

THE ENVIRONMENTAL IMPACT OF SUSTAINABLE AVIATION FUELS IN COMMERCIAL AIRPORTS

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Provas destinadas à obtenção de grau de:

Mestre em Operações de Transporte Aéreo

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VERSÃO FINAL

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Provas para obtenção do grau de Mestre em Operações de Transporte Aéreo

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RESUMO

A indústria da aviação prevê um crescimento do tráfego aéreo na ordem dos 3,7% a 3,8% por ano, resultando num aumento das emissões de gases com efeito de estufa. É necessário alternativas aos combustíveis fósseis afim de reduzir os impactos ambientais.

Ao longo do trabalho adotou-se uma abordagem descritiva, envolvendo um levantamento do estado da arte da tecnologia com base em uma revisão sistemática da literatura, a fim de fazer uma avaliação do impacto ambiental da introdução do combustível de aviação sustentável. Leva em consideração os diferentes combustíveis sustentáveis disponíveis e o potencial de redução das emissões poluentes de cada um. A análise das emissões de poluentes durante o ciclo de descolagens e aterragens antes e depois da introdução desses combustíveis demonstra os benefícios que podem trazer.

Este estudo tem como objetivo principal a análise do impacto ambiental derivado da utilização de combustíveis sustentáveis em aeroportos comerciais. Como objetivos específicos, é possível definir a identificação de diferentes combustíveis e comparar as emissões de gases com efeito de estufa e o impacto ambiental dos motores de aeronaves e do uso do *auxiliary power unit*, antes e depois da modificação.

É realizado um estudo de caso sobre o aeroporto de Lisboa com uma análise dos potenciais benefícios ambientais relacionados com a transição para o combustível sustentável. Os dados utilizados baseiam-se nos movimentos reais do aeroporto de Lisboa no período em análise, tendo em conta o motor que equipa cada uma das aeronaves e suportados em fatores de emissão do banco de dados de emissões de gases de escape da Organização Internacional de Aviação Civil.

Este caso de estudo permitiu identificar a fase mais crítica do ciclo de aterragem e descolagem, as opções de combustível alternativo menos poluentes, a frota mais crítica e outras alternativas para reduzir as emissões durante o táxi. Também permitiu quantificar a redução das emissões de gases com efeito de estufa relacionadas com os movimentos de aeronaves durante o ciclo ao utilizar combustível sustentável.

Palavras-chave

Airports, Aviation, Greenhouse Gases Emissions, Sustainable Aviation Fuel

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ABSTRACT

The aviation industry anticipates a traffic growth around 3.7% to 3.8% per year for the coming years, and consequently an increase in greenhouse gases emissions. It is necessary to create alternatives to fossil fuels in order to reduce its environmental impacts.

A descriptive approach is adopted, involving a survey of the state of the art of technology based on a systematic literature review in order to make an assessment of the environmental impact of introducing Sustainable Aviation Fuel. It takes into account the different Sustainable Aviation Fuels available and the potential for reducing pollutant emissions of each of them. The analysis of pollutant emissions during the landing and takeoff cycle before and after the introduction of sustainable aviation fuel demonstrates the benefits they can bring.

This study has as its main objective the analysis of the environmental impact derived from the use of sustainable aviation fuel at commercial airports. As specific objectives, it is possible to define the identification of different sustainable aviation fuels and comparing the greenhouse gases emissions and environmental impact from aircraft engines and the auxiliary power unit use, before and after the modification.

A case study about Lisbon airport is conducted with an analysis of the potential environmental benefits related to sustainable aviation fuel transition. The data used is based on the real movements of Lisbon airport in the period under analysis, knowing the engine that equips each one of aircraft and supported by emission factors from the International Civil Aviation Organization engine exhaust emission databank. This case study made it possible to identifying the most critical phase of the take-off cycle, the less polluting alternative fuel options, the most critical fleet and the other alternatives to reduce emissions during taxiing. It also quantifies the reduction in Greenhouse Gases Emissions related to the aircraft movements during the landing and takeoff cycle at an airport when using Sustainable Aviation Fuel.

KEYWORDS

Airports, Aviation, Greenhouse Gases Emissions, Sustainable Aviation Fuels

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ABBREVIATIONS AND ACRONYMS

ACA – Airport Carbon Accreditation

AHS – Airport Fuel Hydrant System

AST – Aboveground Storage Tank

ANA – Airports and Air Navigation

ANAC – Autoridade Nacional da Aviação Civil

APU – Auxiliar Power Unit

ATJ – Alcohol to Jet

ATM – Air Traffic Management

ASTM – American Society for Testing and Materials

CAAFI – Commercial Aviation Alternative Fuel Initiative

CHJ – Catalytic Hydrothermolysis Jet

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

EASA – European Union Aviation Safety Agency

EEA – European Environment Agency

EFTA – European Free Trade Association

EGTS – Electric Green Taxiing System

EI – Emission Index

EU – European Union

FCT – Field Constructed Tank

FFAP – Fuel Flow in Approach Conditions

FFCL – Fuel Flow in Climb Conditions

FFID – Fuel Flow in Idle Conditions

FFTO – Fuel Flow in Take-off Conditions

FRL – Fuel Readiness Level

FT – Fischer-Tropsch

GHGs – Greenhouse Gases

HC – Unburnt Hydrocarbons

HEFA – Hydro Processed Esters and Fatty Acids

HC – Hydrocarbon

HFS-SIP – Hydroprocessed Fermented Sugars to Synthetic Iso-Paraffins

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

ISA – International Standard Atmosphere

LCA – Life Cycle Analysis

LIS – Lisbon Airport IATA Code

LHV – Lower Heating Value

LTO – Landing and Take-off Cycle

MSW – Municipal Solid Wastes

PTL – Power-to-Liquid

SAF – Sustainable Aviation Fuel

SPK – Synthetic Paraffinic Kerosene

SPK/A – Synthetic Paraffinic Kerosene with Aromatics

TMAP – Time spent in Approach Phase

TMCL – Time spent in Climb Phase

TMID – Time spent in Taxi Phase

TMTO – Time spent in Take-off Phase

TRL – Technology Readiness Level

UST – Underground Storage Ta

1. INTRODUCTION

1.1. GENERAL

Anticipating the annual traffic growth that the aviation industry foresees for the coming years around 3.7% to 3.8% per year (IATA 2023a; Airbus 2022; Boeing 2022), which will represent a projected increase in the number of passengers transported from around 4 billion in 2019 to approximately 8 billion by 2041 (IATA 2023a), as depicted in Figure 1, it is necessary to create alternatives to fossil fuels to reduce the environmental impacts, in order to comply with the long-term strategy of achieving net-zero Greenhouse Gases (GHGs) emissions by 2050 (European Commission 2018). The projection presented in Figure 1 has 3 different scenarios, starting from a baseline scenario based on the current economic, environmental and social situation. It also presents an UP scenario, more positive, supported by a growth in the global economy, intense investment and sustainable increase in the sector, and a DOWN scenario, associated with a slowdown in the economy, an increase in fuel prices, and possible crises or events that can negatively affect the sector (Eurocontrol 2022). The use of Sustainable Aviation Fuels (SAFs) can significantly contribute for a reduction in the GHGs emissions in the aviation industry due to its significant potential to reduce CO₂ emissions (ICAO 2023), knowing that CO₂ is considered one of the most important contributors to the GHGs (Coelho and Costa 2008), but it is still necessary to understand the better available solutions and make them more economically attractive.

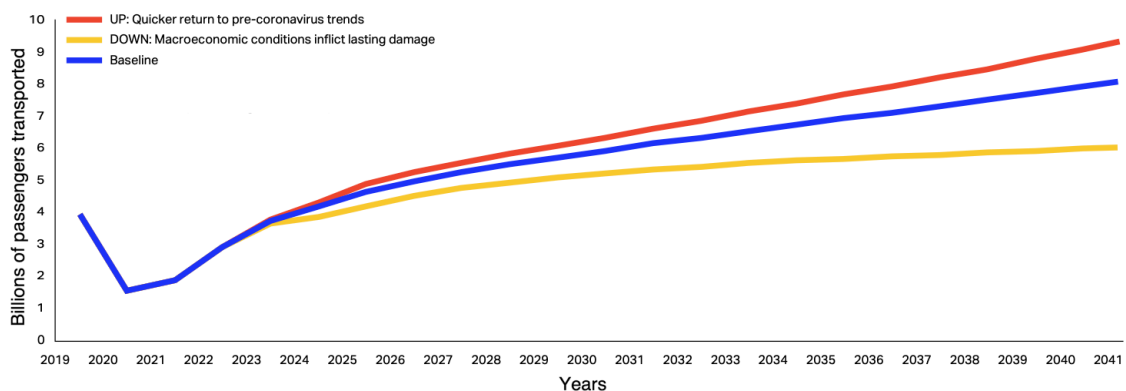


Figure 1: Global air passengers projections
Source: (IATA 2023a)

1.2. SCOPE

The study focuses on researching the current state of the energy transition for (Sustainable Aviation Fuel) SAF, taking into account the different SAFs available and the potential for reducing pollutant emissions of each of them. The analysis of pollutant emissions during the Landing and Takeoff Cycle (LTO) before and after the introduction of SAF demonstrates the benefits they can bring.

A case study about Lisbon airport will be conducted in order to compare the results obtained with the current reality.

1.3. MOTIVATION

The investigation into this subject seems of enormous relevance in order to reinforce and complement existing studies, demonstrating how the use of different alternatives to fossil fuels can reduce aviation's environmental impacts in commercial airports.

Therefore, looks beneficial to proceed with detailed analyses focused on commercial airports about each hypothetical alternative's environmental impact, comparing the different available options.

1.4. OBJECT AND OBJECTIVES

This study has as its main objective the analysis of the environmental impact derived from the use of SAF at commercial airports. This study will analyse the measures already adopted by some airports, the plans for the future, and how the use of SAF can impact air quality in general and in particular in areas close to airports.

As specific objectives, it is possible to define the identification of different SAFs and the estimation of the environmental impact for each option. Comparing GHGs emissions from aircraft engines and the Auxiliar Power Unit (APU) use, before and after the modification, based on hypothetical scenarios and airports where the modifications were already applied.

In this context, the following research question is defined: What are the environmental benefits derived from the introduction of SAF in commercial airports?

This leads to the definition of these working hypotheses:

H1: There will be a transition from jet fuel to SAF.

H2: Implementing SAFs in airports causes an environmental impact.

1.5. METHODOLOGY

To achieve the study's objectives, a descriptive quality approach is adopted, involving a survey of the state of the art of technology based on a systematic literature review in order to make an assessment of the environmental impact of introducing SAF. It takes into account the different SAFs available and the potential for reducing pollutant emissions of each of them. The analysis of pollutant emissions during the LTO cycle before and after the introduction of SAF demonstrates the benefits they can bring.

This work includes a case study about Lisbon airport (LIS), with an analysis of the potential environmental benefits related to SAF transition when comparing the environmental impact of the use of fossil fuels versus the potential emissions reduction of GHGs associated with the use of different SAFs. The data used is based on the real movements of LIS airport in the period under analysis, knowing the engine that equips each one of aircraft and supported by emission factors from the International Civil Aviation Organization (ICAO) Engine Exhaust Emission Databank.

The estimated emissions of several major GHGs (CO, CO₂, HC, NO_x and SO₂) during the LTO cycle at LIS Airport in the period under analysis, emitted by the engines and the APU, will also be analyzed, subsequently comparing them with the theoretical values expected for the same movements after the introduction of SAF.

1.6. WORK STRUCTURE

This dissertation is organized into five main chapters. The themes and organization of these chapters can be summarized as follows:

Chapter 2 (Literature Review) presents a systematic review of the published works and studies about the estimated traffic growth that the aviation, the concerns about the increasing pollution caused by the aeronautical industry due to the increase in traffic

which consequently translates into an increase in GHG emissions from planes and all support vehicles on the airside of an airport. This study analyzes the possible ways to reduce this impact, further deepening existing studies where the utilization of SAF's in the airport infrastructures is analyzed in detail from an environmental point of view. The different production pathways, the capacity and demand for SAF, and the state of readiness for the use of SAFs is one of the topics in focus, as well as the impact on the Life Cycle Analysis (LCA) of each of the pathways and different feedstocks.

An introduction is also made regarding the LTO cycle, describing how it can be used in the theoretical calculation of pollutant emissions, as well as the APU cycle, and how its use can influence GHGs emissions.

Chapter 3 (Case Study: Lisbon Airport) presents a case study developed in the Lisbon Airport, where an analysis of the number of aircraft movements over a week was carried out, as well the average number of movements of all support vehicles at the airport, and relating the data obtained to the amount of pollutants emitted. Subsequently, an analysis was made of the environmental that would be obtained by changing jet fuel to SAF in commercial aircrafts.

Chapter 4 (Result and Discussion) presents an analysis and discussion of the results obtained in the case study, comparing the amount of fuel required, the emissions of gCO₂e/MJ (that is an international measure that aims to establish equivalence between all GHGs and CO₂, which means in theory, all GHGs are converted into CO₂ to make it easier to analyze the environmental impacts (Pavlenko and Searle 2021) and the lower heating value (LHV) for each of the SAFs under analysis, based on these comparisons with the values associated with emissions using jet fuel.

Chapter 5 (Conclusion) exhibit the conclusions and the final remarks of the work.

2. LITERATURE REVIEW

2.1. AVIATION ENVIRONMENTAL IMPACTS

Over the last few years, the aviation sector has experienced stable and constant growth, despite all the challenges that, with greater or lesser frequency, arise, reversing or momentarily stagnating this trend. Once the effect of the pandemic has been overcome, it is expected that aviation will tend to return and overcome the growth of previous years (Eurocontrol 2022; Gudmundsson, Cattaneo, and Redondi 2021). The departing and arriving flights forecast in EU27+EFTA is depicted in Figure 2, based on three different demand scenarios (low traffic, base traffic and high traffic) until the year 2050.

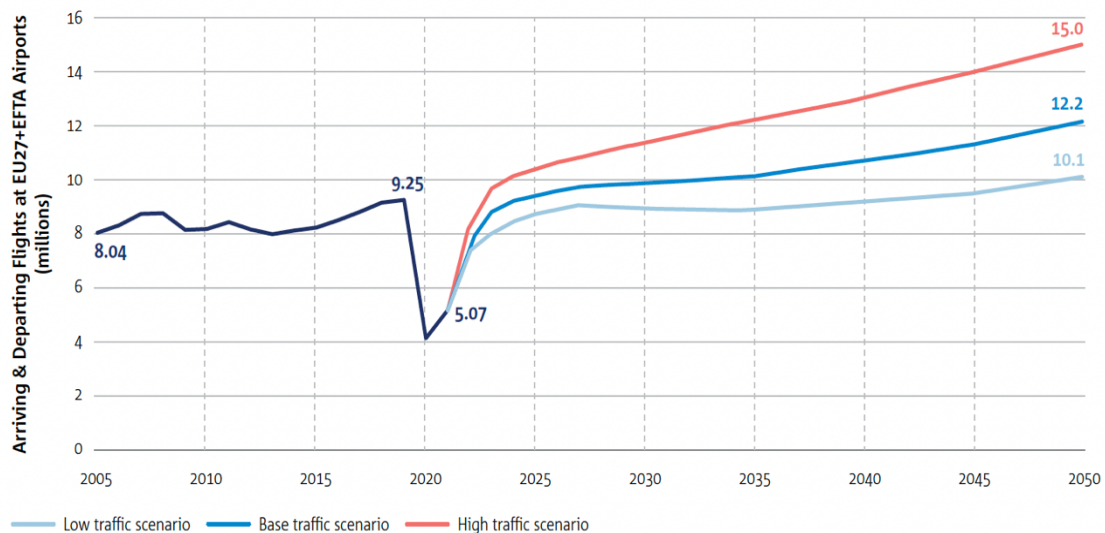


Figure 2: Arriving and Departing Flight Forecast
Source: (EASA, EEA, and Eurocontrol 2022)

However, in a changing world, with the forecast growth of the world's population, it is expected that the world population will exceed 8500 millions already in 2030, and that the number continues to grow reaching up to 11100 millions by 2100 as depicted in the Figure 3 (Sadigov 2022). It is expected an increase in the individuals needing to travel by plane, the problem of climate change and the need for a reduction in GHGs emissions are becoming concerns (Sadigov 2022).

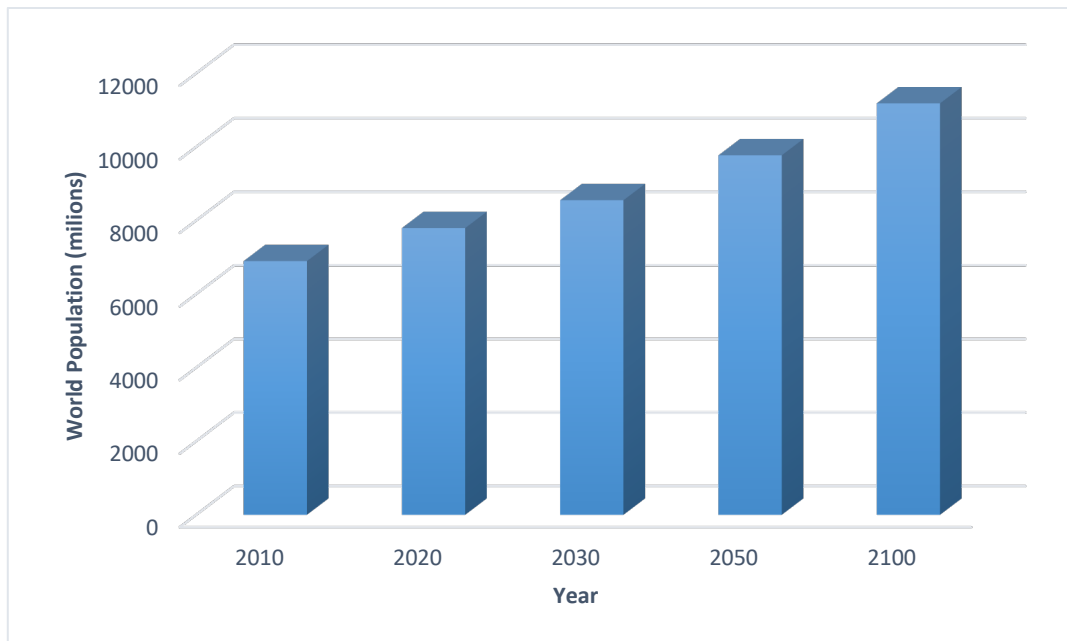


Figure 3: World Population
Source: (Sadigov 2022)

Over the last 20 years, commercial air transport has contributed with its Carbon Dioxide (CO₂) emissions rising by around 50% (EASA, EEA, and Eurocontrol 2022), even with a decrease of 2,3% per year in the average grams of CO₂ emitted per passenger kilometer due to the use of SAF, reaching 89 grams of CO₂ emitted per passenger kilometer in 2019, the number are still high and the time to act is now (EASA, EEA, and Eurocontrol 2022). Figure 4 depicts the actual CO₂ emission for all departures from EU27+EFTA, and the forecast for CO₂ emissions based on three different scenarios previously referred until the year 2050. Figure 5 represents the oxides of nitrogen (NO_x) emissions based on the same assumptions. These numbers are worrying due to the potential negative impact that this increase can have on the environment, on the ozone layer and consequently on the quality of air and the population's life. For these it is necessary to create alternatives to fossil fuels in order to reduce the environmental aviation impact.

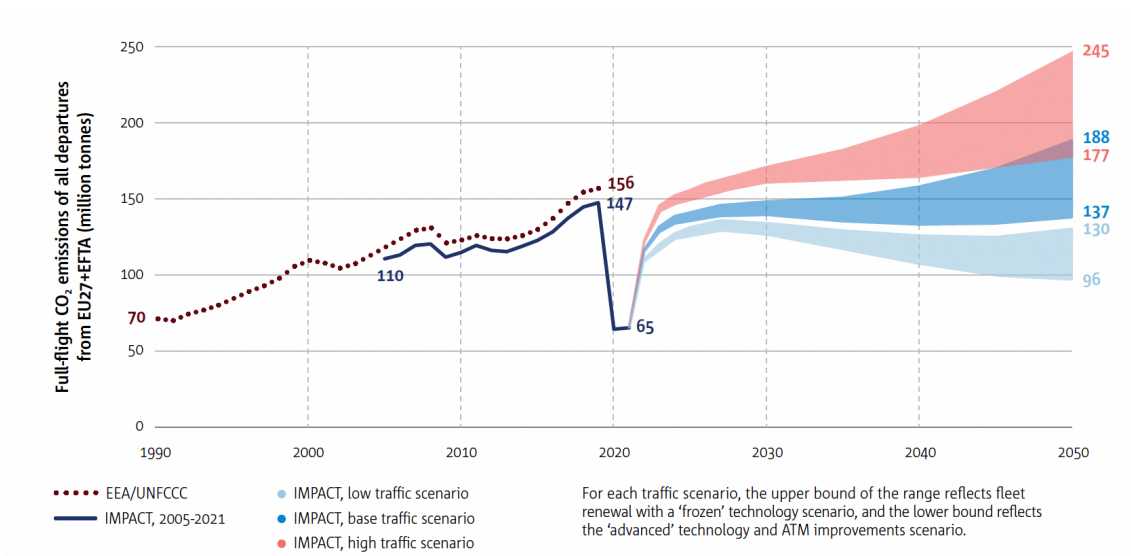


Figure 4: Forecast Full-flight CO₂ emissions of all departures (EU27+EFTA)
 Source: (EASA, EEA, and Eurocontrol 2022)

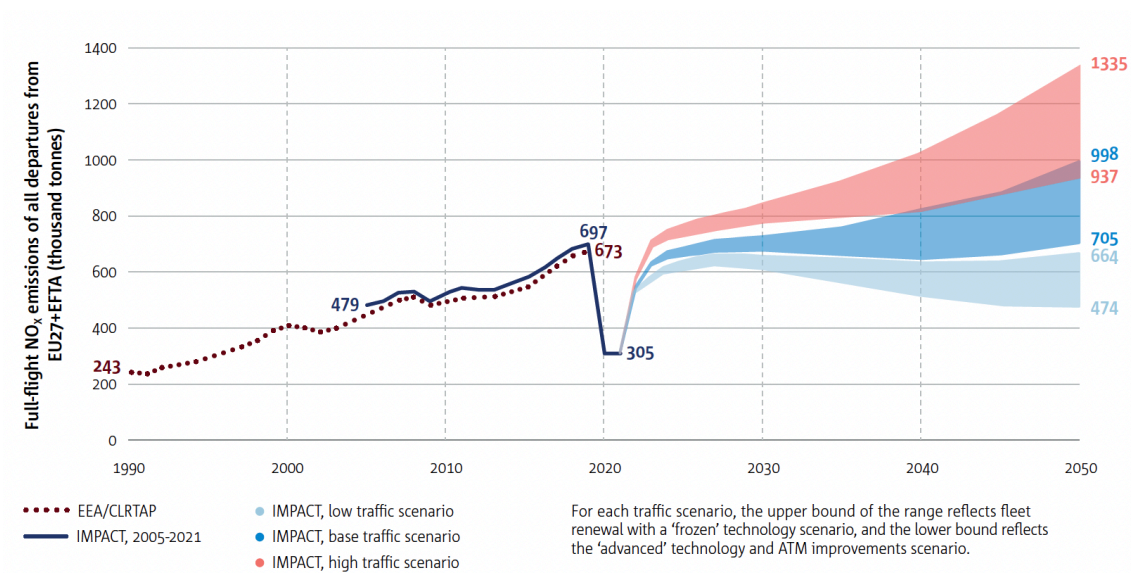


Figure 5: Forecast of Full-flight NO_x emissions of all departures (EU27+EFTA)
 Source: (EASA, EEA, and Eurocontrol 2022)

The aviation sector is estimated to represent about 2.5% to 5% of the world's energy consumption (Arat and Sürer 2017). Before the covid pandemic, the traffic growth trend was estimated at around 5% per year. According to the last prediction by the two leading aircraft manufacturers, Airbus e Boeing, the annual traffic growth is expected to be around 3,7% to 3,8% (Airbus 2022; Boeing 2022). In 2019, just before covid pandemic, passenger flights were responsible for approximately 85% of commercial aviation CO₂ emissions, which represented around 785 million tons (Mt) of CO₂ emitted (Graver,

Zheng, and Rutherford 2020). The traffic growth brought economic benefits but is also associated with negative environmental impacts, like the increasing in emission of GHGs, such as CO₂. Coupled with these environmental concerns, rising fossil fuel prices have also served as a driver in the search for new and ambitious solutions (Bauen et al. 2020). The industry is already looking for alternative solutions for fossil fuel such as the use of SAF and even research into new technologies applied to the sector, such as hydrogen and electrical energy (Bauen et al. 2020). It is already possible to identify a significant increase in the global interest in SAFs, driven largely by global concern about increasing GHG emissions.

SAFs are renewable of waste-derived aviation fuels that meet sustainability criteria, based on the terms defined by the European Union in its long-term strategy. It has been proved that SAF has the most significant potential to reduce CO₂ emissions in the aviation industry (ICAO 2023). Furthermore, a progressive change to SAF would lead to improve air quality and mitigate climate change (EASA, EEA, and Eurocontrol 2022).

