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COMPARISON OF THE IMPACT OF THE COVID-19 PANDEMIC AND TECHNOLOGICAL DEVELOPMENTS ON EMISSIONS OF CO_2 IN THE AIR TRANSPORT

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Air transport is a complex and intricate mode of transportation that has both benefits and consequences resulting from the operations of planes. Air travel offers the advantage of saving time during journeys or business visits, but it also has the disadvantage of contributing to carbon dioxide emissions caused by aircraft operations. These emissions present potential risks to both human health and the environment. In order to reduce the negative impacts, new technical advancements can be utilized to limit emissions and, consequently, the discharge of carbon dioxide. The COVID-19 epidemic caused an unprecedented situation where flights were temporarily suspended and aircraft were grounded, leading to a significant decrease in emissions from airline operations. This research utilizes graphical representations to clarify the main factors that lead to reduced carbon dioxide emissions. Moreover, it examines the effects of particular advancements in air transportation and assesses the impact of the pandemic on the overall decrease in emissions.

Keywords: COVID-19 pandemic, air transport, CO_2 emissions, climate change, innovations

1 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. 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 led to a significant decline in air travel, leading to a major reduction in CO_2 emissions and pollution compared to the highest year of 2019. The pandemic had significant and enduring effects on all parties involved in many industries, resulting in extensive lockdowns, halted flights, financial setbacks at airports, and the implementation of new safety protocols. The COVID-19 epidemic has significantly reduced the demand for air travel, resulting in the worst performance in recent history for the aviation industry in 2020. This decline affected both passenger and cargo transportation.

The total worldwide air transport passenger volume in 2019 amounted to 4.54 billion. Due to the significant impact of the COVID-19 pandemic, there was a sharp decrease in the number of air passengers in 2020. The International Civil Aviation Organization (ICAO) anticipates that the overall number of air passengers decreased significantly to 1.79 billion in 2020, representing a considerable 60.6% fall compared to the previous year. Projections suggest that the number of passengers will almost double in 2022 compared to 2020. Nevertheless, this expected rise was projected to stay far lower than the levels seen in 2019, with an estimated decrease of around 25% [1].

According to the International Air Transport Association (IATA), the COVID-19 pandemic caused a significant decrease in global passenger demand, measured in terms of revenue passenger kilometers (RPKs). In 2020, there was a loss of 65.9% compared to the previous year. This decline led to a simultaneous 68.9% decrease in revenue from airline passengers when compared to the same period in 2019. In April 2020, during the height of the crisis, almost 66% of the global commercial air transport fleet was not in operation because of government measures like border closures and strict quarantines. Examining the repercussions of COVID-19 on global scheduled passenger traffic in 2021 relative to 2019 benchmarks reveals a marginal amelioration. This improvement translated to an overall 40% reduction in the airline seat capacity and a corresponding 49% reduction in the number of passengers transported [1].

The repercussions of aviation mobility within the European Union (EU) region have been profound, manifesting in an average reduction exceeding 88% in scheduled daily flights during the specified timeframe, resulting in the cancellation of more than 157.000 flights overall. By contrast, cargo operations exhibited resilience, emerging as the most active sector, with a daily average surpassing 600 flights. The COVID-19 outbreak had a limited effect on cargo flights, and in certain cases, there was an increase in the number of flights. This phenomenon can be attributed to the rising need for medical equipment and the promotion of international trade since many countries allowed the exchange of products to support economic activity [1].

