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Decarbonization of the Aviation Sector by 2050

(Versão final após defesa)

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> ”Believe you can and you’re halfway there”
>
> *Theodore Roosevelt*

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Resumo

A discussão sobre o impacto ambiental causado pela aviação ganhou maior destaque devido ao aumento da procura deste setor e, consequentemente, ao aumento do número de voos. As preocupações ambientais estimularam o desenvolvimento de novas abordagens para reduzir os poluentes e as emissões de CO_2. A IATA apresentou as metas para reduzir globalmente a quantidade de emissões produzidas pelo consumo de combustível. Para atingir estes objetivos, a IATA propõe uma estratégia baseada em quatro pilares. O presente trabalho fornece dados quantitativos para apoiar a tomada de decisões para o primeiro pilar desta estratégia, que consiste em melhorar a tecnologia, incluindo a implementação de combustíveis alternativos sustentáveis. Futuras tecnologias para aeronaves são identificadas através de uma revisão da literatura. Alguns dos conceitos mais promissores para uma aplicação a médio prazo são escoamento laminar natural, nova arquitetura dos motores, aeronave de asa fixa sem uma linha divisória clara entre as asas e a fuselagem, asa reforçada, ingestão da camada limite, fuselagem de dupla cabine e propulsão elétrica. Neste sentido, o presente trabalho avalia e quantifica o impacto da introdução destas novas tecnologias, bem como a introdução de combustíveis sustentáveis para a aviação na redução das emissões de CO_2. Assim, são utilizadas duas metodologias, um modelo numérico (FSDM) para prever o consumo de combustível e emissões de CO_2 para a frota global de transporte aéreo. Para a análise do combustível de aviação sustentável (SAF) é desenvolvida uma abordagem que considera, além da produção de SAF, as matérias-primas e o processo de produção. São estabelecidos quatro casos e seis cenários para representar as melhorias tecnológicas e quantificar os efeitos dos novos conceitos e tecnologias para as aeronaves nas futuras emissões de CO_2. Para a análise dos SAF são estabelecidos quatro cenários e duas condições para avaliar as diferentes capacidades de produção e matérias-primas. É considerado o efeito combinado das tecnologias com os SAF para verificar se os objetivos propostos pela IATA são alcançados, nomeadamente, um crescimento neutro em carbono a partir de 2020 e uma redução de 50% das emissões em 2050 em relação aos níveis registados em 2005. Os resultados da avaliação revelam que os objectivos não podem ser atingidos, apenas, com a ação combinada das tecnologias e a utilização de combustíveis alternativos. O crescimento neutro em carbono só é alcançado quando se considera o efeito combinado das tecnologias com o cenário em que a quantidade de combustível sustentável para a aviação introduzido é mais elevado (um aumento de 15% por ano entre 2030 e 2050). No entanto, este crescimento neutro em carbono só é possível começar entre 2038 e 2045, dependendo do cenário considerado para o progresso tecnológico.

Palavras-chave

Aviação, Emissões de CO_2, Modelação, Aeronaves, Tecnologias, Cenários, SAF.

Abstract

The discussion about the environmental impact caused by aviation has gained greater prominence due to the increased demand for this sector and, consequently, the increase in the number of flights. Environmental concerns have stimulated the development of novel approaches to reduce pollutants and CO_2 emissions. IATA presented the goals to globally reduce the amount of emissions produced by jet fuel consumption. In order to achieve these goals, IATA proposes a strategy based on four pillars. The present work provides quantitative data to support decision making for the first pillar of IATA strategy, which is to improve technology, including the deployment of sustainable low-carbon fuels. Future aircraft technologies are identified through a literature review. Some of the most promising concepts for a medium-term application are natural laminar flow, new engine architecture, blended wing body, strut-braced wing, boundary layer ingestion, double-bubble fuselage, and electric propulsion. In this sense, the present work evaluates and quantifies the impact of introducing new aircraft technologies, as well as the introduction of Sustainable Aviation Fuels (SAF) on the reductions of CO_2 emissions. Therefore, two methodologies are used, a numerical model (FSDM) to forecast fuel consumption and CO_2 emissions from the global air transport fleet. For the analysis of sustainable aviation fuel (SAF) an approach is developed that considers, besides the SAF production, the feedstocks and the production pathway. Four cases and six scenarios are established to represent the technological improvements and to quantify the effects of new aircraft concepts and technologies on the future CO_2 emissions. For the analysis of SAF, four scenarios and two conditions are established to assess the different production capacities and feedstocks. The combined effect of technologies with SAF is considered verifying if the goals proposed by IATA, namely, 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 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 Sustainable Aviation Fuels introduced is higher (an increase of 15% annually between 2030 to 2050). However, this carbon-neutral growth is only possible to start between 2038 to 2045, depending on each scenario considered for technological improvements.

Keywords

Aviation, CO_2 Emissions, Modeling, Aircraft, Technologies, Scenarios, SAF.

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List of Acronyms

ATAG	Air Transport Action Group
ATM	Air Traffic Management
AIM	Aviation Integrated Model
AEDT	Aviation Environmental Design Tool
AERO	Aviation Emission and Evaluation Options
AIRCAT	Assessment of the Impact of Radical Climate-Friendly Aviation Technologies
ATK	Available Tonne Kilometer
ASK	Available Seat Kilometer
APF	Airline Procedures File
ATJ	Alcholol-to-jet
ASTM	American Society for Testing and Materials
ARIMA	Auto-Regressive Integrated Moving Average
ARMA	Auto-Regressive Moving Average
AR	Auto-Regressive Model
BAU	Business As Usual
BADA	Base of Aircraft Data
BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CDC	Centers for Disease Control and Prevention
CHJ	Catalytic Hydrothermolysis Jet
CMO	Commercial Market Outlook
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus Disease 2019
CROR	Counter Rotating Open Rotor
DTI	Department of Trade and Industry
DLR	German Aerospace Center
EDMS	Emissions and Dispersion Modeling System
EIS	Entry-into-Service
EI	Emission Index
EIA	U.S. Energy Information Administration
EU	European Union
EU ETS	European Union Emissions Trading System
ERA	Environmentally Responsible Aviation
FAA	US Federal Aviation Administration
FATE	Four-dimensional Calculation of Aircraft Trajectories and Emissions
FAST	Future Aviation Scenario Tool
FAP	Fleet Assignment Problem
FCECT	Fuel Consumption and Emissions Calculation Tool

FFWD	Fast Foward
FT	Fischer-Tropsch
FSDM	Fleet System Dynamics Model
FLEET	Fleet Level Environmental Tool
FEGP	Fixed Electrical Ground Power
FRL	Fuel Readiness Level
GDP	Gross Domestic Product
GE	General Electric
GMF	Global Market Forecast
GFMC	Global Fleet Mission Calculator
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HC	Hydrocarbon
HFS	Hydroprocessing of Fermented Sugars
HWB	Hybrid Wing Body
HEFA	Hydro-processed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
INM	Integrated Noise Model
LCA	Life Cycle Analysis
LTA	Large Twin-aisle Aircraft
MAGENTA	Model for Assessing Global Exposure to the Noise of Transport Aircraft
MA	Moving Average Model
MAPE	Mean Absolute Percentage Error
MMT	Million Metric Tons
MSW	Municipal Solid Wastes
NextGen	Next Generation Air Transportation System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
OAG	Official Airline Guide
OPF	Operations Performance File
PCA	Pre-Conditioned Air
PFC	Propulsive Fuselage Concept
PW	Pratt & Whitney
RPK	Revenue Passenger Kilometer
RTK	Revenue Tonne Kilometer
RED	Renewable Energy Directive
RMSE	Root Mean Square of Error
RFS	Renewable Fuel Standard
RLD	Netherlands Department of Civil Aviation

SA	Single-aisle
SAGE	System for Assessing Aviation Global Emissions
SAF	Sustainable Aviation Fuel
SBW	Strut-braced Wing
SESAR	Single European Sky ATM Research
SIP	Synthesized Iso-Paraffins
SMC	Single Mission Calculation
SPC	Single Production Capacity
SPK	Synthesized Paraffinic Kerosene
SRES	Special Report on Emissions Scenarios
SARS	Severe Acute Respiratory Syndrome
SUGAR	Subsonic Ultra Green Aircraft Research
TA	Twin-aisle
TPC	Total Production Capacity
TRL	Technology Readiness Level
TU	Technical University
TSFC	Thrust Specific Fuel Consumption Coefficients
USSR	Union of Soviet Socialist Republics

Nomenclature

Symbols in Latin script

A	Actual value	–
a	Age of aircraft	$year$
ASK	Transport supply (passengers)	$seat \cdot km$
ATK	Transport supply (freight)	$ton \cdot km$
BH	Block hours	h
d	Great circle distance between an O-D pair	km
D	Number of nonseasonal differences needed for stationarity	–
EI	Emission index of CO_2	–
e	Innovation, shock or error term	–
F	Forecast value	–
f	Number of flight frequencies	–
flf	Freight load factor	%
MH	Maintenance hours	h
n	Number of aircraft units	–
P	Number of autoregressive terms	–
p	Number of passengers transported	–
POS	Percentage of survival	%
Q	Number of lagged forecast errors in the prediction equation	–

RPK	Transport demand (passengers)	$seat \cdot km$
RTK	Transport demand (freight)	$ton \cdot km$
s	Number of seats	$seat$
slf	Seat load factor	%
T	Tons of freight capacity	ton
TH	Turn-around hours	h
UH	Utilization hours	h
x	Observed output	Mt
X	Average number of carbon atoms	–
Y	Average number of hydrogen atoms	–

Symbols in Greek script

α	MH/BH-ratio	–
β	Retirement coefficient	–
θ	Parameter of the moving-average component model	–
ϕ	Parameter of the auto-regressive component model	–
μ	Long run average	–

Table of subscripts

i	One particular route of the airline's routes network
j	One particular aircraft unit of the airline's fleet
1	First retirement coefficient

11	Second retirement coefficient
k	One particular flight
max	Maximum value possible
t	Year of simulation

Chapter 1

Introduction

Firstly, in this chapter, the growth of aviation sector and the emissions from air traffic will be presented in order to explain the importance of the present work. Thereafter, the proposed climate goals for aviation by 2050 are presented, to further compare with the results and to verify if these goals can whether or not be met. Finally, the research scope of this work and the organization of this dissertation are presented.

1.1 Background and Motivation

Aviation is the only rapid transport network in the world, being indispensable for economic development, tourism and facilitates world trade. Air transport improves quality of life in countless ways, such as:

- Creating jobs and generating wealth;
- Connects people and ideas, brings together family and friends, promotes tourism and local business;
- Stimulates investment and integration into global production and trade chains, sustainably integrate small and remote communities;
- Promotes access to social and health resources, and allows in emergency cases to provide all necessary care.

Commercial aviation had a very distinct evolution since the 1940s, from the *jet age*, where it was possible to travel at higher speeds and higher altitudes, allowing to fly above the weather and resulting in shorter and more comfortable trips. Until today, aviation remains one of the essential means of transport. This development was accomplished by an increase in air travel demand. In 1960, the number of passengers was about 100 million, rising to 1 billion in 1987. The higher growth was seen at the beginning of 2020, reaching 4 billion passengers in 2018. As the economies expand and more people begin to travel, it is expected that these growths will continue mainly in regions such as China, South Asia and Southeast Asia [2].

According to Figure 1.1, the air travel industry has emerged stronger from all previous external shocks. Since the beginning of the year 2000 the main global shocks that happened was the terrorist attack on World Trade Center (2001) and the financial crisis in 2008/2009, at the regional level the main shock was in Asia, the SARS outbreak. These shocks were accompanied by a jump, with air traffic managing to return to its long-term trend. From 2010, this type of disturbances did not affect the industry and it was possible to meet the need for the number of passengers. The current outbreak of COVID-19 is an unprecedented event in

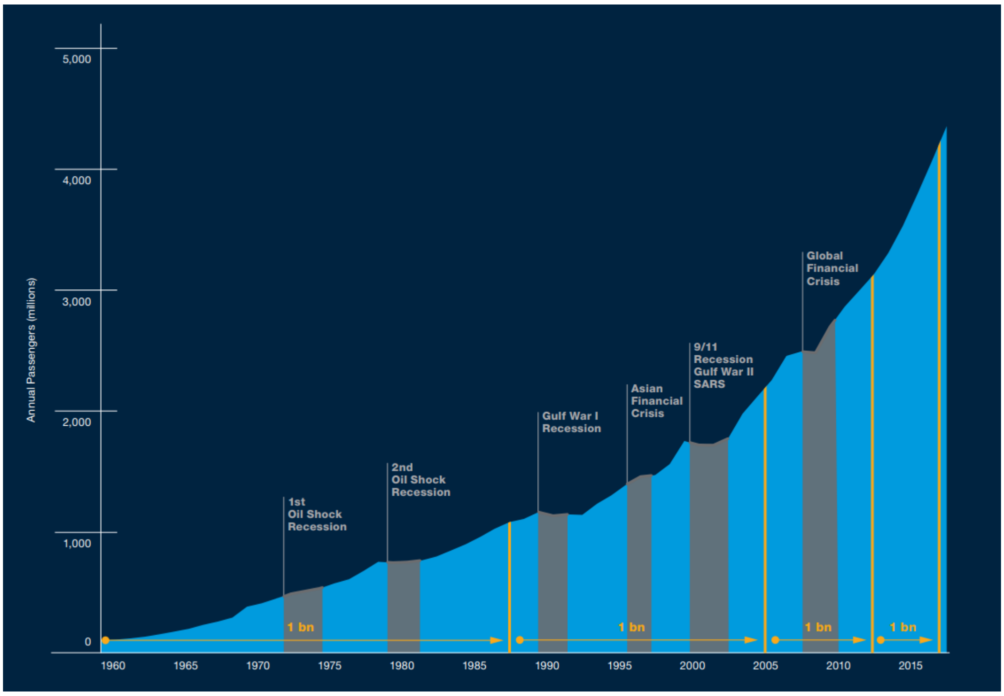


Figure 1.1: Air travel resilient despite financial and geopolitical challenges [2].

air transportation. Aviation is one of the industries that have been suffering most due to the consequences of the pandemic outbreak, although probably being one of its largest initial drivers. According to Czerny et al. [3], 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 ICAO data published in December 2020, the number of cargo flights has an increase of 1.44% compared to the numbers in the previous year [4]. The first aviation market hit hard by COVID-19 was 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 [3]. All aviation markets as China will recover as the pandemic begins to come under control. Some vaccines are already approved and have been proven by US Centers for Disease Control and Prevention (CDC) that most viruses and other germs do not spread easily on flights because of how air circulates and is filtered on airplanes [5].

Airlines since 2015 have made almost the same profit as between 1970 and 2014. Airbus's Global Market Forecast (GMF) predicts traffic will double over the next 15 years, with average air traffic growth of 4.3% over the next 20 years. At the beginning of 2009, the number of aircraft was 22,680, the expected number of aircraft in 2038 is 47,680. As seen in Figure 1.2, 14,210 aircraft are expected to be replaced by 2038, and it is expected a growth of 25,000 aircraft [6].

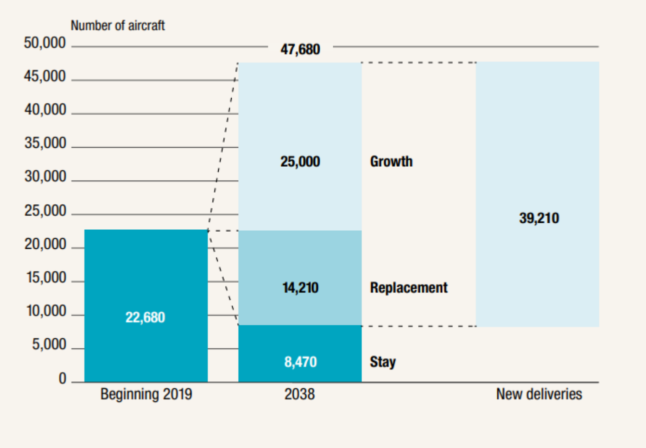


Figure 1.2: Demand for new aircraft by 2038 [6].

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 have an impact on the local air quality and the global atmosphere. The main emissions emitted by aircraft engines in operations are carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), unburnt hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and water vapor (H_2O) [7]. Figure 1.3 shows the pollutants emitted by aircraft jet engines.

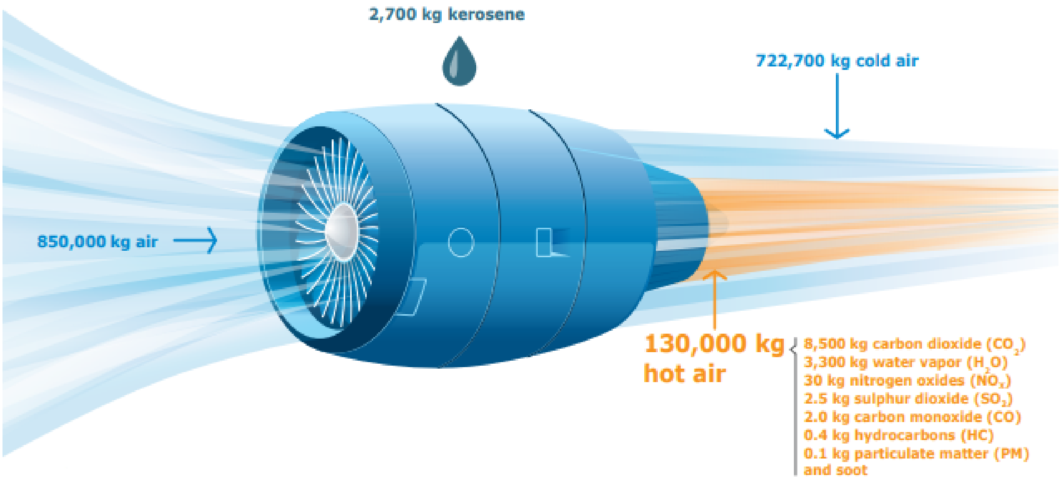


Figure 1.3: Emissions from a typical two-engine jet aircraft during 1-hour flight with 150 passengers [8].

Emissions from aircraft engines affect the radiative balance of the atmosphere. The direct emissions of greenhouse gas carbon dioxide (CO_2), which has a long lifetime in the atmosphere plays an important role in climate change [9]. Carbon dioxide causes the so-called Greenhouse Effect, whose consequences on the climate are being felt recently, and could reach dramatic proportions if the current energy policies are not changed. Global warning's direct consequences are the rising seawater levels due to the thawing of polar caps and changes in precipitation [10]. Carbon dioxide is considered the most important greenhouse gas emitted by aircraft, since aviation is responsible for 2.4% of global CO_2 emissions due to fossil fuel consumption. In 2018, considering all commercial operations, including passenger movement, cargo and mail, 918 million metric tons (MMT) of CO_2 were emitted [11].

In 2008, all the global aviation stakeholders, within the scope of the Air Transport Action Group (ATAG), in order to meet the global challenge of climate change have adopted three major development milestones for the period between 2009 and 2050:

- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth);
- A reduction in CO_2 emissions of 50% by 2050, compared to 2005 levels;
- An average improvement in fuel efficiency (CO_2 per Revenue Tonne Kilometre) of 1.5% per year from 2009 to 2020.

To be able to achieve these goals, the International Air Transport Association (IATA) introduced a possible strategy to help achieving these goals. All stakeholders agreed to follow the "four-pillar strategy" composed of improved technology, more efficient aircraft operations, infrastructure improvements (modernized air traffic management systems) and positive economic measures (single global market-based measure, to fill the remaining emissions gap) [8].

With this growth of the aviation sector reported, the CO_2 emissions will increase if strategies in the industry are not changed. Therefore, it will be necessary to evaluate which best long-term solutions will have to make to reduce the impact caused by aviation and if the climate goals proposed can be met. The motivation of the present work results from the necessity of providing quantitative data for decision-making.

1.2 Research Scope and Goals of Dissertation

The primary objective of the present work is to estimate the contribution of the latest and most important generations of aircraft, new technologies and also the contribution of alternative fuels that have already been approved so far to reduce fuel consumption and CO_2 emissions. To achieve this primary goal, the following sub-ordinate, consecutive objectives are set:

1. Identify the key drivers to decarbonize the aviation sector,
2. Identify general approaches to aviation emissions calculation,
3. Review of future technologies to reduce aircraft CO_2 emissions and alternative aviation fuels,
4. Apply air transport system modeling in order to assess the new technologies,
5. Develop the model to assess the impact of alternative aviation fuels on global aviation emissions.

1.3 Organization of the Dissertation

The work presented in this dissertation is divided into six chapters. **Chapter 1** consists foremost in depicts the motivation and goals of the dissertation and additionally provides background information regarding aviation growth and its adverse impact on the environment.

Chapter 2 provides an introduction of the key drivers that allow reducing the CO_2 emissions in the aviation sector. This chapter also reviews the models and the works published so far to assess the progress of the aeronautical sector in mitigating CO_2 emissions considering various strategies.

Chapter 3 describes the approach of the whole process to calculate aviation emissions up to 2050. Firstly, it is presented the statistic model used in the preliminary phase for calculating the CO_2 emissions for *Business as Usual* scenario. Thereafter, it includes the description of the numerical model Fleet System Dynamics employed to assess the technology progress. Finally, it presents potential future technologies for CO_2 reduction and the scenario planning performed in the present work.

Chapter 4 presents the approach to determine the potential fuel burn savings with the introduction of sustainable aviation fuels.

Chapter 5 presents the main findings and results of this dissertation.

Finally, **Chapter 6** features concluding remarks providing a working balance of what has been achieved in this dissertation. Coupled with that, there are also recommendations for future works.

This dissertation has five appendices that provide the detailed data used to perform the present work and the quantitative results achieved. **Appendix A** gives detailed information on sustainable aviation fuels production capacity, conversion technology and feedstocks. **Appendix B** provides the data used to perform the simulations with the Fleet System Dynamics Model. **Appendix C** provides the validation of fuel efficiency for the aircraft and new technologies analyzed in the present work. **Appendix D** presents the CO_2 emissions results achieved with ARIMA model for all regions. **Appendix E** presents the CO_2 emissions results of global fleet.

Chapter 2

State-of-the-art

This chapter provides an introduction into the understanding of the key drivers that allow to reduce the CO_2 emissions in aviation sector. The most important factors are described highlighting the main options that will allow reducing environmental impacts. However, the focus of this work is the analysis of technologies and biofuels. Assessing the possible emissions reduction that newly implemented technologies and new aircraft can deliver, requires consideration of the entire air transport system and its future development. In this sense, it is necessary to use a model capable of anticipating the future economic development of the airline industry, the development of the air transport system and estimating the performance of air transport in terms of emissions and fuel consumption. This chapter presents existing models with these capabilities. Finally, the chapter reviews the most relevant research work to approach goals similar to the ones of this dissertation.

2.1 Main Factors Influencing the Decarbonization of the Aviation Sector

Nowadays, concerns about rising emissions and climate change have raised the issue of decarbonization. The term decarbonization has been used to describe the gradual elimination of carbon dioxide emissions. The focus of the energy industry on decarbonization has increased exponentially and several companies have changed their strategies to take into account climate effects. The same has happened in the aeronautical sector, adopting various measures to reduce the environmental impact.

The main development strategies for the aviation sector in order to meet the proposed climate objectives are the development of new technologies and increase the efficiency of existing aircraft, optimize air traffic control operations, improve infrastructure to reduce local environmental impact, application of economic measures to pressure companies to reduce emissions, and finally adding biofuels with a reduced carbon life cycle. Figure 2.1 represents schematically the influence that these strategies can produce to meet the climate objectives. The following subsections present the main measures that will be implemented in each area.

2.1.1 Operations

According to ATAG, about 8% of all aviation fuel is lost due to inefficient aircraft routes, therefore, improving the performance of air operations is one of the measures to reduce CO_2 emissions. To improve Air Traffic Management (ATM) performance there are two programs:

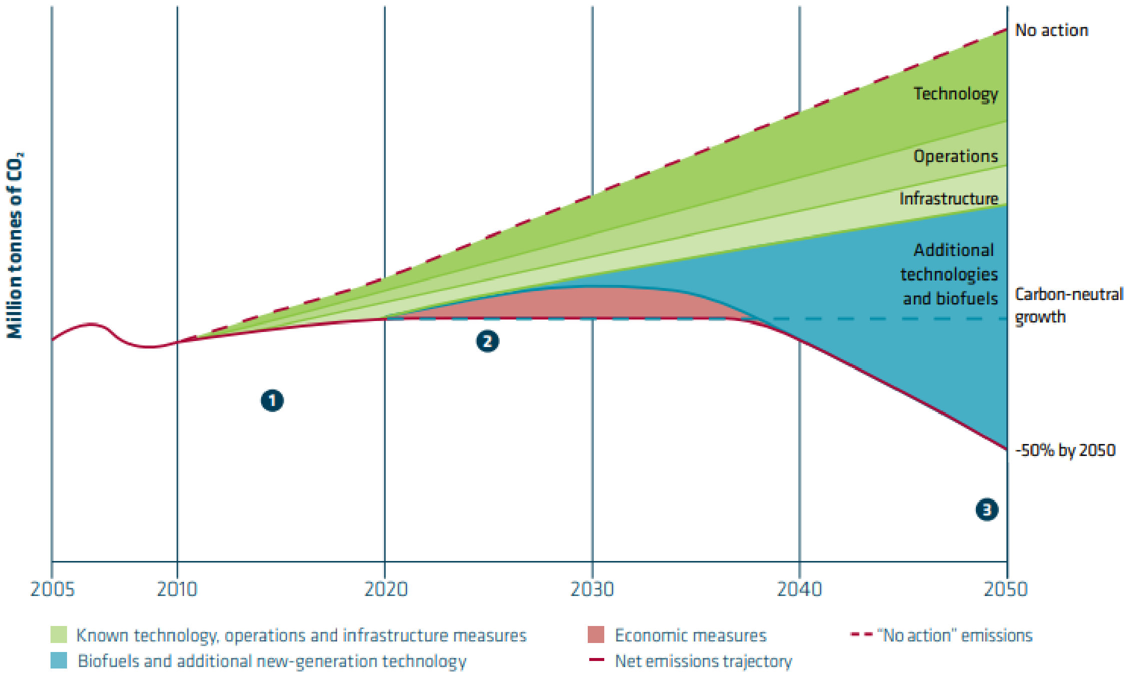


Figure 2.1: Air transport emissions reduction goals and measures [12].

the Single European Sky ATM Research (SESAR), which is intended for the European Union, and The Next Generation Air Transportation System (NextGen) for the United States. These programs will increase the efficiency of operations with the implementation and execution of new procedures and new technologies used in ATM [12]. Hassan and Mavris [13] demonstrated that operational improvements allow a substantial reduction in CO_2 emissions, in addition, this improvement allows an immediate impact on global fuel consumption when applied.

2.1.2 Infrastructures

Infrastructures have played a very active role in improving environmental performance in several areas. The main measures applied to combat environmental impact are: renovation of vehicles used in airports, opting for electric vehicles or powered by biofuels, airports that produce sustainable energy, provide Fixed Electrical Ground Power (FEGP) and Pre-Conditioned Air (PCA) to the aircraft at the airport gate to reduce emissions, and development of improved public transport systems to reduce the use of individual vehicles to improve local air quality [8].

2.1.3 Economic Measures

Economic Measures are part of the approach to reduce emissions. These include both cap and trading additionally as offsetting schemes are designed to mitigate global climate change through in-sector emissions reduction or through incentivizing efforts outside of the aviation sector [8]. The main measures are EU Emissions Trading System (EU ETS) which has been introduced in 2012 for aviation and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as agreed on the level of the International Civil Aviation Organization (ICAO) in October 2016 [14].

2.1.4 Technology

The aviation industry is involved in the development of new technologies in some areas, including aerodynamics, propulsion, structures and systems. New aircraft concepts and innovations have started the certification process to be used commercially in order to meet the environmental challenges of the sector. An in-depth analysis will be needed to assess the impact that these new technologies could have compared to conventional aircraft, in order to see what capacity the technologies could have in mitigating CO_2 emissions. The technologies expected to be implemented in the air fleet are mainly new aircraft engines, hybrid and electric propulsion, strut-braced wing, boundary layer ingestion, double-bubble fuselage, natural laminar flow, and blended wing body. The methodology used to analyze the reduction in fuel consumption that these new technologies could bring will be presented in Chapter 3.

2.1.5 Alternative Aviation Fuels

The need to reduce emissions in the short term has led to the development and research of new alternative fuels for use in commercial aviation. Numerous industrial initiatives have emerged to discover alternative ways of obtaining bio-aviation fuels. These initiatives have led to an increase in research into alternative aviation fuels made from biomass in recent years. The main focus has been on biofuels since they can replace jet fuel without further modifications in existing aircraft engines [15]. So far, seven production processes are certified for the production of sustainable aviation fuels. The seven processes to produce sustainable aviation fuel for commercial aviation are Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene, Hydroprocessed Esters and Fatty Acids, Synthesized Iso-Paraffins, Fischer-Tropsch Synthesized Paraffinic Kerosene with Aromatics, Alcohol-to-Jet Synthetic Paraffinic Kerosene , Catalytic Hydrothermolysis, and Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids. The detailed analysis of biofuels carried out in the present work will be presented in Chapter 4.

2.2 Relevant Work in the Field

Infrastructures, operations, and economic measures are factors that allow a substantial reduction of emissions caused by the aeronautical sector. However, the present work is focused on evaluating the influence of alternative fuels and new implemented technologies in commercial aviation. This section presents the works that have been published by other institutions to assess the progress that the aeronautical sector should make by mitigating CO_2 emissions considering various strategies. The literature review to support this work was set up by dividing the various studies according to their objectives, and the models that have been included in the following section represent a spectrum of modeling approaches to quantify the fuel burn and emissions from global air traffic.

2.2.1 Models for Aviation Emissions Calculation

The need to study the use of aircraft and simultaneously predict the environmental impact of aviation has motivated the development of models/tools to assess the impact of new aircraft concepts and technologies on emissions reduction.

2.2.1.1 FAST - Future Aviation Scenario Tool

The development of the Future Aviation Scenario Tool started in 1990, in the UK Department of Trade and Industry (DTI), and was subsequently used in the European Union (EU) Fifth Framework Programme, TRADEOFF. In this project, FAST was used to calculate global civil aviation emissions for 1992 and projections for 2000, allowing the assessment of aviation impacts, namely the emissions of NO_X, O_3 and CH_4. The FAST system consists on a data set of aircraft movements for one year, this indicates the frequency of flights of a specific aircraft type between O-D pairs (Origin-Destination). Using this database, the aircraft were grouped by the specific type (Large Commercial Aircraft, Regional Jets, Low Thrust Jets, and Turbo-props). For the calculation of aircraft performance, a separate model (PIANO) is used. This provides data on fuel flow for specific aircraft/mission combinations using standard assumptions of load factor and fuel reserves. The calculation of fuel burn considers the departure and arrival location, linked by the great circle distance. It then allocates the emissions into a 3D grid of variable resolution (in latitude longitude and height) [16].

2.2.1.2 AERO - Aviation Emission and Evaluation of Reduction Options

The initiative to develop the AERO modeling system came from the Netherlands Department of Civil Aviation (RLD) of the Netherlands Ministry of Transport, Public Works and Water Management in 1993. The model AERO allows evaluating options for emissions reduction at a global or local level. This model also offers the possibility of comparing the costs of the reduction options. The reduction options that the model allow to analyze include operational, technical, and economic measures. Regarding operational conditions, it is possible to analyze the following options such as flying at lower altitudes, flying using other routes, flying according to other procedures of ascending and descending, flying at lower speeds, and improvement air traffic control. In the case of technical measures the possible options are to analyze strict rules for NOx emissions or the introduction of CO_2 standards. Finally, for the case of economic measures, it is possible to analyze the introduction of excise duties on kerosene and taxes on tickets at the regional or global level [17].

2.2.1.3 AERO2k

The AERO2k tool was developed in the EU Fifth Framework Programme, with the purpose of providing improved methodologies and analytical tools that allow novel and improved evaluations of aircraft emissions on the global atmosphere. To provide new aviation emissions data, AERO2k used the available information on civil and military flights in 2002. The model can consider 40 representative aircraft. The fuel burn for each flight is calculated using performance data from the aircraft performance tool PIANO. The emissions are calculated, using the available information on emissions factors and based on aircraft altitude, weight, and speed, throughout the flight. The calculated emissions corresponding to each flight simulation are then summarized to form fleet-wide quantities that are eventually allocated to one of more than 3 million single cells on a 3D grid of the world globe [18].

2.2.1.4 SAGE - System for Assessing Aviation Global Emissions

The US Federal Aviation Administration (FAA), in 2001, started the development of a new computer model, the System for assessing Aviation's Global Emissions (SAGE), to provide global inventories of commercial aircraft fuel burn and emissions of various pollutants to serve as the basis for scenario modeling. The growth in aviation and the need to clarify emissions modeling capabilities on a global level stimulated the development of SAGE. The SAGE methodology consists of modeling each flight, which allows high-fidelity modeling of global burn and fuel emissions inventories, as all commercial flights worldwide for each day of the year are simulated. SAGE includes approximately 30 million commercial flights per year and accounts for over 200 different aircraft types [19].

