

The alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) pathway was certified in 2016 (using an isobutanol intermediate) and 2018 (using an ethanol intermediate) for blend levels up to 50%. Feedstocks can include sugars from starches, e.g., corn, sugarcane, or sugar beet, or from cellulosic biomass. The pathway using an ethanol intermediate was based on the LanzaTech process, which involves the fermentation of CO_2 off-gases to ethanol. The production of the alcohol intermediate, using a biochemical fermentation process, is followed by the production of hydrocarbons, using dehydration, oligomerization, and hydrogenation to yield hydrocarbons [16].

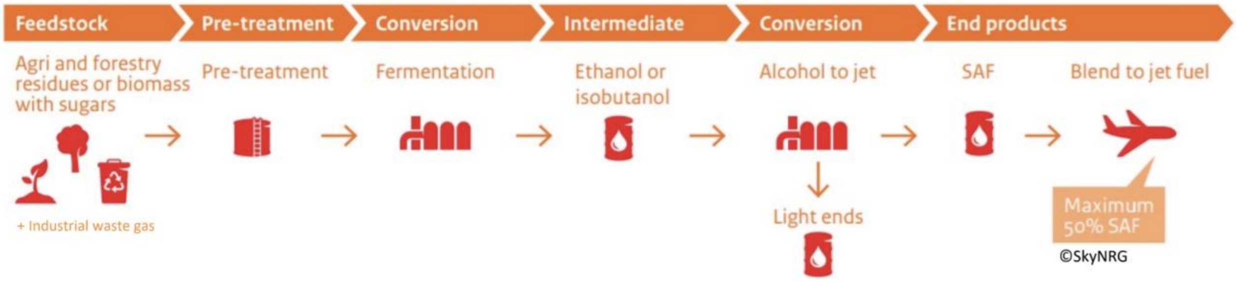


Figure 12. Alcohol-to-Jet [15]

2.3.2.6 *Catalytic hydrothermolysis jet*

The catalytic hydrothermolysis jet (CHJ-SPK) pathway received certification in February 2020. It is based on fatty acid esters and free fatty acids as a feedstock and a hydrothermal liquefaction technology. The blending of up to 50% is permitted. The product contains paraffins, isoparaffins, cycloparaffins and aromatic compounds over the Jet and diesel boiling point range and fractionation is required to produce jet and diesel [16].

2.3.2.7 *Synthesized paraffinic kerosene from hydrocarbon-hydro-processed esters and fatty acid*

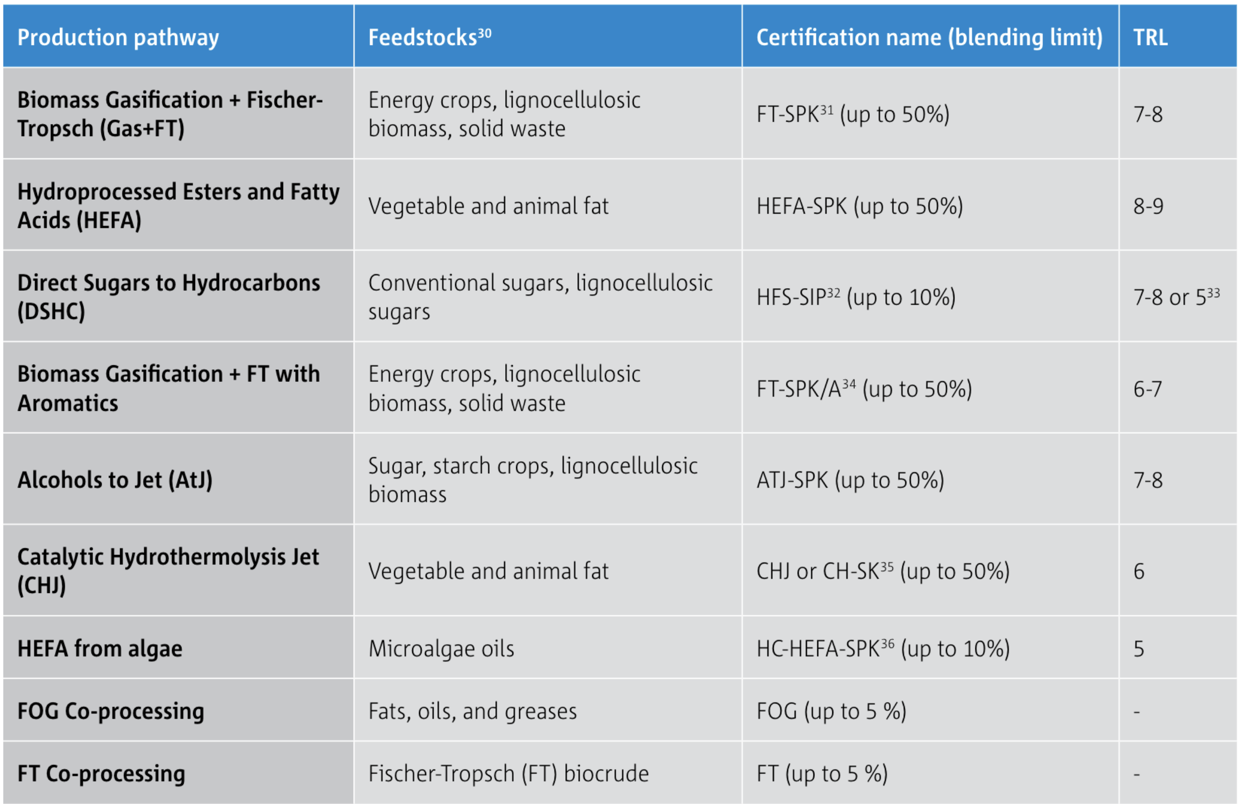
The synthesized paraffinic kerosene from hydrocarbon-hydro-processed esters and fatty acids (HC-HEFA-SPK) pathway received certification in May 2020. The current approved source of the bio-derived lipids is from Botryococcus braunii, a microalgal species, and up to 10% blends with conventional petroleum jet fuel are permitted. This was the first biojet certified through the express process [16].

2.3.2.8 *Co-Processing*

The co-processing of lipids within existing petroleum refineries was granted certification in April 2018 under an amendment to the ASTM1655 standard. Co-processing of up to 5% lipids is permitted in petroleum refinery processes, provided that hydrotreatment is one of the processing steps. In addition, the co-processing of FT liquids at 5% blends in existing refineries was approved in 2020 [16].

In summary, Table 3. Drop-in SAF- approved production pathways includes the production pathways, the feedstocks needed for its production, the certification name with the blending limit, and the TRL (technology readiness level).

Table 3. Drop-in SAF- approved production pathways [7]



Production pathway	Feedstocks[30]	Certification name (blending limit)	TRL
Biomass Gasification + Fischer-Tropsch (Gas+FT)	Energy crops, lignocellulosic biomass, solid waste	FT-SPK[31] (up to 50%)	7-8
Hydroprocessed Esters and Fatty Acids (HEFA)	Vegetable and animal fat	HEFA-SPK (up to 50%)	8-9
Direct Sugars to Hydrocarbons (DSHC)	Conventional sugars, lignocellulosic sugars	HFS-SIP[32] (up to 10%)	7-8 or 5[33]
Biomass Gasification + FT with Aromatics	Energy crops, lignocellulosic biomass, solid waste	FT-SPK/A[34] (up to 50%)	6-7
Alcohols to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	ATJ-SPK (up to 50%)	7-8
Catalytic Hydrothermolysis Jet (CHJ)	Vegetable and animal fat	CHJ or CH-SK[35] (up to 50%)	6
HEFA from algae	Microalgae oils	HC-HEFA-SPK[36] (up to 10%)	5
FOG Co-processing	Fats, oils, and greases	FOG (up to 5 %)	-
FT Co-processing	Fischer-Tropsch (FT) biocrude	FT (up to 5 %)	-

2.3.2.9 Emissions

As mentioned before, the aviation sector has grown at a significant pace in the last years, and even though there have been improvements in aircrafts efficiency, there is still a significant impact on GHG emissions and climate change. To address this, the International Civil Aviation Organization (ICAO) established the carbon offsetting and reduction scheme for international aviation (CORSIA) to help reduce aviation greenhouse gas emissions. The 193 member states of the International Civil Aviation Organization (ICAO) have agreed on a methodology to assess the life-cycle greenhouse gas (GHG) emissions of Sustainable Aviation Fuels (SAFs) within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) system [17]. This methodology includes the life cycle assessment system boundaries, which can be seen in Figure 13, and the core life-cycle assessment values.

Sustainable Aviation fuels (SAFs) offer multiple benefits to the aviation industry, one of the most important is the reduction in greenhouse gas emissions. SAF can significantly reduce lifecycle greenhouse gas emissions, achieving up to 80% reduction compared to fossil fuels, as it can be seen in Figure 14.

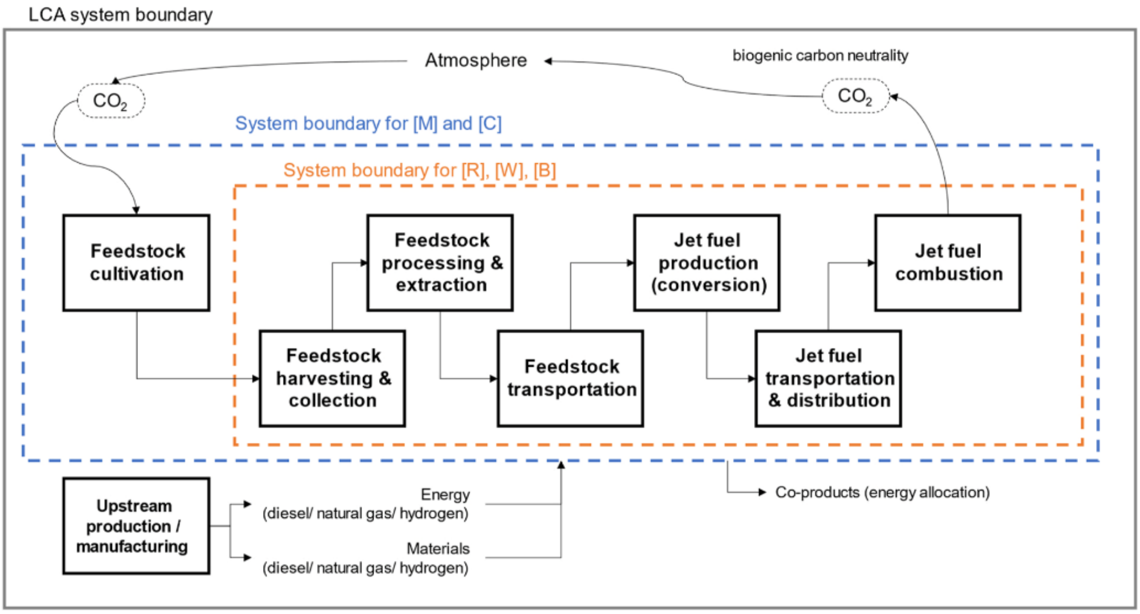


Figure 13. LCA System boundary [17]

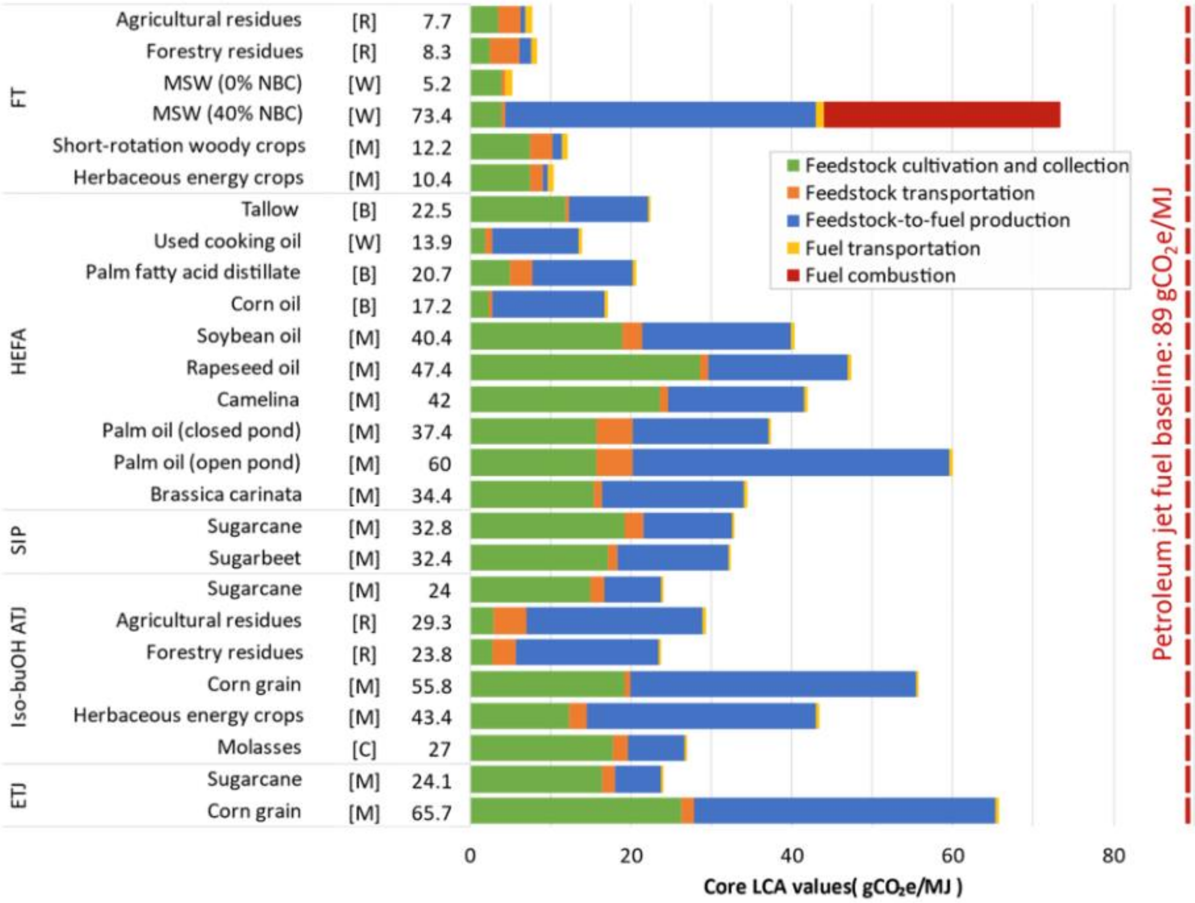


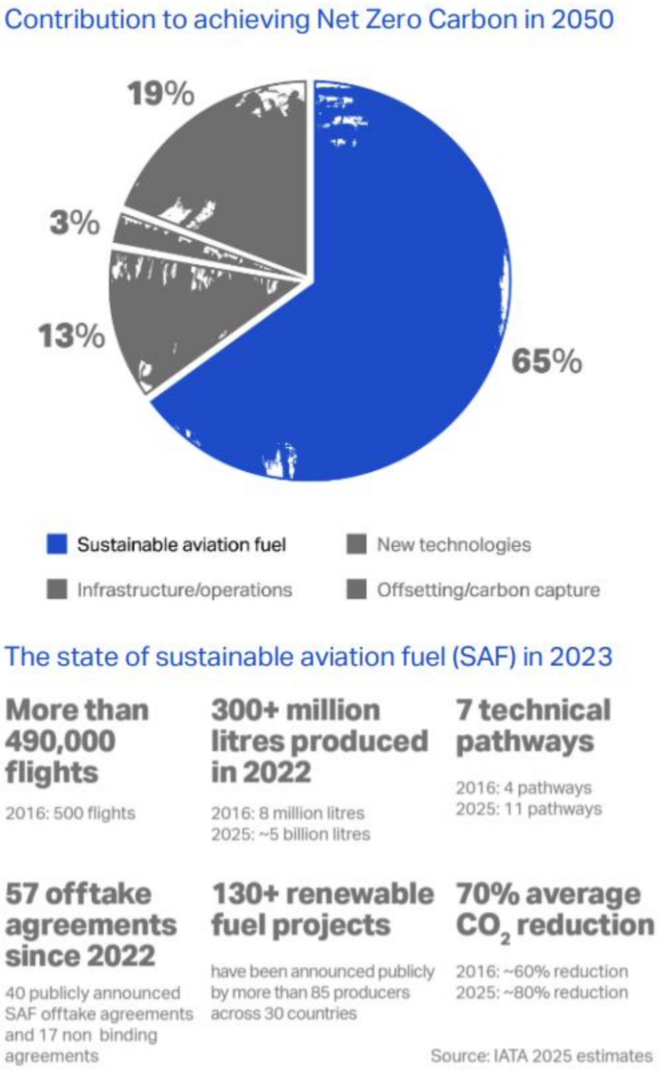
Figure 14. LCA-emissions values [17]

2.3.2.10 SAF production status

Some of the milestones for the sustainable aviation fuels in practice started since the first test flight with bio jet fuel was performed back in 2008 by Virgin Atlantic [18], followed by over 22 airlines performing over 2,500 commercial passenger flights with blends of up to 50% bio jet fuel from feedstock including used cooking oil, jatropha, cameline and algae. In 2022, SAF production tripled to three hundred million litres from one hundred million litres in 2021 [19].

