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Comparison of the impact of the COVID-19 pandemic and technological developments on emissions of CO_2 in air transport

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Table of Contents

Table of Figures 3

List of Tables 4

Acronyms 5

Introduction 6

1. Climate change and air quality 7

2. Aviation and environmental impact 10

2.1. All-flight fuel burn trends and CO_2 emissions 10

2.2. Contribution of alternative fuels to the reduction of fuel consumption and trends in CO_2 emissions 12

3. Technological developments to reduce CO_2 emissions 14

  3.1. Aircraft Technologies 14

  3.2. Sustainable aviation fuels 20

4. Carbon offsetting and reduction scheme in international aviation - CORSIA 27

  4.1. Phases of CORSIA 28

  4.2. Route-based access within CORSIA 29

5. Influence of COVID-19 on air transport and CO_2 emissions 31

  5.1. COVID-19 Impact on Airlines 33

  5.2. Airports 37

  5.3. COVID-19 impact on CO_2 emissions – impact on CORSIA program 39

6. Comparison between CO_2 emissions during the COVID-19 pandemic and emissions reduction due to technological innovations in aviation 42

Conclusion 46

References 47

Table of Figures

Figure 1. Annual global CO_2 emissions from aviation [3] 8
Figure 2. Fuel Burn from International Aviation, 2005 to 2050 [5] 11
Figure 3.CO_2 Emissions from International Aviation, 2005 [5] 12
Figure 4.Net CO_2 Emissions from International Aviation, 2005-2050 [5] 13
Figure 5. Global aviation fuel consumption in the Sustainable Development Scenario and total fuel use in the Stated Policies Scenario, 2019-70 [18] 23
Figure 6. CORSIA access on routes [13] 29
Figure 7. Global air passenger traffic (in revenue passenger kilometers – RPKs) [15] 31
Figure 8. Annual number of passengers in Europe + non-EU (in millions) [15] 32
Figure 9. Daily air traffic for 12 April 2020 [16] 34
Figure 10. Number of flights tracked daily by Flightradar24, 2020 vs 2019. [17] 35
Figure 11. Comparsion of total seat capacity by region [15] 36
Figure 12. Average daily IFR departures at the 34 main airports in Europe [14] 38
Figure 13.Three scenarios of CO_2 emissions for recovery from COVID-19 [14] 39
Figure 14. Return of pre-pandemic CO_2 emissions levels [14] 40
Figure 15. Share of domestic and international aviation in total energy-related CO_2 emissions, OECD countries, 1971-2019 [19] 43
Figure 16. CO2 emissions relative to the same month of 2019, World and OECD countries, January 2020 – December 2021 [19] 44
Figure 17. Assessment of the impact of innovation on CO_2 emissions [20] 45

List of Tables

Table 1. Production of SAF 20

Table 2. Benefits and challenges of different SAF pathways [10] 22

Acronyms

CAEP	Committee on Aviation Environmental Protection
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instrument flight rules
LCAF	Lower Carbon Aviation Fuels
OECD	Organization for Economic Cooperation and Development
RPK	Revenue Passenger Kilometres
SAF	Sustainable Aviation Fuel
VTOL	Vertical Take-Off and Landing

Introduction

Air transport is the safest and fastest mode of transportation, benefiting personal and business needs by saving time. Air transport is indispensable for global connectivity, economic growth, emergency responses, and contemporary life.

However, the rise in air traffic operations has led to increased gas emissions that adversely affect people's lives, climate change, and the environment. Ensuring environmental protection during aircraft operations is a critical international task. The COVID-19 pandemic drastically reduced air travel, resulting in a substantial decrease in CO_2 emissions and pollution compared to the peak year 2019. This pandemic had profound and long-lasting consequences for all industry stakeholders, leading to widespread lockdowns, grounded flights, financial losses at airports, and the adoption of new safety measures.

Currently, older aircraft produce significantly more carbon emissions compared to newer models. In the coming decades, efforts are underway to design, produce, and implement electric aeroplanes. Various initiatives, forecasts, and programs aim to reduce carbon emissions, minimize environmental impact, and safeguard the planet. Preserving the environment is paramount due to its influence on human well-being, health, climate change, and the planet's biodiversity.

Various scenarios, predictions, and programs have been established to enable the reduction of carbon emissions, improve the impact on the environment, and protect it properly. The importance of preserving the environment is reflected in how it affects people's lives and their health, climate change, flora and fauna on Earth.

This thesis will present the technological developments and their influence on CO_2 emissions, such as innovation regarding new electric aircraft. There are tendencies for the use of sustainable aviation fuels, first in combination with fossil fuels, while later, a higher share of these fuels is expected compared to the current use of kerosene. In addition, the data about how much emissions were saved during the COVID-19 pandemic will be presented. The thesis compares the impact of the pandemic and technological developments on CO_2 emissions.

1. Climate change and air quality

Air pollution has an impact on the health of the population, especially in urban areas. The most important pollutants are particles, nitrogen oxides, and ozone. On the territory of Europe, there has been an increase in air pollution caused by aircraft operations.

The World Health Organization has recently renewed guidelines with quantitative health recommendations for air quality management, expressed as long-term or short-term maximum concentrations of pollutants.

Air pollution near airports is caused by aircraft operations, usage of ground equipment, traffic on access roads, and energy "produced" at the airport. Aircraft engines produce emissions that are similar to other sources that use fossil fuels.

Recent research has shown increased levels of $PM_{2.5}$ and related particles at and near airports. When assessing the impact of these particles, their number is important because it represents an important indicator. Exhaust gases produced by aircraft engines can cause concentrations at ground level over large areas located "downwind" of the airport location. Which area will be covered depends on factors related to the direction and speed of the wind, the runway in use, and the phase of the flight. It mostly affects the cities located near the airport [1].

Since the late 1970s, ICAO has been developing measures to address emissions from aircraft engines near airports and from relevant airport sources. The aim is to achieve the primary environmental objective "*to limit or reduce the impact of emissions on local air quality*" [2].

Local air quality regulations address liquid fuel emissions, smoke, non-volatile particulate matter (nvPM), and the main gaseous exhaust emissions from jet engines: hydrocarbons, nitrogen oxides, and carbon monoxide.

The ICAO International Panel on Climate Change is an international organization with several working groups. The first working group facilitates policy implementation and regular assessment related to climate change. The second working group assesses the impact and future risks; the third assesses options and the possibility of adapting to and mitigating climate change. In 2018, the International Panel on Climate Change provided a report on the impact of global warming, with temperatures rising by 1.5°C compared to the pre-industrial period. Maintaining zero net CO_2 emissions at the global level that occur due to human activities and reducing the radiative effect of non-CO_2 gases can stop global warming for a long period [3].

Carbon dioxide is the principal product of the combustion of fossil fuels. CO_2 emissions, the most significant and best-understood element of aviation’s total contribution to climate change, have been estimated at approximately 2% of all such anthropogenic emissions. Because CO_2 has a very long lifetime in the atmosphere, the level and effects of CO_2 emissions are currently believed to be broadly the same regardless of the altitude. Aircraft engine emissions are directly related to fuel burn. The key to minimizing their environmental impacts is to use fuel more efficiently [4].

The burning of fossil fuels causes carbon dioxide gas emissions. Carbon dioxide can remain in the atmosphere for over a hundred thousand years, which leads to its accumulation and increase in concentration. Carbon dioxide circulates between the atmosphere, water surfaces, and the biosphere. Removing CO_2 from the atmosphere involves several processes that must occur in different periods. About 50% of CO_2 will be removed from the atmosphere in 30 years and 30% in the next few centuries. As stated, 20% can remain in the atmosphere for several thousand years [3].

The aviation sector's global carbon dioxide emission share is about 2.5% annually. Recently, there has been a drastic increase in carbon dioxide emissions both by air traffic and at the global level [3].

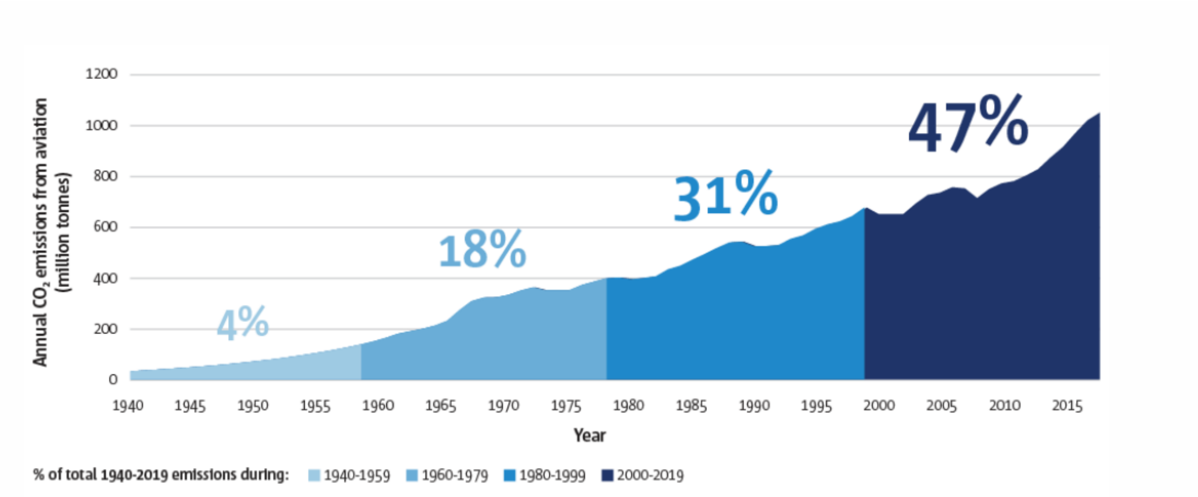


Figure 1. Annual global CO_2 emissions from aviation [3]

Figure 1. shows the annual global value of CO_2 emissions from air traffic from 1940 to 2019. It can be seen from the picture that the highest emission of CO_2 was in the last two decades, and this was achieved due to a 16% increase in emissions.