The European Union defined a long-term strategy with the main objective of achieving net-zero GHGs emissions by 2050 (European Commission 2018), strategy that can be achieved with the use of SAF, as atmospheric CO₂ is absorbed during their production process, meaning that CO₂ emissions on a net basis are reduced, and could even hit zero with the correct production and operational processes. The use of other measures that increase carbon capture can accelerate the process (EASA, EEA, and Eurocontrol 2022). Additionally, in parallel, in 2016 the ICAO launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (Jain et al. 2021). The program aims to encourage air operators to use SAF, and to achieve this objective they create incentives for its use, thus managing to reduce the price of access to SAF and to reduce net CO₂ emissions from international aviation (Jain et al. 2021). The program is divided into two phases, the first being on a volunteer basis until 2026. The second phase, which is expected to take place between 2027 and 2035, will apply mandatorily to all states that have an individual share of international aviation activities above 0.5%. To comply with the objectives defined in CORSIA, airlines can adopt several measures, including: reducing fuel burn through more efficient aircraft and operations, increasing the use of

SAF fuel, reducing CO₂ emissions derived from the fuel burn, among other measures (Sustainable Aviation 2019).

In order to comply with the obligations under the CORSIA agreement, and based on estimated traffic growth for the sector (Airbus 2022; Boeing 2022), it is expected that this may lead to an increased need for greater volumes of SAF (Sustainable Aviation 2019).

Figure 6 depicts the actual CO₂ emission for all departures from EU27+EFTA and the forecast for CO₂ emissions until 2050 based on adopting mitigating measures, such as using alternative fuels, adopting the base traffic scenario referred in Figure 4.

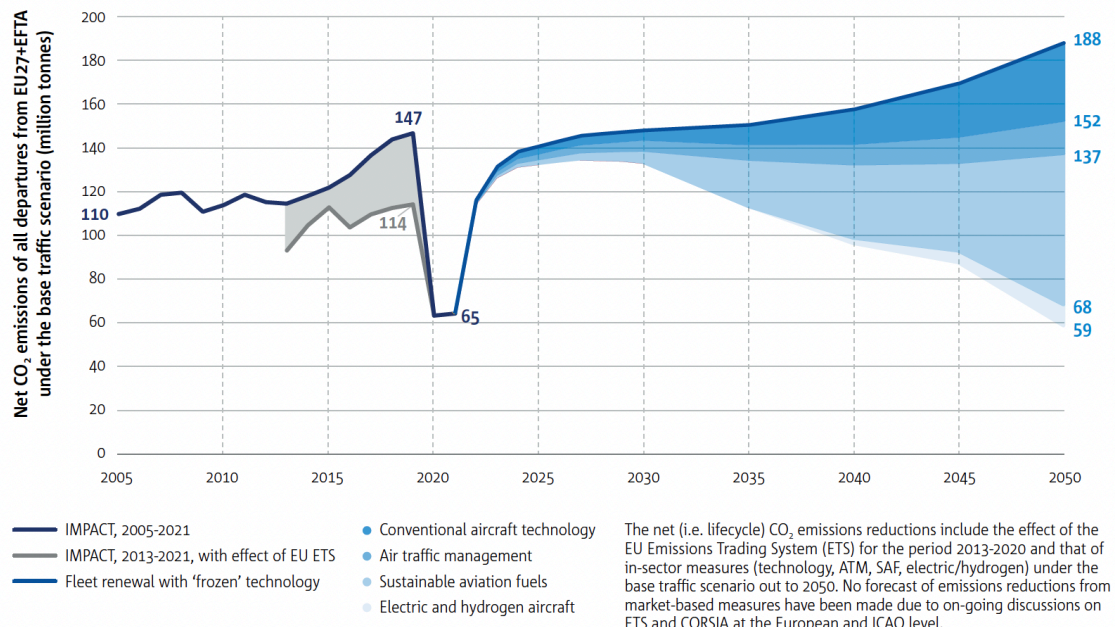


Figure 6: Forecast Net CO₂ emissions for all departures, based in alternative fuels (EU27+EFTA)
Source: (EASA, EEA, and Eurocontrol 2022)

When comparing the Net CO₂ emissions for EU27+EFTA under the base traffic scenario predictions without any mitigation measures (apart from a possible Air Traffic Management (ATM)), by the year 2050 is expected to reach between 137 million tones to 188 million tons of CO₂ issued annually, as illustrated in Figure 4. On the other hand, with full integration of drop-in SAFs (alternative fuel that is fully compatible with existing conventional fuel, which does not require adaptation of either the fuel distribution network or the aircraft itself) or non-drop-in SAF (an alternative fuel that is not fully compatible with conventional fuel, thus requiring adaptation of some components of

the existing fuel distribution network and/or the vehicle itself), like Hydrogen or even Electrically powered aircraft, it is possible to reach a minimum value of 59 million tons of CO₂ issued annually, which represents a reduction of almost 60% even from the current value, and up to 69% when compared to the worst expected value for 2050 in the baseline scenario as illustrated in Figure 6.

Still, concerning flights operated in EU27+EFTA, the departures of long-haul fleet, despite representing only approximately 6% of total departures during 2019, represent half of all CO₂ and NO_x emissions (EASA, EEA, and Eurocontrol 2022). Given this fact, due to the complex process we are talking about, the initial intervention area should focus on the long-haul fleet.

Another critical fact that deserves full attention relates to the fact that over the last 80 years, we have witnessed an increase in CO₂ emissions from aviation, but about half of global CO₂ emissions have occurred since 2000, which indicates a very worrying exponential growth (EASA, EEA, and Eurocontrol 2022).

Taking into account all CO₂ emissions associated with the aeronautical sector, the commercial passenger aviation is responsible for approximately 85% of total emissions CO₂ emissions (Graver, Rutherford, and Zheng 2020). It can also be seen, considering data of the last 5 years, that more than 60% of all passenger flights were operated on narrow-body aircraft, and these represented more than half of CO₂ emissions (Graver, Rutherford, and Zheng 2020). The emission of pollutants in aviation, in particular CO₂, has a direct impact on climate change, as CO₂ is considered one of the most important contributors to the greenhouse effect (Coelho and Costa 2008).

2.2. SUSTAINABLE AVIATION FUEL

2.2.1. SAF INTRODUCTION

In order to meet the targets of achieving net-zero GHGs emissions by 2050 (European Commission 2018) defined by Europe, the commitment to use SAFs could represent an important path, because according to International Air Transport Association (IATA), the use of SAFs in aviation has enormous potential for reducing CO₂ emissions (Hassan, Pfaender, and Mavris 2017).

SAF is the designation to sustainable alternatives to fossil jet fuel and are classified into carbon neutral, drop in alternatives like synthetic or biofuels, and non drop in options such as hydrogen (ICAO 2023). The drop-in options, as they do not require modifications to the engines and commercial aircraft currently in use, constitute a much faster and easier to implement alternative for a short/medium term solution. In order to be used in commercial aviation, drop in SAF must undergo a rigorous testing process to obtain certification, tests that demonstrate chemical and physical characteristics almost identical to those of conventional jet fuel allowing a safely mixed between them. Once this approval is obtained, SAF can then be mixed with fossil aviation fuel in a previously defined maximum blending ratio (EASA, EEA, and Eurocontrol 2022).

SAF has thus become a crucial player when the objective is to reduce CO₂ emissions, and with this it has begun to arouse enormous interest among large aircraft producers, SAF producers, and even governments themselves.

However, the use of SAF in Europe continues to represent less than 0.05% of the total consumption of aviation fuel in the EU (EASA, EEA, and Eurocontrol 2022). The main reason for the difficulty in this transition is mainly related to the low production capacity and higher production cost when compared to the current used jet fuel (Jain et al. 2021). In an attempt to change these low numbers, the European Commission has defined an obligation to supply SAF fuel to EU airports, with minimum SAF participation gradually increasing from 2% in 2025 to 63% in 2050. In order to reach this target, approximately 29 million tons of SAF will be required in 2050 (EASA, EEA, and Eurocontrol 2022), even so, the scenarios projected by ICAO, even with a high ratio of SAF production, remain below the volume needed to achieve the defined goals, as depicted in Figure 7. ICAO demonstrated theoretically that it would be physically possible to achieve 100% of demand by 2050 with SAF, if there was a very substantial investment in increasing production infrastructure, which would only be possible with substantial government support (ICAO 2019).

The simplest way to enable a transition in a relatively short period would be to create a fuel (SAF) that most closely resembles the characteristics of jet fuel, so that no modifications to current aircraft, airports and distribution channels, would be necessary. In practical terms, the chemical characteristics of SAF are very similar to those of

conventional aviation kerosene and can be safely mixed with it in varying degrees. There are currently 7 certified types of SAF production pathways, as depicted in Table 2, authorized by American Society for Testing and Materials (ASTM) from various feedstocks (ASTM 2020). Once produced, and depending on the type of production used, SAF is currently certified for use with a maximum mixing rate of 50% of mixing with Jet A-1 fuel, although the objective will pass through reaching 100% SAF by 2030 (EASA, EEA, and Eurocontrol 2022). Drop-in SAF will play a key role in decarbonization, as SAF and jet fuel use the same supply infrastructure and do not require adaptation of aircraft or engines, which means that they can be automatically incorporated into systems existing supply lines at airports, making the transition much easier.

Figure 7 demonstrates the ICAO projected production capacity scenarios of SAF, with two distinct scenarios, one with an increased production projection, and the other one with the worst-case scenario, demonstrating the enormous variation that could occur in the coming years depending on the support of various companies and governments throughout this transition.

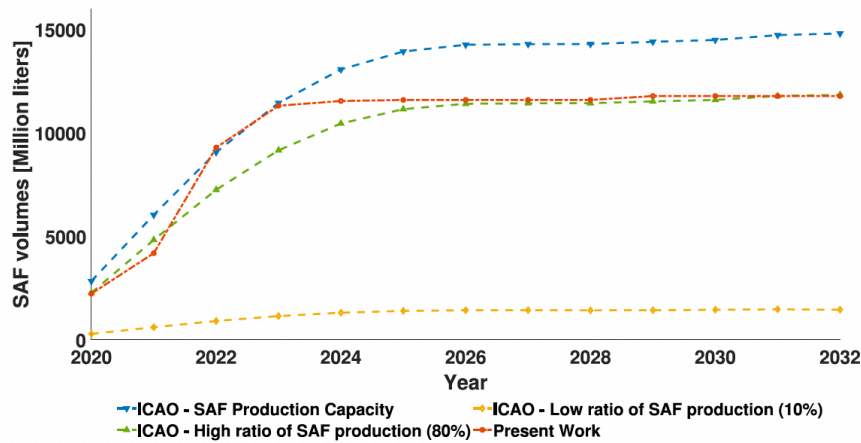


Figure 7: Projected scenarios of SAFs production capacity
Source: (ICAO 2019)

The fact that there is still no production of large-scale because the SAF market remains in its early stages of development, continues to be a problem, which leads to higher cost of SAF production and sell. Currently, depending on the regions, the feedstock used and the production pathway, the cost of producing SAF is estimated to be between 1.5 and, in extreme cases, up to 10 times more than the cost of jet fuel (Bardell and Ashton 2020).

Due to higher cost of production of SAF, the selling price of SAF remains higher than the retail price for conventional jet fuel (IATA 2023b). For use in comparative terms, analyzing the year 2022, the average global SAF price estimate was around 2400 USD per tonne, what represents around two and half times higher than the price of conventional jet fuel (1094 USD per tonne in 2022) (IATA 2023b). The SAF price estimations are subject to fluctuations, and substantial price discrepancies exist among different geographical areas (IATA 2023b).

In Figure 8 it is possible to observe the variation of price and capacity production of SAF since 2019. Furthermore, it is also possible to observe the variation in the price of Jet Fuel in the same period, as well as the quantity of Jet Fuel needed globally.

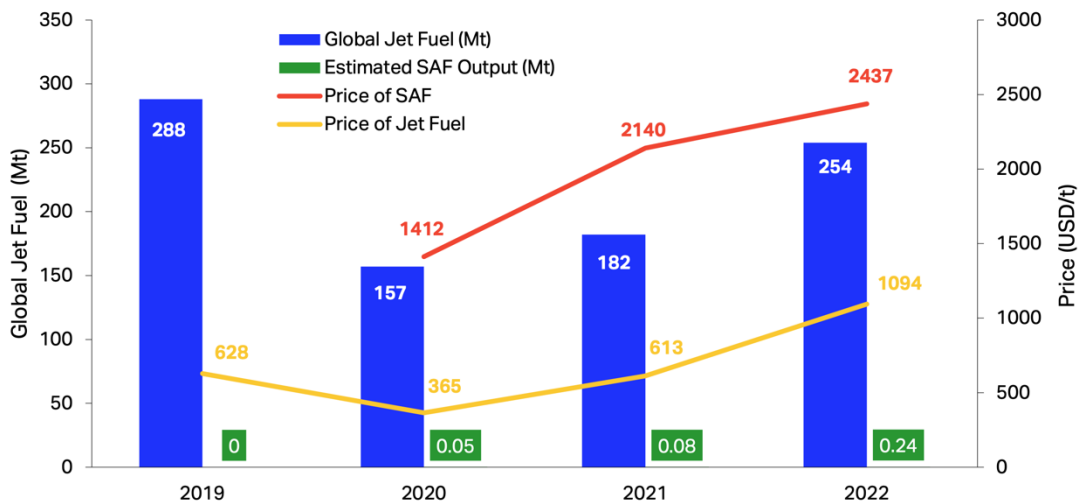


Figure 8: SAF vs Jet Fuel, price and capacity production
Source: (IATA 2023b)

However, as the technology continues in development and more players enter the race to develop SAF, it is expected that the production cost will begin to decrease, and consequently the selling price to the user also decrease (Bardell and Ashton 2020).

2.2.2. DROP-IN SAF PRODUCTION PATHWAYS

ATSM International defines the necessary requirements for each type of alternative aviation fuel (ASTM 2020). Depending on the production routes and feedstocks used, pollutant emissions resulting from the use of SAF varies considerably (Jain et al. 2021).

The maturity level of each of the production paths is defined by the Technology Readiness Level (TRL), which range from 1 to 9. Level 1 is assigned when there are only basic ideas about the technology, up to level 9 which represents tested technology ready for use in operational environment (EASA, EEA, and Eurocontrol 2022).

Any innovation for the aeronautical sector is always dependent on a phase of development and exhaustive testing until a desired level of safety is achieved, in order to be implemented on the market. TRL allows an analysis of the technology's readiness level, however, when talking about SAF, the risk lies not only in the degree of advancement of the technology itself, but in the compatibility of the new fuel created with the aircraft and supply infrastructures. For this reason, the assessment using only the TRL was not considered adequate, so 2009 during the Commercial Aviation Alternative Fuel Initiative (CAAFI), the team of experts present combined Air Force's efforts in conjunction with Airbus' proposal proposed the adoption of the new scale defined as Fuel Readiness Level (FRL), as described in the Table 1 (ICAO 2009).

Table 1: FRL Classification
Source: (ICAO 2009)

FRL	Phase	Description
1	Basic Principles Observed and Reported	Feedstock/process principles identified.
2	Technology Concept Formulated	Feedstock /complete process identified.
3	Proof of Concept	Lab scale fuel sample produced from realistic production feedstock. Energy balance analysis executed for initial environmental assessment. Basic fuel properties validated. Minimum fuel quantity required ¹ : 500 ml
4	Preliminary Technical Evaluation	System performance and integration studies entry criteria/specification properties evaluated (MSDS/D1655/MIL 83133). Minimum fuel quantity required ¹ : 37,8 liters
5	Process Validation	Sequential scaling from laboratory to pilot plant Minimum fuel quantity required ¹ : 302,8 to 851718 liters
6	Full-Scale Technical Evaluation	Fitness, fuel properties, rig testing, and engine testing ² Minimum fuel quantity required ¹ : 302,8 to 851718 liters
7	Fuel Approval	Fuel class/type listed in international fuel standards ³

8	Commercialization Validated	Business model validated for production airline/military purchase agreements. Facility specific GHG assessment conducted to internationally accepted independent methodology
9	Production Capability Established	Full scale plant operational++

¹ Quantities required for risk mitigation reference

² As referenced in ASTM approved protocols

³ As listed in original equipment manufacturers' manuals for aircraft and engines

So far there are seven production pathways approved for SAF production. Table 2 allows to verify the maximum blending ratio of a mixture approved for use in the aeronautical sector, as well as the associated TRL and FRL for each production pathway (EASA, EEA, and Eurocontrol 2022; Abrantes et al. 2021). Furthermore, two routes are approved for the co-processing of renewable raw materials in oil refineries, but the mixing ratio is limited to 5% (EASA, EEA, and Eurocontrol 2022).

Table 2: SAFs production pathways
Source: (EASA, EEA, and Eurocontrol 2022) (Abrantes et al. 2021)

Production pathway	Abbreviation	Feedstocks	Blending Ratio	TRL	FRL
Hydroprocessed Esters and Fatty Acids	HEFA-SPK	Vegetable and animal fat	50%	9	9
Fischer-Tropsch Synthesised Paraffinic Kerosene	FT-SPK	Energy crops, lignocellulosic, biomass, solid waste	50%	7/8	7
Synthesized Iso-Paraffins	HFS-SIP	Conventional sugars, lignocellulosic sugars	10%	5 7/8 ¹	5 7 ¹
Fischer-Tropsch Synthesised Paraffinic Kerosene with Aromatics	FT-SPK/A	Energy crops, lignocellulosic, biomass, solid waste	50%	6/7	7
Alcohol to Jet Synthesized Paraffinic Kerosene	ATJ-SPK	Sugar, starch crops and lignocellulosic biomass	50%	7/8	7
Catalytic Hydrothermolysis Jet	CHJ	Vegetable and animal fat	50%	6	6/7
HEFA from Algae	HC-HEFA-SPK	Microalgae oils	10%	5	6
FOG Co-processing	FOG	Fats, oils and greases	5%	-	1
FT Co-processing	FT	Fischer-Tropsch biocrude	5%	-	1

¹ TRL 7 for conventional sugar feedstock; TRL 5 for lignocellulosic sugar feedstock.

In Figure 9 it is possible to observe the route of SAF production from the different feedstocks to the different production pathways.

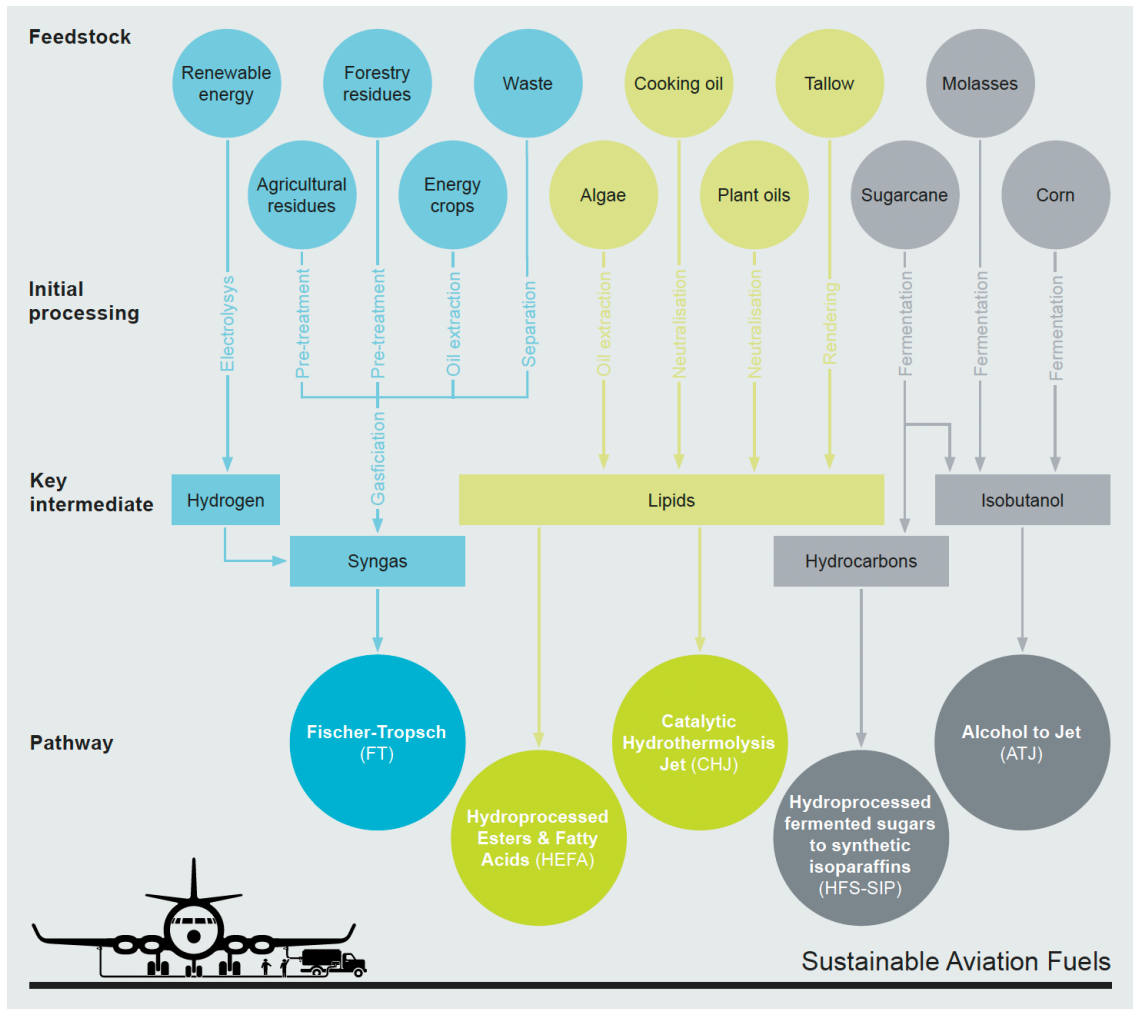


Figure 9: Mapping of feedstocks to pathways
Source: (Sachdeva et al. 2020)

The production pathways with a higher TRL are those that are at a more advanced stage of introduction into the market, and as such should be analyzed in greater detail. Below is a brief analysis of the 4 alternatives with higher TRL/FRL, and for this reason expected to play a major role in the near future (EASA, EEA, and Eurocontrol 2022):

Hydroprocessed Esters and Fatty Acids (HEFA) - Process that results from the conversion of various feedstock sources, including waste, animal fats, vegetable and

algae oils, through the use of hydrogen with the aim of removing oxygen from the chain and thereby producing hydrocarbon fuel. The fact that the first reaction is exothermic allows the energy that comes from it to be used for the following stages of the process, making the entire process even more sustainable and economically attractive. After the conversion process is complete, HEFA can then be mixed with conventional jet fuel at a ratio of up to 50%. HEFA is the only SAF commercialized and currently available on the market with a TRL of 9, making it ready and authorized for use in current commercial aviation. Still, there are challenges, the main one being the availability of sustainable feedstock and the competition with other sectors (EASA, EEA, and Eurocontrol 2022; Abrantes et al. 2021). Emissions from HEFA vary considerably depending on the feedstock, as depicted in Table 3 (Pavlenko and Searle 2021).

Fischer-Tropsch (FT) - Biogas obtained from the gasification of feedstock is then processed within a Fischer-Tropsch reactor, with or without added aromatics (FT-SPK and FT-SPK/A). The feedstocks are first treated to ensure uniform consistency, and then through a partial oxidation process (using a mix of CO, H₂ and a small quantity of CO₂ and CH₄) in order to produce syngas. The syngas is then processed within a Fischer-Tropsch reactor, producing liquid hydrocarbons (gasoline, kerosene, diesel, and lubricants). The common feedstocks for the synthesis of Fischer-Tropsch are energy crops, lignocellulosic, biomass, solid municipal waste, however to be suitable for the production of sustainable aviation fuel the feedstocks must be of natural origin, which limits their origin to achieve this objective, yet the source of solid waste is very abundant. After the conversion process is complete, the FT can then be mixed with conventional jet fuel at a ratio of up to 50%. The FT has significant emissions reduction as depicted in Table 3 (exception for municipal solid waste (MSW) derived from fuel, as the emissions associated with this feedstock vary greatly depending on its nonbiogenic content, which range from 5.2 gCO₂e/MJ as depicted in Table 3 for MSW with lower plastic content, however can reach up to 170 gCO₂e/MJ, which represents an increase of around 3000%) (Pavlenko and Searle 2021). The FT has a large supply potential, however its TRL is still 7/8, and it is not yet available on a commercial scale within the EU (EASA, EEA, and Eurocontrol 2022; Abrantes et al. 2021).

Alcohol to Jet (ATJ) - It is a conversion process through fermentation with the aim of producing aviation fuel mixture based on alcohol. The most common feedstocks are sugar, starch crops (e.g. corn, wheat, sugarcane) and lignocellulosic (agricultural/forest residues) and biomass. At the moment, with a TRL still of 7/8, it is only allowed in a maximum mixture of 50%, however it is one of the most viable options for the future in order to achieve 100% SAF certification (EASA, EEA, and Eurocontrol 2022; Abrantes et al. 2021).

