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Sustainable aviation fuels and imminent technologies - CO_2 emissions evolution towards 2050

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ABSTRACT

Nowadays, concerns about rising emissions and climate change have raised the issue of decarbonization. Several approaches have been promoted in the aeronautical sector to reduce CO_2 emissions. The present work provides quantitative data to support decision-making for the first pillar of International Air Transport Association (IATA) strategy to mitigate aviation climate impact. This strategy comprises improving aircraft technology and deploying sustainable low-carbon fuels. The most promising technologies for an imminent application are new engine architecture and natural laminar flow. On the other hand, efforts have been put to produce Sustainable Aviation Fuel (SAF) reaching the point where some methods for the production of alternative jet fuel are already approved by ASTM. Therefore, the present work quantifies the future reduction of CO_2 emissions by 2050 in the aeronautical sector with these strategies. For this purpose, two methodologies are used, a numerical model to calculate fuel consumption and CO_2 emissions from the global air transport fleet. For the SAF analysis, it is developed an approach that considers, besides the SAF production, the feedstocks, and the production pathway. Two cases and three scenarios represent the technological improvements and quantify the effects of new aircraft concepts and technologies on future CO_2 emissions. For the SAF analysis, four scenarios and two conditions assess the different production capacities and feedstocks. The combined effect of technologies with SAF is considered verifying if the goals proposed by IATA, carbon-neutral growth from 2020, and a reduction of 50% in net emissions by 2050 compared to 2005 levels are achieved. The assessment results reveal that the goals cannot be met only with the combined action of imminent aircraft technologies and the use of alternative fuels. Carbon-neutral growth is only reached when it is considered the combined effect of technologies with the scenario where the amount of SAF introduced is higher (an increase of 15% annually between 2030 and 2050). However, this carbon-neutral growth is only possible to start in 2040. Imminent aircraft technologies can reduce up to 15% in CO_2 emissions when compared to the Business as Usual scenario. The different feedstocks used in each process to produce SAF do not have a considerable impact on reducing CO_2 emissions, the maximum difference registered between each condition was 1.47%.

1. Introduction

Air transport reached a vital role in the everyday life. Civil aviation is the transport mode that is showing a steady growth path, and it is one of the most growing transport sectors (Panahi et al., 2019). The rapid growth in air transportation has as consequence an increased environmental impacts/issues that needs special attention.

The environmental impact of aviation is fundamentally divided into effects related to aircraft noise and due to exhaust gas emissions. The different pollutants emitted from aircraft engines affect the local air quality and the global atmosphere. These pollutants affect the radiative balance of the atmosphere. The direct emissions of the carbon dioxide (CO_2), which has a long lifetime in the atmosphere, play an important role in climate change (Kousoulidou and Lonza, 2016). Carbon dioxide causes the so-called greenhouse effect, whose consequences on the climate are being felt recently and could reach dramatic proportions if current energy policies are not changed (Coelho and Costa, 2008). Carbon dioxide is considered the most important greenhouse gas emitted by aircraft, since aviation handles 2.4% of global CO_2 emissions because of fossil fuel consumption. In 2018, considering all commercial operations, including passenger movement, cargo and mail, 918 million metric tons of CO_2 were emitted (Graver et al., 2019).

In 2008, all the global aviation stakeholders in order to meet the

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Abbreviations

ATAG	Air Transport Action Group
ATJ	Alcohol to Jet
ASTM	American Society for Testing and Materials
BADA	Base of Aircraft Data
BAU	Business as Usual
CAEP	Committee on Aviation Environmental Protection
EIS	Entry-into-Service
FRL	Fuel Readiness Level
FT	Fischer-Tropsch
FSDM	Fleet System Dynamics Model
HEFA	Hydro-processed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LCA	Life Cycle Analysis
RPKs	Revenue Passenger Kilometers
RTKs	Revenue Tonne Kilometers SAF Sustainable Aviation Fuels
SIP	Synthesized Iso-Paraffins

global challenge of climate change have adopted three major development milestones for the period between 2009 and 2050: 1) a cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth); 2) a reduction in CO_2 emissions of 50% by 2050, compared to 2005 levels; 3) an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020 (EASA, 2019). To be able to achieve these goals, the International Air Transport Association (IATA) introduced a possible strategy to help achieve these goals. All stakeholders agreed to follow the "four-pillar strategy" composed of improved technology, more efficient aircraft operations, infrastructure improvements, and positive economic measures (EASA, 2019).

The current outbreak due to COVID-19 pandemic is an unprecedented event in air transportation. Aviation is one of the industries that have been suffering most due to the consequences of the pandemic outbreak. According to Czerny et al. (2021), the global flight numbers decreased by almost 80% as of early April 2020. However, COVID-19 pandemic impacts on air cargo traffic is much less than on passenger traffic. According to International Civil Aviation Organization (ICAO) data (December 2020), the number of cargo flights has an increase of 1.44% compared to the numbers in the previous year (ICAO, 2020). The first aviation market hit hard was the market of China, since the pandemic became largely under control, the Chinese aviation market has been recovering gradually. Compared to most other major economies, the aviation sector in China recovered at a much faster rate mainly on domestic services. At the end of July 2020, it recovered at around 70–80% of the pre-pandemic level in the domestic market. In the previous virus outbreaks, it took at most 7 months for the aviation industry to fully recover (Czerny et al., 2021). All aviation markets, as China, will recover as the pandemic begins to come under control. In the present work, since aviation sector will growth at a lower rate in the following years compared to pre-COVID-19 impact, the revenue passenger kilometers (RPKs) growth rates employed in the simulations performed reflect a pessimistic outlook on the future of commercial aviation.

One of the major issues in assessing the environmental impact of aviation is the calculation of global CO_2 emissions. To overcome this issue, several models with different methodologies have been developed in recent years. Morales et al. (2007) has developed a model, Aviation Integrated Model, based on policy evaluation capability that enable a comprehensive analysis of the interactions between aviation and the environment at the local and global level. Jimenez et al. (2012) proposed a numerical fleet-assessment model that can dynamically simulate the evolution of the US commercial aircraft fleet. Similarly, Hassan et al. (2015) proposed an integrated framework that assesses the performance of the future National Airspace System in different scenarios that consider technological, operational contributions, and the use of biofuels. Others, such as Hollingsworth et al. (2008) and Schaefer (2012), presented methods to clarify and quantify both emissions and fuel consumption caused by the development of technologies and vehicle concepts of the global air transport system. Alternatively, Tetzloff and Crossley (2014) has developed a software for optimization that determines the optimal allocation of existing and future aircraft in a network of routes.

Other models have been developed with the same purpose of quantify fuel burn and emissions of the global air transport system, such as the Fleet System Dynamics Model (FSDM) (Randt, 2016), the Fleet Level Environmental Tool (Moolchandani et al., 2017), the Future Aviation Scenario Tool (Owen et al., 2010), and the Aviation Environmental Design Tool (ICAO, 2019b).

Several studies have investigated the introduction of new technologies (Owen et al., 2010; Randt et al., 2015), aircraft configurations (Terekhov et al., 2018), operational improvements (Ploetner et al., 2017; Hassan and Mavris, 2020) and new alternative fuels (ICAO, 2019b; Schilling et al., 2016; Moolchandani et al., 2017), determining the impact produced by these at the level of fleet emissions, using these models mentioned above.

The works of Owen et al. (2010), Randt et al. (2015), and Terekhov et al. (2018) focused on the analysis of the newly aircraft technologies. These studies show the future amount of carbon dioxide emissions considering the implementation of new generations of aircraft on the global fleet. The main conclusions of the mentioned studies reveal that the new technologies implemented have a slow penetration in the market by nature. Further reductions will have to come from other parts, mainly from sustainable alternative fuels and operational measures.

According to the IATA strategy, the development of bio-aviation fuels has the highest potential to reduce aviation CO_2 emissions (Hassan et al., 2017). For this reason, bio-aviation fuels have become the focus of aircraft manufactures, biofuel companies, researchers, and governments. According to Wang et al. (2019), the number of publications about bio-aviation fuel increased significantly in the last years. Most of these works focused on the production technologies, different feedstocks, and several processing technologies. As reported by Soltanian et al. (2020), there are three dominant strategies for converting biomass into fuel, the chemical routes, the biological routes, and the thermochemical routes. ASTM so far has approved seven bio-aviation fuel production technologies (ASTM D7566-20b, 2020). The properties and conditions of alternative jet fuels produced using these processes are discussed in Section 3.