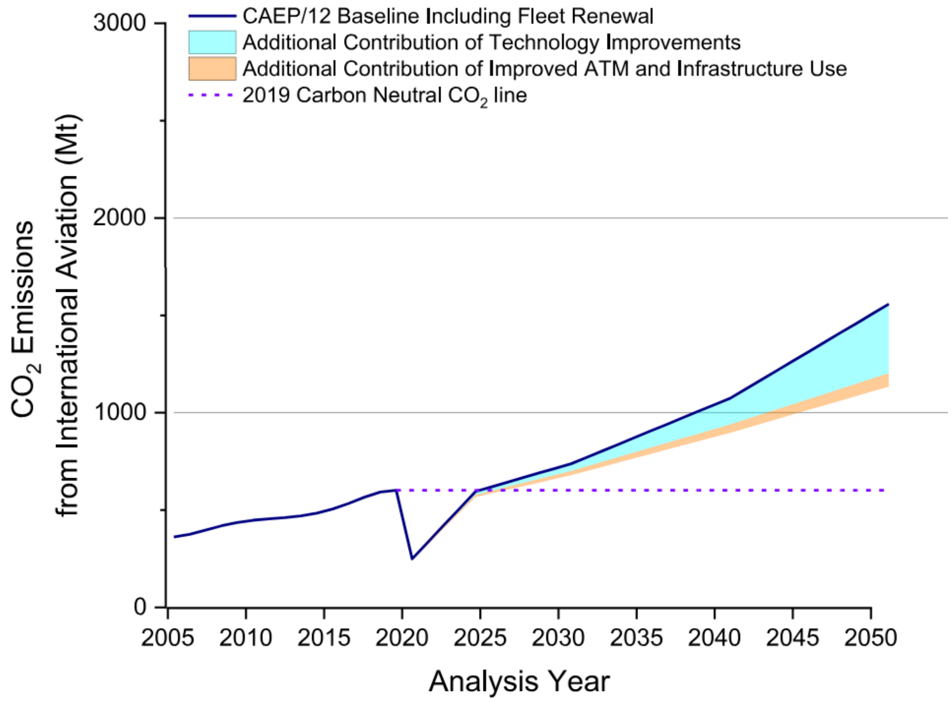
Along with other facets of global aviation endeavors, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has encountered implications resulting from the ongoing pandemic. A comprehensive understanding of the current extent of these ramifications and prospective scenarios is imperative as CORSIA implementation unfolds amid the coexistence of the COVID-19 pandemic. Such an understanding is critical for ensuring that CORSIA effectively contributes to international aviation's environmental integrity and sustainability. In 2020, the COVID-19 epidemic led to a significant decrease in global aviation activity and the resulting carbon dioxide emissions. The most recent projections from the Committee on Aviation Environmental Protection (CAEP) indicate that CO_2 emissions from the international aviation industry experienced a significant decrease of almost 59% in 2020 compared to the levels recorded in 2019.

Presently, antiquated aircraft exhibit a notably higher carbon emission profile relative to their newer counterparts. In the ensuing decades, endeavors are being actively pursued to conceptualize, fabricate, and integrate electric aircraft. Diverse initiatives, prognostications, and initiatives are being deployed with the overarching objective of curtailing carbon emissions, mitigating environmental repercussions, and ensuring planetary conservation. The imperative of environmental preservation is underscored by its profound impact on human welfare, health, climate dynamics, and the biodiversity of the Earth.

This study aims to elucidate the ramifications of the COVID-19 pandemic on both airlines and airports in Europe and globally, focusing on its implications for the CORSIA program. The pertinence of this investigation is underscored by its profound impact on societal well-being and environmental considerations. A comprehensive understanding of the influence exerted by factors such as canceled flights and diminished demand assumes significance in discerning their roles in facilitating the aviation sector's endeavor to curtail CO_2 emissions. This investigation also addresses information about prospective technological developments in air transportation to mitigate carbon dioxide emissions from aircraft.

2 TECHNOLOGICAL DEVELOPMENTS AND THEIR IMPACT ON CO_2 EMISSIONS

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 [2].



Figu. 1. CO_2 Emissions from International Aviation [2]

Figure 1. shows the emissions of CO_2 during the entire summer when performing operations at the international level from 2005 to 2050. Additionally, it demonstrates the anticipated decline in carbon dioxide (CO_2) emissions as a result of advancements in aircraft technology, enhanced air traffic management, and optimized infrastructure utilization. CO_2 emissions are determined exclusively by the process of fuel combustion in the jet engine, with the understanding that every 1 kilogram of fuel consumed produces 3.16 kg of CO_2.