2.2.1.5 AEDT - Aviation Environmental Design Tool

Aviation Environmental Design Tool (AEDT) is a software system developed by the FAA with the purpose of modeling aircraft performance to estimate fuel consumption, emissions, noise, and air quality consequences. The central system of AEDT is based on four emissions modeling applications: Integrated Noise Model (INM) – local noise; Emissions and Dispersion Modeling System (EDMS)– local emissions; Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA)– global noise; and the SAGE that is presented in the section above. AEDT has the capability of processing individual investigations from a single flight at an airport to scenarios at the regional, national, and global levels. This system includes a database of over 4,000 airframe-engine combinations and runway information for over 30,000 airports around the globe. With this database system, the AEDT is capable of quickly building studies and estimate the interdependencies between noise, fuel consumption, and emissions consequences of aviation activity [20].

2.2.1.6 AIM - Aviation Integrated Model

Aviation Integrated Model (AIM) is a global aviation policy assessment tool in development since 2007. It allows comprehensive analyses of aviation, environment, and economic interactions at both local and global levels. AIM is composed of seven modules inter-linked which allows modeling the global aviation system. These modules include an Aircraft Technology & Cost Module, an Air Transport Demand Module, an Airport Activity Module, an Aircraft Movement Module, a Global Climate Module, a Local Air Quality & Noise Module, and a Regional Economics Module. The AIM architecture leads to several benefits, such as temporal and spatial resolution can be tailored to the application, modules can be run independently and allows extensions and developments of the capabilities of different modules. The module that allows assessing the impact of technology is the ”Aircraft Technology & Cost Module”, which simulates fuel burn, emissions, and operating costs by stage length and load factor for airframe and engine technologies to 2050. The fleet is grouped into three categories based on size (<199 seats; 190-330 seats; >300 seats). One of the capabilities of this model is to capture the feasibility of possible future technological improvements [21].

2.2.1.7 FLEET - Fleet Level Environmental Tool

The Fleet-Level Environmental Evaluation Tool (FLEET) is a computational simulation tool developed at Purdue University to assess how aviation's fleet-level environmental impacts evolve over time. The central approach of FLEET is based on an aircraft allocation model that represents airline operations and decision-making. Additionally, the tool has a system dynamics approach that reproduces the economics of airline operations, models the airline's decisions regarding retirement and acquisition of aircraft, and represents passenger demand growth in response to economic conditions. The principal objective of the FLEET is to enable an understanding of how varying external factors such as market conditions, policy implementation, and technology availability will affect aviation environmental impacts into the future [22, 23].

2.2.1.8 FFWD - Fast Foward

The German Aerospace Center (DLR) developed the model FFWD to make a quantitative assessment of the contribution of future aircraft concepts to the CO_2 emission reduction goals on the global fleet-level by 2050. FFWD methodology consists of two separate modules. The first module determines the evolution of the world fleet of commercial passenger aircraft. The second module is intended to forecast the evolution of fuel and CO_2 efficiency based on fuel consumption and performance information of each aircraft model. The global CO_2 emissions and traffic are calculated by aggregating the single aircraft estimates [24].

2.2.1.9 FATE - Four-dimensional Calculation of Aircraft Trajectories and Emissions

The FATE model was developed in the DLR Institute of Transport Research to be able to produce air traffic movements and emissions inventories with a four-dimensional resolution. FATE was one of the first programs in the world with the capability of producing four-dimensional air traffic inventories with waypoint accuracy [25]. Schafer [26] in 2012 within the scope of DLR, created a simulation tool to quantify gaseous emissions from air traffic and to forecast emissions in the short-term and medium-term future. This simulation tool uses some existing software, besides the ones that have been specifically developed for this tool, namely, the VarCycle engine performance tool and the FATE software. The model essentially consists of three modules, an air-traffic-forecasting module, a route-network model, and an aircraft-performance module. The methodology to quantify fuel burn and emissions of global aviation consists of using a bottom approach where the fuel burn and emissions of air traffic are calculated for each flight [26].

2.2.1.10 Hollingsworth, Pfaender and Jimenez Method

Hollingsworth et al. [27] presented a method for assessing the environmental benefit of future aviation technologies. This method was developed to provide a fast evaluation with a range of technologies and future vehicle concepts. This fast assessment is achieved due to the parametric approach presented. This approach has several advantages, such as reducing computational and storage requirements, making the implementation of technologies more practical, and allowing a significant reduction in simulation time. This method for modeling fuel burn and aircraft emissions uses the Aviation Environmental Design Tool (AEDT) [20] and *Boeing Fuel Flow Method 2* [28], respectively.

2.2.1.11 Model used in the present work - FSDM

In order to accomplish the present work, it was necessary to evaluate all the models mentioned above, taking into account certain factors such as the possible simulation period up to 2050, the possibility to quantify the emissions globally, the implementation of new technologies, and a model consistent with the published data.

The model used was the FSDM - Fleet System Dynamics Model [1], developed by Dr. Randt [1] at the Institute of Aircraft Design of Technical University (TU) of Munich, since within the models analyzed it contained all the requirements for the present work. The specifications and the changes made to the FSDM are described in chapter 3.

A different feature of the FSDM model compared to the other more recent models is the way it groups the aircraft to perform the simulations, as it is not possible to simulate all the aircraft that exist in the aeronautical sector, so these models simplify the problem by grouping the aircraft, for example according to capacity or type of aircraft (single-aisle or twin-aisle). Most of the models mentioned above use the capacity of each aircraft type to group aircraft. Although this approach represents well the overall fleet in terms of transport capacity, it does not represent the fleet in terms of technological and operational performance characteristics. Technical representation of the global fleet is fundamental to the proposed objectives of the present work concerning technology assessment.

2.2.2 Global Air Traffic Emissions Scenarios

Several studies have investigated the introduction of new technologies, aircraft configurations, operational improvements and new alternative fuels, determining the impact produced by these at the level of fleet emissions, using the models mentioned above. The most recent studies assessed the viability of CO_2 emissions targets combining the following factors technological improvements only, technological improvements & alternative aviation fuels, and operations & technological improvements.

2.2.2.1 Technological Improvements Scenarios

The works of Owen et al. [29], Randt et al. [30], Terekhov et al. [31], and Jimenez et al. [32] focused only on the investigation of the newly implemented technologies. Owen et al. [29] reported the methodology and results for the calculation of future global emissions of carbon dioxide and NO_x from air traffic by 2050, with an additional perspective by 2100. The four scenarios created by the IPCC/SRES (Intergovernmental Panel on Climate Change / Report A1B, A2, B1 and B2) was analyzed. The model used to calculate emissions for the various scenarios was the FAST. The results in this study showed that aviation contributed with 677 Tg of CO_2 emissions in 2000, that is 12% of total transport CO_2 emissions. In 2100, aviation is expected to contribute between 723 and 5067 Tg of CO_2 emissions, compared with total SRES Transport of between 9656 and 20 773 Tg of CO_2 emissions. Emissions of CO_2 from aviation between 2000 and 2050 are projected to grow between a factor of 2.0 and 3.6, depending on the scenario.

Jimenez et al. [32] presented a method for assessing the impact of vehicle technologies and new aircraft concepts similar to the approach of Hollingsworth et al. [27] and reported a quantitative assessment of vehicle concepts and technologies from Environmentally Responsible Aviation (ERA) project. Seven scenarios were defined to enable the quantitative characterization of air transport improvements resulting from the introduction of ERA concepts and technologies. The results showed that the introduction of National Aeronautics and Space Administration (NASA) vehicle technologies into the fleet in 2025 can reduce almost 436.5 Mt of fuel burned by 2050, assuming a 2050 total fuel-burn cap at 2006 levels.

Randt et al. [30] investigated the impact of new generations of aircraft on the fuel demand of the global commercial air transport fleet and analyzed the gap between the emissions produced and the proposed climate targets for aviation. The model used was the FSDM. Three technological scenarios representing the developments of the next-generation aircraft were evaluated. The results obtained show that the IATA goals cannot be reached only with the integration of next-generation aircraft types in the global fleet.

Terekhov et al. [31] presented the prediction model of the world fleet FFWD (*Fast Forward*), that allows predicting the world fuel consumption and CO_2 emissions. This forecast is based on current demand forecasts, fleet data, retirement curves, aircraft expected entry and markets penetration. The model FFWD requires some databases due to the different information needed. The size of the aircraft, use of the aircraft, number of aircraft in service and year of production of aircraft operated by airlines, were taken from the Ascend database. Two scenarios were considered, in the first scenario is only considered the first new generation of aircraft, there is no introduction of any new aircraft program (hypothetical). The second scenario considers the use of conventional fuel and additional improvements through the new aircraft configurations (aircraft and engine), for each aircraft program, is always combined an aircraft configuration and an engine configuration. The results in this study showed that considering the maximum of technological assumptions in 2030 it will be possible to have carbon-neutral growth.

The main conclusions of the mentioned studies, reveal that the new technologies implemented have a slow penetration in the market by nature, and this weakly contributes to the required CO_2 emissions reduction. Further reductions will have to come from other parts, mainly from sustainable alternative fuels and operational measures.

2.2.2.2 Technological & Operational Improvements and Alternative Aviation Fuels Scenarios

Other studies were made, focused on the impacts of the introduction of alternative fuels and technologies. This was the case of the International Civil Aviation Organization (ICAO) that developed environmental trends, based on the latest data from the air travel demand forecast obtained by CAEP (Committee on Aviation Environmental Protection). This analysis also considered the long-term availability of sustainable alternative fuels, noting that it would be physically possible to meet 100% of demand by 2050 with SAF, which corresponds to a 63% reduction in emissions. However, this fuel production level could only be achieved with extremely high capital investments in sustainable alternative fuel production infrastructures and substantial political support [33].

Schilling et al. [34], in the framework of the AIRCAT (Assessment of the Impact of Radical Climate-Friendly Aviation Technologies) project, conducted by IATA and DLR (German Aerospace Center), investigated the benefits, challenges and emissions resulting from the introduction of new technologies and other fuels in fleets, such as fully electric aircraft, strut-braced wing with open rotor, blended wing body, liquid drop-in fuel (fischer-tropsch kerosene), liquid non-drop-in fuel (liquid natural gas). The model used to evaluate the introduction of new aircraft configurations into the global fleet and their impact on global CO_2 emissions was the FFWD (Fast Foward) developed by DLR. The methodology used to evaluate the technology was done as follows: in a first phase, a qualitative analysis of the multi-stakeholder system was performed to identify the specific impacts of each of the different parts in the aviation sector. In the second phase, the impacts were assessed by identifying the main stimulators and prerequisites for the expected technical and operational feasibility and estimating the time required for operational preparation. Finally, the impact of the expected emission reduction on the global fleet was estimated. The results showed that the potential CO_2 reduction of these radical aircraft concepts in 2050 can reach about 20-25% compared to the baseline scenario, assuming that there are favorable economic conditions to carry out all programs. Even under these conditions, the expected market penetration of these new aircraft concepts is still relatively low in 2050. This means that the emission reductions needed to achieve the targets by 2050 would have to come from low-carbon fuels.

Moolchandani et al. [35] presented the Fleet-Level Environmental Evaluation Tool capabilities using scenarios to assess the effects of the new technology in aircraft and biofuels on aviation's emissions. Three scenarios were considered. In the first scenario, it is introduced advanced technologies for aircraft configurations ”tube-and-wing” (generation N+3); In the second scenario, it is introduced the configuration of the aircraft ”hybrid wing-body” (HWB); In the last scenario, it is considered the entry of low carbon fuels. To represent the air fleet, all available aircraft were divided into six classes based on their capacity and four technology groups, based on the date of entry into service of the aircraft. Technology groups are defined as representative-in-class aircraft, best-in-class, new-in-class, and future-in-class. The results of the study for the advanced aircraft technologies showed that the introduction of HWB aircraft did not result in any significant difference in demand levels compared to ”large twin-aisle” (LTA) aircraft. LTA aircraft, which come into service in early 2020, need more than a decade to achieve sufficient penetration to start showing the effect of emission reductions. In contrast, HWB aircraft, which assuming they enter in 2025, will lead to relatively faster emissions reductions. Despite this, the benefits of HWB aircraft have disappeared in the years after 2040. The possible cause is that the aircraft class with higher capacity are used for a few trips and are mainly used for long-distance international routes. The results of the biofuels scenario showed that from 2023 onwards the airline’s operating costs start to increase due to the higher cost of biofuels, which led to an increase in ticket prices and a decrease in demand due to the elasticity of demand. In 2050, the demand met was 8.13% lower compared to the ongoing fleet renewal scenario. However, the advantage of using biofuels is obvious by the significant emission reductions, and in 2050, they are 50.93% lower compared to the first scenario. These results make it clear that the introduction of low carbon fuels would be highly advantageous for the objective of reducing carbon emissions in aviation.

Hassan et al. [36] proposed an integrated framework that assesses the performance of the future National Airspace System (NAS) in different scenarios that consider from technological contributions, operational to biofuels. This study aimed to assess whether the objectives set by the International Air Transport Association (IATA) will or not be met. The model used was the method described by Hollingsworth et al. [27]. The five scenarios consider only the configuration of tube and wing aircraft with turbofan engines, so the blended body configuration is not studied in this work. The results showed that, as predicted, the least effective scenario was the Business as Usual scenario (BAU) since no new technologies were introduced. By contrast, all other scenarios showed significant reductions in fuel consumption and CO_2 emissions. In this work, none of the scenarios completely achieved the environmental objectives of IATA. However, except for the BAU scenario, most scenarios were able to achieve carbon-neutral growth from 2020 onwards.

Dray et al. [37], in addition to analyzing the improvements on technologies & operations and the use of alternative fuels, have studied the impact of economic emissions mitigation measures on global aircraft emissions. The model used was the AIM. The scenarios in this study are specified for the period between 2000 and 2050, and the main differences in these scenarios are in terms of the global distribution of Gross Domestic Product (GDP), oil, and carbon prices. The options assumed in the technology part of this work include retrofits, increased maintenance, biofuels, open rotor engines for narrow-body aircraft, and improved

Air Traffic Management (ATM). The results show that in 2050 aviation-related CO_2 emissions may range from twice the levels of 2005 to five times the levels of 2005. For the more radical cases emissions are practically stable from 2020 onwards. The technologies that had the most influence in reducing emissions were open rotor and biofuels.

2.2.2.3 Operations & Technological Improvements Scenarios

Two recent studies have analyzed the environmental impact of aviation by combining the effects of technology and operations. Ploetner et al. [38] have estimated the impact of new aircraft types entering 2020 and have created fifteen scenarios based on various technologies, production, and operations that will contribute to the long-term emissions target. The model FSDM was used to quantify fuel demand across the fleet and the impact of reducing carbon emissions. Scenarios were defined based on aircraft technologies and configurations, aircraft production ramp-ups, aircraft productivity, Revenue per kilometer (RPK) growth changes, and retrofit options. The results showed that the new technologies applied in aircraft with up to radical ramp-up timelines might lower fleet-level fuel burn until the year 2050 between 17% to 27%. Another way to reduce emissions, that were observed in this work was by increasing the productivity of aircraft production by increasing the load factors, that is, installing more seats and thus increasing the use of aircraft. With this, it was possible to observe a reduction in fuel consumption at the fleet level of about 7% to 8% by 2050. The application of retrofit solutions for in-fleet aircraft can reduce the fleet-level fuel burn in the year 2050 by around 3%.

Hassan and Mavris [13] studied the potential to reduce fuel consumption with the development of technologies and operations to achieve the goals set worldwide. This study is also focused on evaluating the benefits of the cooperation between both technology and operations can bring. The approach used to quantify the impact of vehicle technologies and operational improvements on system fuel burn was the method presented by Hassan et al. [39]. The results shown suggested that vehicle technologies are indispensable for future system fuel burn reductions. Although, in the near term they have a very minimal impact because it depends on the fleet turnover. The interdependencies between technological and operational solutions showed a significant impact on system performance.

The results of all works mentioned above, with the exception of the work of Hassan et al. [36] and Dray et al. [37], show that the objectives proposed by IATA can not be fulfilled. The studies that evaluate technologies show that it is impossible to achieve half of the emissions recorded in 2005 by 2050. However, it was reported that for the scenarios that consider the technologies & operational improvements and alternative fuels, it is possible to have a carbon-neutral growth, although it is not verified from 2020 which does not meet the other objective of IATA. The technological improvements are indispensable to decrease the emissions, however, since they have slow market penetration, it takes a few years for the reduction in CO_2 emissions to be relevant.

Chapter 3

Air Traffic Emissions Calculation

This chapter presents the whole process to calculate aviation emissions up to 2050. At a preliminary stage, the calculation of emissions was based on a statistical model, but this approach did not enable the proposed objectives to be accomplished. In order to meet the goals of the present work, air transport system model was used since assessing the impact that the development of technology has on the long-term CO_2 emission reductions requires the simulation of the global fleet. This simulation was conducted using the Fleet System Dynamics Model. In this chapter, this model and the added features are explained which allowed the analysis of the desired technologies. Finally, the technologies analyzed in this work and the scenario planning are presented.

3.1 Forecasting Air Traffic Emissions

In the preliminary phase to calculate CO_2 emissions from the aeronautical sector for the *Business as Usual* scenario, the approach chosen was to use a statistical model, using existing global fuel consumption data. Jet fuel consumption data was collected through the U.S. Energy Information Administration (EIA) [40] for the seven regions of the world (Africa, Asia & Oceania, Central & South America, Eurasia, Europe, Middle East, and North America). The EIA only provides fuel consumption data from 1987 to 2018. This jet fuel consumption data has been converted into CO_2 emissions according to the equation (3.1) provided by Young and Hirst [41].

$$EI_{CO_2} = \frac{Mass_{CO_2}}{Mass_{Fuel}} = \frac{44.01}{12.01 + (Y/X)} = 3.16 \tag{3.1}$$

The ratio between the mass of fuel consumed and the mass of individual species produced is determined by the chemistry of the combustion process. The ratio is usually expressed as an emission index (EI) and for the case of carbon dioxide is expressed according to the equation (3.1), where Y is the average number of hydrogen atoms and X the average number of carbon atoms in a *molecule* of hydrocarbon fuel. In the case of jet fuel $(Y/X) \approx 1.91$. Therefore, for every kilogram of jet fuel burned, 3.16 kilograms of carbon dioxide are produced and emitted into the atmosphere [41].

In order to select the most suitable model to calculate possible emissions until 2050, considering the fuel consumption of the sector, the selection was made according to the works of Malik et al. [42], Chèze et al. [43] and Melikoglu [44]. Malik et al. [42] forecasted CO_2 emissions until 2030 from energy consumption in Pakistan using the Auto-Regressive Integrated Moving Average (ARIMA) model. Similarly, Melikoglu [44] forecasted the jet fuel demand and the potential bio-based jet fuel demand for Turkey by 2023 using semi-empirical models (exponential, linear, and quadratic). Chèze et al. [43] reported projections of jet fuel demand at the global level and for eight geographical positions by 2025, the approach was first forecasting air traffic using dynamic panel-data econometrics and then converting the air traffic projections into jet fuel quantities.

From the works mentioned above, it was concluded that the most suitable model for the present work would be ARIMA, as it presented considerably lower error rates when compared to historical data. The ARIMA model was implemented using the Microsoft Excel software and the NUMXL extension.

ARIMA model

ARIMA(P,Q,D) models are linear statistical models for time series analysis. The abbreviation ARIMA stands for *Auto-Regressive Integrated Moving Average*. ARIMA model is a generalization of *Auto-Regressive Moving Average* (ARMA) model because when the data is not stationary, difference is taken to make the data stationary, and the ARMA model is converted into ARIMA. The ARMA model is the grouping of both AR(p) and MA(q) models. In ARIMA(P,D,Q) the *P* denotes auto-regressive (AR) model order, *D* denotes difference taken to make the data set stationary, and *Q* denotes moving average (MA) model order.

The AR(P) model is based on the following equation:

$$x_t = \phi_0 + \phi_1 \cdot x_{t-1} + \phi_2 \cdot x_{t-2} + ... + \phi_P \cdot x_{P-1} + e_t \quad (3.2)$$

x_t : Observed output at time *t*;
ϕ : Parameters of the auto-regressive (i.e. AR) component model (starting with the lowest lag);
e_t : Innovation, shock or error term at time *t*;
P : Order of the last lagged variables;

The MA(Q) model is based on the following equation:

$$x_t = \mu + \theta_1 \cdot e_{t-1} + \theta_2 \cdot e_{t-2} + ... + \theta_Q \cdot e_{Q-1} + e_t \quad (3.3)$$

θ : Parameters of the moving-average (i.e. AR) component model (starting with the lowest lag);

μ : Long run average;

e_t : Innovation, shock or error term at time *t*. Time series observations are independent and identically distributed, following a Gaussian distribution;

Q : Order of the last lagged innovation or shock;

To measure the accuracy of the results obtained using the different variations of the ARIMA model, two indicators were used based on the work reported by Lee and Tong [45]. The first indicator is the root mean square of error (RMSE), which evaluates the forecasted values with actual time series data as shown in equation (3.4). The second indicator is the mean absolute percentage error (MAPE) developed by Lewis [46] to evaluate the effectiveness of a forecasting model. This indicator statistically indicates the accuracy of the forecasted values with actual data as shown in equation (3.5). Table 3.1 shows an accuracy scale based on MAPE.

$$RMSE = \sqrt{\sum_{t=1}^{N} \frac{(F_t - A_t)^2}{N}} \quad (3.4)$$

$$MAPE = \frac{1}{N} \sum_{t=1}^{N} \left| \frac{F_t - A_t}{F_t} \right| \times 100 \quad (3.5)$$

F_t : Forecast value at the year *t*;

A_t : Actual value at year *t*;

Table 3.1: Scale of forecast accuracy [44].

MAPE [%]	**Evaluation**
<10%	High Accuracy
10%<MAPE<20%	Good Forecast
20%<MAPE<50%	Reasonable Forecast
>50%	Inaccurate Forecast

Recognizing that this approach using statistical models would not initially meet the objectives proposed since it was not possible, for example, to quantify the reduction in emissions that new aircraft could bring, having only the results provided by the ARIMA model. From here, the methodology migrated to the use of air transport system modeling to better assess the impact of introducing new technologies.

3.2 Air Transport System Modeling

The air transport system contains three key areas which have responsibility for transporting passengers, freight, and mail. These three areas are: airlines and other commercial aircraft operators, which generate the current capacity of the air transport system through aircraft operations; airports provide the necessary infrastructure for the handling and processing of passengers, cargo, and mail; and Air Traffic Control (ATM) ensures the safety and economic execution of all air operations [47, 1].

The Fleet System Dynamics Model (FSDM) was developed to quantitatively assess the effects of technological progress on the future performance of the air transport system. The considerations of the FSDM about the modeling of the air transport system are presented below. The various modules of the model are also explained, such as: Aircraft utilization modeling, Aircraft retirement modeling, Aircraft production modeling, Aircraft network allocation, and Aircraft performance modeling. Finally, the data required to use the model and the existing limitations are presented.

3.2.1 Fleet System Dynamics Model

In the FSDM model, the air transport system is considered only as a system of aircraft operating on a specific network of air routes. Airports are not included, and ATM authorities are only taken into account considering the influence they have on aircraft that are legally operated. The characteristics and metrics that are employed in the model are those listed in the Table 3.2.

Table 3.2: Characteristics and metrics of the global air transport fleet [1].

Aircraft Fleet	Size (number of operating aircraft) Composition (types of operating aircraft) Age distribution (age of individual aircraft units) Capacity (seats, freight volume, range capabilities) Performance (fuel burn, emission quantities, flight speed)
Air routes network	Number of air routes Length of air routes Geographical position of air routes

In order to be able to model the air transport system, it is necessary to contain a fleet planning inserted in the model. Fleet planning is the process in which airlines acquire and properly manage aircraft capacity to serve markets in a defined variety of periods to maximize the corporate wealth [48]. In recent years two approaches to fleet planning have been developed. The two approaches are the *macro approach* or also known as the *top-down approach*, and the *micro approach* to fleet planning or the *bottom approach*.

The FSDM uses the macro approach for fleet planning. The principle of this approach is to determine *capacity gap* (in the case of the model it is the new aircraft needed) from the year of interest until the following year. *Capacity gap* is the result of the change from year to year in the supply of transport by the airline, but also the loss in the supply of transport due to the need to retire aircraft that are in service. Figure 3.1 shows schematically the macro approach used in the model.

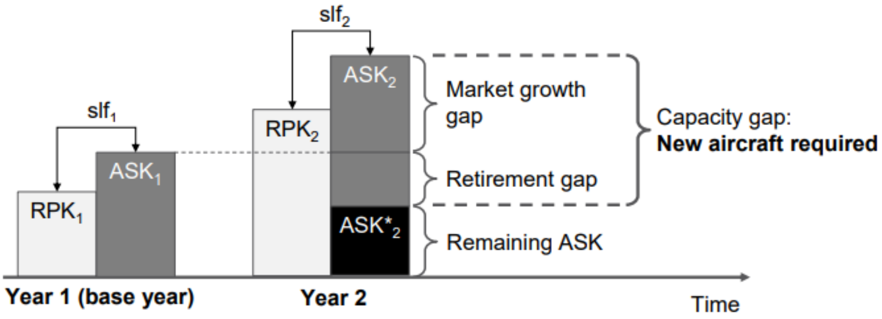


Figure 3.1: FSDM macro approach [1].

The model calculates transport demand according to equation (3.6), with Revenue Passenger Kilometer for the year *t* (RPK_t).

$$RPK_t = \sum_k p_k \cdot d_k \quad (3.6)$$

RPK_t : Transport demand (passengers) in year t;
k : Addressing one flight performed by the airline;
p : Number of passengers transported;
d : Great circle distance between origin-destination pair of flight k;

To provide sufficient supply to meet transport demand (RPK_t) and to avoid unnecessarily high demand, the airline usually offers the market more seats than the number of passengers that could be carried (ASK_t). The seat load factor (slf) then represents the ratio between seats kilometers offered and seats kilometers sold.

$$slf_t = \frac{RPK_t}{ASK_t} \cdot 100 \quad (3.7)$$

slf_t : Seat load factor in year t;
ASK_t : Transport supply (passenger seats) in year t;

In order to determine how many new aircraft will have to be added to reach the *capacity gap* the following equation (3.8) is used, which defines the ASK metric.

$$ASK_{i,j} = \sum_{i,j} n_i \cdot f_{i,j} \cdot d_{i,j} \cdot s_{i,j} \quad (3.8)$$

i : Addressing one particular route of the airline's routes network;
j : Addressing one particular aircraft unit of the airline's fleet;
n_i : Number of aircraft operating on route i;
$f_{i,j}$: Number of frequencies with which aircraft j operates on route i;
$d_{i,j}$: Great circle distance flown by aircraft j on route i;
$s_{i,j}$: Number of seats transported by aircraft j on route i;

Concerning freight planning, the macro approach is also used with the difference that instead of using passenger transport as the general metric to determine transport capacity and demand, the freight transported is used. So instead of using equation (3.8), is used the equation (3.9). Like the *seat load factor* used to represent the relationship between seats kilometers and seats kilometers sold in the case of freight transport, the *freight load factor* (flf) is used to determine the ratio between demand and supply of freight. The *seat load factor* and *freight load factor* is treated as a constant during simulations. The values used are present in Appendix B.

$$ATK_{i,j} = \sum_{i,j} n_i \cdot f_{i,j} \cdot d_{i,j} \cdot T_{i,j} \quad (3.9)$$

$T_{i,j}$: Tons of freight capacity transported by aircraft j on route i;

The methodology foundations of FSDM consists in the *aircraft fleet model* and the *air transport network model* components. This uses a dynamic form 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 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 (given in ASKs/ATKs or RPKs/RTKs and the corresponding load factor) that the initial fleet has to comply with.

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 [49]. In this model, stocks and flows are used to capture the dynamics of the evolution of the fleet as a function of time.

Figure 3.2 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 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.

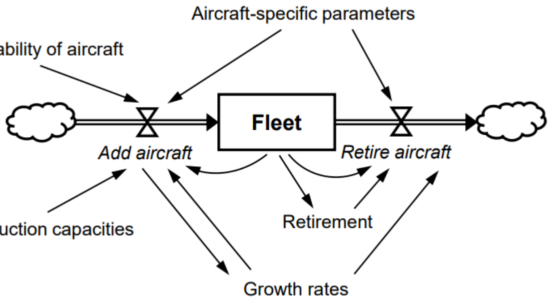


Figure 3.2: System Dynamics- based functional scheme of the FSDM [1].

The following subsections explain how the different parts of fleet planning included in the FSDM are modeled.

Aircraft utilization modeling

One of the major prerequisites for fleet planning is to be able to accurately model the use of aircraft. The total time an aircraft needs for the execution of a flight is defined as Utilization Hours (UHs). The Utilization Hours (UHs) comprise the following three sub-categories. Block Hours (BHs) are the number of hours an aircraft requires to perform a flight mission. Turn-around Hours (THs) are the number of hours an aircraft requires to be ready for the next flight mission. Maintenance Hours (MHs) are the number of hours an aircraft requires to maintain airworthiness [50, 1]. Equations (3.10) and (3.11) show how the utilization hours are calculated.

$$UH = BH + TH + MH = \left(1 + \frac{MH}{BH}\right) BH + TH \quad (3.10)$$

$$UH = \alpha \cdot BH + TH \quad (3.11)$$

The α in equation (3.11) that corresponds to MH/BH ratio can be determined with equation (3.12).

$$\alpha = 1 + \frac{Daily\,Check + A, C, \&D\;Checks}{Taxi\,Time + Flight\,Time} \quad (3.12)$$

The α values were set according to aircraft range (long-range, mid-range, and short-range). Table 3.3 shows the values considered for the α variable.

Table 3.3: Values for α variable according to aircraft range [1].

Aircraft range	α
Long-range	1.57
Mid-range	1.82
Short-range	2.07

The *Maximum Utilization Hours* (UH_{max}) define the daily limit of use of the aircraft within a predefined time. Boeing Commercial Airplanes [1] suggests that for 777 and 737 aircraft, the values of UH_{max} are 20 and 15 hours, respectively. For a certain value of UH, the maximum number of flights per day for a specific aircraft on a given route can be determined using the equation (3.13).

$$f_{i,j,max} = \frac{UH_{max}}{UH} \quad (3.13)$$

$f_{i,j,max}$: Maximum number of flight frequencies per day achievable for a specific aircraft on a specific route;
UH_{max} : Maximum Utilization Hours;

The UH_{max}, likewise the α values, were established according to the range of the aircraft. Table 3.4 shows the UH_{max} values used in the simulations.

Table 3.4: Maximum utilization hours employed in FSDM [1].

Aircraft range	UH_{max} **[h]**
Long-range	20
Mid-range	17.5
Short-range	15

Aircraft Retirement Modeling

One of the equally crucial tasks related to fleet planning, especially in the long term, is the modeling of the retirement of aircraft in service. In the context of the model, the aircraft is considered retired from service when the aircraft does not resume long-term operations. In order to represent the decisions which are taken by the airlines to retire their aircraft from service, the FSDM has a module which approximates the retirement of aircraft through an age-related function of the aircraft. For this purpose the *survival curves* are used, which describe the percentage of aircraft that remain in the fleet depending on their respective age (POS- percentage of survival: equation (3.14)). These curves can be interpreted as the mathematical description of the degree of probability of an aircraft remaining in the fleet as it is getting older. Figure 3.3 shows the survival curves for three different types of aircraft (Turboprop Aircraft, Widebody Jet Aircraft, and Narrowbody Jet Aircraft).

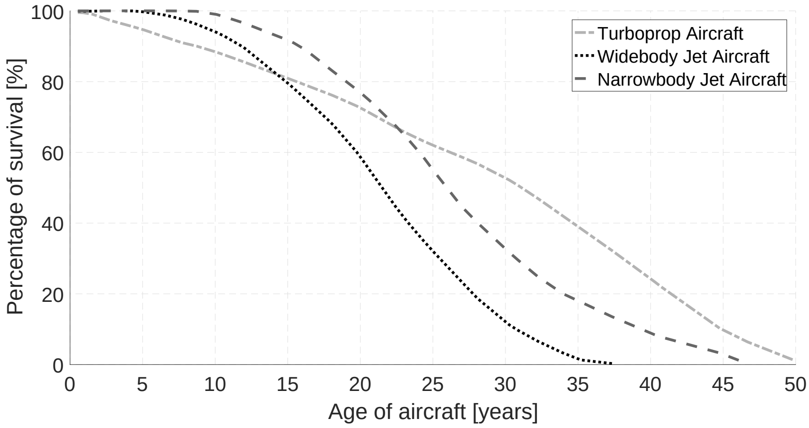


Figure 3.3: Survival Curves for different groups of aircraft [26].

The shape of the *survival curve* is determined by the two factors β_1 and β_{11} from equation (3.14), these are determined empirically for each aircraft type and category. Due to this purely statistical approach, the FSDM retires aircraft in each simulation year by determining their POS individually, regardless of the current situation of aircraft demand expressed by the *capacity gap* (Figure 3.1). This means that in a situation of significant growth with high demand for transport capacity (and therefore high demand for additional aircraft units), the FSDM will retire aircraft in exactly the same way as in a situation of strong retraction. However, the reality is that airlines adapt their reform strategies based on transport demand situation as seen during 2020.