2. Aviation and environmental impact

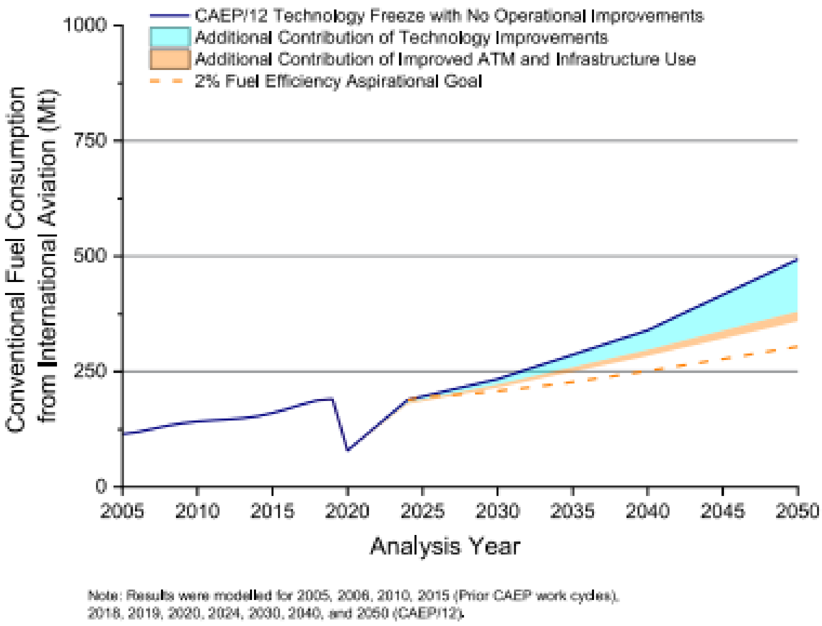
At the end of each three-year work cycle, the International Civil Aviation Organization's Aviation Environmental Protection Committee conducts an assessment of future environmental trends in aviation that includes:

- Greenhouse gas emissions from aircraft engines that affect the global climate;
- Aircraft noise;
- Aircraft engine emissions are affecting local air quality. [5]

Data presented for years before 2018 are reproduced from previous CAEP trend estimates. The presented trend results for fuel burn and emissions relate only to international aviation. Here, the trends are developed in the context of a long-term view, assuming no airport infrastructure constraints or airspace operational constraints. However, these trends can be significantly affected by a wide range of factors, including fluctuations in fuel prices, the use of alternative jet fuels, and global economic conditions, including the recovery of air traffic caused by the COVID-19 pandemic. [5]

2.1. All-flight fuel burn trends and CO_2 emissions

Figure 2. shows the results for the fuel burn during the entire flight for the performance of international aircraft operations from 2005 to 2050. In this period, the effects of aircraft technology, improved air traffic management, and the use of infrastructure on fuel consumption were observed. In the figure, the blue line represents the situation with no operational improvements, while the dashed line illustrates the fuel burn that could be achieved if the 2% fuel efficiency target was achieved.



Note: Results were modelled for 2005, 2006, 2010, 2015 (Prior CAEP work cycles), 2018, 2019, 2020, 2024, 2030, 2040, and 2050 (CAEP/12).

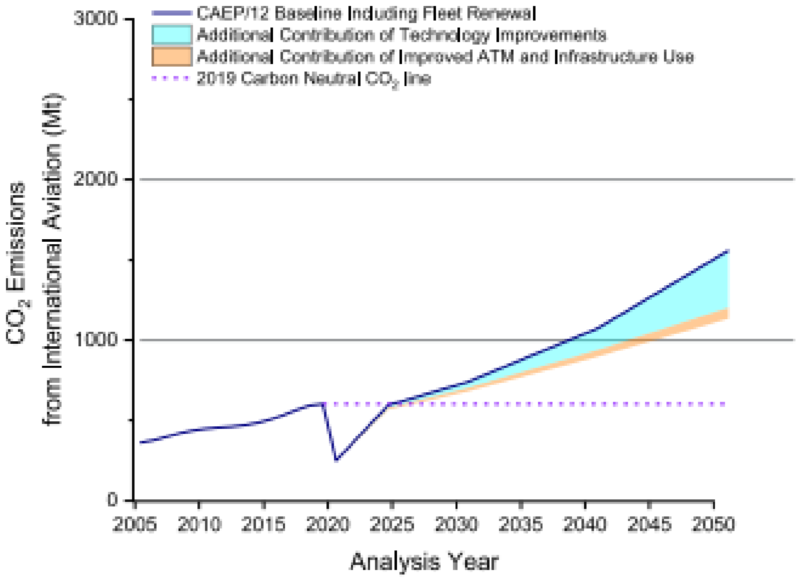
Figure 2. Fuel Burn from International Aviation, 2005 to 2050 [5]

By 2050, it is assumed that there will be advances in aircraft technology as well as operational improvements, which will ensure a reduction in conventional fuel burning in aircraft operations on a global scale. The reduction is expected in the range of 135 to 493 million tons. Globally, improvements in aircraft design technology will lead to a reduction of 177 million tons, while the reduction by operations is forecast to be around 38 million tons.

When looking at the most restrictive scenario, the improvement in fuel combustion technology is expected to average around 1.53% per year. This improvement is under the ICAO target of 2% fuel burn in international aviation. Technological and operational improvements lead to an approximately 27% reduction in fuel consumption in international and global aviation by 2050 [5].

Figure 3. shows the emissions of CO_2 during the entire summer when performing operations at the international level from 2005 to 2050. It also shows the expected reduction in CO_2 emissions due to the development of aircraft technology, improved air traffic management, and infrastructure use.

CO_2 emissions are based solely on fuel combustion in the jet engine, assuming that 1 kg of fuel burned generates 3.16 kg of CO_2.



Note: Results were modelled for 2005, 2006, 2010, 2015 (Prior CAEP work cycles), 2018, 2020, 2024, 2030, 2040, and 2050 (CAEP/12).

Figure 3.CO_2 Emissions from International Aviation, 2005 [5]

Due to the difference in fuel consumption values, we observe a difference between the highest expected fuel consumption in 2019 and the lowest expected fuel consumption in 2050. The expected minimum CO_2 emissions in 2050 would be 532 Mt compared to 2019 [5].

2.2. Contribution of alternative fuels to the reduction of fuel consumption and trends in CO_2 emissions

Figure 4. shows the CO_2 emissions generated during aircraft operations at the international level from 2005 to 2050. The reduction of CO_2 when using alternative fuels is shown. If we work to reduce CO_2 emissions, the greatest effect will be achieved using alternative aviation fuels with less carbon.

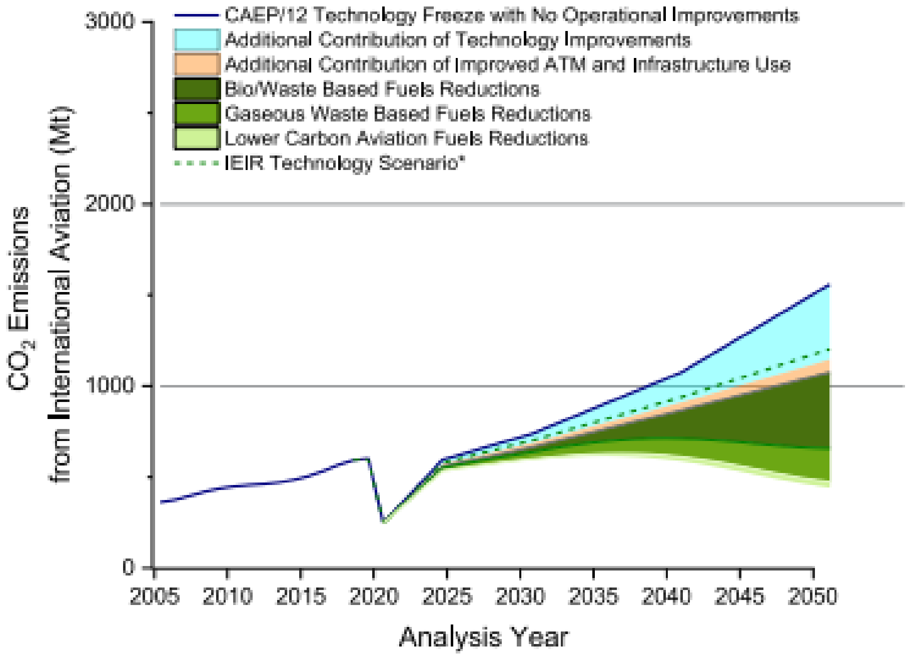


Figure 4.Net CO_2 Emissions from International Aviation, 2005-2050 [5]

The ICAO working group, which deals with analyzing and designing appropriate solutions for achieving long-term goals for reducing CO_2 emissions, has assessed the potential in the future production and use of LCAF and SAF-CO_2. SAF-CO_2 projections are based on the availability of CO_2 for sources to generate ethanol and ammonia.

Other sources of CO_2 production are too expensive and relate to the production of electricity, iron, steel, and cement. LCAF projections are based on the availability of fuel conversion technology to reduce CO_2 during LCAF production, including the use of renewable energy and hydrogen, venting avoidance, and the carbon intensity of crude oil.

To estimate CO_2 reduction trends using alternative fuels, linear increase functions were used to determine the estimate of the use of these fuels in the period from 2020 to 2035 and the period from 2035 to 2050. The assumption is based on the fact that by 2050, air carriers will 100% replace the fuels used today with alternative fuels. Using alternative fuels provides an additional reduction of CO_2 emissions by 56% internationally [5].

3. Technological developments to reduce CO_2 emissions

With the expected growth of international civil aviation, innovations are essential to achieve the environmental goals defined by ICAO and support aviation's contribution to the United Nations' Sustainable Development Goals. ICAO pursues research and development initiatives that can support these goals. New innovative technologies and energy sources for aviation are developing rapidly. ICAO has a significant amount of work to keep pace with the timely environmental certification of such new technologies, as appropriate. ICAO constantly monitors new technologies for conventional aircraft types, including innovative fuels such as sustainable and low-carbon ones. The mentioned fuels have potential environmental benefits, technical feasibility, and economic justification. ICAO also monitors the evolution of new propulsion concepts such as electric, hybrid, and hydrogen aircraft propulsion. ICAO also encourages the spread and application of circular economy technology in the aviation sector [6].