Synthesized Iso-Paraffins (HFS-SIP) - Biofuel obtained from sugars converted into a synthetic hydrocarbons molecule using advanced sugar fermentation (Abrantes et al. 2021). Sugar feedstock may include conventional or lignocellulosic sugars, being that, the most used feedstock is sugarcane, which is highly available but has significant land and water use concerns After the conversion process is complete, HFS-SIP can then be mixed with conventional jet fuel at a ratio of up to 10%, what represents a value significantly below other approved process. HFS-SIP is currently the most expensive pathway (Sachdeva et al. 2020).

2.2.3. LIFE CYCLE ANALYSIS OF SUSTAINABLE AVIATION FUEL

The Life Cycle Analysis (LCA) can be used in order to assess the environmental impacts and the overall climate benefit from the use of SAF. This type of analysis accounts for all the entire supply chain of the production and use of SAF, from the feedstock cultivation, harvesting, processing and transportation, fuel production, transportation and distribution, and finally the fuel consumption by aircraft. Figure 10 illustrates the components of lifecycle steps from Well-To-Pump until Pump-to-Wing final step for both fossil-based jet fuel and SAF.

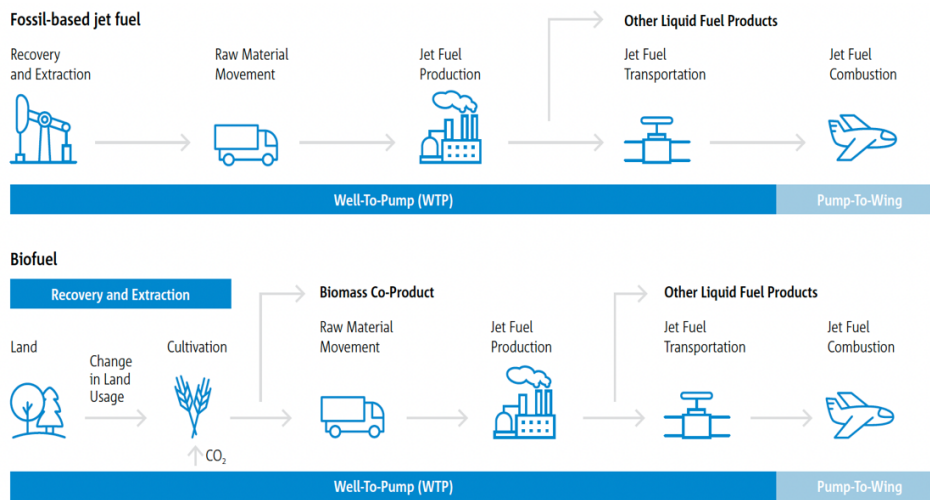


Figure 10: Fuel production steps - Fossil-based jet fuel and Biofuel

Source: (EASA, EEA, and Eurocontrol 2022)

The GHGs emissions of SAFs can vary greatly according to the feedstock used and production path chosen. The functional unit are provided in grams of carbon dioxide equivalent per megajoule ($\text{gCO}_2\text{e/MJ}$), allowing for an easier comparison with the fossil jet fuel emissions, in order to calculate the overall GHGs emissions reduction. Table 3 show the LCA value for the most relevant conversion processes, depending on the feedstock used, in ascending order of LCA value for each process analyzed (HEFA, FT and ATJ).

Table 3: Summary of Life Cycle Analysis

Source: (Abrantes et al. 2021)

Conversion process	Feedstock	LCA value ($\text{gCO}_2\text{e/MJ}$)
Hydroprocessed esters and fatty acids (HEFA)	Used cooking oil	13,9
	Corn oil	17,2
	Palm fatty acid distillate	20,7
	Tallow	22,5
	Brassica carinata	34,4
	Palm oil-close pond	37,4
	Soybean oil	40,4
	Rapeseed oil	47,4
	Palm oil-open pond	60

Fischer-Tropsch (FT)	Municipal Solid Wastes*	5,2
	Agricultural residues	7,7
	Forestry residues	8,3
	Herbaceous energy crops	10,4
	Short-rotation woody crops	12,2
Alcohols to Jet (ATJ)	Forestry residues	23,8
	Sugarcane	24,0
	Molasses	27,0
	Agricultural residues	29,3
	Herbaceous energy crops	43,4
	Corn grain	55,8

* MSW from nonbiogenic content

Table 3 shows that, for the HEFA conversion process, LCA values can vary substantially, with the lowest value being 13.9 gCO₂e/MJ achieved for the production of HEFA using used cooking oil as feedstock, up to a maximum value of 60 gCO₂e/MJ when the feedstock used is palm oil-open pond. For the FT conversion process, LCA values vary from the lowest value of 5.2 gCO₂e/MJ using solid waste from nonbiogenic content as municipal feedstock, up to a maximum value of 12.2 gCO₂e/MJ when the feedstock used is short-rotation woody crops. Regarding the ATJ conversion process, LCA values range from the lowest value of 23.8 gCO₂e/MJ when forestry residues are used as feedstock, up to a maximum value of 55.8 gCO₂e/MJ when the feedstock used is corn grains.

In order to make it easier to compare GHG emissions produced using different production pathways, E4Tech created the profiles depicted in Table 4, based on the average emissions of each path (Sustainable Aviation 2019).

Table 4: Average GHG emissions profiles modelled by E4Tech
 Source: (Sustainable Aviation 2019)

Route	GHGs emissions (gCO ₂ e/MJ)
Gasification with Fischer-Tropsch	13.7
Hydroprocessing of oils and fats	14
RFNBO:FT Catalysis	19.5
Other thermochemical (APR and HTL)	20
Fast pyrolysis with Fischer-Tropsch	22
Aerobic fermentation	25
Alcohol catalysis	35

2.2.4. SAF PRODUCTION CAPACITY AND DEMAND

The production and consequent use of SAF is still at a very embryonic stage throughout Europe. However, the goals set for the coming years are quite ambitious, in line with what was defined in the July 2021 package, 'Fit for 55', in order to meet the EU's climate objective of reaching 2050 with net-zero GHGs emissions, and in the context of the "ReFuelEU Aviation" initiative, harmonized regulations were proposed for all of Europe, with fuel suppliers would be required to produce SAF enough for at least 2% of European air traffic to be fed by SAF by 2025, 5% by 2030 and at least 63% by 2050 (EASA, EEA, and Eurocontrol 2022).

In Figure 11 it is possible to observe the SAF projects in operation (represented by circles), under construction (represented by triangles) and planned (represented by diamonds) in Europe, data for the month of March 2022 (EASA, EEA, and Eurocontrol 2022). The legend identifies the type of SAF used or being studied, and the size of the icon corresponds to the current or estimated annual production capacity.

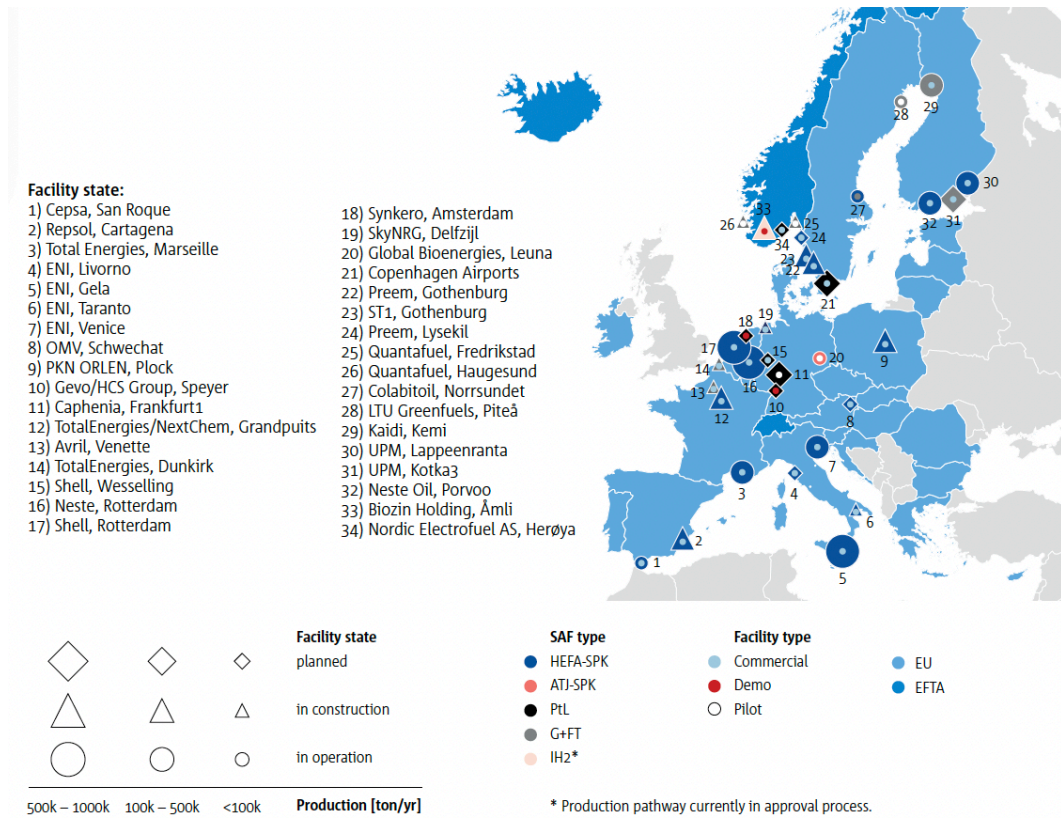


Figure 11: Current announced SAF projects in Europe

Source: (EASA, EEA, and Eurocontrol 2022)

In order to meet the targets proposed by the European Commission in the Legislative Package called “Fit for 55”, European airports would need around 2.3 million tons of SAF annually by 2030, to comply with the mandatory 5% SAF on all flights departing from airports in Europe (EASA, EEA, and Eurocontrol 2022). However, the estimated production capacity in Europe is only 0.24 million tons, which corresponds to just 10% of the required capacity. In order to achieve the defined goals, it is imperative that more companies enter the market, and there is greater investment in the sector. According to Figure 12, HEFA and ATJ are the pathways that will have the greatest estimated production capacity by 2030 in Europe, however it is estimated that by 2050, PtL, ATJ and Gasification + FT will assume the preponderant role in increasing SAF production capacity in Europe, as depicted in Figure 12 (EASA, EEA, and Eurocontrol 2022). To meet the defined targets of at least 60% SAF on all flights taking off from Europe, it is estimated that there will be a need for 28.6 million tonnes of SAF by 2050 (EASA, EEA, and Eurocontrol 2022).

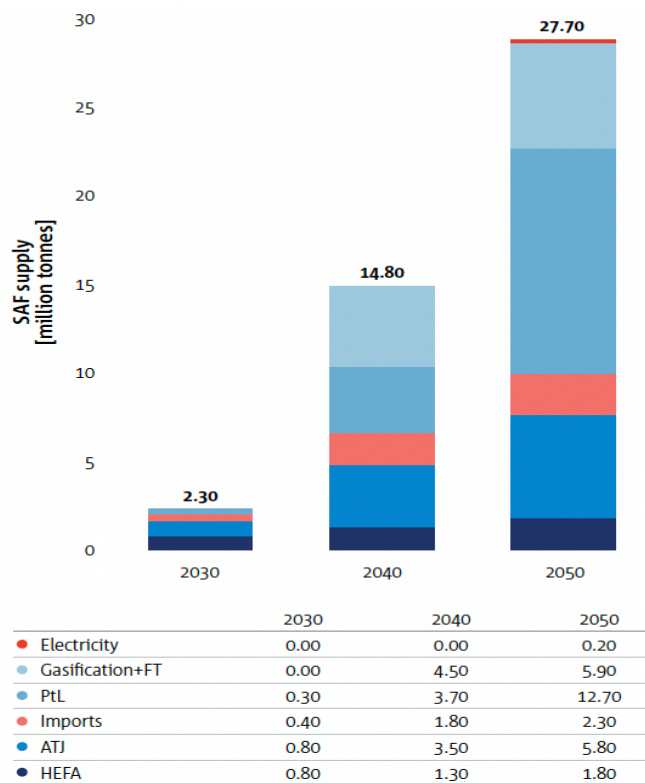


Figure 12: ReFuelEU modelled SAF supply per production pathway in the EU27

Source: (EASA, EEA, and Eurocontrol 2022)

2.2.5. SAF BLENDING LOCATION OPTION

Initially, as long as the quantities of SAF in use are limited, the storage location and method of transportation of SAF from its origin to aircraft refueling may not be a major problem, however, over time and anticipating a greater use of SAF by the aeronautical industry, it is necessary to analyze what options are available to mix SAF with Jet A, and what the implications of each option are (Moriarty and Kvien 2018).

The ways of transporting fuel from its origin to the airport are very varied, from the use of a pipeline, to the use of vessels, rail or even road transport. However, Jet fuel and SAF may be produced in different locations, and therefore it is necessary to have capable and approved infrastructures to mix the fuel at the ratios indicated for each type (Moriarty and Kvien 2018).

In order to guarantee effective quality control and a mixing percentage in accordance with the maximum percentages allowed for each type of SAF, there are several

requirements that must be met (Moriarty and Kvien 2018). Here are some of the possible options:

As depicted in Figure 13, one option would be to store SAF and Jet Fuel together in the same tank at the terminal, but this option could lead to minor challenges as this method would difficult the detailed inventory tracking as tanks are constantly receiving and dispensing fuel, as well as the potential need to add mixing equipment to account for variability in density between the two fuels.

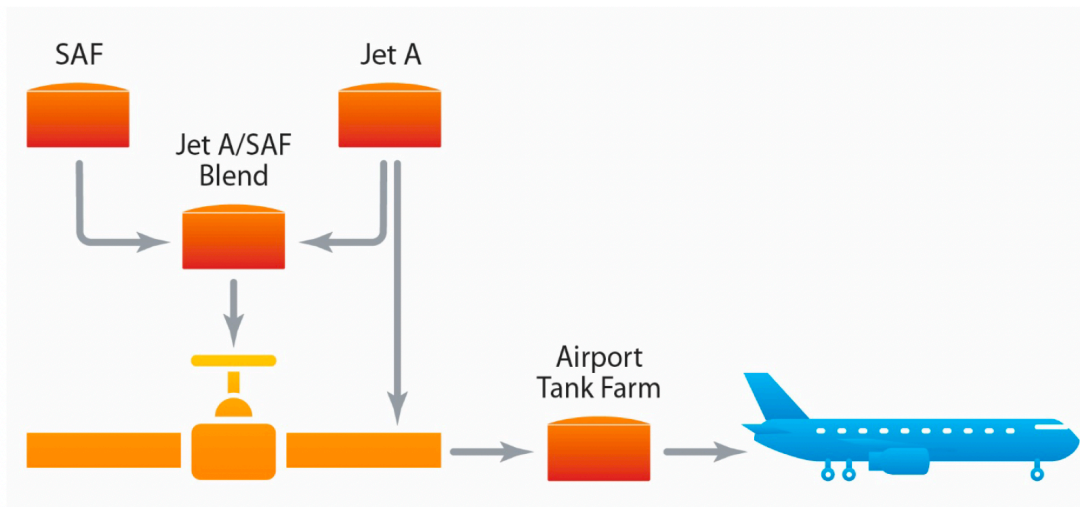


Figure 13: SAF and Jet A stored together at a fuel terminal
Source: (Moriarty and Kvien 2018)

Another option could involve delivering and storing Jet Fuel and SAF separately at the airport, as depicted in Figure 14 and mixing it at the airport facilities, this method was the advantages of ensure more quality and allow for total control of percent volume of SAF. However, this route would require a modification to the equipment and the hiring of qualified technical personnel to carry out this mixing, thus allowing quality control to be carried out at the airport itself (Moriarty and Kvien 2018).

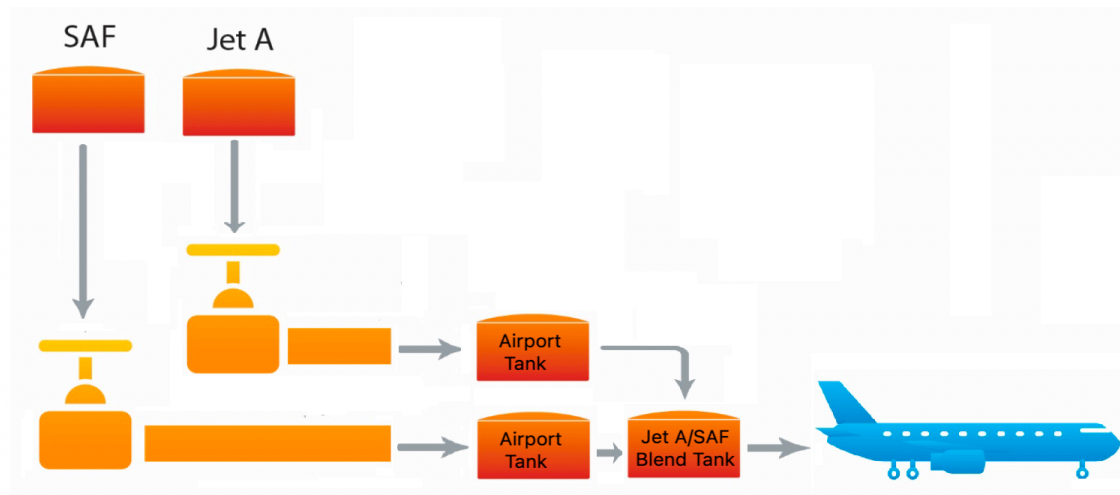


Figure 14: SAF and Jet A stored separately at the airport
Source: (Moriarty and Kvien 2018)

2.2.6. AIRPORT INFRASTRUCTURES

This section provides an overview of the types of airport structures for storing different fuels. Fuels are involved in a number of different types of structures at airports, including above ground storage tanks (ASTs), field constructed tanks (FCTs), airport fuel hydrant systems (AHSs), connected pipelines, and trucks transporting fuel to airports. SAF and Jet A meets the same ASTM fuel quality standard, and therefore there are no compatibility issues (Moriarty and Kvien 2018).

Aboveground Storage Tank (ASTs)

ASTs are storage tanks that sit above ground, and can be used as single tanks or in a larger group of tanks, often called a tank farm. Because they often represent a source of environmental contamination, several regulations were created to ensure that they comply with technical standards to protect against leaks (Moriarty and Kvien 2018).

Airport Fuel Hydrant Systems (AHSs) and Field Constructed Tanks (FCTs)

AHSs are tanks that lie beneath the ground, distribute fuel directly to aircraft and operate under high pressure with large diameter piping that ends in hydrants. AHSs often have more than one tank (Moriarty and Kvien 2018).

Jet Fuel Truck Transport

As the name suggests, these are trucks that transport jet fuel within the airport itself, from the fuel warehouse to the planes. Using trucks to transport fuels could increase GHG emissions airside of the airport due to emissions associated with the burning of fuel by the vehicles themselves to move around. Furthermore, there is also an increased risk of serious accidents due to transport and spillage of fuel in the event of an accident. (Moriarty and Kvien 2018).

2.2.7. CASE STUDIES

Virgin Atlantic was the first airline to conduct a test flight using SAF on a commercial aircraft in 2008. Due to the success achieved in this test flight and subsequent tests, in October 2011, Virgin announced their partnership with LanzaTech (a company dedicated to carbon-rich waste recycles gases to produce ethanol, from which jet fuel can be made) (Sustainable Aviation 2019).

KLM was the first European airline to use an alternative fuel based on used cooking oil for a commercial flight, the flight was conducted between two big European cities in 2011. The first demonstration flights were completed by the airline in 2014 with 200 tonnes of fuel used. Lufthansa has also operated the Frankfurt to Berlin route using a 10% sugarcane-based SAF blend and the Frankfurt-Washington route using a 46.8% Jatropha-based HEFA fuel blend, camelina and animal fats. Since 2013, Air France has been using a SAF mixture with 10% sugarcane-based blend on the route from Toulouse to Paris. Iberia also operated a Madrid-Barcelona route using a mixture based on 25% HEFA and 75% jet fuel (EASA, EEA, and Eurocontrol 2022). In 2016, KLM, with the Embraer E190, began a series of 80 flights between Oslo and Amsterdam using SAF with a mixture of 47% SAF (Baxter, Srisaeng, and Wild 2020).

In October 2018, Virgin Atlantic joined the airlines with scheduled flights using SAF, via the route from Orlando to London Gatwick (Sustainable Aviation 2019).

Oslo Airport was the first airport in the Europe to offer SAF to all airlines refueling there since 2016. The SAF has been mixed with the fossil fuels (JetA1) in the central tanking facility and distributed in a mixed ratio (50/50). The infrastructure sharing allowed a significant reduction in costs (Baxter, Srisaeng, and Wild 2020). By decision of the

government of Norway, since 2019, all jet fuel distributed in the country must have at least 1% SAF, and the objective will be to reach 30% by 2023 (Baxter, Srisaeng, and Wild 2020).

In 2019, International Airlines Group (IAG) committed to achieving net zero emissions by 2050 through a program called “Flightpath Net Zero” combined with a large financial investment with the aim of developing new sustainable fuel supply chains (Sustainable Aviation 2019).

Also in 2019, British Airways, in collaboration with Velocys and Shell, started a joint project called Altato, a project that aims to guarantee the annual conversion of around 500,000 tonnes of waste into SAF. For each ton of SAF produced, a 70% reduction in GHG emissions, a 90% reduction in reduction of HC, and a 100% reduction in SO₂ are expected (Sustainable Aviation 2019).

In 2020, ANA, the largest domestic air carrier in Japan, and one of the largest in the world, began a strategic alliance with Neste (world’s leading producer of SAF from Finland) for the medium and long-term supply of SAF, with the aim of being used on regular flights departing from Haneda and Narita airports (Japan). Together with some others Japanese companies in the sector, they also began studies on a new carbon recycling business model that reuses CO₂ from exhaust gases, transforming them into SAF (ANA 2020; 2021).

Currently, all the SAFs available have maximum blending ratios, however, several companies (ICAO 2023;Pratt & Whitney 2022) like Pratt & Whitney, Airbus and Embraer are joining forces to obtain approval for the use of 100% SAF by the year 2030. In October 2021, a test flight with SAF 100% made from cooking oil and other waste fat (HEFA) was made by an A319neo. In 2022, Pratt & Whitney and Embraer have successfully tested a GTF engine running with 100% SAF, engine that powers the E195-E2 aircraft. The test was successfully conducted, demonstrating that the engine operates at 100% SAF without any compromise on safety or performance. This test demonstrates that the Embraer E2 equipped with this engine model is ready for certification and operation with 100% SAF, which will represent a reduction in emissions of up to 85% (Pratt & Whitney 2022).

Several European airlines have also set targets regarding the use of SAF for the coming years, for example, the International Airlines Group (IAG) has committed to using 10% of SAF by 2030, while Ryanair aims to reach 12.5% SAF usage across its entire network by 2030 (EASA, EEA, and Eurocontrol 2022).

According to ICAO data (ICAO 2023), 60 airports worldwide (which still represents only about 0.12% of the total number of airports in the world) are currently offering SAF, either continuously or in batches. The project that was born at the international airport of Vienna in 2022, the Österreichische Mineralölverwaltung (OMV) at OMV's Schwechat refinery, one of the largest and most complex inland refineries in Europe, is currently producing 2,000 metric tons of SAF per year in 2022 and planning to achieve production levels of more than 700,000 metric tons of SAF per year by 2030 (ICAO 2023).

2.3. ALTERNATIVE SOLUTIONS: HYDROGEN AND ELECTRICITY

In parallel, hydrogen has also been placed as an option in order to reduce CO₂ emissions in the aviation sector. However, this solution proved to be much more challenging since it requires very significant changes in the existing airport structures and in the aircrafts itself (Kivits, Charles, and Ryan 2010).

Airbus has been leading the research into the use of hydrogen, with an ambition to reach a zero emissions commercial aircraft by 2035 (Airbus SAS 2021), focusing on what Airbus classifies as the technology truly capable of reducing the climate impact of aviation.

In 2020, Airbus unveiled the ZEROe, a hydrogen-powered concept aircraft, an aircraft aimed at the long-haul market, the most promising market for the application of this technology (Airbus SAS 2021). At the same time, Airbus has also collaborated with several airports in order to understand the requirements in terms of modifying infrastructure to receive hydrogen, not only for the planes, but also to decarbonize the airport's support and handling vehicles (Airbus SAS 2021).

Despite being one of the most abundant elements in the universe, hydrogen does not exist by itself because it readily reacts with other elements naturally present. The most practical and economical way to obtain hydrogen would be through Steam Methane Reforming using fossil fuels, especially natural gas (Arat and Sürer 2017). However, this

method is less interesting due to the emission of polluting gases. Electrolysis has been shown as the most exploited alternative in order to obtain hydrogen with the least possible impact since the separation of the water molecule into hydrogen and oxygen is part of an ecological process. However, this process presents as counterpart a high amount of electrical energy needed to complete the process, and this energy requirement necessary for the production can jeopardize the ecological process if the energy sources are not renewable (Arat and Sürer 2017).

The high cost of producing hydrogen also represents a huge challenge to be faced in order to make hydrogen a viable solution for large-scale production, as hydrogen is currently more expensive per kWh than jet fuel (Airbus SAS 2021).