The coefficients used in the simulations performed, both for existing aircraft and for new technologies introduced, are listed in the table B.2 on Appendix B.

$$POS = \frac{1}{1 + e^{-\beta_1 - \beta_{11} a}} \quad (3.14)$$

POS : percentage of survival;
a : aircraft age (in years);
β_1, β_{11} : retirement coefficients specific for each type of aircraft;

Aircraft Production Modeling

In fleet planning, the purchase of new aircraft is also included, so it is necessary to decide when to make these purchases. In the aeronautical sector, it must be take into account that the units ordered are not delivered by the manufacturers immediately. The airline may have to wait a certain period until the manufacturer delivers the aircraft.

The model, after determining the number of aircraft that are retired in each year of the simulation, calculates the *capacity gap* to be able to define how many aircraft have to be added to the fleet in the following year, following the macro approach of fleet planning. The FSDM in each year of the simulation places new aircraft in order to minimize the total fuel consumption of the global fleet. As aircraft manufacturers obviously cannot deliver an unlimited number of aircraft of a specific type in a certain period of time, especially when new aircraft programs are introduced. Therefore, the unlimited supply of aircraft cannot be guaranteed by the manufacturer, since first it still needs to prepare the necessary facilities for the production of a new aircraft model. In order to be able to represent fleet simulations more realistically, the FSDM allows limiting the number of aircraft that are available to be added in each year of the simulation. The model distinguishes the supply of aircraft on two levels:

- Total production capacity (TPC) - is the maximum number of aircraft that can be supplied annually, with all aircraft manufacturers worldwide. Total production capacity is divided into two classes, the single-aisle (SA) and twin-aisle (TA). For each aircraft type that is included in the model, it is necessary to define to which class the aircraft belongs in order to be able to restrict production capacity. The TPC values used in the simulations are listed in the Table B.11 (Appendix B).

- Single production capacity (SPC) - is the maximum number of aircraft of each aircraft type (not an aircraft cluster) that can be supplied annually by the specific manufacturer. For the new implemented technologies that have been inserted in the model the SPC has been determined according to Engelke [51]. The SPC values used in the simulations performed are listed in the Table B.10 (Appendix B).

In the simulations performed in the present work, the single production capacity for the new aircraft models introduced and the total production capacity has been limited, in order to be able to represent the practices that take place in real life, in particular the limitations that exist in the individual production of each aircraft type and the overall aircraft production.

Aircraft Network Allocation

In air transport, once airlines have completed fleet planning and stipulated the network of routes they wish to serve, the next step is to place the fleet on the route network and develop a schedule of planned flights including the fleet rotation plan. This process is called *schedule development* [52, 1].

One of the most essential parts of the schedule development is the Fleet Assignment Problem (FAP), that determines which aircraft type in the airline's fleet and how many aircraft of each type are supposed to operate on each route, given a network of planned routes and a flight schedule. The FAP is a mathematical optimization problem that many airlines deal with using large-scale network optimization mathematical methods. Normally, the objective function of the FAP is minimize costs, or maximize profit, since is a common airline problem. FSDM solves the FAP with the objective function of minimizing the fuel consumption of the fleet by using the *fmincon* (interior-point) function available in MATLAB ®, which determines a minimum of a constrained nonlinear multivariable function.

Aircraft Performance Modeling

The aircraft performance modeling included in FSDM is fundamentally based on the Base of Aircraft Data (BADA) that was created and is now being maintained and distributed by Eurocontrol [53]. 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 NO_x, 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* [28]. The tool to model aircraft performance was entitled Fuel Consumption and Emissions Calculation Tool (FCECT). Figure 3.4 shows the algorithm of this tool.

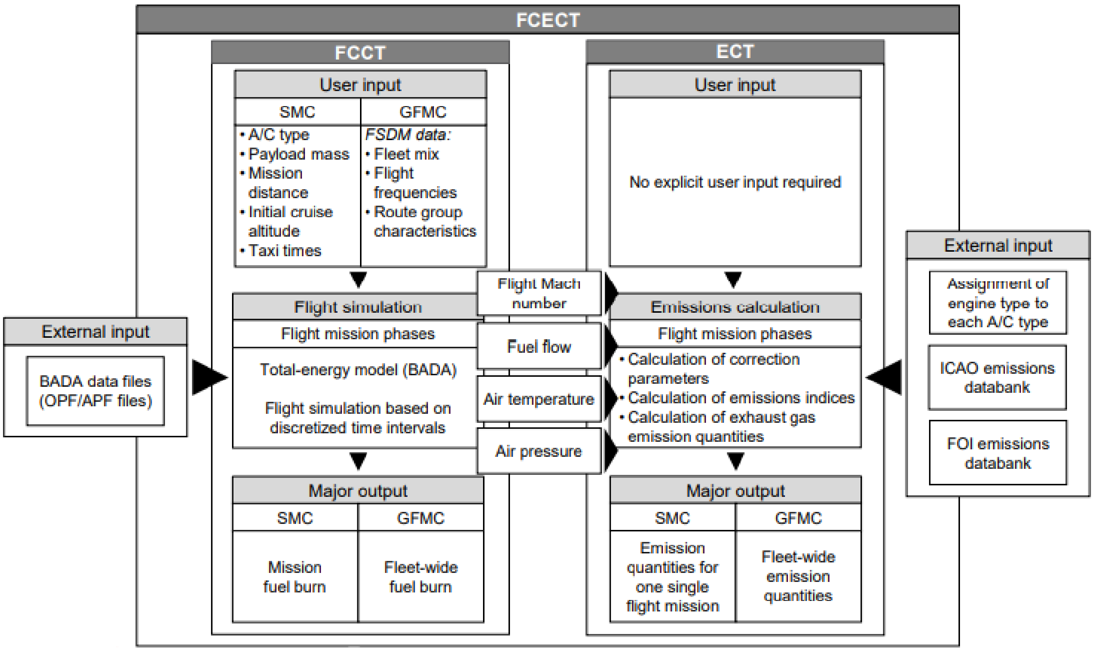


Figure 3.4: Functioning scheme of the Fuel Consumption and Emissions Calculation Tool [1].

The FCECT allows determining the performance of aircraft from the fleet being simulated. The performance characteristics that are calculated in this tool that are most important for the work performed are the fuel consumption of the global fleet and the CO_2 emissions emitted by air transport. The operation of FCECT, as shown in Figure 3.4, consists first of using

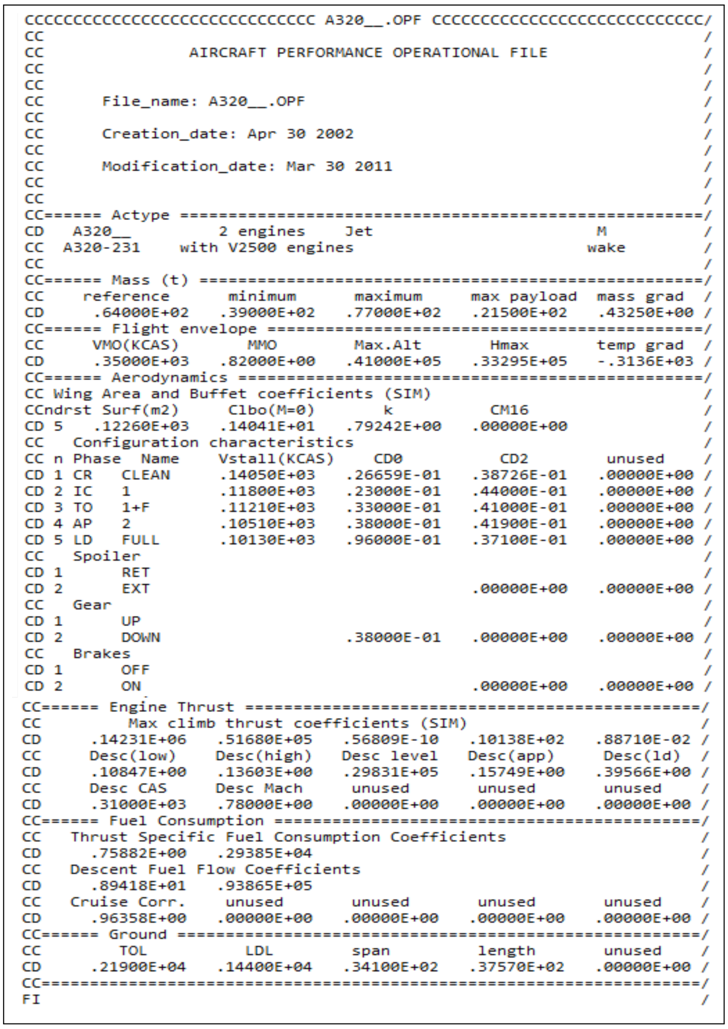
Single Mission Calculation (SMC), which simulates a given flight considering the various variables (payload mass to be carried, mission distance, cruise altitude, and taxi time). Considering these inputs, the SMC allows the calculation of the required block hours, the vertical flight profile, and the calculation of the fuel burn during this particular mission. The Global Fleet Mission Calculator (GFMC) calls the SMC for each simulation of a flight. This routine simulates all the flights in the FSDM fleet and summarizes the results obtained to form various fleet-level metrics, such as fuel burn of the global fleet in a specific year of simulation.

In order to meet the proposed objectives of evaluating the new technologies, since do not exist the required data in the BADA database to model the performance of the new concepts, a new tool had to be developed in this work to create such data. This developed tool creates the *External Input* (→ Figure 3.4) used in FCECT.

For the new technologies that will enter in the global fleet, it is necessary to create the BADA OPF (Operations Performance File) and APF (Airline Procedures File) files. The Operations Performance File provides for each aircraft type the specified parameter values for the mass, flight envelope, drag, engine thrust, and fuel consumption. The Airline Procedures File provides the nominal maneuver speeds for each aircraft type. The tool has been developed to use existing aircraft as a reference and change the various coefficients required to achieve the desired fuel efficiency.

The tool developed produces the OPF file (Figure 3.5) for the new aircraft using the data from the aircraft's OPF file used as a comparison for calculating fuel efficiency. In the OPF files, the coefficients changed are the Thrust Specific Fuel Consumption Coefficients (TSFC) and the Descent Fuel Flow Coefficients. The Cruise Correction Coefficient was left untouched. TSFC is the fuel efficiency of an engine design with respect to thrust output. TSFC can also be defined by the mass of fuel burned by an engine in one hour divided by the thrust that the engine produces. Descent Fuel Flow Coefficients are used to determine the minimum fuel flow for the optimum thrust condition, and also in the case of approach and landing [53]. In order to achieve the desired fuel efficiency for the new concept to be analyzed these coefficients were calculated iteratively until they reached the correct value for fuel efficiency. Appendix C shows the validation of the OPF files created for the new aircraft. Figure 3.5 shows an example of an Airbus A320 OPF file.

In the case of APF files, no change was necessary because it does not directly affect fuel efficiency.



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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCC A320__.OPF CCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC                                                                    /
CC                AIRCRAFT PERFORMANCE OPERATIONAL FILE               /
CC                                                                    /
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CC       File_name: A320__.OPF                                        /
CC                                                                    /
CC       Creation_date: Apr 30 2002                                   /
CC                                                                    /
CC       Modification_date: Mar 30 2011                               /
CC                                                                    /
CC                                                                    /
CC====== Actype ======================================================/
CD    A320__          2 engines    Jet                         M      /
CC   A320-231    with V2500 engines                           wake    /
CC                                                                    /
CC====== Mass (t) ====================================================/
CC      reference       minimum       maximum      max payload  mass grad  /
CD       .64000E+02   .39000E+02   .77000E+02   .21500E+02   .43250E+00 /
CC====== Flight envelope =============================================/
CC       VMO(KCAS)        MMO          Max.Alt        Hmax       temp grad  /
CD       .35000E+03   .82000E+00   .41000E+05   .33295E+05   -.3136E+03 /
CC====== Aerodynamics ================================================/
CC Wing Area and Buffet coefficients (SIM)                            /
CCndrst Surf(m2)      Clbo(M=0)       k            CM16               /
CD 5    .12260E+03   .14041E+01   .79242E+00   .00000E+00             /
CC    Configuration characteristics                                   /
CC n Phase  Name     Vstall(KCAS)     CD0           CD2          unused   /
CD 1 CR    CLEAN      .14050E+03   .26659E-01   .38726E-01   .00000E+00 /
CD 2 IC    1          .11800E+03   .23000E-01   .44000E-01   .00000E+00 /
CD 3 TO    1+F        .11210E+03   .33000E-01   .41000E-01   .00000E+00 /
CD 4 AP    2          .10510E+03   .38000E-01   .41900E-01   .00000E+00 /
CD 5 LD    FULL       .10130E+03   .96000E-01   .37100E-01   .00000E+00 /
CC    Spoiler                                                         /
CD 1       RET                                                        /
CD 2       EXT                                .00000E+00   .00000E+00 /
CC    Gear                                                            /
CD 1       UP                                                         /
CD 2       DOWN                   .38000E-01   .00000E+00   .00000E+00 /
CC    Brakes                                                          /
CD 1       OFF                                                        /
CD 2       ON                                 .00000E+00   .00000E+00 /
CC====== Engine Thrust ===============================================/
CC          Max climb thrust coefficients (SIM)                       /
CD      .14231E+06   .51680E+05   .56809E-10   .10138E+02   .88710E-02 /
CC      Desc(low)    Desc(high)   Desc level   Desc(app)     Desc(ld)  /
CD      .10847E+00   .13603E+00   .29831E+05   .15749E+00   .39566E+00 /
CC      Desc CAS     Desc Mach     unused       unused       unused    /
CD      .31000E+03   .78000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Fuel Consumption ============================================/
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CD      .75882E+00   .29385E+04                                       /
CC    Descent Fuel Flow Coefficients                                  /
CD      .89418E+01   .93865E+05                                       /
CC    Cruise Corr.    unused        unused       unused       unused    /
CD      .96358E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Ground ======================================================/
CC         TOL          LDL          span         length       unused    /
CD      .21900E+04   .14400E+04   .34100E+02   .37570E+02   .00000E+00 /
CC====================================================================/
FI                                                                    /
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Figure 3.5: Airbus A320-231 OPF file.

3.2.2 Simulation Data Required

For the model to work properly, it is necessary to provide the data that will be discussed below, namely the global fleet, route network, and transport performance.

In air transport in 2008, there were almost 200 different types of aircraft contributing to transport capacity. Including all these aircraft would increase the complexity of the model. So to keep complexity within acceptable limits, the FSDM has defined nine distinct categories of aircraft to represent the fleet in 2008. The aircraft categorization has been conducted taking into account multiple aircraft type-specific criteria, including transport performance, operational and technical metrics. The k-medoids algorithm [54] was used for aircraft categorization. With this algorithm, the optimal number of *aircraft clusters* was identified.

Aircraft cluster is a term used to represent the specific aircraft type group in the FSDM. For the initial fleet, the FSDM has selected to represent each cluster the aircraft with the highest ASK value for passenger aircraft and the highest ATK value for cargo aircraft. Table 3.5 shows the nine clusters, the representative aircraft type, and the ASKs/ATKs value for each cluster.

Table 3.5: FSDM initial fleet aircraft clusters [1].

Cluster	Cluster name (SA/TA class)	Representative aircraft type (OAG name)	Approx. ASK/ATK-share within cluster
1	Long-range combi (TA)	Boeing (Douglas) MD-11	43%
2	Long-range heavy (TA)	Boeing 747-400	77%
3	Mid-range freighter (n/a)	Boeing 767-300F (Freighter)	25%
4	Jet commuter (SA)	Embraer 190	9%
5	Long-range freighter (n/a)	Boeing 747-400F (Freighter)	47%
6	Turboprop commuter (SA)	ATR 72-500	100%
7	Mid-range (TA)	Boeing 767-300	22%
8	Long-range (TA)	Boeing 777-200	16%
9	Narrow-body (SA)	Airbus A320	23%

The size and distribution of the nine clusters are shown in the Table B.12 in Appendix B. In addition to these data the model also needs the values of ASKs and ATKs for air transport in 2008 to start the macro approach. The characteristics of the route networks in the FSDM have been defined according to the Official Airline Guide (OAG) database [55]. In FSDM, the route network is defined in 21 *route groups*, as shown in Figure 3.6. This representation enables the complexity of the problem to be kept within acceptable regimes and to represent all routes globally. The distances of the 21 *route groups* were determined using the median values of the frequency weighted average stage lengths flown by each one of the nine aircraft clusters on each route group (where applicable).

Figure 3.6: Global regions and route groups used by the FSDM [1].

The characteristics of the seat and cargo capacities that each aircraft cluster can transport on each *route group* on a respective flight were determined using the same method as described above for determining route distances. Appendix B shows the transport performance characteristic values that the FSDM model uses.

In addition to the data mentioned above, the FSDM requires a variety of other parameters that must be provided before running the simulation in order to function correctly. Table 3.6

shows briefly the parameters that have to be provided, their values are present in Appendix B.

Table 3.6: Summary of the data required by the FSDM

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 the user 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 and RTKs 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

3.2.3 Model Assumptions and Limitations

The model takes into account some 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 (FAP) is to maximize profit, but doing 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 companies are not considered. So to solve the FAP, 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 OAG database [55]. 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 O-D pairs (Origin-Destination), according to the OAG database [55]. 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.

3.3 Technological Options for Aviation

This section presents new concepts and technologies for aircraft, which are intended to be applied in the aeronautical sector by 2050. At the beginning of the section, new aircraft and technologies are presented with an expected entry into service by 2025 and are therefore called imminent technologies in this work. This is followed by the so-called revolutionary concepts in the literature, as these are new aircraft configurations and technologies that are being developed with characteristics quite different from what is certified to be used in aviation today.

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. Further reductions are therefore expected in the future with the entry of new technologies. Although, when a new and more efficient aircraft is introduced, it requires 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 [56].

3.3.1 Imminent Technologies

The aircraft that have entered service in recent years have 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 case of the Boeing 747-800 with a reduction of 16% in fuel consumption, that has suffered changes in the engine and wing compared to the Boeing 747-400. Another example is the case of the Boeing 747-400F, intended for cargo transportation, which was replaced by the Boeing 747-8F. In narrow body (SA) type aircraft Airbus has released the A320neo family, which is one of many upgrades introduced by Airbus to help maintaining its A320 product line position as the most advanced and fuel efficient in the world [57]. The A320neo has two engine options (the PurePower PW1100G-JM from Pratt and Whitney (PW) 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% [30]. Like 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 to achieve a 16% reduction in fuel consumption [30]. 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 [30]. 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 [57]. 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 [30].

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% to 25% [58], 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 [58]. Figure 3.7 shows the engine configuration of the Advanced Turbofan and Ultrafan.

Figure 3.7: Rolls-Royce Advance Turbofan (left) and Ultrafan (right) concepts [58].

The introduction of the *Natural Laminar Flow* concept in 2020 it 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 [56]. Boeing, in 2022, will launch the B777X that will be equipped with the latest engine from General Electric (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% [56].

3.3.2 Revolutionary Technologies

The technologies presented above which are based on conventional tube-and-wing concepts with turbofan engines have a limited potential for emission reductions. According to IATA [59], in order to achieve the climate objective (reducing global net aviation CO_2 emissions by 50% by the year 2050 relative to 2005), it is necessary to have an 80% reduction in CO_2 emissions by 2050. Most of this reduction will have to be supported by Sustainable Aviation Fuels (SAF), the analysis of alternative fuels is presented in chapter 4. However, the aviation industry is committed to developing new design concepts and technologies to increase fuel efficiency. The main focus is on the development of new aircraft configurations, as well as revolutionary propulsion technologies, materials, and structures. In this section, radically new concepts with high fuel efficiency benefits will be described.

3.3.2.1 Blended Wing Body

The blended wing body (BWB) configuration was originally introduced at concept study level in the late 1980s and further analyzed in the 1990s [34]. The BWB is basically a large flying wing, which contains a payload area within its center section. The shape of the center body and the outer wings are smoothly blended. The aerodynamic shape allows generating lift by the entire aircraft, which is significantly higher compared to conventional tube-and-wing configurations [59].

Several BWB concepts have been presented, DLR presented an example with a capacity of 500 seats with an estimated EIS in 2040. Other examples of concepts are being developed in NASA's X-Plane project [60], where various manufacturers are developing different ideas for BWB aircraft. The Boeing concept is based on the X-48 experimental aircraft. BWB aircraft design displays a wing blended with the main hull, with two engines and a pair of small vertical fins installed on the rear edge of the aircraft [61]. Lockheed Martin is also developing a hybrid wing body (HWB) concept. Lockheed Martin's concept combines features of blending the wing into the aircraft body, yet still retaining the suggestion of a T-tailed tube-and-wing configuration. Another unique feature is that its twin engines are mounted on pylons attached to the trailing-edge, with the engine inlets rising above the top of the wing [60]. Figure 3.8 shows the various concepts mentioned above.

(a) DLR (b) Boeing (c) Lockheed Martin

Figure 3.8: Blended Wing Body concepts [24, 60].

DZYNE, in cooperation with NASA, has developed a small BWB concept with a capacity of 120 seats. It contains the same features as the other BWB concepts described above, although the vertical stabilizer fins on this vehicle are part of the wingtips, appearing as oversize winglets. The small BWB concept was made possible by the development of a landing gear storage mechanism that needs less height and allows a flatter design of the entire aircraft. This concept in a commercial jet configuration is expected to enter the market around 2025 [59].

Fuel efficiency projections for the various BWB concepts range from 27% to around 50%

compared to aircraft of similar size and range [62]. According to Page et al. [63] for the new small BWB design the fuel savings estimated is around 30% compared to current reference aircraft. Figure 3.9 shows the BWB design by DZYNE.

Figure 3.9: Blended Wing Body concept designed by DZYNE [60].

3.3.2.2 Strut-braced Wing

The concepts of structurally optimized aircraft, such as the Strut-braced Wing (SBW), have been widely studied in the scientific community [34, 59]. The concept of SBW consists of using wing support to allow for larger wingspans without increases in structural weight. With the increase of wing span, the induced drag is reduced. Another advantage of this concept is that the high wing arrangement allows for bigger engine sizes, such as open rotors. Boeing in the *Subsonic Ultra Green Aircraft Research* (SUGAR) program designed a high aspect-ratio, low induced-drag SBW aircraft with a capacity of 154 seats. Figure 3.10 shows the first configuration designed with advanced turbo-fan engines for an entry into service in 2030-35 [59].

Figure 3.10: Strut-braced wing concept designed by Boeing [64].

This concept is about 29% more efficient over a 900 nm mission (design range of 3,500 nm) than a Boeing 737-800 with CFM56 engines. According to Bradley and Droney [65] the SBW concept combined with an open rotor could potentially lead to a block fuel saving of up to 53% compared to the evolutionary baseline fleet. Its EIS could be possible around 2040.

3.3.2.3 Boundary Layer Ingestion

Boundary Layer Ingestion (BLI) is a promising idea that the scientific community is investigating to reduce fuel consumption. This idea is presented as the ”Propulsive Fuselage Concept” (PFC), which allows the entire fuselage to act as a propulsive thrust. The concept of BLI has been investigated in various projects. Some of those include NASA’s “FuseFan”, the Bauhaus Luftfahrt “Claire Liner”, the MIT “D8” concept and the NASA “STRAC-ABL” [59].

In the BLI technology the engines are located near the rear of the aircraft so that air flowing over the aircraft body becomes part of the mix of air going into the engine. According to NASA [66] the BLI technology is capable of reducing the aircraft fuel burn by 8.5% compared to aircraft operating today. Figure 3.11 shows a propulsive fuselage concept by Bauhaus Luftfahrt, integrating boundary layer ingestion and airframe wake filling.

Figure 3.11: Propulsive fuselage concept designed by Bauhaus Luftfahrt [59].

Another project that is also developing the BLI concept is the CENTRELINE that is part of the Horizon 2020 Framework Programme. The CENTRELINE project aims to maximize the benefits of aft-fuselage wake filling under real systems design and operating conditions. The main objectives are to achieve a Technology Readiness Level (TRL) of 3 and 4 for the PFC concept at the end of the project and to achieve an 11% reduction in CO_2 emissions compared to current aircraft. This concept has a potential entry into service in 2035 [59, 67].

3.3.2.4 Double-bubble Fuselage

In NASA's X-plane project [60], Aurora Flight Sciences designed the Double-bubble fuselage, also called D8 aircraft. The main feature of this concept is a *double-bubble* fuselage that can be thought of consisting of two blended side-by-side tubes. The wide flattened fuselage body generates additional lift. This design allows the wings to be smaller and lighter, which leads to a significant reduction in fuel burn compared to conventional configurations. Another advantage of the concept shown in Figure 3.12 is that the engines are attached at the rear of the fuselage allowing the air flow over the top of the aircraft and move through the engines which reciprocally helps reducing the drag (BLI). The Double-bubble fuselage concept has the potential of achieving up to 20% compared to the A320neo [59].

Figure 3.12: Double-bubble fuselage designed by Aurora Flight Sciences [61].

3.3.2.5 Open Rotor

The engine architectures in the past decades have suffered several changes to increase engine efficiency. One of the most promising engine architectures is the Counter Rotating Open Rotor (CROR). The open rotor architecture consists of a hybrid system between a propeller and a turbofan engine, characterized by two counter-rotating, unshrouded fans. This concept allows a reduction of fuel burn and CO_2 emissions of typically 30% compared to conventional turbofan engines, such as CFM56. The open rotor concept began to be developed in the 80s, although its development has been slow due to difficulties in reducing noise levels which are higher compared to turbofan engines. Manufacturers expect this concept to go into service around 2030 [59]. Figure 3.13 shows the open rotor being developed by Safran.

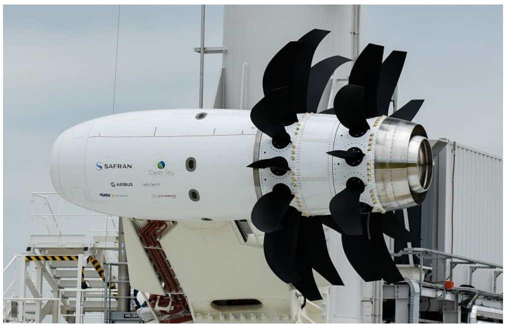


Figure 3.13: Open-rotor concept [68].

3.3.2.6 Electric Aircraft

Both electric and hybrid propulsion is evolving rapidly to replace the transport technologies used today. While the introduction of electric propulsion in aircraft is a revolutionary step in the aviation industry, this is an area that has been widely explored and examined for its environmental advantages [34, 59, 69]. The main advantage is that electric motors do not produce emissions during operations, making them a fundamental technological element in achieving environmental goals for 2050. However, it must be considered that electric power generation is not currently produced without emissions, as fossil fuels are still used in many countries for electric power generation. Although electric energy production is not completely emission-free, the use of electric propulsion could contribute to a considerable decrease in emissions by 2050, due to the investment in renewable energies in all sectors of the global economy. Another important advantage of electric propulsion over conventional propulsion is that it requires less maintenance compared to combustion engines, resulting in cost benefits for airlines.

Hybrid-electric aircraft are being considered as a suitable choice for conventional short and medium-range aircraft in the future. Several companies in the aircraft sector such as Airbus, Siemens, Rolls-Royce, and Boeing are investigating this hypothesis.

Airbus, Rolls-Royce, and Siemens formed a partnership in 2017 to develop and build a hybrid-electric aircraft called E-Fan X. The E-Fan X project is characterized by containing hybrid electrical technology in series to power a 2-megawatt electric motor. The main long-term objective is to build a commercial aircraft equipped with E-Fan X technology with a capacity for 50-100 passengers and a range capable of making regional flights. The expected EIS is around 2035 [59]. Figure 3.14 shows the hybrid electric aircraft design being developed.

Figure 3.14: E-Fan X hybrid-electric aircraft [70].

Boeing HorizonX and JetBlue Technology Ventures have supported and invested in Zunum Aero, which aims to develop the first commercial hybrid-electric aircraft. Zunum plans to introduce one aircraft in 2027 with a capacity of 50 passengers and a range of 1000 nm. Zunum is also planning to develop an aircraft with a capacity of 100 passengers and a range of 1500 nm. This aircraft will reduce emissions by 80%, and the estimated year of entry into service is 2030 [59]. Figure 3.15 shows the hybrid electric aircraft being developed by Zunum.

Figure 3.15: Hybrid-Electric Aircraft designed by Zunum Aero [71].

3.4 Scenario Planning

With these new technologies described above, all manufacturers express the efficiency of new aircraft or new concepts compared to existing aircraft. However, one question arises, how much CO_2 emissions will these technologies reduce when they are introduced into the global fleet? This section presents the various scenarios created to assess quantitatively the emissions produced by these new concepts.

Scenario planning is fundamental in this work where one of the objectives is to provide quantitative data to support business decision making. The quantitative scenarios created allow a more solid basis for a decision to be taken and are more likely to lead to immediate action in a company. In this sense, the basic idea of scenario planning is to create and reflect on multiple futures. These scenarios have been created according to parameters such as entry year, type of aircraft configuration, as well as considering the technology readiness level. Table 3.7

shows the concepts that will be evaluated in this work.

Table 3.7: List of new technology concepts (2020-2050).

Group	Concept	Fuel Efficiency
New aircraft concept	Blended Wing Body	27% to 50%
	Small BWB	27%
	Strut-Braced Wing	29%
	Double Bubble Fuselage	20%
	Strut-Braced Wing with Open Rotor	53%
	Boundary Layer Ingestion	11%
Propulsion Technology	Advanced Turbofan	20%
	Ultrafan	25%
	Open Rotor	30%
Eletric Aircraft	Zunum Aero 50	80%
	Zunum Aero 100	80%
	ATR 72 Fully Eletric [1]	100% [2]
	Embraer 190 Fully Eletric [1]	100% [2]
Aerodynamics Technology	Natural Laminar Flow	4.6%

[1] To analyze the influence that fully electric aircraft can have on global CO_2 emissions, the ATR 72 Fully Electric and the Embraer 190 Fully Electric were considered, with a capacity for 50 and 100 passengers, respectively.
[2] Assuming that energy does not come from fossil fuels.

The capacity in terms of passengers and cargo carried by each concept was defined according to the capacity of the aircraft used as a reference in the efficiency calculations published in the literature. The capacities of all the concepts and aircraft simulated in this work are listed in Appendix B in Table B.1.

In order to assess all the concepts presented in section 3.3, the following scenarios were created:

- *Business As Usual (BAU)*
- *Scenario 1 - New aircraft programs introduced by 2020*
- *Scenario 2 - Imminent new technologies*
- *Scenario 3 - New aircraft configurations (BAD)*
- *Scenario 4 - New aircraft configurations (BEST)*
- *Scenario 5 - Radically newer propulsive designs*
- *Scenario 6 - Towards electrification*

Scenario 3 and *Scenario 4* play the role of demonstrating the ability to reduce the fuel consumption that new aircraft configurations can achieve if they are implemented in the aviation sector. The difference between them is that *Scenario 3* within the configurations to be analyzed groups those with lower fuel efficiency. On the other hand, *Scenario 4* groups the most efficient configurations.

In order to assess two important aspects highlighted in the literature, namely the entry year of the technologies and the production capacity of the aircraft, four analysis have been created. For each case it has the following characteristics:

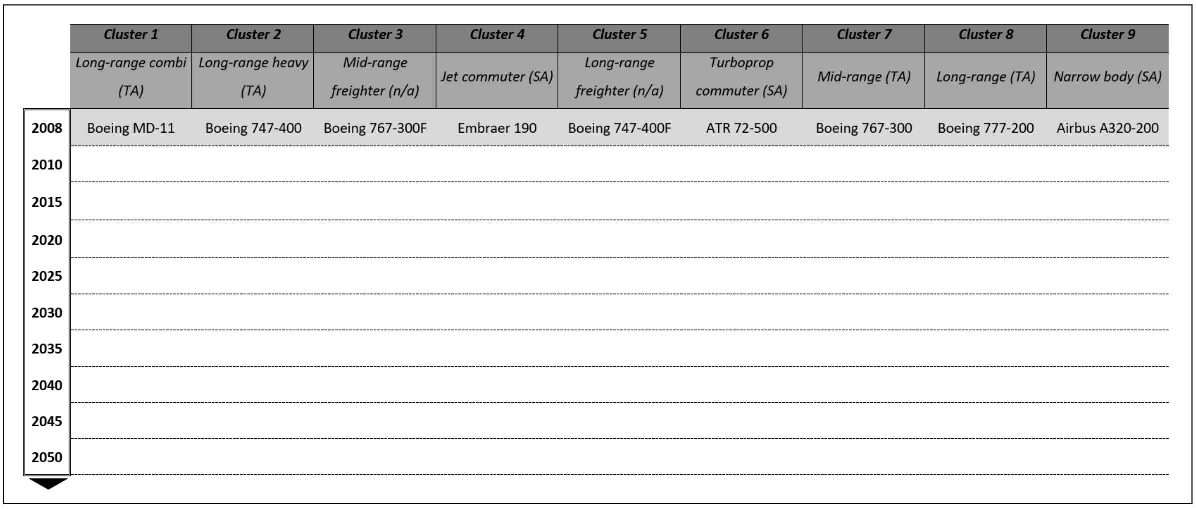
- **Case 1** - The technologies introduced up to the year 2020 are constant for all scenarios, except for scenario BAU;
- **Case 2** - The technologies introduced up to the year 2025 are constant for all scenarios, except for scenario BAU;
- **Case 3** - In this case, it is considered that Case 1 has an increase in aircraft production capacity of 15%;
- **Case 4** - In this case, it is considered that Case 2 has an increase in aircraft production capacity of 15%;

Table 3.8: Summary of technological cases for all the scenarios.