ICAO's new initiatives are designed through:

- Aircraft technologies;
- Electric aircraft - E-HAPI;
- Use of hydrogen in aviation fuels;
- Aircraft operations;
- Sustainable aviation fuels. [6]

3.1. Aircraft Technologies

Aviation technologies are constantly evolving, from engines to aircraft structures to improvements in aerodynamics. They represent incremental advances in the aviation industry, such as more efficient combustion of jet engines, equipping aircraft with vertical winglets, or the design and production of new aircraft.

From a short- to medium-term perspective, the current aviation fleet is being improved by the continued development of conventional airframe and propulsion technologies toward "cleaner operations". From a mid-to-long-term perspective, manufacturers and researchers present new aircraft and propulsion designs to reduce CO_2 emissions and a wide range of options for sustainable aviation fuels and clean energy sources, such as hydrogen or electrification.

Aircraft technologies are aimed at increasing efficiency and reducing carbon emissions. In the short term, sustainable aviation fuels have a greater role in decarbonization than other mitigation measures because these fuels will reduce carbon emissions [7].

3.1.1. Aircraft configuration - new concepts

- Aerodynamics of the aircraft - Specific aviation technology applied to the local geometry of the aircraft

Due to the complete redesign of the aircraft configuration, there are improvements to the local geometry of the aircraft. Improvements include wing tip devices, laminar flow control, airfoil reshaping, and finned skin surfaces [7].

- Aircraft systems - more efficient and electric

Significant improvements to aircraft systems are emerging in advanced concepts. Advanced aircraft system capabilities provide low-power use to prevent aircraft wing icing, improved battery energy efficiency and single-pilot operations, improved fly-by-wire system, aviation fuels containing hydrogen fuel cells, improved fly-by-wire system, and fly-by-light [7].

- Aircraft structure - load reduction, structural efficiency

The structure's efficiency should be such that it can withstand the extreme loads that are constantly increasing, and solutions should be found to reduce the aircraft's total weight. New and improved technologies for reducing the load on the aircraft's structure are being designed, affecting the weight reduction resulting from improved manufacturing processes. The improved ability to deploy these technologies and improved manufacturing processes extend their benefit to the entire fleet [7].

- Materials – light materials and alloys

Lightweight materials and alloys represent an improvement in the ratio of weight and payload over previous generations of aircraft. The use of new alloys requires processes closely related to the abovementioned technology to reduce the load on the aircraft structure. Structures that address the types of loads and necessary material characteristics will be produced as "*engineered composite materials" instead of the previous reliance on available "raw materials*" [7].

- Aircraft engines - increasing the efficiency of turbine engines, hybrid-electric engines

Three technological ways that can reduce the fuel consumption of a turbine engine, thereby reducing CO_2 emissions, are:

- Increasing the thermal efficiency by increasing the total pressure ratio in the compressor, which can lead to an increase in the temperature of the engine;
- Increasing drive efficiency by increasing the degree bypass motor;
- By reducing the weight of the built-in motor and the resistance.

The essential importance of the aircraft fuel system is the use of sustainable aviation fuels. For medium-term and long-term applications, replacing turbine engines with electric engines, hybrid-electric engines, or fuel tanks and using hydrogen in the fuel composition are under development. Such processes are essential for short-range aircraft [7].

- Alternative aviation fuels - impact on aircraft design

Technologically advanced alternative aviation fuels will be presented as achievements leading to reductions in CO_2 emissions. Improved fuels will affect aircraft size, shape, and new safety standards. Alternative fuels offer corresponding environmental benefits [7].

3.1.2. Electric aircraft - E-HAPI

Electric aircraft have huge potential to reduce CO_2 emissions, noise, and aircraft operating efficiency in a range of different applications to support aviation to achieve zero CO_2 emissions by 2050. Constant growth is occurring in the electrification of aircraft systems, propulsion research, and investment in electric or hybrid aircraft design. Electric and hybrid aircraft projects are divided into:

- Category of general aviation aircraft or recreational aircraft with a maximum take-off weight of 300 to 1000 kg. Aircraft of this category are electrically powered, where the cabin capacity is limited to 2 seats. The planes are already manufactured and certified;
- Aircraft category for business aviation and regional aircraft operations, where the aircraft range is 1000 km with a cabin capacity of up to 10 seats;
- The category of large commercial aircraft, which are hybrid-electric and have a cabin capacity of 100-135 seats, and the start of use is expected by 2030;
- The VTOL category has a cabin capacity of 1-5 seats, a maximum take-off weight between 450 and 2200 kg, and an aircraft range of 16 to 300 km. This aircraft category has an electric drive, and its use is expected in 2020-2025. years. [6]

The electric aircraft sector is still developing, and the direct benefits are difficult to assess, especially for urban air mobility. The comprehensive study highlighted the potential of electricity in aviation to reduce operating costs, open up previously uneconomic regional destinations, reduce CO_2 emissions, reduce noise intensity, increase availability, and be a driver of economic development activities. Cost reduction can also be seen in fuel and maintenance costs. Replacing fossil-fueled aircraft with electric-powered aircraft leads to a reduction in greenhouse gas emissions.

One of the key findings is that replacing a fossil-fueled aircraft with a similar electric aircraft can reduce fuel costs from approximately $400 to $50, along with a reduction in CO_2 emissions of up to 95% [7].

- Innovations - challenges and opportunities

The evolutionary shift towards more electric aircraft is a slow and complex process. Significant technological developments and the adoption of electric cars in the last decade have made electric aircraft design possible. Aviation witnessed a shift towards more electric aircraft when Boeing produced the Boeing 787 in 2011.

The Boeing 787 uses an electrical system instead of a pneumatic system and provides much more efficient power generation and distribution for use, reduced system weight, and larger capacity electrical energy storage systems.

In addition to relevant technological advances, economies of scale, and growth, the new supply bases have reduced system component costs. System components such as electric motors and converters are defined as electric motors and battery or fuel tanks instead of conventional fuel systems. Today's most modern lithium batteries for commercial use are 50 times heavier than jet fuel. Electric motors are much lighter than internal combustion engines. The rapid development of solid-state batteries, reaching four times the energy and power density, significantly overcomes lithium batteries' performance, safety, and processing limitations. This concept is estimated to be available in 2030 in electric vehicles and aircraft [7].

Three key challenges and opportunities faced by researchers and designers during the given projects are:

- The fuel tank, which contains hydrogen, is another energy storage system. It is an electrochemical device that directly converts hydrogen into electricity for an electric motor, releasing heat and water. The tank with compressed hydrogen of 700 bar is not conventionally placed inside the wing but in the fuselage, which allows the reduction of passenger capacity unless a new configuration of the aircraft structure is applied;
- All new and retrofitted electric aircraft must be certified for airworthiness by regulatory authorities. Before certifying electric aircraft, regulatory authorities must examine whether there is knowledge and experience necessary to address deficiencies in existing standards and regulations;

- The readiness of the ecosystem to enable the operation of electric aircraft, such as the availability of "clean" energy and distribution to the plug-in electric aircraft for charging. This ecosystem includes airports from an infrastructure and operations perspective, airlines that will need to modify their existing ground processes and flight routes to take advantage of the capabilities of electric aircraft, and the energy industry that could be a supplier, on-site storage, or management distributor [7].

3.1.3. Hybrid-electric driven systems of aircraft

To achieve the targets for reducing greenhouse gas emissions, a concept where the internal combustion engine and electric motors are combined in the drive to increase the efficiency of the vehicle is analyzed. This alternative is called hybrid-electric propulsion. This "hybridization" can be achieved by combining internal combustion engines or fuel cells with electric motors and batteries.

The Hybrid Electric Propulsion System is emerging as the most viable solution for energy-efficient, cleaner, and quieter aviation propulsion, as it can combine the advantages of a conventional propulsion system and an all-electric approach. Despite this, several goals must be achieved for the technology to be sustainable.

The More Electric Aircraft concept aims to change aircraft systems to be fully electric. Only monitoring devices and auxiliary systems are electric, while more demanding devices still work with hydraulic or pneumatic systems.

The hybrid-electric driven systems offer operational flexibility due to the greater number of components. Fuel and battery sources allow more possibilities to control the propulsion system in different phases of flight and reduce energy consumption compared to traditional ones. Aircraft propulsion will gradually evolve from small all-electric Urban Air Vehicles to medium-sized hybrid-electric aircraft and later to hybrid-electric propulsion regional aircraft over the next three decades.

To meet this increasing demand and environmental requirements, revolutionary aircraft concepts are needed to reduce take-off and landing noise in urban areas around airports, to reduce energy consumption and emissions, and to keep aircraft economically viable. Large airports with runways longer than 3050 m are largely used, while thousands of smaller airports with runways shorter than 910 m are underutilized and represent a market for new aircraft concepts [8].

3.2. Sustainable aviation fuels

Sustainable aviation fuels are renewable or waste aviation fuels that meet the appropriate criteria and are one of the elements of ICAO measures to reduce emissions from aircraft, including technology and standards, as well as operational improvement and a carbon reduction scheme for international aviation [7].

CORSIA allows airlines to reduce offset requirements using CORSIA-eligible fuels, including sustainable and low-carbon aviation fuels. CORSIA includes the SAF in Sustainability and Life Cycle Assessment Standards to enable this, representing the industrial sector's first global approaches to sustainability and life cycle assessment.

By applying a holistic approach of accounting for all fuel lifetime emissions, life-cycle reductions in greenhouse gas emissions from SAF use can be as high as 70% or over 90% compared to fossil jet fuel [9].

There are different production routes for SAF with several different raw materials available. Raw material refers to the source of the fuel [9].

Table 1. Production of SAF

Raw material	Subtype of raw material
Municipal solid waste	Product packaging, garden waste, food waste, paper waste
Cellulosic waste	Residues from agriculture
Cooking oil	Unused leftover oil after eating
Crops and plants	Algae, marsh grasses
Power and hydrogen	Renewable electricity, water, and CO_2 produced through water electrolysis

Table 1., shows the raw materials and which subtypes of raw materials can be used to produce SAF. It can be seen from the table that it is mostly already used raw material, i.e., waste used in everyday life.

Low-carbon jet fuel can serve as a complementary measure to sustainable jet fuel to reduce greenhouse gas emissions. LCAF can only be certified as a CORSIA-eligible fuel if it meets the CORSIA sustainability criteria [5].