Some of the most important achievements of the current state of SAF production and deployment are summarized in Figure 15. Contribution to achieving net zero carbon 2050 [19]. Here it can be depicted how according to IATA, 65% of the contributions to achieving NetZero carbon in 2050 is given to the emissions reductions given by the use of sustainable aviation fuels, with the rest being Infrastructure and operations, development, and deployment of new technologies, and lastly offsetting and carbon capture of emissions which otherwise wouldn’t be able to reduce.

The sustainable aviation fuel (SAF) industry has seen significant growth and achievements recently. In 2022 alone, more than 490,000 flights utilized SAF, demonstrating a strong commitment to environmental sustainability. This was made possible by the production of over three hundred million litres of SAF during the year. The industry has developed seven technical pathways for the production of SAF, providing a variety of methods to meet demand. Since 2022, there have been fifty-seven offtake agreements, indicating a robust market for these fuels. Furthermore, there are now over 130 renewable fuel projects in operation, contributing to a more sustainable future. Most impressively, these efforts have resulted in an average CO_2 reduction of 70%, a testament to the effectiveness of SAF in combating climate change.



The state of sustainable aviation fuel (SAF) in 2023

More than 490,000 flights

2016: 500 flights

300+ million litres produced in 2022

2016: 8 million litres
2025: ~5 billion litres

7 technical pathways

2016: 4 pathways
2025: 11 pathways

57 offtake agreements since 2022

40 publicly announced SAF offtake agreements and 17 non binding agreements

130+ renewable fuel projects

have been announced publicly by more than 85 producers across 30 countries

70% average CO_2 reduction

2016: ~60% reduction
2025: ~80% reduction

Source: IATA 2025 estimates

Figure 15. Contribution to achieving net zero carbon 2050 [19]

The production of Sustainable Aviation Fuels (SAF) in Europe is still in its initial stages, with the current maximum potential SAF production capacity in the EU estimated at around 0.24 million tonnes [7]. This is only about 10% of the amount of SAF required to meet the proposed mandate by 2030.

The European Commission has proposed a SAF blending mandate for fuel supplied to EU airports, with minimum shares of SAF gradually increasing from 2% in 2025 to 63% in 20502. To reach 5% of SAF by 2030 for all flights departing from EU airports, approximately 2.3 million tonnes of SAF would be required [7]. However, the production has grown faster in the US due to the availability of support and incentive programs. Most SAF used by European operators is tanked or imported from third countries [20].

The ReFuelEU Aviation Initiative estimates that seven additional SAF production plants would be needed in the EU by 2030, and 104 additional plants by 2050 [7]. If all existing biofuel facilities in Europe were calibrated to maximise SAF production, potential capacity could reach around 2.3 million tonnes.

2.3.3 Hydrogen

Hydrogen is a raw material and an energy vector that has shown great promise worldwide as a solution for meeting climate challenges. This is because it is able to store and supply large quantities of energy per mass unit without creating CO_2 emissions during combustion. Hydrogen can play a significant role in decarbonizing world energy supply to mitigate climate change. The research forecasts demand for hydrogen to carry energy to rise from about 1,000 tonnes today to 39–161 million tonnes of per annum in 2050, under various scenarios [21]. Several authors [22] have calculated the GHG impacts of blue and grey hydrogen, this is later included into assumptions later in the methodology. Figure 16 shows the variation on GHG emissions depending on the amount of carbon capture and storage and the methane emission rate depending on the source of the natural gas used for the production of hydrogen. On the other hand, there is green hydrogen, which is produced by the electrolysis of water, using renewable electricity. This process results in significantly lower greenhouse gas emissions compared to the production of grey hydrogen, which is derived from fossil fuels without carbon capture.

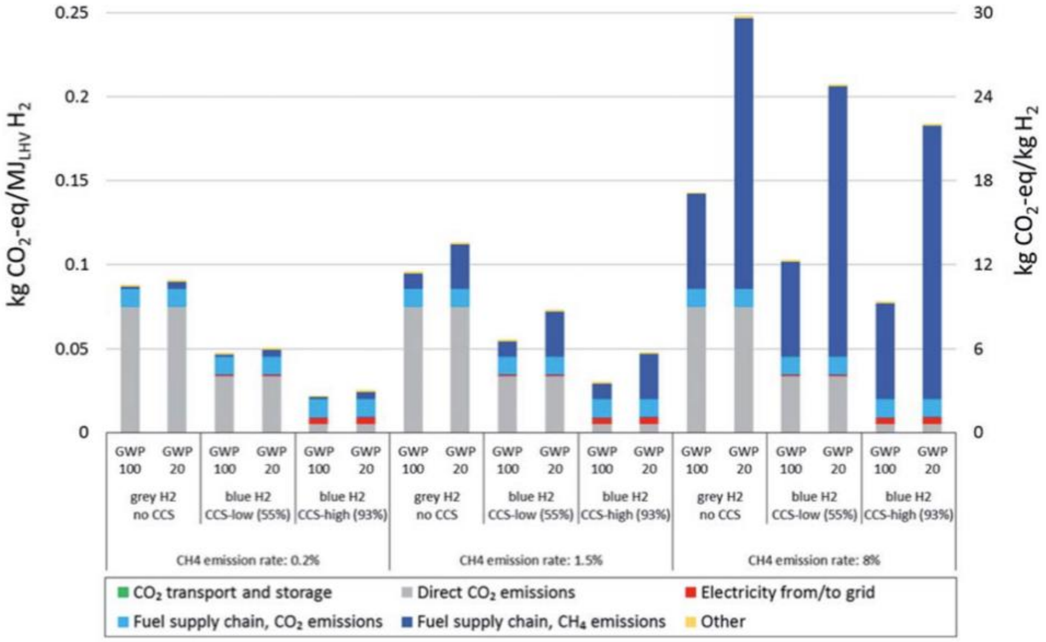


Figure 16. GHG emissions from grey and blue hydrogen [22]

Current developments in the use of hydrogen in the aviation industry includes Airbus approach. Airbus' ambition is to bring to market the world's first hydrogen-powered commercial aircraft by 2035. Their ZEROe project is exploring a variety of configurations and technologies, as well as preparing the ecosystem that will produce and supply the hydrogen. All four ZEROe concepts are powered by hydrogen. Within the four concepts there is a turbofan powered aircraft, a turboprop powered aircraft, a fully electrical concept, and a revolutionary Blended-wing body [23]. The ZEROe demonstrator was unveiled in 2022 and marks a step forward in Airbus' mission to bring hydrogen-powered aviation to reality. It is equipped with four liquid hydrogen tanks and a hydrogen combustion engine which is mounted along the rear fuselage, as shown in Figure 17.

Figure 17. Airbus ZEROe demonstrator [24]

On the other hand, ZeroAvia is a pioneer in the field of hydrogen-electric aviation. Their mission is to develop hydrogen-electric engines for zero-emission flight. They believe that hydrogen-electric powertrains are the only viable, scalable solution for zero-emission aviation, the first ZA600 commuter platform is expected to be ready for service in 2025 [25].

Lastly, Universal Hydrogen is another company working towards the development of an aircraft powered with hydrogen. Universal Hydrogen's approach involves using green hydrogen produced through electrolysis with clean power. They transport hydrogen in modular capsules over the existing intermodal container freight network. To accelerate market adoption, they are also developing a conversion kit to retrofit existing regional airplanes with a hydrogen-electric powertrain [26]. A significant milestone for Universal Hydrogen was the maiden flight of a partially-hydrogen-powered Dash 8 aircraft, with magniX's magni650 as EPU, which took place on March 2, 2023. The flight demonstration represented the largest aircraft ever to cruise mainly on hydrogen power.

2.3.4 Battery-electricity

Electric powered aviation has made considerable progress in recent years, with several companies investing in new electric and hybrid-electric technologies to make the aviation sector more sustainable. Currently some companies such as Heart Aerospace and Eviation are leading the movement towards electric aviation. Heart Aerospace has been developing an electric regional airliner, the ES-30, which can carry up to thirty passengers for over 200 kilometres on a fully electric power and for over 400 kilometres when in hybrid configuration, Figure 18 [27].

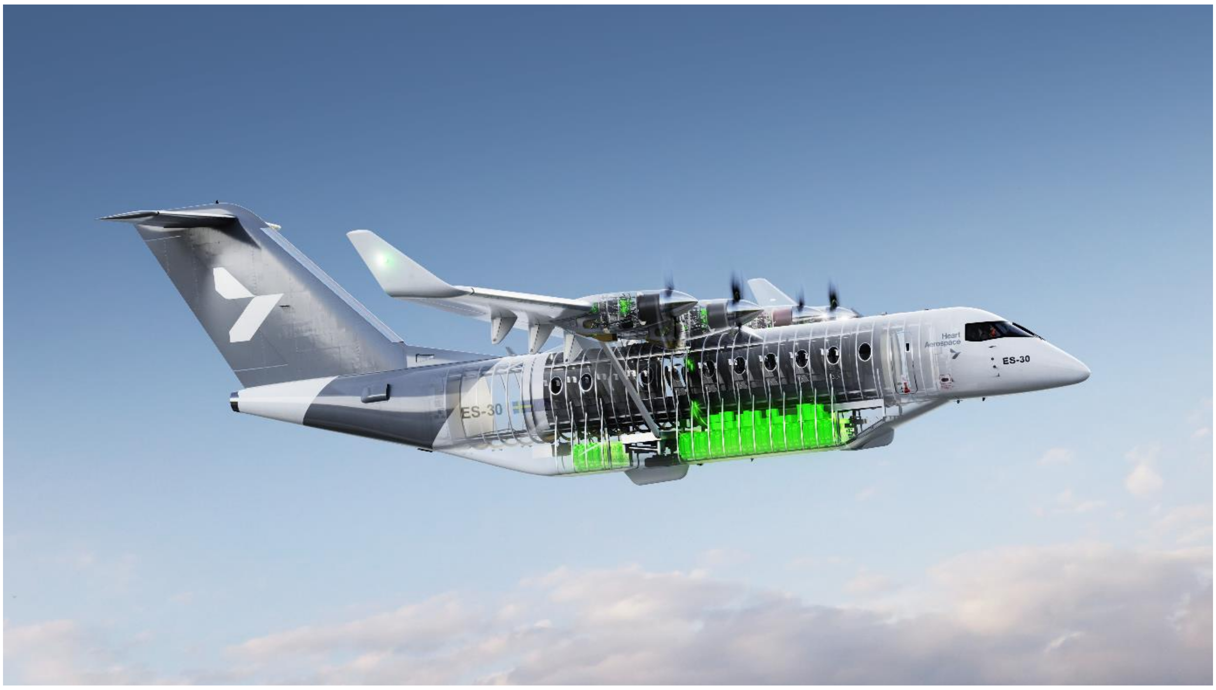


Figure 18. ES-30 aircraft from Heart Aerospace, Battery system in green [27].

On the other side, Eviation, a US based start-up, is developing a zero-emission aircraft, Alice, which has capacity for up to 9 passengers, Figure 19. Aircraft specifications are summarized in Table 4. Future prospects of the electric aviation will be characterized not only by the advancement in battery technology but also electric technology as well as other aerodynamic design advancement.

Figure 19. Alice aircraft from Eviation, first flight [28]

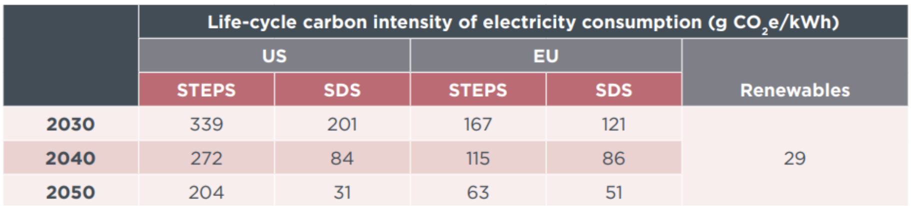
Table 4. Eviation Alice aircraft specifications

Performance	Max Operating Speed	**260 ktas**
	Day VFR Range	250 nm*
	Landing Distance (MTOW, ISA, Sea Level, Dry)	2,040 ft
	Take-off Distance (MTOW, ISA, Sea Level, Dry)	2,750 ft
Weights	MTOW	18,400 lbs
	Useful Payload (Commuter)	2,500 lbs
Power plant	Model	2 x magni650
	Output	700 kW each

Current advancement on electrification in the aviation industry targets the commuter and regional haul flights sector. Both these companies, as others, target to be available in commercial phase by around 2030, as early as 2028 [27].

The primary source of emissions in the operation of electric aircraft is the consumption of electricity. Efforts to reduce carbon emissions from electricity grids are steadily leading to a decrease in the carbon intensity of electricity at the source. However, the future of energy production remains uncertain, due to the evolving landscape of policies and incentives [29]. Previous studies [30], have used life-cycle carbon intensity of electricity considering the uncertainty of future energy production by basing its analysis on two contrasting scenarios proposed by the International Energy Agency (IEA) in its World Energy Outlook. The Stated Policies Scenario (STEPS) is based on projections from current policy statements, while the Sustainable Development Scenario outlines a path to achieve the targets set by the Paris Agreement without compromising energy availability. These two scenarios are summarized in Table 5.