Cases	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Case 1	x	x	x	x	x	x
Case 2			x	x	x	x
Case 3	x	x	x	x	x	x
Case 4			x	x	x	x

3.4.1 Scenario - Business As Usual (BAU)

The *Scenario BAU* assumes that there is no introduction of new technology into the simulation. This scenario represents a very conservative case in which manufacturers continue to produce the aircraft with more relevance in transport capacity without the development of new vehicle types. In the simulation, this scenario includes only the aircraft that started in 2008, without adding any aircraft until 2050. Figure 3.16 shows the aircraft assumed in each cluster for *Scenario BAU*.



	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*	*Cluster 5*	*Cluster 6*	*Cluster 7*	*Cluster 8*	*Cluster 9*
	Long-range combi (TA)	*Long-range heavy (TA)*	*Mid-range freighter (n/a)*	*Jet commuter (SA)*	*Long-range freighter (n/a)*	*Turboprop commuter (SA)*	*Mid-range (TA)*	*Long-range (TA)*	*Narrow body (SA)*
2008	Boeing MD-11	Boeing 747-400	Boeing 767-300F	Embraer 190	Boeing 747-400F	ATR 72-500	Boeing 767-300	Boeing 777-200	Airbus A320-200
2010									
2015									
2020									
2025									
2030									
2035									
2040									
2045									
2050									

Figure 3.16: Aircraft modeled on BAU scenario.

3.4.2 Scenario 1 - New Aircraft Programs Introduced by 2020

Scenario 1 aims at assessing the most efficient aircraft programs introduced in the world fleet so far. The aircraft introduced are the Boeing 747-800, Embraer 190 E-2, Boeing 747-8F, ATR advanced, Airbus A330neo, Airbus A350-900, and Airbus A320neo, as shown in Figure 3.17. So far, for Cluster 6 did not have been announced next-generation turboprops aircraft programs or significant improvements to existing products, neither for the Bombardier Q-400 families nor for the ATR. However, as the market will indeed require a further reduction in fuel combustion in this category of aircraft, as was done in the work of Dr. Randt [1], the ATR 72 advanced aircraft[1] is assumed. Figure 3.17 shows the aircraft modeled in each cluster with their respective year of entry into the global fleet.

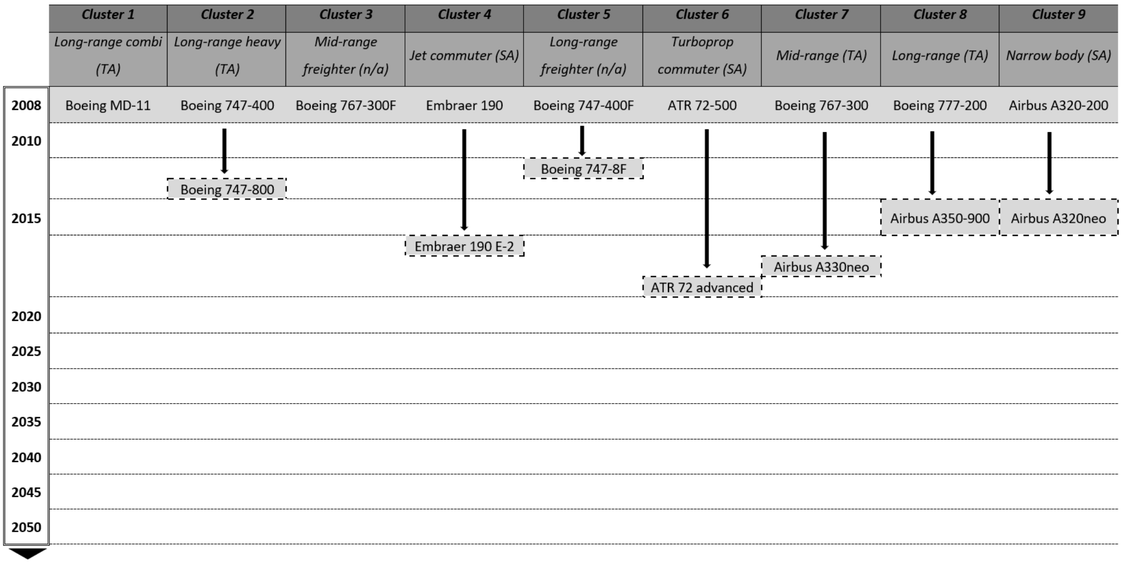


Figure 3.17: Aircraft modeled on Scenario 1.

3.4.3 Scenario 2 - Imminent New Technologies

Scenario 2 represents the technological evolution of aircraft until 2025. Therefore in this scenario the aircraft and technologies expected in the aeronautical sector until 2025 are considered. Concepts that are introduced in addition to those added in *Scenario 1* are the Boeing 777X aircraft, the Rolls Royce engines (Advanced Turbofan and Ultrafan)[2], and lastly the Natural Laminar Flow[3]. Figure 3.18 shows the aircraft modeled in each Cluster with their respective year of entry into the global fleet. Represented by the solid line are the technologies added in addition to those analyzed in *Scenario 1*.

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[1] ATR 72 advanced aircraft have a 15% reduction in fuel consumption, a capacity of 68 seats, and with entry into service in 2019.

[2] The engines are applied to Boeing 777-200 aircraft.

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

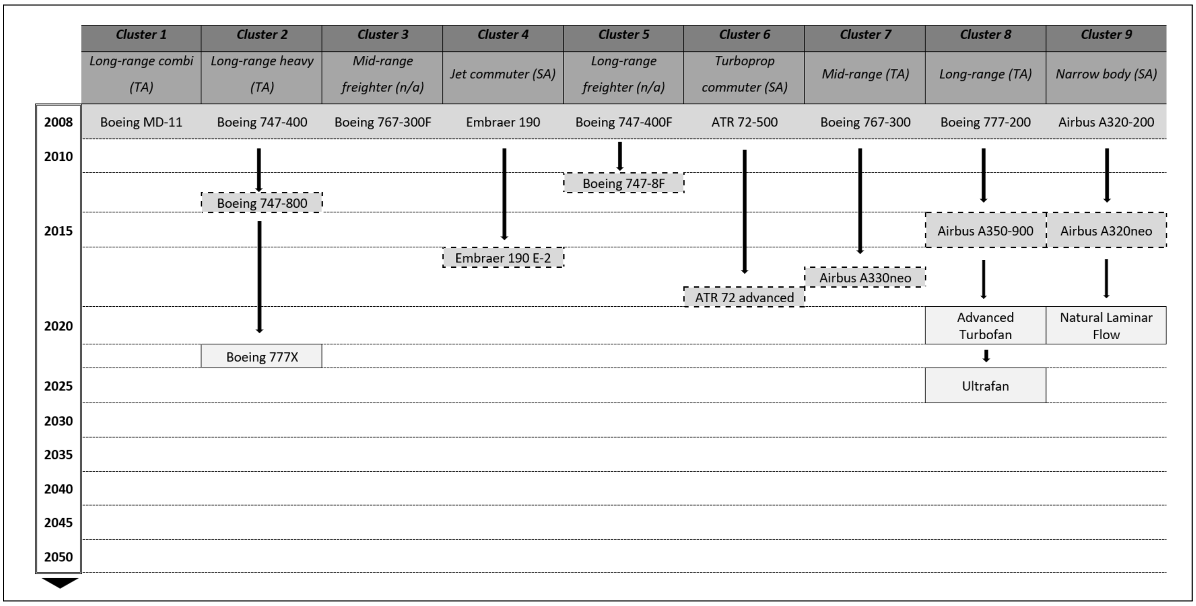

Figure 3.18: Aircraft modeled on Scenario 2.

3.4.4 Scenario 3 - New Aircraft Configurations - *BAD*

Aerodynamic perfection of recent passenger aircraft is going to the “limit” and the struggle is for the decimals of lift-to-drag. In order to achieve a significant breakthrough in this area, it needs new aircraft configurations, which are based on ideas of active or passive flow control. *Scenario 3* introduces the analysis of three new aircraft configurations. In Cluster 2, is inserted the Blended Wing Body with a fuel efficiency of 27% compared to the Boeing 747-400. In Cluster 4, are inserted the Small Blended Wing Body and Boundary Layer Ingestion configurations. The Small BWB has a capacity of 120 seats and fuel efficiency of 27% compared to the Embraer 190. The Boundary Layer Ingestion has a capacity of 120 seats and efficiency of 11% compared to the Embraer 190. Finally, in Cluster 9, the Strut-Braced Wing with a capacity of 150 seats and fuel efficiency of 29% compared to the Boeing 737-800 is added.

3.4.4.1 Case 1

As explained at the beginning of section 3.4 in *Scenario 3*, there are two cases of analysis where aircraft between 2008 and 2025 change. In *Case 1*, the aircraft inserted until 2020 are the same as Scenario 1 (section 3.4.2). These are represented in Figure 3.19 by the dashed line. The solid line represents the aircraft considered for this scenario. Figure 3.19 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 1* in *Scenario 3*.

3.4.4.2 Case 2

For this case, the aircraft inserted until 2025 are the same as Scenario 2 (section 3.4.3). These are represented in Figure 3.20 by the dashed line. The concepts analyzed in this Scenario are represented by solid line. Figure 3.20 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 2* in *Scenario 3*.

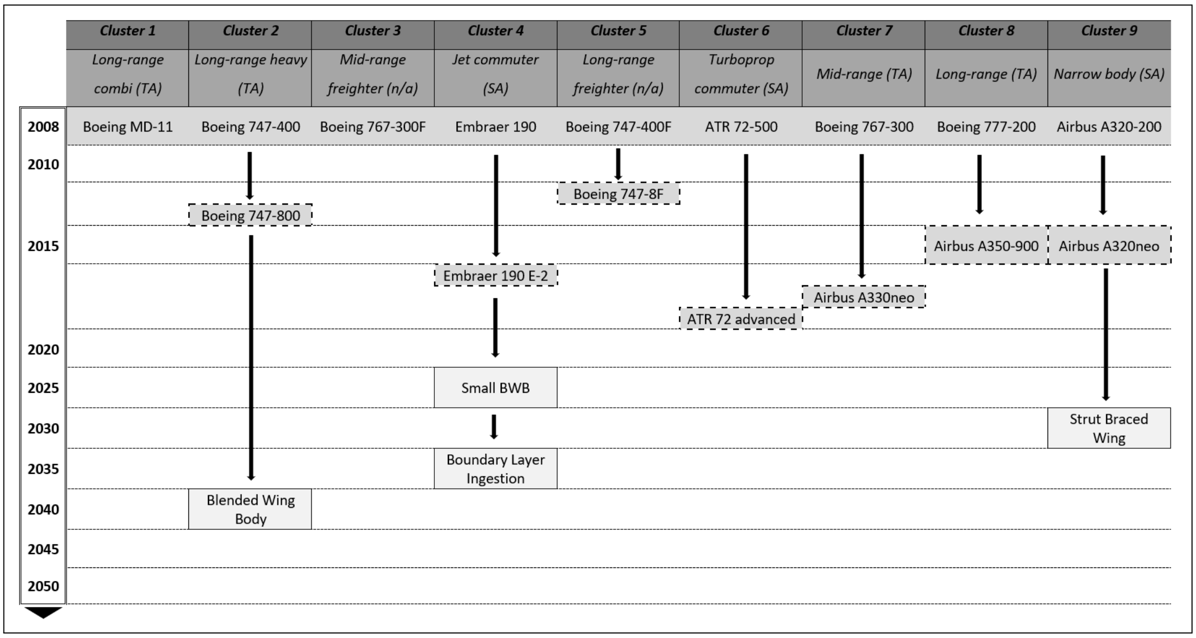

Figure 3.19: Aircraft modeled on Scenario 3 - Case 1.

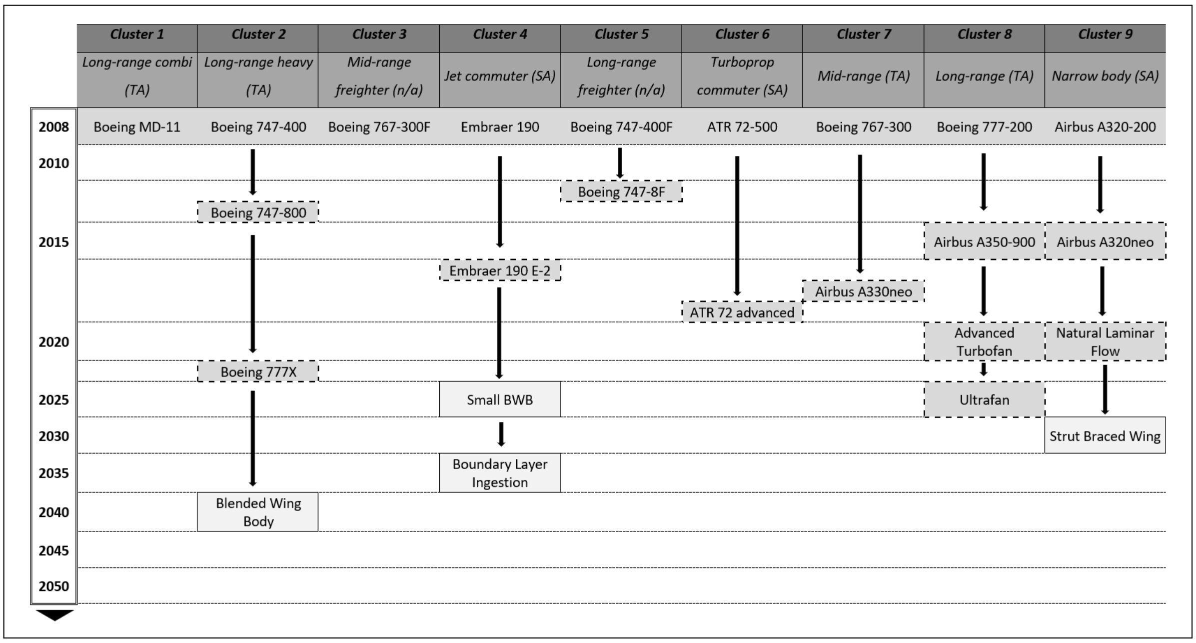

Figure 3.20: Aircraft modeled on Scenario 3 - Case 2.

3.4.5 Scenario 4 - New Aircraft Configurations - *BEST*

Scenario 4 represents the innovative configurations under development to be implemented in the aeronautical sector. Scenario 4 groups the concepts with the highest emissions reduction. In this scenario are considered the Small BWB, Blended Wing Body, Strut-Braced Wing, and Double-Bubble Fuselage configurations. As in Scenario 3, in Cluster 2, the Blended Wing Body is inserted, although it is assumed that it has an efficiency of 50% to evaluate the effects caused by this concept if the efficiency is the most optimistic. In Cluster 4, the Small BWB is maintained with an efficiency of 27%. In Cluster 9, besides of Strut-braced Wing has added in 2045 the Double-Bubble Fuselage concept with an efficiency of 20% compared to

A320neo.

3.4.5.1 Case 1

For this case, the aircraft inserted until 2020 are the same as *Scenario 1* (section 3.4.2). These are represented in Figure 3.21 by the dashed line. The concepts analyzed in this scenario are represented by solid line. Figure 3.21 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 1* in *Scenario 4*.

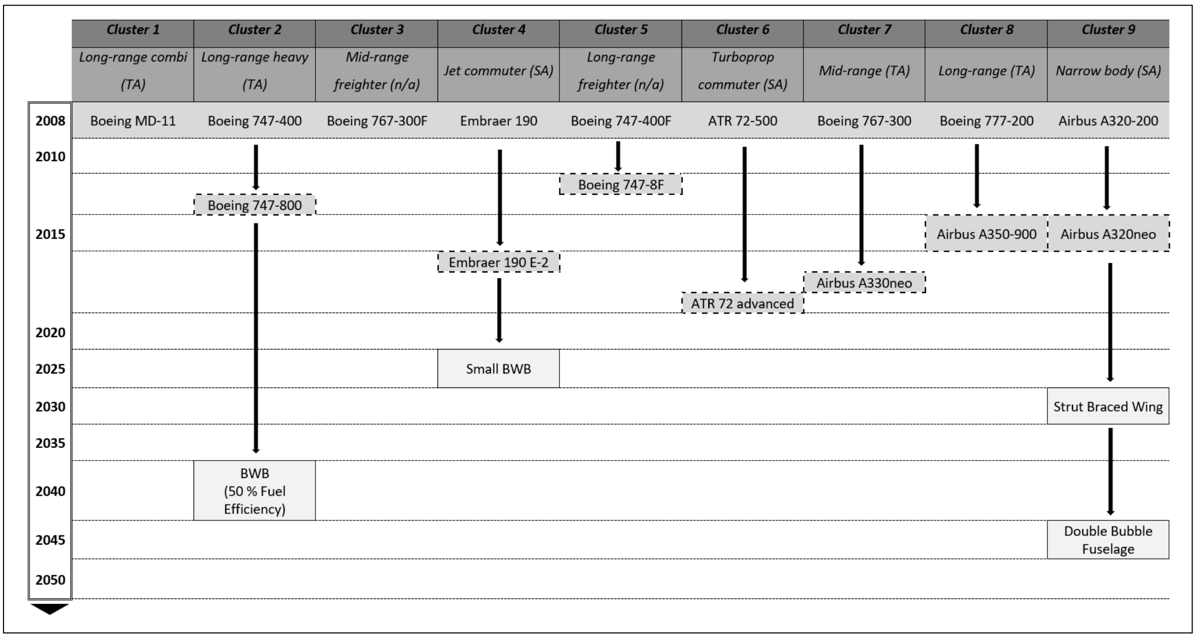

Figure 3.21: Aircraft modeled on Scenario 4 - Case 1.

3.4.5.2 Case 2

For this case, the aircraft inserted until 2025 are the same as *Scenario 2* (section 3.4.3). These are represented in Figure 3.22 by the dashed line. The concepts analyzed in this scenario are represented by solid line. Figure 3.22 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 2* in *Scenario 4*.

3.4.6 Scenario 5 - Radically Newer Propulsive Designs

Scenario 5 examines the ability that the introduction of new engine configurations could have in reducing CO_2 emissions. Therefore, in this scenario, it is inserted in Cluster 2 an aircraft (Open Rotor C2) with an fuel efficiency of 30% compared to the Boeing 747-400. This assumption is to represent if aircraft from 2030 onwards use the Open Rotor configuration. In Clusters 7 and 8, the same procedure is done, adding the aircraft in 2030 with a 30% fuel efficiency.[4] These concepts in Figure 3.23 and 3.24 are called Open Rotor (C2), Open Rotor (C7), and Open Rotor (C8). In Cluster 9, is introduced the Strut-Braced Wing with Open

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[4] The aircraft reference for the fuel efficiency calculation is Boeing 767-300 for Cluster 7 and Boeing 777-200 for Cluster 8.

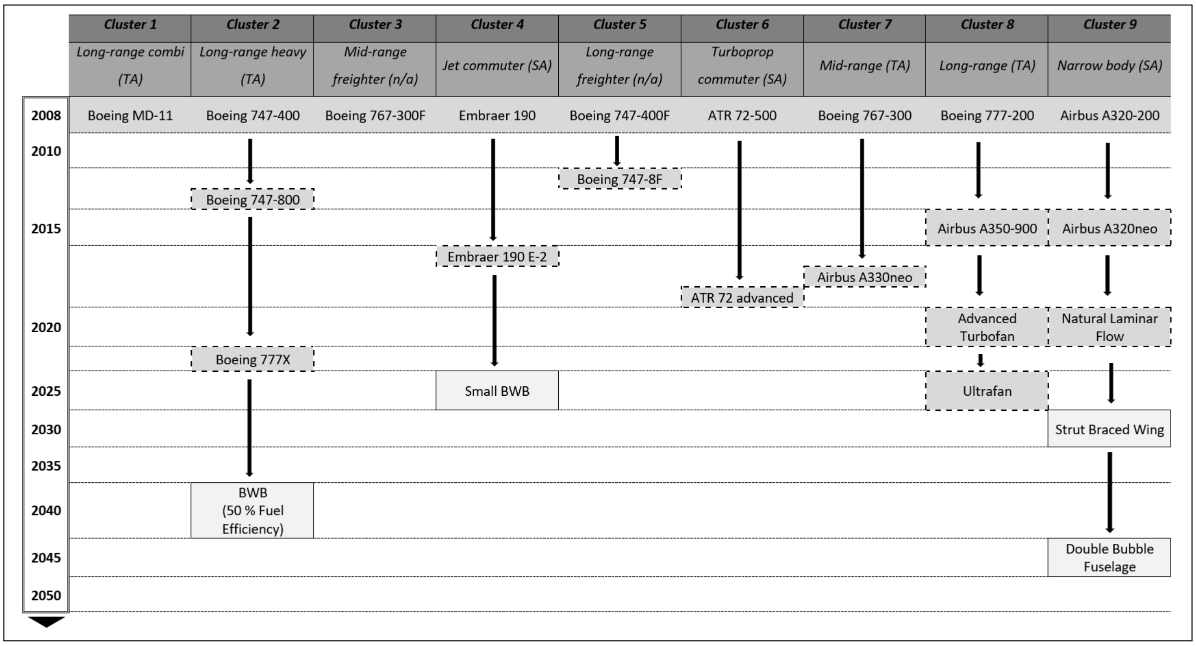

Figure 3.22: Aircraft modeled on Scenario 4 - Case 2.

Rotor in order to assess its performance in reducing emissions from the global fleet, since efficiency is 53% compared to the B737-800.

3.4.6.1 Case 1

For *Case 1* in *Scenario 5*, the concepts that are inserted are represented by the solid line in Figure 3.23. Represented by the dashed line are the aircraft inserted until 2020. Figure 3.23 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 1* in *Scenario 5*.

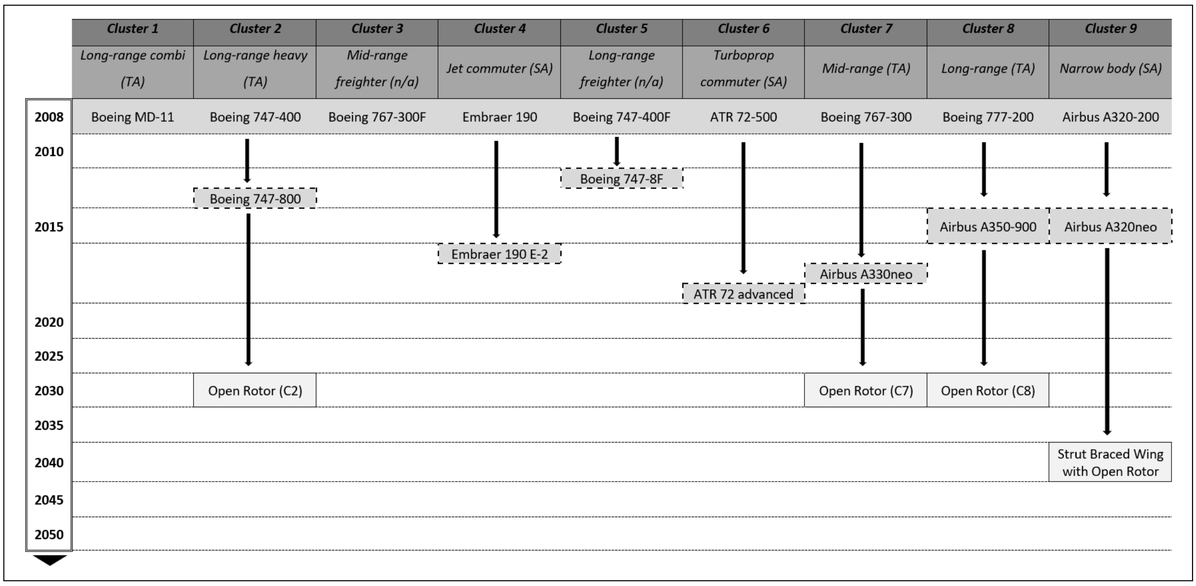

Figure 3.23: Aircraft modeled on Scenario 5 - Case 1.

3.4.6.2 Case 2

For *Case 2* in *Scenario 5*, the concepts inserted are represented by the solid line in Figure 3.24. Represented by the dashed line are the aircraft inserted until 2025. Figure 3.24 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 2* in *Scenario 5*.

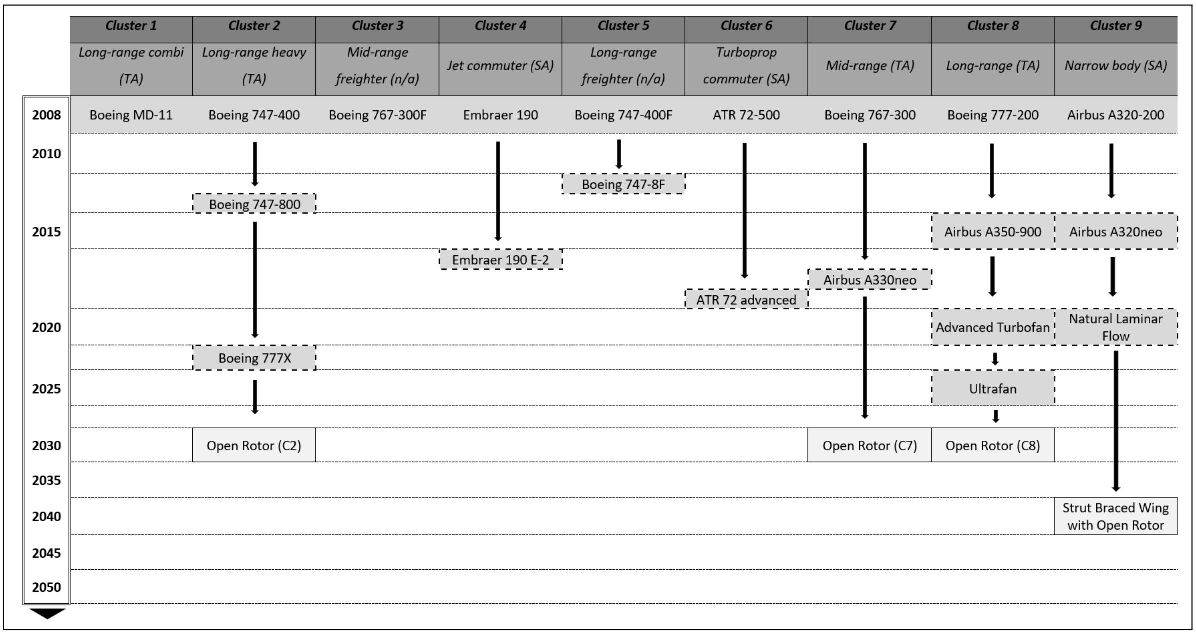

Figure 3.24: Aircraft modeled on Scenario 5 - Case 2.

3.4.7 Scenario 6 - Towards Electrification

Scenario 6 represents the future of aviation towards electric propulsion, using both hybrid and electric propulsion. Given the range and passenger restrictions mentioned in section 3.3.2.6, the concepts considered have been added only to Clusters 4 and 6, as these only operate regional flights. In this scenario, are inserted the Zunum Aero 50 and Zunum Aero 100 aircraft using hybrid propulsion, allowing for an 80% reduction in CO_2 emissions. In addition to these aircraft, are considered the ATR 72 Fully Electric and the Embraer 190 Fully Electric to assess the influence of fully electric aircraft. These are inserted in the global fleet in 2040. In this scenario, the energy used by aircraft is considered to be 100% renewable.

3.4.7.1 Case 1

For *Case 1* in *Scenario 6*, the concepts that are inserted are represented by the solid line in Figure 3.25. Represented by the dashed line are the aircraft inserted until 2020. Figure 3.25 shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 1* in *Scenario 6*.

3.4.7.2 Case 2

For *Case 2* in *Scenario 6*, the concepts that are inserted are represented by the solid line in figure 3.26. Represented by the dashed line are the aircraft inserted until 2025. Figure 3.26

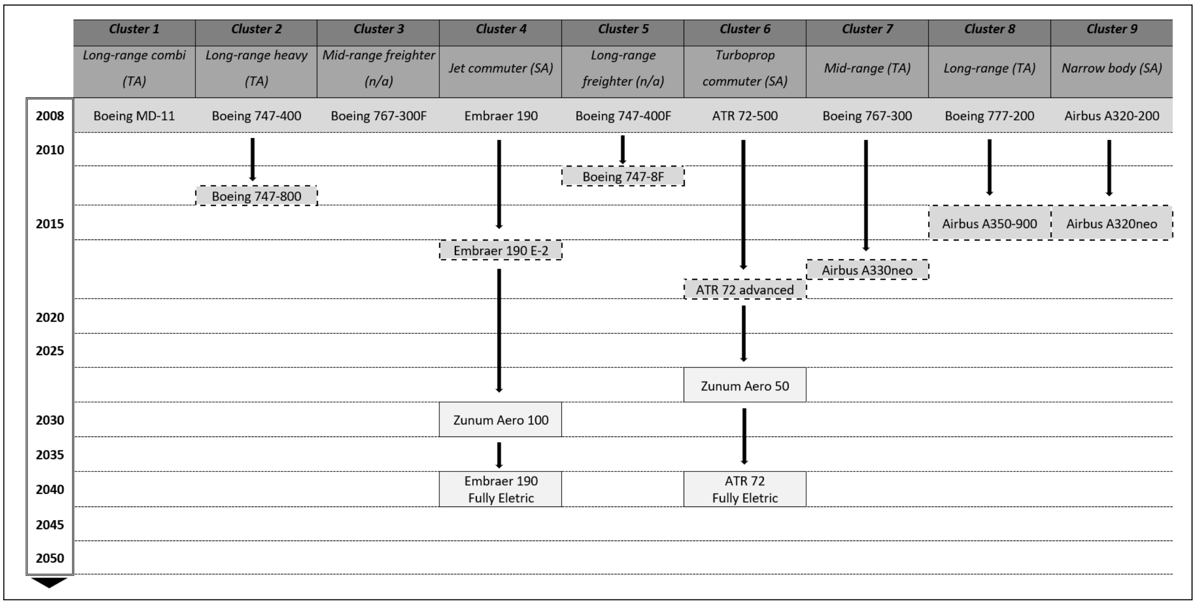

Figure 3.25: Aircraft modeled on Scenario 6 - Case 1.

shows the concepts/aircraft modeled in each Cluster with the respective year of entry into the global fleet for *Case 2* in *Scenario 6*.

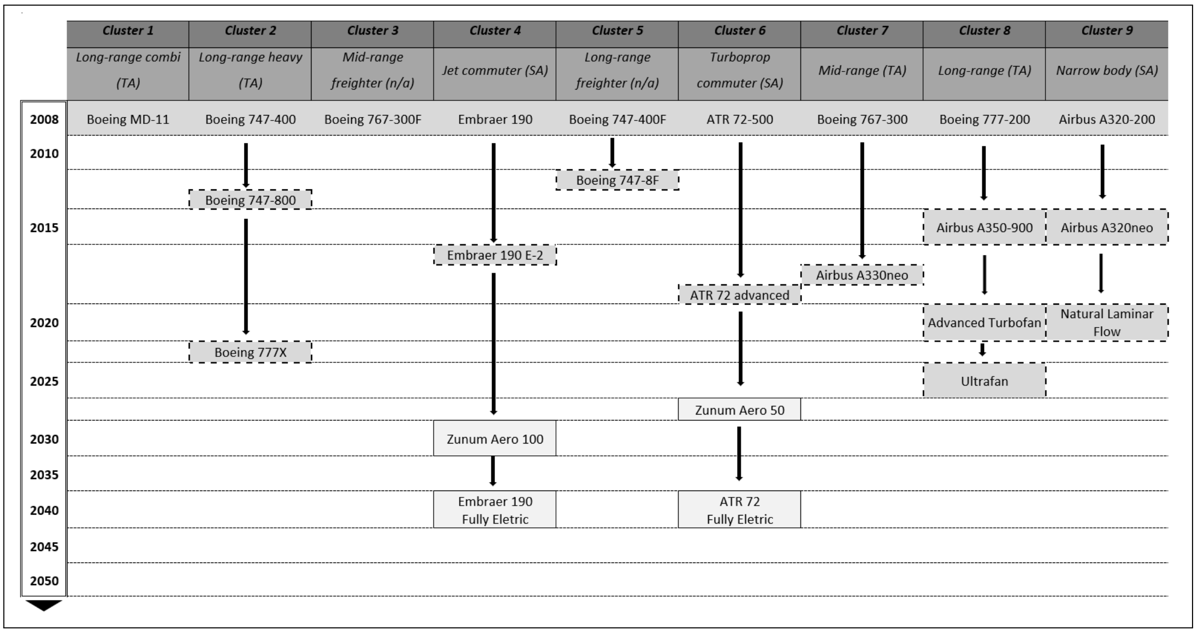

Figure 3.26: Aircraft modeled on Scenario 6 - Case 2.