SAF and LCAF represent a measure of support for the CORSIA program. The advantages these two types of fuel contribute to are that SAF enables the reduction of emissions in the combustion phase of the fuel's life cycle, while LCAF enables the reduction of emissions in the production phase of the fuel's life cycle. LCAF also offers short-term reductions in greenhouse gas intensity, while SAF production increases in future years [7].

Different SAF types' costs and market readiness evolve and may influence policy support allocations. Advanced SAFs (biochemical, thermochemical and power-to-liquid) can deliver large-scale emission reductions but are currently the most expensive options. First-generation biofuels (oleochemical) are the cheapest SAF today and maximize emission reductions if produced from waste feedstock, but maintaining supply may become difficult as fuel production increases. While these fuels will deliver the most short-term market growth due to their cost competitiveness and existing production scale, they may lose market shares to more advanced SAF types as they become more competitive mid- and long term [10]. The benefits and challenges of different SAF pathways, are respresented in *Table 2*.

Table 2. Benefits and challenges of different SAF pathways [10]

Pathway category	**Scalability**	**Costs**	**Emissions benefits**
Oleochemical/lipid	(+) most commercial technology that can support early sustainable aviation fuel scale-up; (-) sustainable feedstock supply faces limitations	(+) low technology costs; (-) limited cost reduction potential, waste feedstock limitations may increase costs	(+) high if using waste feedstock; (-) limited if using energy crops
Biochemical	(+) high feedstock availability; (-) early technology deployment stage	(+) cheap feedstock ; (-) high technology costs, competing feedstock uses for some fuels	(+) high, especially if using agriculture and forestry residues *Power-to-Liquid*
Thermochemical	(+) high feedstock availability; (-) early technology deployment stage	(+) cheap feedstock; (-) high technology costs	(+) highest emission benefits among bioenergy pathways
Power-to-Liquid	(+) not dependent on biomass feedstock; (-) nascent technology deployment stage of electrolyzers and direct air capture	(+) high cost reduction potential; (-) high costs and uncertainty of cost reductions	(+)high if produced with renewable electricity; (-)savings depend on fast power grid decarbonisation

Figure 5. shows that what is the value of emissions of CO_2 if there will be usage of the synthetic fuels, biofuels or fossil jet kerosene from 2020.

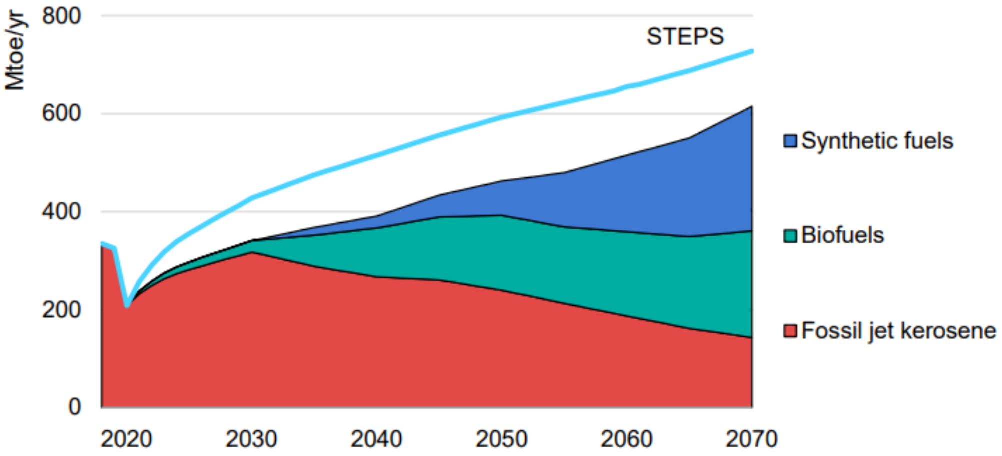


Figure 5. Global aviation fuel consumption in the Sustainable Development Scenario and total fuel use in the Stated Policies Scenario, 2019-70 [18]

Sustainable aviation fuels play a pivotal role in reducing emissions from aviation in the Sustainable Development Scenario, especially during the second half of the projection period. However, they do not entirely displace jet kerosene which continues to supply one-quarter of the market in 2070.

- Biofuels destined for aviation, blended into conventional petroleum-based jet fuel, currently account for only 0.01% of total aviation fuel consumption, but that share will rise to about one-quarter by 2040 and about 35% by 2070. Around 4.4 mboe/d of biofuels were used in aviation in 2070, more than double the total biofuels produced in 2019 for road transport purposes;
- Synthetic jet kerosene is produced from CO_2 captured from concentrated industrial sources, using biomass feedstocks, or via direct air capture and low-carbon hydrogen. It complements biojet fuel, the supply of which is constrained by the limited availability of sustainable biomass and the demand for biomass in other energy sectors. Synthetic jet fuel’s building blocks are not limited in the same way as biomass, and synthetic methods can produce a hydrocarbon fuel with characteristics identical to conventional jet kerosene, allowing the fuel to be

> blended or entirely replace jet kerosene. Commercial-scale synthetic jet kerosene production starts in the 2030s in the Sustainable Development Scenario, and the share of the jet fuel market taken by synthetic production will reach more than 40% by 2070. In 2070, of synthetic fuels will be used in aviation, equivalent to about three-quarters of jet kerosene consumption in 2019. [18]

In the Sustainable Development Scenario, CO_2 emissions from aviation are reined in through a suite of rigorous and concerted government policies to support investment in the production of alternative, sustainable aviation fuel pathways and fuel efficiency technologies for airframes and engines. Operational efficiency gains and shifts to less energy-intensive modes of travel also reduce fuel use. In the medium term, technical and operational efficiency gains play a supporting role alongside the faster deployment of sustainable aviation fuels. In the longer term, synthetic fuels make an important contribution to reducing upstream and operational CO2 emissions, particularly after 2050 [18].

3.2.1. Biofuels

Globally, aviation produced 915 million tons of CO_2 in 2019. Aviation contributes about 2% of CO_2 emissions and about 12% of all emissions from traffic. Non-CO_2 emissions from aviation also significantly impact climate, contributing almost two-thirds of net radiation. All these values are projected to double by 2050 under the standard scenario.

Aircraft usually use jet kerosene, refined from crude oil. This accounts for almost all aviation energy consumption, the remainder being jet fuel and sustainable aviation fuels [7].

Biofuel is the name for fuels that either belong to biomass or were created by processing biomass - by processing plants, animals, and microorganisms and are renewable energy sources. Biofuels also include fuels that are a byproduct of other processes and would otherwise be waste.

Biofuels are divided into:

- Solid - wood, straw, hay, plant waste;
- Liquid - alcoholic biofuels, bio-oils, gaseous biofuels in a liquid state;

- Gaseous - biogas, generator gases produced by biomass processing, distillation gases produced by biomass processing.

Engines that use fuel obtained in this way (only from biomass) emit carbon compounds previously absorbed by plants, significantly contributing to environmental protection. Today's types of fuel obtained from crude oil processing do not allow the recycling of carbon dioxide but generate additional emissions of this gas. Aviation fuel is obtained from biomass - the so-called "drop-in fuel". This fuel must provide energy per unit mass, equal to or greater than traditional fuels and must have the ability to maintain the same characteristics both in the heat of deserts and in the extremely cold conditions that prevail at high altitudes.

Airlines can only use industry-approved fuels, limited to biofuels and e-fuels. SAF production covers less than 1% of global jet fuel demand, with around 100 million litres of SAF produced in 2021. Production of sustainable aviation fuels and biofuels is increasing as more countries and airlines commit to reducing CO_2 emissions by using SAF. They are used with fossil fuels as a mixture of 50% and 50% biofuels. HEFA-SPK7 is currently the most in production, while ICAO has not yet approved other fuels.

In the ReFuelEU initiative, the European Union proposed that fuel suppliers mix sustainable aviation fuels with fossil fuels and that the mixture should be 2% by 2025, 5% by 2030, 32% by 2040, and 63% by 2050—years of sustainable aviation fuels in the fuel mixture [7].

The use of biofuel would account for 47% of the total fuel consumption. That is, around 204 billion litres of biofuel would be produced. To date, nine routes have been certified with ASTM certification, which allows biofuels to be blended with petroleum-derived or processed jet fuel [5].

Synthetic kerosene is a fuel that, theoretically, can provide transportation fuels with very low carbon intensity. A key process step is using renewable energy sources for water electrolysis and hydrogen production. Hydrocarbon fuels can be produced when "green" hydrogen is combined with "green" or waste carbon sources CO or CO_2 [7].

3.2.2. Renewable hydrogen for aviation

Regarding technologies that can help decarbonize civil aviation and reduce emissions, hydrogen has been identified as playing a major role in future solutions. The fact that H_2 can be produced and consumed without producing CO_2 and that H_2 is widely available in water are two main factors that make it attractive as a solution, marking it as a means to achieve the stated goals. Research so far has shown promising results, and the development of hydrogen as an aviation fuel is needed [11].

Civil aviation segments such as regional and short and medium-haul routes represent the first target groups that need to use H_2 as an aircraft fuel. Using H_2 in larger passenger aircraft would require significant changes in aircraft design to accommodate the required amount of hydrogen.

Hydrogen is used in refinery processes to remove undesirable elements such as sulfur from the product. It is often produced by steam-reforming natural gas into hydrogen and carbon dioxide. Hydrogen with a lower carbon content obtained from the storage of carbon emissions is called "blue hydrogen". Hydrogen produced using renewable electricity to split water into hydrogen and oxygen is called "green hydrogen". These alternative sources of hydrogen can be used in fossil fuel production to reduce greenhouse gas emissions further [7].

4. Carbon offsetting and reduction scheme in international aviation - CORSIA

CORSIA is the first global market measure for any sector and represents a cooperative approach that moves away from national or regional regulatory initiatives. It offers a coordinated way to reduce carbon emissions from international aviation, minimizing market distortion while respecting the particular circumstances and respective capabilities of ICAO Member States.

CORSIA aims to stabilize CO_2 emissions at 2020 levels by requiring airlines to limit the growth of their emissions after 2020. Airlines will be required to monitor emissions on all international routes. CORSIA complements the other measures to offset the CO_2 emissions that cannot be reduced using technological improvements, operational improvements, and sustainable aviation fuels [12].

The airlines are required to submit a verified emissions report to the state on an annual basis. The emissions report will contain information on CO_2 emissions from the previous calendar year and will be accompanied by a verification report produced by a third-party verifier. The operator and verification body shall independently submit a verified emissions report and related verification report to the state authority.