Table 5. Life-cycle carbon intensity of electricity consumption [30]



	Life-cycle carbon intensity of electricity consumption (g CO_2e/kWh)				
	US		EU		Renewables
	STEPS	SDS	STEPS	SDS	
2030	339	201	167	121	29
2040	272	84	115	86	
2050	204	31	63	51	

Chapter 3

Method

This chapter explains the methodology used to answer the research question. First, an extensive literature review is done to better understand the topic, understand previous findings, different methodologies, and data available. Afterwards, data is gathered from different public and research-oriented databases and further analysed following several methods found in the literature review. Next, an emissions inventory is executed with the fuel burned and emissions modelled using the Aviation emissions calculator from the European Environment Agency (EEA [31]). Finally, an analysis of multiple decarbonization pathways using different energy carriers such as electrification through batteries, hydrogen and sustainable aviation fuel is done following different methods found in the literature review. The following sections will describe these methods and steps in detail.

3.1 Data Gathering

From the previous step, emissions were given on a year basis and forecasts of technologies were given in per year basis. To be able to estimate emissions, a bottom-up approach was used. Following this, data gathering was an important step, considering the different sources of data available, the granularity of this and the practicality needed in a study like this. Several databases were explored for the right granularity of information which could be useful for building the model. These databases included some public or research-oriented ones such as Euro control and Eurostat, also other commercial databases providers such as Flight radar, Flight Aware, among others were explored. Due to the availability and granularity of information, Eurocontrol flight data for R&D purposes was used.

Eurocontrol, also referred to as the European Organisation for the Safety of Air Navigation, is a global organization that strives for safe and effective air traffic control throughout Europe. It was established in 1963; it has 41 member nations; and its headquarters are in Brussels, Belgium. All of Europe's air traffic control is coordinated and planned by Eurocontrol. To create pan-European solutions for air traffic management, this entails collaborating with national authorities, air navigation service providers, users of civil and military airspace, airports, and other stakeholders [37].

Eurocontrol releases flight data for R&D purposes. The data source for the flights and their profiles through points and airspaces is flight plans submitted by airlines and other aircraft operators to EUROCONTROL Network Manager (NM) and the flight profiles generated by NM’s ATFM systems [38]. Data is release with a delay of 2 years and only available for sample months, which are March, June, September, and December, which gives broad access to seasonal patterns and large-scale data. The database contains several million flights.

The database is organized in CSV files, one flight per row and containing the following information in each column. Table 6 explains the data included and the description.

Table 6. Flights files data description by Eurocontrol

ECTL_ID	Unique numeric identifier for each flight in Eurocontrol PRISME DWH
ADEP	ICAO airport code for the departure airport of the flight
ADEP Latitude	Latitude of departure airport in decimal degrees.
ADEP Longitude	Longitude of departure airport in decimal degrees.
ADES	ICAO airport code for the destination airport of the flight.
ADES Latitude	Latitude of destination airport in decimal degrees.
ADES Longitude	Longitude of destination airport in decimal degrees

AC Type	The ICAO aircraft type designator
AC Operator	Three-letter ICAO operator code
Market Segment	Market segment as defined by Eurocontrol
Requested FL	Requested cruising flight level from the flight plan.
Actual Distance Flown (nm)	Distance flown in nautical miles, corresponding to the ‘actual’ profile below.

3.2 European Environment Agency

The European Environment Agency (EEA) is an agency of the European Union that provides independent information on the environment. Its goal is to support sustainable development and to help achieve significant and measurable improvements in Europe's environment [39]. The EEA developed and released the EMEP/EEA guidebook for air pollutant emission inventory, which aids in the submission of emission data under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) and the EU National Emission Ceilings Directive, offers specialized advice on assembling an inventory of atmospheric emissions. The EEA publishes the Guidebook, while the CLRTAP Task Force on Emission Inventories and Projections oversees the chapters’ technical aspects [31].

3.3 Analytical tools

In this subsection, the several analytical tools used during the analysis process are mentioned. Databases from Eurocontrol are downloaded in a CVS format and converted into excel workbook for easier data handling and visualization. Afterwards using excel, the data is subdivided into the countries of interest which will be used later into the aviation emission calculator from the EEA [40]. For the purpose of having different European countries, for the case study it was chosen three countries such as Portugal, the Netherlands, and Norway. These countries were chosen to further understand how decarbonization could work on countries very different and in a different stage of decarbonization. With the results from the emissions calculator, fuel consumption which in this case is our useful energy will be converted into final energy through the application of an efficiency factor. Later this final energy will be used to approximate the amount of energy needed from other energy carrier vectors. This energy vectors are hydrogen and sustainable aviation fuel. Lastly, a forecasting will be done following the goals and mandates in-place or planned for the aviation sector. Each of the tools involved in this process will be explained in the next subsections.

3.4 Aviation EMEP/EEA guidebook 2019

The Aviation EMEP/EEA air pollutant emission inventory guidebook 2019 introduces a robust methodology designed to estimate the volume of atmospheric pollutants produced by aircraft within a given country [40].

3.4.1 Aircraft engine emissions

The pollutants generated by aviation primarily originate from the combustion of jet fuel and aviation gasoline, which are utilized as fuel for the aircraft. This combustion process leads to the production of several emission species. These include Carbon Dioxide (CO_2), Nitrogen Oxides (NO_X), Water Vapor (H_2O), Methane (CH_4), Carbon Monoxide (CO), Sulphur Oxides (SO_X), Non-Methane Volatile Organic Compounds (NMVOCs), and Particulate Matter (PM). Figure 20 provides a visual representation of this process, illustrating the airflow through an aircraft engine and the resulting species from the combustion process. The lower portion of this figure offers an indication of the proportions of each input and output gas.

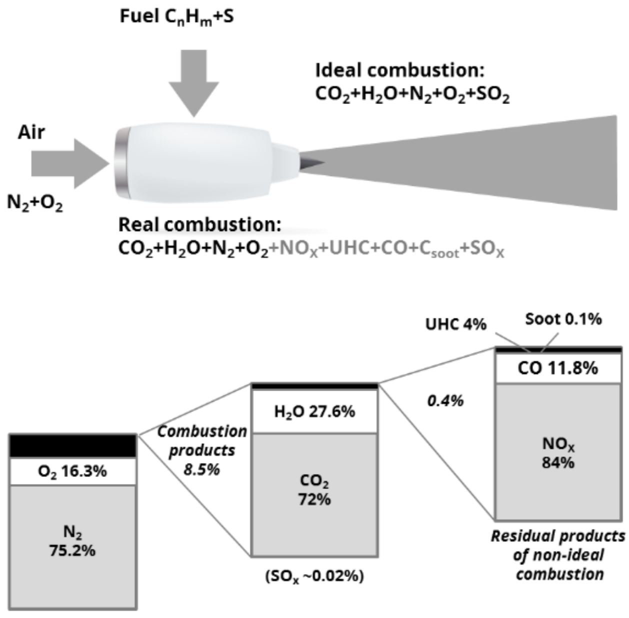


Figure 20. Aircraft fuel combustion [40]

3.4.2 Phases of flight

The flight phases that need to be modelled encompass a variety of stages. These phases can be visualized in Figure 21.

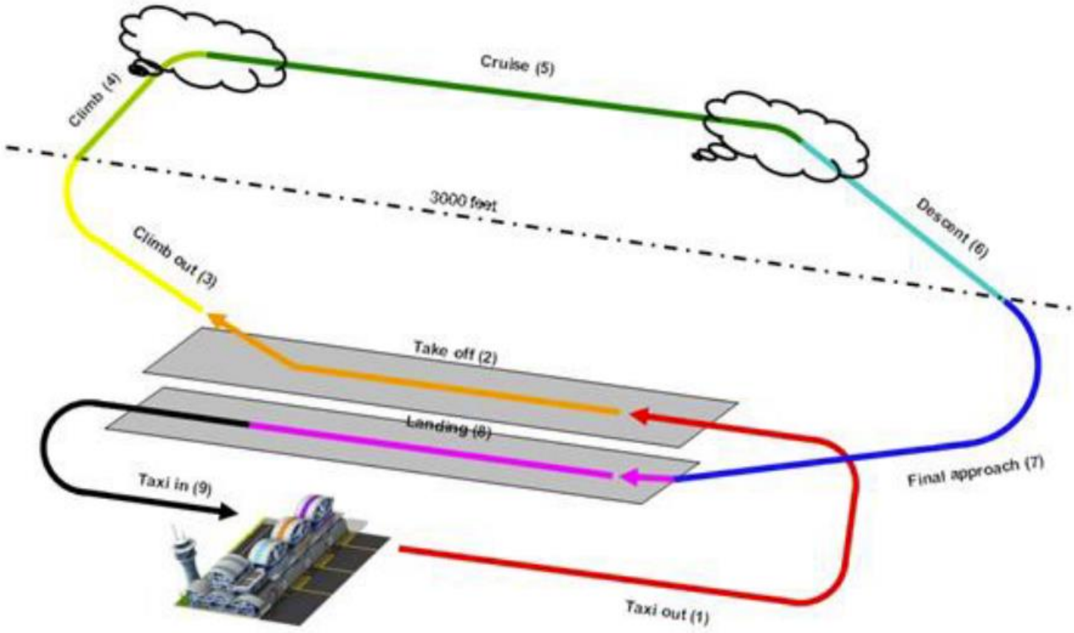


Figure 21. Typical phases of flight [40]

In here, the phases of a flight can be described as follows:

Taxi-out: This is the phase where the aircraft moves under its own power from its parking area to the take-off point on the runway.

Take-off: During this phase, the aircraft transitions from being on the runway to flying in the air.

Climb: This phase, which is divided into ‘climb-out’ and ‘climb’, involves the aircraft ascending to a predetermined cruising altitude after take-off. While a single climb phase is typical, there may also be multiple step climb phases.

Cruise: This phase occurs between the climb and descent phases and is usually the longest part of a journey. It ends as the aircraft approaches its destination and begins the descent phase in preparation for landing. During this phase, the aircraft may climb or descend from one flight level to another due to operational or air traffic control (ATC) reasons. The cruise phase consumes most of the fuel for most commercial passenger aircraft.

Descent: This is when the aircraft decreases its altitude in preparation for landing. It can be continuous or stepped due to operational or ATC reasons, with continuous descent being the most fuel-efficient option.

Final approach: This is the last leg of an aircraft’s approach to landing when it aligns with the runway and descends for landing.

Landing: This phase involves the aircraft returning to the ground up until the taxi-in starts.

Taxi-in: This is when the aircraft moves under its own power from the point where it turns off the landing runway (after returning to normal taxi speed) to its parking spot on the ground.

In the domain of aviation inventory, the activities conducted during the departure and arrival phases of a flight are collectively referred to as ‘Landing and Take-off’ (LTO) activities. On the contrary, activities occurring during the Cruise, Climb, and Descent (CCD) phases are grouped and reported as ‘Cruise’ activities. These activities are more clearly illustrated in Figure 22.

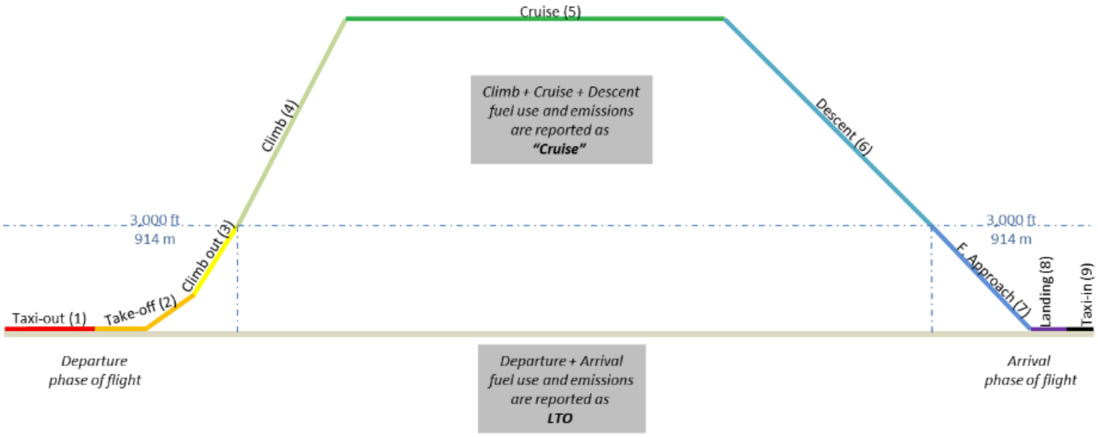


Figure 22. Aviation inventory activities vs. typical phases of flight [40]

3.4.3 Choice of method

This approach is divided into three calculation levels, known as Tier 1, Tier 2, and Tier 3, each corresponding to the amount of available information. The accuracy of the estimates improves with more information, thereby reducing the margin of error. In principle, the more data available, the closer the estimates align with reality.

Tier 1

For this first level of calculation, information on aviation fuel sales divided into domestic and international use is required, where it is assumed that total fuel sales are equal to total fuel use. In addition to knowing the total LTO cycles also divided into domestic and international. The calculation consists of using a generic fleet of aircraft in order to have an average generic Emission Factor for LTO and CCD cycles.

Tier 2

For this second level, in addition to the information on aviation fuel sales divided into domestic and international, the specific division of fuel consumption for each aircraft is required. Specific emission factors for each aircraft for LTO cycles and for each aircraft for LTO cycles and generic emission factors for CCD cycles.

Tier 3

The calculation level under discussion is subdivided into two categories: Tier 3.a and Tier 3.b. This level needs data for each flight, including the aircraft model and the total distance covered, further categorized into domestic and international flights.

In the context of Tier 3.a, calculations are performed using specific information for each aircraft derived from the EMEP/EEA database. On the other hand, Tier 3.b requires not only the complete flight path data but also a specialized computer software capable of processing this information. Examples of such software include the EUROCONTROL Advanced Emissions Model (AEM), US/Federal Aviation Administration (FAA), Aviation Environmental Design Tool (AEDT), or similar software.

Figure 23 describes the decision tree for determining the appropriate tier method to apply, considering how detailed is the information available. In the case of the present work, Tier 3.a. is the chosen option as the complete flight path is not available nor the access to specialized computer software. Calculations will be performed with the help of the EMEP/EEA database.