Chapter 4

Aviation Alternative Fuels

Sustainable Aviation Fuels have become a decisive factor in the aviation industry's strategy to reduce environmental impacts and operating costs. Several organizations, such as biofuel companies, governments, and refinery industry researchers, are working to develop viable and sustainable processes to produce an alternative fuel that has a reduced life-cycle impact on the greenhouse effect and low production costs.

This chapter will address the various alternative fuels already approved by the American Society for Testing and Materials (ASTM) for use in commercial aviation. The respective production processes and life cycles are presented. Finally, the methodology developed to analyze the impact biofuels could have on CO_2 emissions by 2050 is explained.

4.1 Sustainable Aviation Fuels

The aeronautical sector has been, in the last decade, one of those that most invested in more efficient and ecological solutions [72]. One of the most attractive options for reducing CO_2 emissions and decrease dependence of fossil fuel sources in a relatively short period is the introduction of sustainable aviation fuels (SAF) [73, 74]. These must have the same qualities and characteristics as conventional jet fuel in order to be used in existing aircraft [75]. This factor is very relevant because manufacturers do not have to redesign engines or aircraft and also fuel suppliers and airports do not have to build new fuel supply systems [76]. This is one of the reasons why the industry is focused on producing SAF, in order to replace the conventional jet fuel [59]. 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 [77, 78].

The certification and qualification of any alternative aviation fuel should follow the requirements specified by the organization responsible for aviation fuels. The organization responsible for the certification of aviation fuels is ASTM International [79]. At the moment, seven production pathways have been certified for blending with conventional aviation fuel. Table 4.1 shows the approved conversion processes with the respective possible feedstocks and the blending ratio by volume.

The technological maturity of each production pathway can be defined through the Technology Readiness Level (TRL) [80], which ranges from 1 for basic principles observed, up to 9

Table 4.1: Conversion processes approved [79].

Conversion Process	**Abbreviation**	**Possible Feedstocks**	**Blending ratio by Volume**
Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	FT-SPK	Coal[1], natural gas[1], biomass	50%
Hydroprocessed Esters and Fatty Acids	HEFA-SPK	Bio-oils, animal fat, recycled oils	50%
Synthesized Iso-Paraffins	HFS-SIP	Biomass used for sugar production	10%
Fischer-Tropsch Synthesized Paraffinic Kerosene with Aromatics	FT-SPK/A	Coal[1], natural gas[1], biomass	50%
Alcohol-to-Jet Synthetic Paraffinic Kerosene	ATJ-SPK	Biomass used for starch and sugar production and cellulosic biomass for isobutanol production	30%
Catalytic Hydrothermolysis	CHJ-SPK	Bio-oils	50%
Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids	HC-HEFA-SPK	Hydroprocessed hydrocarbons, esters and fatty acids	10%

[1] These feedstocks are not renewable consequently are not appropriate for SAF production, alternately these could be used to produce alternative aviation fuel for military applications.

for an actual system proven in operational environment. Defining the maturity level of each biofuel production pathway, both technologically and commercially, can be difficult, as only a few ASTM certified pathways are supplying fuel on a commercial scale and the commercial development of a certain fuel could be different due to various other factors, for example, certification and cost issues. To better clarify the progress of biofuel production towards commercialization the Fuel Readiness Level (FRL) [81] was developed, the US Commercial Aviation Alternative Fuels Initiative was the one who develop this indicator which was later supported by ICAO. The FRL also ranges from 1 for basic principles observed, to 9 for established production capacity. Table 4.2 shows the FRL and TRL of processes that have been approved by ASTM.

Table 4.2: TRL and FRL of the seven production pathways certified by ASTM for use in commercial flights.

Production Pathway	**TRL**	**FRL**
FT-SPK	6-8	7
HEFA-SPK	9	9
HFS-SIP	7-8	5-7
FT-SPK/A	6-7	7
ATJ-SPK	6-7	7
CHJ-SPK	7-8	6-7
HC-HEFA-SPK	6-7	6

The only process that can establish production on a large scale is HEFA-SPK, the other processes are still in the phase of full-scale technical evaluation, fuel approval (fuel class/type listed in international fuel standards), and Commercialization Validated.

4.1.1 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 come from more sustainable sources. It is also noteworthy that triglycerides, and the building blocks of fats and oils, are the main feedstock.

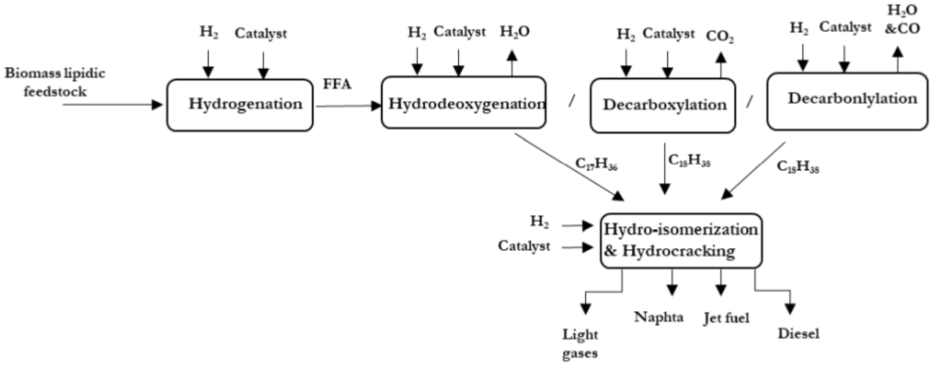

Figure 4.1: General process flow HEFA pathway [82].

Figure 4.1 shows the general process flow of HEFA pathway. 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 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 [82, 83, 84].

4.1.2 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 H_2). 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. To increase the efficiency of the thermochemical process involved, the feedstocks indicated above must have high concentrations of carbon and hydrogen [33]. Figure 4.2 shows the general process flow of FT pathway.

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

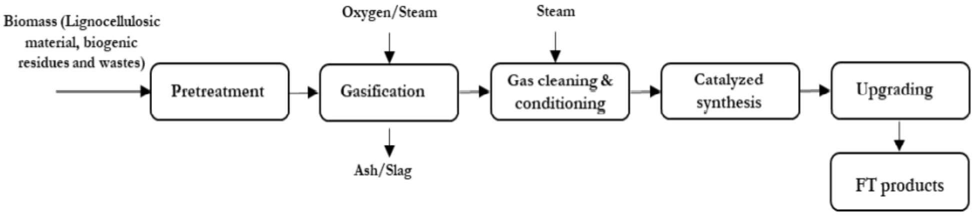

Figure 4.2: General process flow Fischer-Tropsch pathway [82].

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 [83].

4.1.3 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.

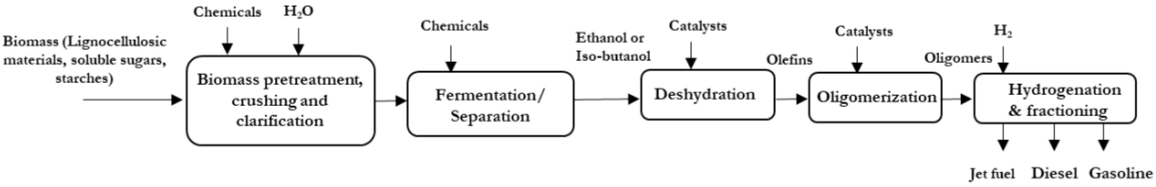

Figure 4.3: General process flow Alcohol-To-Jet pathway [82].

Figure 4.3 shows the general process flow of ATJ pathway. 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, alcohols can be produced through fermentation processes. ATJ obtained from ethanol or butanol intermediates are allowed in a maximum mixture of 30% [82, 83, 84].

4.1.4 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.

Figure 4.4 shows the general process flow of SIP pathway. 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

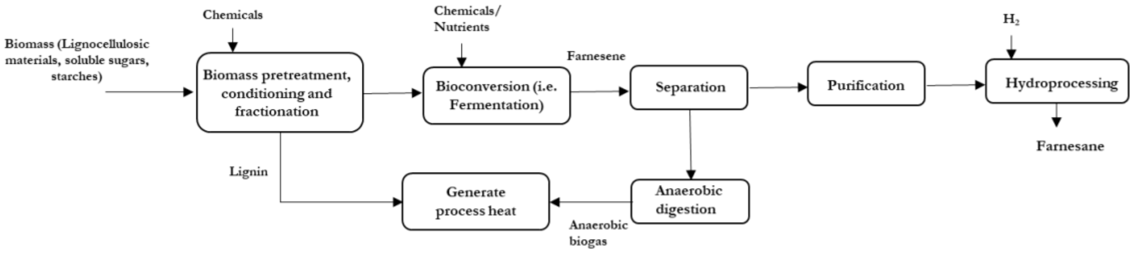

Figure 4.4: General process flow Synthesized Iso-Paraffins pathway [82].

is possible to mix up to 10% by volume of the SIP component with conventional Jet A or Jet A-1 fuel [82].

4.2 Life Cycle Assessment - Alternative Fuels

The method normally used to assess technologies, processes and products is the Life Cycle Analysis (LCA). LCA in transport is applied in order to assess the environmental impacts caused both on human and ecological health, water consumption, land use changes and biodiversity [85].

In the case of fuel production, the LCA structure can be used to assess the emissions and environmental impact throughout the production cycle. The methodology used in these analyses is usually standardized within a normative context, such as the EU Renewable Energy Directive (RED) and US Renewable Fuel Standard (RFS). There are some standardized calculation methods and tools, such as SimaPro, GREET, BioGrace and GHGenius [84].

The processes that are included in the LCA are determined through the LCA system boundary. This should be consistent with the objectives of the LCA study [86]. The system boundary of the LCA values considering on the present work is presented in Table 4.3, that consists of the entire supply chain of the production and use of SAF. The emissions of the stages that are counted, as shown in Figure 4.5 are 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 [82].

Table 4.3 shows the values for emissions generated during operational activities, such as the operation of a fuel production facility and feedstock cultivation, as well as emissions incorporated in all used utilities, such as chemical processing, electricity and natural gas. Although, emissions during the construction and manufacturing activities of, e.g., fuel production facilities, are not included.

According to Figure 4.5, 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, it is considered that there are no greenhouse gas (GHG) emissions during the feedstock production step of the life cycle, however, the emissions generated during their collection, recovery and extraction, and processing of wastes, residues and by-products are considered.

The functional unit selected for the LCA results, shown in Table 4.3, is grams of CO_2 per Mega Joule [MJ] of fuel produced ($g\text{CO}_2e/MJ_{SAF}$) and combusted in an aircraft engine (using the lower heating value characterizing fuel energy content).

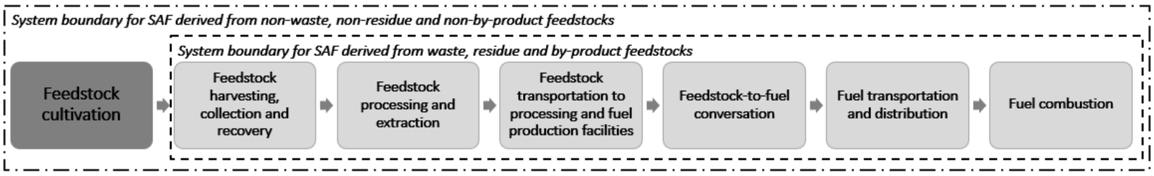

Figure 4.5: System boundaries and life cycle steps [82].

Table 4.3: Summary of LCA values to date [82].

Conversion process	**Feedstock**	**LCA value [gCO_2e/MJ]**
Fischer-Tropsch	Agricultural residues	7.7
	Forestry residues	8.3
	MSW	5.2
	Short-rotation woody crops	12.2
	Herbaceous energy crops	10.4
Hydro-processed 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	42.0
	Palm oil- close pond	37.4
	Palm oil-open pond	60.0
	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

4.3 Supply Evolution of Alternative 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 [87]. 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 Figure 4.6 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 4.4 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 for Sustainable Aviation Fuels and ICAO Stocktaking Seminar on aviation in-sector CO_2 emissions reductions. As shown in Figure 4.6, 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 SAF production scenario. [1]

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 (MSW). Table 4.4 shows the projected production, based on the data collected for HEFA, FT and ATJ until 2030.

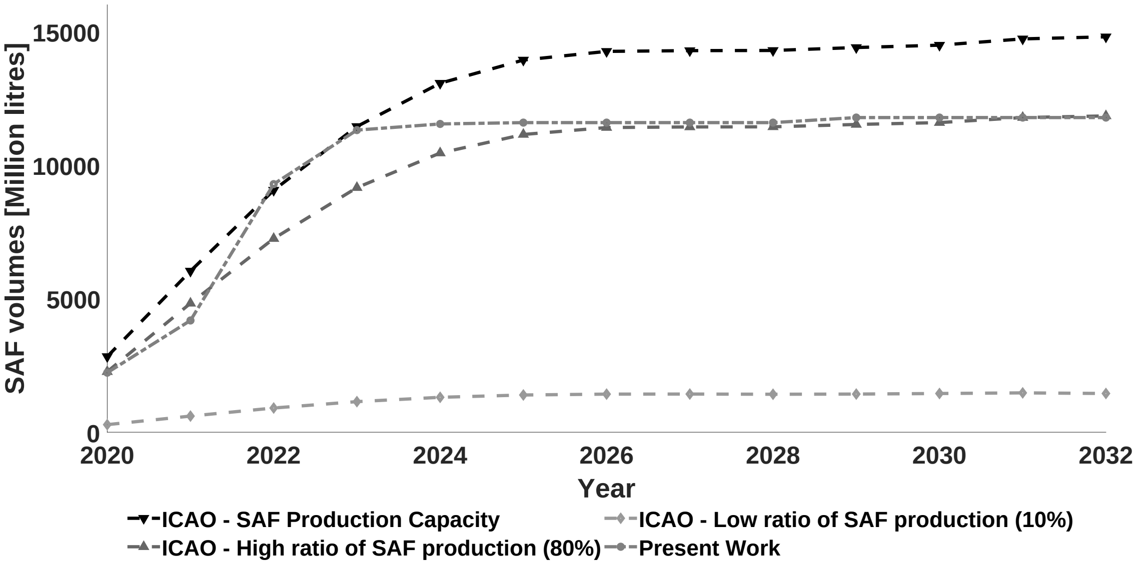

Figure 4.6: Projected scenarios of SAF production.

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[1] The data used for the SAF production was collected from https://www.icao.int/environmental-protection/Pages/SAF-Stocktaking.aspx. Accessed: 02/07/2020

Table 4.4: Estimated production of SAF for each process.

	Conversion Process		
Year	**HEFA [Mt]**	**ATJ [Mt]**	**FT [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

4.4 Biofuels Impact Analysis

The analysis of the impact of biofuels was based on the formula provided by the CAEP Market-Based Measures Task Group [33]. This formula allows to analyze the introduction of sustainable fuels using the amount of available biofuel and the life cycle of the respective biofuel. Figure 4.7 shows the equation and the methodology developed, where:

- $CJF(t)$ - 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} - is the life cycle of conventional jet fuel ($89gCO_2e/MJ$);
- $CO_2\ Emissions(t)$ - total emissions in kilograms of CO_2 for the respective year t;
- t - year of simulation.

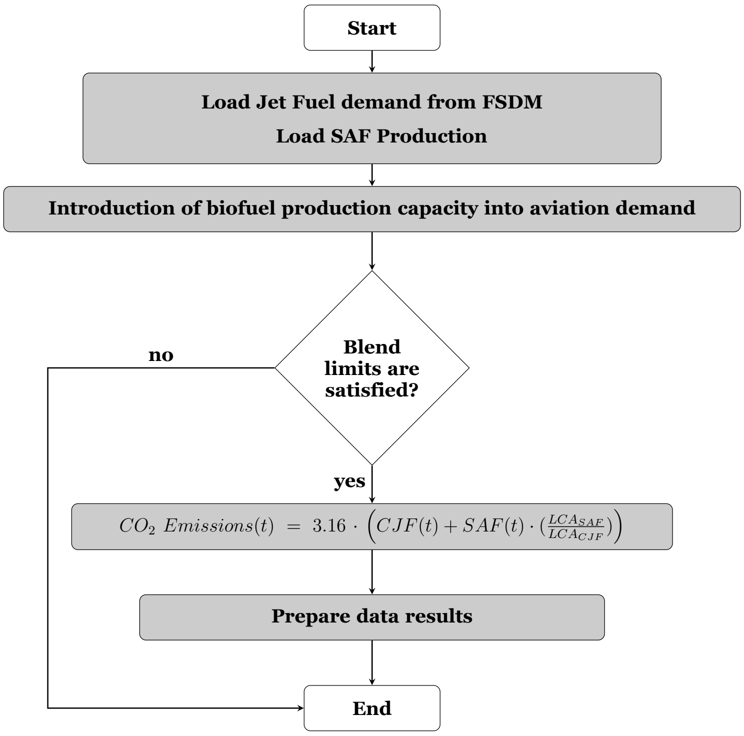


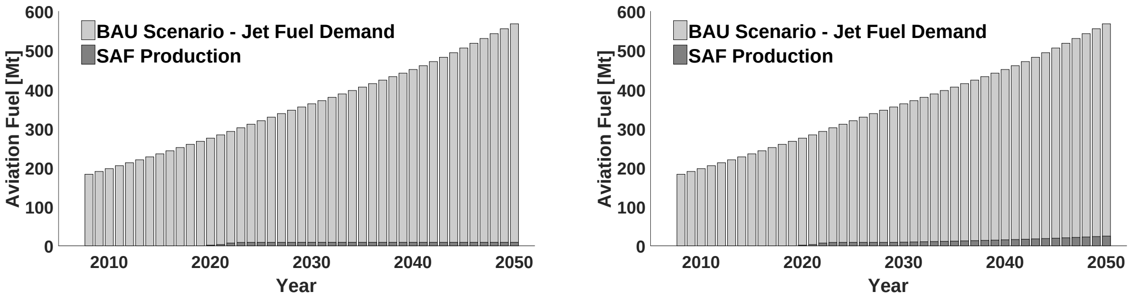
Figure 4.7: Flowchart of the methodology developed.

According to Figure 4.7, 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 for each year.

As seen in Figure 4.6, the forecast of SAF production is limited until 2032 and from 2030 begins to stabilize because there is no more information on the introduction of new plants for biofuel production, 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 Figure 4.6 keeping the value constant between 2030 to 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. Figure 4.8 shows the SAF production for each scenario and the Jet Fuel demand for the BAU Scenario.

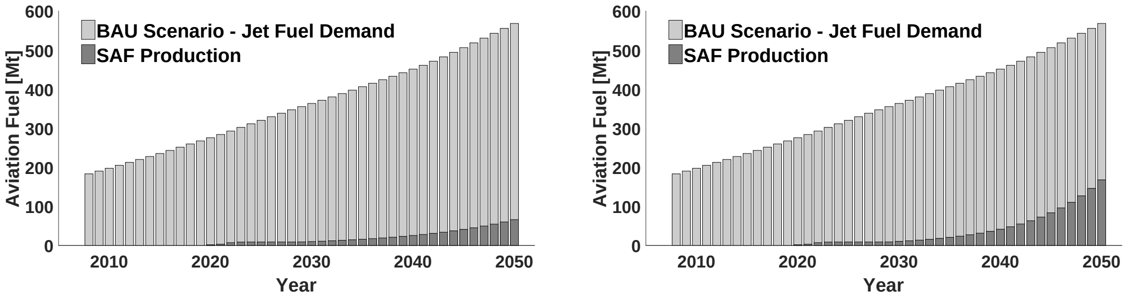
The reason for the highest annual rate being 15% is because if a rate greater than 17% was considered, the blend limits will not be satisfied since it is assumed that all SAF produced is introduced into the fleet fuel burn and the corresponding amount of jet fuel is retired to maintain the same fuel demand in each year. Consequently, with rates higher than 17%, there is not the required amount of jet fuel to meet the blend limits.

In addition to the four scenarios 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, as shows Table A.1 in Appendix A, 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

Figure 4.8: SAF production and Jet fuel demand.[2]

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[2] Jet Fuel demand resulted from the simulations performed in the present work for BAU Scenario.

Chapter 5

Results and Discussion

This chapter presents the results and their respective analysis for the various scenarios and cases. The following studies have been performed:

- A forecast of transport performance, fuel burn and CO_2 emissions of the global fleet for the years 2008-2050;
- Sensitivity analysis regarding selected aircraft production capacity assumption and the entry into service date of future aircraft types;
- An analysis of the introduction of SAF in the aeronautical sector CO_2 emissions.

Section 5.1 presents the CO_2 emissions forecast for the BAU scenario obtained using the ARIMA model for the global case and Europe. This section also compared the results of both FSDM and ARIMA models. In section 5.2 the results regarding the global fleet emissions for the various scenarios and analysis cases representing the technological improvements are presented. Sensitivities of aircraft production capacity assumption and the entry into service of future aircraft types are also evaluated in this section. Section 5.3 presents the results of the analysis of the introduction of SAF in the aeronautical sector. Finally, section 5.4 presents the combined effect of technological progress with the introduction of alternative fuels, and the respective analysis of whether it will be possible to decarbonize the sector.

5.1 Air Traffic Emissions Forecast

As explained at the beginning of Chapter 3, the ARIMA statistical model was used in the preliminary phase to forecast emissions for the BAU scenario for seven regions and the global case. This section presents the results obtained and a comparison between the results of the ARIMA model and the FSDM.

The results of CO_2 emissions, from the global consumption of jet fuel, were achieved by grouping the forecasts of the seven regions analyzed. Table 5.1 shows the variations of the ARIMA(P,Q,D) model employed to obtain the best possible forecast. The table also shows the two indicators used to assess the accuracy of the results. The accuracy of the results obtained for almost all regions is highly accurate (MAPE<10%), except for the Middle East and Eurasia regions. However, the forecast for the Middle East region is considered a good forecast (10%<MAPE<20%), and for Eurasia is a reasonable forecast (30%<MAPE<50%). The fact that it was not possible to obtain a better accuracy for Eurasia is due to the fluctuations in historical data resulting from the dissolution of the USSR. By grouping all these regions was achieved a MAPE of 3.1% for the global forecast. This forecast of CO_2 emissions is highly accurate. The calculation of the accuracy was performed using historical data from 1990-2017. Figure 5.1 shows the forecast for Scenario BAU resulting from the statistical model.

Table 5.1: RMSE and MAPE values of CO_2 emissions forecasting models.

Region	**Africa**	**Asia & Oceania**	**Central & South America**	**Eurasia**	**Europe**	**Middle East**	**North America**	**World**
Model	ARIMA(1,1,3)	ARIMA(2,1,3)	ARIMA(1,1,3)	ARIMA(4,1,2)	ARIMA(0,1,1)	ARIMA(2,1,3)	ARIMA(0,1,1)	-
MAPE [%]	4.62	6.84	8.74	35.41	5.04	13.28	8.28	3.10
RMSE [Mt]	1.62	18.98	3.69	15.94	9.36	5.07	23.74	29.98

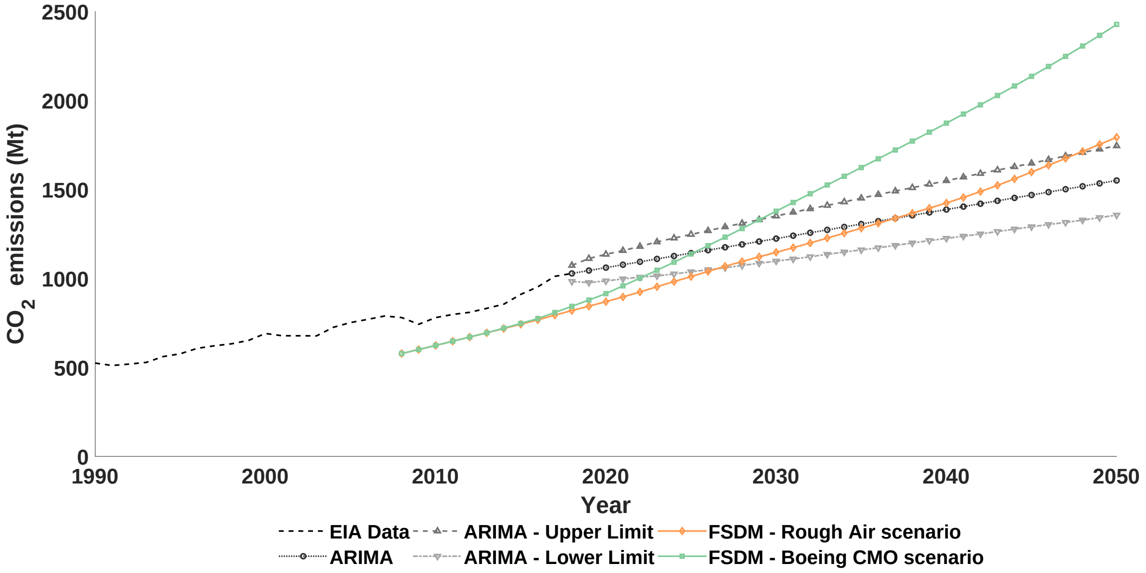


Figure 5.1: Scenario BAU for both ARIMA and FSDM models.

In addition to the CO_2 emissions forecast for the ARIMA model, Figure 5.1 presents the limits of the forecast with a 95% confidence interval. The results of the FSDM simulations for the BAU scenario are presented in this figure to compare the results. It should be noted that for the simulations performed in the present work was analyzed the influence of different evolutions of the aviation markets on CO_2 emissions. For this purpose, two alternative future scenarios published by Dr. Randt [1] are used to handle the uncertain development of the global commercial air transport market. The first option is the Boeing CMO scenario, which represents an optimistic scenario for the next two decades and then extrapolated to 2050. The second option is the Rough Air scenario, which represents a rather pessimistic outlook on the future of commercial aviation, this describes a mediocre image of the industry's perspective as opposed to the Boeing CMO scenario. The respective growth rates (RPKs/RTKs) for each route group of both scenarios are in Appendix B in the Tables B.3, B.4, B.5, and B.6.

As shown in Figure 5.1, the scenario in terms of growth of the sector that is closest to the evolution in terms of emissions is Rough Air scenario. The main reason is that in the Boeing CMO Scenario exists a strong economic growth and market liberalization, increasing the number of operations and aircraft leading to an increase in CO_2 emissions. Therefore, for all the simulations performed in the present work, the growth factors (RPK/RTK grow factors) of the sector used were those represented in the Rough Air Scenario. The differences between the FSDM results and the EIA data from 2008-2017 are because historical data contain all jet fuel consumption worldwide, while in the simulations performed with FSDM, it is not possible to take into account emissions from military and particular domestic flights.

Figure 5.2 shows the forecast CO_2 emissions from the aeronautical sector in Europe. Appendix D presents the results for the other regions. Between 2000 and 2050, CO_2 emissions are predicted to more than double if no strategies are introduced to mitigate the sector's impact, more specifically improvements in existing technologies and the use of alternative fuels. In Figure 5.2, it is possible to observe the impact of the financial crisis (2008/2009) and the terrorist attack on the World Trade Center (2001), since there was a notable reduction in emissions in those years. However, despite these retractions in the economy, the aeronautical sector is characterized by strongly emerging and returning to the long term trend.

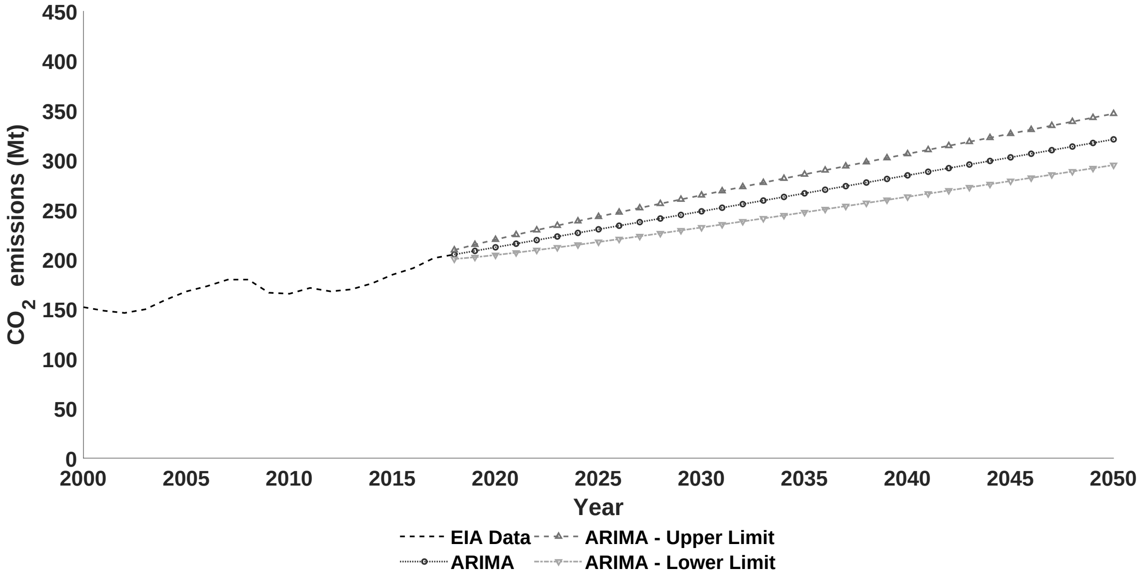


Figure 5.2: Scenario BAU for Europe.

5.2 Technological Improvements Scenarios

This section presents the results for the various cases and scenarios representing technological progress. These make it possible to quantify the emissions reduction resulting from the evolution of technology. The following subsections will present the results for each case.

5.2.1 Case 1

In this subsection, the results for Case 1 are presented. This case has the peculiarity that the technologies introduced up to the year 2020 are constant for all scenarios, except for scenario BAU. Figure 5.3 shows emissions reduction for the six scenarios compared to the BAU scenario until 2050.

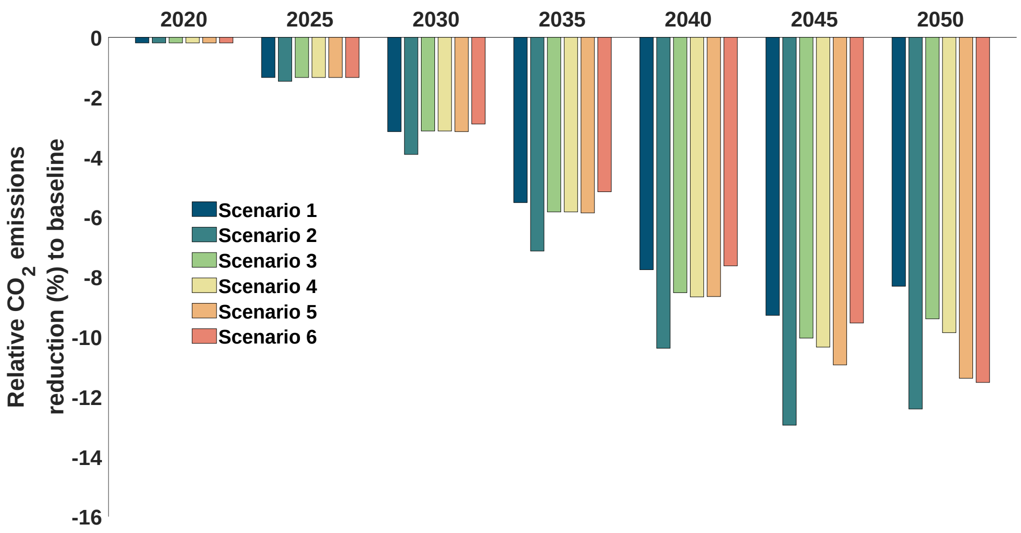


Figure 5.3: Fleet-level CO_2 emissions reductions from 2020 to 2050 of Case 1 relative to baseline.

Analyzing the graph of Figure 5.3, the scenario that allows the most significant emissions reduction for these scenarios is Scenario 2, which corresponds to the imminent technologies that are about to enter the market. At first glance, it may not seem to make much sense as the other scenarios have higher efficiencies than Scenario 2. However, in the other scenarios, entry into service is later than 2025, and the production capacity in the first years tends to be lower. So these scenarios can not achieve such high reductions compared to Scenario 2 as the technologies in Scenario 2 enter between 2020 and 2025, allowing production capacity to be already considerable by 2050.

According to Figure 5.3, the results show that the introduction of new aircraft has a significant impact on fuel consumption, showing that they are indispensable for decarbonizing the sector. In 2050 the reductions in CO_2 emissions compared to the baseline are 8.3% and 12.4%, for scenarios 1 and 2, respectively. 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.

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 major 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 the increase of the percentage reduction in emissions, the aircraft added should be more efficient compared to those being added.

Equation (5.1) represents an additional way of assessing which scenario allows further emissions reductions considering also the transport supply capacity. The CO_2 *performance* corresponds to the amount of CO_2 produced in grams per available seat kilometer.

$$CO_2\,performance = \frac{fleet\,CO_2\,emisions\,[grams]}{total\,ASK} \quad (5.1)$$

Figure 5.4 shows the year-on-year variations in CO_2 performance of the global fleet for the various scenarios. From this graph, it can be seen that CO_2 *performance* decreases for all scenarios except for BAU, which maintains a constant value since there is no introduction of new technology into the simulation. The scenario with the lower CO_2 *performance* is Scenario 2, reaching 74.8 [grams of CO_2 per ASK] in 2050. The second lower value of CO_2 *performance* is achieved by Scenario 5, reaching 76.4 [grams of CO_2 per ASK] in 2050.