After the State has received the emissions reports from all the airlines attributed, the State will aggregate the CO_2 emissions and use the CORSIA Central Registry to submit the necessary information to ICAO.

An airline's annual emissions report includes CO_2 emissions from all international flights by airport pair or country pair (as decided by the country), regardless of whether these flights are subject to CORSIA offset requirements [13].

As discussed before, for CO_2 reduction, SAF fuels are used, and therefore, the CORSIA definition of acceptable fuel includes:

- CORSIA sustainable aviation fuel, which an operator can use to reduce their compensation requirements;
- CORSIA Low Carbon Aviation Fuel – fossil fuel-based aviation fuel that meets CORSIA sustainability criteria;

- CORSIA sustainable aviation fuel - Aviation fuel from renewable sources or from waste that meets CORSIA sustainability criteria. [14]

4.1. Phases of CORSIA

CORSIA is implemented in three phases:

- pilot phase (2021-2023);
- first phase (2024-2026);
- second phase (2027-2035).

Participation is voluntary for the first two phases (2021-2026). From 2027 onwards, participation will be determined based on RTK data for 2018 [12].

The difference between the first phase and the pilot phase is how the state determines the requirements for compensation of CO_2 emissions by the airline. Specifically - for the pilot phase, states have two options to determine the basis of the airline's claim for compensation:

1) Use CO2 emissions of airlines covered by CORSIA in a given year (2021, 2022, 2023);
2) They use airline emissions from 2019.

For the first phase, the calculation for determining the requirement for compensating CO_2 emissions from the airline companies is based on emissions in a given year [13].

Unlike the voluntary participation of states in CORSIA compensation in the pilot and first phase, the second phase of CORSIA from 2027 to 2035 applies to all member states. However, there are two exemption categories based on aviation-related and socio-economic criteria. For aviation-related criteria, there are two thresholds:

- States whose individual share of international aviation activities in revenue from RTK in 2018 is below 0.5% of total RTK;
- Countries that are not part of the list of countries that account for 90% of total RTKs when sorted from highest to lowest amount of individual RTKs. [13]

For socio-economic criteria, States defined as least developed countries, small island developing States, and landlocked developing countries, regardless of their level of participation in international RTK aviation, are exempt from the requirement for compensation in the second phase of CORSIA. However, these states may voluntarily participate in the second phase of CORSIA. [13]

4.2. Route-based access within CORSIA

The approach within the scheme is to ensure equal treatment of all airlines on a given route. It applies to routes covered by CORSIA CO_2 offsets if both countries connecting the route participate in the scheme and routes not covered by CORSIA CO_2 offsets if one or both countries do not participate [13].

Figure 6. shows the route-based approach, where the country participating in the CORSIA program and the routes that meet the requirements for compensation and monitoring, reporting, and verification of CO_2 emissions are marked in green, while the countries that do not participate in the program are shown in grey. CORSIA program, as well as monitored, reported, and verified routes.

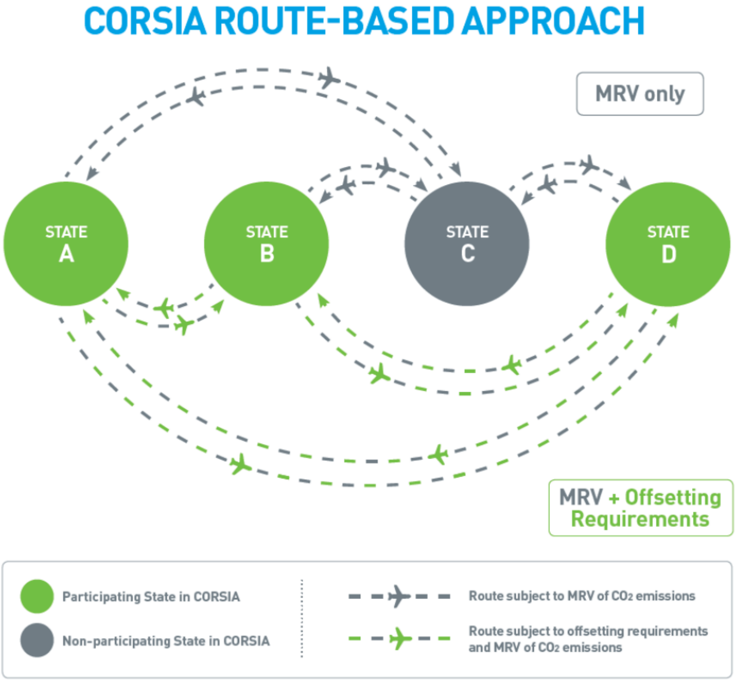


Figure 6. CORSIA access on routes [13]

Figure 6. shows that if it moves from country A to country C, that route is monitored, reported, and verified for CO_2 emissions but does not meet the requirements for CO_2 emissions compensation. If travelling from country D to country B, that route is also monitored, verified, and reported on CO_2 emissions and meets the requirements for compensation of CO_2 emissions.

5. Influence of COVID-19 on air transport and CO_2 emissions

The pandemic caused by the COVID-19 disease has had a very negative impact on air travel demand, driving the aviation industry in 2020 to perform the worst results in the recent history of civil aviation, both in terms of the transport of passengers and the transport of goods. As of 24 March 2020, many airlines had temporally suspended their operations, and to make matters worse, the recovery of the operations pattern for COVID-19 turned out to be highly uncertain and substantially different than the short-sharp V-shaped pattern observed after the SARS outbreak [15].

IATA reported that the COVID-19 pandemic caused global passenger demand (revenue passenger kilometers or RPKs) to drop by 65.9% in 2020 compared to 2019, consequently leading to a decrease in airline passenger revenue by 68.9% drop compared to 2019. According to IATA Outlook, in 2020, airlines posted the largest ever collective net loss. At the peak of the crisis, in April 2020, 66% of the world's commercial air transport fleet was grounded as governments closed borders or imposed strict quarantines. The impact of COVID-19 on global scheduled passenger traffic in 2021, compared to 2019 levels, was slightly better, resulting in an overall 40% reduction in seats offered by airlines and a 49% reduction in passengers carried.

As shown in *Figure 7.*, there is a short-sharp V-shaped pattern that shows the decrease in revenue passenger kilometers in the years before, during, and after COVID-19:

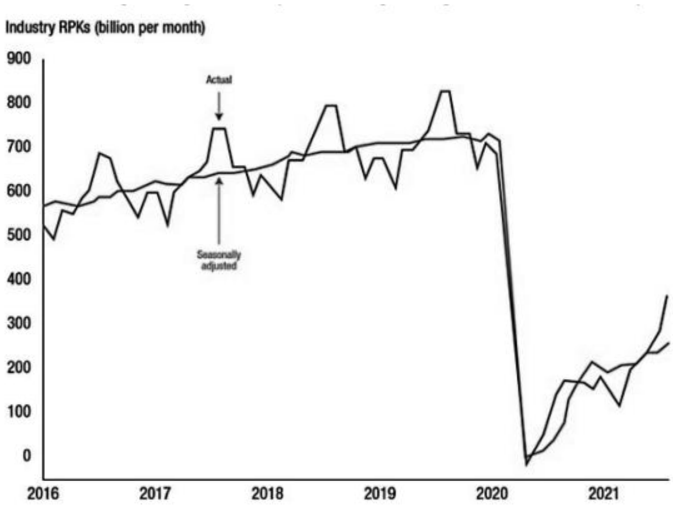


Figure 7. Global air passenger traffic (in revenue passenger kilometers – RPKs) [15]

The total number of passengers in air transport in 2019 was 4.54 billion. Due to the crisis caused by the COVID-19 pandemic, the number of air passengers in 2020 decreased drastically and, according to ICAO estimates, amounted to 1.79 billion, which is 60.6% less than in 2019. It can be expected that the number of passengers in 2022 will almost double compared to 2020, but that number will also be significantly lower than in 2019 (app. 25% less).

Due to the impact of the COVID-19 pandemic, the number of passengers decreased drastically in 2020 by more than three times compared to 2019. Air passenger transport in the European Union (EU-27) amounted to only 276.5 million passengers in 2020. This is a 76% decrease compared to 2019 [15].

Figure 8. shows the annual number of passengers per year (in millions) in Europe, encompassing the EU, Iceland, Norway, Switzerland, Turkey, Serbia, Montenegro, Bosnia and Herzegovina, North Macedonia, and Albania. Also, it is shown that the number of passengers has decreased by almost 3.2 times in 2020 compared to 2019:

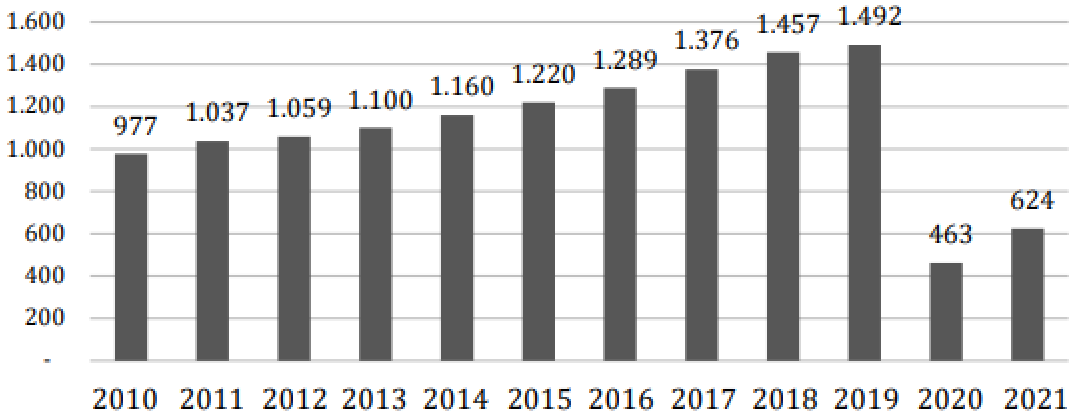


Figure 8. Annual number of passengers in Europe + non-EU (in millions) [15]

Air transport mobility during the current COVID-19 outbreak has strongly affected the EU region and other parts of the world. Many countries had closed their borders or imposed severe travel regulations, which reduced airline movement globally by over 40%. A significant number of countries worldwide have completely closed their borders for airline transportation, while in other cases, some countries have denied entry into the country for specific nationalities. The movement was drastically reduced, and the global situation was far from usual. Passengers were either forbidden to travel or discouraged from doing so due to the restrictions in the arriving countries that requested quarantine. Due to previous reasons, travelling was mostly limited to business travel in these pandemic circumstances [16].