Considering the importance of developing an alternative fuel, there is also the necessity to assess the environmental impact caused by it. Therefore, a few publications have focused on the environmental effects at the global level of introducing bio-aviation fuel. ICAO reported trends for fuel burn and aircraft emissions that affect the global climate. These trends consider the contribution of aircraft technology, improved air traffic management, operational improvements, and implementation of SAF. Regarding the production of SAF, ICAO showed it would be physically possible to meet 100% of demand by 2050 with SAF, which corresponds to a 63% reduction in emissions. This fuel production level could only be achieved with extremely high capital investments in SAF production infrastructures and substantial political support. Although, the goal of carbon-neutral growth after 2020 is unlikely to be met (ICAO, 2019b). Schilling et al. (2016) investigated the benefits, challenges, and emissions resulting from introducing new technologies and other fuels in fleets, such as fully electric aircraft, the strut-braced wing with an open rotor, blended wing body, liquid drop-in fuel (fischer-tropsch kerosene), and liquid non-drop-in fuel (liquid natural gas). Similarly, Moolchandani et al. (2017) have considered three scenarios. In the first scenario, it is introduced advanced technologies for aircraft configurations *tube-and-wing*; In the second scenario, it is introduced the configuration of the aircraft *hybrid wing-body*; In the last scenario, it is considered the entry of low carbon fuels. The results show that aviation CO_2 emissions do not reach the levels associated with the environment goals.

The motivation of the present work results from the necessity of providing quantitative data for decision-making on strategies for the decarbonization of the aeronautical sector by 2050. The primary objective of this study is to estimate the contribution of the latest and most important generations of aircraft, new technologies expected by 2025, and also the contribution of alternative fuels that have already been approved so far, to reduce fuel consumption. In order to assess the contribution of new aircraft generations, the model FSDM was used. To evaluate the contribution of SAF, the approach considered was based on the equation presented by the Committee on Aviation Environmental Protection (CAEP), using the results provided by the FSDM of the demand for Jet Fuel and using the data collected from the production of sustainable fuels for aviation. The present work evaluates whether the technologies together with alternative fuels will allow meeting the objectives proposed by IATA.

2. Air traffic emissions calculation

Assessing the impact that the development of technology has on the long-term of CO_2 emission reductions requires the global fleet simulation, taking into account new technologies to visualize the effects produced by these technologies. A simple comparison between the performance of the current technologies and configurations used in commercial aviation and those that are expected to enter the market becomes insufficient when the objective of the work is quantifying the fuel burn and emissions of the global fleet. To assess the effects caused on CO_2 emissions with the introduction of new technologies, the FSDM, which was developed at the Institute of Aircraft Design of Technical University of Munich was used (Randt, 2016).

2.1. Fleet system dynamics model

The model consists in the “aircraft fleet model” and the “air transport network model” components. This uses a dynamic approach to determine the size and structure of the commercial air transport fleet from year to year, so the smallest time interval that the model can consider is one year. As the FSDM uses a macro approach, this leads to two decisive consequences in the functioning of the FSDM. The first one is, in each year of the simulation, the model requires the desired amount of RPKs (Revenue Passenger Kilometers) and RTKs (Revenue Tonne Kilometers) together with the load factor in order to determine the” capacity gap”. In this way, it is possible to determine the amount of new aircraft to be added to the fleet. The other consequence is, in order for the user to start the model, it has to define the year in which he wants to start the simulation, along with the initial fleet of aircraft (in terms of size, composition, and age distribution) and also with the initial transport performance that the initial fleet has to comply.

The dynamic evolution of the fleet is determined using the principles of *System Dynamics*. *System Dynamics* is an approach to modeling the dynamics of systems that have strong multiple interactions. The main principle is to describe complex systems by applying a control circuit (feedback loops). Stocks and flows are the basic elements of the “System Dynamics” model. This help describing how the system is connected by feedback loops, which in turn creates non-linearity that often exists in everyday problems (Seel, 2012). In this model stocks and flows are used to capture the dynamics of the evolution of the fleet as a function of time.

Fig. 1 shows the general functioning of the model, in which it has two flows, the “Add aircraft” - inflow and the “Remove aircraft” - outflow. Inflow is intended for the entry of new aircraft into the fleet based on the air traffic growth rates defined before the start of the simulation. The introduction of new aircraft is limited by the availability of aircraft and the ability of manufacturers to deliver the required amount of aircraft. In the outflow, the aircraft are retired, taking into account the survival curves of each aircraft defined by the user. The model applies the survival curves to the various types of aircraft incorporated into the simulation and determines the amount of aircraft that have to be retired in each year of the simulation.

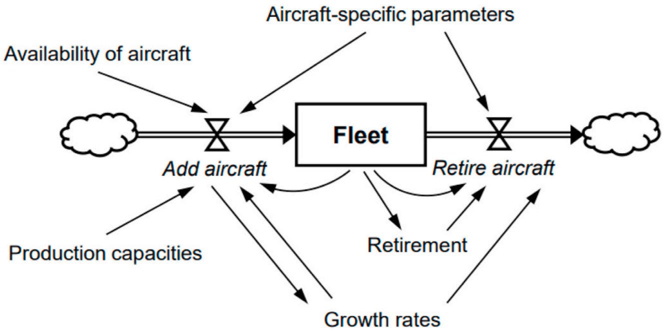

Fig. 1. Functional scheme of the Fleet System Dynamics Model based on the System Dynamics philosophy (Wache, 2014; Randt, 2016).

2.1.1. Input data required

The FSDM model requires a variety of parameters that the user has to provide in order to function properly, Table 1 shows the required data.

2.1.2. Aircraft performance modeling

One of the essential capabilities of FSDM is the modeling of aircraft performance. The *aircraft performance model* used is fundamentally based on the Base of Aircraft Data (BADA) that was created and is now being maintained and distributed by Eurocontrol (Angela Nuic and Mouillet, 2010). BADA has become recognized and used in the international scientific community and, nowadays, it is considered a standard tool for the performance simulations of civil aircraft. The BADA was implemented in the FSDM mainly to determine the fuel consumption of the global fleet and the amount of CO_2 emissions. The model also allows the calculation of NOx, CO, and unburned hydrocarbons, if appropriate data are available (ICAO Aircraft Engine Emissions Databank). The model then determines the quantities of these substances using the *Boeing Fuel Flow Method 2* (DuBois and Paynter, 2006). New aircraft that are not available in the BADA database were simulated using the BADA parameters of existing aircraft but varying them until the desired mission performance is achieved (fuel burn in particular).

Table 1
User input required by the Fleet System Dynamics Model (adapted from Randt (2016)).

User input data	
Target year of simulation	Final year of the fleet simulation
Current aircraft production intervals	Time intervals during which the types of the initial fleet are produced
Next-generation aircraft data	Types of aircraft that will enter the fleet in the future, for each aircraft must provide the aircraft performance and utilization data, and survival curves
Next-generation aircraft production	Time intervals during which the future types are produced
Production capacities	Total amount of aircraft that can potentially enter the fleet
Regional market growth factors	RPKs[a] and RTKs[b] growth rates for the 21 route groups between 2008 and the target year of simulation
Target payload factors	Seat and freight load factors expected to achieve in each one of the 21 regional markets

[a] Revenue Passenger Kilometers.
[b] Revenue Tonne Kilometers.

2.1.3. Model assumptions and limitations

Since the air transport system is very complex and dependent on several variables, it is necessary to make certain simplifications to reduce complexity of modeling. The model takes into account the following assumptions in order to simplify the modeling efforts and reduce complexity.

- **Airline competition** - FSDM considers that it simulates only one airline that allows meeting all the demand that exists in terms of passengers and cargo.
- **Fleet allocation** - Usually, the objective function to solve the fleet assignment problem is to maximize profit, but to do the modeling in this way is necessary the understanding of various commercial models of airlines and the implementation of cost functions. Since FSDM only simulates an airline, the models and cost functions of the companies are not considered, so to solve the fleet assignment problem, the model uses the minimization of the total fleet consumption in each year of the simulation as an objective function for the problem.
- **Possible time intervals of simulation** - The minimum time interval that can be used is 1 year and in any simulation that is done initiates at the year of 2008. The functionality of the model was only verified in simulation periods until 2050, so it is only possible to perform simulations until that year.
- **Representation of the global aircraft fleet** - The total air transport offer is supported by almost 200 different types of aircraft, as can be found in the Official Airline Guide database (Official Airline Guide, 2008). Including all these types will increase the level of complexity of the model. To maintain complexity at acceptable levels, the FSDM defines a distinct number of aircraft categories to simulate the global fleet, each aircraft category is represented by a specific type of aircraft.
- **Representation of the global routes network** - The global air route network is supported by more than 37000 different Origin-Destination pairs, according to the Official Airline Guide database (Official Airline Guide, 2008). Representing these pairs, all in one model would raise the level of complexity, making modeling quite difficult. To reduce complexity the FSDM defines six global regions (Europe, North America, Latin America, Africa, Middle East, and Asia). These regions together form 21 regional and interregional connections defined as route groups that allow representing the global network.
- **Further Limitations** - The aircraft utilization characteristics (i.e., the maximum utilization hours values for each type of aircraft) are treated as constants. The aircraft retirement is always defined through the survival curves set by the user, regardless of the current condition of aircraft demand. Similar to the aircraft utilization characteristics, the seat and freight load factors are treated as constants.