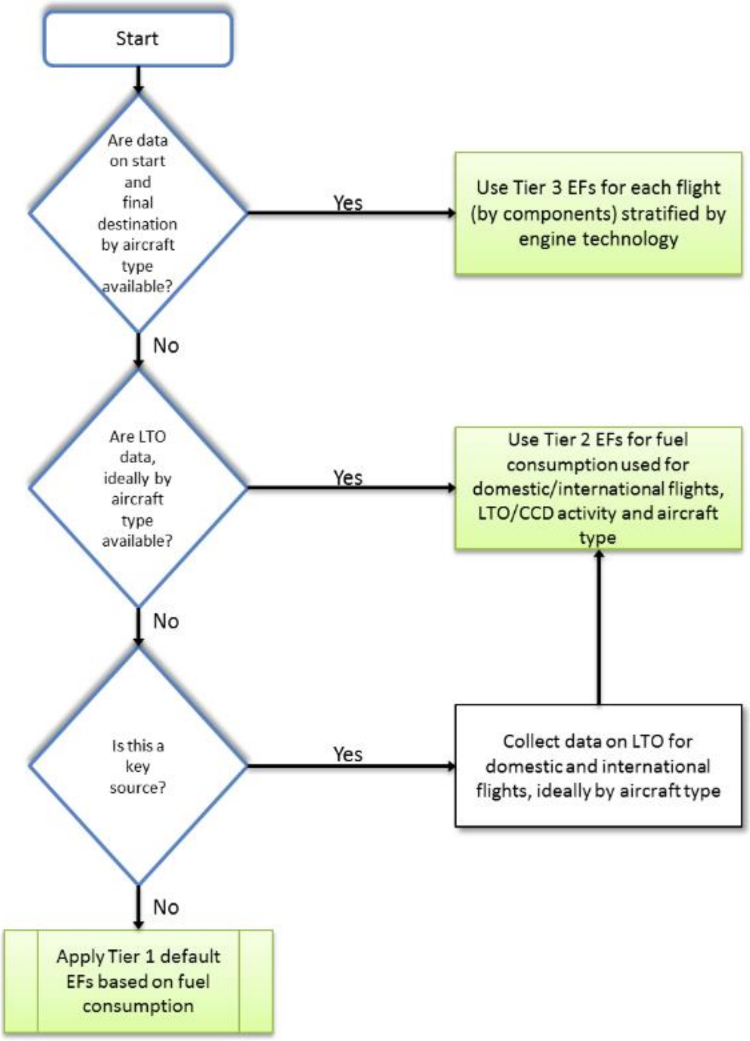
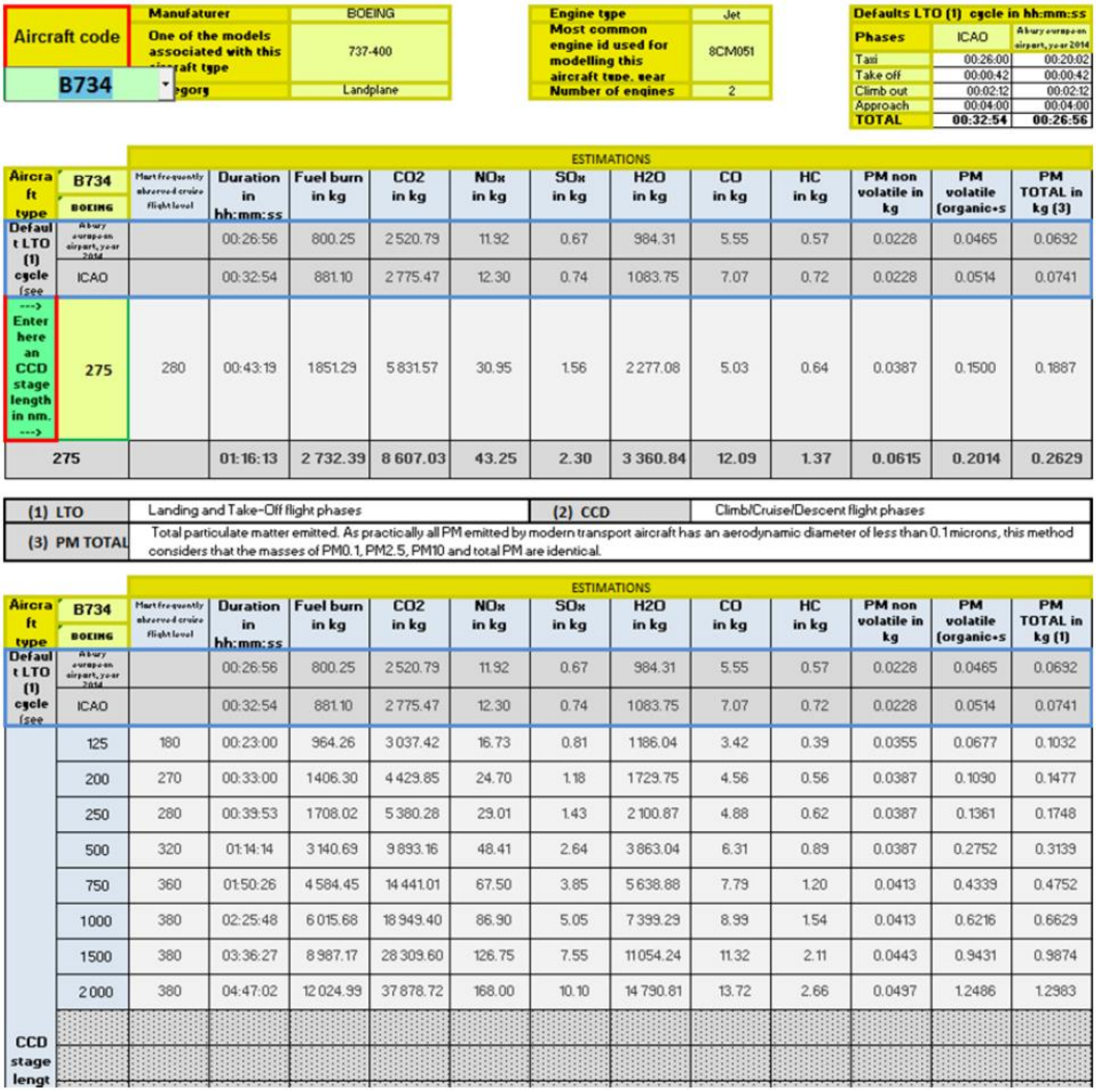


Figure 23. Decision tree for determining tier method to apply [40]

3.4.4 Methodology for Tier 3a

The Tier 3 methodologies are based on actual flight movement data, in this case from origin and destination (OD) data. The Tier 3A methodology accounts for CCD emissions across various flight distances, requiring specific information about the departure and arrival airports, as well as the aircraft type for both domestic and international flights. This approach models inventories using average fuel consumption and emissions data for the landing and Take-off (LTO) phase and different lengths of the Cruise, Climb, and Descent (CCD) phase, across a range of representative aircraft categories [40].

The methodology acknowledges that emission quantities differ between flight phases. It also recognizes that while fuel consumption is related to flight distance, it can be disproportionately higher over shorter distances compared to longer ones. This is attributed to the fact that aircrafts consume more fuel per distance during the LTO cycle than during the ‘en-route’ phase. Figure 24 shows the Annex 5. Emission calculator which comes with the EMEP/EEA guidebook. This spreadsheet was used to estimate and build the emission inventory for the case studies used in the present work.



Aircraft code	Manufaturer	BOEING
B734	One of the models associated with this aircraft type	737-400
	egory	Landplane

Engine type	Jet
Most common engine id used for modelling this aircraft type, year	8CM051
Number of engines	2

Defaults LTO (1) cycle in hh:mm:ss		
Phases	ICAO	Any european airport, year 2014
Taxi	00:26:00	00:20:02
Take off	00:00:42	00:00:42
Climb out	00:02:12	00:02:12
Approach	00:04:00	00:04:00
TOTAL	00:32:54	00:26:56

		ESTIMATIONS											
Aircraft type	B734 BOEING	Most frequently observed cruise flight level	Duration in hh:mm:ss	Fuel burn in kg	CO2 in kg	NOx in kg	SOx in kg	H2O in kg	CO in kg	HC in kg	PM non volatile in kg	PM volatile (organic+s	PM TOTAL in kg (3)
Default LTO (1) cycle (see	Any european airport, year 2014		00:26:56	800.25	2 520.79	11.92	0.67	984.31	5.55	0.57	0.0228	0.0465	0.0692
	ICAO		00:32:54	881.10	2 775.47	12.30	0.74	1083.75	7.07	0.72	0.0228	0.0514	0.0741
---> Enter here an CCD stage length in nm. --->	275	280	00:43:19	1851.29	5 831.57	30.95	1.56	2 277.08	5.03	0.64	0.0387	0.1500	0.1887
275			01:16:13	2 732.39	8 607.03	43.25	2.30	3 360.84	12.09	1.37	0.0615	0.2014	0.2629

(1) LTO	Landing and Take-Off flight phases	(2) CCD	Climb/Cruise/Descent flight phases
(3) PM TOTAL	Total particulate matter emitted. As practically all PM emitted by modern transport aircraft has an aerodynamic diameter of less than 0.1microns, this method considers that the masses of PM0.1, PM2.5, PM10 and total PM are identical.		

		ESTIMATIONS											
Aircraft type	B734 BOEING	Most frequently observed cruise flight level	Duration in hh:mm:ss	Fuel burn in kg	CO2 in kg	NOx in kg	SOx in kg	H2O in kg	CO in kg	HC in kg	PM non volatile in kg	PM volatile (organic+s	PM TOTAL in kg (1)
Default LTO (1) cycle (see	Any european airport, year 2014		00:26:56	800.25	2 520.79	11.92	0.67	984.31	5.55	0.57	0.0228	0.0465	0.0692
	ICAO		00:32:54	881.10	2 775.47	12.30	0.74	1083.75	7.07	0.72	0.0228	0.0514	0.0741
CCD stage lengt	125	180	00:23:00	964.26	3 037.42	16.73	0.81	1 186.04	3.42	0.39	0.0355	0.0677	0.1032
	200	270	00:33:00	1406.30	4 429.85	24.70	1.18	1 729.75	4.56	0.56	0.0387	0.1090	0.1477
	250	280	00:39:53	1 708.02	5 380.28	29.01	1.43	2 100.87	4.88	0.62	0.0387	0.1361	0.1748
	500	320	01:14:14	3 140.69	9 893.16	48.41	2.64	3 863.04	6.31	0.89	0.0387	0.2752	0.3139
	750	360	01:50:26	4 584.45	14 441.01	67.50	3.85	5 638.88	7.79	1.20	0.0413	0.4339	0.4752
	1000	380	02:25:48	6 015.68	18 949.40	86.90	5.05	7 399.29	8.99	1.54	0.0413	0.6216	0.6629
	1500	380	03:36:27	8 987.17	28 309.60	126.75	7.55	11 054.24	11.32	2.11	0.0443	0.9431	0.9874
	2 000	380	04:47:02	12 024.99	37 878.72	168.00	10.10	14 790.81	13.72	2.66	0.0497	1.2486	1.2983

Figure 24. Spreadsheet output for a Boeing 737 [40]

After having built the emissions inventory with over 200,000 flights and quantified the fuel burnt per flight, data was examined and further prepared for analysing the different decarbonization options.

3.5 Decarbonization options

In this section, the different approaches used to compare the baseline in energy and fuel consumption and GHG emissions generated is further developed. Different scenarios are also developed in order to compare different approaches in the case studies and main assumptions are listed.

3.5.1 Energy flow analysis

In order to make a comparison between the current propulsion system which run on jet fuel as a baseline with an alternative propulsion system which will run with alternative energy vectors such as hydrogen and electricity, an energy flow analysis was proposed. In this case, energy from the fuel burnt is transformed into the actual useful energy which is used into the propulsion system making the aircraft move, this energy is labelled as the required energy for the flight. Based on this energy required the amount needed of the alternative energy carrier is calculated, considering the actual efficiency of the alternative propulsion system. Following this analysis, energy requirements of hydrogen and electricity are estimated. In the case of sustainable aviation fuels (SAF), the amount of fuel burnt is the same as the amount of jet fuel given by EMEP/EEA methodology. Main assumptions, well-to-wheel emission factors, efficiencies and limitations are further described in section 3.5.3.

3.5.2 Scenarios' definition

Three different case studies are considered to analyse how the commercial aviation sector works in each of them, considering the number of flights per month, difference in percentage in each of the flight categories (Regional, short-medium, and long-haul flights), and total energy required in each of the case studies.

In the pessimistic scenario, it is considering a situation where kerosene, the traditional aviation fuel, is entirely replaced by a blend of Sustainable Aviation Fuels (SAF) for all types of flights under study. This scenario operates under several key assumptions. Firstly, it assumes that the volume of fuel consumed remains consistent with Conventional Aviation Fuel (CAF). Secondly, the emissions factor applied is an average derived from various available SAF options such as Hydro processed Esters and Fatty Acids (HEFA), Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), and others. Lastly, this scenario suggests that SAF could feasibly replace 100% of kerosene, a hypothesis supported by some flight tests [41].

In the second scenario, named as “Towards hydrogen development”, hydrogen is envisioned to replace kerosene in regional as well as short to medium-haul flights. Meanwhile, Sustainable Aviation Fuels (SAF) are proposed to replace kerosene in long-haul flights. This scenario is based on several key assumptions. Firstly, it presumes that the same amount of useful energy is required, regardless of the fuel type. Secondly, it maintains that air traffic levels will remain constant. Lastly, it evaluates hydrogen as if it were either green hydrogen derived from renewable sources or blue hydrogen derived from natural gas with a high rate of carbon capture and storage (CCS) and a methane emissions rate of 1.5%.

In the third scenario, referred to as the “Towards electrification”, electricity is proposed to replace kerosene in regional flights, while Sustainable Aviation Fuels (SAF) are suggested to replace kerosene in short to medium and long-haul flights. This scenario is based on several key assumptions. Firstly, it assumes that the same amount of useful energy is required, irrespective of the fuel type. Secondly, it maintains that air traffic levels will remain unchanged. Lastly, it evaluates electricity as if it were green electricity derived from renewable sources or grid electricity using the average per country.

3.5.3 Main assumptions

In this subsection, main assumptions will be listed which will be used for each of the case studies and corresponding scenarios. The scenarios to be assessed are a pessimistic scenario, a scenario towards hydrogen development and lastly a scenario towards electrification. Table 7 describes the energy content used for comparing different energy carriers. In this case, the low heating value (LHV) is used to be able to compare both energy carriers.

Table 7. Energy content

Energy content	LHV	Unit
Kerosene [42]	43	MJ/kg
Hydrogen [42]	120	MJ/kg

Next, Table 8 describes the different emissions factors used in the different scenarios. For an appropriate comparison, well-to-wake emissions are considered for all the scenarios. Well-to-wake emissions, also known as Life-cycle emissions, incorporate both upstream (well-to-tank) and downstream (tank-to-wake) emissions. These emissions are not limited to carbon dioxide (CO_2), but also include other greenhouse gases such as methane and nitrous oxide [43].

Table 8. Emission factors for different scenarios

Emissions Well to Wake	CO_2e	Unit	Scenario in which is used
Kerosene [44]	89	g CO_2e/MJ	Current scenario
Average SAF [44]	31	g CO_2e/MJ	Pessimistic scenario
Blue H2 High-CCS [22]	29	g CO_2e/MJ	Hydrogen scenario
Green H2 [22]	3	g CO_2e/MJ	Hydrogen scenario
Average renewable [45]	17	g CO_2e/kWh	Electricity scenario
Average emissions in Grid PT [46]	234	g CO_2e/kWh	Electricity scenario
Average emissions in Grid NL [46]	356	g CO_2e/kWh	Electricity scenario
Average emissions in Grid NO [46]	29	g CO_2e/kWh	Electricity scenario

Next, Table 9 describes the summarized efficiencies taken for the comparison of the complete efficiencies in each of the scenarios. These efficiencies were taken as an average of several found in literature or as found in different manufacturers webpage [27], [28], [47].