Figure 9. shows the daily air traffic for 12 April 2020. As shown in *Figure 8*, some countries were more affected than others, depending on the type of flight. When domestic flights are observed, it can be observed that the most affected by the COVID-19 pandemic and its restrictions were Norway, the Canaries, Italy, and Greece. When international flights were observed, the most affected countries were the Netherlands, Germany, Luxembourg, Israel, and Turkey. The country that was the most affected by overflights was Albania.

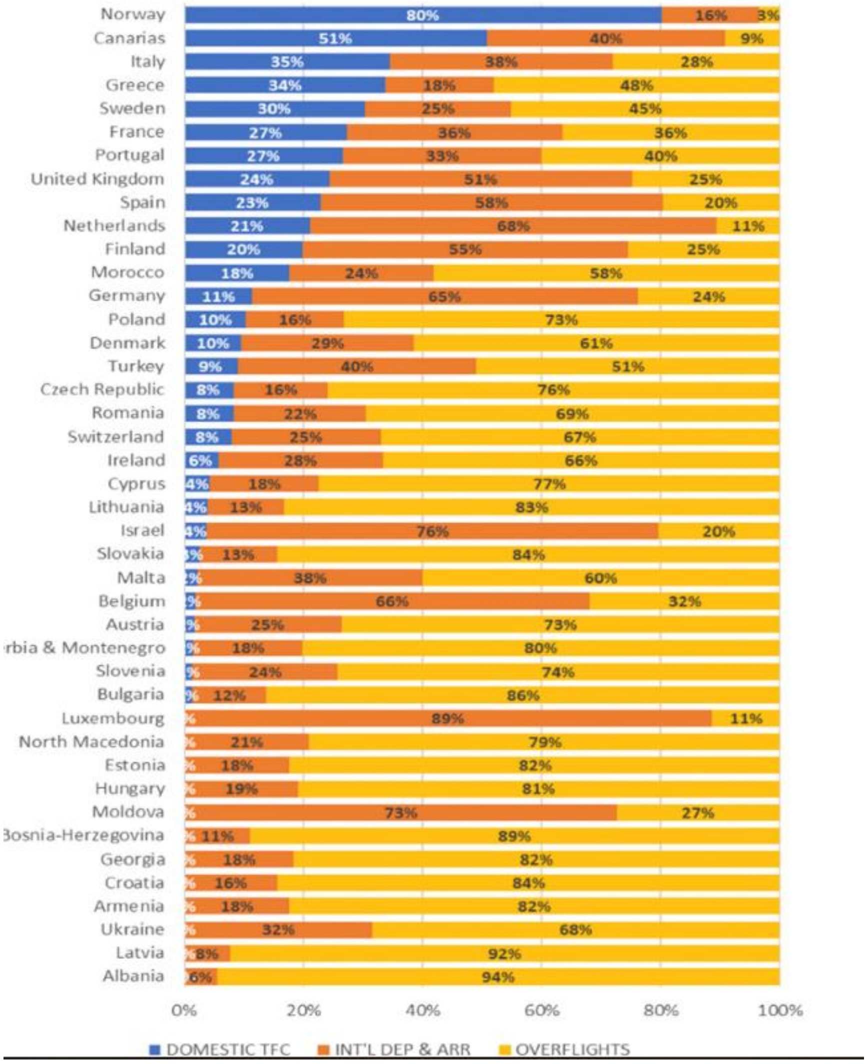


Figure 9. Daily air traffic for 12 April 2020 [16]

The impact on aviation mobility in the EU region is severe, with an average reduction of scheduled daily flights of more than 88% for the given period, which means more than 157.000 cancelled flights overall. The lowest days regarding air transportation were usually on Sundays or Saturdays. The busiest flights were related to cargo operators, with over 600 flights per day. In general, cargo flights were not severely affected by the COVID-19 outbreak. Moreover, in some cases, there was even an increase in the number of flights because of medical equipment supplies and because most countries allowed the exchange of goods to have economic activity [16].

5.1. COVID-19 Impact on Airlines

The shock's size has put airline companies' liquidity buffers under pressure, even if a significant share of its costs are variable, and the recent drop in oil prices has decreased airlines' operating costs.

In the medium run, airline companies face two uncertainties:

- The cost of health-related measures - operating costs are likely to increase in the short run for airlines and airports because of additional health and safety requirements before they can be passed on to consumers. Moreover, social distancing measures could reduce passenger load by up to 50% if implemented for air transport.
- The shape of the recovery for commercial flights - international travel restrictions, the contraction of economic activity, and changes in transport behaviour by cautious consumers may prevent a return to pre-crisis demand levels, even as lockdowns and domestic travel restrictions measures are loosened in many countries.

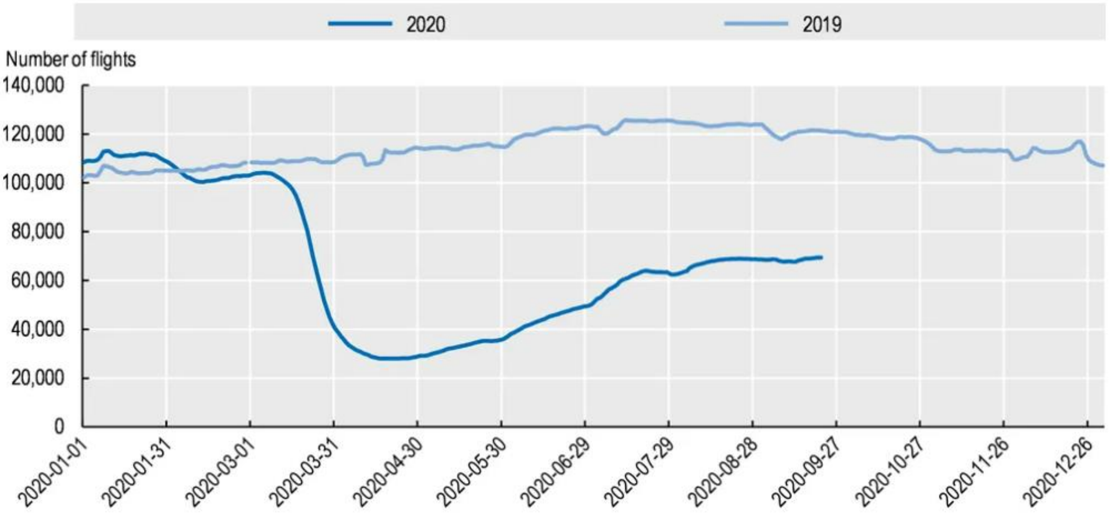


Figure 10. Number of flights tracked daily by Flightradar24, 2020 vs 2019. [17]

Commercial air traffic is slow to recover: as of September 2020, the number of flights remains more than 40% below the pre-pandemic level globally. This hides differences across flight lengths: the drop is even more pronounced for long-haul flights. In the long run, consumer behaviour changes may result in structural changes in air transport demand [17].

The combination of negative demand and supply shocks and the uncertainty around the medium-run outlook create an uncertain perspective for airline companies. Through inter-industry linkages, this uncertainty affects the whole aviation industry. Moreover, the industry remains exposed to a possible resurgence of the pandemic, as governments may impose new air travel restrictions to tackle flare-ups or a potential second wave of infections. This may threaten the existence of some firms in the industry, as production and revenues are likely to remain inferior to pre-crisis levels for some time.

5.1.1. Worldwide

The airline industry is very sensitive to major external events such as terrorism, political instability, natural disasters, energy crises, and major public health risks. Each of these events may severely affect both their operations and passenger demand. The same effect occurred when the COVID-19 pandemic began in early 2020 – the airline industry experienced a sharp decline in traffic operations. Comparing data between 2019 and 2020, as well as 2019 and 2021, states that there were -50% passengers flown and -40% passengers flown, respectively.

The impact of the COVID-19 pandemic on international flights appeared to be much greater than on domestic flights, causing more financial damage to traditional air carriers than to low-cost carriers. However, at the beginning of 2021, the recovery of the airline industry was slowed down again by the impact of a new COVID-19 variant. Countries worldwide started to reimpose travel restrictions to slow the spread of the infection. Despite all the restrictive measures, overall travel demand strengthened in 2021 due to passengers' desire to travel – particularly for visiting friends and family purposes and holidays – and an increased number of vaccinated people [15].

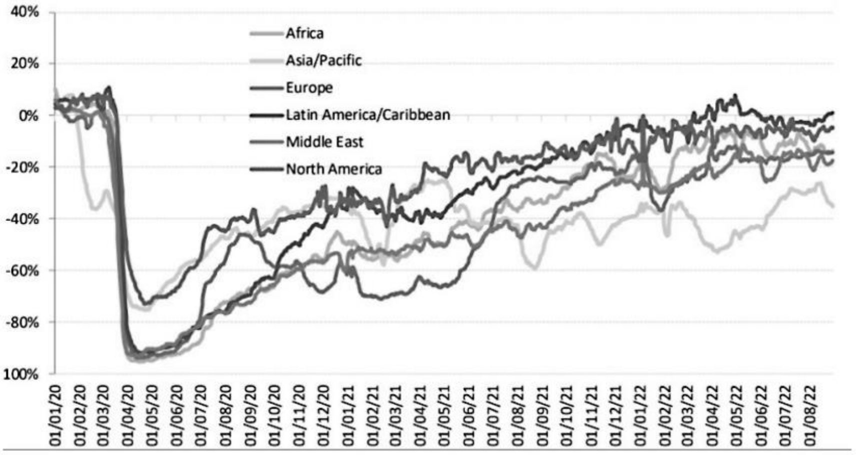


Figure 11. Comparsion of total seat capacity by region [15]

Figure 11. shows the comparison between total seat capacity by region on a 7-day average compared to data in 2019. As can be observed, the worst scenario was when there was almost more than a 90% decrease in total seat capacity.