2.2. Technological options for aviation

Increasing aircraft efficiency plays a key role in achieving carbon reduction targets by 2050. Since the beginning of the *jet age*, technological innovations such as lighter materials, higher engine performance, and aerodynamic improvements have led to a 70% reduction in passenger-km or ton-km consumption of aircraft. Therefore, further reductions are therefore expected in the future with the entry of new technologies. However, when a new and more efficient aircraft is introduced, it takes a few years after entering into service (EIS) until they can penetrate the market with a sufficient number for the benefits to be noticeable in the overall efficiency of the fleet (IATA, 2020).

The aircraft that have entered service in recent years has the same configuration as the previous ones, however, they are equipped with new components or systems that allow greater efficiency. As an example, we have the Boeing 747–800 case with a reduction of 16% that has suffered changes in the engine and wing compared to Boeing 747–400. Another example, is the Boeing 747-400F case, intended for cargo transportation, which was replaced by the Boeing 747-8F. In narrow body type aircraft Airbus has released the A320neo, which is one of many upgrades introduced by Airbus to maintain its A320 product line position as the most advanced and fuel efficient in the world. The A320neo has two engine options (the Pure Power PW1100G-JM from Pratt and Whitney and the LEAP-1A from CFM International) and is equipped with wingtips known as Sharklets, which allow increasing aerodynamic efficiency as well as emission reductions, these being compared to the A320-200 are 15%. As the A320 family, Airbus has also improved the performance of the A330 family. The A330neo was launched in 2018 with the new generation of Rolls-Royce Trent 7000 engines, along with improvements in aerodynamic performance (new wingtips, increased lift and decreased drag). These upgrades will allow achieving a 16% reduction in fuel consumption. In turn, with regard to long-range commercial aircraft, from 2015 the aircraft of the A350XWB family were launched about 18% more efficient than the previous models. This is due to the advanced materials (carbon composites, titanium, and modern aluminum alloys) that make it possible to have a lighter and more efficient aircraft, as well as the fact that they are equipped with the latest generation Rolls-Royce Trent XWB engines. In order to increase the efficiency of aircraft used in regional flights, Embraer launched the Embraer 190 E-2 in 2016. This has undergone upgrades in the engines, wings and avionics to reduce fuel consumption, obtaining an efficiency of 16% compared to the previous model (Randt et al., 2015).

In the coming years, new technologies are expected to offer greater reductions in fuel consumption. Rolls Royce, between 2020 and 2025, expects to launch two new engines, the Advanced Turbofan and the Ultrafan, which will allow a reduction of 20%–25%, respectively, in fuel consumption compared to the Trent 800. The Advance engine presents a three-shaft architecture with a new high-pressure core. The Ultrafan is a step further using the advance core but with a two-shaft configuration coupled to a geared turbofan. The introduction of the *Natural Laminar Flow* concept in 2020 is also expected, which, in principle will be applied to narrow-body aircraft because the dimensions of the laminar sections are more appropriate for the wings of these types of aircraft. In 2022 Boeing, will launch the B777X that will be equipped with the latest engine from GE (GE9X), allowing a reduction of 10% compared to the engine GE90-115B. It will have the capacity to carry 426 passengers and operating costs will be reduced by 10% (IATA, 2020).

Through the information published by both aircraft manufacturers and aviation analysts, it was possible to estimate the efficiency of new aircraft and technologies in relation to existing aircraft. For the new technologies, since BADA files do not exist, they were created using a tool developed for this purpose.

Fig. 2 shows the scenarios created, taking into account the improvements in aircraft that are presented in this section along with the EIS expected. In the present work, three scenarios will be considered the Business as Usual (BAU), the Scenario 1, and the Scenario 2. The scenario BAU assumes that it does not exist any introduction of new technology into the simulation. This scenario represents a very conservative case in which manufacturers continue to produce their best existing aircraft without the development of new vehicle types. In the simulation, this scenario simulates only the aircraft that represent the initial fleet in 2008, without adding any new aircraft more efficient until 2050.

Scenario 1 aims at assessing the most efficient aircraft programs introduced in the global fleet so far. The aircraft introduced are the Boeing 747–800, Embraer 190 E-2, Boeing 747-8F, Airbus A330neo, Airbus A350-900, and Airbus A320neo. Alternatively, Scenario 2 represents the technological evolution of aircraft until 2025. Therefore in this scenario the aircraft and technologies expected in the aeronautical

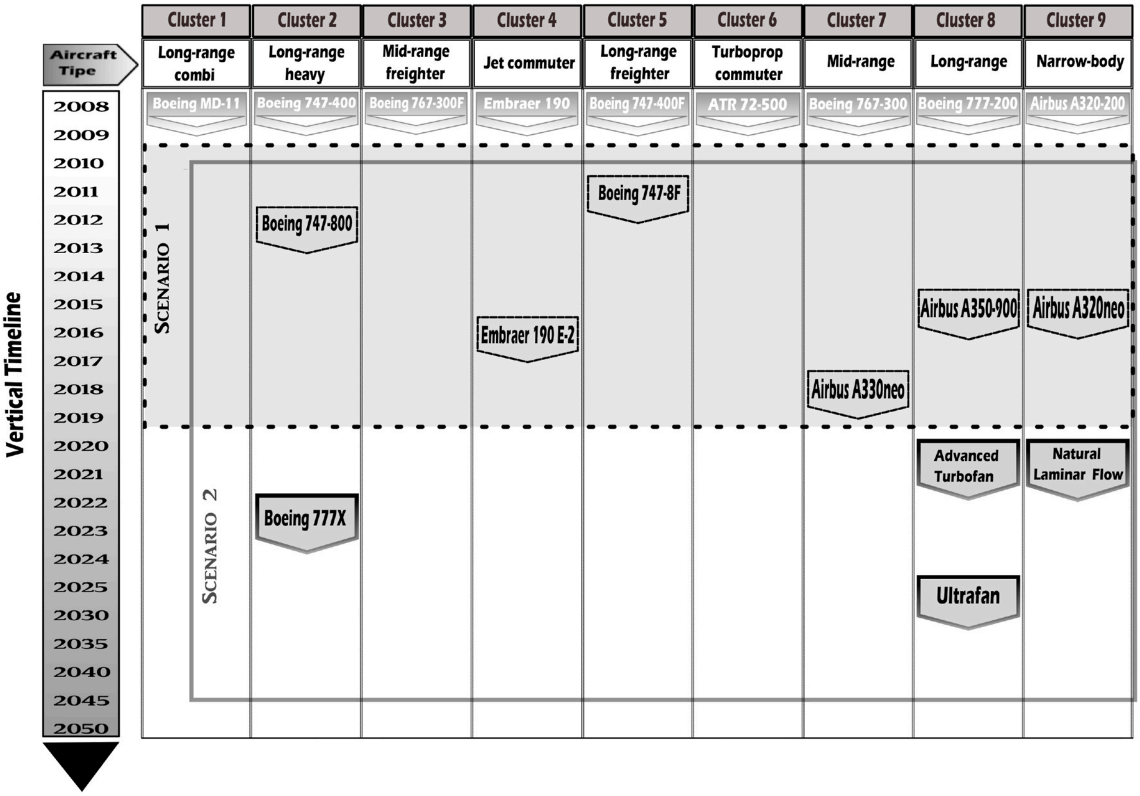

Fig. 2. Scheme of aircraft/technologies used in each scenario.

sector until 2025 are considered. The concepts that are introduced in addition to those added in Scenario 1 are the Boeing 777X, the Rolls Royce engines (Advanced Turbofan and Ultrafan),[1] and lastly the Natural Laminar Flow.[2] In Fig. 2, Scenario 1 is delimited by a dashed line, and Scenario 2 is delimited by a solid line.

Two cases were created to assess what effect aircraft production capacities have on the amount of new and more efficient aircraft added to the market. Case 1 includes Scenario 1 and Scenario 2 with no improvement on the production capacity of aircraft. On the other hand, Case 2 also includes Scenario 1 and 2, but with a 15% improvement on the production capacity of aircraft.

3. Sustainable aviation fuels

One of the most attractive options for reducing CO_2 emissions in a relatively short period is the introduction of sustainable aviation fuels (SAF). These must have the same quality and characteristics as conventional jet fuel in order to be used in existing aircraft. This factor is very relevant because manufacturers do not have to redesign engines or aircraft and fuel suppliers and airports do not have to build new fuel supply systems. The other relevant reason for the use of these fuels is that the aeronautical sector has some advantages from a technical point of view for the implementation of drop-in fuels because there is a great homogeneity in the existing aircraft, engines and fuel specifications (Noh et al., 2016).

3.1. Production processes of sustainable aviation fuels

The production of SAF can follow different technology pathways, this subsection reviews the main processes approved to produce bio-fuel aviation. The certification and qualification of any alternative aviation fuel should following the requirements specified by ASTM International (American Society for Testing and Materials) (ASTM D7566-20b, 2020). The ASTM approval doesn't consider the emissions, contrail formation, and operating costs. It is only considered safety and airworthiness (Zhang et al., 2020). At the moment, seven production pathways have been certified for blending with conventional aviation fuel.