The disparity in fuel consumption numbers results in a noticeable contrast between the projected maximum fuel consumption in 2019 and the projected minimum fuel consumption in 2050. In 2050, the projected minimal amount of CO_2 emissions is estimated to be 532 million metric tons, which can be compared to the emissions recorded in 2019 [2].

In order to achieve the environmental goals set by the International Civil Aviation Organization and align with the United Nations' Sustainable Development Goals, it is crucial to prioritize innovation due to the expected expansion of international civil aviation. ICAO actively engages in research and development initiatives aimed at aligning with these goals. Rapid advancements are observed in novel technologies and energy sources within the aviation sector. ICAO is confronted with the substantial task of maintaining synchronization with the expeditious environmental certification processes for emergent technologies. This encompasses the continuous scrutiny of innovative technologies for conventional aircraft, encompassing environmentally favorable fuels with sustainable and low-carbon attributes. Such fuels are evaluated for their potential environmental benefits, technical viability, and economic rationale [3].

ICAO is concurrently vigilant regarding the evolution of pioneering propulsion concepts, including electric, hybrid, and hydrogen-based aircraft propulsion. Additionally, the organization promotes the proliferation and application of circular economy technology within the aviation sector [3].

ICAO's novel initiatives are formulated through several strategic avenues:

- Aircraft technologies;
- Electric aircraft (E-HAPI);
- Integration of hydrogen in aviation fuels;
- Advancements in aircraft operations;
- Development and utilization of sustainable aviation fuels [3].

2.1 Aircraft technologies

In the realm of aviation, technological developments continuously progress across multiple facets, encompassing engines, aircraft structures, and aerodynamics. These developments denote incremental enhancements within the industry, including more efficient combustion in jet engines, integration of vertical winglets on aircraft, and the design and production of novel aircraft models [4].

From a near- to mid-term perspective, ongoing efforts are directed toward refining the existing aviation fleet through the continuous evolution of conventional airframe and propulsion technologies, aiming at achieving "cleaner operations." Manufacturers and researchers are developing advanced aircraft and propulsion designs to reduce CO2 emissions in the medium to long term. Furthermore, the study examines a wide range of choices for sustainable aviation fuels and clean energy sources, including hydrogen and electrification [4].

Aircraft technologies are fundamentally geared towards enhancing efficiency and mitigating carbon emissions. In the short term, sustainable aviation fuels emerge as pivotal contributors to decarbonization, exhibiting a more substantial role than other mitigation measures due to their capacity for carbon emission reduction [4].

Aircraft configurations as new concepts can be observed that specific aviation technologies can be applied to the local geometry of the aircraft for improvement of the aerodynamics of the aircraft, aircraft systems will be more efficient and electric, aircraft structure will have a more efficient structure that can withstand extreme loads, materials that are going to be used are light materials and alloys. If aircraft engines are observed it can be stated that the engines will be more efficient and hybrid-electric, which will be achieved by 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 and by reducing the weight of the built-in motor and the resistance [4].

2.2 Electric aircrafts

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. The electric aircraft sector is currently in a developmental phase, and evaluating its direct benefits, particularly in the context of urban air mobility, poses challenges. Nevertheless, a comprehensive study has underscored the considerable potential of electricity in aviation, showcasing its capacity to lower operational expenses, open up previously economically unviable regional destinations, diminish CO_2 emissions, mitigate noise intensity, enhance aircraft availability, and stimulate economic development activities [4].

Notable cost reductions are evident in both fuel and maintenance expenses. An important finding from the study emphasizes that substituting a fossil-fueled aircraft with an identical electric aircraft might result in a significant decrease in fuel expenses, dropping from around $400 to $50, along with a spectacular reduction in CO_2 emissions of up to 95% [4].