Undoubtedly, different and uncoordinated restrictive measures and the speed of their abolition influenced the number of flights and total seat capacity by regions to recover at different paces. While the crisis impacted all regions, regional differences in resilience and speed of recovery depended on the operations of the domestic airlines. Airlines with larger domestic markets or large cargo operations were certainly in better positions, and their operations led the industry on an upward trend [15].

5.1.2. Europe

After the first European COVID-19 case was reported in January 2020, major European airlines reduced and eventually ceased their operations in China by the end of that month. In the following few months, all European airlines grounded their fleets more or less completely due to the imposed travel restrictions. During the summer, European and domestic flights within countries recovered quicker than intercontinental ones but dropped again in September, with airlines adjusting their schedules due to the second wave of COVID-19. The major obstacle for passengers to fly in Europe was the numerous national rules regarding quarantine and testing requirements.

During 2021, airlines in Europe started to increase the number of flights, but this trend was not followed by an increase in the number of passengers, which resulted in an average global passenger load factor of around 70%, lower than the pre-pandemic levels of >80%. This increase in the number of flights (despite demand showing no signs of recovery) was possibly driven by the need to retain slot rights [15].

5.2. Airports

5.2.1. Worldwide

The COVID-19 pandemic severely hit airports worldwide in terms of traffic and revenues during 2020 and 2021, with flights being cut by airlines, closed borders, travel restrictions, quarantine rules, and associated demand loss. Many of them were closed by governments to contain the spread of the virus. During the first two years of the pandemic, the COVID-19 outbreak reduced the number of passengers at the world’s airports by 11.3 billion (ACI 2022). Despite increasing vaccination rates and some international travel restrictions gradually being revoked, the total number of passengers did not show signs of recovery in 2021, at 4.4 billion (48.3% compared to 2019).

International passenger traffic was weak in the first half of 2021, with a slight upturn by the end of the year due to the increasing number of people vaccinated. Domestic passenger traffic recovered faster than international traffic in 2021, and this was especially noted in the main markets, such as the USA, which started to recover in 2020 and accelerated in 2021 [15].

5.2.2. Europe

Flights in Europe took off during 2020 and 2021, though slower and far below the level in 2019. In 2021, aircraft movements were up 23.3% compared to 2020 but down 48% against pre-pandemic levels throughout the European airport network. The COVID-19 pandemic profoundly impacted smaller regional airports in the EU, which mainly depend on tourism and experienced an even sharper traffic drop. [15]

Figure 12. shows the number of IFR departures at 34 main European airports during 2019-2021:

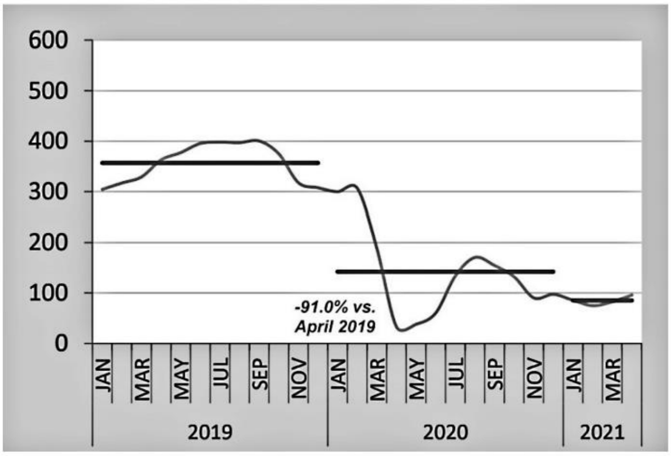


Figure 12. Average daily IFR departures at the 34 main airports in Europe [14]

Countries with more severe COVID-19 outbreaks, including Spain, Italy, the UK, and Austria, enforced strict lockdowns and domestic aviation capacity restrictions, which affected operations and recovery. Air traffic recovery in Europe was significantly impeded due to a general fear of more waves and a significant increase in COVID-19 cases during 2020 (especially during the summer months), causing very low airport operations until the end of the year [15].

5.3. COVID-19 impact on CO_2 emissions – impact on CORSIA program

The emergence of the COVID-19 pandemic in the early months of 2020 had a profound and immediate impact on the aviation sector, with lasting effects that are still noticeable into 2023. As with any other aspect of international aviation activity, CORSIA has also been affected by the pandemic. A clear understanding of the extent of such impact to date and future scenarios as CORSIA implementation progresses in co-existence with COVID-19 is paramount to ensure that CORSIA contributes to international aviation's environmental integrity and sustainability.

The immediate impact of the COVID-19 pandemic has led to a sharp decline in international aviation activity and related CO_2 emissions in 2020. Based on the latest estimate by CAEP, CO_2 emissions from the international aviation sector fell by approximately 59% in 2020 compared to 2019.

Due to the induced decline in CO_2 emissions recorded in 2020, CAEP developed three recovery scenarios based on air traffic forecasts in consultation with ICAO's Aviation Data and Analysis Panel. These three scenarios consider different recovery rates for 2019 international aviation CO_2 emissions levels. The most recent version of these recovery scenarios was developed in November 2021, which served as the basis for the information provided to the council in March 2022 [14].

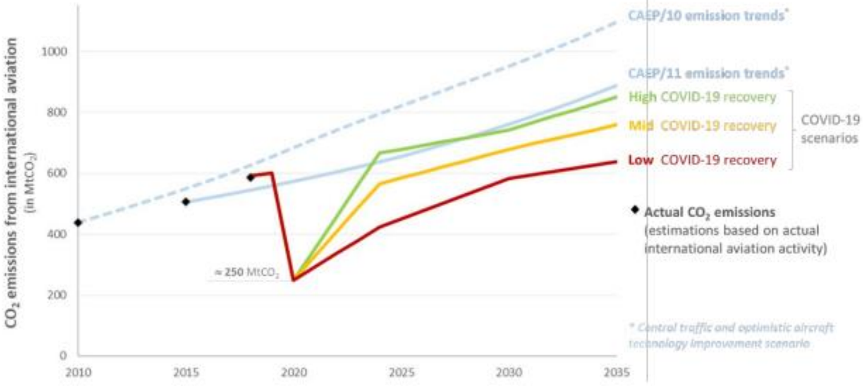
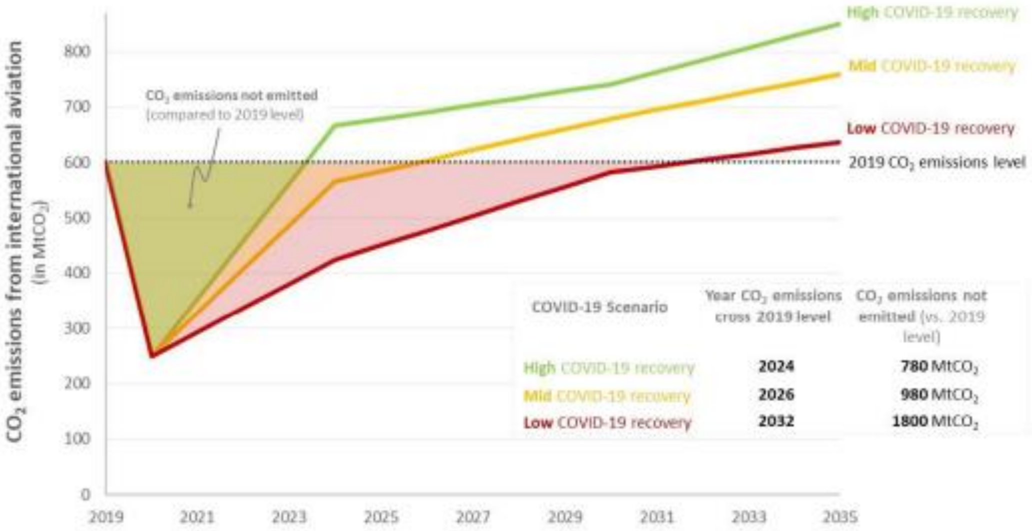


Figure 13.Three scenarios of CO_2 emissions for recovery from COVID-19 [14]

Figure 13. shows all three scenarios of CO_2 emissions after recovery from the COVID-19 pandemic and the planned emissions trend. The green line shows the largest recovery in terms of emissions, which is close to the CAEP/11 emissions trend. Actual CO_2 emissions declined in 2022, from which three scenarios were projected to calculate post-pandemic CO_2 emissions. CAEP/11 emission trends are much lower than the previously determined CAEP/10 emissions trend.

The development of three COVID-19 recovery scenarios allowed CAEP to estimate the years when international aviation could reach pre-COVID-19 levels regarding CO_2 emissions [14].



COVID-19 Scenario	Year CO_2 emissions cross 2019 level	CO_2 emissions not emitted (vs. 2019 level)
High COVID-19 recovery	**2024**	**780** $MtCO_2$
Mid COVID-19 recovery	**2026**	**980** $MtCO_2$
Low COVID-19 recovery	**2032**	**1800** $MtCO_2$

Figure 14. Return of pre-pandemic CO_2 emissions levels [14]

Figure 14. shows a diagram that shows, by scenario, when it is possible to expect the level of emissions before the COVID-19 pandemic. We can see that for the largest recovery, that level of emissions is expected in 2024, for the medium level of recovery in 2026, and towards the smallest recovery in 2032.

In the context of CAEP's assessment of the impact of COVID-19 on CORSIA, one of the aspects considered was the impact on the volume of CORSIA compensation claims. In this regard, three factors have been identified as relevant:

- Decrease in CO_2 emissions from 2019 to 2020;

- The sector's recovery path towards pre-pandemic activity levels;
- Definition of the CORSIA baseline after the pilot phase of the scheme.

6. Comparison between CO_2 emissions during the COVID-19 pandemic and emissions reduction due to technological innovations in aviation

If the goal of the Paris Agreement of 2015 is to be met, the clean energy transition will need to bring about a rapid reduction in emissions of greenhouse gases to zero on a net basis over the coming decades.

The Paris Agreement set a goal of “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”. It also calls for greenhouse gas emissions to peak as soon as possible and for a rapid reduction thereafter in order to achieve net-zero emissions – in the second half of this century. Achieving net-zero emissions requires any remaining anthropogenic emissions to be entirely offset by anthropogenic carbon sinks such as changes in land-use systems or the removal of carbon dioxide through bioenergy with carbon capture and storage or direct air capture with storage [18].