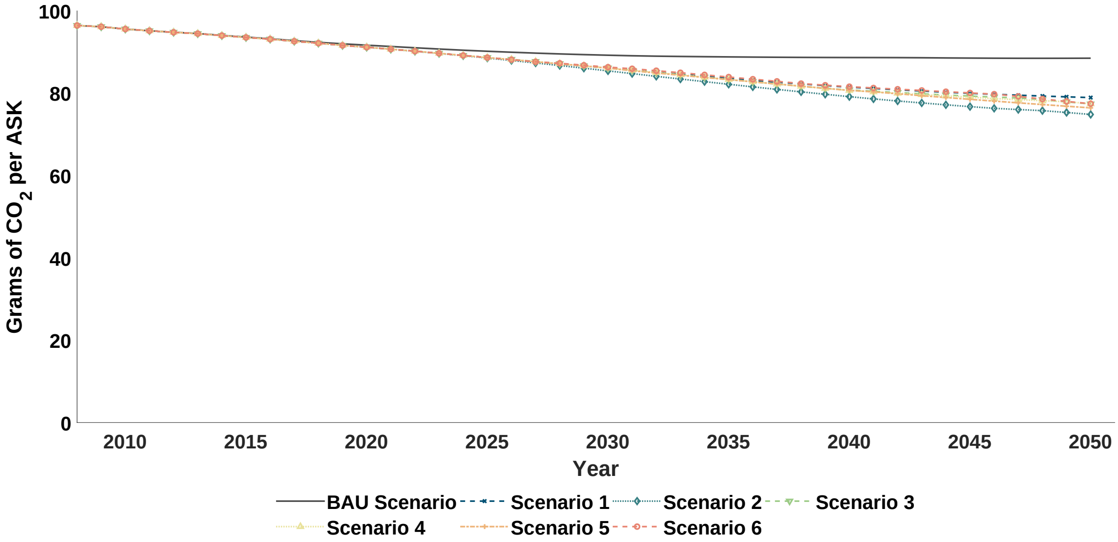


Figure 5.4: CO_2 performance for Case 1.

Figure 5.5 shows the evolution of CO_2 emissions for the global fleet according to each scenario. As explained before, the scenario with higher reduction on CO_2 emissions is Scenario 2. According to the results for Scenario 2, the possible emissions for the global fleet by 2050 will be 1570 Mt, compared to BAU Scenario is a reduction of 222 Mt. In conclusion, technologies introduced by 2025 can lead to a reduction of 222 Mt of CO_2 emissions by 2050, which highlights the importance of technology development in emission reduction strategies.

5.2.2 Case 2

In this subsection, the results for Case 2 are presented. This case has the peculiarity that the technologies introduced until 2025 are constant for all scenarios, except for scenario BAU. Therefore, in this case, only Scenarios 3, 4, 5, and 6 are considered. This sensitive analysis of considering the technologies implemented until 2025 was performed, since the scenario that produced the highest emission reductions in Case 1 was Scenario 2, as it includes the introduction of new aircraft by 2025. In order to better assess the capability of emissions reduction of the other scenarios, Case 2 has been created as described and presented in sec-

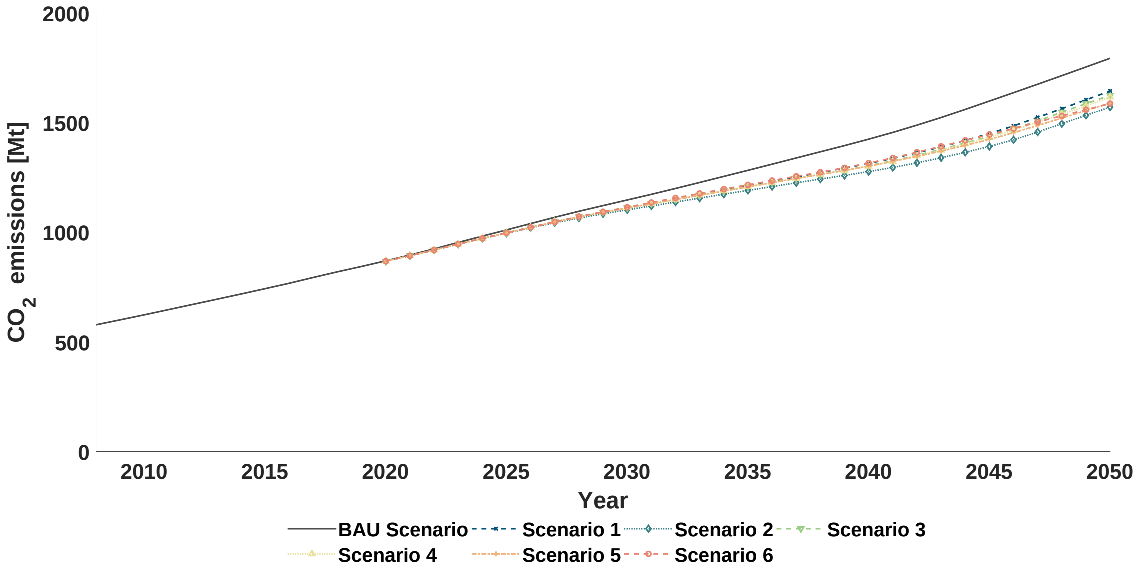


Figure 5.5: Fleet-level CO_2 emissions from 2008 to 2050 of Case 1.

tion 3.4. The following graphics will show the results of Scenarios 1 and 2 of Case 1 to allow comparison with the results of Case 2.

For Case 2, as shown in Figure 5.6, it is possible to observe emissions reduction of CO_2 for Scenarios 3, 4, 5, and 6. In this case, considering the technologies introduced until 2025 in these four scenarios, they stand out for their potential reductions in fuel consumption. In Case 1 this potential reduction in fuel consumption were overcome by Scenario 2 because the EIS proved to be an important factor in emissions reduction until 2050. The most prominent scenario in 2050 is Scenario 6, with a reduction of 18.38%. However, it can be seen that this highlight became more prominent between 2045 and 2050 because in this scenario electric propulsion is considered. Fully electric aircraft are introduced in 2040 and hybrid aircraft in 2030. Until these aircraft enter the global fleet in sufficient numbers it will not be possible to see their potential in reducing emissions. Another essential factor for the reductions not to be higher in this scenario is that electric aircraft have a limited capacity and range. These results are in agreement to the results published by IATA [59] where it is shown that electric propulsion has a powerful impact on CO_2 emissions reduction.

As it is shown in Figure 5.7, Scenario 6 in terms of CO_2 *performance* no longer stands out as in Figure 5.6. The major reason is the capacity and range provided by electric propulsion, which is substantially lower compared to other aircraft. Therefore, besides electric and hybrid aircraft reduce considerably emissions, the fact that they have low capacities means that the total ASK is lower than that provided by the other scenarios, so the CO_2 *performance* does not stand out when compared to the other scenarios. The opposite is happening in Scenarios 3, 4, and 5. Although they do not have such high fuel efficiency, they allow more passengers and more freight to be transported. For the four scenarios, in this case, CO_2 *performance* reached a value of approximately 72 [grams of CO_2 per ASK].

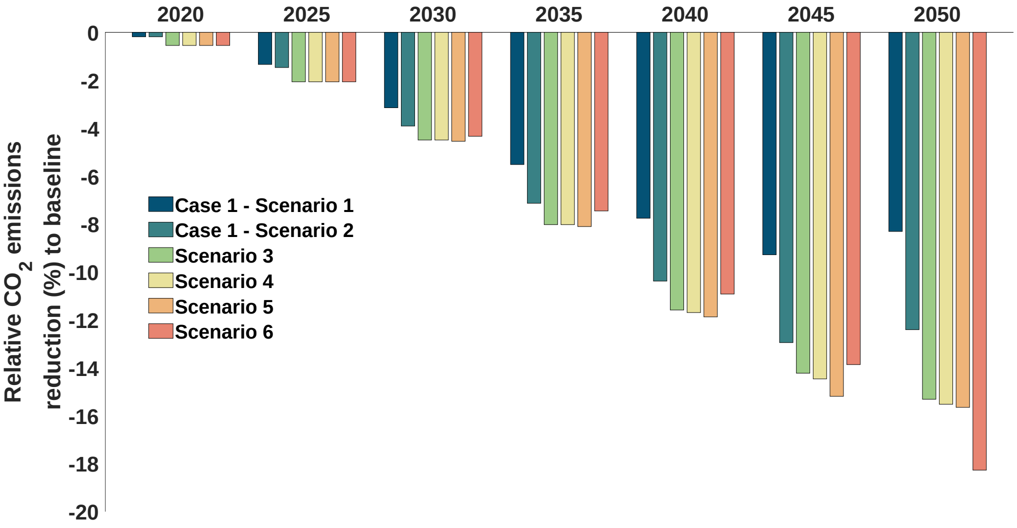


Figure 5.6: Fleet-level CO_2 emissions reduction from 2020 to 2050 of Case 2 relative to baseline.

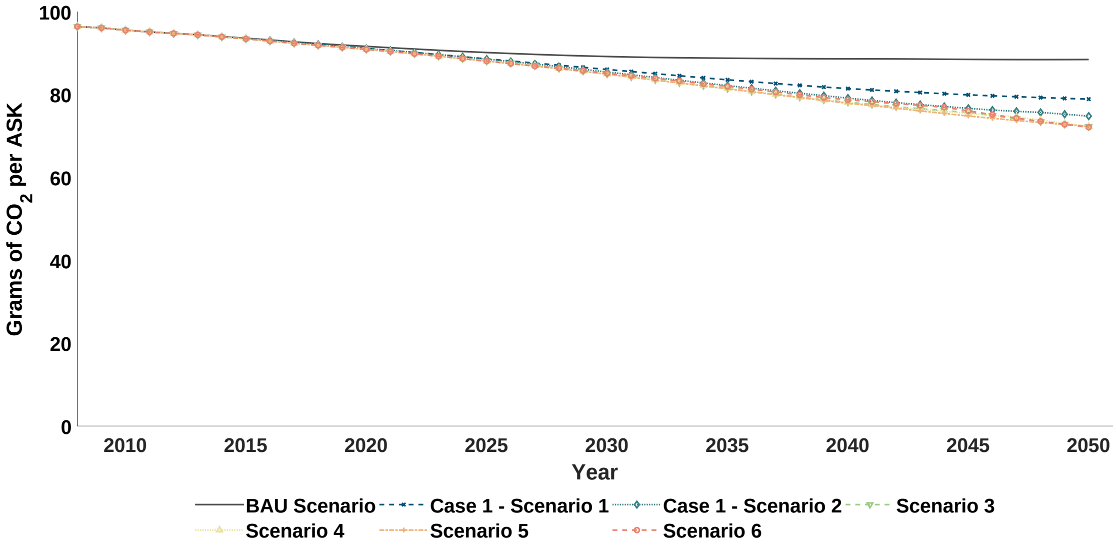


Figure 5.7: CO_2 performance for Case 2.

Figure 5.8 shows the evolution of CO_2 emissions year after year for the global fleet in Case 2. For this case, the scenario that allows reducing the most emissions by 2047 is Scenario 5, which corresponds to new propulsion designs. However, from 2047 onwards, Scenario 6 is the one with the lower emissions. This scenario, in 2050, registers 1465 Mt of CO_2, it is a reduction of 327 Mt compared to the BAU scenario.

5.2.3 Case 3

Case 3 is identical to Case 1, with the difference that in this case for all six scenarios, the simulations considered an increase of 15% in individual productions of all aircraft/concepts analyzed in the respective scenarios. This sensitivity analysis was conducted to verify the effect that increased aircraft production capacity can have on CO_2 emissions. As mentioned

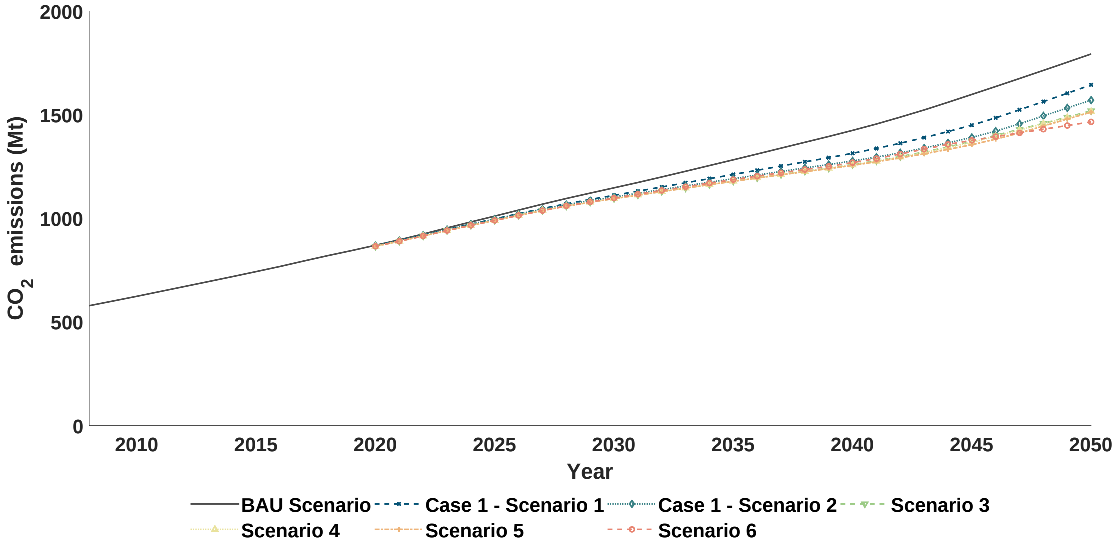


Figure 5.8: Fleet-level CO_2 emissions from 2008 to 2050 of Case 2.

in the previous cases, the number of aircraft introduced has a strong influence on the effect caused by technological progress on emissions reduction.

Figure 5.9 shows the results of CO_2 emissions reduction for case 3. If comparing Figure 5.3 and Figure 5.9, the increase in percentage reductions is fairly visible. This difference is mainly clear in 2045, as in Case 1 for Scenario 2, the reduction was 12.41%, and in this case, it is 14.5%. Therefore, the increase in production capacity by 15% reduced emissions by 2% approximately. Table 5.2 shows the results of the emission reductions for Case 1 and Case 3.

Table 5.2: Fleet-level CO_2 emissions reduction relative to baseline for Case 1 and Case 3.

	Case 1						**Case 3**					
Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
2020	-0.19%	-0.19%	-0.19%	-0.19%	-0.19%	-0.19%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%
2025	-1.34%	-1.47%	-1.34%	-1.34%	-1.34%	-1.34%	-1.53%	-1.69%	-1.53%	-1.53%	-1.53%	-1.53%
2030	-3.15%	-3.91%	-3.13%	-3.13%	-3.15%	-2.89%	-3.60%	-4.49%	-3.59%	-3.59%	-3.60%	-3.35%
2035	-5.52%	-7.14%	-5.83%	-5.83%	-5.86%	-5.16%	-6.24%	-8.12%	-6.61%	-6.61%	-6.62%	-5.90%
2040	-7.76%	-10.38%	-8.53%	-8.67%	-8.66%	-7.63%	-8.75%	-11.90%	-9.40%	-9.42%	-9.77%	-8.45%
2045	-9.29%	-12.95%	-10.04%	-10.35%	-10.94%	-9.54%	-10.46%	-15.04%	-11.19%	-11.40%	-12.45%	-10.69%
2050	-8.31%	-12.41%	-9.40%	-9.86%	-11.39%	-11.53%	-9.48%	-14.53%	-10.41%	-11.05%	-12.96%	-12.52%

Another fact that is noted here with the increase in capacity is the difference between Scenario 3 and 4. As expected, the scenario that allows a higher reduction in CO_2 emissions is Scenario 4 because it groups the configurations with higher fuel efficiency. The other difference that also exists between Case 3 and 1 is that in this case, Scenario 5 is always the second scenario with the highest emissions reduction, while in Case 1, this is outpaced by Scenario 6. The main explanation is due to the increase in production capacity, which in this case allowed more aircraft to be added in Scenario 5, increasing the emissions reduction. Although Scenario 6 has also added more aircraft, the limitations already mentioned prevent it from exceeding Scenario 5 again, as in Case 1.

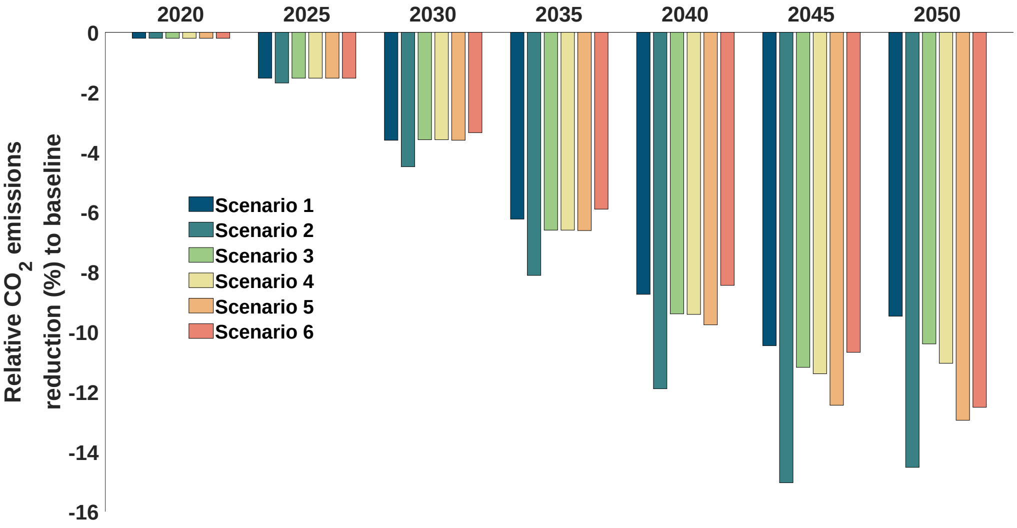


Figure 5.9: Fleet-level CO_2 emissions reduction from 2020 to 2050 of Case 3 relative to baseline.

As shows Figure 5.10, the scenario with the lower *CO_2 performance* is Scenario 2, as in Case 1. However, the increase in production capacity has allowed the other scenarios to come closer to Scenario 2. As shown in Figure 5.10, Scenario 2 reached 72.9 [grams of CO_2 per ASK] in 2050, followed by Scenario 5 with 74.6 [grams of CO_2 per ASK].

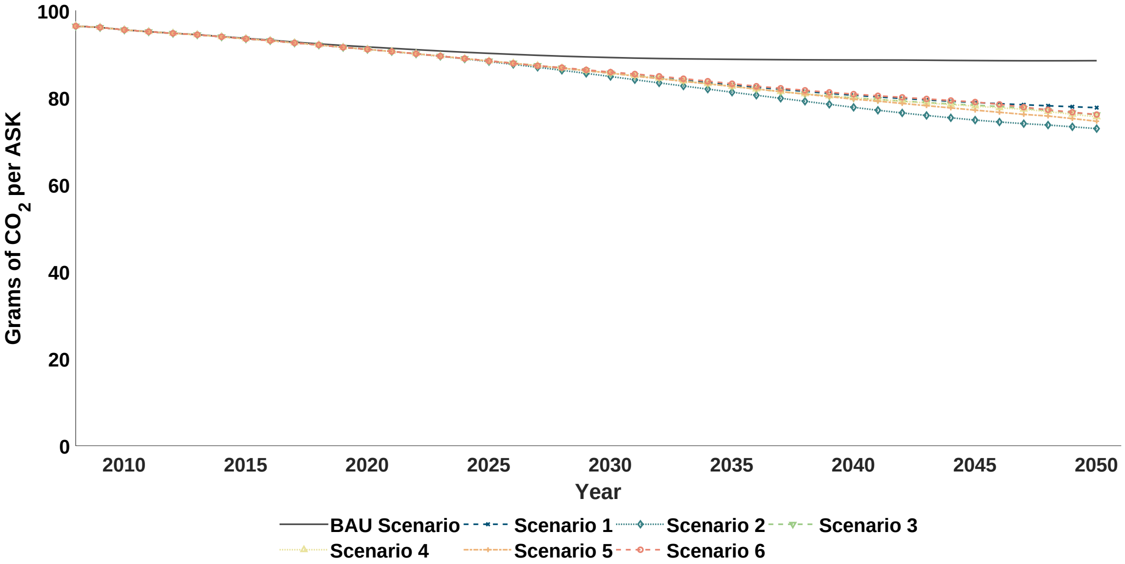


Figure 5.10: CO_2 performance for Case 3.

Figure 5.11 shows the evolution of CO_2 emissions year-on-year for the global fleet in Case 3. In this case, as in Case 1, the scenario with the lowest environmental impact is Scenario 2. However, this in 2050 reached 1532 Mt, compared to the same scenario in Case 1, it is a difference of 38 Mt. This means that, in quantitative terms, an increase of 15% in aircraft production capacity is possible to reduce an additional 38 Mt of CO_2 emissions.

These results support what was reported by Randt [30], concluding that only the implemen-

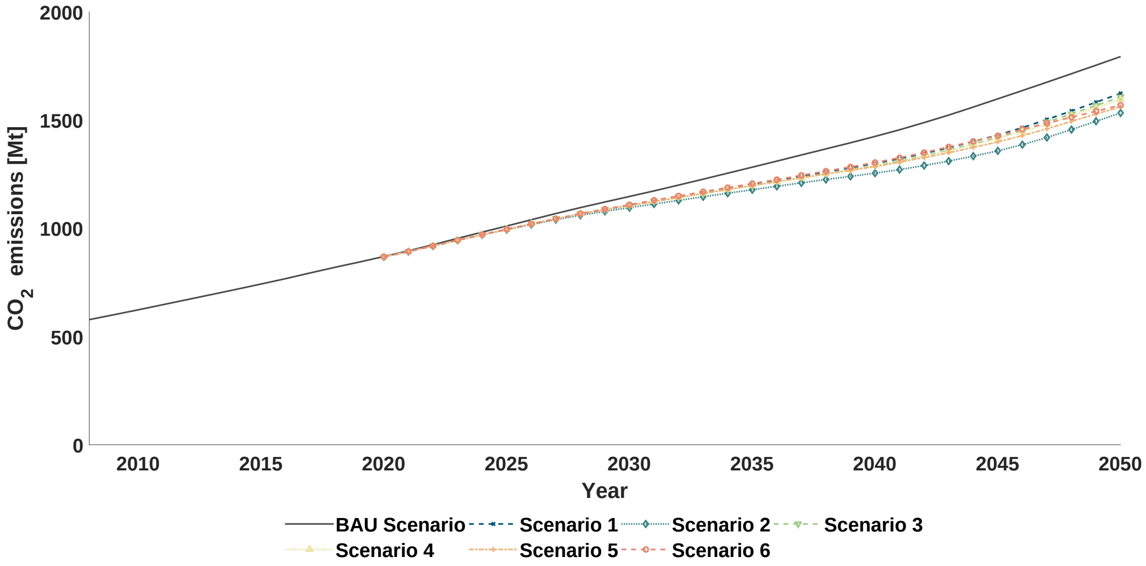


Figure 5.11: Fleet-level CO_2 emissions from 2008 to 2050 of Case 3.

tation of new aircraft or new concepts on the global fleet will be insufficient to meet the targets proposed by IATA, mainly the reduction of CO_2 emissions in 50% by 2050, compared to 2005 levels and carbon-neutral growth from 2020. Even increasing the production capacity as was done for this case, it will not be possible.

5.2.4 Case 4

Similar to the analysis process between Cases 1 and 3, the same was repeated for Cases 2 and 4. Case 4 is identical to Case 2, with the difference that in this case, the simulations performed for all four scenarios considered an increase of 15% in individual productions of all aircraft/concepts analyzed in the respective scenarios. Figure 5.12 shows the results of the CO_2 emissions reduction in the global fleet compared to the BAU scenario. Within all cases analyzed, Case 4 shows the highest emissions reduction. As Figure 5.12 shows, technological progress in 2050 reaches 20% for Scenario 6. When comparing Case 2 with Case 4, it can be seen that for all the simulated scenarios there is an increase in emissions reduction. Table 5.3 shows the emissions reduction for Case 2 and 4 compared to the BAU scenario.

These results are consistent with those published by Schilling et al. [34] and by Ploetner et al. [38]. According to Schilling et al. [34], the CO_2 reduction potential from radical aircraft concepts in 2050 can reach about 20% to 25% compared to the emissions in the baseline scenario. According to Ploetner et al.[38], the new aircraft technologies together with radical ramp-up timelines might lower global fleet fuel burn until year 2050 between 17% to 27%. In the present work, the results for Case 4 can reach about 17% to 20% compared to the baseline scenario.

Figure 5.13 shows the CO_2 *performance* until 2050 for Case 4. Analyzing the results, it can be seen that the scenario with a lower CO_2 *performance* is Scenario 5. This proves once again

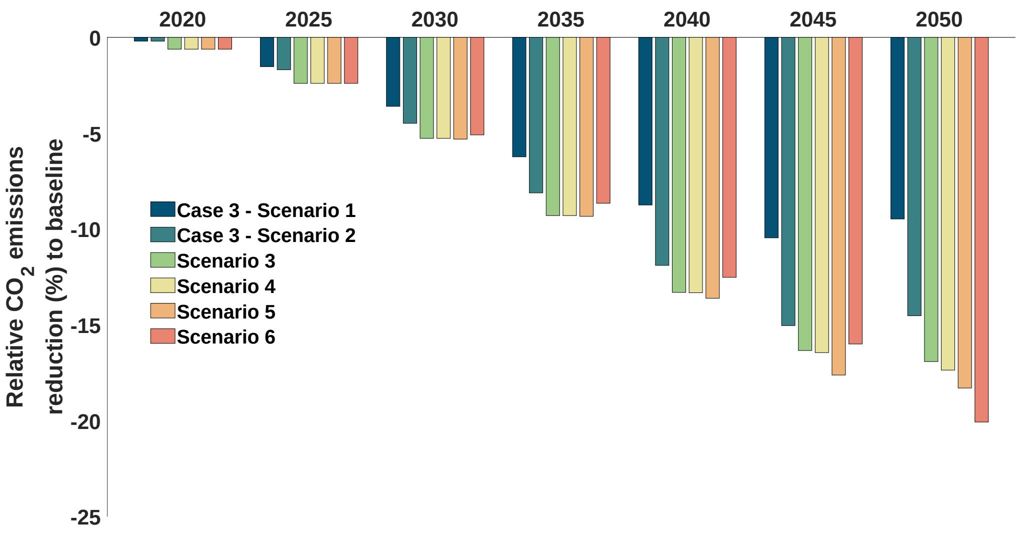


Figure 5.12: Fleet-level CO_2 emissions reduction from 2020 to 2050 of Case 4 relative to baseline.

Table 5.3: Fleet-level CO_2 emissions reduction relative to baseline for Case 2 and Case 4.

	Case 2				**Case 4**			
Scenario	**3**	**4**	**5**	**6**	**3**	**4**	**5**	**6**
2020	-0.55%	-0.55%	-0.55%	-0.55%	-0.62%	-0.62%	-0.62%	-0.62%
2025	-2.07%	-2.07%	-2.07%	-2.07%	-2.40%	-2.40%	-2.40%	-2.40%
2030	-4.50%	-4.50%	-4.55%	-4.34%	-5.27%	-5.27%	-5.31%	-5.09%
2035	-8.03%	-8.03%	-8.11%	-7.46%	-9.30%	-9.30%	-9.34%	-8.66%
2040	-11.59%	-11.70%	-11.88%	-10.93%	-13.31%	-13.33%	-13.62%	-12.52%
2045	-14.23%	-14.47%	-15.20%	-13.87%	-16.34%	-16.45%	-17.62%	-16.00%
2050	-15.32%	-15.53%	-15.66%	-18.28%	-16.92%	-17.36%	-18.30%	-20.08%

the importance of aircraft transport capacity in reducing emissions. Scenario 5 has a lower CO_2 *performance* as it allows for more available seat kilometers, although the efficiencies of the technologies analyzed in this scenario are not as high compared to Scenario 6. The CO_2 *performance* recorded in 2050 for Scenario 5 is 69.75 [grams of CO2 per ASK]. For all cases analyzed, this was the lowest value.

Figure 5.14 shows the evolution of CO_2 emissions until 2050. Scenario 6 from 2047 shows the lowest emissions, although its CO_2 *performance* is not as low as Scenario 5. The major reason is that although Scenario 5 has a lower CO_2 performance since a seat load factor of 83% is assumed, this means each aircraft goes with 83% of available seating capacity filled with passengers. If the seat load factor was 100%, Scenario 5 would reduce more emissions, since it would have a higher ASK than Scenario 6, because the aircraft considered in Scenario 5 has more capacity than the aircraft considered in Scenario 6.

According to the results of the present work, these do not corroborate what Terekov et al.

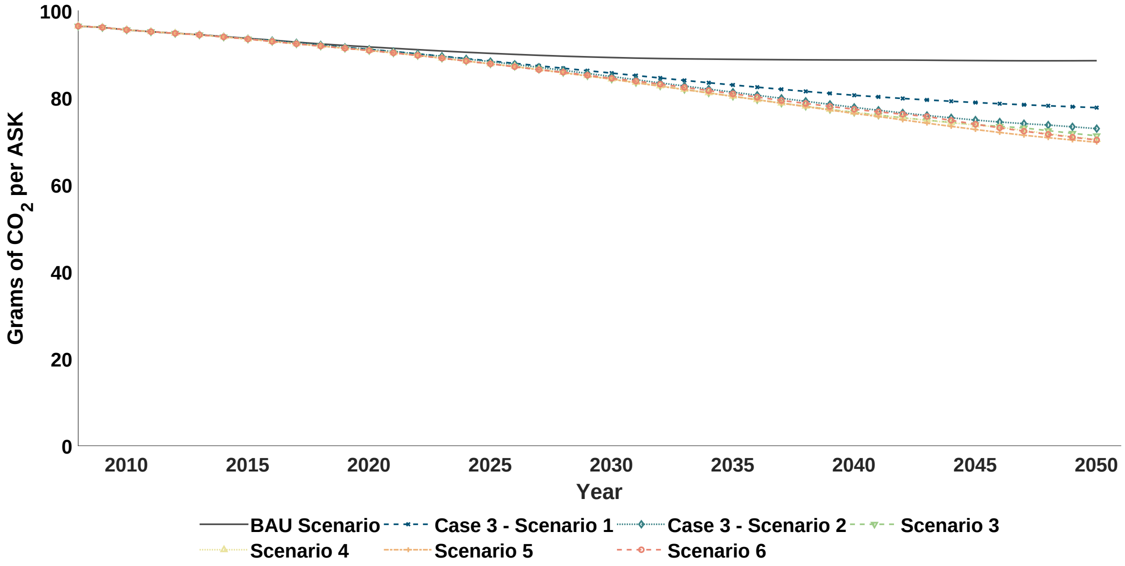


Figure 5.13: CO_2 performance for Case 4.

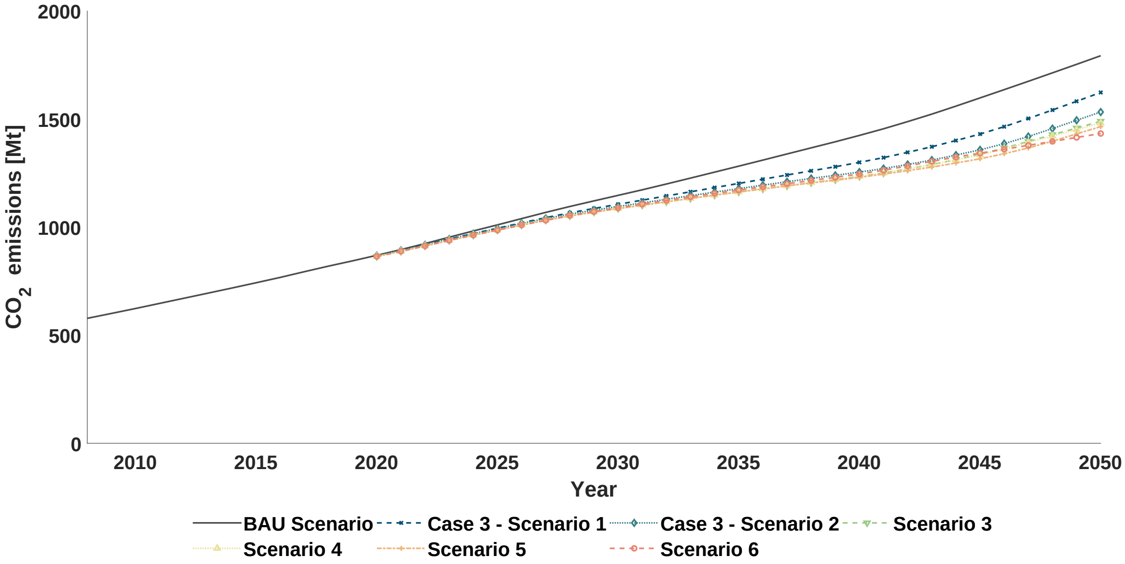


Figure 5.14: Fleet-level CO_2 emissions from 2008 to 2050 of Case 4.