Researchers and designers encounter three significant problems and opportunities in the supplied projects:

- One of these is the fuel tank, which serves as an energy storage system for hydrogen. An electrochemical device that directly turns hydrogen into energy for an electric motor, while simultaneously generating heat and water. The compressed hydrogen tank, operating at a pressure of 700 bar, is positioned in the fuselage rather than the wing, resulting in a decrease in passenger capacity unless the aircraft structure is modified accordingly;
- Regulatory authorities are responsible for certifying the airworthiness of all newly built and modified electric aircraft. Before certifying electric aircraft, regulatory agencies must assess if there is sufficient knowledge and expertise to address any shortcomings in current norms and rules;

- The preparedness of the ecosystem to facilitate the functioning of electric aircraft, including the accessibility of environmentally friendly energy and its distribution to the plug-in electric aircraft to charge. This ecosystem comprises airports from an infrastructure and operations standpoint, airlines that will need to adapt their current ground processes and flight routes to leverage the capabilities of electric aircraft, and the energy industry that could serve as a supplier, on-site storage provider, or management distributor [4].

Hybrid-electric propulsion systems provide operational flexibility by including a larger number of components. The utilization of fuel and battery sources provides greater flexibility in managing the propulsion system at various stages of flight, resulting in less energy consumption compared to conventional methods. Over the next three decades, the development of aircraft propulsion will progress from small all-electric Urban Air Vehicles to medium-sized hybrid-electric aircraft, and eventually to hybrid-electric propulsion regional aircraft [4].

To address the growing demand and meet environmental regulations, it is necessary to develop innovative aircraft designs that can minimize noise during take-off and landing in metropolitan areas near airports, reduce energy usage and emissions, and maintain economic feasibility. Major airports with runways above 3050 m are extensively utilized, however numerous smaller airports with runways shorter than 910 m are not fully utilized and allow innovative aircraft ideas [4].

2.3 Sustainable aviation fuels

Sustainable aviation fuels (SAF) are aviation fuels derived from renewable sources or waste materials that meet specific criteria. They are part of the International Civil Aviation Organization's (ICAO) comprehensive approach to reducing emissions from aircraft, which includes technological advancements, adherence to standards, operational improvements, and a carbon reduction scheme for international aviation [4].

Engines that use fuel obtained only from biomass emit carbon compounds that have previously been absorbed by plants, which significantly contributes to environmental protection. This fuel must provide energy (per unit mass) equal to or greater than traditional fuels and must have the ability to retain its characteristics both in the heat of deserts and in extremely cold conditions prevailing at high altitudes [4].

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.

Sustainable aviation fuels are crucial for decreasing emissions from aviation under the Sustainable Development Scenario, particularly in the latter half of the projected timeframe. Nevertheless, jet kerosene still contributes to a significant portion (25%) of the market in 2070, albeit not completely replacing it.

- Currently, biofuels used in aviation make up a very small portion, about 0.01%, of the total amount of fuel consumed by airplanes. However, it is projected that by the year 2040, this percentage will increase to approximately 25%, and by 2070, it will reach around 35%. In 2070, the aviation industry utilized approximately 4.4 million barrels of oil equivalent per day (mboe/d) of biofuels, which is more than twice the number of biofuels produced in 2019 for road transportation purposes.
- Synthetic jet kerosene, on the other hand, is manufactured by capturing CO2 from concentrated industrial sources, utilizing biomass feedstocks, or through direct air capture and low-carbon hydrogen. The availability of sustainable biomass is restricted, which constrains the supply of bio-jet fuel. Additionally, there is a high demand for biomass in other energy sectors. The constituents of synthetic jet fuel are not subject to the same limitations as biomass. Synthetic methods can be used to create a hydrocarbon fuel that possesses the exact characteristics of traditional jet kerosene. This enables the fuel to be mixed with or completely substitute jet kerosene. In the Sustainable Development Scenario, the manufacture of synthetic jet kerosene on a large scale will begin in the 2030s. By 2070, synthetic production would account for almost 40% of the market share for jet fuel. By 2070, the aviation industry will utilize synthetic fuels, which will account for approximately 75% of the amount of jet kerosene consumed in 2019 [5].