Table 2 shows the approved conversion processes with the respective possible feedstocks, the blending ratio by volume, and the Fuel Readiness Level (FRL), which represents the progress of fuel production towards commercialization (CAAFI, 2010; Mawhood et al., 2016). However, the only process that can establish production on a large scale is Hydroprocessed Esters and Fatty Acids (HEFA-SPK), with a complete, qualified and operational system (Vásquez et al., 2017), while the other processes are still in the full-scale technical evaluation, fuel approval (fuel class/type listed in international fuel standards), and Commercialization Validated.

In the following subsections, it will be discussed the most promising alternatives to supply significant amounts of biofuel for aviation. Although, as is discussed in Section 3.3, the only production processes that will be implemented by fuel producers in the mid-term are HEFA, FT, and ATJ.

3.1.1. Hydroprocessed esters and fatty acids

Hydroprocessed Esters and Fatty Acids, HEFA, is a process that is obtained from the reaction of feedstocks based on animal fats, vegetable oils, and algae oils, and these are derivatives available in nature. In this sense, it turns out that HEFA often uses residual oils and fats that are more sustainable sources. It is also noteworthy that triglycerides, the building blocks of fats and oils, are the main feedstock. The first reaction is exothermic, which causes the energy involved in the first reaction to lead to a decrease in energy costs for the whole process, which has positive economic and environmental implications, so it is an advantage

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[1] The engines are applied to Boeing 777–200.

[2] Considered applied on the A320neo because the prevision is to be applied first on narrow-body aircraft.

Table 2
Conversion processes, feedstocks, and Fuel Readiness Level of the seven production pathways certified by ASTM for use in commercial flights.

Conversion Process	Abbreviation	Possible Feedstocks	Blending Ratio	FRL[a]
Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene	FT-SPK	Coal, natural gas, biomass	50%	7
Hydroprocessed Esters and Fatty Acids	HEFA-SPK	Bio-oils, animal fat, recycled oils	50%	9
Synthesized Iso-Paraffins	HFS–SIP	Biomass used for sugar production	10%	5–7
Fischer-Tropsch Synthesized Paraffinic Kerosene with Aromatics	FT-SPK/A	Coal, natural gas, biomass	50%	7
Alcohol to Jet Synthesized Paraffinic Kerosene	ATJ-SPK	Biomass used for starch and sugar production and cellulosic biomass for isobutanol production	30%	7
Catalytic Hydrothermolysis	CHJ-SPK	Bio-oils	50%	6–7
Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids	HC-HEFA-SPK	Hydroprocessed hydrocarbons, esters, and fatty acids	10%	6

[a] Fuel Readiness Level.

that stands out from this process. All stages encompass various mechanisms of catalytic reactions in the presence of hydrogen. In view of the presence of oxygen and unsaturated carbon bonds, it is necessary to perform deoxygenation and hydrogenation steps in order to produce a saturated hydrocarbon fuel. After this conversion procedure, it is possible to mix up to 50% by volume of the HEFA component with conventional jet A or Jet A-1 fuel. Thus, this process has a high level of maturity and commercially available conversion technology (ICAO, 2019a; Doliente et al., 2020; De Jong et al., 2017).

3.1.2. Fischer-tropsch

The Fischer-Tropsch (FT) process is a chemical process used for the production of liquid hydrocarbons (gasoline, kerosene, diesel, and lubricants) based on synthesis gas (CO and H2). The nature and proportion of the originating products depend on the type of reactor and catalyst. The common feedstocks for the synthesis of FT are coal, natural gas, or biomass. However, coal and natural gas are not renewable sources and are therefore not suitable for the production of sustainable aviation fuel (ICAO, 2019b). To increase the efficiency of the thermochemical process involved, the feedstocks indicated above must have high concentrations of carbon and hydrogen. FT synthesis can be described as a set of catalytic processes, and the catalysts are based on iron or cobalt, depending on the synthesis temperature and the desired products. In this sense, FT comprises steps such as biomass gasification, cleaning, and conditioning of the produced synthesis gas and subsequent synthesis to obtain liquid biofuels. As with HEFA, it is also possible to mix up to 50% by volume of the FT component with conventional Jet A or Jet A-1 fuel (Doliente et al., 2020).

3.1.3. Alcohol-to-jet

Alcohol-to-Jet, ATJ, is a biochemical conversion process for the production of aviation fuel mixture based on alcohol. There are several feedstocks that can be used. The most common practice for obtaining alcohol derivatives is the fermentation of edible plant sugars. The fermentation of inedible plants, although it also exists, implies the use of advanced techniques involving pre-treatment, specific microbes, and additional process units. Only after the pre-treatment and conditioning of biomass can alcohols be produced through fermentation processes. ATJ obtained from ethanol or butanol intermediates are allowed in a maximum mixture of 30% (ICAO, 2019a; Doliente et al., 2020; De Jong et al., 2017).

3.1.4. Synthesized iso-paraffins

Synthesized Iso-Paraffins, SIP, are synthetic hydrocarbons produced by the hydroprocessing and fractionation of farnesene from sugar fermentation. Sugar feedstock may include sugar cane and beet, corn grain, and pre-treated lignocellulosic biomass. In the first stage, the biomass is pre-treated by enzymatic hydrolysis, and the solubilized sugars are separated and concentrated. Subsequently, the pre-treated material undergoes a biological conversion to produce an intermediate hydrocarbon and, finally, is oligomerized and hydrotreated for fuel. In this sense, it turns out that, to obtain farnesene, there is a separation of the intermediate component in a solid and liquid part and then in an oily and aqueous phase by centrifugation. It is possible to mix up to 10% by volume of the SIP component with conventional jet A or Jet A-1 fuel (ICAO, 2019a).

3.2. Life cycle assessment of sustainable aviation fuels

The Life Cycle Analysis (LCA) is a methodology that allows to assess the environmental impacts caused both on human and ecological health of a system (Agusdinata et al., 2012; Wang et al., 2019). The production processes that are included in the LCA are determined through the LCA system boundary, and all inputs and outputs of each process or stages are included. (De Jong et al., 2017; Pan et al., 2018). The system boundary of the LCA values considering on the present work is presented in Fig. 3, which consists of the entire supply chain of the production and use of SAF. The LCA covers the fundamental processes: feedstock cultivation, feedstock harvesting, collection and recovery, feedstock processing and extraction, feedstock transportation to processing and fuel production facilities, feedstock-to-fuel conversion processes, fuel transportation and distribution, and fuel combustion in an aircraft engine (ICAO, 2019a).

According to Fig. 3, different approaches are used to calculate the LCA as a function of the type of feedstocks. In the particular case of waste, residue, and by-product feedstocks, the greenhouse gas emissions were not considered for the production step. However, the emissions generated during their collection, recovery and extraction, and processing are considered. Table 3 shows the LCA values considered in the present work to assess the CO_2 reduction capacity of SAF. The functional unit selected for the LCA results is grams of CO_2 per Mega joule [MJ] of fuel produced and combusted in an aircraft engine.

3.3. Supply evolution of sustainable aviation fuels

The medium and long-term production forecasts for alternative aviation fuels are highly complex, as the development of these fuels depends on policy measures and investment mobilization opportunities to overcome the marketing challenges (IATA, 2015). Another factor that also makes it difficult to do this forecast, is the production capacity that will be directed to the production of SAF compared to other fuels. To this end, ICAO projected possible production capacity scenarios. As shown in Fig. 4, there are two scenarios (“high ratio “and “low ratio”) to highlight this uncertainty.

Given that, ICAO forecasts provided on 19th May 2020, do not include the amount of fuel that is produced by each conversion process and by feedstock, only the amount of fuel produced is provided. However, the methodology presented in section 3.4 requires the data of the quantity produced in each process and the feedstocks used. The data was collected through the information published by the industry and the data collected by ICAO on Stocktaking Seminar toward the 2050 Vision

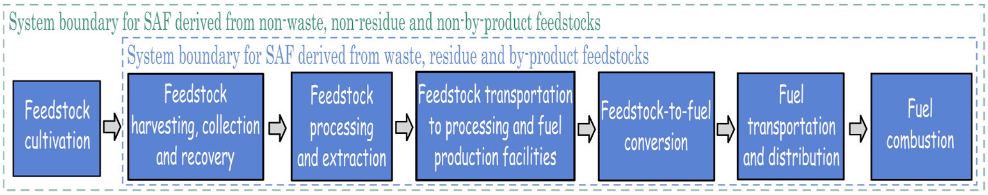

Fig. 3. System boundaries and life cycle steps (ICAO, 2019a).

Table 3
Summary of Life Cycle Analysis values to date (ICAO, 2019a).