[31] have shown. Terekov et al. [31] reported that for the maximum technology assumptions, it is possible to have a near to CO_2 neutral growth from 2030 on. In the four cases of analysis, it has not been possible to achieve carbon-neutral growth with only technological improvements.

Given these case studies performed in the present work, two factors have been demonstrated to be relevant for the implementation of new technologies. The first is the entry into service (EIS), if the new technologies are implemented in the years before 2050 the effect that this technology will have will be very low. 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.

5.3 Alternative Aviation Fuels Scenarios

This section presents the results for the scenarios mentioned in Chapter 4, which allow assessing the effect of the impact of the introduction of sustainable aviation fuels on commercial aviation. Compared to jet fuel from petroleum sources, SAF promise significant reductions of CO_2 emissions from a life-cycle perspective, as CO_2 is absorbed while the feedstock is grown. In order to compare the life-cycle emissions of different fuels, the Equivalent CO_2 emissions (CO_2e emissions) are considered. These CO_2e emissions, as explained in section 4.2, include GHG emissions during the production, distribution and consumption phase of the fuel.

First, the results of the influence of feedstocks on CO_2 emissions are presented. Each scenario has two conditions, the condition *High* considers the higher LCA value and the condition *Low* considers the lowest LCA value for each feedstock used for the production of SAF. Figure 5.15 shows the effect of feedstocks for the various scenarios and conditions used in CO_2 emissions. The Jet Fuel demand for this analysis was generated by Case 1 - Scenario 1, which represents the existing technologies today.

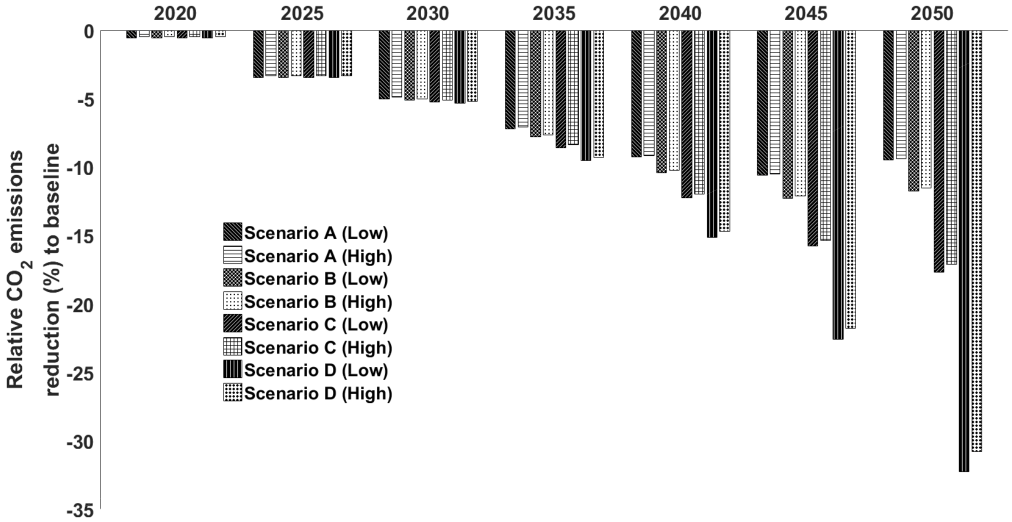
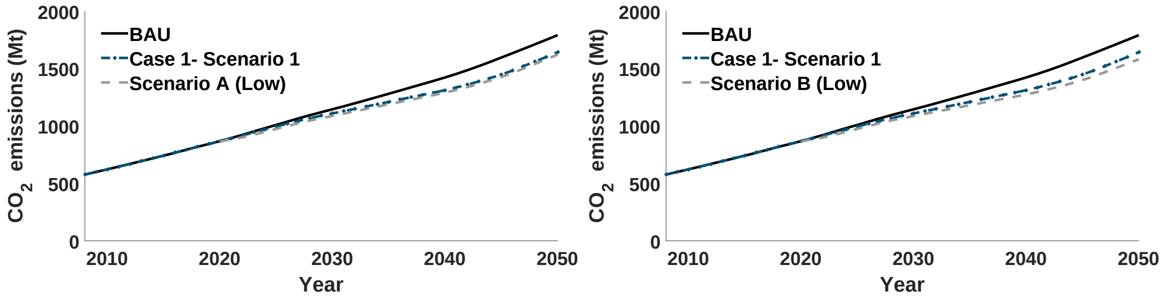


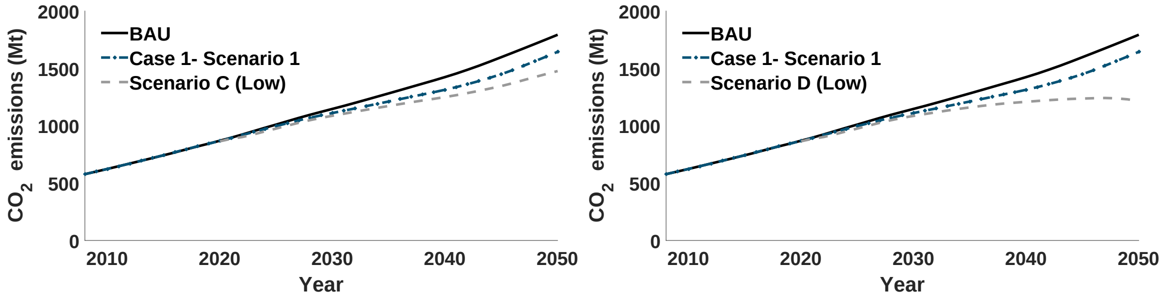
Figure 5.15: Influence of feedstocks in the CO_2 emissions.

According to Figure 5.15, which demonstrates the cumulative reductions for each scenario and condition in relation to BAU Scenario, the influence that the feedstocks used in each process have on the emissions of CO_2 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. Important to note the differences between the ”Low” and ”High” conditions increase when the production capacity of biofuels is higher.

The results of Figure 5.16 show the impact of the introduction of SAF on global CO_2 emissions from the air transport fleet. In Scenario A, the impact on global fleet emissions is extremely low, around 1.66% per year. This scenario represents the forecast made by ICAO for SAF production (”High ratio”), showed in Figure 4.6. The expected production in this scenario,



(a) Scenario A (b) Scenario B



(c) Scenario C (d) Scenario D

Figure 5.16: CO_2 emissions trends from global fleet, 2008 to 2050.

compared to the required demand of Jet fuel for the aeronautical sector evidence a large discrepancy, as the expected jet fuel demand generated by Case 1 - Scenario 1 in 2030 is about 345 Mt and the forecast production of SAF is 8.9 Mt. In Scenario B, it is possible to see a substantial reduction on CO_2 emissions, but still insufficient to achieve the proposed objectives, and therefore it is necessary to increase biofuel production. For Scenario C, the value of emissions in 2050 was 1476.2 Mt of CO_2, which indicates a reduction of 17.7% of emissions comparing with the BAU scenario. Finally, Scenario D shows a higher reduction in emissions (32.3% compared to baseline) and the only scenario to achieve carbon-neutral growth from around 2045 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, it is necessary to take into account that 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.

Figure 5.17 shows CO_2 emissions trends for civil aviation between 2008 and 2050, considering all four scenarios and the conditions using jet fuel demand based on Case 1 - Scenario 1. These results mainly for Scenario C and D prove in quantitative terms the statements published by Moolchandani et al. [35], Dray et al. [37], and Schilling et al. [34], who said that biofuels would be vital for reducing emissions from commercial aviation. As shows Figure 5.17, 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. In summary, when the SAF production increase, the effect of feedstocks in CO_2 emissions also increases.

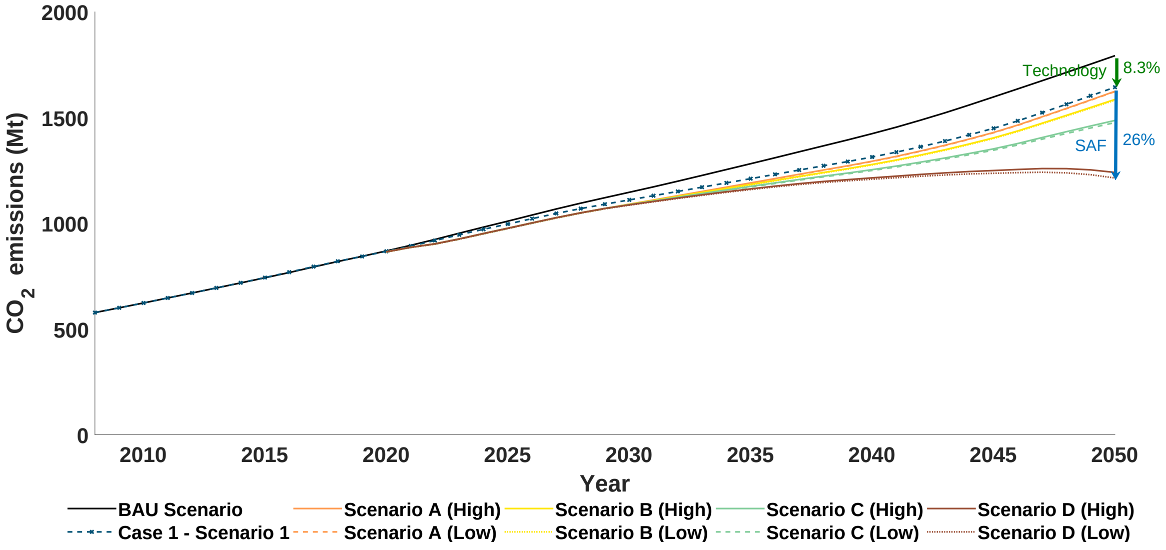


Figure 5.17: CO_2 emissions trends considering jet fuel demand of Case 1 - Scenario 1.

If a different scenario is used allowing further emission reductions, such as Case 2 - Scenario 2, which represents the technologies introduced up to 2025, the effect of the combination of technological progress and SAF on CO_2 emissions can be better analyzed. Figure 5.18 shows CO_2 emissions trends for civil aviation between 2008 and 2050, considering all four scenarios and the conditions using jet fuel demand based on Case 2 - Scenario 2. This graph shows that carbon-neutral growth is possible from around 2040 onwards, while in the graph of Figure 5.17, carbon-neutral growth is only possible around 2045. It is also established that as jet fuel demand declines with technological development, the effect of SAF increases. The following section will analyze the effects on CO_2 emissions considering the scenarios that reduce most emissions within each strategy.

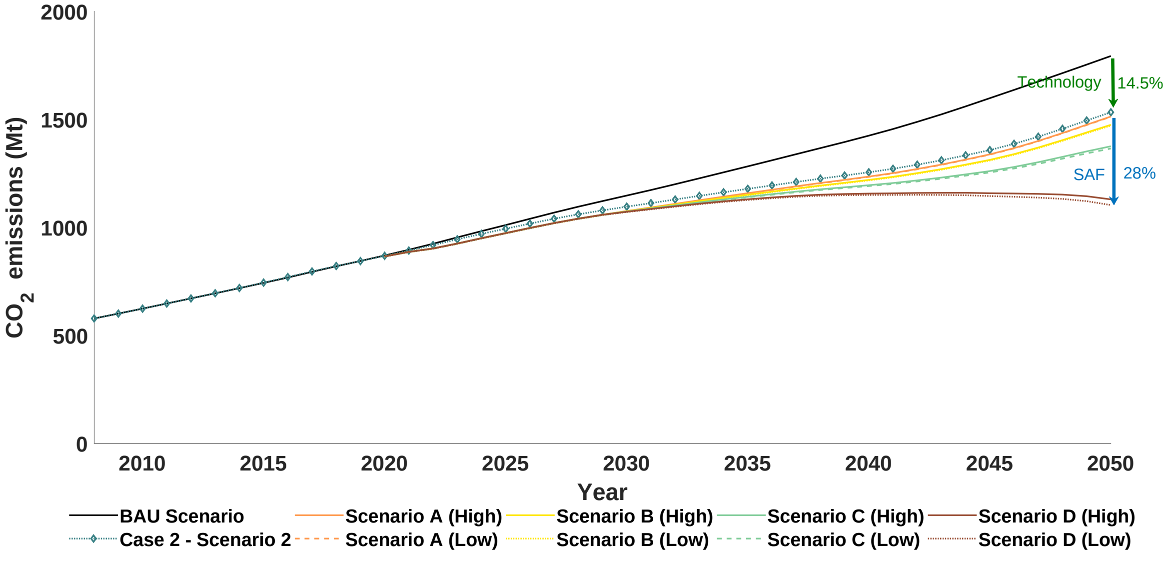


Figure 5.18: CO_2 emissions trends considering jet fuel demand of Case 2 - Scenario 2.

5.4 Technological Improvements & Alternative Aviation Fuels Scenarios

This section presents the results of combining technological improvements with the use of alternative fuels. In the previous section was presented the effect of the impact of introducing sustainable aviation fuels on commercial aviation. The conclusion obtained from these results was that it is not possible to achieve the objectives proposed by using only the technologies that exist nowadays with the introduction of SAF. This section answers the various questions raised in the literature whether the joining of technological improvements by 2050, together with the use of SAF will be possible to achieve the goals. Therefore, the analysis will study the reductions caused by the junction of Scenarios 5 and 6, from Case 4 with Scenario D for the condition *Low*, given that they were the scenarios with the highest emissions reduction.

Figure 5.19 shows the effect of combining the Case 4 - Scenario 5 and Scenario D (*Low*) on the evolution of CO_2 emissions. A considerable reduction of emissions is observed by 2050, about 757 [Mt] compared to BAU scenario. However, when comparing with the IATA goals, it turns out that it is not possible to meet any of the goals presented in Chapter 1. However, it is possible to have carbon-neutral growth around 2038 and a gradual reduction in emissions by 2050, but it is not possible to reach the levels recorded in 2020. The gap to achieve the levels of 2020 is around 165 Mt.

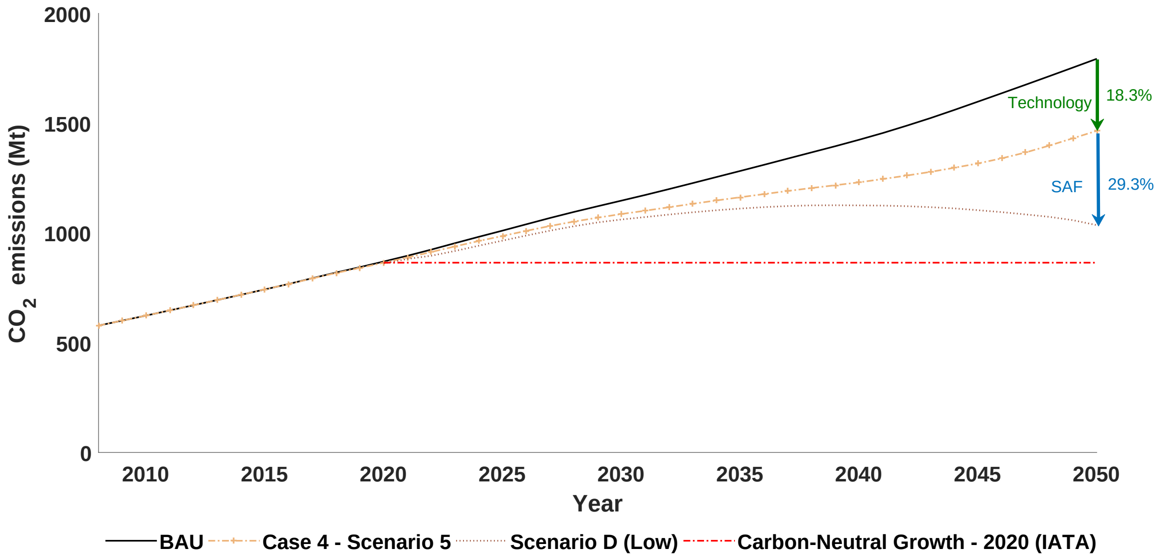


Figure 5.19: CO_2 emissions trends for civil aviation considering the overall effect of Case 4 - Scenario 5 with Scenario D (Low).

Figure 5.20 shows the effect of the combination of Case 4 - Scenario 6 and Scenario D (Low) on the evolution of CO_2 emissions. This graphic shows a higher reduction in emissions compared to the graphic in Figure 5.20. A reduction of 790 Mt is observed compared to the baseline (BAU scenario). However even joining these scenarios is not possible to meet the objectives. In this graph the carbon-neutral growth is possible to obtain from around 2040 with a gradual reduction in CO_2 emissions in the following years, although the gap to achieve the levels of 2020 is around 133 Mt.

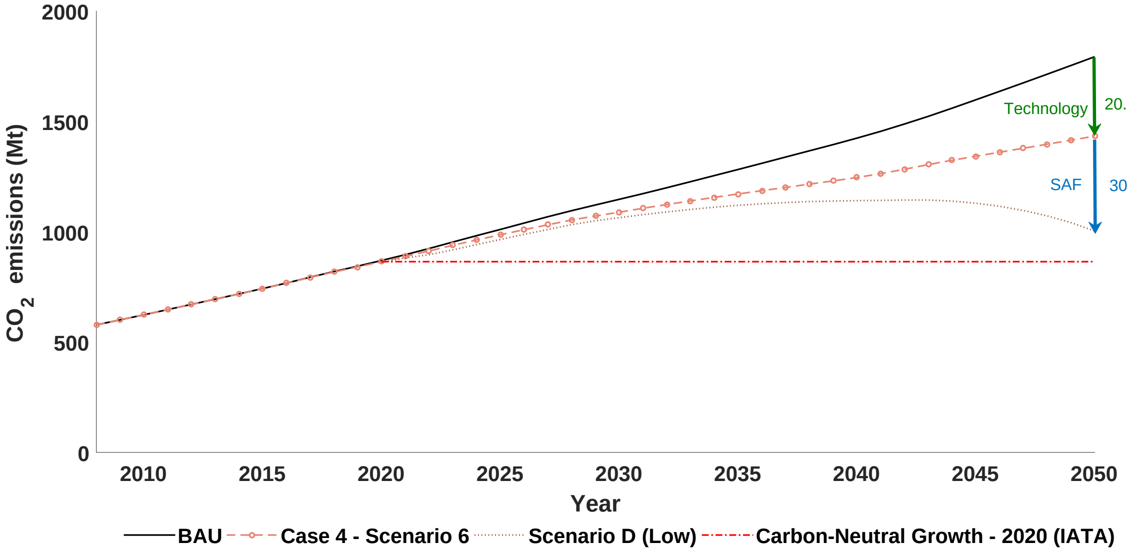


Figure 5.20: CO_2 emissions trends for civil aviation considering the overall effect of Case 4 - Scenario 6 with Scenario D (Low).

The results clearly show, for both Figure 5.19 and Figure 5.20, that only these analyzed technologies and alternative fuels will not be sufficient to achieve the goals. Carbon neutral growth from 2020 will certainly not be met. Recording half the emissions of 2005 in 2050 will be challenging as the results of this work in 2050 showed that it was not possible to achieve the CO_2 levels recorded in 2020. In order to attempt to meet this target, the effect of possible economic measures (EU ETS and CORSIA), improvements in operations and air traffic control, and the inclusion of hydrogen propulsion will have to be accounted for. The aviation industry (airlines, governments, non government organizations, suppliers, manufactures) must work together to make advancements that catapult the industry into the future. Governments must get involved and support the development as well as remove obstacles for companies leading the environmental movement.

5.5 Summary

In general, it can be stated that there are several interesting facts highlighted with the results presented. First, the results for the BAU scenario show the importance of having to apply measures and strategies to mitigate the impact of the aeronautical sector. CO_2 emissions from aviation between 2008 and 2050 are projected to grow between a factor of 1.34 and 1.95, according to ARIMA results. According to the results of FSDM, CO_2 emissions are projected to grow between a factor of 2.7 and 3.5, depending on the scenario used for the growth rates of the aviation market.

The results for technological evolution have shown several points that need to be considered given their influence on reducing CO_2 emissions. The major factors reported were production capacity, year of entry of the technology/concept, and the transport capacity and range of aircraft. The sensitivity study on the production capacity of new aircraft/concepts showed that with a 15% increase, emissions reduction can be increased by between 1 and 2.6%, depending on the case and scenario. On the other hand, increasing the aircraft production capacity could lead to a problem of overcapacity. Another problem is when the aircraft manufactures make the decision to develop a new aircraft type, they do not have many options to adjust their capacity strategy.

Another factor that also proved decisive was the year of entry of new aircraft. As mentioned in case 1 and 3, implementing new technologies by 2025 resulted in a reduction of emissions in 2050 between 12.41% and 14.53%, depending on the established production capacity. This reduction is quite considerable and is mainly because of introducing the new Rolls-Royce engines and the Boeing 777X. It was shown, for both Case 1 and Case 3, that these technologies were the ones that allowed the highest reduction of emissions, surpassing the other scenarios that contemplated higher efficiencies. Therefore, it is concluded that implementing these technologies will be crucial to combat the increase in CO_2 emissions in the aeronautical sector.

In Cases 2 and 4, the scenarios that allowed the highest reduction in fuel consumption were notably Scenarios 5 and 6. Scenario 5 represents the new engine configurations, whose results showed the importance of the development of engine technologies, given that it was the scenario with the lowest value of CO_2 *performance* for Case 2 and 4. Engine manufactures in the past years have invested in technology to provide clean, quiet, affordable, reliable, and efficient power. This is a continuous process with constant investments to maintain and increase the overall performance of in-service and in-production aircraft. Engine technologies are designed, tested, and implemented since they become mature. This has the advantage of being applied more easily than for example the new aircraft configurations. Electric propulsion has proven to be an essential approach in mitigating CO_2 emissions. However, the results revealed that its ability to reduce emissions is limited. First, because of the transport capacity of the technologies considered, second, because its range is small when compared to other aircraft, being these technologies restricted only to regional flights.

The results for the scenarios of the new aircraft configurations show a significant reduction in CO_2 emissions. For all cases, these scenarios up to 2045 allow reducing more emissions than Scenario 6, which considers electric propulsion. Although, novel aircraft configurations will need further regulation and certification to be applied in the aeronautical sector.

One of the strategies that have been mentioned most in the literature to meet climate objectives and substantially reduce GHG emissions is the use of alternative fuels. However, in the present work, it has been shown that the capacity to produce SAF (ICAO High Ratio Scenario) by 2030 for commercial aviation is very low compared to the demand for jet fuel. Therefore, the influence on CO_2 emissions that SAF has until 2030 is around 1.66% per year. On the other hand, in the scenarios where higher production capacities are considered from

2030, it is possible to visualize the effect of introducing SAF. The effect is most noticeable mainly in scenarios C and D. In the study where it was considered the joint effect of current technologies and SAF, it was reported that is possible to have carbon-neutral growth from 2045. However, it must be reminded that to get these production capacities requires having sufficient feedstocks and refineries capable of supplying these quantities. 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, the development of alternative fuels should not raise problems for human health. Another factor to be considered is that refineries may not reach these production capacities, mainly because of technical and economic constraints. SAF will need economic support to improve production technologies and to reduce costs to become competitive with Jet Fuel.

None of the objectives of IATA have been met by technological progress alone or by introducing new alternative fuels using current technologies. The results showed that when fuel consumption decreases with technological progress, the influence of SAF increases. The reason is due to the decrease in the difference between jet fuel demand and production capacity. The combined effect of the most emission-reducing technological scenarios together with Scenario D has shown that is possible to achieve a very significant reduction in CO_2 emissions, but still insufficient to meet the proposed goals. However, the results show that carbon-neutral growth is possible from 2038 onwards and with a gradual reduction in emissions. These results reflect the efforts that have been and will be made to combat climate change and make the aviation sector sustainable.

Chapter 6

Conclusions and Future Work

In this dissertation, the influence of new aircraft programs, new technologies and alternative fuels on the air global fleet emissions was 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 feedstocks and the production process used. This chapter briefly summarizes the most important findings of this work, gives some high-level conclusions in this regard, and provides recommendations for future work.

6.1 Conclusions

Aviation has a considerable contribution to the economic growth of the global economy. According to the various studies of the largest institutions associated with the commercial aviation industry, they predict that global demand for air transport will continue to increase. From an economic point of view, this development is considered very positive. However, this vigorous growth of the aviation sector will cause an adverse impact on the environment, both locally (especially near airports) and globally, affecting the environment. Currently, the environmental impact because of this sector is already considerable, establishing about 2.4% of global CO_2 emissions. Therefore, the expected increase in the sector will cause several consequences in civilization if no measures are taken.

The increased concern for environmental aspects, both by the political community and the general population, has led to regulatory measures to reduce air traffic emissions. The aviation industry has set medium and long-term objectives to reduce environmental impacts continuously. The major goals set are to globally reduce the amount of emissions produced by jet fuel consumption. IATA presented the following goals: (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, and (3) An average improvement in fuel efficiency (CO_2 per Revenue Tonne Kilometre) of 1.5% per year from 2009 to 2020.

IATA in order to achieve these goals has proposed a strategy. This strategy is based on four pillars: (1) improved technology, including the deployment of sustainable low-carbon fuels, (2) improved aircraft procedures and operations, (3) optimization of the aviation infrastructure, (4) economic measures to fill the remaining emissions gap. However, to date, a few studies have estimated the quantitative effects of each part of this strategy.

This dissertation is therefore aimed at supplying a scientific contribution to the ongoing efforts in this area of research. In doing so, it focuses on the first aspect of the four pillar strategy, the impact of improved technologies, including the deployment of sustainable low-carbon fuels. Two methodologies were used to estimate the effects of the first pillar of this strategy. In order to assess the impact of technological progress the approach was modeling the air transport system using the FSDM model. FSDM constitutes a numerical tool that consistently translates the scenario load data into data addressing the evolution of the global fleet. In this sense, introduction and propagation effects of recent aircraft entering the fleet at a precise point in time can be predicted, which enables the study of the impact of these aircraft on fleet-wide performance parameters such as the total fuel demand and the CO_2 emissions. The methodology to quantify the effect of inclusion of sustainable aviation fuels was developed based on the CAEP formula and added as a new tool to the FSDM. This developed tool allows to analyze the introduction of SAF considering the amount of biofuel, and its respective life cycle. The production processes and the feedstocks are very important to determine how much biofuels can really reduce CO_2 emissions.

The major findings and conclusions achieved in the present work are that it will not be possible to achieve the proposed objectives only with the implementation of new technologies and the use of Sustainable Aviation Fuels. The remaining emission reductions will have to come from the other three pillars of the IATA strategy. However, the results of the present work show that technologies and fuels have a fundamental contribution to the decarbonization of the aeronautical sector. Improvements in technology can contribute up to 20% in emissions reduction compared to the baseline scenario. Within the technology scenarios, the technologies that proved to be most important in reducing emissions were those implemented up to 2025, new engine configurations, and electric propulsion. The viability of electric propulsion was limited as a result of capacity and range restrictions. Overall, the reductions in CO_2 induced by technologies take a few years to be visualized because of the slow penetration of these new aircraft in the global fleet.

Analysis of sustainable aviation fuels shows that the capacity projected by ICAO in the production of SAF will have a very small effect on CO_2 emissions. It was also seen that the effect of different feedstocks used in each process on CO_2 emissions is very low. Although, the differences between the *Low* and *High* conditions increase when the production capacity of SAF is higher. The effect of SAF on CO_2 emissions is only visible in scenarios where production capacity is higher. It was concluded that when jet fuel demand declines because of technological improvements, the effect of SAF increases. The combined effect of technological improvements and sustainable aviation fuels scenarios shows that is possible to have a carbon-neutral growth from 2038 onwards with a gradual reduction in CO_2 emissions.

6.2 Future Work

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. The scientific community, in recent years, has been employing efforts to develop and research the best solutions for commercial aviation. The present work provides quantitative data to support decision making on strategies for the decarbonization of the aeronautical sector by 2050. In order to continue the research scope of the present work, the following studies should be addressed:

- Techno-economic analysis of sustainable aviation fuel;
- Study the effect of economic emissions mitigation measures on global fleet emissions;
- Study the implementation of hydrogen propulsion on global fleet emissions, since Airbus has introduced the ZEROe concept aircraft;
- Study the contribution of air traffic management and operations on reducing international aviation CO_2 emissions;
- Estimate the impact of COVID-19 on international aviation CO_2 emissions.

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Appendix A

SAF Production Capacity

Table A.1: 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

Appendix B

Simulation Data

Table B.1: Aircraft Operational Profile.

A/C Type	Entry-into-service year	Cluster Number	Seat Capacity	Freight capacity [tons]
Boeing 747-8F	2011	5	0	112
Boeing 787-8	2011	7	242	14
Boeing 747-8	2012	2	467	20
Airbus A350-900	2015	8	315	34
Airbus A320neo	2015	9	150	4
Airbus A330neo	2018	7	300	20
Embraer 190 E-2	2016	4	97	2
ATR 72 Advanced	2019	6	68	0
Boeing 777X	2022	2	426	21
Advanced Turbofan	2020	8	317	21
Ultrafan	2025	8	317	21
Natural Laminar Flow	2020	9	150	4
Blended Wing Body	2040	2	500	20
Small BWB	2025	4	120	2
Boundary Layer Ingestion	2035	4	120	2
Strut Braced Wing	2030	9	150	4
Double Bubble Fuselage	2045	9	150	4
Open Rotor (C2)	2030	2	467	20
Open Rotor (C7)	2030	7	300	20
Open Rotor (C8)	2030	8	315	34
Strut Braced Wing – Open Rotor	2040	9	150	4
ATR Fully Eletric	2040	6	50	0
Embraer 190 Fully Eletric	2040	4	100	0
Zunum Aero 50	2027	6	50	0
Zunum Aero 100	2030	4	100	0

Table B.2: β factors used in the retirement modeling of the aircraft clusters 1 through 9 [1].

Cluster Number	β_1	β_{11}
1	2.4099	-0.1350
2	7.1835	-0.3366
3	5.8592	-0.1881
4	4.8128	-0.1942
5	6.0198	-0.2425
6	3.9517	-0.1684
7	6.9248	-0.2961
8	5.8329	-0.2556
9	6.8054	-0.3010

Table B.3: RPK growth rates from 2009 to 2050 for Rough Air Scenario [1].