Table 9. Efficiencies for different scenarios

Efficiencies	
Conventional (Turbines) [48]	40%
Hydrogen (turbines/fuel cells) [25]	50%
Electric (powertrain/battery) [27]	90%

Chapter 4

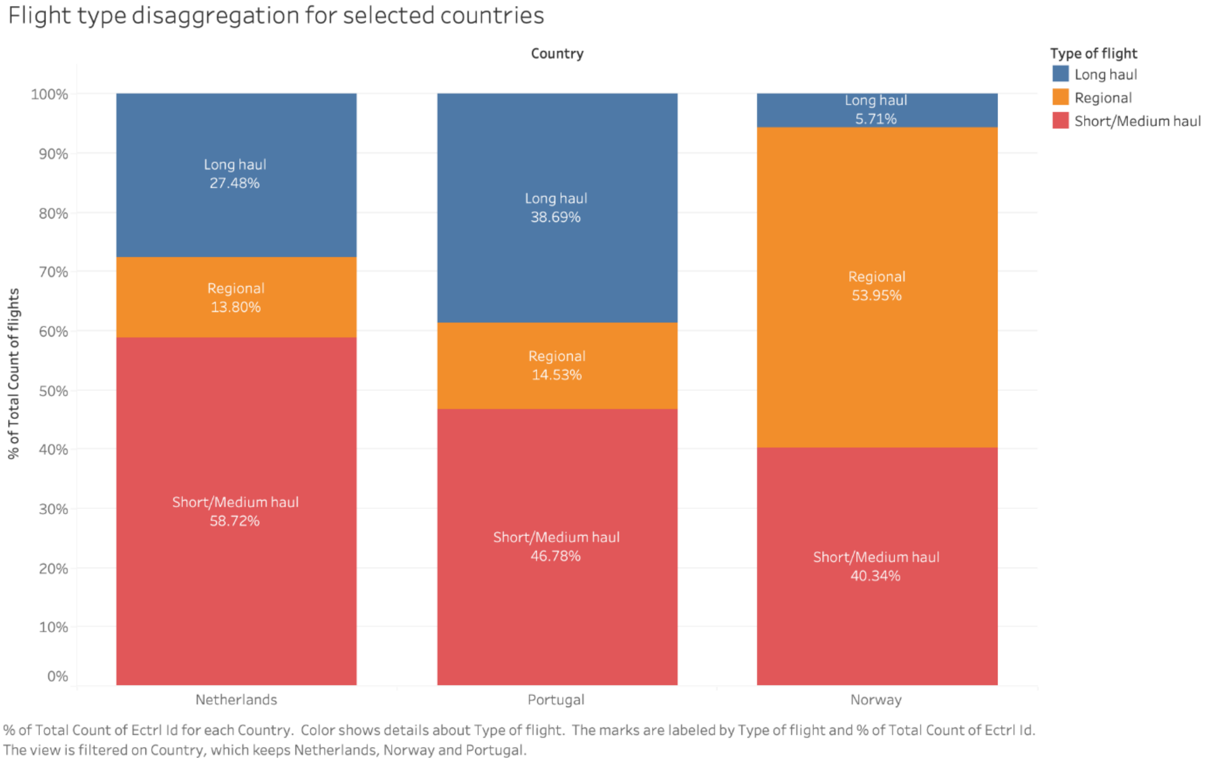
Results and Discussion

This chapter presents the characterization of the current situation which is derived from using the EEA methodology to determine the emissions inventory of the commercial aviation industry for the selected countries for the case study, The Netherlands, Norway, and Portugal. Following, a comprehensive analysis of the best performing energy carriers which are able to help decarbonize the hard to abate industry such as the aviation industry. Subsequently, an interpretation and comparison of the results regarding their energy intensity and emissions intensity of each of the options. Lastly, a comparison of the requirements of energy carriers in each of the options stated and the available or current level or production or capacity installed in each of the countries in the case study.

4.1 Characterization of current situation

The present section describes the present situation of the aviation industry. For this, a dataset from real aviation data is used. The data corresponds to all flights which occurred between the first and last day of December 2019. For the present work, three countries were selected, being them the Netherlands, Norway, and Portugal. These countries were chosen as they represent different realities of the European aviation sector.

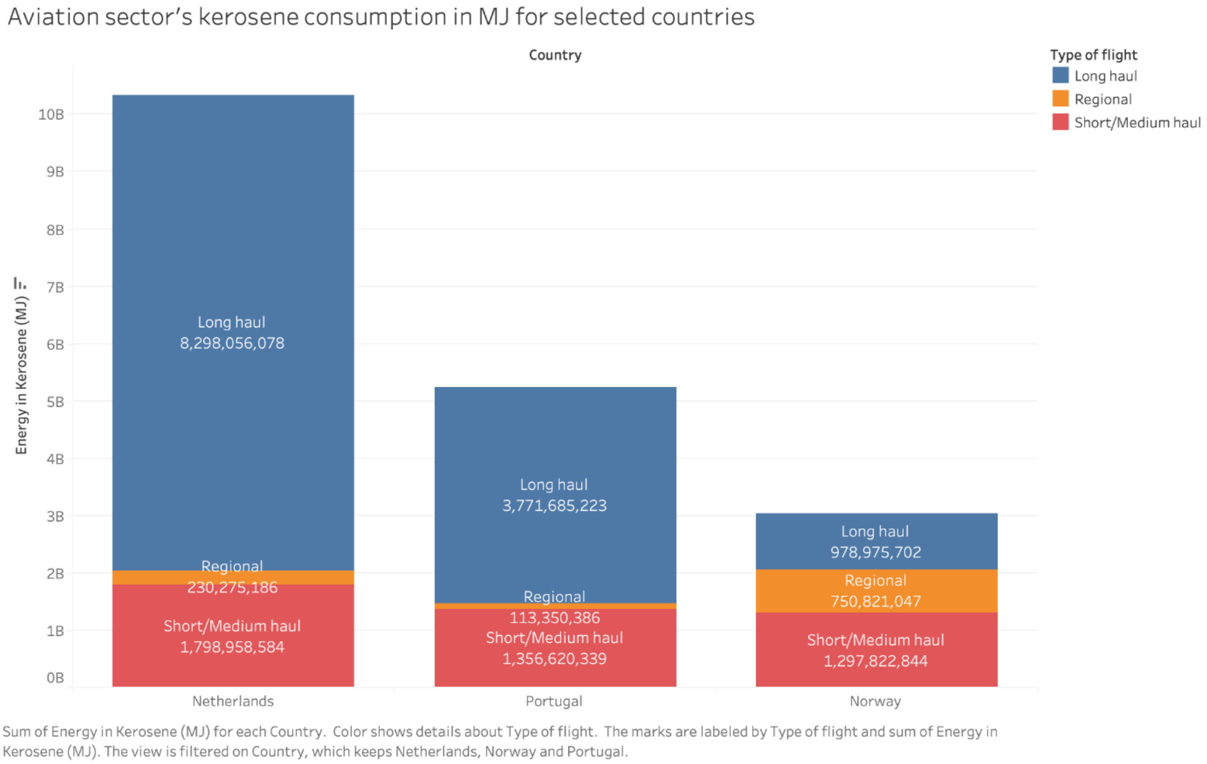
For the purpose of characterizing and being able to compare the result with other reports, flight type was separated into three categories, regional flights, short/medium haul flights and long-haul flights. For this, regional flights were considered flights shorter than one hour of flight, short/medium haul flights were considered flights between 1 and 2.5 hours of flight, and long-haul flights were considered flights longer than 2.5 hours. Figure 25 shows the disaggregation of the total number of flights per flight type. From this, it can be grasped that Portugal, and the Netherlands commercial aviation industry is composed of a majority of flights being short, medium, and long haul. In contrast, most of the flights occurring in Norway are regional and short/medium haul flights.


Flight type disaggregation for selected countries

% of Total Count of Ectrl Id for each Country. Color shows details about Type of flight. The marks are labeled by Type of flight and % of Total Count of Ectrl Id. The view is filtered on Country, which keeps Netherlands, Norway and Portugal.

Figure 25. Flight type disaggregation (%) for selected countries, (December,2019)

For the same period of time, energy used in megajoules/petajoules was calculated. Figure 26 shows the aviation sector’s kerosene consumption for the selected period and selected countries. Here it can be identified how long-haul flights are the ones using most of the energy. This is notably the case for the Netherlands and Portugal where consumption from this category is over 8 petajoules and 3 petajoules respectively. In the case of Norway, every category consumes 1 petajoule of energy. For comparing reasons, 1 petajoule is the same as 278 gigawatt hours of energy which is enough energy to power 19,000 homes in a year, or 868,000 refrigerators in a year [49].

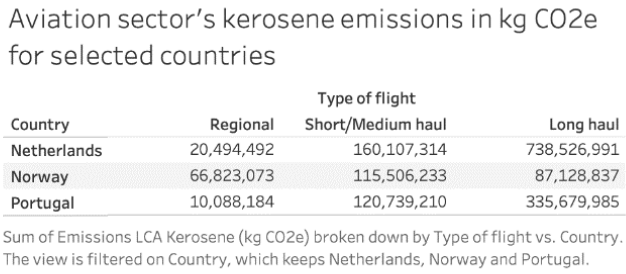


Sum of Energy in Kerosene (MJ) for each Country. Color shows details about Type of flight. The marks are labeled by Type of flight and sum of Energy in Kerosene (MJ). The view is filtered on Country, which keeps Netherlands, Norway and Portugal.

Figure 26. Aviation sector's kerosene consumption in MJ for selected countries, (December,2019)

When considering the emissions resulted from the consumption of kerosene from these three countries, it can be observed a similar trend. Figure 27 shows the aviation sector's emissions resulting from the kerosene consumption for the selected period and selected countries. The Netherlands has the highest percentage of total emissions of kerosene (CO_2) for long haul flights at 83.25%, which represents 738 kt of CO_2 equivalent. Portugal is next of the three with its highest percentage of total emissions of kerosene (CO_2) for long haul flights at 71.96%, which represents 335 kt of CO_2 equivalent. Lastly, Norway with its highest percentage of total emissions of kerosene (CO_2) for short/medium haul flights at 42.87%, which represents 115kt of CO_2 equivalent. Table 10 includes the emissions for all the flight types considered for the selected countries.

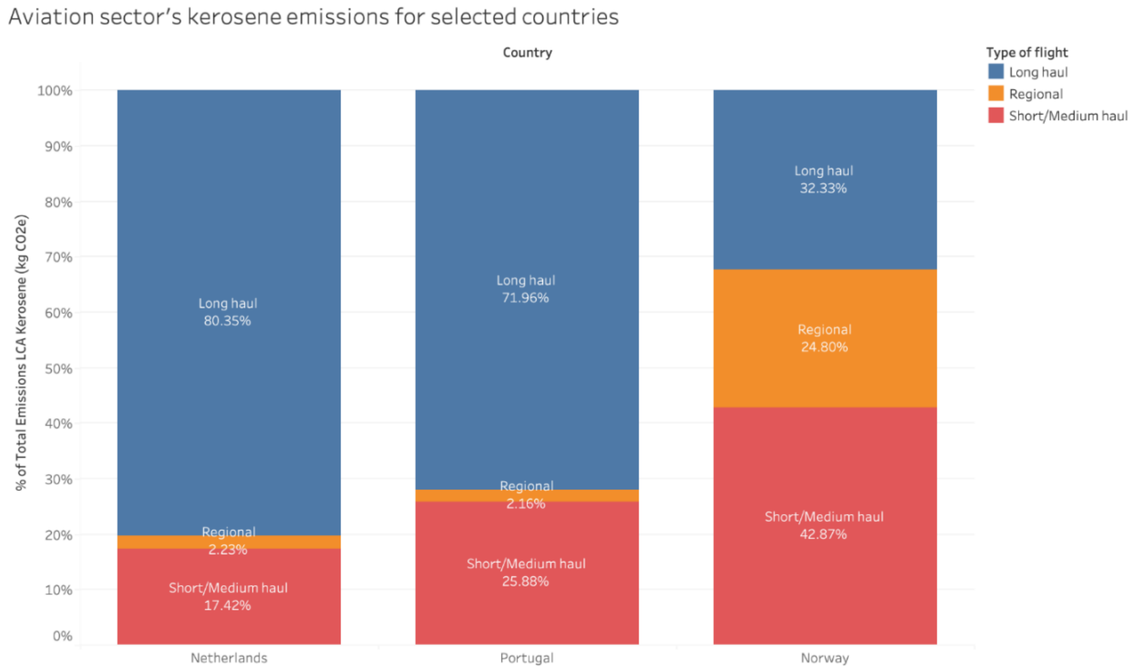
Table 10. Aviation sector's kerosene emissions in kg CO_2e, (December,2019)



Aviation sector's kerosene emissions in kg CO2e for selected countries

Country	Type of flight Regional	 Short/Medium haul	 Long haul
Netherlands	20,494,492	160,107,314	738,526,991
Norway	66,823,073	115,506,233	87,128,837
Portugal	10,088,184	120,739,210	335,679,985

Sum of Emissions LCA Kerosene (kg CO2e) broken down by Type of flight vs. Country. The view is filtered on Country, which keeps Netherlands, Norway and Portugal.



% of Total Emissions LCA Kerosene (kg CO2e) for each Country. Color shows details about Type of flight. The marks are labeled by Type of flight and % of Total Emissions LCA Kerosene (kg CO2e). The view is filtered on Country, which keeps Netherlands, Norway and Portugal.

Figure 27. Aviation sector's kerosene emissions for selected countries, (December,2019)

Table 11 shows the amount of carbon dioxide equivalent (CO_2e) emissions per passenger kilometre (Pk) for different types of flights in the Netherlands, Norway, and Portugal. For regional flights, Norway has the lowest emissions at 189.25g CO_2e/Pk, followed by the Netherlands at 183.37g CO_2e/Pk, and Portugal with the highest at 190.57g CO_2e/Pk. In terms of short/medium haul flights, Norway also leads with 108.20g CO_2e/Pk, while the Netherlands emits 109.21g CO_2e/Pk, and Portugal has the least emissions at 97.33g CO_2e/Pk. For long haul flights, the Netherlands has the highest emissions at 94.21g CO_2e/Pk, Portugal is slightly lower at 87.15g CO_2e/Pk, and Norway has the lowest emissions at 86.87g CO_2e/Pk.

This data is crucial for understanding the environmental impact of air travel in these countries and will help to better compare with the emissions intensity of the other decarbonization options in the next section.

Table 11. CO_2e emissions per passenger kilometre for selected countries, (December,2019)

Country	Flight type	Kerosene (g CO_2e/Pk)
Netherlands	Regional	183.37
	Short/Medium haul	109.21
	Long haul	94.21
Norway	Regional	189.25
	Short/Medium haul	108.20
	Long haul	86.87
Portugal	Regional	190.57
	Short/Medium haul	97.33
	Long haul	87.15

4.2 Case Study: (1) The Netherlands

In this case study, the aviation industry of the Netherlands will be assessed with different decarbonization options in three scenarios. First scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the towards development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircrafts. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircrafts is pushed. Here, short/medium and long-haul flights are decarbonized with sustainable aviation fuel.

4.2.1 Scenario A: pessimistic

Table 12 provides an overview of the energy consumption in terajoules (TJ) for different types of flights under the pessimistic scenario, where Sustainable Aviation Fuels (SAF) replace kerosene. For regional flights, the average energy consumption with SAF is 230.3 TJ. In the case of short to medium-haul flights, the energy consumption increases significantly to 1799.0 TJ. The highest energy consumption is observed in long-haul flights, where it reaches 8298.1 TJ when using SAF.

Table 12. Average energy per flight type, Netherlands, pessimistic scenario

Type of flight	**Pessimistic (SAF)**	**Energy (TJ)**
Regional	SAF	230.3
Short/Medium haul	SAF	1799.0
Long haul	SAF	8298.1

Figure 28 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under two scenarios: Business as Usual and the Pessimistic scenario. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is of 65% in life cycle emissions. While being able to use the same fleet of aircrafts and same infrastructure in current airports.