Conversion process	Feedstock	LCA[a] value [gCO$_2$e/MJ]
Fischer-Tropsch	Agricultural residues	7.7
	Forestry residues	8.3
	Municipal Solid Wastes	5.2
	Short-rotation woody crops	12.2
	Herbaceous energy crops	10.4
Hydroprocessed esters and fatty acids	Tallow	22.5
	Used cooking oil	13.9
	Palm fatty acid distillate	20.7
	Corn oil	17.2
	Soybean oil	40.4
	Rapeseed oil	47.4
	Camelina	42
	Palm oil- close pond	37.4
	Palm oil-open pond	60
	Brassica carinata	34.4
Synthesized Iso-Paraffins	Sugarcane	32.8
	Sugarbeet	32.4
Iso-butanol Alcholol-to-jet	Sugarcane	24.0
	Agricultural residues	29.3
	Forestry residues	23.8
	Corn grain	55.8
	Herbaceous energy crops	43.4
	Molasses	27.0
Ethanol Alcohol-to-jet	Sugarcane	24.1
	Corn grain	65.7

[a] Life Cycle Analysis.

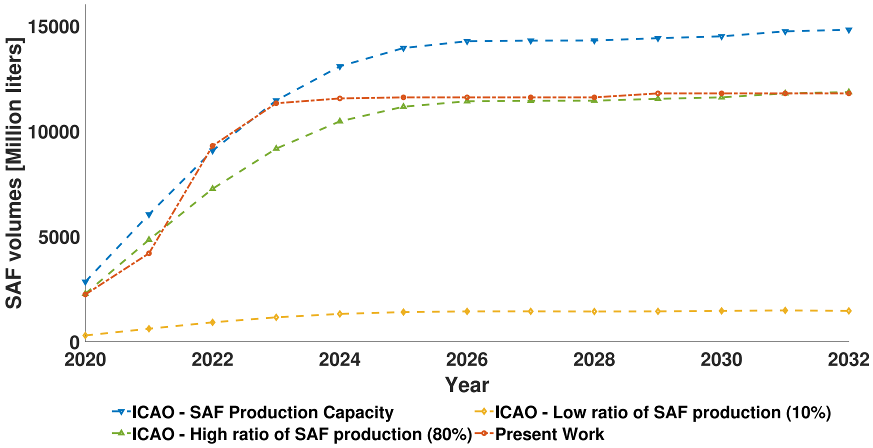

Fig. 4. Projected scenarios of Sustainable Aviation Fuels production, expressed in million liters (ICAO, 2019b and authors calculations).

for Sustainable Aviation Fuels and ICAO Stocktaking Seminar on aviation in-sector CO$_2$ emissions reductions. As shown in Fig. 4, the total collected production capacity of SAF, which includes all production capacities (HEFA, FT, and ATJ), is the line that approaches the high ratio of the SAF production scenario.[3]

The production processes that will be implemented in the refineries for the production of SAF are only HEFA, FT, and ATJ. The feedstocks that will be used in these processes are mainly used cooking oils, soybean oil, rapeseed oil, camelina, sugarcane, forestry residues and municipal solid wastes, as shown in Table A5. Table 4 shows the projected production, based on the data collected, for HEFA, FT and ATJ until 2030.

3.4. *Biofuels impact analysis*

The analysis of the impact of biofuels was based on the formula provided by the CAEP Market-Based Measures Task Group (ICAO, 2019b). This formula allows to analyze the introduction of sustainable fuels using the amount of available biofuel and the life cycle of the respective biofuel. Fig. 5 shows the equation used, where:

Table 4
Estimated production of Sustainable Aviation Fuels for each process.

Year	Conversion Process		
	HEFA[a] [Mt]	ATJ[b] [Mt]	FT[c] [Mt]
2020	1.53	0.13	0.03
2022	6.68	0.18	0.16
2024	7.46	0.97	0.30
2026	7.47	0.99	0.30
2028	7.47	0.99	0.30
2030	7.47	0.99	0.45

[a] Hydroprocessed esters and fatty acids.
[b] Alcholol-to-jet.
[c] Fischer-Tropsch.

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[3] The data used for the SAF production was collected from https://www.icao.int/environmental-protection/Pages/SAF-Stocktaking.aspx.

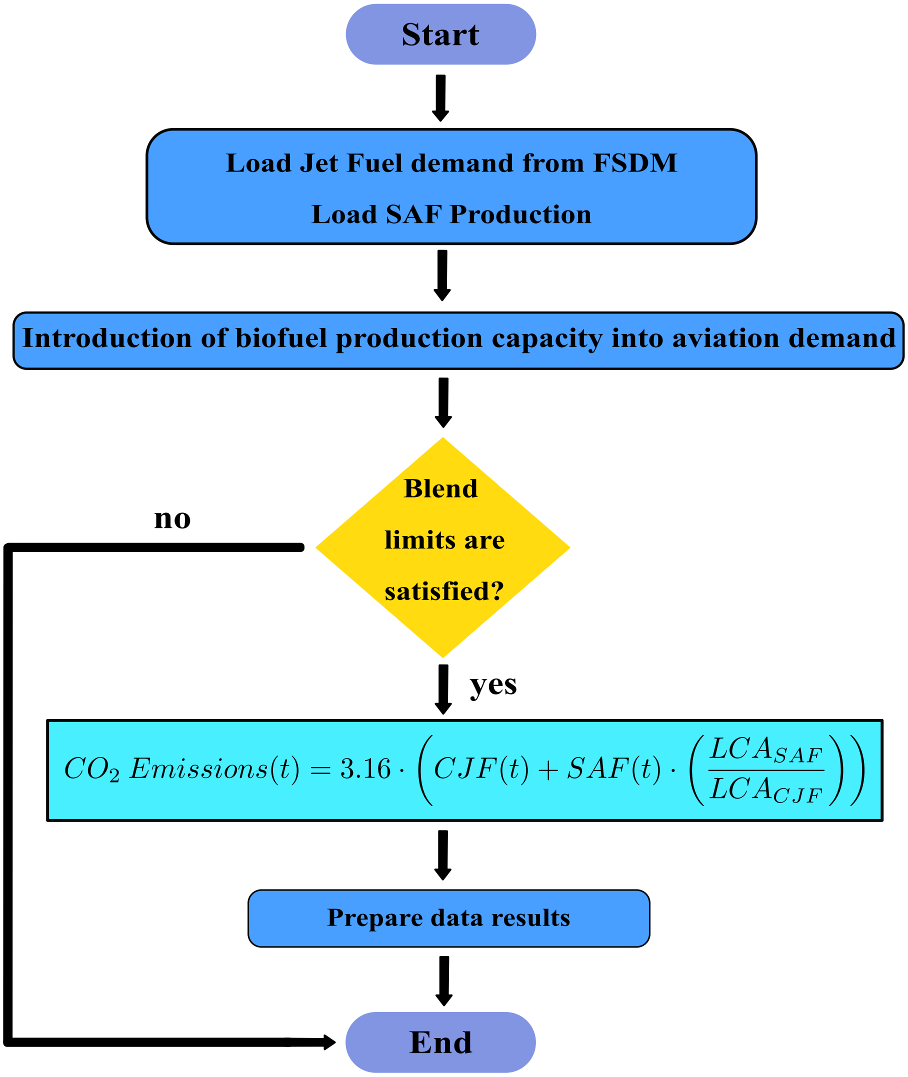


Fig. 5. Flowchart of the methodology developed.

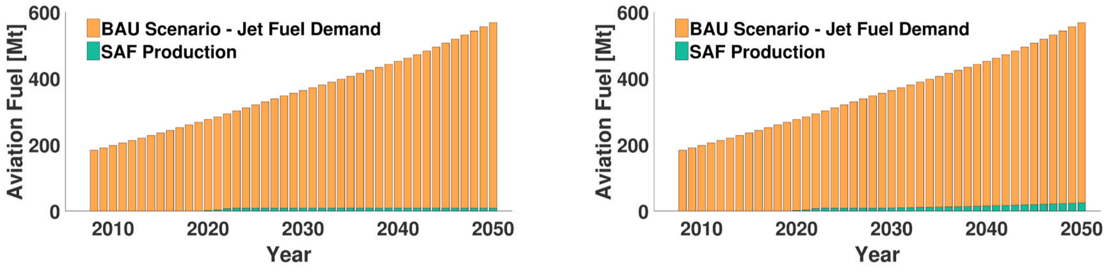
- $CJF(t)$ - corresponds to the amount in kilograms of conventional jet fuel for the year t;
- $SAF(t)$ - is the amount of a given biofuel in kilograms introduced for the year t;
- LCA_{SAF} - corresponds to the life cycle of the added biofuel (gCO_2e/MJ);
- LCA_{CJF} - it is the life cycle of conventional jet fuel ($89gCO_2e$/MJ);
- $CO_2\ Emissions(t)$ - total emissions of CO_2 for the respective year t;
- t - year of simulation.

According to Fig. 5, the initial step of the process is to load the jet fuel demand given by the simulation made in FSDM and the production capacity for each sustainable aviation fuel stipulated for each scenario. The second step is to introduce the alternative fuel that is produced in the fuel demand that the aeronautical sector needs, after introducing the alternative fuels is checked for each year whether there is jet fuel needed to meet the blending standards of each biofuel. If it is possible to meet the standards, then the total emissions of CO_2 resulting from the consumption of jet fuel with the addition of biofuels are calculated.