Hydrogen due to its lower volumetric energy density, when compared to the jet fuel currently used in aviation, or with the lithium batteries used in the electrical system, is an excellent alternative because it allows to reach longer distances with a lower volume of storage (Airbus SAS 2021).

Depending on the alternative energy option chosen, that could significantly impact the airport infrastructure and the costs these modifications may implicate. In order to receive hydrogen, airport infrastructure would require enormous changes, from transportation to storage (Airbus SAS 2021). The aviation industry is not characterized by fast technological adaptation, and based on that, we can say that in average, a major modification can take up to 20 years for the total airport infrastructures adaptation and certification before new technologies are fully implemented (Kivits, Charles, and Ryan 2010).

Electric propulsion was initially introduced into the market in 2014, in the sailplanes type. In 2020, EASA certified the Pipistrel Velis Electro, the first fully electric general aviation aircraft. More projects are taking place, Finnair would like to introduce a 19 seat regional electric turboprop, while Airbus and Boeing focused on hybrid-electric, single aisle aircraft with seat capacities of around 100 passengers, expected to be on the market after 2030. Continuing technical challenges linked to battery technology include the need for increased energy density to reduce weight and increase flight time duration in order to expand the operational uses of electric aircraft (EASA, EEA, and Eurocontrol 2022).

2.4. LANDING AND TAKE-OFF CYCLE

To study and measure the air quality associated with the GHGs emissions in the area of an airport, the Landing and Take-off Cycle (LTO) represented in Figure 15 is generally used as a reference (EASA, EEA, and Eurocontrol 2016).

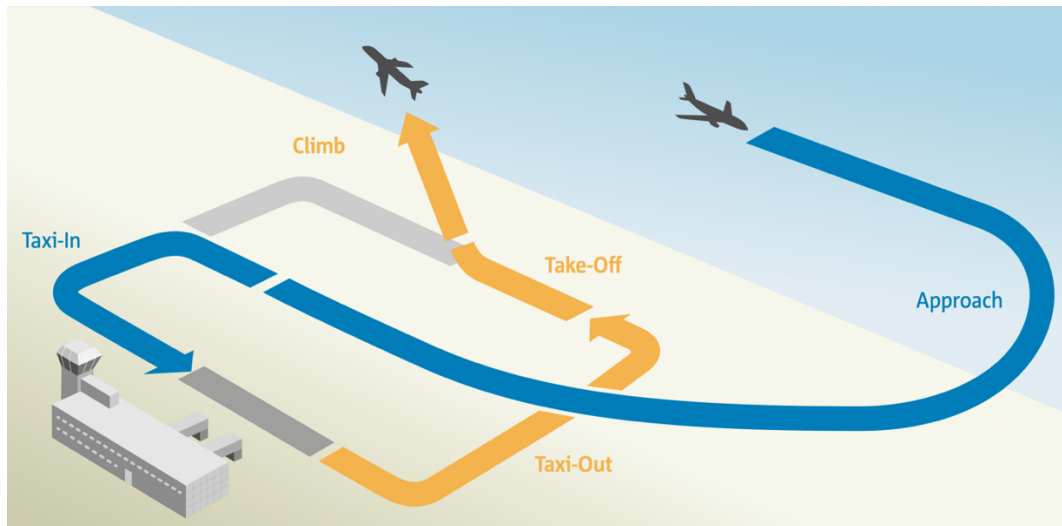


Figure 15: LTO Cycle
Source: (EASA, EEA, and Eurocontrol 2016)

The LTO cycle is defined by the ICAO as the Landing and Take-off Cycle, and is divided in four phases as described in Table 5 (EASA, EEA, and Eurocontrol 2016). The Take-off phase assumes a thrust of 100% during 0,7 minutes, followed by a Climb out phase with a setting thrust of 85% during 2,2 minutes, thus analyzing the initial climb to 3000 feet. The approach is considered below 3000 feet, assuming a rating thrust of 30% during 4 minutes. The taxi phase is composed by the taxi-in and taxi-out, with 7% of engine thrust resulting in a total of 26 minutes (EASA, EEA, and Eurocontrol 2016).

Table 5: LTO Cycle details
Source: (EASA, EEA, and Eurocontrol 2016)

Mode	Thrust (%)	Time (min)
Take-Off (T/O)	100	0,7
Climb (C/O)	85	2,2
Approach (App)	30	4
Taxi (Idle)	7	26

2.5. AUXILIAR POWER UNIT

The Auxiliar Power Unit (APU) must be taken into consideration when it is intended to address the issue of GHG emissions in aviation, due to its usage time in each operation cycle. The APU is a self-contained unit that allows the aircraft to remain independent of external electrical and pneumatic power supply. The APU has four operating modes, the "Idle" mode, which represents the mode that consumes the least energy, where the APU is turned on, but does not supply electricity or bled air for the air condition. The APU can then be used to supply electrical power to the aircraft, or just to provide bleed air for the air condition system and for the engine start, or in a combination of both (Padhra 2018a). The APU average consumption varies from about 100kg/h up to more than 300kg/h, which despite the apparent residual value, when compared to the engine consumption (range approximately from 1000kg/h to 2500kg/h), when multiplied by all the flights operated daily represents a very significant value, that's why it should be taken into account when the subject under analysis is the environmental impact of aviation. During the aircraft turnaround the APU represents the main source of emissions (Padhra 2018b). The need for air conditioning during the turnaround period can also lead to longer use of the APU, if there is no possibility of having external air conditioning.

2.5.1. APU CYCLES

To analyze the emissions related to the use of the APU, we can divide its use into two periods, a first period related to the use of APU after landing until reaching the stand and having an external energy power source available (arrival cycle), and a second period related to the time elapsed from the time where the APU is switched on before passenger boarding until the moment during the taxi in which the APU (departure cycle) is turned off. Figure 16 represents in a more intuitive way the event sequence during the turnaround which ensures that the aircraft is continually powered since the aircraft arrival to the stand and parking brake is applied, until the parking brake is released in order to start the pushback or the taxi out. During most of the turnaround time, the APU is usually switched off as the vast majority of airports have an external energy source available (Padhra 2018b).

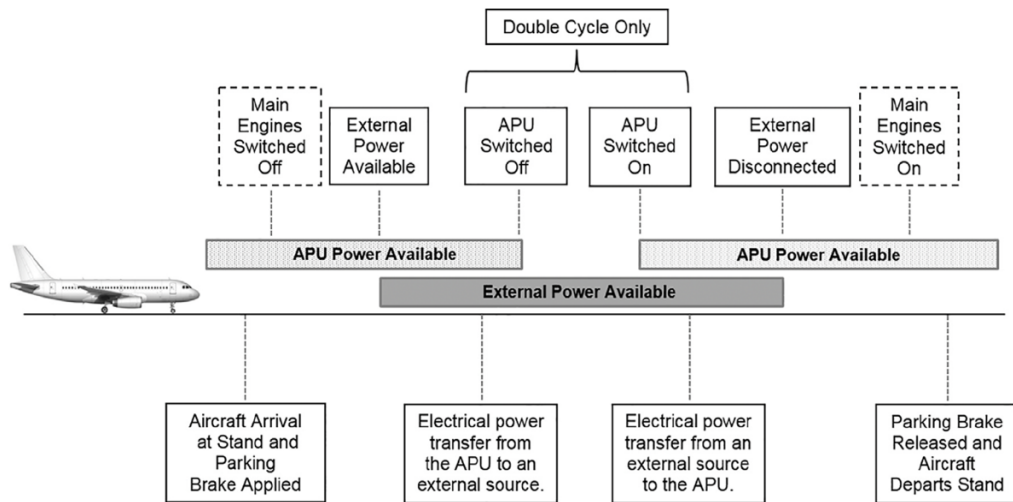


Figure 16: APU Cycles
Source: (Padhra 2018b)

When the APU is used during two periods for each LTO cycle, as explained in detail above (which is the majority of cases), it's called double cycle. If there is no external power available, or if external air conditioning is required, the APU can remain ON throughout the rotation, becoming a single cycle, resulting in increased consumption and emissions.

2.5.2. APU CONSUMPTION AND EMISSIONS

APU emissions cannot be neglected when compared to main engine emissions due to similar Emission Index (EI) values and longer operating periods of APUs compared to main engines during the operation on the ground in the airport (Schäfer et al. 2003). Real measurements of APU emissions at airports demonstrated the higher emissions values associated with the use of the APU when compared to the emissions produced by the engine during the entire time of rotation (Padhra 2018a).

The total APU fuel consumption (F), expressed in kg, can be calculated using the following equation (1):

$$F = FF \times t \tag{1}$$

Where FF represents the fuel flow rate, in kg/h, which is strongly related to the APU operating mode, and t represents the period of utilization of APU, in hours (Padhra 2018a).

Figure 17 shows the difference in APU fuel flow rate of a common type of APU installed in a medium-haul aircraft, with the purpose of analyzing the average variations in the fuel flow rate associated with the different operating modes. (Padhra 2018b).

The lower and upper bars in the Figure 17 represent the minimum and maximum values, respectively, and the solid diamond markers represents the average values (Padhra 2018b).

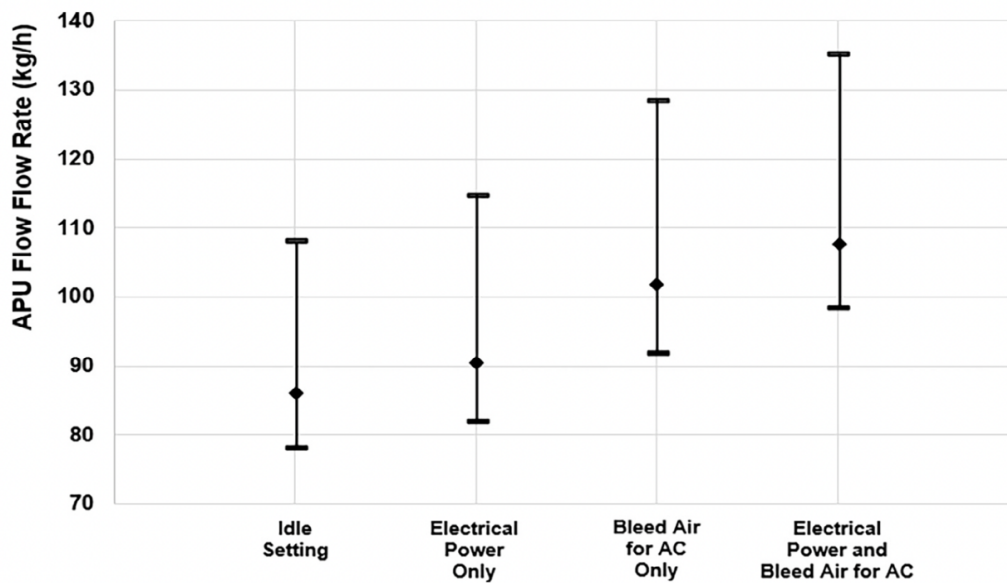


Figure 17: APU fuel flow rate for the different modes of operation

Source: (Padhra 2018b)

Table 6 shows the EI for carbon monoxide (CO), nitrogen oxides (NOx) and total hydrocarbons (THC) of two of the most used APU models. After analyzing other studies, such as the example below, it was possible to determine an average emission index (EI) value for the APU, and this value will be used to determine emissions later throughout this work.

Table 6: Emissions Index (EI) for the most commonly used APU models (conventional jet fuel)
Source: (Padhra 2018b)

Model	Source	CO (g/kg)	THC (g/kg)	NO _x (g/kg)
APU 131-9	(Wade 2002)	2,540	0,180	3,490
	(CSSI and FAA Office of Environment and Energy 2007)	5,650	0,428	7,680
	(Watterson, Walker, and Eggleston 2004)	4,880	0,370	6,640
APU GTCP 36- 300	(CSSI and FAA Office of Environment and Energy 2007)	1,602	0,117	7,890
	(Energy and Environmental Analysis Inc. (EEAI) 1995)	2,050	-	10,100
	(Fleuti and Hofmann 2005)	2,040	0,180	10,180
	(Watterson, Walker, and Eggleston 2004)	2,050	0,150	10,100
Average APU emissions (EI)		2,973	0,204	8,011

The values of carbon dioxide (CO₂) and sulfur dioxide (SO₂), resulting from the use of the APU, and which are present throughout the next tables and in the Results section, were achieved from the application of the following conversion (Correia 2009):

$$CO_2 = 3,1564 \times APU \text{ consumption } (t) \quad (2)$$

$$SO_2 = 0,1 \times APU \text{ consumption } (t) \quad (3)$$

For the calculation of CO₂ emissions, as shown in equation (2), the constant 3.1564 was considered, which represents the number of tonnes of CO₂ produced by burning a tonne of jet fuel (ICAO 2017). This constant is then multiplied by the fuel consumption by the APU.

For the calculation of SO₂ emissions, as shown in equation (3), the constant 0.1 was considered, which represents the number of tonnes of SO₂ produced by burning a tonne of jet fuel (Correia 2009). This constant is then multiplied by the fuel consumption by the APU.

Table 7: APU consumption for various aircraft type
Source: Own development based on (Padhra 2018b)

Aircraft Type	APU consumption (kg/h)
CRJ 200	100
B737	110
A320	126
A330	210
B777	312

In order to obtain and simplify the analysis an average APU consumptions value, and given the substantial variations in consumptions between models, and based on Table 7, the classification was divided into 3 groups with similar consumption, resulting in an average consumption per group, classified as: Short and Medium-haul, Long-Haul and Other, as shown in Table 8.

Table 8: APU consumption for similar aircraft groups
Source: Own development based on (Padhra 2018b)

Group	APU consumption (kg/h)
Short and Medium-Haul	118
Long-Haul	261
Other	100

2.6. AIRPORT CARBON ACCREDITATION

Airport Carbon Accreditation (ACA) is a global carbon management certification program for airports, that assesses and recognizes the efforts of airports to manage and reduce their carbon emissions through 6 levels of certification.

Through the ACA program referred as mapping it is expected that airports will be able to determine the sources of carbon emissions, and consequently calculate the annual carbon emissions (ACA 2023).

ACA program is a voluntary initiative, launched in 2009 by the Airports Council International Europe, and data from 2021 refers the ACA program already includes 362 airports, of which 155 are European airports, represented in Figure 18, corresponding to 65.2% of European passenger major airports. It provides a common framework for

carbon management with the primary objective to encourage and enable airports to reduce their CO₂ emissions (EASA, EEA, and Eurocontrol 2022).

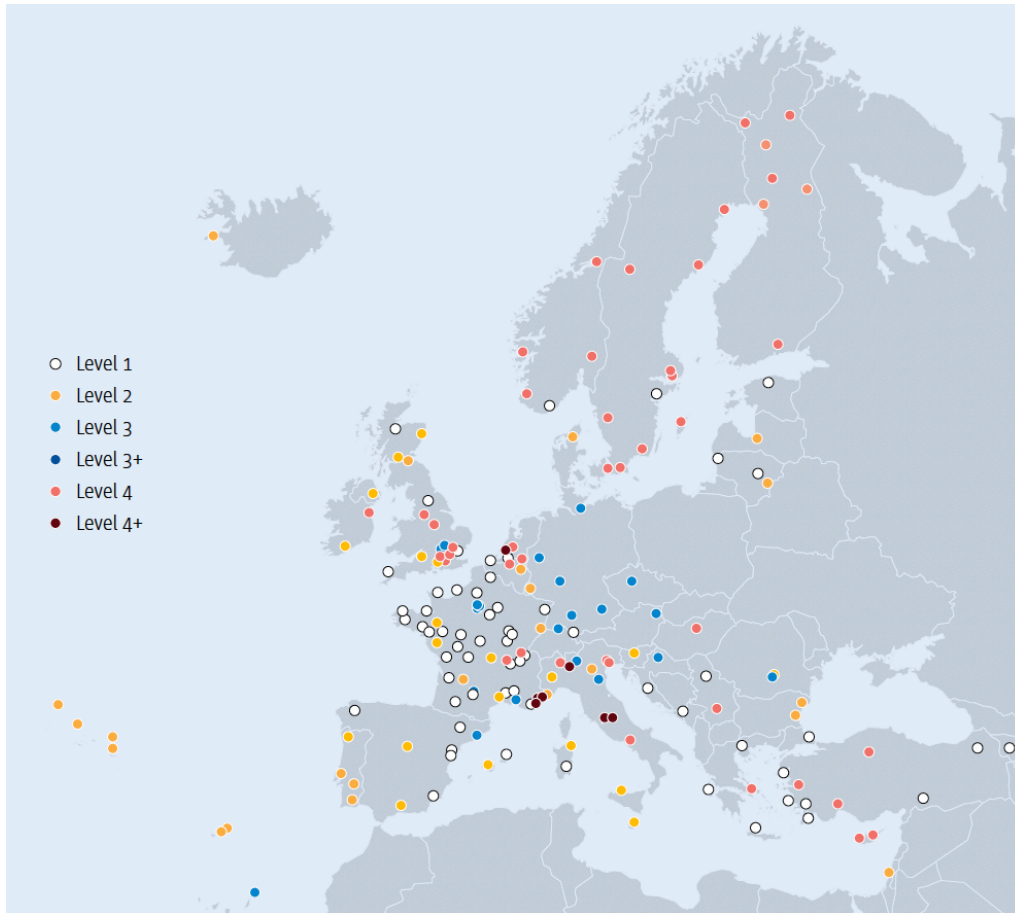


Figure 18: European airports participating in the ACA programme
Source: (EASA, EEA, and Eurocontrol 2022)

As depicted in the Figure 18, 7 European airports have already achieved accreditation at the highest level, Level 4+ (Milan Linate Airport, Cannes-Mandelieu Airport, Nice Côte d’Azur Airport, La Môle-Saint-Tropez Airport, Rome-Fiumicino International Airport, Rome-Ciampino International Airport and Rotterdam The Hague Airport) (EASA, EEA, and Eurocontrol 2022).

The ACA program was initially structured with four levels of certification, from Level 1 to Level 4. The program's area of activity is further divided into 3 main scopes, as described in Table 9 from direct airport emissions (Scope 1), through indirect emissions under airport control from consumption of purchased electricity, heat or steam (Scope 2), and finally related to the emissions by others operating at the airport such as aircraft and surface vehicles (Scope 3) (ACA 2023).

Table 9: Summary of GHG scope emissions for airports
Source: (ACA 2023)

	Scope 1	Scope 2	Scope 3
Definition	GHG emissions come from on-site sources that airport owns	GHG emission come from purchase of off-site energy	GHG emissions come from on-site sources thar are controlled by tenants
Examples	<ul style="list-style-type: none"> ▪ On-site natural gas combined heat and power plant ▪ Airport-owned vehicles 	<ul style="list-style-type: none"> ▪ Utility supplied electricity 	<ul style="list-style-type: none"> ▪ GSE owned by airlines ▪ Concessionaire activities ▪ Passenger/employee transportation to and from airport

Level 1 is designated as Mapping, where there must be a policy of commitment to greenhouse gas, carbon or energy reduction at the highest level, focused on Scope 1 and 2 emissions. Level 2 is described as Reduction, being necessary to fully comply with the requirements of Level 1 and develop and demonstrate that the Carbon Management Plan is being implemented effectively, being also applied within the scope of Scope 1 and 2. Level 3 based on Optimization, being It is necessary to fully comply with Level 2 requirements, and the specific Scope 3 emissions must already be included in the carbon footprint. In addition, the carbon footprint must present a report of emissions from all aircraft using the airport, based on the LTO cycle to at a height of 3,000 feet, includes emissions generated during approach, taxi-in and ground idle, taxi-out and ground idle, take off and climb. Finally, there is the Level 3+, called Neutrality, being necessary to fully comply with the Level 3 requirements and create residual emissions offset under airport control.

In order to comply with the targets of achieving net-zero GHGs emissions by 2050 (European Commission 2018) defined by Europe, in 2020, Levels 4 (Transformation) and 4+ (Transition) have been added to the existing levels of certification. To obtain this certification, in addition to complying with all the requirements of the previous certification levels, it is necessary to develop a Carbon Management Plan (which includes solutions for reducing emissions in Scope 1, 2 and 3 (ACA 2023). Figure 19

describes the main requirements of airport carbon accreditation for all levels of accreditation and all the scopes (ACA 2023).

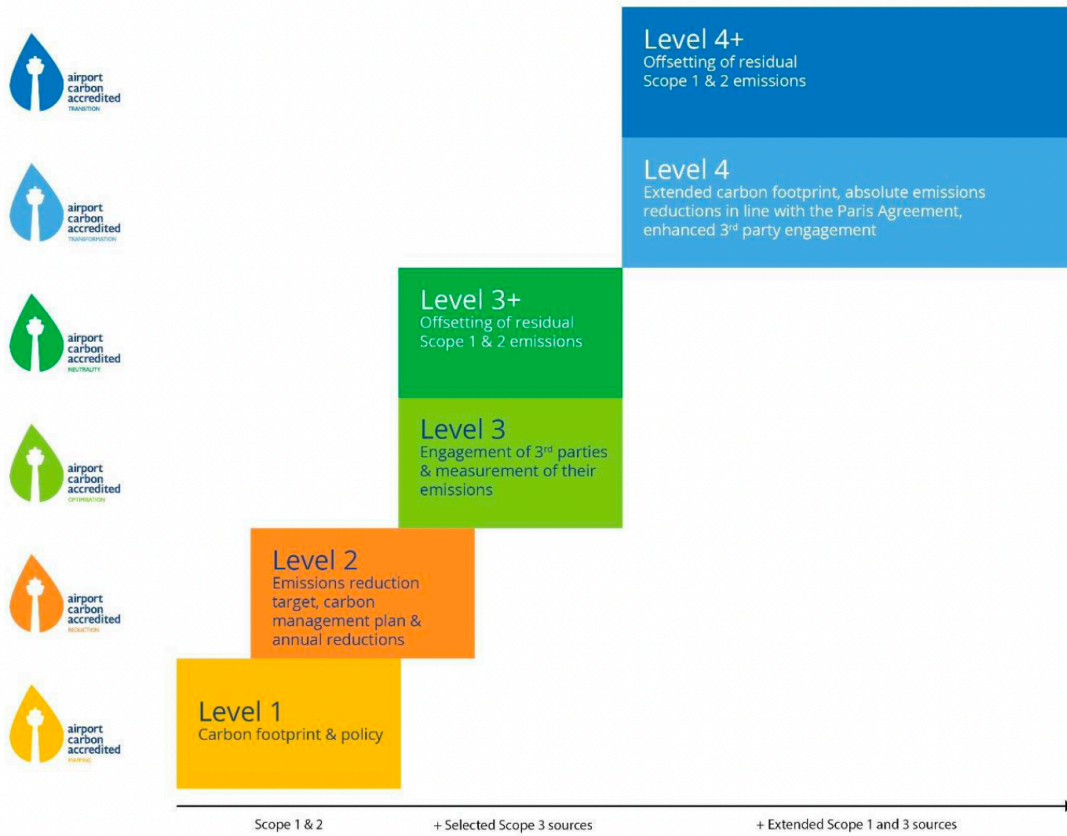


Figure 19: Main Requirements of Airport Carbon Accreditation
Source: (ACA 2023)

Figure 20 shows the relationship between CO₂ emissions per passenger and the number of accredited European airports, showing a strong correlation between the decrease in CO₂ emissions per passenger and the increase in the number of accredited European airports. In 2010, when Europe only had 43 airports with ACA credit, CO₂ emissions per passenger were around 3.7kg CO₂/passenger, after around 10 years, in 2020/2021, Europe has 155 airports with ACA credit, an incredible increase of 353%, which helped to reduce CO₂ emissions per passenger to values in the order of 1.1kg CO₂/passenger, which is equivalent to a reduction of 70% (EASA, EEA, and Eurocontrol 2022). Even so, of this group of 155 accredited airports in Europe, only a small part reached the highest

level of accreditation, which still shows a long way to go, and a very high potential for reducing CO₂ emissions per passenger (EASA, EEA, and Eurocontrol 2022).