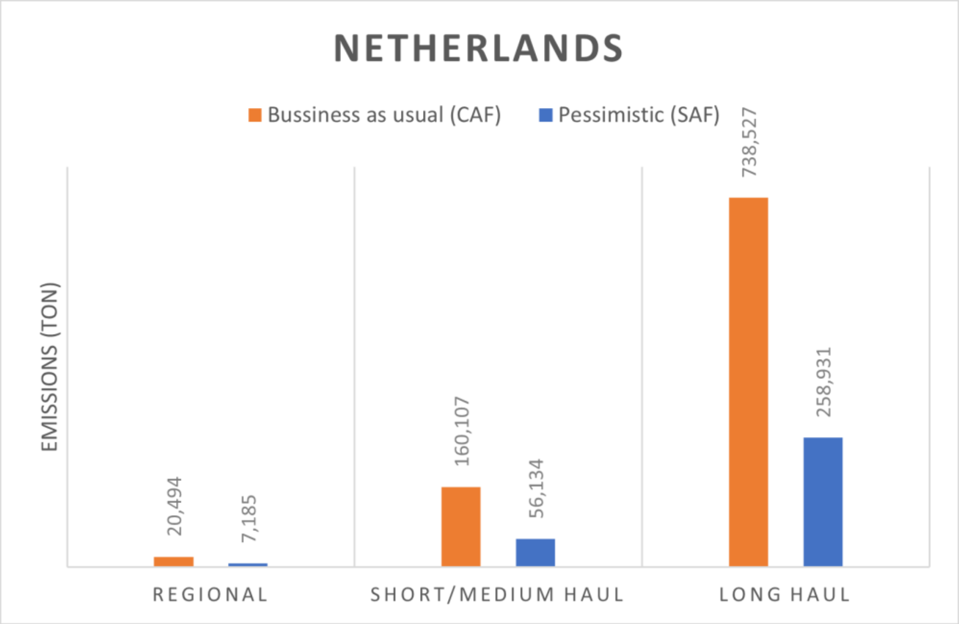


Figure 28. Emissions per flight type, Netherlands, BAU vs pessimistic

4.2.2 Scenario B: Towards hydrogen development

The Table 13 outlines an overview of the energy consumption in terajoules (TJ) for different types of flights under the “Towards hydrogen development” scenario, where hydrogen replace kerosene for the regional and short medium haul flights while kerosene being replaced by Sustainable aviation fuels (SAF) for the long-haul flights. For regional flights, hydrogen is used as the fuel source, resulting in an energy consumption of 184.2 TJ. Similarly, for short to medium-haul flights, hydrogen is used, leading to an energy consumption of 1439.2 TJ. However, for long-haul flights, Sustainable Aviation Fuels (SAF) are used instead of hydrogen, with an energy consumption reaching 8298.1 TJ.

Table 13. Energy per flight type, Netherlands, Towards hydrogen development scenario

Type of flight	**Towards hydrogen development**	**Energy (TJ)**
Regional	H2	184.2
Short/Medium haul	H2	1439.2
Long haul	SAF	8298.1

Figure 29 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and “towards hydrogen development” using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, and short/medium, the emissions are noticeably lower in the “towards hydrogen development” scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, “towards hydrogen development” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

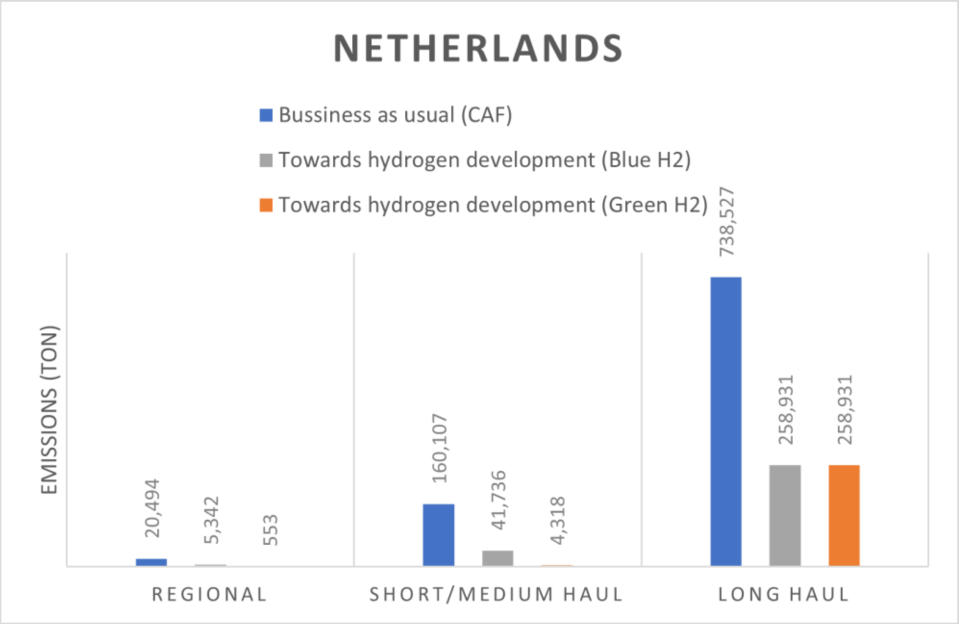


Figure 29. Emissions per flight type, Netherlands, BAU vs Hydrogen development

Emissions reductions observed in Figure 29 correspond to a reduction in emissions for both regional and short/medium haul flights of 74% with the use of blue hydrogen and 97% with the use of green hydrogen. For long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

4.2.3 Scenario C: Towards electrification

The Table 14 summaries an overview of the energy consumption in terajoules (TJ) for different types of flights under the “Towards electrification” scenario, where regional flights are electrified through batteries while kerosene being replaced by Sustainable aviation fuels (SAF) for the short medium haul flights and the long-haul flights. For regional flights, electricity is used as the fuel source, resulting in an energy consumption of 102.3 TJ. However, for short to medium-haul flights, Sustainable Aviation Fuels (SAF) are used instead of electricity, leading to an energy consumption of 1799.0 TJ and with an energy consumption reaching 8298.1 TJ for long-haul flights.

Table 14. Energy per flight type, Netherlands, Towards electrification scenario

Type of flight	**Towards electrification**	**Energy (TJ)**
Regional	Electric	102.3
Short/Medium haul	SAF	1799.0
Long haul	SAF	8298.1

Figure 30 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and “Towards electrification” using two sources of electricity generation, Electricity from the countries’ grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional flight category, the emissions are noticeably lower in the “Towards electrification” scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircrafts can significantly reduce emissions for these types of flights. Moreover, the use of renewable energy can reduce the emissions even further compared to using the national grid average, at least while this one is decarbonized. For short/medium haul and long-haul flights the, “towards electrification” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

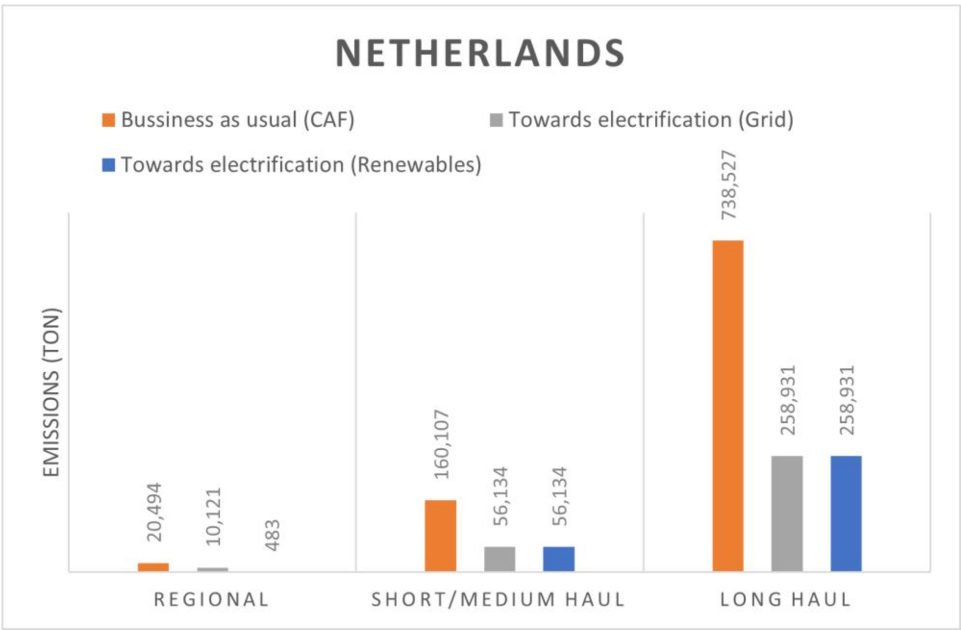


Figure 30. Emissions per flight type, Netherlands, BAU vs electrification

Emissions reductions observed in Figure 30 correspond to a reduction in emissions for regional of 51% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

4.3 Case Study: (2) Norway

Like previous case study, the aviation sector of Norway will be assessed with different decarbonization options in three scenarios. First scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircrafts. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircrafts is pushed. Here, short/medium, and long-haul flights are decarbonized with sustainable aviation fuel.

4.3.1 Scenario A: pessimistic

Table 15 provides an overview of the energy consumption in terajoules (TJ) for different types of flights under the pessimistic scenario, where Sustainable Aviation Fuels (SAF) replace kerosene. For regional flights, the energy consumption with SAF is 750.8 TJ. The highest energy consumption is observed in the case of short to medium-haul flights, the energy consumption increases significantly to 1297.8 TJ. In the case of long-haul flights, the energy consumption decreases slightly to 979.0 TJ.

Table 15. Energy per flight type, Norway, pessimistic scenario

Type of flight	**Pessimistic (SAF)**	**Energy (TJ)**
Regional	SAF	750.8
Short/Medium haul	SAF	1297.8
Long haul	SAF	979.0

Figure 31 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under two scenarios: Business as Usual and the Pessimistic scenario. The flights are categorized into three types: regional, short/medium haul, and long haul.

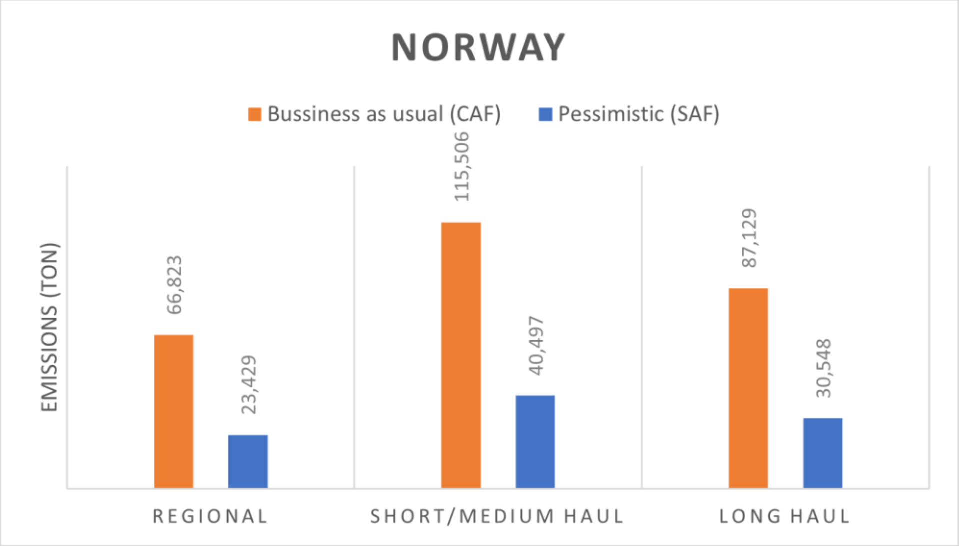


Figure 31. Emissions per flight type, Norway, BAU vs pessimistic

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of

Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is of 65% in life cycle emissions. While being able to use the same fleet of aircrafts and same infrastructure in current airports.

4.3.2 Scenario B: Towards hydrogen development

The Table 16 outlines an overview of the energy consumption in terajoules (TJ) for different types of flights under the "Towards hydrogen development" scenario, where hydrogen replace kerosene for the regional and short medium haul flights while kerosene being replaced by Sustainable aviation fuels (SAF) for the long-haul flights. For regional flights, hydrogen is used as the fuel source, resulting in an energy consumption of 600.7 TJ. Similarly, for short to medium-haul flights, hydrogen is used, leading to an energy consumption of 1038.3 TJ. However, for long-haul flights, Sustainable Aviation Fuels (SAF) are used instead of hydrogen, with an energy consumption reaching 979.0 TJ.

Table 16. Energy per flight type, Norway, Towards hydrogen development scenario

Type of flight	**Towards hydrogen development**	**Energy (TJ)**
Regional	H2	600.7
Short/Medium haul	H2	1038.3
Long haul	SAF	979.0

Figure 32 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under three scenarios: Business as Usual and "towards hydrogen development" using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are once again, categorized into three types: regional, short/medium haul, and long haul.

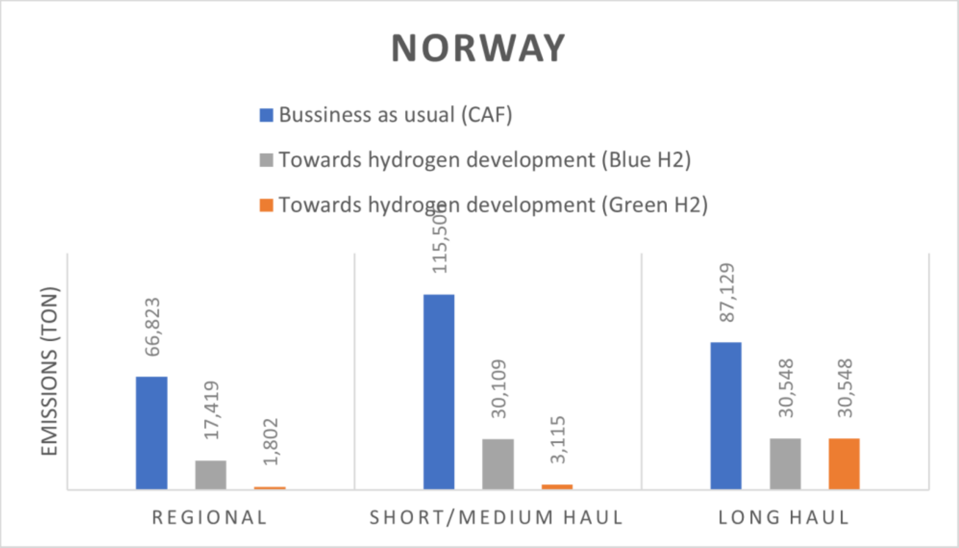


Figure 32. Emissions per flight type, Norway, BAU vs Hydrogen development

In the regional, and short/medium, the emissions are noticeably lower in the “towards hydrogen development” scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, “towards hydrogen development” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in Figure 32 correspond to a reduction in emissions for both regional and short/medium haul flights of 74% with the use of blue hydrogen and 97% with the use of green hydrogen. For long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario. For a country such as Norway, decarbonizing its shorter haul flights which include regional and shorter haul flights is a key, as it can be observed from the figure that is it were most of the emissions are currently being emitted.

4.3.3 Scenario C: Towards electrification

The Table 17 summaries an overview of the energy consumption in terajoules (TJ) for different types of flights under the “Towards electrification” scenario, where regional flights are electrified through batteries while kerosene being replaced by Sustainable aviation fuels (SAF) for the short medium haul flights and the long-haul flights. For regional flights, electricity is used as the fuel source, resulting in an energy consumption of 303.7 TJ. However, for short to medium-haul flights, Sustainable Aviation Fuels (SAF) are used instead of electricity, leading to an energy consumption of 1297.8 TJ and with an energy consumption reaching 979 TJ for long-haul flights.