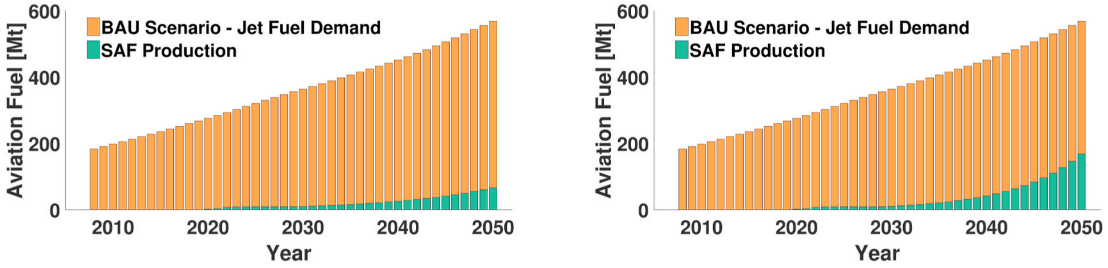
As seen in Fig. 4, the SAF production forecast is limited until 2032 and from 2030 begins to stabilize because there is no more information on the introduction of biofuel production new plants, or increase in production on those that already exist. To verify more clearly what the impact of the introduction of SAF will be, four scenarios were created in which the annual production rate of SAF is varied from 2030 to 2050. Scenario A represents a conservative scenario, where the production capacity used is shown in Fig. 4 keeping the value constant between 2030 and 2050. In Scenario B, from 2030 it is considered an increase of 5% annually in production capacity until 2050. In Scenario C, instead of an increase of 5% annually, it is considered an increase of 10% annually in production capacity until 2050. For Scenario D, an increase of 15% annually was chosen to represent the case of a large investment on biofuels. Fig. 6 shows the SAF production for each scenario and the Jet Fuel demand for the BAU Scenario.

The reason for the highest annual rate being 15% is because if a rate greater than 17% was considered, the blend limits would not be satisfied since it is assumed that all the SAF produced is introduced into the fleet fuel burn and the corresponding amount of jet fuel is retired to maintain the same fuel demand in each year. Consequently, with rates higher than 17%, there is no required amount of jet fuel to meet the blend limits.

In addition to the four scenarios created related to the annual growth rates of SAF production, two conditions were applied to each scenario to assess the influence of the feedstocks used in the processes. Since in the data collected, some of the companies use a variety of feedstocks, for these data was chosen the feedstock with the lower LCA value, this represents the “Low” condition, and was chosen the feedstock with the higher LCA value, for the “High” condition.



(a) Scenario A (b) Scenario B



(c) Scenario C (d) Scenario D

Fig. 6. Sustainable Aviation Fuels production for each scenario, and Jet fuel demand for the Business as Usual Scenario.

4. Results and discussion

This section presents the results, in quantitative terms, of the impact of the implementation of new technologies and sustainable aviation fuels in civil aviation. The methodology used is previously reported in previous sections with the necessary data. In addition to the data used, it is worth highlighting some considerations used in the FSDM model, namely the production capacities of each new aircraft program that have been defined through the type of aircraft (single-aisle or twin-aisle). To better capture what happens in real life, aircraft added into the global fleet during simulations were restricted to existing limitations of new aircraft production and global limitations of aircraft production.

4.1. Scenarios description

This subsection describes and summarizes the key elements of all the scenarios and cases analyzed in this study. These scenarios are used as an input into climate change impact assessment since scenarios are a way of understanding the dynamics that shape the future. As shown in Fig. 7, the SAF assessment depends on technological improvements because it is necessary to consider the jet fuel demand resulting from introducing new aircraft more efficient into the global fleet. In relation to the technological improvements, two cases are considered. The fundamental difference between the cases is the aircraft production capacity: in the first case is considered a normal aircraft production capacity, while in the second case the production capacity is improved by 15%. In each case, as shown in Fig. 7, there are two scenarios. Scenario 1 considers all the aircraft implemented by 2020, meanwhile Scenario 2 considers all the technologies/aircraft implemented by 2025. Regarding the analysis of SAF, four scenarios and two conditions are considered. The various scenarios are distinguished by the production capacity assumed for the sustainable aviation fuels. The High and Low conditions define the LCA value for refineries that have various feedstock options, as shown in Table A5.

4.2. Technological improvements

The COVID-19 pandemic at 2020 generates another important factor that has to be recognized in the air transport system modeling. The correct growth of the aviation market has to be considered, given its influence on the number of passengers transported and the number of flights performed. Fig. 8 shows the study realized to choose the growth rates that better represent the growth of the aviation market. In order to handle the uncertain development of the global commercial air transport market, two options for the growth rates of aviation sector are analyzed. The first option is the BAU Scenario – Optimistic Growth, which considers passenger traffic growth of 5.0% annually, and cargo traffic growth of 4.7% annually. This represents an optimistic BAU scenario extrapolated to 2050. The second option is the BAU Scenario – Pessimistic Growth, which describes a very pessimistic perspective on the future of commercial aviation. This illustrates an inferior vision of the industry's perspective as opposed to the BAU Scenario – Optimistic Growth. Fig. 8 also shows the results obtained by Air Transport Action Group (ATAG) for the BAU scenario considering the impact of COVID-19 (ATAG, 2020), the scenario closest to ATAG results is the scenario with a pessimistic growth (air traffic growth by 1.5% per year on average). All the simulations performed in the present work used the same growth rates of BAU Scenario – Pessimistic Growth.

According to Fig. 9, the results show that the introduction of new aircraft has a significant impact on fuel consumption, showing that they are indispensable for the decarbonization of the sector. In case 1, in 2050, the reductions in CO_2 emissions compared to the baseline are 8.3% and 12.4%, for scenarios 1 and 2, respectively. For Case 2, in 2050, the reductions in scenarios 1 and 2 are 9.5% and 14.5%. The reduction of fuel consumption and consequently of emissions of CO_2 increases over time due to the slow penetration of these new aircraft in the market, since production capacities in the initial years are reduced.

For Case 1, the maximum reduction in emissions compared to the BAU scenario, both for Scenario 1 and Scenario 2, happens in 2045, with a reduction of 9.28% and 12.95%, respectively. The reason for the higher reduction in 2045 is the fact that the limit has been reached at which the introduction of new aircraft no longer brings benefits in reducing fuel consumption of those that occurred in 2045. In order to continue to increase the percentage reduction in emissions, the aircraft added should be more efficient compared to those being added into the global fleet.

In Case 2, the production capacities of all aircraft that were simulated, were increased by 15%. This sensitivity analysis was carried out to observe what impact aircraft production capabilities may have when there is the introduction of new technology. The results obtained for