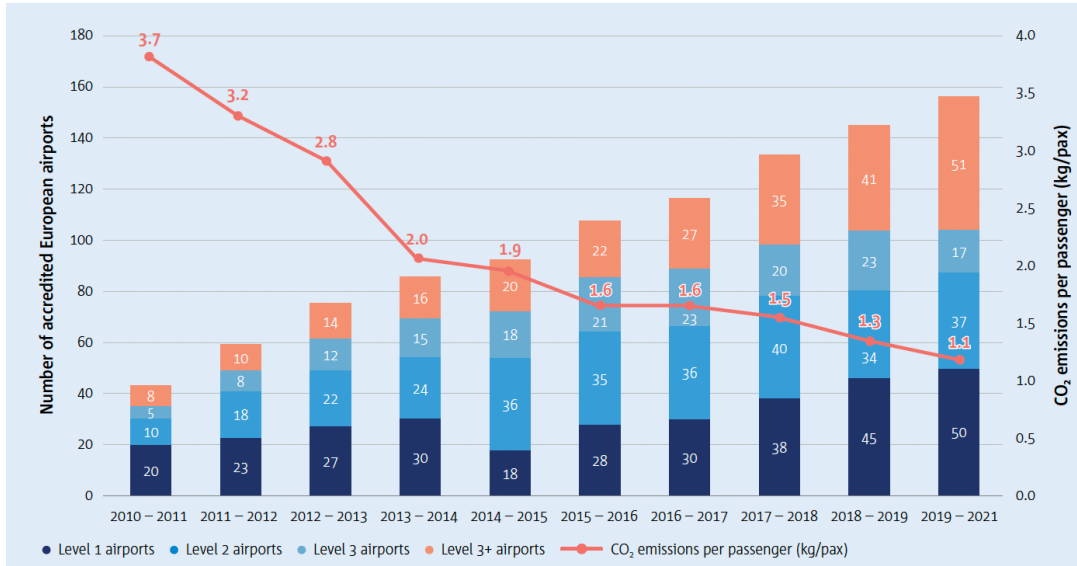


Figure 20: Relation between CO₂ emissions per passenger and number of accredited European airports
Source: (EASA, EEA, and Eurocontrol 2022)

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3. CASE STUDY: LISBON AIRPORT

The Lisbon airport (LIS) is the Portuguese largest and busiest airport and it is close to reach its full capacity of air traffic movements, contributing to the high number of pollutants in the vicinity of the airport (Roque 2017). This is even more concerning due to its location, within the city center, surrounded by residential areas, as depicted in Figure 21. There is a consensus among scientists that emissions from airplanes negatively affect the health and life quality of people living in the region close to the airport, causing an increase in global air pollution (Tokuslu 2021). For these reasons, Lisbon airport was chosen to carry out the analysis, with the aim of finding out what reduction in GHGs emissions could be obtained through a transition to the use of alternative fuels. This analysis will focus exclusively on the airside of the airport.

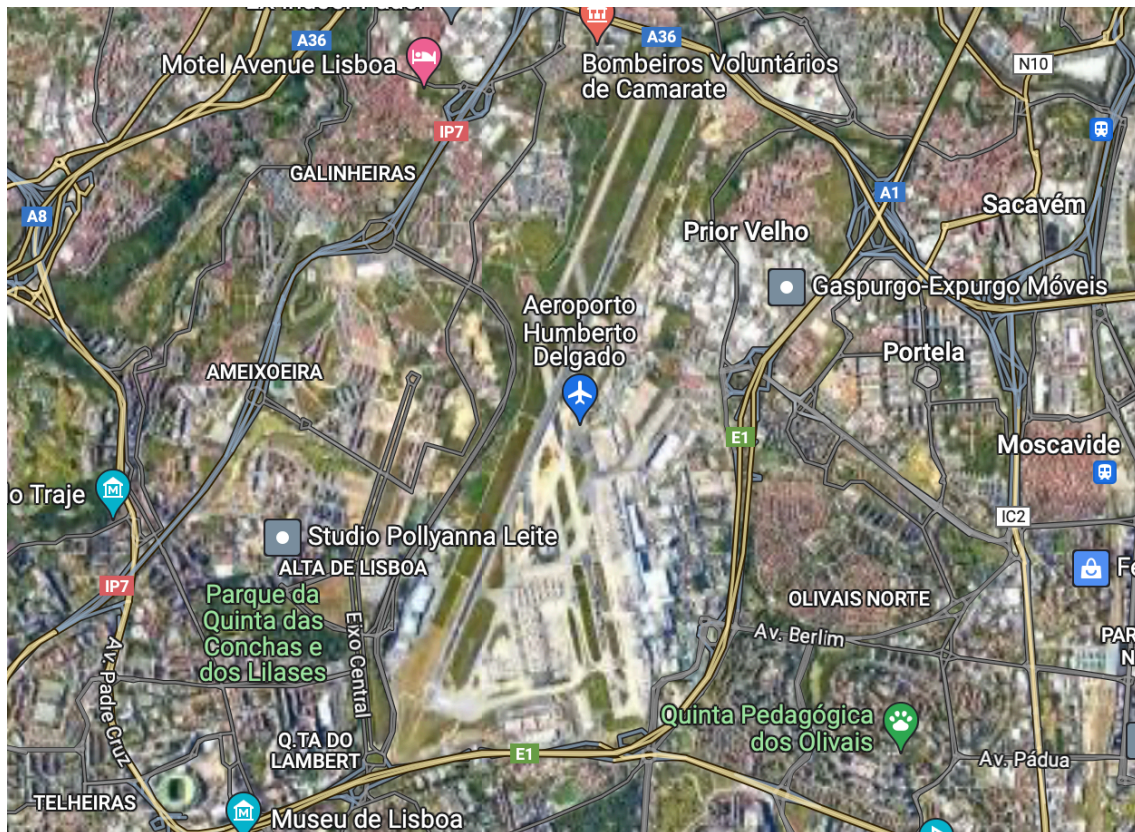


Figure 21: LIS airport and its vicinity
Source: (Google Maps 2024)

LIS has domestic and international flights to different continents. The monthly distribution of passengers and consequently aircraft movements relative to the year 2023 is demonstrated in

Table 10 (ANAC 2023).

Table 10: Aircraft movements and distribution of passengers at LIS per month

Source: Own development based on (ANAC 2023)

Month/Year	Aircraft Movements	Passengers
JAN/2023	16759	2242783
FEB/2023	15569	2249612
MAR/2023	17747	2632438
APR/2023	18244	2835772
MAY/2023	18949	2928798
JUN/2023	19329	2993080
JUL/2023	20607	3265819
AUG/2023	20749	3298202
SEP/2023	19925	3143669
OCT/2023	19931	3067858
NOV/2023	17091	2449708
DEC/2023	17850	2490484

Figure 22 illustrates the variation in aircraft movements at LIS throughout the months of 2023.

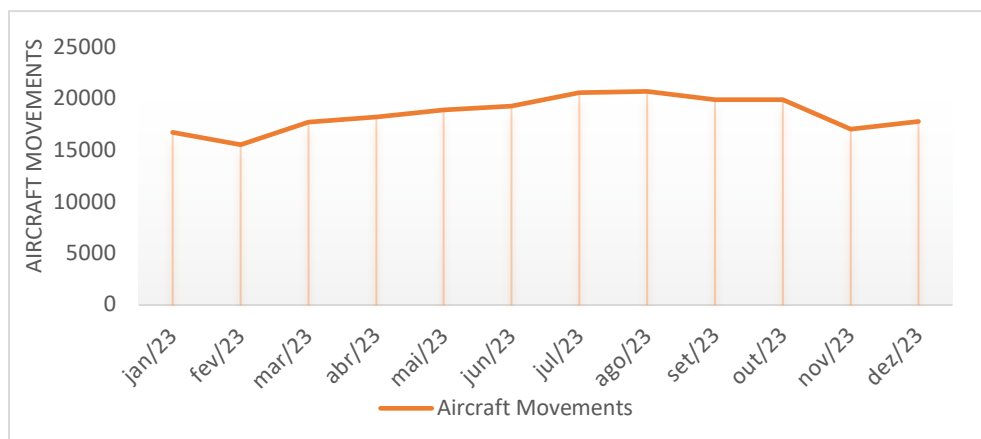
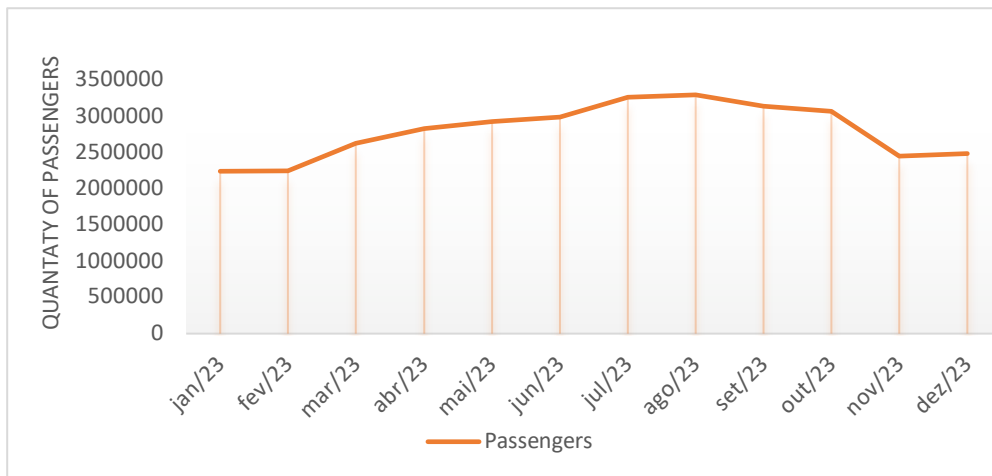


Figure 22: Aircraft movements variation at LIS per month
Source: Own development based on (ANAC 2023)

Figure 23 illustrates the variation in passengers at LIS throughout the months of 2023. The peak months were July and August probably due to the summer time. For the work under analysis, it is important to focus on the month of March 2023, which will be the month under analysis. During the month of March 2023, Lisbon airport had a total of

17,747 aircraft movements, around 4.6% below the average monthly movements for the year 2023. During the same period, March 2023, 2,632,438 passengers passed



through Lisbon airport, around 8.7% below the average monthly movement for the year 2023 (ANAC 2023).

Figure 23: Passengers variation at LIS per month
Source: Own development based on (ANAC 2023)

LIS airport was accredited with ACA level 4+, thus recognizing its contribution to the decarbonization of the aviation sector, as well as the implementation of real-time monitoring of CO₂ emissions during aircraft taxiing (ACA 2023).

As depicted in Figure 24, the airfield of the LPPT has one runway, 02/20 (the designation of the runways is given according to their orientation relatively to the magnetic north, rounded to the tens, and taking into account both orientations in which a single runway can be used) and two terminal (1 and 2). This information is relevant to understand the different taxi configurations adopted at LIS airport, and how it influences the fuel consumption and emission of pollutants for each LTO cycle. The different taxi configurations and the variations in taxi times and emissions depending on the configuration in use will be explained in detail in section 3.5 of this work denominated “Taxi Time, Consumption and Emissions”.

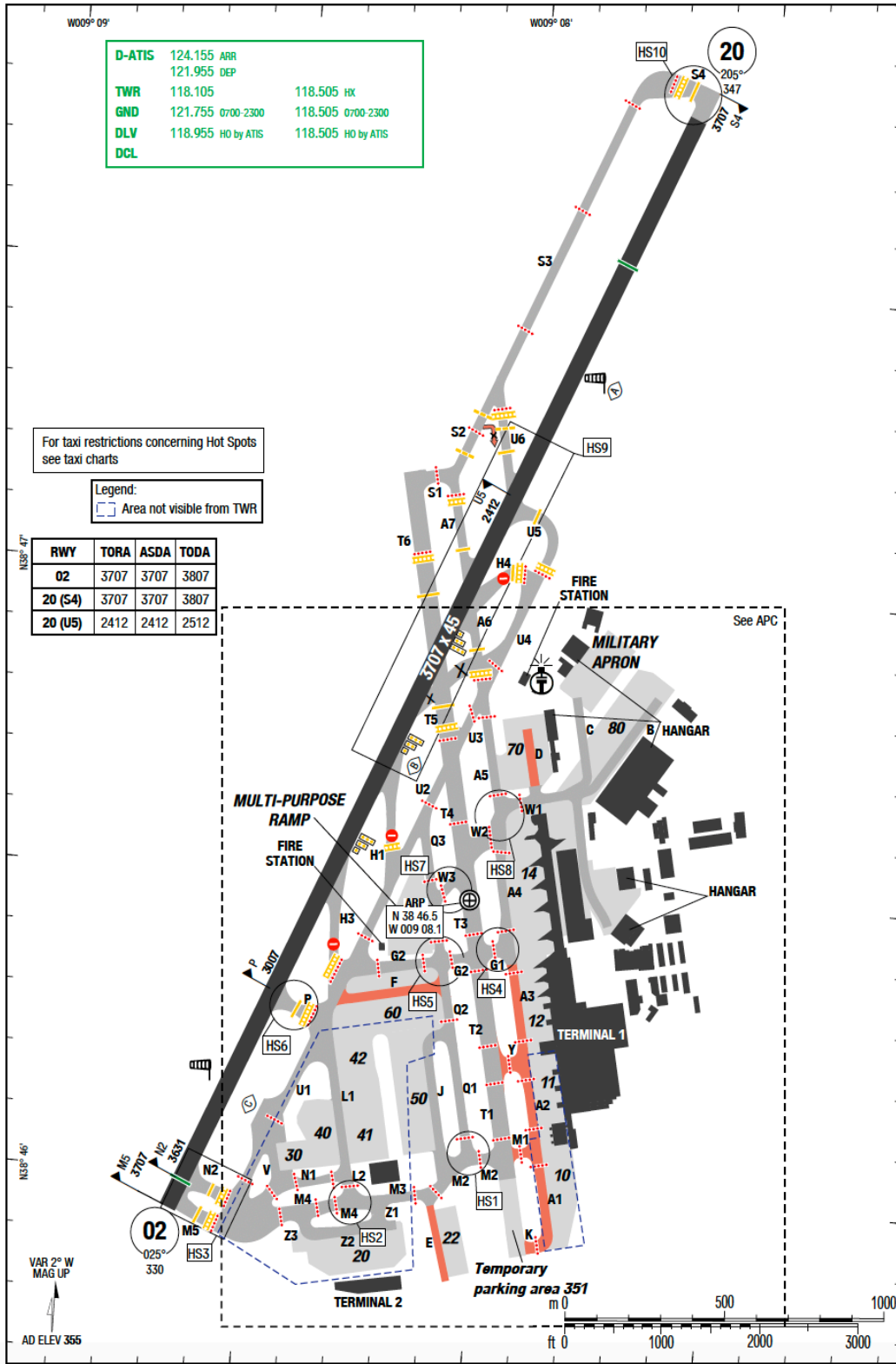


Figure 24: LIS AGC - Airport Ground Chart
Source: (LIDO Lufthansa System 2024)

3.1. AIRCRAFT MOVEMENTS

The aircraft movements are one of the biggest generators of GHGs in the airport structure. To compare the GHGs emissions associated with the aircraft movements before and after the use of alternative fuels, the average emissions of these gases were calculated for Lisbon airport, taking into account the following assumptions:

- Use as a reference the LTO cycle, up to 3000ft;
- Statistical data from one week, including the real number of movements for each type of aircraft (engine) at Lisbon airport, analysis conducted from March 7, 2023 until March 13, 2023. The chosen period was based on the application of the randomness criterion and availability to obtain this information. The traffic sample for the referred period is obtained from an online database (Flight Radar 2024) which keeps data relatively to all the arrivals and departure from LIS airport. The data acquired by the database is from different sources, the main one being Automatic Dependent Surveillance-Broadcast (ADS-B). According to the analyzed data available at ANAC, the period under analysis, regarding the monthly traffic variation at the airport, represents approximately an average month (only around 4.6% below the average monthly movements for the year 2023), which seems appropriate for this analysis given that the aim is to achieve an annual average of movements and emissions. This fact has been observed for the current year, fact that is in line with previous years, was also observed that the month of February corresponds to the month with the lowest air traffic, and the month of August represents the peak of operations at the airport under analysis (ANAC 2023).
- Supported by taxi-in and taxi-out real-time statistics (due to the existing differences between the LTO taxi time and the real taxi time at LIS airport).

In order to guarantee easier access to the information related to the aircraft engines emissions, EASA is hosting a databank called ICAO Engine Emissions Databank, where all the accurate information is provided by the engine manufacturers after regulatory testing has been performed and approval from the certifying authority is obtained (EASA 2023).

Departures at LIS airport (per engine type) Table 12 and Table 13 were created based on the number of departures reported at Lisbon airport, full report available online at <http://hdl.handle.net/10400.6/14451>. The number of movements is separated by type of engine due to the difference in emissions of each model.

Table 11: Departures at Lisbon airport - Short and Medium-haul
Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Departures - Short and Medium-haul (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total
ATR72-500	PWC PW127F	2	3	2	3	0	1	0	11
ATR72-600	PWC PW127M	1	3	0	2	4	3	1	14
A220-100/300	PW1524G	3	2	2	4	4	4	3	22
A319	CFMI CFM56-5B5/3	6	2	2	4	3	4	4	25
	CFMI CFM56-5B6/P	7	6	7	5	6	5	5	41
	IAE V2522-A5	1	1	0	1	1	2	1	7
A320 CEO	CFMI CFM56-5B6/3	1	1	0	2	1	0	0	5
	CFMI CFM56-5B4/P	56	63	62	60	57	56	61	415
	IAE V2527-A5	5	4	4	3	3	5	1	25
A320 NEO	CFMI LEAP-1A26	24	23	27	25	29	26	32	186
	PW1127G	5	3	6	5	5	2	1	27
A321 CEO	CFMI CFM56-5B1/3	0	0	0	1	0	0	1	2
	CFMI CFM56-5B3/P	1	2	7	8	3	6	6	33
	IAE V2533-A5	4	7	3	6	2	7	7	36
A321 NEO	CFMI LEAP-1A32	35	36	39	43	40	46	44	283
	CFMI LEAP-1A33	1	2	3	2	2	4	3	17
	PW1133G	4	5	3	6	3	3	4	28
B737-600/700	CFMI CFM56-7B22	2	1	2	3	1	2	2	13
	CFMI CFM56-7B24	0	0	2	1	1	0	2	6
B737-800/900	CFMI CFM56-7B24E	0	1	0	0	0	0	0	1
	CFMI CFM56-7B26	27	25	29	36	36	31	39	223
	CFMI CFM56-7B27	5	9	7	7	4	5	6	43
B737-43QF	CFMI CFM56-3B2	0	1	0	0	0	0	0	1
	CFMI CFM56-3C1	3	2	3	3	0	1	1	13
B737 MAX 8	CFMI LEAP-1B	5	6	5	7	4	5	7	39
E190/E195	GE CF34-10E5A1	3	4	6	4	4	6	3	30
	GE CF34-10E6	5	6	6	5	4	7	5	38
	GE CF34-10E7	21	26	28	28	31	30	28	192

Table 12: Departures at Lisbon airport - Long-haul
Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Departures - Long-haul (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total

A330-200	GE CF6-80E1A4	2	2	3	3	2	2	3	17
A330-300	RR Trent 772B-60	1	1	1	1	2	2	2	10
A330-900 NEO	RR Trent 7000-72	14	14	13	14	15	14	13	97
A340-312	CFMI CFM56-5C3/F	1	0	1	1	0	0	2	5
B757-200	PW2037	1	1	0	0	0	0	0	2
	PW2040	0	0	1	1	0	0	0	2
	RR RB211-535 E4	0	0	0	0	0	0	1	1
B767-200	GE CF6-80A2	0	1	0	0	0	0	0	1
	GE CF6-80C2B2F	1	0	0	1	0	0	1	3
B767-300	PW4056	1	0	0	1	2	0	1	5
	PW4060	1	1	1	1	1	1	1	7
B767-400	GE CF6-80C2B7F	1	1	1	1	1	1	1	7
B777-243(ER)	GE GE90-94B	0	1	0	0	0	0	0	1
B787-900	RR Trent 1000	1	1	1	1	1	0	1	6
B777-31H	GE GE90-115B	2	2	2	2	2	3	2	15

Table 13: Departures at Lisbon airport – Others
Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Departures - Others (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total
Bombardier G5000	RR BR710-A220	1	0	0	0	0	0	0	1
Bombardier G7500	BR700-710A220	0	1	0	0	0	1	0	2
Hawker 400XP	PW JT15D-5	0	0	1	0	0	0	0	1
Hawker 800XP	TFE731-5BR-1H	0	1	0	0	0	0	0	1
D Falcon-2000EX	PW308C	1	0	0	1	2	1	0	5
E Phenom 300	PW535E	1	1	0	0	0	0	0	2
Cessna 525A C. CJ2	FJ44-2	0	1	0	0	0	0	0	1
Cessna 525B C. CJ3	FJ44-3	0	1	1	0	0	0	0	2
Cessna 525C C. CJ4	FJ44-4A	0	1	0	0	0	0	0	1
Cessna 650 C. III	TFE731-3B	0	1	0	1	0	0	0	2
Cessna Sovereign	PW306C	0	1	0	0	0	0	0	1
Learjet 60	PW305A	0	1	0	0	0	0	0	1
GLEX	RR Pearl 15	0	0	0	1	0	0	0	1
Diamond DA-62	Austro Eng. E4	0	1	0	0	0	0	0	1

3.2. ARRIVALS AT LIS AIRPORT (PER ENGINE TYPE)

Table 14, Table 15 and Table 16 were based on the number of arrivals reported at Lisbon airport, full report available online at <http://hdl.handle.net/10400.6/14450>. The number of movements is separated by type of engine due to the difference in emissions of each model.

Table 14: Arrivals at Lisbon airport - Short and Medium-haul
Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Arrivals - Short and Medium-haul (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total
ATR72-500	PWC PW127F	1	2	2	1	2	0	1	9
ATR72-600	PWC PW127M	1	2	1	1	3	3	2	13
A220-100/300	PW1524G	3	2	2	4	3	4	3	21
A319	CFMI CFM56-5B5/3	5	3	2	3	4	4	4	25
	CFMI CFM56-5B6/P	6	7	6	5	6	5	5	40
	IAE V2522-A5	2	0	1	0	2	1	1	7
A320 CEO	CFMI CFM56-5B6/3	1	1	0	2	1	0	0	5
	CFMI CFM56-5B4/P	56	59	65	59	51	61	58	409
	IAE V2527-A5	4	3	4	3	3	5	1	23
A320 NEO	CFMI LEAP-1A26	26	23	25	28	25	28	33	188
	PW1127G	5	4	4	6	4	2	1	26
A321 CEO	CFMI CFM56-5B1/3	0	0	0	1	0	0	1	2
	CFMI CFM56-5B3/P	1	4	4	7	5	5	7	33
	IAE V2533-A5	4	7	3	6	4	6	7	37
A321 NEO	CFMI LEAP-1A32	33	37	36	43	41	47	46	283
	CFMI LEAP-1A33	1	2	2	1	4	5	3	18
	PW1133G	4	5	4	5	3	3	4	28
B737-600/700	CFMI CFM56-7B22	1	1	2	3	1	2	2	12
	CFMI CFM56-7B24	0	0	2	1	1	0	2	6
B737-800/900	CFMI CFM56-7B26	28	23	29	35	34	31	39	219
	CFMI CFM56-7B27	6	7	7	6	4	6	5	41
B737-43QF	CFMI CFM56-3B2	0	1	0	0	0	0	0	1
	CFMI CFM56-3C1	3	2	3	3	0	1	1	13
B737 MAX 8	CFMI LEAP-1B	5	6	5	7	4	5	7	39
E190/E195	GE CF34-10E5A1	4	3	5	5	4	5	5	31
	GE CF34-10E6	6	5	7	4	5	6	5	38
	GE CF34-10E7	22	20	27	28	30	28	33	188

Table 15: Arrivals at Lisbon airport - Long-haul
Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Arrivals - Long-haul (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total
A330-200	GE CF6-80E1A4	2	3	2	3	3	1	3	17
A330-300	RR Trent 772B-60	1	1	1	1	2	1	2	9
A330-900 NEO	RR Trent 7000-72	13	14	14	13	15	15	13	97

A340-312	CFMI CFM56-5C3/F	1	0	1	1	1	0	1	5
B757-200	PW2037	1	1	0	0	0	0	0	2
	PW2040	0	0	1	1	0	0	0	2
	RR RB211-535 E4	0	0	0	0	0	0	1	1
B767-200	GE CF6-80A2	0	1	0	0	0	0	0	1
	GE CF6-80C2B2F	1	0	0	1	0	0	1	3
B767-300	PW4056	0	0	1	1	1	0	1	4
	PW4060	1	1	1	1	1	1	1	7
B767-400	GE CF6-80C2B7F	1	1	1	1	1	1	1	7
B787-900	RR Trent 1000	1	1	1	1	1	0	1	6
B777-31H	GE90-115B	2	2	2	2	2	2	2	14

Table 16: Arrivals at Lisbon airport – Others

Source: (Own development based on Airfleets 2023 and FlightRadar24 2023)

Arrivals - Others (07/03/2023 - 13/03/2023)									
Aircraft	Engine	7/03	8/03	9/03	10/03	11/03	12/03	13/03	Total
Bombardier G7500	BR700-710A220	1	0	0	0	0	1	0	2
Hawker 400XP	PW JT15D-5	0	0	1	0	0	0	0	1
Hawker 800XP	TFE 731-5BR-1H	0	0	0	0	0	0	0	0
D Falcon-2000EX	PW308C	0	0	1	0	1	1	1	4
E Phenom 300	PW535E	0	1	0	0	0	0	0	1
Cessna 525A C. CJ2	FJ44-2	0	1	0	0	0	0	0	1
Cessna 525B C. CJ3	FJ44-3	0	1	0	0	0	0	0	1
Cessna 525C C. CJ4	FJ44-4A	0	1	0	0	0	0	0	1
Cessna 650 C. III	TFE731-3B	0	0	0	1	0	0	0	1
Cessna Sovereign	PW306C	0	1	0	0	0	0	0	1
Learjet 60	PW305A	0	1	0	0	0	0	0	1
GLEK	RR Pearl 15	0	0	0	1	0	0	0	1
Diamond DA-62	Austro Engine E4	1	0	0	0	0	0	0	1

3.3. AIRCRAFT CONSUMPTION AND EMISSIONS USING JET FUEL

The emissions data for unburnt hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) shown in Table 17 relative to PW1524G engine, are provided by the ICAO Engine Emissions Databank (EASA 2023), having been subjected to rigorous testing and approved by the competent authorities. However, the values also have their limitations, being based on International Standard Atmosphere (ISA), as well as the durations and powers associated with each phase of the LTO cycle defined in Table 5 (T/O - Take off

phase, C/O – Climb phase, App - Approach phase, Idle – Taxi phase) (EASA, EEA, and Eurocontrol 2022).