Table 17. Energy per flight type, Norway, Towards electrification scenario

Type of flight	**Towards electrification**	**Energy (TJ)**
Regional	Electric	333.7
Short/Medium haul	SAF	1297.8
Long haul	SAF	979.0

Figure 33 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under three scenarios: Business as Usual and “Towards electrification” using two sources of electricity generation, Electricity from the countries’ grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional flight category, the emissions are noticeably lower in the “Towards electrification” scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircrafts can significantly reduce emissions for these types of flights.

Moreover, the reduction between the national countries grid with compared to 100% renewables is similar as the national grid in Norway and the Nordic countries is mostly based on renewables and. For short/medium haul and long-haul flights the, “towards electrification” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in Figure 33 correspond to a reduction in emissions for regional of 96% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

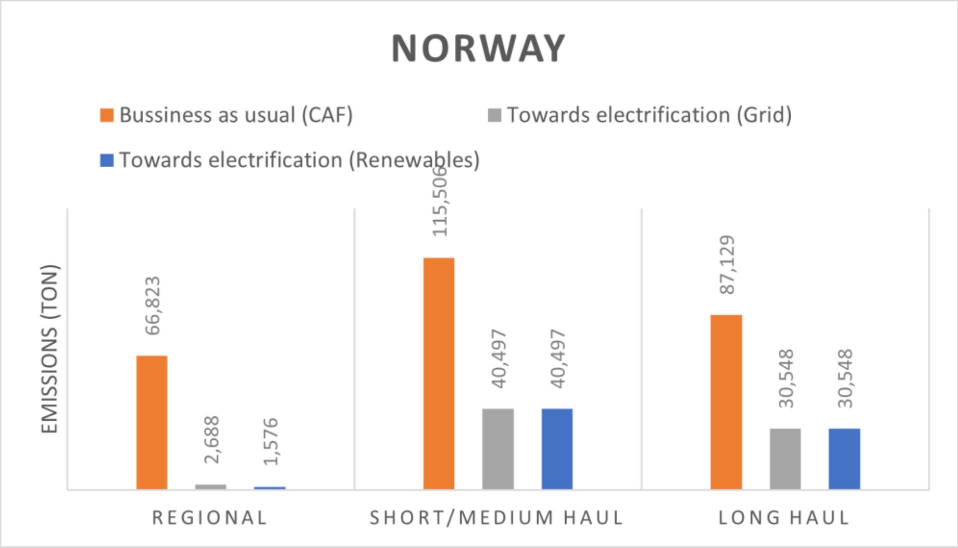


Figure 33. Emissions per flight type, Norway, BAU vs Electrification

4.4 Case Study: (3) Portugal

In this last case study, the aviation sector of Portugal will be assessed with different decarbonization options in three scenarios. First scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the towards development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircrafts. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircrafts is pushed. Here, short/medium, and long-haul flights are decarbonized with sustainable aviation fuel.

4.4.1 Scenario A: pessimistic

Table 18 provides an overview of the energy consumption in terajoules (TJ) for different types of flights under the pessimistic scenario, where Sustainable Aviation Fuels (SAF) replace kerosene. For regional flights, the energy consumption with SAF is 113.4 TJ. In the case of short to medium-haul flights, the energy consumption increases significantly to 1356.6 TJ. The highest energy consumption is observed in long-haul flights, where it reaches 3771.7 TJ when using SAF.

Table 18. Energy per flight type, Portugal, pessimistic scenario

Type of flight	**Pessimistic (SAF)**	**Energy (TJ)**
Regional	SAF	113.4
Short/Medium haul	SAF	1356.6
Long haul	SAF	3771.7

Figure 34 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Portugal under two scenarios: Business as Usual and the Pessimistic scenario. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is of 65% in life cycle emissions. While being able to use the same fleet of aircrafts and same infrastructure in current airports.

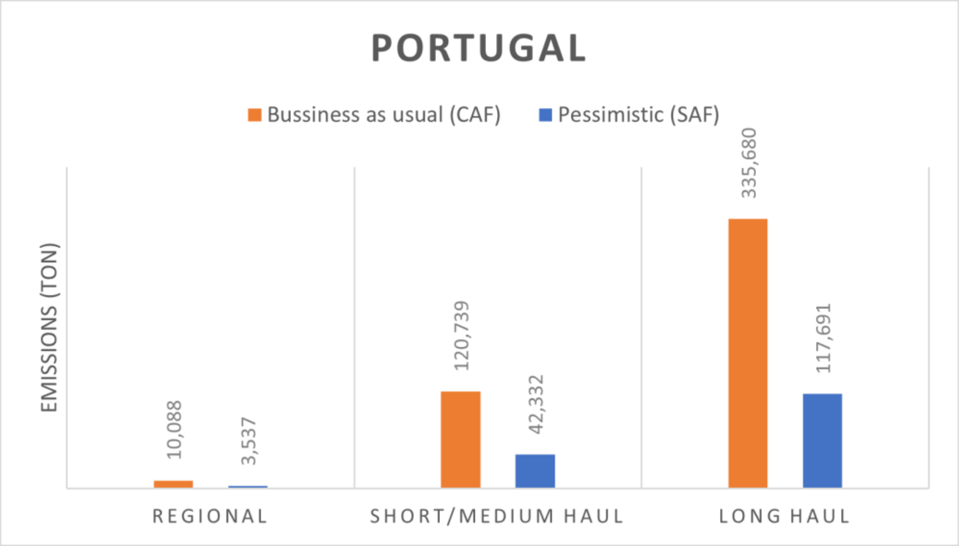


Figure 34. Emissions per flight type, Portugal, BAU vs pessimistic

4.4.2 Scenario B: Towards hydrogen development

The Table 19 outlines an overview of the energy consumption in terajoules (TJ) for different types of flights under the “Towards hydrogen development” scenario, where hydrogen replace kerosene for the regional and short medium haul flights while kerosene being replaced by Sustainable aviation fuels (SAF) for the long-haul flights. For regional flights, hydrogen is used as the fuel source, resulting in an energy consumption of 90.7 TJ. Similarly, for short to medium-haul flights, hydrogen is used, leading to an energy consumption of 1085.3 TJ. However, for long-haul flights, Sustainable Aviation Fuels (SAF) are used instead of hydrogen, with an energy consumption reaching 3771.7 TJ.

Table 19. Energy per flight type, Portugal, Towards hydrogen development scenario

Type of flight	**Towards hydrogen development**	**Energy (TJ)**
Regional	H2	90.7
Short/Medium haul	H2	1085.3
Long haul	SAF	3771.7

Figure 35 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and “towards hydrogen development” using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, and short/medium, the emissions are noticeably lower in the “towards hydrogen development” scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, “towards hydrogen development” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

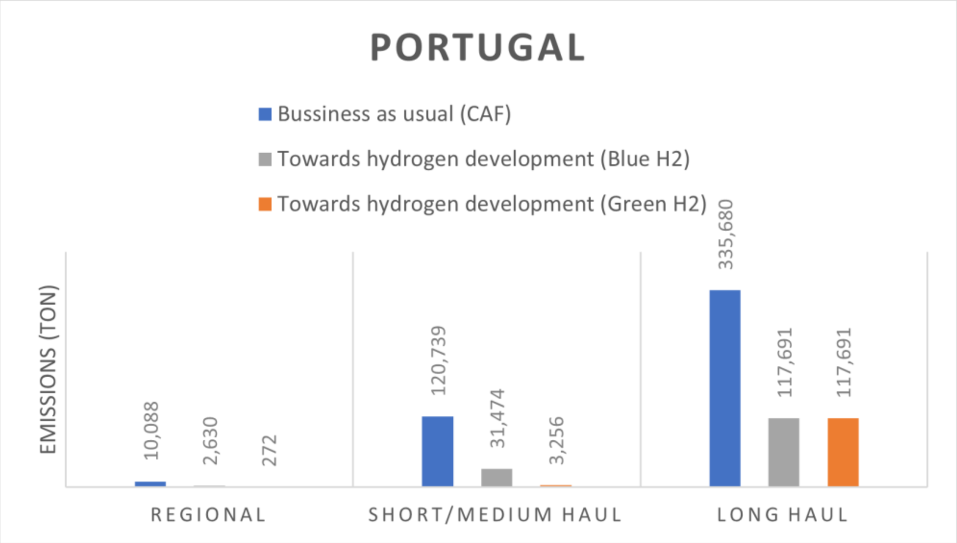


Figure 35. Emissions per flight type, Portugal, BAU vs Hydrogen development

Emissions reductions observed in Figure 35 correspond to a reduction in emissions for both regional and short/medium haul flights of 74% with the use of blue hydrogen and 97% with the use of green hydrogen. For long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

4.4.3 Scenario C: Towards electrification

The Table 20 summaries an overview of the energy consumption in terajoules (TJ) for different types of flights under the “Towards electrification” scenario, where regional flights are electrified through batteries while kerosene being replaced by Sustainable aviation fuels (SAF) for the short medium haul flights and the long-haul flights. For regional flights, electricity is used as the fuel source, resulting in an energy consumption of 50.4 TJ. However, for short to medium-haul flights, Sustainable Aviation Fuels (SAF) are used instead of electricity, leading to an energy consumption of 1356.6 TJ and with an energy consumption reaching 3771.7 TJ for long-haul flights.

Table 20. Energy per flight type, Portugal, Towards electrification scenario

Type of flight	**Towards electrification**	**Energy (TJ)**
Regional	Electric	50.4
Short/Medium haul	SAF	1356.6
Long haul	SAF	3771.7

Figure 36 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and “Towards electrification” using two sources of electricity generation, Electricity from the countries’ grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional flight category, the emissions are noticeably lower in the “Towards electrification” scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircrafts can significantly reduce emissions for these types of flights. Moreover, the use of renewable energy can reduce emissions even further compared to using the national grid average, at least while this one is continuing its decarbonization journey. For short/medium haul and long-haul flights the, “towards electrification” keeps sustainable aviation fuels (SAFs) as the alternative and that’s why emissions decrease but not as much as for the previous categories.

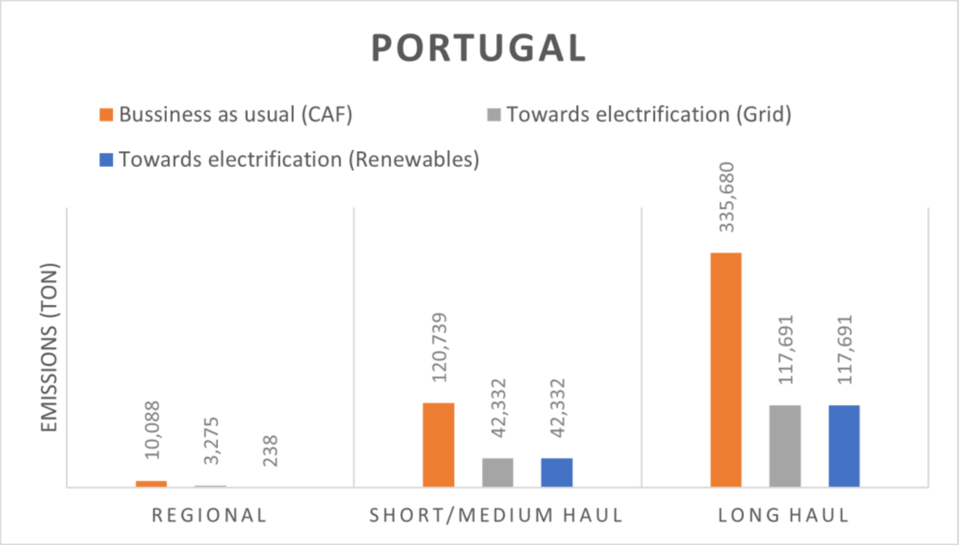


Figure 36. Emissions per flight type, Portugal, BAU vs Electrification

Emissions reductions observed in Figure 36 correspond to a reduction in emissions for regional of 68% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

Next section will discuss the key findings and provide further analysis of the decarbonization options results.

4.5 Key findings

Final emission intensities are obtained dividing the total emissions by the total number of passengers and kilometres travelled and presented in Table 21. For hydrogen and electric powered aircrafts, the total number of seats most likely will decrease, this was not considered in this study. This table offers a comprehensive comparison of the emissions intensity in the aviation sector across three selected countries for the case studies: the Netherlands, Norway, and Portugal. It also summarizes several decarbonization options, including blue and green hydrogen, grid and renewable electrification, and sustainable aviation fuel (SAF).

From the table, it’s evident that the regional flights have the highest emissions intensity in its aviation sector, while long haul flights have the lowest. This could be attributed to various factors such as the volume of air traffic, efficiency of aircrafts, and load factors assumed in section 3.5. The emissions intensity notably decreases when decarbonization options are assessed in the scenarios. For regional flights the lowest emissions intensity is found using renewable energy or green hydrogen resulting in 5 g CO_2e/Pk. Next for the short-medium haul flights, the lowest emissions intensity is found using green hydrogen resulting in around 3 g CO_2e/Pk. Lastly, long haul flights were only evaluated using sustainable aviation fuels (SAF), decreasing the emission intensity to 30 g CO_2e/Pk.

Table 21. CO_2e emissions per passenger kilometre (Decarbonization options summary)

Countries	Flight categories	Kerosene (gCO2e/Pk)	SAF (g CO2e/Pk)	Towards hydrogen development (Blue) (gCO2e/Pk)	Towards hydrogen development (Green) (gCO2e/Pk)	Towards electrification (Grid) (gCO2e/Pk)	Towards electrification (Renewable) (gCO2e/Pk)
Netherlands	Regional	183.4	64.3	47.8	4.9	90.6	4.3
	Short/Medium haul	109.2	38.3	28.5	2.9	38.3	38.3
	Long haul	94.2	33.0	33.0	33.0	33.0	33.0
Norway	Regional	189.3	66.4	49.3	5.1	7.6	4.5
	Short/Medium haul	108.2	37.9	28.2	2.9	37.9	37.9
	Long haul	86.9	30.5	30.5	30.5	30.5	30.5
Portugal	Regional	190.6	66.8	49.7	5.1	61.9	4.5
	Short/Medium haul	97.3	34.1	25.4	2.6	34.1	34.1
	Long haul	87.1	30.6	30.6	30.6	30.6	30.6

Following this analysis, the most natural question would be to assess how far we are to obtaining the enough production of these energy carriers, in such a way to be able to replace jet fuel partially or fully with a more sustainable alternative.

4.5.1 Sustainable Aviation fuels (SAF)

Table 22 presents the data on the quantity of sustainable aviation fuel (SAF) required to substitute jet fuel in selected countries, based on an annualized calculation using December's traffic data. For instance, The Netherlands would need 2,882 kt of SAF annually, equivalent to 123 Petajoules of energy. In comparison, Norway would need a lesser amount, 844 kt of SAF, which is equivalent to 36 Petajoules of energy per year. Portugal, on the other hand, would require 1,462 kt of SAF annually, translating to 62 Petajoules of energy.

Table 22. Sustainable aviation fuel required.