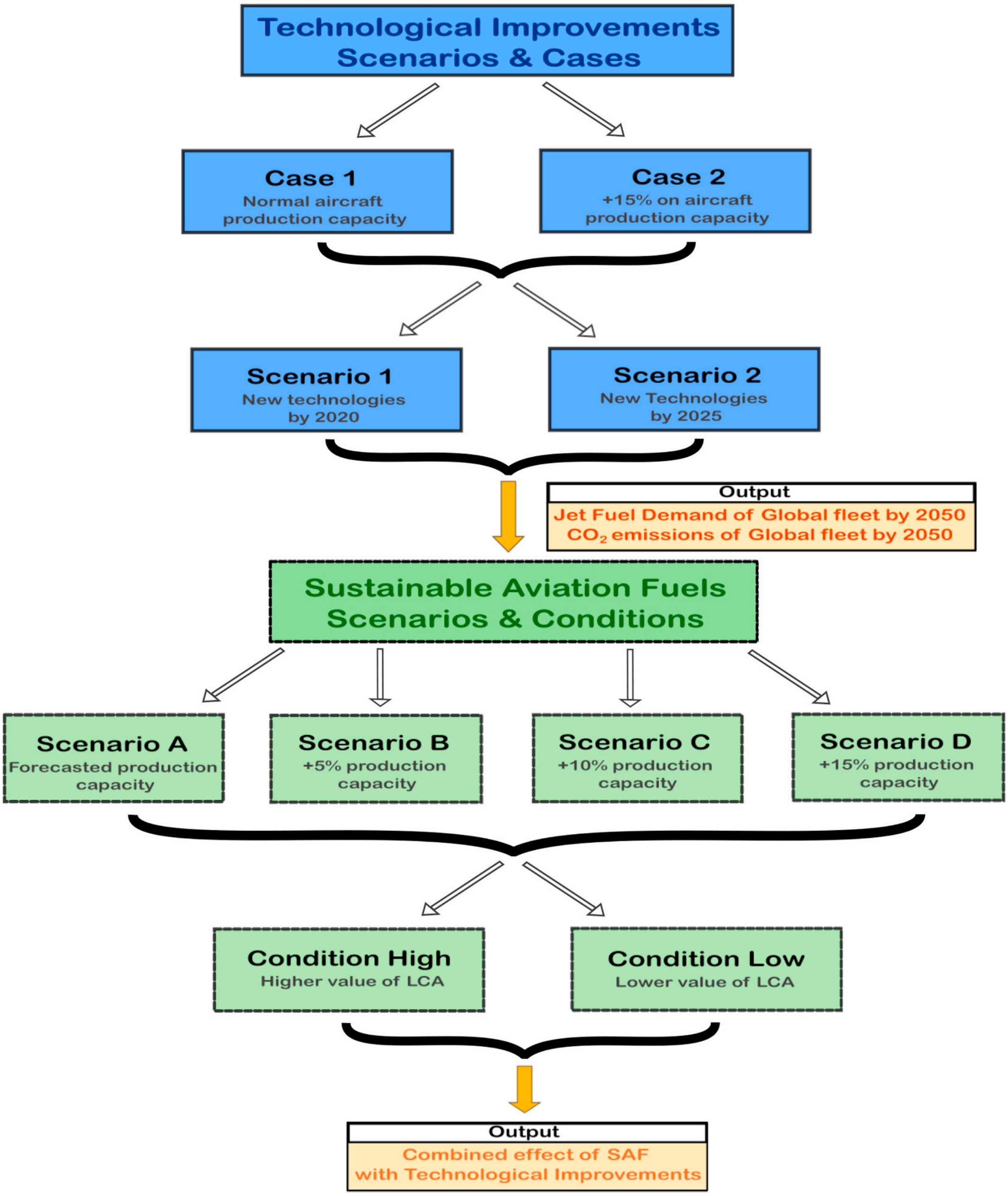


Fig. 7. Scheme of all cases and scenarios analyzed.

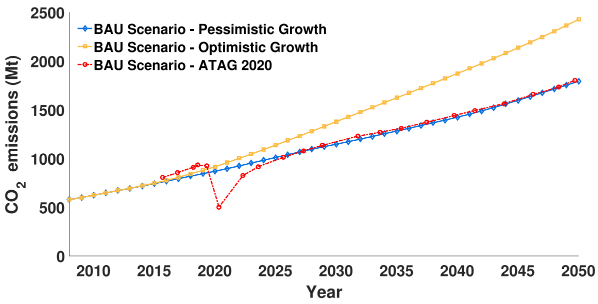
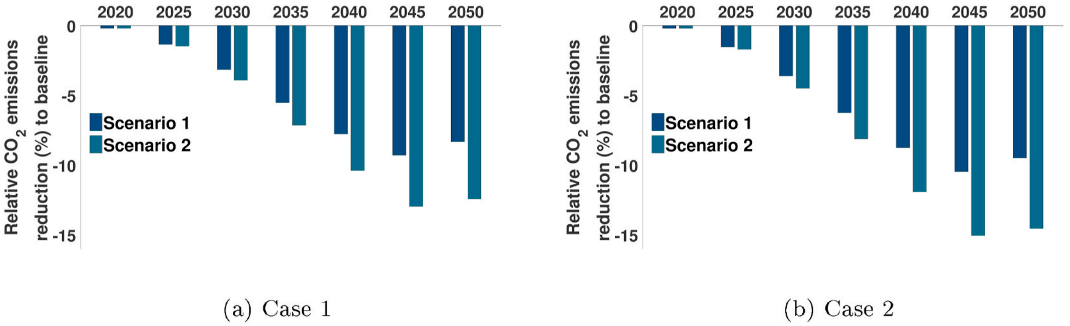


Fig. 8. CO_2 emissions evolution for different growth rates of the aviation market.

Case 2 show that the possible reductions are 10.46% for Scenario 1 and 15.04% for Scenario 2 in 2045. As expected, with the increase of production capacities, the penetration of these new aircraft is greater, which allows to reduce fuel consumption further.

Scenario 2, for both Case 1 and Case 2, is the scenario that has the greatest reduction of emissions because this includes the new technologies that will be introduced between 2020 and 2025. Although, the major difference between Scenario 1 and 2, for both cases, is in 2050 (4% for Case 1 and 5% for Case 2). The introduction of new configurations and new technologies in the years leading up to 2025 could further reduce fuel consumption globally, it will be interesting to make this assessment.

Two factors are relevant for the implemented new technologies, the first is the entry into service (EIS), if the new technologies are implemented in the last year before 2050 the effect that this technology will have will be very low. As it is possible to see in Fig. 9a, in Scenario 1 that represents the technologies implemented by 2020, the reductions in CO_2



(a) Case 1

(b) Case 2

Fig. 9. Fleet-level CO_2 emissions from 2008 to 2050 of (a) Case 1 and (b) Case 2, relative to baseline.

emissions in 2025 are only 1.5%. The other factor is the production capacity that will determine whether the market penetration will be faster or whether it will take a few years to achieve some relevance and visualize the effect caused in fuel burn.

4.3. *Sustainable aviation fuels*

Fig. 10 shows the results of the impact of SAF introduction on global CO_2 emissions from the air transport fleet. In Scenario A, the impact on global fleet emissions is extremely low, around 1.71% per year. This scenario represents the forecast made by ICAO for SAF production ("High ratio"), showed in Fig. 4. The expected production in this scenario, compared to the required demand of Jet fuel for the aeronautical sector evidence a large discrepancy, as the expected demand in 2030 is about 363 Mt and the forecast production of SAF is 8.9 Mt. In Scenario B, it is possible to see a substantial reduction of 18% on CO_2 emissions compared to the baseline, but still insufficient to achieve the proposed objectives, and therefore it is necessary to increase biofuel production.

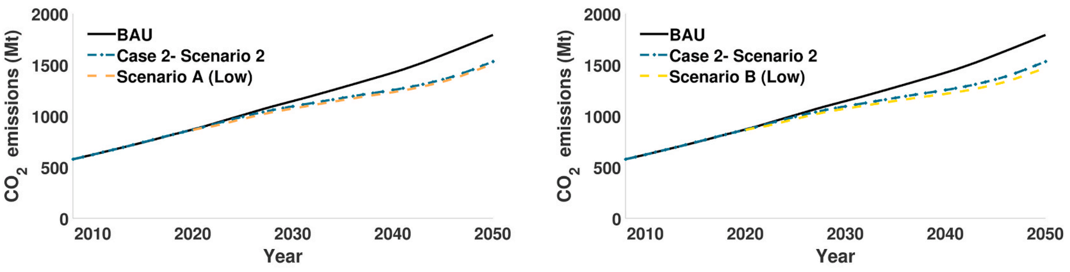
Fig. 11 shows the International aviation CO_2 emissions for the Scenario 2 of Case 2, and for Scenario C (Low) and Scenario D (Low). It is possible to verify for Scenario C, that the value of emissions in 2050 was 1365 Mt of CO_2, which indicates a reduction of 24% of emissions comparing with the BAU scenario. Finally, Scenario D shows a higher reduction in emissions (38.5% compared to baseline) and the only scenario to achieve carbon-neutral growth from 2040 onwards. However, in 2050 it is not possible to obtain half of the emissions recorded in 2005. Although it is the scenario that allows the higher reduction of emissions. In order to achieve this level of SAF production, there will have to be a high investment, as well as policy measures for biofuels have more importance in the market and be competitive with conventional jet fuel in terms of costs. It must be also reminded that to get these production capacities requires having sufficient feedstocks and refineries capable of supplying these quantities of SAF. The feedstocks used should preferably be non-food biomass in order to ensure that the food chain is not affected and that will not exist competition between the transport and food sectors. Another problem that may emerge with the use of agricultural land is the utilization of fertilizers and insecticides, which can cause soil destruction and water pollution. Therefore, sustainable aviation fuels must use, recycle, and sequester existing CO_2 emissions if they are to be truly green and useful in combating climate change, without raising problems for human health.

According to Fig. 12, which demonstrates the cumulative reductions for each scenario and condition in relation to the BAU scenario, the influence that the considered feedstocks have in each process on the CO_2 emissions are very low, the percentage difference between each condition for the Scenarios A, B, C and D is 0.08%, 0.22%, 0.58%, and 1.47%, respectively. The differences between the "Low" and "High" conditions increase when the production capacity of biofuels is higher. Fig. 13 shows CO_2 emissions trends for civil aviation between 2008 and 2050, considering all four scenarios and the conditions used.

These results, mainly for Scenario C and D, prove in quantitative terms the statements published by Moolchandani et al. (2017) and Schilling et al. (2016), who reported that biofuels would be vital for reducing emissions from commercial aviation. As mentioned by ICAO (ICAO, 2019b), in these results is possible to visualize that SAF has the potential to fill the gap to carbon-neutral growth, but not in the short term. As shown in Fig. 13, the differences between the conditions "High" and "Low", in Scenario A and B, in the CO_2 emissions trend for civil aviation are practically invisible. However, mainly for Scenario D from 2045, it is possible to see the difference between each condition. Concerning the feasibility of the IATA environment goals, the present work shows that these goals cannot be reached with only imminent aircraft technologies and sustainable aviation fuels. Although, as reported by Hassan et al. (2017), these goals might be accomplished with medium and low demand growth, coupled with high technology introduction rates and faster retirement of old aircraft.