Table 17: A220-100/300 (Engine: PW1524G) emissions
Source: (EASA 2023)

A220-100/300 (Engine: PW1524G)			
Flight Phases	HC (g/kg)	CO (g/kg)	NOx (g/kg)
T/O	0*	0*	26
C/O	0*	0*	20,5
App	0,1	1,8	10,4
Idle	0,1	16,7	6

*The values of 0g for HC and CO, despite being taken directly from the ICAO Engine Emissions Databank, represent an approximate value, as the value is so low that it ends up being disregarded (EASA 2023).

NOx emissions are formed in the engine combustor, and its rate is dependent upon the temperature of the flame and system pressure (higher temperature and pressure result higher NOx formation) (European Commission 2020).

The remaining values shown in the Table 18, carbon dioxide (CO₂) and sulfur dioxide (SO₂) are resulting from the application of the following equation (4) (Correia 2009):

$$Emissions = \alpha \sum_{i=1}^4 FF (i) x TM (i) \quad (4)$$

Where α equals to 3.1564 for CO₂ and 0.1 for SO₂, which represents respectively the number of tonnes of CO₂ and SO₂ produced by burning a tonne of jet fuel (ICAO 2017) (Correia 2009). The CO₂ and the SO₂ emissions are obtained by multiplying the fuel flow (FF) by the time spent (TM) in each of the four phases (T/O, C/O, approach and idle).

The emission of CO₂ is also directly proportional to the fuel burnt, and for aviation kerosene as state by the IPCC, the Emission Index is 3.16kg of CO₂ per kg of fuel burnt (IPCC 2006).

As a demonstration of the calculation method used for each of the engines under analysis, an example applied to the PW1524G engine that is used in the Airbus A220-100 and A220-300 models, as depicted in Table 18.

Table 18: A220-100/300 (Engine: PW1524G) consumption and emissions
Source: Own development, EASA 2023

A220-100/300 (Engine: PW1524G) - based on 1 standard LTO cycle								
Flight Phases	Time (min)	Fuel Flow (kg/min)	Fuel Total (kg)	HC (kg)	CO (kg)	CO₂ (kg)	NO_x (kg)	SO₂ (kg)
T/O	0,7	47,4	33,2	0*	0*	102,62	0,86	3,32
C/O	2,2	39	85,8	0*	0*	270,8	1,76	8,58
App	4	13,8	55,2	0,006	0,099	174,24	0,57	5,52
Idle	26	4,8	124,8	0,012	2,084	393,9	0,75	12,48
Total	32,9		299	0,018	2,183	942	3,9	29,9

*The values of 0 kg for HC and CO, despite being taken directly from the ICAO Engine Emissions Databank, represent an approximate value, as the value is so low that it ends up being disregarded (EASA 2023).

As depicted in Figure 25, during a standard LTO cycle, CO₂ represents the major pollutant with a relative percentage of 96% when compared with all the other pollutants followed by SO₂ with a representation of 3%. The remaining pollutants all together (CO, HC, NO_x) represent just 1% of total pollutant emissions, values that are similar to those obtained in identical studies (Winther and Rypdal 2019).

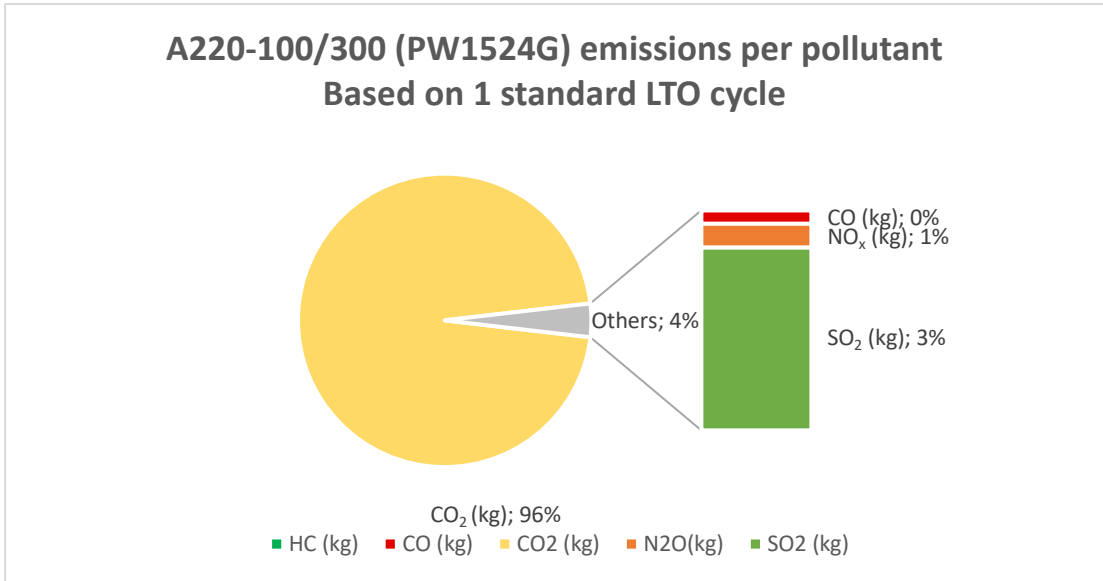


Figure 25: A220-100/300 (PW1524G) emissions per pollutant
Source: Own development

According to Figure 26, it is possible to observe that, although the Idle phase (Taxi phase) presents the lowest fuel flow and therefore the lowest emissions per minute, the long duration of 26 minutes puts it as the phase with more emissions during a standard LTO cycle. The C/O phase represents the phase with the second highest pollutant emissions followed by App and finally by T/O. The distribution of each type of pollutant across the different phases of the LTO cycle can be seen in Figure 27, Figure 28, Figure 29, Figure 30 and Figure 31.

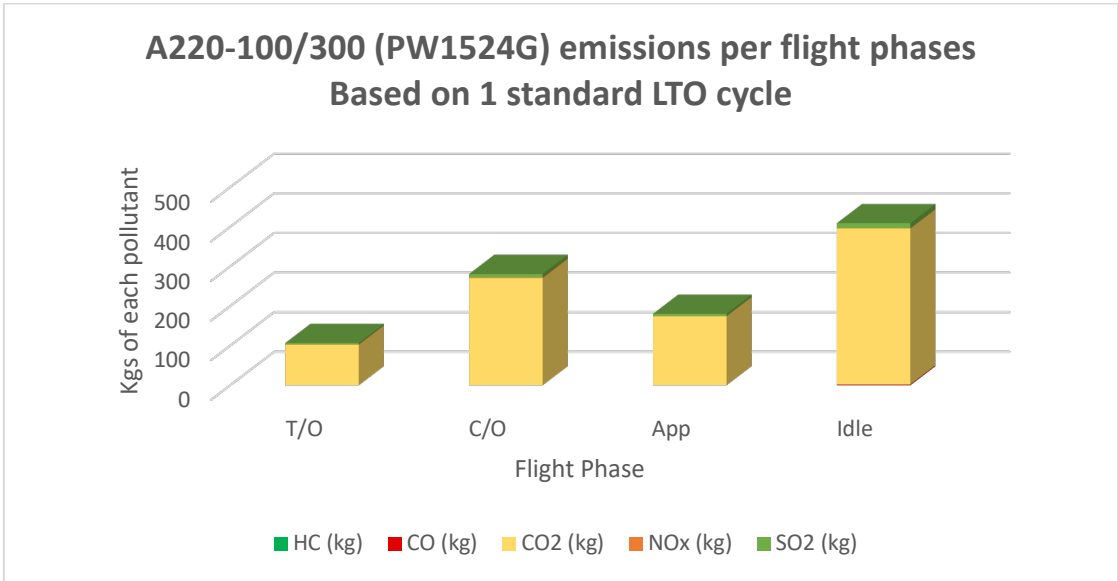


Figure 26: A220-100/300 (PW1524G) emissions per flight phases
Source: Own development

Figure 27 illustrates the HC distribution for each LTO Phase based on 1 standard LTO cycle for a A220-100/300 aircraft equipped with PW1524G engine. The idle phase represents the phase with the highest amount of HC emissions, accounting for 67% of the cycle's total emissions, which is equivalent to 0.012kg of HC. The App phase represents the second phase with the highest amount of HC emissions, accounting for 33% of the cycle's total emissions, which is equivalent to 0.006kg of HC. The values of 0 kg of HC for the T/O and C/O phases, despite being taken directly from the ICAO Engine Emissions Databank, represent an approximate value, as the value is so low that it ends up being disregarded (EASA 2023).

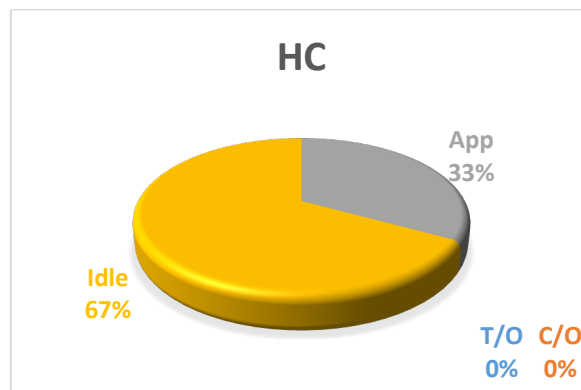


Figure 27: HC distribution for each LTO Phase
Source: Own development

Figure 28 shows the CO distribution for each LTO Phase based on 1 standard LTO cycle for a A220-100/300 aircraft equipped with PW1524G engine. The idle phase represents the phase with the highest amount of CO emissions, accounting for 95% of the cycle's total emissions, which is equivalent to 2.084kg of CO. The App phase represents the second phase with the highest amount of CO emissions, accounting for just 5% of the cycle's total emissions, which is equivalent to 0.099kg of CO. The values of 0 kg of CO for the T/O and C/O phases, despite being taken directly from the ICAO Engine Emissions Databank, represent an approximate value, as the value is so low that it ends up being disregarded (EASA 2023).

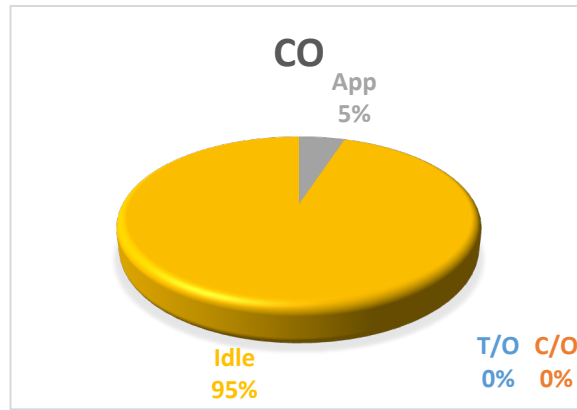


Figure 28: CO distribution for each LTO Phase
Source: Own development

Figure 29 illustrates the NO_x distribution for each LTO Phase based on 1 standard LTO cycle for a A220-100/300 aircraft equipped with PW1524G engine. The C/O phase represents the phase with the highest amount of NO_x emissions, accounting for 44% of the cycle's total emissions, which is equivalent to 1.76kg of NO_x, followed by the T/O phase, accounting for 22% of the cycle's total emissions, which is equivalent to 0.86kg of NO_x. The third phase with the highest number of NO_x emissions is the Idle phase, with 19% of total emissions, which is equivalent to 0.75kg of NO_x. Lastly, the phase with the least amount of NO_x emissions is the App phase, representing only 15% of the cycle's total emissions, which is equivalent to 0.57kg of NO_x.

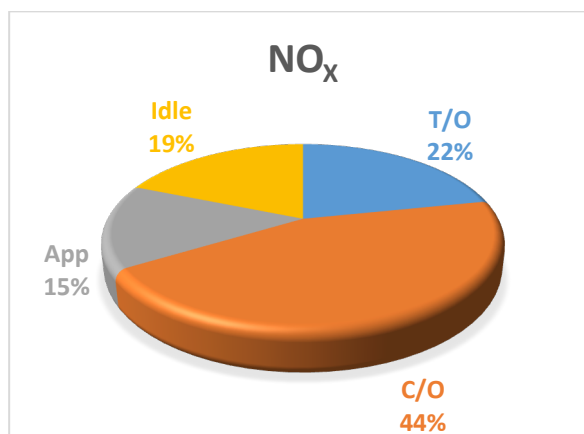


Figure 29: NO_x distribution for each LTO Phase
Source: Own development

Figure 30 illustrates the CO₂ distribution for each LTO Phase based on 1 standard LTO cycle for a A220-100/300 aircraft equipped with PW1524G engine. The Idle phase represents the phase with the highest amount of CO₂ emissions, accounting for 42% of the cycle's total emissions, which is equivalent to 393.8kg of CO₂, followed by the C/O phase, accounting for 29% of the cycle's total emissions, which is equivalent to 270.8kg of CO₂. The third phase with the highest number of CO₂ emissions is the App phase, with 18% of total emissions, which is equivalent to 174.24kg of CO₂. Finally, the phase with the lowest amount of CO₂ emissions is the T/O phase, representing only 11% of the cycle's total emissions, which is equivalent to 102.62kg of CO₂.

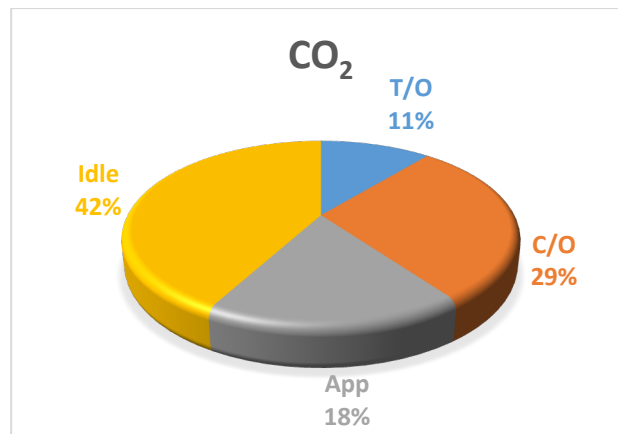


Figure 30: CO₂ distribution for each LTO Phase
Source: Own development

Figure 31 illustrates the SO₂ distribution for each LTO Phase based on 1 standard LTO cycle for a A220-100/300 aircraft equipped with PW1524G engine. The Idle phase represents the phase with the highest amount of SO₂ emissions, accounting for 42% of the cycle's total emissions, which is equivalent to 12.48kg of SO₂, followed by the C/O phase, accounting for 29% of the cycle's total emissions, which is equivalent to 9.58kg of SO₂. The third phase with the highest number of SO₂ emissions is the App phase, with 18% of total emissions, which is equivalent to 5.52kg of SO₂. Finally, the phase with the lowest amount of SO₂ emissions is the T/O phase, representing only 11% of the cycle's total emissions, which is equivalent to 3.32kg of SO₂.

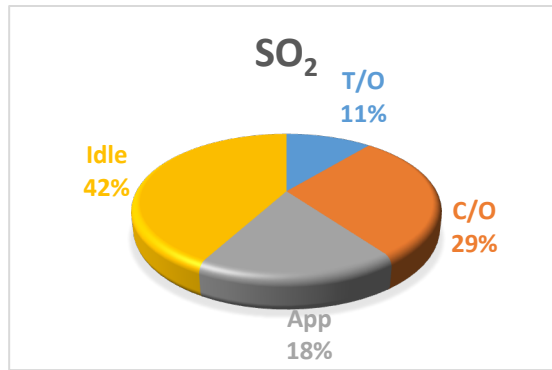


Figure 31: SO₂ distribution for each LTO Phase
Source: Own development

In Table 5 presented before, the duration of each phase of the LTO cycle was considered, and assuming the fuel flows extracted from the ICAO Engine Emissions Databank (EASA 2023) it was obtained the consumption of fuel for each phase of the cycle. Examples of calculations for carbon dioxide (CO₂) and sulfur dioxide (SO₂) emissions using equation (4) can be observed below:

Emissions of CO₂ and SO₂ - A220-100/300 (PW1524G):

$$Emissions = \alpha \sum_{i=1}^4 FF(i) \times TM(i) \quad (4)$$

$$CO_2 = 941,56\text{kg}$$

$$SO_2 = 29,90\text{kg}$$

The weekly emissions at LIS associated with the total aircraft movements (departures and arrivals) of the A220-100/300 observed between 07/03/2023 and 13/03/2023 are accounted in Table 19, and it was obtained through the sum of the total departures according to Table 11 with the total arrivals extracted from Table 14.

Table 19: Weekly Emissions – A220-100/300 (PW1524G)
Source: Own development

Weekly Movements: A220-100/300 (Engine: PW1524G)								
Dep.	Arr.	LTO Cycles*	Fuel (kg)	HC (kg)	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)
22	21	43,0	12857	1	94	40506	168	1286

* Each LTO cycle represents the Landing and Take-off Cycle, each two movements (one departure plus one arrival) represent one cycle for the emission calculations.

The total number of movements was then multiplied by the single engine emissions values from Table 18 by the number engines plane has, 2 engines as depicted in Figure 32. As each LTO cycle represents the Landing and Take-off Cycle, each two movements (one departure plus one arrival) represent one cycle for the emission calculations.



Figure 32: A220-100/300 illustration (2 engines PW1524G)
Source: (Blueprints 2024)

For the remaining movements, the same process was applied, resulting in the following weekly emission for each different aircraft/engine related to the short and medium-haul movements (departures and arrivals), observed between 07/03/2023 and 13/03/2023, as shown in Table 20. Through the analysis of Table 20, it is possible to observe which models of small and medium-haul aircraft are responsible for the majority of pollutant emissions associated with movements at LIS airport during the period considered. The A320 CEO equipped with the CFMI CFM56-5B4/P engines represents 25% of the total CO₂ emissions emitted, placing it as the main aircraft responsible for the airport's CO₂ emissions, followed by the A321 NEO equipped with the CFMI LEAP-1A32 engines, however this analysis alone is not representative of how polluting the model is, as this analysis must take into account the amount of movement of each model.

Table 20: Weekly Emissions - Short and Medium-haul Emissions
Source: Own development

Weekly Emissions - Movements Short and Medium-haul											
Aircraft	Engine	Dep.	Arr.	LTO Cycles	Fuel (kg)	HC (kg) *	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)	% CO ₂ **
ATR72-500	PWC PW127F	11	9	20	4660	0	30	14700	44	460	0%
ATR72-600	PWC PW127M	14	13	27	6291	0	41	19845	59	621	0%
A220	PW1524G	22	21	43	12857	1	94	40506	168	1286	1%
A319	CFMI CFM56-5B5/3	25	25	50	17150	26	317	54132	153	1715	1%
	CFMI CFM56-5B6/P	41	40	81	29766	74	371	93953	347	2977	2%
	IAE V2522-A5	7	7	14	5698	0	39	17985	66	570	0%
A320 CEO	CFMI CFM56-5B6/3	5	5	10	3610	4	59	11395	34	361	0%
	CFMI CFM56-5B4/P	415	409	824	338640	681	3420	1068883	4681	33864	25%
	IAE V2527-A5	25	23	48	21850	2	138	68967	269	2185	2%
A320 NEO	CFMI LEAP-1A26	186	188	374	120528	15	1164	380435	1060	12053	9%
	PW1127G	27	26	53	16362	4	182	51645	186	1636	1%
A321 CEO	CFMI CFM56-5B1/3	2	2	4	1792	1	20	5656	23	179	0%
	CFMI CFM56-5B3/P	33	33	66	31548	47	183	99578	552	3155	2%
	IAE V2533-A5	36	37	73	37224	3	161	117494	623	3722	3%
A321 NEO	CFMI LEAP-1A32	283	283	566	215080	23	1709	678879	4415	21508	16%
	CFMI LEAP-1A33	17	18	35	12920	1	103	40781	265	1292	1%
	PW1133G	28	28	56	21000	4	199	66284	296	2100	2%
B737-6/700	CFMI CFM56-7B22	13	12	25	10140	11	104	32006	119	1014	1%
	CFMI CFM56-7B24	6	6	12	4944	5	48	15605	62	494	0%
B737-8/900	CFM56-7B24E	1	0	1	398	0	6	1256	4	40	0%

	CFMI CFM56- 7B26	223	219	442	196686	161	1574	620820	2743	19669	14%
	CFMI CFM56- 7B27	43	41	84	39216	29	296	123781	578	3922	3%
B737- 43QF	CFMI CFM56-3B2	1	1	2	842	1	12	2658	8	84	0%
	CFMI CFM56-3C1	13	13	26	11648	8	145	36766	125	1165	1%
B737 MAX8	CFMI LEAP- 1B	39	39	78	29640	6	170	93556	612	2964	2%
E190/E1 95	GE CF34- 10E5A1	30	31	61	19380	41	376	61171	200	1938	1%
	GE CF34- 10E6	38	38	76	23028	65	514	72686	216	2303	2%
	GE CF34- 10E7	192	188	380	124032	265	2408	391495	1279	12403	9%
TOTAL		1776	1755	3531	1356930	1477	13884	4282918	19184	135679	100

* The value of 0g HC represent an approximate value, as the value is so low that it ends up being disregarded.

** The percentage of 0% represent a quantity of emissions < 1% when compared to the total emissions of 1776 departures.

Table 21 it is possible to compare CO₂ emissions per cycle, and the A320 CEO equipped with the CFMI CFM56-5B4/P engines, which was responsible for the largest amount of CO₂ emissions at LIS airport, is however not the most polluting (becoming 9th position, where 1st represents the most polluting and 26th represents the least polluting model), as well as the A321 NEO equipped with CFMI LEAP-1A32 engines, which occupied second position as the model responsible for 16% of CO₂ emissions, however, through this analysis it ranks 13th as the most polluting aircraft. It is thus demonstrated that although certain aircraft models are not responsible for the majority of CO₂ emissions, they can be considered the most polluting in this field. In Table 21 it is possible to observe that the least polluting jet model is the A220 equipped with PW1524G engines, only surpassed by the ATR-72-500/600 turboprop, with very different characteristics from all the other models under analysis).

Table 21: CO₂ Emissions per cycle - Short and Medium-haul

Source: Own development

Aircraft	Engine	LTO Cycles	CO ₂ (kg)	CO ₂ emissions per cycle (kg)	Classification
ATR72-500	PWC PW127F	20	14700	735	26
ATR72-600	PWC PW127M	27	19845	735	25
A220	PW1524G	43	40506	942	24
A319	CFMI CFM56-5B5/3	50	54132	1083	18
	CFMI CFM56-5B6/P	81	93953	1160	16
	IAE V2522-A5	14	17985	1285	10
A320 CEO	CFMI CFM56-5B6/3	10	11395	1139	17
	CFMI CFM56-5B4/P	824	1068883	1297	9
	IAE V2527-A5	48	68967	1437	4
A320 NEO	CFMI LEAP-1A26	374	380435	1017	20
	PW1127G	53	51645	974	22
A321 CEO	CFMI CFM56-5B1/3	4	5656	1414	5
	CFMI CFM56-5B3/P	66	99578	1509	2
	IAE V2533-A5	73	117494	1610	1
A321 NEO	CFMI LEAP-1A32	566	678879	1199	13
	CFMI LEAP-1A33	35	40781	1165	15
	PW1133G	56	66284	1184	14
B737-6/700	CFMI CFM56-7B22	25	32006	1280	11
	CFMI CFM56-7B24	12	15605	1300	8
B737-8/900	CFM56-7B24E	1	1256	1256	12
	CFMI CFM56-7B26	442	620820	1405	6
	CFMI CFM56-7B27	84	123781	1474	3
B737-43QF	CFMI CFM56-3B2	2	2658	1329	7
	CFMI CFM56-3C1	26	36766	1414	5
B737 MAX8	CFMI LEAP-1B	78	93556	1199	13
E190/E195	GE CF34-10E5A1	61	61171	1003	21
	GE CF34-10E6	76	72686	956	23
	GE CF34-10E7	380	391495	1030	19

Still regarding the emissions associated with each aircraft model, Table 22 represents the CO₂ emissions per seat/LTO cycle, which allows us to assess, through joint analysis with the historical load factors of each route, which models are most polluting, and from there demonstrate which are the most viable aircraft options for each type of operation /route, in order to reduce emissions of GHGs. In this field, and considering a load factor of 100% to facilitate comparison, within jet aircraft, the A321 NEO equipped with CFMI LEAP-1A32 engines is assumed to be the least polluting, and the B737-600/700 equipped with engines CFMI CFM56-7B22 takes the position of most polluting, only surpassed by the turboprop ATR72-500/600 (aircraft of a completely different category).