Country	Fuel required SAF (kt/yr)
Netherlands	2,882.03
Norway	844.92
Portugal	1,462.79

Sustainable aviation fuel from Hydrotreated Esters and Fatty Acids (HEFA) is currently the most common pathway found by different producers of sustainable aviation fuel. Hydro processed Esters and Fatty Acids (HEFA) is a process that transforms vegetable oils, waste oils, or fats into Sustainable Aviation Fuel (SAF) using hydrogen. The process begins with the removal of oxygen through hydrodeoxygenation. Following this, the straight paraffinic molecules undergo cracking and isomerization to achieve the appropriate chain length for jet fuel [50]. Teixeira et al. [51] mentions that for the Netherlands has a total potential for UCO of 0.058 MT/year, with a current collection ratio of 76.5%, and an estimated collected UCO estimate of 0.044 MT/year. Next, Portugal has a total potential for UCO of 0.055 MT/year, with a current collection ratio of 58.7 %, and an estimated collected UCO estimate of 0.032 MT/year. For Norway, the author doesn't include any data.

Staples et al. [52] carried out an extensive study on the worldwide availability of feedstock, estimating a maximum availability of 510 EJ/yr, a minimum of 41 EJ/yr, and a baseline estimate of 178.7 EJ/yr. Factors influencing these calculations include the suitability threshold of agro climate (impact of climate change), yields of feedstock crops, thresholds of land use change emissions, among others. Assuming all feedstocks (ranging from minimum to maximum availability) are used exclusively for bio jet fuel production (disregarding other uses and feedstock costs), bio jet fuel production could range from 34.4 EJ/yr to 201.9 EJ/yr. In the scenario with the least feedstock availability, nearly 90% of jet fuel demand could be satisfied if all feedstocks are dedicated to bio jet production [53].

The estimated investment required for SAF producers from 2021 to 2050 is approximately €10.4-10.5 billion. This is because there is a need to construct an additional 104 to 106 SAF facilities within the EU by 2050 in order to meet the demand for SAF production capacity [54]. This to be able to fulfil the requirement from the Refuel aviation mandates which are that starting from 1st January 2025, there will be a requirement for a minimum of 2% of aviation fuel to be Sustainable Aviation Fuel (SAF). This requirement will increase over time, with a minimum of 5% SAF by 2030, which includes at least 0.7% synthetic aviation fuels. By 2035, the minimum SAF requirement will rise to 20%, including at least 5% synthetic fuels. In 2040, the minimum SAF share will be 32%, with synthetic fuels making up at least 8% of this. By 2045, the minimum SAF volume share will increase to 38%, with synthetic fuels constituting at least 11%. Finally, by 2050, the minimum volume share of SAF will be 63%, with synthetic fuels making up at least 28% of this [55].

4.5.2 Hydrogen

Table 23 presents the data on the quantity of hydrogen required to substitute jet fuel in selected countries, based on an annualized calculation using December’s traffic data. For instance, The Netherlands would need 162 kt of H2 annually, equivalent to 19 Petajoules of energy. In comparison, Norway would need 163 kt of H2, which is equivalent to 19 Petajoules of energy per year. Portugal, on the other hand, would require 117 kt of H2 annually, translating to 14 Petajoules of energy. Hydrogen quantities calculated are only for replacing jet fuel usage in regional and short to medium haul flights, long haul flights would still require sustainable aviation fuel. Based on calculations from [56], [57] to satisfy the fuel requirements of green hydrogen in the selected countries, it would be needed to install 1 GW of installed capacity for both the Netherlands and Norway, and 750 MW of installed capacity in Portugal.

Table 23. Hydrogen required for replacing current jet fuel usage.

Country	Fuel required H2 (Kt/yr)
Netherlands	162.34
Norway	163.89
Portugal	117.60

To better understand the magnitude of hydrogen fuel needed from the estimations made in the current work, it is good to compare with the hydrogen production capacity currently installed in each of the countries selected. Figure 37 displays the production of hydrogen per year for each of the countries in the European continent. From this, it stands out The Netherlands with the second highest production of all with 1.5 Mt of hydrogen per year, next comes Norway with under 200 kt of hydrogen production and later comes Portugal with around additional 100 kt of hydrogen production per year (currently, 2023, Portugal is producing ~150 kt/year). This graph also indicated whether the hydrogen is a by-product, merchant, or captive. In Blue it is Captive hydrogen production, which is mainly on-site production for own consumption within the same facility. Next in green, Merchant includes excess capacity in dedicated facilities which is sold to external merchant companies for further resale. And at the end in grey, by-product hydrogen is hydrogen that is used as feedstock for internal processes.

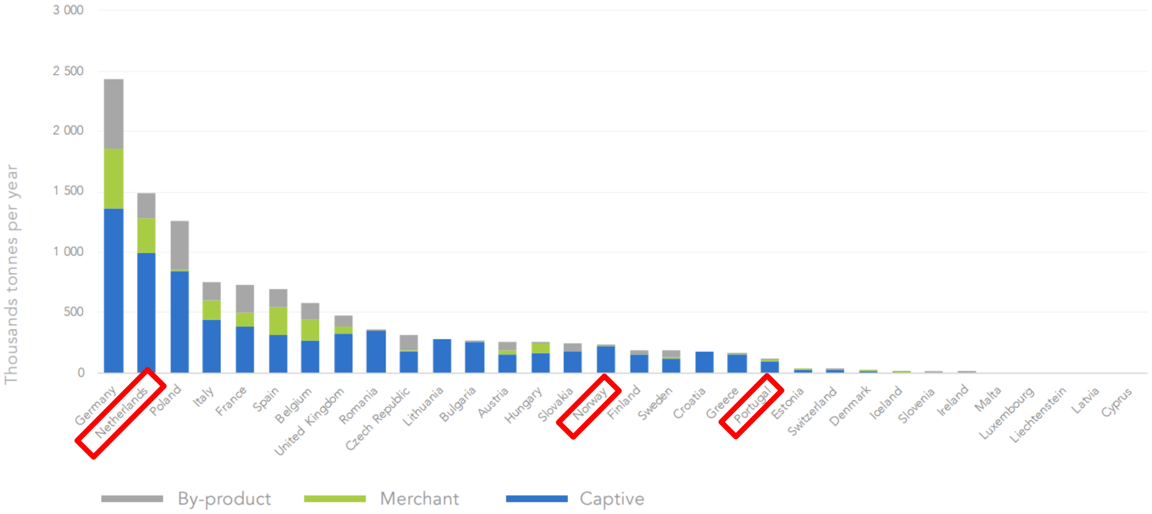


Figure 37. Total hydrogen production capacity by country [56]

One of the leading countries in hydrogen production is the Netherlands, which generates about 175 PJ (1.5 Mt) of hydrogen every year, mostly for industrial purposes [58]. The main applications of hydrogen in the Netherlands include oil refining, ammonia production, methanol production, and steel production. The country has an ambitious goal of increasing its green hydrogen production capacity to at least 4 gigawatts by 2030 and 8 gigawatts by 2032 [59].

On the other side, Norway has a strong potential to become a leader in hydrogen production. The company Norwegian Hydrogen is expected to launch its green hydrogen operations by the end of this year, with a fully developed capacity of 270 MW which translates to 40 kt of green hydrogen annually [60]. Even more, with its abundant renewable energy resources and ambitious plans to expand wind power, Norway can leverage its competitive advantage in the hydrogen market [61], [62]. Norway also intends to contribute to the European hydrogen network as an importer and transit hub [57].

Lastly, Portugal also plans to start producing green hydrogen by the end of 2022 [63]. It already has private investment worth around 12 billion euros lined up for eight projects that are expected to move forward. Portugal’s hydrogen strategy includes building hydrogen fuel stations and making fuel cell buses. In addition, the share of hydrogen used in the national gas network is expected to rise to 15% by 2030 [64].

Overall, The EU's hydrogen consumption is mainly based on natural gas, which accounts for about 8 million tonnes per year. However, this source of hydrogen has a high carbon footprint and is not compatible with the EU's climate goals. Therefore, the EU aims to increase the production of renewable hydrogen, which is obtained from water electrolysis using electricity from renewable sources. Currently, the EU produces less than 0.3 million tonnes of electricity-based hydrogen per year, with an electrolyser output capacity of around 160 MW (hydrogen production capacity). To reach the target of 10 million tonnes of renewable hydrogen by 2030, the EU will need to install between 80-100 GW of electrolysers, which will require an additional 150-210 GW of renewable electricity generation capacity at low cost. This is a challenging but feasible objective, which will make renewable hydrogen a competitive and sustainable alternative to fossil-based hydrogen [65].

4.5.3 Electricity

Table 24 presents the data on the quantity of renewable electricity required to substitute jet fuel in selected countries for the regional type of flights, based on an annualized calculation using December’s traffic data. For instance, The Netherlands would need 341 GWh of electricity annually, equivalent to 1.23 Petajoules of energy. In comparison, Norway would need 1,112 GWh of electricity annually, which is equivalent to 4 Petajoules of energy per year. Portugal, on the other hand, would require 168 GWh of electricity annually, translating to 0.6 Petajoules of energy.

To meet the increased electricity demand from this amount of energy production, additional renewable energy capacity would have to be installed. Assuming an average capacity factor [66], [67] of 25% for solar PV and 35% for wind energy, the additional capacity required would be 160 MW in the Netherlands, 510 MW in Norway and 80 MW in Portugal. This is based on calculations using the current energy mix and demand patterns in each country and not considering future increase in demand.

Table 24. Electricity required for replacing current jet fuel usage.

Country	Electricity required (GWh/yr)
Netherlands	341
Norway	1,112
Portugal	168

The Netherlands’ electricity generation installed capacity was 52 GW in 2022 from which 55% was renewable. The renewable capacity is divided into 66% solar energy, 31% wind energy, and 3% bioenergy. Total electricity generation for 2021 was 122,132 GWh from which 67% was non-renewable and 33% was from renewable sources such as wind, solar and bioenergy [68].

Next, Norway’s electricity generation installed capacity was 40 GW in 2022 from which 98% was renewable. The renewable capacity is divided into 86% hydropower energy, 13% wind energy, and 1% solar. Total electricity generation for 2021 was 157,966 GWh from which 1% was non-renewable and 99% was from renewable sources such as Hydro and marine, and wind energy predominantly [69].

Lastly, Portugal’s electricity generation installed capacity was 23 GW in 2022 from which 72% was renewable. The renewable capacity is divided into 46% hydropower energy, 33% wind energy,16% solar and 4% bioenergy. Total electricity generation for 2021 was 50,980 GWh from which 38% was non-renewable and 62% was from renewable sources such as hydro and marine, wind energy, solar energy, and bioenergy [70].

Chapter 5

Conclusions

The present thesis aimed to analyse the overall performance of the different decarbonization options available for the aviation sector, mainly focusing on the use of different energy carriers. Three case studies such as The Netherlands, Norway and Portugal were analysed under three scenarios which tried to simulate the amount of energy that would be needed in each of these scenarios and the emissions from a life cycle perspective it will be entitled to. In this chapter, main findings are presented displaying a critical analysis of the limitations encountered. Lastly, future work directions are mentioned.

5.1 Main Findings

The present dissertation explores the multifaceted strategies that the aviation industry could adopt to achieve decarbonization and reach net-zero emissions by 2050, a commitment many have pledged to uphold [71]. The aviation industry's path to this goal is complex and requires a multi-pronged approach. Key actions include fleet renewal, adoption of disruptive propulsion technologies such as hydrogen fuel-cells and/or battery-powered, improvements in operational efficiency, increased usage of sustainable aviation fuel (SAF), and carbon offsetting [71].

In the present work, one of the several pathways to achieve the so deserved decarbonization and guilt-free flying is explored, here in the substitution of current jet fuel, with more sustainable alternatives such as drop-in Sustainable aviation fuels (SAF), hydrogen and direct electrification with batteries. Through a comprehensive emissions inventory made following European emissions reporting methods and a later well-to-wheel (wake) emissions analysis in which GHG emissions avoidance is compared to the baseline considering the assumptions and limitations. Lastly, a comparison of the current production or capacity installed of these more sustainable alternatives versus the amount needed to replace this energy requirement, on a high-level basis.

While Sustainable Aviation Fuel (SAF) is a leading development for decarbonization in the aviation industry. Other research areas include alternative energy sources such as hydrogen and electric power [72]. The presented analysis of the different decarbonization options has given rise to different path for each of the flight types, each with a different level of GHG emissions avoidance.

From the perspective of sustainable aviation fuels (SAF) as a decarbonization vector, different production methods and feedstock have a different emission factor which could compromise the sustainability of the fuel. Current production levels are low worldwide, with Europe and the United States leading with policies and mandates which are investing heavily into increasing the production of sustainable aviation fuel from both biological and non-biological feedstock. From the current work comparison, SAF is the best and only solution as of now to help reduce the emissions of long-haul flights, with an average emission avoidance of 65%. For the other flight types, regional and short-medium haul flights, the use of hydrogen and electrification wins in emissions avoidance but might take longer to be deployed according to recent technology advancements and hydrogen/energy production.

From the perspective of hydrogen as a decarbonization vector, again different production methods have a different emission factor which could compromise the sustainability of the fuel. From the current work comparison, highest GHG emissions avoidance were obtained when green hydrogen was used. Emissions avoidance for the moderate case were blue hydrogen with a high CCS usage and moderate methane emissions was found to be ten times higher emissions than its green hydrogen counterpart but still resulting in GHG overall emissions avoidance compared to baseline with jet fuel or the use of sustainable aviation fuel as decarbonization vector.

Lastly, from the perspective of electrification and the use of batteries as a decarbonization vector, emissions are highly connected to how electricity is produced and could compromise the overall sustainability of the option. From the current work comparison, highest GHG emission avoidance was obtained when electrification was achieved with renewable energy, in this case from wind and hydropower energy. Emissions avoidance for the moderate case where electricity is used from the grid resulted in different emission intensities depending on the current state of decarbonization of the grid. Having the highest emission intensity when using electricity from the grid in the Netherlands with a share of renewable energy in the grid of 33% and an emission intensity of 90.55 gCO_2e/Pk, next Portugal with a share of renewable energy in the grid of 62% and an emission intensity of 61.9 gCO_2e/Pk, and with the lowest emission intensity Norway with a share of renewable energy in the grid of 99% and an emission intensity of 7.61 gCO_2e/Pk.

Ultimately, this research presents contributions towards the important task of decarbonizing the aviation sector by providing a high-level overview of the studied decarbonization vectors and their GHG emissions avoidance contributions to policy makers, researchers and to the general public. An effective strategy for decarbonizing the aviation sector hinges on the thoughtful selection of alternative energy vectors such as SAF, hydrogen and electricity, and their respective power systems combinations. This approach should be a combination of all different options were better suitability and should not be only limited to the change of energy vector or technology but should also come together with policies to a sustainable decarbonization of the aviation sector for the whole society.

5.2 Future work

As the aviation industry continues to work continuously into a more sustainable future, further research can explore the use of emerging technologies solutions applied not only in the fuel source but also in overall system including improvements in practical opportunities to increase efficiency such as electrifying land taxing, improved aerodynamics, change in operations like continuous descent/climb among others stated in [9]. On the other hand, a deeper comparison with other means of transport such as passenger rail, bus, and cars as a more meaningful holistic way of comparing the different alternative and finding the best combined solutions for someone who would like to transport in a more sustainable way. This could be explored with a complete framework for the evaluation of sustainable energy systems such as a full techno-economic analysis [73] or a life cycle analysis with a multi criteria decision making [74] adding the cost variable into the analysis. Lastly, another interesting perspective to explore, could be into the market-based solutions such as carbon markets and cultural and behavioural shifts needed into achieving this greater sustainable goal.

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