In 2019, just before the COVID-19 pandemic started, global CO_2 emissions from domestic and international aviation were roughly similar to Japan's total energy-related CO_2 emissions, accounting for 3% of global energy-related CO_2 emissions. In OECD countries, this share was 5% and was characterized by a rapidly increasing trend, mainly driven by the development of international air transport over the last decades.

The COVID-19 pandemic had a disproportionate adverse impact on air transport, with activity and CO_2 emissions dropping by 75% globally in April-May 2020 compared to the corresponding period of 2019. While CO_2 emissions from domestic flights have returned to their pre-pandemic level since March 2021, those from international flights remained around 45% lower in December 2021.

Nevertheless, recent projections by the International Transport Forum show that, without accelerated technological developments and more ambitious policy measures, aviation-related CO_2 emissions would be multiplied by 2.5 between 2015 and 2050, largely driven by international air transport. This scenario comes close to pre-pandemic forecasts and suggests that technological development and policy action will be key to curbing CO_2 emissions from air transport.

To track aviation-related CO_2 emissions, the OECD has developed a near real-time database covering most countries since 2013. It builds on air traffic data provided by the International Civil Aviation Organisation and a CO_2 emission calculator provided by the European Organisation for the Safety of Air Navigation. It will help track CO_2 emissions during the recovery phase after the COVID-19 pandemic, the impact on CO_2 emissions of technological developments affecting the fleet of aircraft in operation, and the impact of environmental policies such as carbon taxation [19].

The countries on the OECD member list are Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israël, Italy, and Japan.

As shown in *Figure 15.*, domestic and international aviation shares sum the overall OECD share of aviation CO_2 emissions, marked by the orange line. *Figure 14.* shows that from 1971-2019, there was a larger percentage of CO_2 emissions in domestic aviation than in international aviation until approximately 2003. After 2003, CO_2 emissions from international aviation were in a larger percentage than the ones produced by domestic aviation due to the increase in international flights and routes. Also, it can be observed that in 2019, the emissions of CO_2 reached 5%:

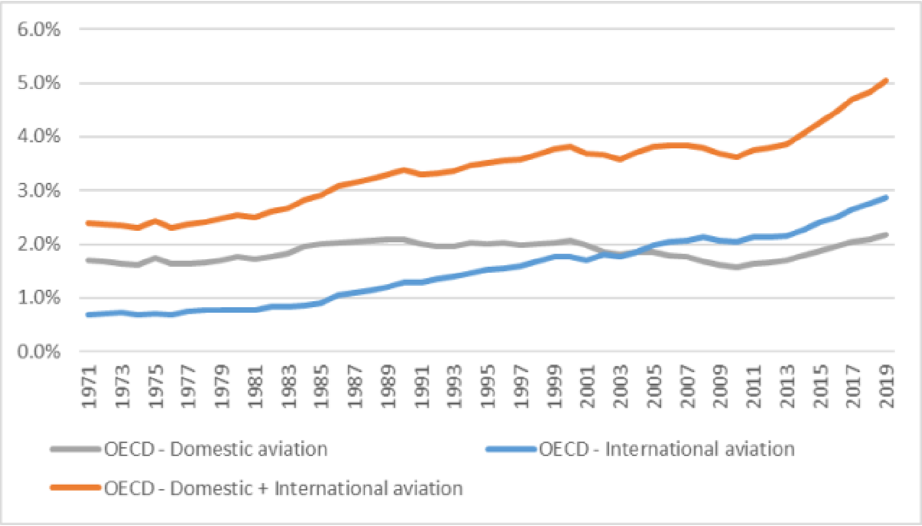


Figure 15. Share of domestic and international aviation in total energy-related CO_2 emissions, OECD countries, 1971-2019 [19]

As said in this thesis, before the outbreak of the COVID-19 pandemic, air transport was expected to continue growing at a fast pace. The ICAO forecasted that if technological and operational improvements are absent until 2050, CO_2 emissions will be triple relative to the emissions of CO_2 in 2019.

Figure 16. shows that in April-May 2020, there was a reduced number of flights due to the COVID-19 pandemic and that the difference in CO_2 emissions was as much as 75% due to the reduction of flights. From May 2020 to December 2021, there was fluctuation due to changes in CO_2 emissions due to different restrictions in countries because of COVID-19. If it is observed the value of emissions of CO_2 in November 2020 and November 2021, it can be stated that the difference between those two emissions was around 30%.

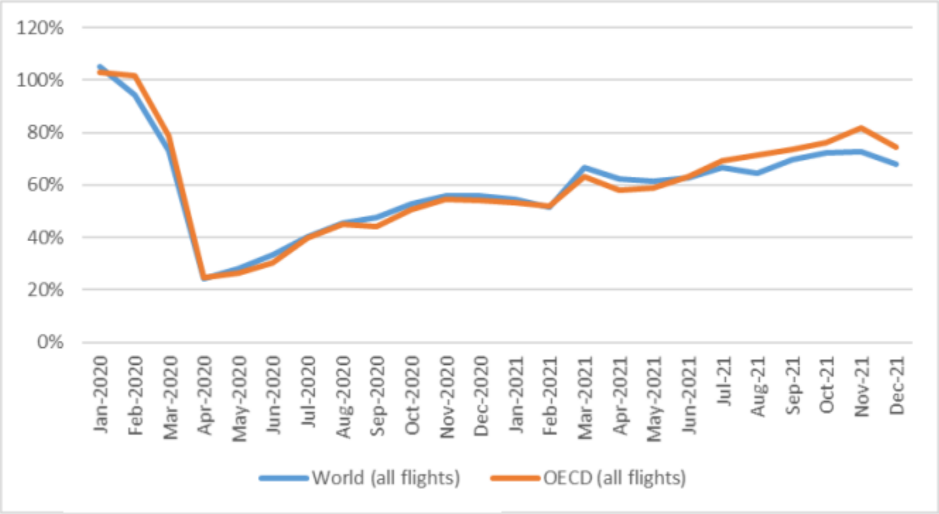


Figure 16. CO2 emissions relative to the same month of 2019, World and OECD countries, January 2020 – December 2021 [19]

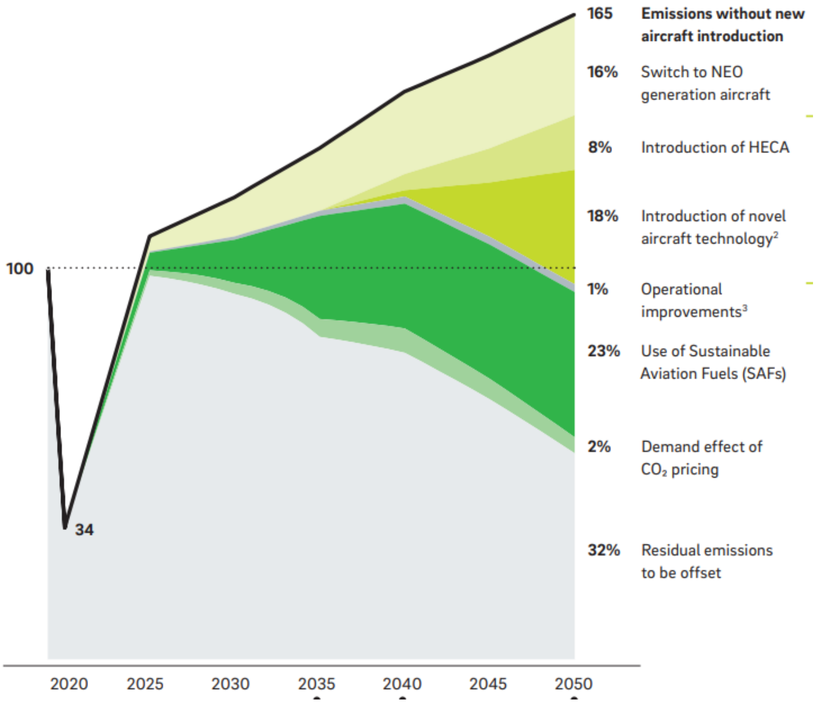


Figure 17. Assessment of the impact of innovation on CO_2 emissions [20]

Figure 17. shows the assessment of the impact of innovation on CO_2 emissions. Innovations mean using sustainable aviation fuels, biofuels, fuels with a certain percentage of hydrogen, electric aircraft, and improvements in aircraft operations. Unless innovation is implemented, CO_2 emissions will continue to rise. As can be observed, the most efficient impact is using SAFs and novel aircraft technology and switching to electric generation aircraft.

Once new technology is introduced, CO_2 emissions could return to pre-2020 levels. With each new application of some of the innovations, there is a reduction in CO_2 emissions.

Conclusion

Due to the increased volume of air traffic, the need for innovations in reducing gas emissions, especially carbon emissions, is also increasing. Innovations are improvements that can lead to a reduction in aviation's environmental impact. The impact of aviation on the environment is large, but with appropriate measures, it is assumed that by 2050, carbon emissions will be reduced by 50% compared to the amount of emissions achieved in 2019, considered one of the most successful years in air transport.

Airlines and airports are becoming increasingly aware of how important environmental protection is for human life, flora, and fauna on Earth in aircraft operations. With various measures and recommended standards, they began implementing reducing carbon emissions at the national, regional, and global levels.

As part of the final work, innovations related to aircraft technologies were presented, where the aircraft being designed and whose application is expected in the future are shown. Also, an innovation related to sustainable aviation fuels, whose use is expected shortly, was presented. Sustainable aviation fuels, mixed in a certain percentage with fossil fuels, will reduce carbon emissions.

CORSIA is one of the measures related to reducing carbon emissions, and implementing this measure at the global level can lead to increased decarbonization in aviation. ICAO members have started implementing this measure while it is still voluntary, and later, it is expected that all countries will have to implement this measure at the level of their state.

Based on the data presented in the research paper, it is necessary to state that the drop in flights during the COVID-19 pandemic led to many CO_2 emissions being saved. Due to various restrictions and limitations on traveling and flying by plane, airlines and airports suffered the most, besides passengers. It is important to state that the COVID-19 pandemic saved more CO_2 emissions than the new technological innovations will. Also, technological innovations require a lot of investments and they cost a lot, so even if they are implemented, the cost of those innovations and their required equipment, policy, regulations, staff education, and prequalification, will be high.

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