Table 22: CO₂ emissions per seat/LTO cycle for different aircraft models
Source: Own development

Aircraft	Engine	Seat Capacity *	CO ₂ emissions per seat/cycle (kg)
ATR72-500	PWC PW127F	68	10,81
ATR72-600	PWC PW127M	70	10,50
A220	PW1524G	145	6,50
A319	CFMI CFM56-5B5/3	156	6,94
	CFMI CFM56-5B6/P	146	7,94
	IAE V2522-A5	143	8,98
A320 CEO	CFMI CFM56-5B6/3	174	6,55
	CFMI CFM56-5B4/P	186	6,97
	IAE V2527-A5	180	7,98
A320 NEO	CFMI LEAP-1A26	174	5,85
	PW1127G	168	5,80
A321 CEO	CFMI CFM56-5B1/3	219	6,46
	CFMI CFM56-5B3/P	216	6,98
	IAE V2533-A5	220	7,32
A321 NEO	CFMI LEAP-1A32	216	5,55
	CFMI LEAP-1A33	190	6,13
	PW1133G	182	6,50
B737-6/700	CFMI CFM56-7B22	142	9,02
	CFMI CFM56-7B24	189	6,88
B737-8/900	CFM56-7B24E	189	6,65
	CFMI CFM56-7B26	189	7,43
	CFMI CFM56-7B27	189	7,80
B737-43QF	CFMI CFM56-3B2	**	**
	CFMI CFM56-3C1	**	**

B737 MAX8	CFMI LEAP-1B	197	6,09
E190/E195	GE CF34-10E5A1	118	8,50
	GE CF34-10E6	106	9,02
	GE CF34-10E7	118	8,73

* Based on the configuration used for each model by the most relevant airlines operating at Lisbon airport

** Cargo aircraft

Table 23 presents the weekly emissions related to the long-haul movements, observed between 07/03/2023 and 13/03/2023. Table 23 shows that the A330-900 NEO equipped with RR Trent 7000-72 engines is the long-haul aircraft that most contributes to pollutant emissions associated with movements at LIS airport in the period considered, however this does not mean that it is the most polluting. As an example, the A330-900 NEO represents 52% of CO₂ emissions related to long-haul aircraft movements in LIS, however, these values are only due to the fact that it is also the most used long-haul aircraft at the airport in the period under analysis. When comparing CO₂ emissions per cycle, as can be seen in the the A330-900 NEO occupies the 6th position as the most polluting aircraft (where 1st represents the most polluting and 15th represents the least polluting model). The least polluting model of the models under analysis is the B777-243(ER) equipped with GE GE90-94B engines, and the most polluting model in the analysis is the B757-200 equipped with PW2037 engines.

Table 23: Weekly Emissions - Long-haul Movements
Source: Own development

Weekly Emissions - Movements Long-haul											
Aircraft	Engine	Dep	Arr.	LTO Cycles*	Fuel (kg)	HC (kg)	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)	%
A330-200	GE CF6-80E1A4	17	17	34	32742	127	471	103347	614	3274	9%
A330-300	RR Trent 772B-60	10	9	19	21700	21	212	68494	353	2170	6%
A330-900 NEO	RR Trent 7000-72	97	97	194	180614	0	599	570090	4086	18061	52%
A340-312	CFMI CFM56-5C3/F	5	5	10	9660	20	129	30491	155	966	3%
B757-200	PW2037	2	2	4	2344	2	22	7399	32	234	1%
	PW2040	2	2	4	2524	2	21	7967	40	252	1%
	RR RB211-535 E4	1	1	2	1366	0	8	4312	23	137	0%
B767-200	GE CF6-80A2	1	1	2	1462	3	15	4615	24	146	0%

	GE CF6-80C2B2F	3	3	6	4410	21	90	13920	50	441	1%
B767-300	PW4056	5	4	9	8360	7	76	26388	120	836	2%
	PW4060	7	7	14	12418	8	101	39196	197	1242	4%
B767-400	GE CF6-80C2B7F	7	7	14	11676	43	195	36854	170	1168	3%
B777-243(ER)	GE GE90-94B	1	0	1	2406	0	12	7594	61	241	1%
B787-900	RR Trent 1000	6	6	12	10608	0	37	33483	219	1061	3%
B777-31H	GE90-115B	15	14	29	43590	59	571	137587	1023	4359	13%
TOTAL		179	175	354	345880	313	2559	1091737	7168	34588	100%

* The value of 0g HC represent an approximate value, as the value is so low that it ends up being disregarded.

** The percentage of 0% represent a quantity of emissions < 1% when compared to the total emissions of 179 departures.

In Table 24 the A330-900 NEO occupies the 6th position as the most polluting aircraft (where 1st represents the most polluting and 15th represents the least polluting model). The most polluting model of the models under analysis is the B777-243(ER) equipped with GE GE90-94B engines, and the least polluting model in the analysis is the B757-200 equipped with PW2037 engines.

Table 24: Emissions per cycle - Long-haul
Source: Own development

Aircraft	Engine	LTO Cycles	CO ₂ (kg)	CO ₂ emissions per cycle (kg)	Classification
A330-200	GE CF6-80E1A4	34	103347	3 040	5
A330-300	RR Trent 772B-60	19	68494	3 605	3
A330-900 NEO	RR Trent 7000-72	194	570090	2 939	6
A340-312	CFMI CFM56-5C3/F	10	30491	3 049	4
B757-200	PW2037	4	7399	1 850	15
	PW2040	4	7967	1 992	14
	RR RB211-535 E4	2	4312	2 156	13
B767-200	GE CF6-80A2	2	4615	2 308	12
	GE CF6-80C2B2F	6	13920	2 320	11
B767-300	PW4056	9	26388	2 932	7

	PW4060	14	39196	2 800	8
B767-400	GE CF6-80C2B7F	14	36854	2 632	10
B777-243(ER)	GE GE90-94B	1	7594	7 594	1
B787-900	RR Trent 1000	12	33483	2 790	9
B777-31H	GE90-115B	29	137587	4 744	2

Comparing the most polluting aircraft in the long-haul fleet with the medium-haul fleet, the long-haul model B777-243(ER) equipped with GE GE90-94B engines, registers 1850kg of CO₂ emitted per LTO cycle, being which in the configuration of the model used during the analysis period has 293 seats, which represents 6,32 kg of CO₂ emitted per cycle per passenger. While in the medium-haul fleet, the B737-600/700 model equipped with CFMI CFM56-7B22 engines, in the analyzed configuration of 142 seats, registers 1280kg of CO₂ emitted per LTO cycle, takes the position of most polluting with 9,02kg of CO₂ emitted per cycle per passenger. Which allows us to conclude that, for a total occupancy (load factor of 100%), despite the most polluting medium-haul aircraft emits 30.8% less CO₂ per LTO cycle when compared to the most polluting long-haul aircraft, the most polluting medium-haul aircraft records an emission of more than 42.7% of CO₂ emitted per cycle per passenger.

3.4. TAXI TIME, CONSUMPTION AND EMISSIONS USING JET FUEL

The average taxi time at Lisbon airport varies depending on the runway in use due to the prevailing winds at the time. Average taxi times were obtained taking into account the taxi times of some of the largest airlines operating at Lisbon airport, based on a random selection criteria and availability to obtain this information.

The average taxi times shown in Table 25 were separated by scenario A and scenario B, as explained previously. For scenario A, an average taxi-out time of 15 min was reached for flights departing from Lisbon, and 7 min for flights landing in Lisbon. For scenario B, an average taxi-out time of 20 min was found for flights departing from Lisbon, and 6 min for flights landing in Lisbon.

Table 25: Average taxi times at LIS airport
Source: Own development

Scenario	Average taxi-in duration (min)	Average taxi-out duration (min)	Average taxi time – LTO cycle (min)
Cenário A (Pista 02)	7	15	22
Cenário B (Pista 20)	6	20	26

The difference in taxi time between scenario A or scenario B is due to the longer route that aircraft have to perform the take-off from runway 20 when compared to the route to runway 02, combined with the fact that aircraft from long-haul aircraft use runway 20 from the beginning, which involves crossing an active runway (where landings and take-offs take place), a constraint that further increases the associated taxi times.

It is possible to observe that the real duration of average taxi time during an LTO cycle at LIS airport in scenario B, when runway 20 is in use, is the same as the standard LTO cycle. However, scenario A, with runway 02 in use, corresponds to an average reduction in total taxi time of 4 minutes per LTO cycle.

Table 26: LTO Emission for Idle phase (different durations)
Source: Own development

A220-100/300 (Engine: PW1524G) LTO cycle with different duration of Idle phase								
Flight Phases	Time (min)	Fuel Flow (kg/min)	Fuel Total (kg)	HC (kg)	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)
Idle	22	4,8	105,6	0,010	1,763	333,32	0,63	10,56
	26		124,8	0,012	2,084	393,9	0,75	12,48
	30		144	0,014	2,405	454,52	0,87	14,4

Table 26 demonstrates how a variation of +/- 4min in the total taxi time of an aircraft (Idle phase) leads to a variation of approximately +/- 15.4% in consumption and consequent emission of pollutants.

In Figure 33 is possible to observe that GHG emissions naturally increase with increasing taxi time. A reduction of 4 minutes in total taxi time corresponds to a reduction of approximately 15.4% in LTO emissions associated with Idle time, and approximately 6.5% in the total emissions of an LTO cycle, percentages of reduction that will be considered in emissions calculations relating to scenario A. The values from scenario B

will be those considered for the standard LTO cycle, given that the average real Idle time calculated for scenario B is equal to the time of a standard LTO cycle.

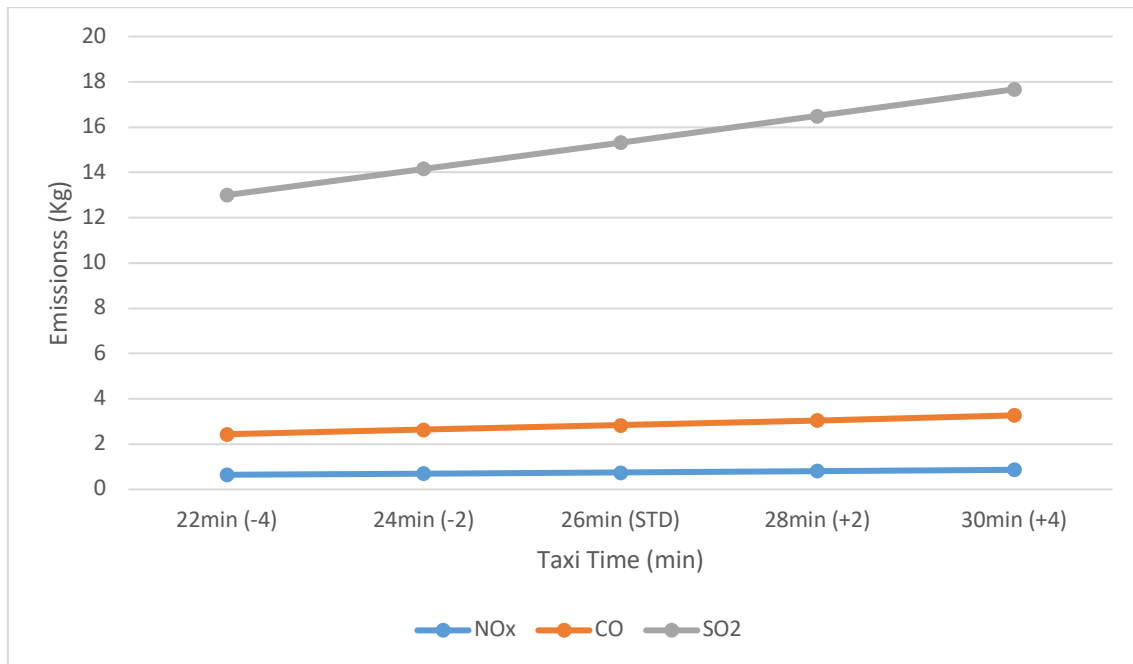


Figure 33: Effect of taxi time in LTO emissions
Source: Own development

As demonstrated previously, in Figure 27 and Figure 28, the Idle phase of the LTO cycle represents the phase with the greatest amount of CO and HC emissions, essentially due to its duration. During the taxi period, the aircraft's engines end up consuming a substantial amount of fuel and consequently end up leading to an increase in GHG emissions. In order to reduce these values during the taxi and with the aim of helping to meet the goal of achieving net-zero GHGs emissions by 2050 (European Commission 2018), the use of alternative forms of taxi supported by alternative energy is seen as an option (Edem et al. 2017).

Another way to reduce GHG emissions during the Idle phase is to use a single engine taxi. As the name suggests, during this taxi period, only one engine will be used to move the plane on the ground, however it is necessary to take into account that during taxi-out, for the engines to be ready for take-off, it is necessary to comply with the warm up time, which is necessary for them to reach adequate operating temperatures and stabilize before take-off. Similarly, after landing it is also necessary to comply with an engine cooldown period before turning off the engine, thus allowing it to reach lower

temperatures before turning it off. When in single engine operation, the use of the APU follows the use of the engine in operation, thus slightly increasing the associated emissions and consumption (Edem et al. 2017).

3.5. ALTERNATIVE TAXI SYSTEMS

Another solution that would substantially reduce fuel consumption and, consequently, GHG emissions produced during the taxi phase would involve its electrification.

There are several technologies identified that enable the electrification of taxis, the most recognized being the Electric Green Taxiing System (EGTS), the TaxiBot and the Wheel tug. (Edem et al. 2017). EGTS and Wheel tug are autonomous taxi systems integrated into the aircraft itself, they work in a similar way, but with different principles, with the wheel tug pulling the aircraft using the nosewheel while EGTS uses the principles of pushing during taxi, being which both present as their biggest disadvantage the fact that they slightly increase the weight of the plane due to the weight of its own structure (Edem et al. 2017). The TaxiBot, on the other hand, does not have the disadvantage of increased weight on the plane, however it is an external vehicle and still requires a driver to carry out the maneuvers. Furthermore, these technologies also allowed the aircraft to perform pushback (moves in the backward direction away from the airport gate, which is carried out with the help of pushback tractors, which also ends up contributing to GHG emissions on the side airport air) (Edem et al. 2017).

In order to better visualize the impact that this system has, and taking the consumption and emissions values during the Idle phase that we obtained in Table 26, We can calculate taxi fuel and GHGs emissions using one of the most promising systems mentioned above, EGTS, for the A220-100/300 equipped with PW1524G engines.

Considering an average taxi time of 26min, time corresponding to the Idle phase defined in the LTO cycle (EASA, EEA, and Eurocontrol 2016), and assuming the assumptions presented below together with the data contained in Table 27, it is possible to obtain the records in Table 28:

Time considered for engine warm up = 5 minutes ^{a)}

Time considered for engine cooling = 3 minutes ^{b)}

Table 27: Fuel Flow for each taxi alternative
Source: Own development

	Double Engine Taxi	Single Engine Taxi	EGTS	APU
Fuel Flow (kg/min)	9,6	4,8	2	2

Table 28: Durations and consumption of each taxi alternative
Source: Own development

		Double Engine Taxi	Single Engine Taxi	EGTS
Duration (min)	Taxi-out	13	7 + 5 ^{a)}	7 + 5 ^{a)}
	Taxi-in	13	3 ^{b)} + 10	3 ^{b)} + 10
Engines (kg)	Taxi-out	124,8	33,6 + 48	48 ^{a)}
	Taxi-in	124,8	28,8 + 48	28,8 ^{b)}
APU (kg)	Taxi-out	2 ^{c)}	14	14
	Taxi-in	2 ^{c)}	20	20
EGTS (kg)		-	-	34
Fuel Total (kg)		254	192	145

^{a)} The 5 minutes considered for engine warm up is based in the warm up time of the most representative type of aircraft operating during the period under analysis at LIS

^{b)} The 2 minutes considered for engine cooling is based in the warm up time of the most representative type of aircraft operating during the period under analysis at LIS

^{c)} The 2 minutes relating to the time of use of the APU in the case of taxi-in and taxi-out for the double engine taxi situation, reflect approximate times relating to the necessary period of use of the APU to start the engines at the beginning of the taxi, and cut engines at the end of the taxi before entering the stand.

Table 28 shows the positive impact that measures such as single engine taxis or taxi electrification have on aircraft consumption during the taxi period on the ground, and consequently the impact on reducing GHG emissions. When compared to the taxi with two engines, for the set of aircraft/engines under analysis, and for the conditions considered, the single engine taxi presents a potential for reducing fuel consumption by up to 25%, as shown in Figure 34. The EGTS goes even further, for the same conditions it has a potential to reduce fuel consumption of up to 43%, as shown in Figure 34, although in this case, the existing penalty in consumption during the flight will always have to be considered due to the increase in the weight of the aircraft after installing the EGTS, which adds around 320kg to the aircraft original weight (Edem et al. 2017).

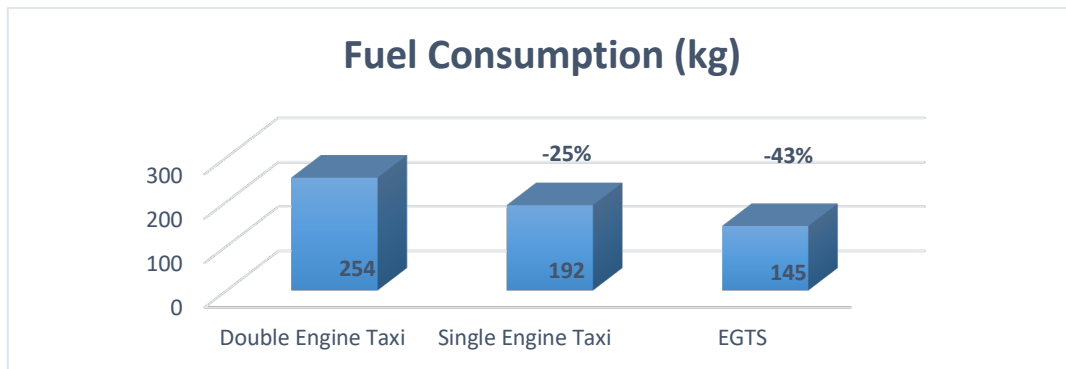


Figure 34: Fuel Consumption for each taxi alternative
Source: Own development

As the production and emission of GHGs varies depending on fuel consumption, it is possible to conclude that GHG emissions in relation to the taxi period would vary in a similar way to the variation in fuel consumption. As an example, in Figure 35 it is possible to observe the CO₂ emissions for each of the cases under analysis, calculations carried out by applying the constant of 3.1564, which represents the tonnes of CO₂ produced by burning a tonne of jet fuel (ICAO 2017).

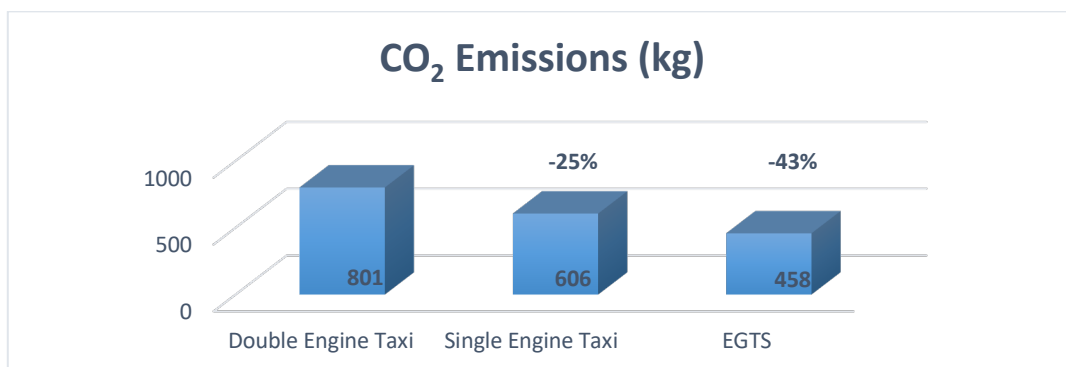


Figure 35: CO₂ emissions for each taxi alternative
Source: Own development

3.6. APU CONSUMPTION AND EMISSIONS USING JET FUEL

The average time of use of the APU at Lisbon airport is 44min for outbound flights, and 20min for inbound flights, regardless of whether the aircraft is short-medium or long haul, no significant variations were detected that deserve to be highlighted. The values were obtained taking into account the APU usage times of some of the largest airlines operating at Lisbon airport, based on a random criteria and availability to obtain this information. Table 29 describe the average APU consumption for each type of aircraft

group. The APU consumption values presented in Table 30 for departures and Table 31 for arrivals are based on the average APU consumption divided by groups mentioned in Table 29. Total seminal consumption resulting from the use of the APU can be achieved by multiplying the total aircraft movements by the APU usage time of each group by the APU fuel consumption per hour.

Table 29: APU consumption by aircraft group
Source: Own development based on (Padhra 2018b)

Group	APU consumption (kg/h)
Short and Medium-Haul	118
Long-Haul	261
Other	100

Table 30: APU weekly consumption – Departures
Source: Own development

APU weekly consumption - Departures			
Group	Departures	APU usage (hours)	Consumption (kg)
Short and Medium-Haul	1776	1302	153636
Long-Haul	179	131	34191
Other	22	16	1600
Total	1977	1449	189427

Table 31: APU weekly consumption – Arrivals
Source: Own development

APU weekly consumption – Arrivals			
Group	Departures	APU usage (hours)	Consumption (kg)
Short and Medium-Haul	1755	585	69030
Long-Haul	175	58	15138
Other	22	7	700
Total	1952	650	84868

The emissions values of carbon monoxide (CO), oxides of nitrogen (NO_x) and total hydrocarbons (THC) presented in Table 32 were obtained directly through the analysis of several studies published, as mentioned previously.

Table 32: Average APU Emissions Values
Source: Own development based on (Padhra 2018b)

Average APU Emissions Values		
HC (g/kg)	CO (g/kg)	NO _x (g/kg)
0,204	2,973	8,011

The CO₂ emissions calculations were based on the constant of 3.1564, value extracted from equation (2), which represents the tonnes of CO₂ produced by burning a tonne of jet fuel (ICAO 2017). This constant is then multiplied by the fuel used by the APU during the LTO cycle, for the period under analysis.

For the calculation of SO₂ emissions, the constant 0.1 was considered, value extracted from equation (3), which represents the number of the number of tonnes of SO₂ produced by burning a tonne of jet fuel (Correia 2009). This constant is then multiplied by the fuel used by the APU during the LTO cycle, for the period analyzed.

Using the average EI values obtained in Table 6, and also knowing the average consumption values (FF) of the APU, values present in Table 29, together with the weekly APU usage time obtained in this study and represented in the Table 30 and

Table 31, it is then possible to determine the total emissions (E), in grams, associated with the operation of the APU for each pollutant, represented in the Table 33, using the following equation (5):

$$E = FF \times t \times EI \quad (5)$$

Where FF is the APU fuel flow, in kg/h, t is the APU usage time, in hours, and EI represents the emission Index value of each pollutant gas, in g/kg.

Using the formula (5) for the different pollutant gases, it is possible to obtain the weekly consumption and emissions values of the APU, represented in Table 33.

Table 33: APU weekly consumption and emissions
Source: Own development

APU weekly consumption and emissions							
	APU usage (hours)	Fuel Total (kg)	HC (kg)	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)
Departures	1449	189427	39	563	597907	1518	19
Arrivals	650	84868	17	252	267877	680	9
Total	2099	274295	56	815	865784	2198	28

Taking into considerations the total CO₂ emissions from aircraft during their LTO cycles at Lisbon airport in the period considered, emissions related to the use of the APU represent around 13.9% of total CO₂ emissions, as depicted in Table 34.

3.7. AIRCRAFT AND APU CONSUMPTION AND EMISSIONS USING SAF

Through the introduction of the different analyzed SAFs, in this specific case, at Lisbon airport, a reduction in GHG emissions associated with aircraft movements on the airside of the airport is expected, considering the same level of movements that had been considered for the calculation of GHG emissions before the introduction of SAFs. In order to estimate the possible reduction that this measure could have, 3 scenarios were created. The SAF fuels previously analyzed were based in the SAFs which present a higher FRL/TRL and which, at the same time, present a greater estimated production and distribution capacity for the coming years (HEFA, TF and ATJ).

Table 34 shows the total weekly emissions of the engines and APU during the period under analysis before the introduction of SAF.

Table 34: Total Weekly Emissions
Source: Own development

Total Weekly Emissions						
	Fuel (kg)	HC (kg)	CO (kg)	CO ₂ (kg)	NO _x (kg)	SO ₂ (kg)
Short and Medium-haul (Aircraft engines)	1.357.328	1.477	13.890	4.284.174	19.188	135.719
Long-haul (Aircraft engines)	345.880	313	2.559	1.091.737	7.168	34.588
Total Engines	1.703.208	1.790	16.449	5.375.911	26.356	170.307
Total APU	274.295	56	815	865.784	2.198	28
TOTAL	1.977.503	1.846	17.264	6.241.695	28.554	170.335

In order to compare the ability of each GHG to trap heat in the atmosphere over a specified period of time when compared to another gas the global warming potential (GWP) can be used.