	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
2009	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2010	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2011	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2012	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2013	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2014	2.00%	6.50%	6.50%	5.50%	5.50%	2.00%	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%	6.50%	5.50%	5.50%	5.50%	5.50%	5.50%	2.00%
2015	2.00%	6.00%	6.00%	5.30%	5.30%	2.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	5.30%	5.30%	5.30%	5.30%	5.30%	2.00%
2016	2.00%	5.50%	5.50%	5.20%	5.20%	2.00%	5.50%	5.50%	5.50%	5.50%	5.50%	5.50%	5.50%	5.50%	5.50%	5.20%	5.20%	5.20%	5.20%	5.20%	2.00%
2017	1.90%	5.00%	5.00%	5.00%	5.00%	1.90%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	1.90%
2018	1.90%	4.50%	4.50%	4.80%	4.80%	1.90%	4.50%	4.50%	4.80%	4.80%	4.50%	4.50%	4.80%	4.80%	4.50%	4.80%	4.80%	4.80%	4.80%	4.80%	1.90%
2019	1.80%	4.00%	4.00%	4.50%	4.50%	1.80%	4.00%	4.00%	4.50%	4.50%	4.00%	4.00%	4.50%	4.50%	4.00%	4.50%	4.50%	4.50%	4.50%	4.50%	1.80%
2020	1.80%	4.10%	4.10%	4.30%	4.30%	1.80%	4.10%	4.10%	4.30%	4.30%	4.10%	4.10%	4.30%	4.30%	4.10%	4.30%	4.30%	4.30%	4.30%	4.30%	1.80%
2021	1.70%	4.20%	4.20%	4.00%	4.00%	1.70%	4.20%	4.20%	4.20%	4.20%	4.20%	4.20%	4.20%	4.20%	4.20%	4.00%	4.00%	4.00%	4.00%	4.00%	1.70%
2022	1.70%	4.30%	4.30%	4.10%	4.10%	1.70%	4.30%	4.30%	4.30%	4.30%	4.30%	4.30%	4.30%	4.30%	4.30%	4.10%	4.10%	4.10%	4.10%	4.10%	1.70%
2023	1.70%	4.40%	4.40%	4.10%	4.10%	1.70%	4.40%	4.40%	4.40%	4.40%	4.40%	4.40%	4.40%	4.40%	4.40%	4.10%	4.10%	4.10%	4.10%	4.10%	1.70%
2024	1.70%	4.00%	4.00%	4.20%	4.20%	1.70%	4.00%	4.00%	4.20%	4.20%	4.00%	4.00%	4.20%	4.20%	4.00%	4.20%	4.20%	4.20%	4.20%	4.20%	1.70%
2025	1.70%	3.60%	3.60%	4.20%	4.20%	1.70%	3.60%	3.60%	4.20%	4.20%	3.60%	3.60%	4.20%	4.20%	3.60%	4.20%	4.20%	4.20%	4.20%	4.20%	1.70%
2026	1.70%	3.50%	3.50%	4.30%	4.30%	1.70%	3.50%	3.50%	4.30%	4.30%	3.50%	3.50%	4.30%	4.30%	3.50%	4.30%	4.30%	4.30%	4.30%	4.30%	1.70%
2027	1.60%	3.30%	3.30%	4.30%	4.30%	1.60%	3.30%	3.30%	4.30%	4.30%	3.30%	3.30%	4.30%	4.30%	3.30%	4.30%	4.30%	4.30%	4.30%	4.30%	1.60%
2028	1.00%	3.20%	3.20%	4.20%	4.20%	1.00%	3.20%	3.20%	4.20%	4.20%	3.20%	3.20%	4.20%	4.20%	3.20%	4.20%	4.20%	4.20%	4.20%	4.20%	1.00%
2029	0.60%	3.00%	3.00%	4.10%	4.10%	0.60%	3.00%	3.00%	4.10%	4.10%	3.00%	3.00%	4.10%	4.10%	3.00%	4.10%	4.10%	4.10%	4.10%	4.10%	0.60%
2030	0.20%	3.00%	3.00%	4.00%	4.00%	0.20%	3.00%	3.00%	4.00%	4.00%	3.00%	3.00%	4.00%	4.00%	3.00%	4.00%	4.00%	4.00%	4.00%	4.00%	0.20%
2031	0.00%	3.00%	3.00%	3.90%	3.90%	0.00%	3.00%	3.00%	3.90%	3.90%	3.00%	3.00%	3.90%	3.90%	3.00%	3.90%	3.90%	3.90%	3.90%	3.90%	0.00%
2032	-0.10%	2.90%	2.90%	4.20%	4.20%	-0.10%	2.90%	2.90%	4.20%	4.20%	2.90%	2.90%	4.20%	4.20%	2.90%	4.20%	4.20%	4.20%	4.20%	4.20%	-0.10%
2033	-0.10%	2.70%	2.70%	4.40%	4.40%	-0.10%	2.70%	2.70%	4.40%	4.40%	2.70%	2.70%	4.40%	4.40%	2.70%	4.40%	4.40%	4.40%	4.40%	4.40%	-0.10%
2034	-0.20%	2.60%	2.60%	4.50%	4.50%	-0.20%	2.60%	2.60%	4.50%	4.50%	2.60%	2.60%	4.50%	4.50%	2.60%	4.50%	4.50%	4.50%	4.50%	4.50%	-0.20%
2035	-0.20%	2.40%	2.40%	4.60%	4.60%	-0.20%	2.40%	2.40%	4.60%	4.60%	2.40%	2.40%	4.60%	4.60%	2.40%	4.60%	4.60%	4.60%	4.60%	4.60%	-0.20%
2036	-0.30%	2.30%	2.30%	4.70%	4.70%	-0.30%	2.30%	2.30%	4.70%	4.70%	2.30%	2.30%	4.70%	4.70%	2.30%	4.70%	4.70%	4.70%	4.70%	4.70%	-0.30%
2037	-0.40%	2.20%	2.20%	4.80%	4.80%	-0.40%	2.20%	2.20%	4.80%	4.80%	2.20%	2.20%	4.80%	4.80%	2.20%	4.80%	4.80%	4.80%	4.80%	4.80%	-0.40%
2038	-0.70%	2.10%	2.10%	4.90%	4.90%	-0.70%	2.10%	2.10%	4.90%	4.90%	2.10%	2.10%	4.90%	4.90%	2.10%	4.90%	4.90%	4.90%	4.90%	4.90%	-0.70%
2039	-1.00%	2.00%	2.00%	5.00%	5.00%	-1.00%	2.00%	2.00%	5.00%	5.00%	2.00%	2.00%	5.00%	5.00%	2.00%	5.00%	5.00%	5.00%	5.00%	5.00%	-1.00%
2040	-1.00%	2.00%	2.00%	5.00%	5.00%	-1.00%	2.00%	2.00%	5.00%	5.00%	2.00%	2.00%	5.00%	5.00%	2.00%	5.00%	5.00%	5.00%	5.00%	5.00%	-1.00%
2041	-1.00%	2.00%	2.00%	5.00%	5.00%	-1.00%	2.00%	2.00%	5.00%	5.00%	2.00%	2.00%	5.00%	5.00%	2.00%	5.00%	5.00%	5.00%	5.00%	5.00%	-1.00%
2042	-0.80%	2.20%	2.20%	4.80%	4.80%	-0.80%	2.20%	2.20%	4.80%	4.80%	2.20%	2.20%	4.80%	4.80%	2.20%	4.80%	4.80%	4.80%	4.80%	4.80%	-0.80%
2043	-0.50%	2.30%	2.30%	4.50%	4.50%	-0.50%	2.30%	2.30%	4.50%	4.50%	2.30%	2.30%	4.50%	4.50%	2.30%	4.50%	4.50%	4.50%	4.50%	4.50%	-0.50%
2044	-0.30%	2.50%	2.50%	4.30%	4.30%	-0.30%	2.50%	2.50%	4.30%	4.30%	2.50%	2.50%	4.30%	4.30%	2.50%	4.30%	4.30%	4.30%	4.30%	4.30%	-0.30%
2045	0.00%	2.60%	2.60%	4.00%	4.00%	0.00%	2.60%	2.60%	4.00%	4.00%	2.60%	2.60%	4.00%	4.00%	2.60%	4.00%	4.00%	4.00%	4.00%	4.00%	0.00%
2046	0.30%	2.70%	2.70%	4.30%	4.30%	0.30%	2.70%	2.70%	4.30%	4.30%	2.70%	2.70%	4.30%	4.30%	2.70%	4.30%	4.30%	4.30%	4.30%	4.30%	0.30%
2047	0.50%	2.80%	2.80%	4.50%	4.50%	0.50%	2.80%	2.80%	4.50%	4.50%	2.80%	2.80%	4.50%	4.50%	2.80%	4.50%	4.50%	4.50%	4.50%	4.50%	0.50%
2048	0.80%	2.90%	2.90%	4.80%	4.80%	0.80%	2.90%	2.90%	4.80%	4.80%	2.90%	2.90%	4.80%	4.80%	2.90%	4.80%	4.80%	4.80%	4.80%	4.80%	0.80%
2049	1.00%	3.00%	3.00%	5.00%	5.00%	1.00%	3.00%	3.00%	5.00%	5.00%	3.00%	3.00%	5.00%	5.00%	3.00%	5.00%	5.00%	5.00%	5.00%	5.00%	1.00%
2050	1.00%	3.00%	3.00%	5.00%	5.00%	1.00%	3.00%	3.00%	5.00%	5.00%	3.00%	3.00%	5.00%	5.00%	3.00%	5.00%	5.00%	5.00%	5.00%	5.00%	1.00%

Table B.4: RTK growth rates from 2009 to 2050 for Rough Air Scenario [1].

	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
2009	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2010	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2011	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2012	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2013	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2014	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2015	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2016	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2017	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2018	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2019	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2020	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2021	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2022	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2023	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2024	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2025	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2026	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2027	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2028	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2029	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2030	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2031	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2032	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2033	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2034	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2035	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2036	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2037	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2038	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2039	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2040	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2041	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2042	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2043	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2044	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2045	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2046	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2047	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2048	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2049	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2050	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%
2051	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%

Table B.5: RPK growth rates from 2009 to 2050 for Boeing CMO Scenario [1].

	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
2009	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2010	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2011	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2012	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2013	1.60%	1.50%	11.30%	2.20%	3.10%	0.40%	9.20%	12.90%	-5.00%	17.90%	3.70%	6.40%	15.30%	8.70%	16.40%	5.20%	17.90%	14.20%	10.80%	5.30%	0.50%
2014	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2015	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2016	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2017	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2018	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2019	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2020	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2021	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2022	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2023	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2024	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2025	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2026	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2027	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2028	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2029	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2030	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2031	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2032	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2033	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2034	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2035	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2036	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2037	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2038	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2039	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2040	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2041	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2042	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2043	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2044	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2045	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2046	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2047	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2048	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2049	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%
2050	3.50%	5.30%	5.40%	4.90%	4.90%	3.10%	6.40%	7.40%	7.10%	8.80%	4.30%	5.20%	7.30%	0.00%	6.30%	6.70%	8.00%	6.10%	6.90%	4.70%	2.30%

Table B.6: RTK growth rates from 2009 to 2050 for Boeing CMO Scenario [1].

	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
2009	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2010	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2011	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2012	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2013	0.80%	1.00%	6.70%	5.20%	3.00%	0.00%	1.10%	6.90%	5.40%	3.10%	0.20%	12.70%	11.10%	8.90%	5.90%	9.70%	7.40%	4.40%	5.10%	2.10%	-0.80%
2014	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2015	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2016	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2017	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2018	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2019	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2020	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2021	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2022	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2023	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2024	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2025	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2026	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2027	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2028	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2029	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2030	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2031	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2032	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2033	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2034	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2035	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2036	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2037	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2038	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2039	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2040	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2041	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2042	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2043	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2044	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2045	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2046	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2047	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2048	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2049	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%
2050	2.00%	5.30%	4.00%	4.30%	4.80%	3.10%	6.50%	4.70%	4.70%	4.70%	5.40%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	4.70%	5.20%	2.10%

Table B.7: Seat load factor for each cluster.

Cluster | Route Group	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
Cluster 1	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 2	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 3	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 4	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 5	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 6	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 7	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 8	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
Cluster 9	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%

Table B.8: Freight load factor for each cluster.

Cluster | Route Group	EU/EU	EU/AS	EU/ME	EU/AF	EU/LA	EU/NA	AS/AS	AS/ME	AS/AF	AS/LA	AS/NA	ME/ME	ME/AF	ME/LA	ME/NA	AF/AF	AF/LA	AF/NA	LA/LA	LA/NA	NA/NA
Cluster 1	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 2	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 3	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 4	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 5	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 6	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 7	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 8	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%
Cluster 9	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%	53%

Table B.9: Characteristic stage lengths [1].

	Route group																				
Cluster Number	**EUEU**	**EUAS**	**EUME**	**EUAF**	**EULA**	**EUNA**	**ASAS**	**ASME**	**ASAF**	**ASLA**	**ASNA**	**MEME**	**MEAF**	**MELA**	**MENA**	**AFAF**	**AFLA**	**AFNA**	**LALA**	**LANA**	**NANA**
Cluster 1 | Long-range combi	253	7976	4075	6668	8604.5	7065.5	1698	2862	n/a	n/a	8543	0	0	0	0	449	6193	0	1438	0	1090.5
Cluster 2 | Long-range heavy	454.5	9151	4274	7819.5	8327	7045.5	2237	4590.5	10330	12688	10194.5	980	2043.5	0	9609.5	1180	6883	5750	811.5	6171.5	4209.5
Cluster 3 | Mid-range freighter	1681	4612	3468	3562.5	9786	4495	1483.5	2517.5	3833	0	5807.5	1271.5	2704.5	0	0	2086.5	0	0	1369.5	2863	1874
Cluster 4 | Jet commuter	696.5	2041	1629	1395.5	0	4582	772	1644	0	0	4758	614	1173.5	0	0	722.5	0	0	651.5	1457.5	807
Cluster 5 | Long-range freighter	1419	7445.5	4601	5088.5	8874.5	6771.5	2526.5	5650.5	7517	8000	7783	868.5	2927	12000	10821	2745	5506	12181	2194	4010.5	3760
Cluster 6 | Turboprop commuter	293.5	385	444	361.5	0	0	368.5	0	0	0	0	318.5	0	0	0	333.5	0	0	342	323	345.5
Cluster 7 | Mid-range	1757	5495	3727	4378.5	8017	6333	1601	3810.5	5576.5	4908.5	7352.5	901.5	2568.5	10573	9477	1819.5	2746.5	7310	2171.5	3231.5	2269.5
Cluster 8 | Long-range	1562.5	8438.5	4720	6747.5	8386	6808	2394	4492	8165	9834	10186.5	893.5	3742	11980.5	10580.5	2137.5	7434	7963	1731	7103	3323.5
Cluster 9 | Narrow-body	992.5	2627.5	2571.5	1936.5	5954	6675.5	1002.5	2518.5	0	0	6627	805.5	1887	6577	7734	1068	0	6024	950	2195.5	1333

Table B.10: Single annual aircraft production capacity limits [1, 51].

Year of introduction of new technology	**Cluster 2**	**Cluster 4**	**Cluster 6**	**Cluster 7**	**Cluster 8**	**Cluster 9**
1	5	1	2	5	5	1
2	7	19	36	7	7	18
3	10	54	70	10	10	35
4	12	105	104	12	12	52
5	15	156	138	15	15	69
6	17	207	172	17	17	86
7	20	258	206	20	20	103
8	22	309	240	22	22	120
9	25	360	274	25	25	137
10	27	411	308	27	27	154
11	30	462	342	30	30	171
12	32	513	376	32	32	188
13	35	564	410	35	35	205
14	37	615	444	37	37	222
15	40	666	478	40	40	239
16	42	717	512	42	42	256
17	45	768	546	45	45	273
18	47	819	580	47	47	290
19	50	870	614	50	50	307
20	52	921	648	52	52	324
21	55	972	682	55	55	341
22	57	1023	716	57	57	358
23	60	1074	750	60	60	375
24	62	1125	784	62	62	392
25	65	1176	818	65	65	409
26	67	1227	852	67	67	426
27	70	1278	886	70	70	443
28	72	1329	920	72	72	460
29	75	1380	954	75	75	477
30	77	1431	988	77	77	494

Table B.11: Total production capacity for each aircraft class type [1].

	Total production capacity	
Year	**Single-aisle Class**	**Twin-aisle class**
2008	1012	337
2009	1041	342
2010	1069	347
2011	1098	352
2012	1127	357
2013	1155	363
2014	1184	368
2015	1213	373
2016	1242	378
2017	1270	383
2018	1299	388
2019	1328	393
2020	1357	398
2021	1385	403
2022	1414	408
2023	1443	414
2024	1471	419
2025	1500	424
2026	1529	429
2027	1558	434
2028	1586	439
2029	1615	444
2030	1644	449
2031	1673	454
2032	1701	459
2033	1730	464
2034	1759	470
2035	1787	475
2036	1816	480
2037	1845	485
2038	1874	490
2039	1902	495
2040	1931	500
2041	1960	505
2042	1989	510
2043	2017	515
2044	2046	521
2045	2075	526
2046	2103	531
2047	2132	536
2048	2161	541
2049	2190	546
2050	2218	551

Table B.12: Size and age distribution of the global aircraft fleet in 2008 [1].

Age	**Number of aircraft units per aircraft cluster**								
[years]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0	0	10	191	16	33	36	128	615
1	0	1	11	170	13	15	29	123	619
2	0	6	13	237	11	6	41	94	491
3	0	5	14	285	13	8	39	81	426
4	0	17	8	266	10	7	53	83	390
5	0	15	6	264	17	15	63	103	447
6	0	20	17	264	14	14	92	103	575
7	0	13	8	200	18	13	89	110	522
8	0	47	13	164	19	24	105	125	541
9	1	55	15	135	18	19	109	95	462
10	3	36	24	76	13	20	90	95	301
11	5	23	24	38	13	11	77	58	179
12	6	19	21	32	17	26	99	30	164
13	7	27	28	37	18	27	116	24	208
14	4	47	40	56	31	27	143	20	275
15	4	52	48	49	42	25	172	5	412
16	1	49	30	42	34	27	167	1	458
17	2	52	32	22	16	14	144	1	363
18	0	40	27	25	6	6	97	0	284
19	2	12	42	11	6	0	102	0	249
20	0	9	26	32	10	0	58	0	204
21	2	21	25	20	3	0	48	0	170
22	4	10	40	26	4	0	34	0	128
23	2	5	34	58	2	0	19	0	39
24	1	6	41	59	2	0	19	0	31
25	0	0	1	0	0	0	0	0	0
26-30	32	25	131	470	34	0	3	0	148
31-35	7	6	30	206	11	0	0	0	46
>35	0	1	110	72	0	0	0	0	96
sum	83	619	869	3507	411	337	2044	1279	8843

Table B.13: Transport supply of the initial aircraft fleet in 2008 [1].

Route group	**Route group name**	**ASK-supply [x10^{11}]**	**ATK-supply [x10^{10}]**
1	EUEU	7.5515	1.4132
2	EUAS	5.0806	5.4519
3	EUME	1.4101	1.7767
4	EUAF	1.7650	1.0991
5	EULA	2.2044	1.5178
6	EUNA	5.5493	3.8263
7	ASAS	11.7117	6.0302
8	ASME	1.6962	1.8877
9	ASAF	0.2753	0.1802
10	ASLA	0.0408	0.0124
11	ASNA	3.8580	5.0545
12	MEME	0.4618	0.1758
13	MEAF	0.4892	0.2993
14	MELA	0.0265	0.0136
15	MENA	0.4578	0.2059
16	AFAF	0.6272	0.2587
17	AFLA	0.0180	0.0811
18	AFNA	0.1414	0.0598
19	LALA	1.8725	1.1236
20	LANA	2.2423	1.1351
21	NANA	12.4379	3.8539
sum		59.9174	35.4565

Appendix C

Validation Data

Table C.1: Validation data for the new technologies.

Aircrafts		Profile of characteristic flight mission				
New Aircraft Concept	Basic A/C type (BADA)	Stage Length (Km)	Mission fuel burn (kg)			
			New Aircraft Concept	Basic A/C type	Delta	Target Delta
Blended Wing Body	Boeing 747-400	5750	49544.93	67901.17	-27.03%	-27%
Small BWB	Embraer 190	722.5	1840.886	2525.539	-27.11%	-27%
Advanced Turbofan	Boeing 777-200	4720	31140.7	38929.86	-20.00%	-20%
Ultrafan	Boeing 777-200	7963	47464.84	63430.26	-25.17%	-25%
Strut-Braced Wing with Open Rotor	Boeing 737-800	1068	2121.449	4517.563	-53.04%	-53%
Strut-Braced Wing	Boeing 737-800	6675.5	15777.01	22092.42	-28.59%	-29%
A320Neo with Natural Laminar Flown	Airbus A320Neo	805.5	2802.34	2949.986	-4.86%	-4.6%
Double Bubble Fuselage	Airbus A320Neo	1936.5	4736.46	5933.117	-20.17%	-20%
Boundary Layer Ingestion	Embraer 190	1644	4494.855	5044.984	-10.90%	-11%
Open Rotor (C2)	Boeing 747-400	980	10170.43	14508.86	-29.90%	-30%
Open Rotor (C7)	Boeing 767-300	3231.5	14054.96	20113.19	-30.12%	-30%
Open Rotor (C8)	Boeing 777-200	2394	14942.28	21322.52	-29.92%	-30%
BWB (50% Fuel Efficiency)	Boeing 747-400	9609.5	57467.14	113846.4	-49.52%	-50%
Zunum Aero 50	ATR 72-500	293.5	143.5	718.1	-80.01%	-80%
Zunum Aero 100	Embraer 190	614	453.05	2275.23	-80.09%	-80%

Appendix D

ARIMA - CO_2 Emissions Results

Table D.1: CO$_2$ emissions trend for all regions from 2018 to 2050.

	CO2 emissions [Mt]							
Year	**Europe**	**North America**	**Middle East**	**Central & South America**	**Eurasia**	**Africa**	**Asia & Oceania**	**World**
2018	205.04	280.87	67.82	47.48	39.60	33.66	353.46	1027.93
2019	208.66	283.72	69.29	48.23	38.92	34.22	361.23	1044.25
2020	212.28	286.56	70.76	48.98	38.23	34.77	369.00	1060.58
2021	215.90	289.41	72.22	49.73	37.55	35.33	376.76	1076.90
2022	219.53	292.26	73.69	50.48	36.86	35.88	384.53	1093.23
2023	223.15	295.11	75.16	51.23	36.18	36.44	392.30	1109.55
2024	226.77	297.95	76.62	51.98	35.50	37.00	400.06	1125.88
2025	230.39	300.80	78.09	52.72	34.81	37.55	407.83	1142.20
2026	234.02	303.65	79.55	53.47	34.13	38.11	415.60	1158.53
2027	237.64	306.49	81.02	54.22	33.45	38.66	423.37	1174.85
2028	241.26	309.34	82.49	54.97	32.76	39.22	431.13	1191.18
2029	244.89	312.19	83.95	55.72	32.08	39.77	438.90	1207.50
2030	248.51	315.04	85.42	56.47	31.40	40.33	446.67	1223.83
2031	252.13	317.88	86.89	57.22	30.71	40.89	454.43	1240.15
2032	255.75	320.73	88.35	57.97	30.03	41.44	462.20	1256.48
2033	259.38	323.58	89.82	58.72	29.35	42.00	469.97	1272.80
2034	263.00	326.42	91.29	59.47	28.66	42.55	477.73	1289.13
2035	266.62	329.27	92.75	60.22	27.98	43.11	485.50	1305.45
2036	270.24	332.12	94.22	60.97	27.29	43.66	493.27	1321.78
2037	273.87	334.97	95.69	61.72	26.61	44.22	501.03	1338.10
2038	277.49	337.81	97.15	62.47	25.93	44.78	508.80	1354.43
2039	281.11	340.66	98.62	63.22	25.24	45.33	516.57	1370.75
2040	284.74	343.51	100.09	63.97	24.56	45.89	524.33	1387.08
2041	288.36	346.35	101.55	64.72	23.88	46.44	532.10	1403.40
2042	291.98	349.20	103.02	65.47	23.19	47.00	539.87	1419.73
2043	295.60	352.05	104.49	66.22	22.51	47.55	547.63	1436.05
2044	299.23	354.90	105.95	66.97	21.83	48.11	555.40	1452.38
2045	302.85	357.74	107.42	67.72	21.14	48.67	563.17	1468.70
2046	306.47	360.59	108.88	68.47	20.46	49.22	570.93	1485.03
2047	310.09	363.44	110.35	69.22	19.78	49.78	578.70	1501.35
2048	313.72	366.28	111.82	69.97	19.09	50.33	586.47	1517.68
2049	317.34	369.13	113.28	70.72	18.41	50.89	594.23	1534.00
2050	320.96	371.98	114.75	71.47	17.72	51.44	602.00	1550.33

Appendix E

FSDM - CO_2 Emissions Results

Table E.1: CO_2 emissions of Case 1.

	CO_2 emissions [Mt]					
Year	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
2008	577.86	577.86	577.86	577.86	577.85	577.86
2009	600.46	600.46	600.46	600.46	600.46	600.46
2010	623.31	623.31	623.31	623.31	623.31	623.31
2011	646.98	646.98	646.98	646.98	646.98	646.98
2012	670.56	670.56	670.56	670.56	670.56	670.56
2013	694.53	694.53	694.53	694.53	694.52	694.53
2014	718.77	718.77	718.77	718.77	718.76	718.77
2015	743.49	743.49	743.49	743.49	743.49	743.49
2016	769.16	769.16	769.16	769.16	769.16	769.16
2017	795.27	795.27	795.27	795.27	795.27	795.27
2018	820.59	820.59	820.59	820.59	820.59	820.59
2019	843.35	843.35	843.35	843.35	843.35	843.35
2020	867.89	867.89	867.89	867.89	867.88	867.89
2021	892.70	892.52	892.70	892.70	892.70	892.70
2022	918.67	918.33	918.67	918.67	918.67	918.67
2023	945.74	945.37	945.74	945.74	945.74	945.74
2024	971.81	971.13	971.81	971.81	971.81	971.81
2025	996.71	995.41	996.71	996.71	996.70	996.71
2026	1022.08	1019.84	1022.86	1022.86	1022.08	1022.08
2027	1046.75	1043.33	1047.50	1047.50	1046.75	1046.75
2028	1069.57	1064.66	1070.26	1070.26	1069.57	1071.37
2029	1090.53	1083.83	1091.04	1091.04	1090.53	1092.87
2030	1110.67	1101.92	1110.90	1110.90	1110.67	1113.58
2031	1130.58	1119.58	1130.45	1130.45	1128.65	1135.17
2032	1150.83	1137.42	1150.12	1150.12	1148.50	1156.00
2033	1170.96	1155.28	1169.42	1169.42	1167.97	1176.42
2034	1191.08	1173.11	1188.48	1188.48	1187.58	1196.49
2035	1211.21	1190.47	1207.21	1207.21	1206.78	1215.84
2036	1231.55	1207.74	1226.15	1226.09	1225.90	1235.38
2037	1251.99	1225.08	1244.92	1244.86	1245.01	1254.77
2038	1272.19	1242.18	1263.25	1263.16	1263.47	1273.34
2039	1292.06	1258.79	1281.19	1281.06	1281.71	1293.52
2040	1313.56	1276.18	1302.61	1300.61	1300.78	1315.37
2041	1336.61	1294.85	1325.45	1323.10	1323.08	1338.53
2042	1362.06	1316.16	1350.71	1347.91	1345.70	1364.24
2043	1389.00	1339.02	1377.38	1374.01	1369.50	1391.41
2044	1418.33	1364.25	1406.44	1402.40	1395.66	1418.61
2045	1449.26	1390.69	1437.15	1432.35	1422.82	1445.20
2046	1484.48	1421.08	1471.41	1465.21	1453.72	1472.05
2047	1523.41	1456.64	1506.50	1501.03	1486.53	1502.43
2048	1562.98	1494.41	1547.48	1537.63	1520.05	1530.29
2049	1603.12	1532.82	1585.52	1574.93	1554.18	1558.22
2050	1643.77	1570.27	1624.25	1615.97	1588.67	1586.16

Table E.2: CO_2 emissions of Case 2.

	CO_2 emissions [Mt]			
Year	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
2008	577.86	577.86	577.86	577.86
2009	600.46	600.46	600.46	600.46
2010	623.31	623.31	623.31	623.31
2011	646.98	646.98	646.98	646.98
2012	670.56	670.56	670.56	670.56
2013	694.31	694.31	694.31	694.31
2014	718.32	718.32	718.32	718.32
2015	742.75	742.75	742.75	742.75
2016	766.78	766.78	766.78	766.78
2017	792.59	792.59	792.59	792.59
2018	817.54	817.54	817.54	817.54
2019	840.68	840.68	840.68	840.68
2020	864.74	864.74	864.74	864.74
2021	889.00	889.00	889.00	889.00
2022	914.25	914.25	914.25	914.25
2023	940.46	940.46	940.46	940.46
2024	965.53	965.53	965.53	965.53
2025	989.38	989.38	989.38	989.38
2026	1014.68	1014.68	1013.47	1013.47
2027	1037.92	1037.92	1036.68	1036.68
2028	1058.93	1058.93	1057.75	1059.57
2029	1077.64	1077.64	1076.69	1078.76
2030	1095.22	1095.22	1094.62	1097.01
2031	1112.30	1112.30	1110.88	1116.00
2032	1129.48	1129.48	1128.18	1134.18
2033	1146.14	1146.14	1145.13	1151.86
2034	1162.87	1162.87	1161.94	1169.36
2035	1179.04	1179.04	1178.02	1186.37
2036	1195.10	1195.03	1193.88	1203.12
2037	1211.13	1211.01	1209.54	1219.53
2038	1226.70	1226.54	1224.54	1235.17
2039	1241.73	1241.55	1239.23	1250.36
2040	1258.98	1257.46	1254.89	1268.48
2041	1277.08	1275.27	1272.74	1287.95
2042	1297.70	1295.58	1291.27	1310.00
2043	1319.60	1317.08	1310.70	1333.54
2044	1344.18	1340.99	1332.28	1356.53
2045	1370.28	1366.47	1354.85	1376.02
2046	1400.33	1395.41	1381.58	1393.85
2047	1428.94	1425.77	1411.56	1411.77
2048	1458.02	1455.88	1445.17	1429.59
2049	1487.71	1484.82	1478.53	1447.36
2050	1518.19	1514.45	1512.10	1465.14

Table E.3: CO_2 emissions of Case 3.

	CO_2 emissions [Mt]					
Year	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
2008	577.86	577.86	577.86	577.86	577.85	577.86
2009	600.46	600.46	600.46	600.46	600.46	600.46
2010	623.31	623.31	623.31	623.31	623.31	623.31
2011	646.98	646.98	646.98	646.98	646.98	646.98
2012	670.56	670.56	670.56	670.56	670.56	670.56
2013	694.58	694.58	694.58	694.58	694.58	694.58
2014	718.89	718.89	718.89	718.89	718.89	718.89
2015	743.69	743.69	743.69	743.69	743.68	743.69
2016	769.46	769.46	769.46	769.46	769.46	769.46
2017	795.50	795.50	795.50	795.50	795.49	795.50
2018	820.75	820.75	820.75	820.75	820.75	820.75
2019	843.42	843.42	843.42	843.42	843.42	843.42
2020	867.80	867.80	867.80	867.80	867.80	867.80
2021	892.38	892.20	892.38	892.38	892.38	892.38
2022	918.05	917.67	918.05	918.05	918.05	918.05
2023	944.75	944.30	944.75	944.75	944.74	944.75
2024	970.37	969.47	970.37	970.37	970.37	970.37
2025	994.80	993.16	994.80	994.80	994.80	994.80
2026	1019.60	1016.94	1020.36	1020.36	1019.60	1019.60
2027	1043.66	1039.60	1044.42	1044.42	1043.66	1043.66
2028	1065.81	1059.95	1066.49	1066.49	1065.81	1067.59
2029	1086.06	1078.19	1086.56	1086.56	1086.06	1088.38
2030	1105.46	1095.32	1105.65	1105.65	1105.46	1108.36
2031	1124.59	1111.83	1124.34	1124.34	1122.62	1129.18
2032	1144.01	1128.61	1143.07	1143.07	1141.57	1149.16
2033	1163.23	1145.38	1161.33	1161.33	1160.25	1168.63
2034	1182.69	1161.89	1179.44	1179.44	1178.99	1187.66
2035	1202.01	1177.88	1197.28	1197.28	1197.09	1206.26
2036	1221.40	1193.81	1215.00	1214.95	1215.19	1224.68
2037	1241.01	1209.66	1232.74	1232.66	1233.03	1244.54
2038	1260.19	1225.01	1251.44	1251.30	1250.45	1263.97
2039	1279.16	1239.46	1269.90	1269.70	1267.33	1283.05
2040	1299.46	1254.57	1290.17	1289.91	1284.95	1303.71
2041	1321.41	1270.74	1311.73	1311.12	1305.17	1325.54
2042	1345.77	1289.67	1335.72	1334.62	1326.45	1349.97
2043	1371.75	1310.09	1361.22	1359.47	1348.90	1375.67
2044	1400.38	1333.11	1389.39	1386.88	1373.32	1401.49
2045	1430.44	1357.31	1418.86	1415.45	1398.66	1426.87
2046	1464.58	1386.21	1451.80	1446.86	1427.78	1457.22
2047	1502.36	1419.14	1491.03	1480.85	1459.17	1484.97
2048	1541.65	1455.81	1528.25	1519.88	1493.94	1512.71
2049	1581.95	1494.18	1566.75	1556.65	1527.75	1540.53
2050	1622.86	1532.32	1606.25	1594.64	1560.53	1568.31

Table E.4: CO$_2$ emissions of Case 4

	CO$_2$ emissions [Mt]			
Year	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
2008	577.86	577.86	577.86	577.86
2009	600.46	600.46	600.46	600.46
2010	623.31	623.31	623.31	623.31
2011	646.98	646.98	646.98	646.98
2012	670.56	670.56	670.56	670.56
2013	694.33	694.33	694.33	694.33
2014	718.36	718.36	718.36	718.36
2015	742.81	742.81	742.81	742.81
2016	766.86	766.86	766.86	766.86
2017	792.57	792.57	792.57	792.57
2018	817.39	817.39	817.39	817.39
2019	840.34	840.34	840.34	840.34
2020	864.14	864.14	864.14	864.14
2021	888.01	888.01	888.01	888.01
2022	912.81	912.81	912.81	912.81
2023	938.44	938.44	938.44	938.44
2024	962.88	962.88	962.88	962.88
2025	985.98	985.98	985.98	985.98
2026	1010.43	1010.43	1009.20	1009.20
2027	1032.66	1032.66	1031.42	1031.42
2028	1052.54	1052.54	1051.39	1053.24
2029	1070.01	1070.01	1069.10	1071.30
2030	1086.32	1086.32	1085.87	1088.38
2031	1101.99	1101.99	1100.83	1106.20
2032	1117.71	1117.71	1116.77	1123.12
2033	1132.95	1132.95	1132.34	1139.51
2034	1148.14	1148.14	1147.63	1155.64
2035	1162.71	1162.71	1162.23	1170.99
2036	1177.09	1177.04	1176.60	1185.95
2037	1191.14	1191.07	1190.70	1200.45
2038	1205.56	1205.51	1204.25	1215.61
2039	1219.25	1219.12	1216.92	1230.13
2040	1234.49	1234.29	1230.15	1245.72
2041	1250.58	1250.24	1245.20	1262.99
2042	1269.28	1268.86	1260.94	1282.86
2043	1289.43	1288.71	1277.62	1304.03
2044	1312.14	1311.01	1296.29	1323.75
2045	1336.52	1334.77	1316.07	1341.95
2046	1365.62	1362.01	1339.39	1360.10
2047	1395.98	1392.05	1366.00	1378.12
2048	1427.29	1421.21	1397.37	1396.32
2049	1457.99	1451.00	1430.98	1414.66
2050	1489.47	1481.49	1464.70	1432.89