5. Conclusions and future directions

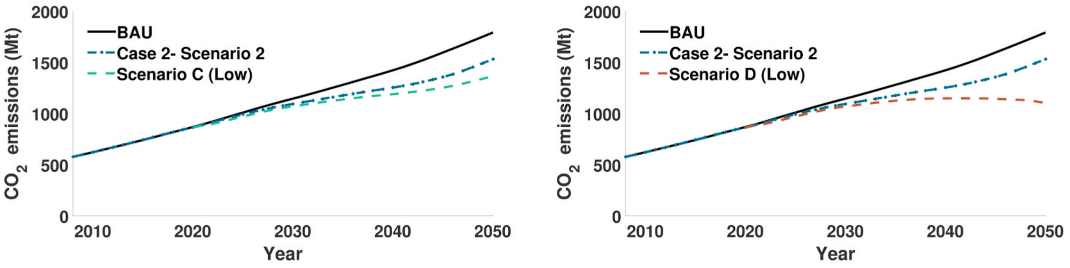
In this study, the influence of new aircraft programs, new technologies and alternative fuels on the air global fleet emissions is evaluated. Two methodologies were used. The FSDM for the simulation of the air transport fleet and for the analysis of sustainable aviation fuels was used an approach that considers, in addition to the SAF production, the



(a) Scenario A

(b) Scenario B

Fig. 10. International aviation CO_2 emissions for the Scenario 2 of Case 2, and for a) Scenario A (Low) and b) Scenario B (Low).



(a) Scenario C (b) Scenario D

Fig. 11. International aviation CO_2 emissions for the Scenario 2 of Case 2, and for a) Scenario C (Low) and b) Scenario D (Low).

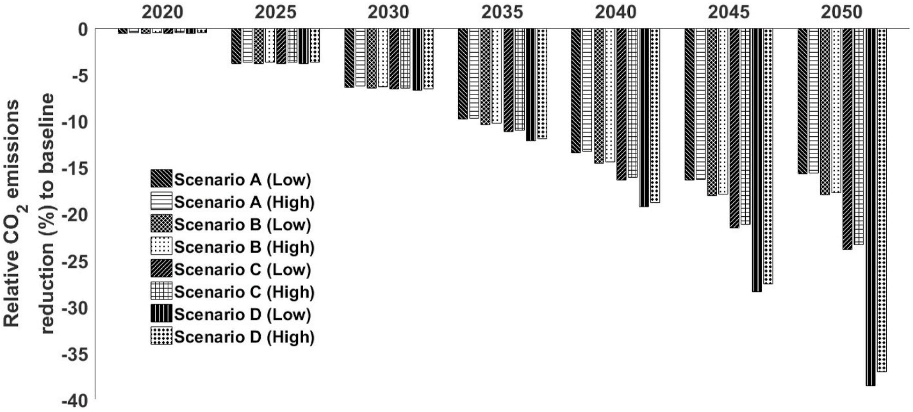


Fig. 12. Influence of feedstocks used to produce Sustainable Aviation Fuels on CO_2 emissions.

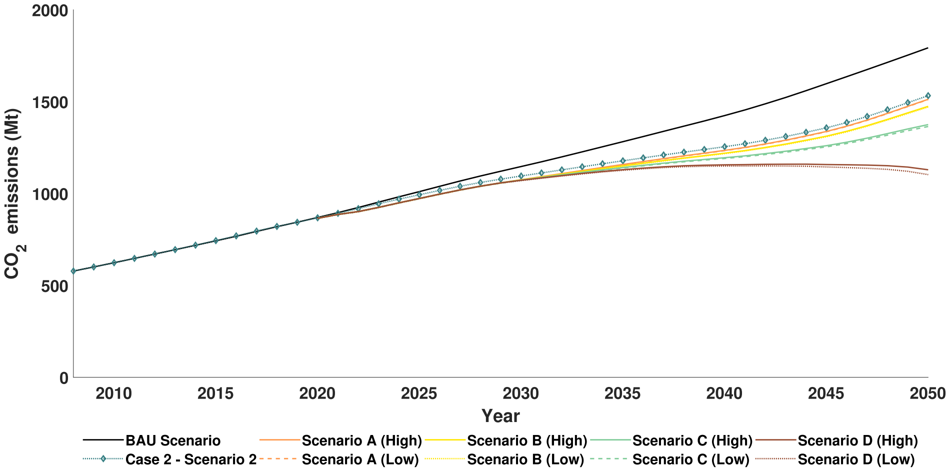


Fig. 13. CO_2 emissions trends for civil aviation considering the aircraft technologies of Scenario 2 on Case 2 with the Sustainable Aviation Fuels scenarios.

feedstocks and the production process used. The production processes and the feedstocks are very important to determine how much biofuels can really reduce CO_2 emissions. The results obtained show that:

1. The maximum reduction in CO_2 emissions possible relative to baseline is 15%, for the case of the new technological options;
2. The reductions in CO_2 induced by technologies take a few years to be possible to visualize the effect because of the slow penetration of these new aircraft in the global fleet;
3. The use of alternative fuels and counting on the introduction of technologies show that the capacity projected by ICAO in the production of SAF will have a very small effect on the emissions of CO_2. Only for the scenario that considers a high SAF production (Scenario D), it is possible to achieve carbon-neutral growth from 2040 onward. However, the results clearly show that it is not possible to obtain half of the emissions in 2050 of those recorded in 2005.

The question that arises with this work developed is whether new configurations and radical technologies that will enter in the global fleet along with biofuels will be sufficient to meet all the objectives proposed by IATA?

The area explored in the present work is extremely important for the various organizations responsible for the aeronautical sector and the companies representing this sector. This work is beneficial for evaluating the overall CO_2 emissions reduction resulting from introducing SAF in civil aviation and from the imminent aircraft technologies. Further research efforts should be contributed to assessing the impact of new aircraft design concepts and technologies, but also assessing the contribution of air traffic management and operations on reducing international aviation CO_2 emissions.

CRediT authorship contribution statement

Ivo Abrantes: Investigation, Formal analysis, results analysis and, Visualization, Writing – review & editing, Writing – original draft. **Ana F. Ferreira:** Methodology, Formal analysis, results analysis, Data curation, Validation, Visualization, Writing – review & editing, Writing – original draft, corresponding author. **André Silva:** Conceptualization, Methodology, Formal analysis, result analysis, Data curation, Validation, Visualization, Writing – review & editing, Writing – original draft, Supervision. **Mário Costa:** Conceptualization, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. SAF production capacity

Table A.5

SAF production capacity, Conversion Technology and Feedstocks.

Producer	Capacity [ton/year]	EIS	Conversion technology	Feedstocks	Blend limit %
PREEM	757406	2023	FT	Forest Residues	50
TOTAL	472629	2020	HEFA	Rapeseed, sunflower, soybean, oil palm, corn	50
ECB	724555	2022	HEFA	Soybean, animal fats and used cooking oil	50
Hollyfrontier	358053	2023	HEFA	Soybean oil	50
ST1 Oy	189052	2022	HEFA	Used Cooking oils	50
Diamond Green	1933484	2022	HEFA	Animal fats, used cooking oil	50
REG	214832	2020	HEFA	Used Cooking oils	50
Marathon	527053	2021	HEFA	Soybean oil	50
World Energy	876513	2021	HEFA	Animal fats, vegetable oils	50
Fulcrum	30124	2020	FT	Municipal Solid Waste (MSW)	50
GEVO	143	2020	ATJ	Isobutanol	30
GEVO	143297	2024	ATJ	Isobutanol	30
GEVO	286594	2029	ATJ	Isobutanol	30
Lanzatech	28659	2020	ATJ	Municipal Solid Waste (MSW)/Residual Biomass	30
Lanzatech	85978	2022	ATJ	Municipal Solid Waste (MSW)/Residual Biomass	30
RedRock	43321	2020	FT	Forest and sawmill residues	50
Velocys	57379	2020	FT	Woody biomass	50
LTU Greenfuels	500	2020	FT	Forest residues	50
LTU Greenfuels	50000	2022	FT	Forest residues	50
Caphenia	227	2024	FT	Recycling of organic residues (FT)	50
Neste	88797	2019	HEFA	Animal fats, used cooking oil	50
Neste	908021	2022	HEFA	Animal fats, used cooking oil	50
Neste	416200	2023	HEFA	Animal fats, used cooking oil	50
Lanzatech	75661	2021	ATJ	Municipal Solid Waste/Residual Biomass	30
Velocys	30411	2024	FT	Municipal Solid Waste	50
SAF plus consortium	22665	2025	FT	Forest Residues	50
Flexjet project	15181	2025	HEFA	Used Cooking oils	50
ENI	750000	2020	HEFA	Used vegetable oil	50

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