GWP was introduced in the First Assessment Report of the IPCC (IPCC 2006) as a representation of the difficulties existing at the time to compare the climate impacts of

emissions of different gases (European Commission 2020). GWP defines a metric for calculating the “CO₂-equivalent emissions”, an in aviation is useful in order to determine CO₂ emission equivalencies of the other GHGs, in a projection for 100-year time horizon global warming potentials (European Commission 2020).

The most recent values were used, as depicted in the Table 35, adapted from the IPCC Fifth Assessment Report, AR5, 2014 (IPCC 2014).

Table 35: Global Warming Potential
Source: Own development based on (IPCC 2014)

Global Warming Potential			
	CO₂	NO_x (kg)	SO₂ (kg)
TOTAL (kg)	6.241.695	28.554	170.307
GWP	1	265	negative
Index	6.241.695	7.566.810	-

As can be observed in Table 35, the GWP value for NO_x is much higher than the GWP value for CO₂, being for the values under analysis the specific case of Lisbon airport, and assuming the total emissions during the period under analysis, the index that results from multiplying each of the GHGs under analysis by its GWP, despite the absolute value of NO_x emissions represent only 0,49% when compared to CO₂ emissions, the global harmful power for just one week is more than 20% higher for NO_x. CO concentrations due to its short-lived in the atmosphere and spatially variable it is not possible to accurately determine GWP values related to the CO concentrations, although there are studies that indicate some ranges of values.

Through this analysis it is possible to conclude that more measures must be taken regarding the reduction of GHGs, in particular NO_x, establishing tighter targets for the coming years.

The lower heating value (LHV), sometimes called the net heat of combustion, represents the source of energy which is converted to usable power. Engine manufactures rely on LHV to assess engine performance and thermal efficiency. Higher LHVs offer the potential for lower fuel consumption and consequently the potential to achieve greater reductions in GHG emissions (Boehm et al. 2022).

To enable a comparison of the possible reduction of GHGs through the use of the various SAFs under analysis, the following assumptions are made:

- Jet fuel density at 15°C: 807,5 kg/m³ (775 – 840) (Colket and Heyne 2021)
- Jet fuel LHV medium value: 43.1MJ/kg (Colket and Heyne 2021)
- Fossil fuel baseline: 94 g CO₂e/MJ (Mellios and Gouliarou 2020)
-

3.7.1. HEFA

HEFA can then be mixed with conventional jet fuel at a ratio of up to 50% and is the only SAF commercialized and currently available on the market with a TRL and FRL of 9, which is why the SAF was chosen with which the analysis was carried out. The LHV for SAF can actually be higher or lower than the LHV for jet fuel depending on their composition, however, all the SAF blend components actually used and covered by ASTM D7566 specifications have LHVs >42.8 MJ/kg *because they are composed almost entirely of saturated hydrocarbons* (Boehm et al. 2022). HEFA presents an average LHV of 43.9MJ/Kg, remaining within the range of 1–2% higher than the average LHV values for jet fuels (Boehm et al. 2022).

Regarding HEFA, for subsequent analyzes the following values were considered:

- HEFA density at 15°C: 780 kg/m³ (775-785) (F3Center 2016)
- HEFA LHV (average value): 43.9 MJ/kg (Boehm et al. 2022)
- HEFA baseline (average values for hydroprocessing oils and fats): 14.0 gCO₂e/MJ (Boehm et al. 2022)

Taking into account the estimated total fuel consumption of the aircraft's engines and APU throughout the week under analysis of 1,977,503kg, and assuming a SAF HEFA with a mix ratio of 50%, we arrived at the values mentioned in Table 36.

Table 36: LHV and Baseline life cycle emissions value for 50% HEFA / 50% jet fuel
Source: Own development

SAF HEFA (mixing ratio 50%)	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Jet Fuel	988.751	42.615.168	4.005.826.000
SAF HEFA	955.079	41.927.968	586.991.552
TOTAL	1.943.830	84.543.136	4.677.360.688

In Table 37 it is possible to observe the values of LHV and the baseline life cycle emissions for 100% jet fuel, and a comparison in percentage with the values obtained in the previous Table 36 for the mixture 50% HEFA / 50% jet fuel.

Table 37: LHV and Baseline life cycle emissions value for jet fuel vs HEFA

Source: Own development

Jet Fuel 100%	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Values	1.977.503	85.230.397	8.011.657.000
Variation	+0,9%	+0,9%	+71%

Due to the lower density of HEFA when compared to Jet Fuel (assuming the same conditions for both, 15°C, 1013hPa), for the period under analysis, according to Table 30, the quantity of jet fuel to be transported would be 0.9% higher than if the mixture was used (Jet Fuel 50% + SAF HEFA 50%). The lower heating value (LHV) assumes a variation identical to that of the quantity, due to the very similar LHV between them. The most drastic and expected variation lies in the analysis of g CO₂e/MJ, where the use of only jet fuel represents an increase in CO₂ emissions equivalent to approximately 71% when compared to the mixture under analysis. This value only represents the time period of one week, the period under analysis in the study, which when extrapolated to the monthly and annual period will represent an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel in order to achieve the defined environmental goals.

3.7.2. FT

FT can then be mixed with conventional jet fuel at a ratio of up to 50%, however its TRL is still 7/8, and it is not yet available on a commercial scale.

Regarding FT, for subsequent analyzes the following values were considered:

- FT density at 15°C: 750 kg/m³ (730-770) (Boehm et al. 2022)
- FT LHV (average value): 44.1 MJ/kg (Boehm et al. 2022)
- FT baseline (average values for FT produced from waste wood): 13.7 gCO₂e/MJ (Abrantes et al. 2021)

Taking into account the estimated total fuel consumption of the aircraft's engines and APU throughout the week under analysis of 1,977,503kg, and assuming a SAF FT with a mix ratio of 50%, we arrived at the values mentioned in Table 38:

Table 38: LHV and Baseline life cycle emissions value for 50% FT / 50% jet fuel

Source: Own development

SAF FT (mixing ratio 50%)	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Jet Fuel	988.751	42.615.168	4.005.826.000
SAF FT	918.344	40.498.996	554.836.246
TOTAL	1.907.095	83.114.164	4.560.662.246

In Table 39 it is possible to observe the values of LHV and the baseline life cycle emissions for 100% jet fuel, and a comparison in percentage with the values obtained in the previous Table 38 for the mixture 50% FT / 50% jet fuel.

Table 39: LHV and Baseline life cycle emissions value for jet fuel vs FT

Source: Own development

Jet Fuel 100%	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Values	1.977.503	85.230.397	8.011.657.000
Variation	+3,7%	+2,5%	+75%

Due to the lower density of FT when compared to Jet Fuel (assuming the same conditions for both, 15°C, 1013hPa), for the period under analysis, according to Table 31, the quantity of jet fuel to be transported would be 3,7% higher than if the mixture was used (Jet Fuel 50% + SAF FT 50%). The lower heating value (LHV) assumes a variation of 2,5%, due to the very similar LHV between them. The most drastic and expected variation lies in the analysis of g CO₂e/MJ, where the use of only jet fuel represents an increase in CO₂ emissions equivalent to approximately 78% when compared to the mixture under analysis. This value only represents the time period of one week, the period under analysis in the study, which when extrapolated to the monthly and annual period will represent an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel in order to achieve the defined environmental goals.

3.7.3. ATJ

ATJ present a TRL still of 7/8 and it is only allowed in a maximum mixture of 50%. For subsequent analyzes the following values were considered:

- ATJ density at 15°C: 757 kg/m³ (Boehm et al. 2022)
- ATJ LHV (average value): 42.8 MJ/kg (Boehm et al. 2022)
- ATJ baseline (average values for ATJ produced from corn stover): 35 gCO₂e/MJ (Abrantes et al. 2021)

Taking into account the estimated total fuel consumption of the aircraft's engines and APU throughout the week under analysis of 1,977,503kg, and assuming a SAF ATJ with a mix ratio of 50%, we arrived at the values mentioned in Table 40.

Table 40: LHV and Baseline life cycle emissions value for 50% ATJ / 50% jet fuel
Source: Own development

SAF ATJ (mixing ratio 50%)	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Jet Fuel	988.751	42.615.168	4.005.826.000
SAF FT	926.916	39.672.005	1.388.520.000
TOTAL	1.915.667	82.287.173	5.394.346.000

In Table 41 it is possible to observe the values of LHV and the baseline life cycle emissions for 100% jet fuel, and a comparison in percentage with the values obtained in the previous Table 40 for the mixture 50% ATJ/ 50% jet fuel.

Table 41: LHV and Baseline life cycle emissions value for jet fuel vs ATJ
Source: Own development

Jet Fuel 100%	Quantity (kg)	LHV (MJ/Kg)	Baseline (g CO ₂ e/MJ)
Values	1.977.503	85.230.397	8.011.657.000
Variation	+3,2%	+3,6%	+48%

Due to the lower density of ATJ when compared to Jet Fuel (assuming the same conditions for both, 15°C, 1013hPa), for the period under analysis, according to Table 34, the quantity of jet fuel to be transported would be 3,2% higher than if the mixture was used (Jet Fuel 50% + SAF ATJ 50%). The lower heating value (LHV) assumes a variation of 3,6%, due to the very similar LHV between them. The most drastic and

expected variation lies in the analysis of g CO₂e/MJ, where the use of only jet fuel represents an increase in CO₂ emissions equivalent to approximately 48% when compared to the mixture under analysis. This value only represents the time period of one week, the period under analysis in the study, which when extrapolated to the monthly and annual period will represent an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel in order to achieve the defined environmental goals.

4. RESULTS AND DISCUSSION

The GWP defines a projection for 100-year time horizon global warming potentials. The GWP can be used in order to compare the ability of each GHG to trap heat in the atmosphere over a specified period of time.

During the period under analysis, resulting from a total consumption of 1977t of fuel at LIS, the total emissions generated from aircraft were calculated as 6242t of CO₂, 170t of SO₂, 28t of NO_x, 17t of CO and 1.8t of HC. Despite the absolute value of NO_x emissions represented only 0,49% when compared to CO₂ emissions, the GWP value for NO_x (265) is much higher than the GWP value for CO₂. For that reason, during the period under analysis, the values of GWP were more than 20% higher for NO_x. Through this analysis it is possible to conclude that more measures must be taken regarding the reduction of GHGs, in particular NO_x, establishing tighter targets for the coming years.

Figure 36, Figure 37 and Figure 38, demonstrate in a more simplified way, for the period under analysis, comparisons of the simulations of the required fuel, LHV and Baseline for each of the SAFs that present a higher FRL/TRL, as well as showing a greater capacity of production for the coming years.

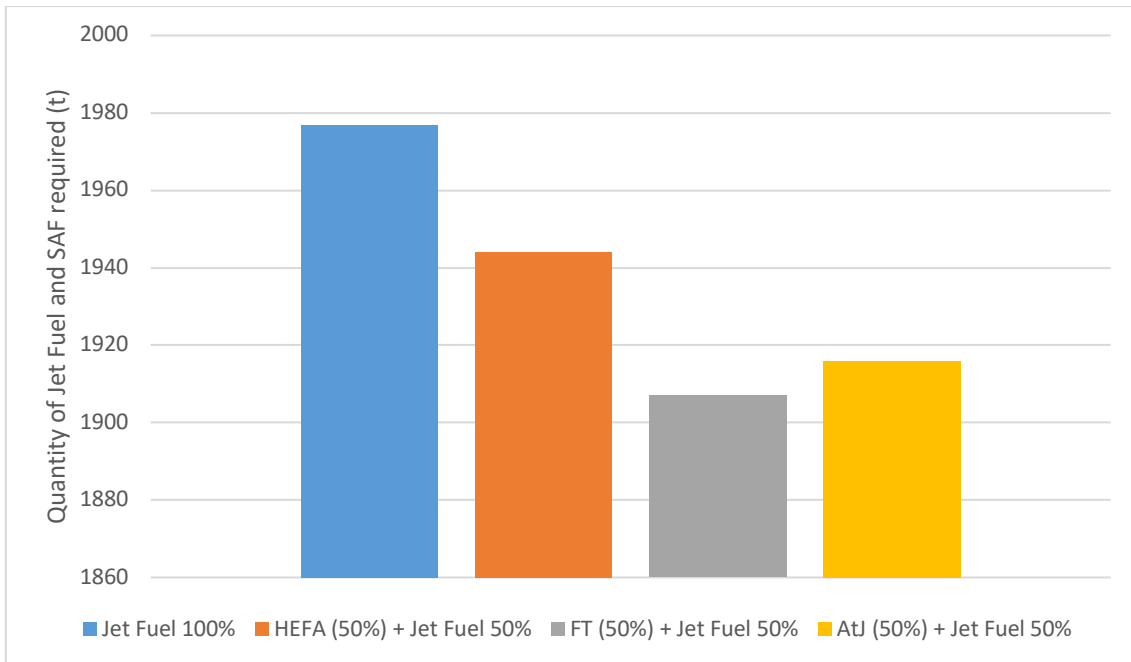


Figure 36: Comparison of quantity of Jet Fuel and the different SAF options
Source: Own development

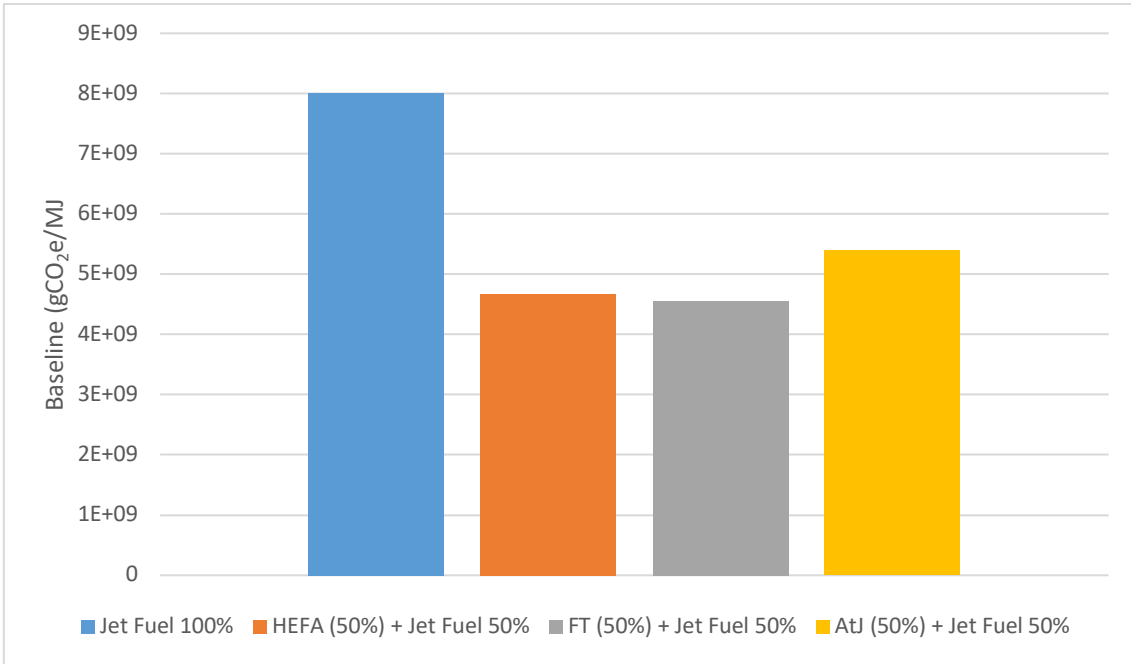


Figure 37: Comparations of baseline for Jet Fuel and different SAF options.
Source: Own development

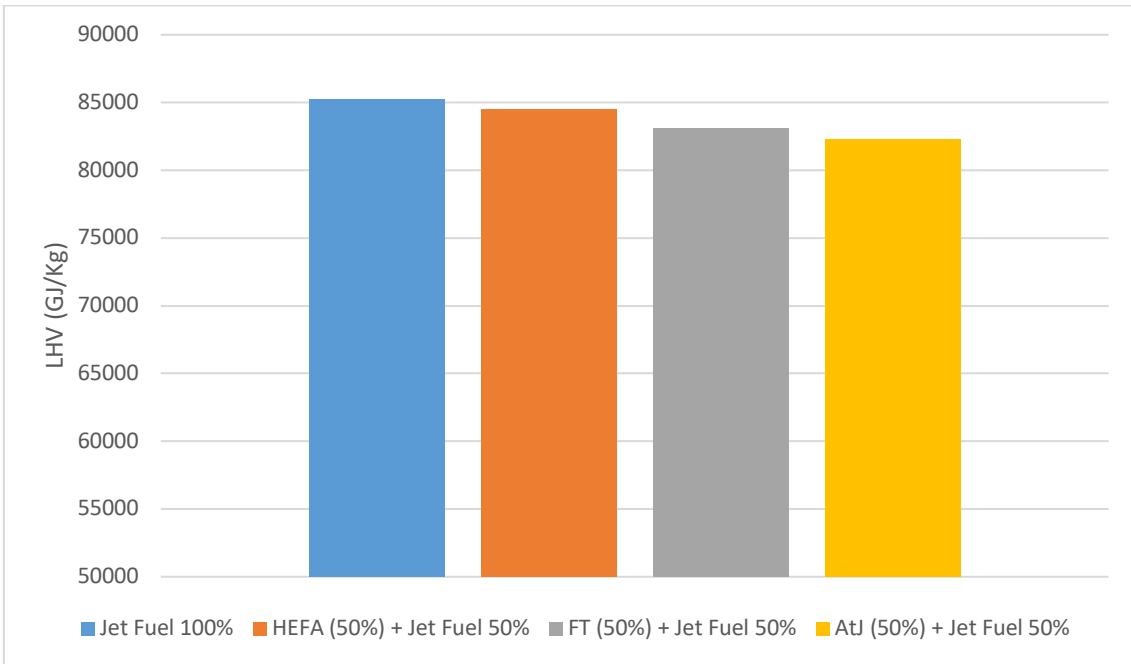


Figure 38: Comparations of LHV for Jet Fuel and different SAF options.
Source: Own development

Taking into consideration the CO₂ equivalent emissions (g CO₂e/MJ) for each type of SAF included in the study, with a mixture of 50% HEFA and 50% jet fuel, using this SAF mix the quantity of jet fuel to be transported would be 0.9% lower than compared to jet

fuel. When compared to the mixture under analysis. The use of only jet fuel represents an increase in CO₂e/MJ to approximately 71%. For a mixture of 50% FT and 50% jet fuel the quantity of jet fuel to be transported would be 3.7% lower than compared to jet fuel. When compared to the mixture under analysis. the use of only jet fuel represents an increase in CO₂e/MJ to approximately 75%. Finally, for a mixture of 50% ATJ and 50% jet fuel, the total quantity of jet fuel to be transported would be 3.2% lower than compared to jet fuel. When compared to the mixture under analysis. the use of only jet fuel represents an increase in CO₂ emissions equivalent to approximately 48%

Other analyzed ways that allow the reduction of emissions of GHGs during the Idle phase were to use a single engine taxi or electrifying the taxi. The single engine taxi presented a potential for reducing fuel consumption by up to 25%, while the EGTS went even further, for the same conditions it presented a potential to reduce fuel consumption of up to 43% (although the existing penalty in consumption during the flight will always have to be considered due to the increase in the weight of the aircraft after installing the EGTS).

During a standard LTO cycle, CO₂ represents the largest pollutant with a relative percentage of 96% of total GHG emissions. Although the Idle phase (Taxi phase) presents the lowest fuel flow and therefore the lowest emissions per minute, the long duration of 26 minutes puts it as the phase with more emissions during a standard LTO cycle. By analyzing CO₂ emissions per LTO cycle, it is possible to conclude which aircraft models and types of engines are more and less polluting, and with that data influence the industry and airlines to make more sustainable choices. Small and medium-haul aircraft are responsible for the majority of pollutant emissions associated with movements at LIS airport during the period considered. In short and medium haul aircraft, the A320 CEO equipped with the CFMI CFM56-5B4/P engines represented 25% of the total CO₂ emissions emitted, however not the most polluting, being the most polluting in terms of CO₂ emissions per cycle LTO the A321 CEO equipped with IAE V2533-A5 engines, reached 1610 kg CO₂ or LTO cycle. The least polluting jet aircraft in this analysis was the A220 equipped with PW1524G engines, with around 942kg CO₂ per LTO cycle, as illustrated in Table 42. In long-haul aircraft, the A330-900 NEO equipped with RR Trent 7000-72 engines was the long-haul aircraft that most contributes to pollutant emissions

associated with movements at LIS airport in the period considered (52% of total CO₂ emissions) , however this does not mean that it was the most polluting, as it has 2939 kg of CO₂ per LTO cycle, when the most polluting aircraft model in the analysis was the B757-200 equipped with PW2037 engines, with 7594 kg of CO₂ per cycle, compared to 1850 kg of CO₂ per cycle of the less polluting plane (B777-243(ER) equipped with GE GE90-94B engines), as illustrated in Table 43.

Table 42: Most and least polluting aircrafts/engines in medium-haul
Source: Own development

Medium-haul		
	Aircraft model /engine	CO ₂ emissions per cycle LTO (kg)
Most polluting	A321 CEO / IAE V2533-A5	1610
Least polluting	A220 / PW1524G	942

Table 43: Most and least polluting aircrafts/engines in long-haul
Source: Own development

Long-haul		
	Aircraft model / engine	CO ₂ emissions per cycle LTO (kg)
Most polluting	B757-200 / PW2037	7594
Least polluting	B777-243(ER) / GE GE90-94B	1850

The results obtained for LIS indicate some differences in the theoretical and calculated emissions due to the different taxi times in LIS when compared with the LTO standard taxi times. The taxi phase determines the results of harmful emissions in the entire LTO cycle due to the fact that this phase lasts the longest, and the taxi time is directly related to the infrastructure of the airport airside and the traffic congestion at that airport. A variation of +/- 4min in the total taxi time of an aircraft (Idle phase) leads to a variation of approximately +/- 15.4% in consumption and consequent emission of pollutants associated with Idle time, and approximately 6.5% in the total emissions of an LTO cycle.

5. CONCLUSIONS

This study gives an overview of the environmental impacts of different types of aviation fuels allowing the quantification and evaluation of the overall benefit of introducing SAF in general and in more detail and in particular at Lisbon airport, through a case study based on aircraft movements and pollutant emissions.

The results obtained show that:

1. HEFA is the only SAF commercialized and currently available, ready and authorized for use with a TRL of 9 and an average GHGs emission of 14 gCO₂e/MJ.
2. During a standard LTO cycle, CO₂ represents the largest pollutant if we only take into account the quantity of emissions, with 96% of total GHGs emissions, being that the Idle phase is the most polluting phase of the LTO cycle.
3. Comparing to the use of 100% Jet Fuel, the use of SAF mixture (50% FT + 50% Jet Fuel) during the LTO cycle for the same period, represents a reduction of around 78% emissions CO₂e/MJ. The SAF mixture (50% HEFA + 50% Jet Fuel) represents a reduction of 71%. The mix (50% ATJ + 50% jet fuel) represents a reduction of 48%.
4. The GWP value for NO_x is much higher than the GWP value for CO₂. Despite the absolute value of NO_x emissions represented only 0,49% when compared to CO₂ emissions for this period, the values of GWP is 20% higher for NO_x.
5. The APU represented around 13.9% of total CO₂ emission during the LTO cycles (at Lisbon airport in the period considered).
6. Despite representing only approximately 6% of total departures during 2019, the long-haul fleet represent half of all CO₂ and NO_x emissions comparing with the medium-haul fleet.
7. For a total occupancy (load factor of 100%), despite the most polluting medium-haul aircraft emits 30.8% less CO₂ per LTO cycle when compared to the most polluting long-haul aircraft, the most polluting medium-haul aircraft records an emission of more than 42.7% of CO₂ emitted per cycle per passenger.

8. GHGs consumption and emissions during taxi can be reduced by up to 25% through the use of single engine taxi, or even up to 43% through the use of EGTS.
9. Hydrogen, although apparently very promising in order to reduce CO₂ emissions, presents a high production cost e it would require numerous changes and certifications in the airport structures and in the planes themselves.

The results of this work should be analyzed taking into account the data is limited and related to a short and defined period of time, which means that when extrapolated to a longer time period the data must be executed with due precautions.

In summary, the main objectives of this study were achieved, and it was possible to conclude the environmental impact derived from the use of SAF at commercial airports. The GHG emissions before and after the introduction of SAF were also compared as proposed. All scenarios indicate that there is a there is currently a slow and gradual transition to introduce the use of SAF at commercial airports, which will lead to a series of environmental benefits through the reduction of GHG emissions as detailed throughout the work. New technologies must continue to be investigated and applied to the sector, in order to reduce GHG emissions from aviation and meet environmental targets for the sector.

Limitations of the study

One of the major limitations of the study which would have some relevance due to the large number of combustion vehicles in circulation daily on the airport's airside was the difficulty in obtaining data relating to the movements of handling and support vehicles on the airport's airside, which made it impossible to include this data in the study, despite the numerous attempts made to obtain that information.

Suggestions for future studies

As a suggestion for future research/investigations, it is proposed complementary research to this study, that involves the quantification of emissions produced by all handling and support vehicles that circulate on the airside of the airport. That information could be added to the study in order to quantify emissions on the airside of

an airport more precisely, and analyze the potential for reducing pollutant emissions through the use.

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