2.4 Renewable hydrogen for aviation

In the context of mitigating carbon emissions within civil aviation, hydrogen has emerged as a pivotal element in prospective solutions. Its appeal stems from its capacity to be generated and utilized without concurrent carbon dioxide emissions, coupled with its widespread availability in water—these attributes position hydrogen as a viable avenue for achieving the overarching sustainability objectives. Preliminary research has yielded promising outcomes, emphasizing the imperative for the continued development of hydrogen as a viable aviation fuel source [6].

Targeting specific segments within civil aviation, particularly regional, short-haul, and medium-haul routes, is deemed as the initial focal point for the incorporation of hydrogen as an aircraft fuel. The integration of hydrogen into larger passenger aircraft, however, necessitates substantial modifications to existing aircraft designs to accommodate the requisite volume of hydrogen [6].

Hydrogen currently serves a role in refinery processes, facilitating the removal of undesirable elements, such as sulfur, from the product. In general, hydrogen is generated by steam-reforming natural gas, resulting in the production of hydrogen and carbon dioxide. Variants of hydrogen characterized by lower carbon content, derived from carbon emission storage, are referred to as "blue hydrogen." Conversely, hydrogen produced via the electrolysis of water, utilizing renewable electricity, is denoted as "green hydrogen." These alternative hydrogen sources hold the potential for further reductions in greenhouse gas emissions when employed in fossil fuel production processes [4].

3 CORSIA

CORSIA, being the first worldwide market measure that applies to all sectors, represents a collaborative paradigm that differs from national or regional regulatory initiatives. This initiative provides a synchronized approach to curbing carbon emissions within international aviation, aiming to minimize market distortions while accommodating the diverse circumstances and capabilities of International Civil Aviation Organization Member States [7].

The primary objective of CORSIA is to stabilize carbon dioxide emissions at 2020 levels by imposing restrictions on airlines to curtail the growth of their emissions post-2020. Airlines are mandated to monitor emissions on all international routes. CORSIA operates synergistically with other measures to offset CO_2 emissions that remain unabated despite technological advancements, operational improvements, and the utilization of sustainable aviation fuels [7].

Airlines are obligated to submit annually a verified emissions report to the relevant state authority. This report includes information on CO_2 emissions from the preceding calendar year, accompanied by a verification report generated by a third-party verifier. The airline operator and the verification body each send the verified emissions report and the corresponding verification report to the state authority separately [8].

Upon receipt of emissions reports from all attributed airlines, the state aggregates the CO_2 emissions and utilizes the CORSIA Central Registry to furnish requisite information to ICAO. An airline's annual emissions report encompasses CO_2 emissions from all international flights, categorized by airport pair or country pair (as determined by the country), irrespective of whether these flights fall under CORSIA offset requirements [8].

As previously mentioned, Sustainable Aviation Fuel plays a pivotal role in CO_2 reduction under CORSIA. Consequently, the CORSIA definition of acceptable fuel comprises:

- CORSIA Sustainable Aviation Fuel refers to aviation fuel derived from renewable resources or waste that meets the sustainability criteria set by CORSIA. Operators can use this fuel to offset their compensation requirements.
- CORSIA Low Carbon Aviation Fuel refers to fossil fuel-based aviation fuel that meets the sustainability criteria set by CORSIA.
- CORSIA Sustainable Aviation Fuel refers to aviation fuel sourced from renewable resources or waste that adheres to the sustainability criteria set by CORSIA [9].

4 INFLUENCE OF THE COVID-19 PANDEMIC ON AVIATION SECTORS AND THE CORSIA PROGRAM

4.1 Influence of COVID-19 pandemic on airlines

The aviation industry is highly responsive to major external events, such as terrorism, political instability, natural disasters, energy shortages, and large public health emergencies. Such events possess the potential to exert profound impacts on both operational functionalities and passenger demand within the industry. The emergence of the COVID-19 pandemic in early 2020 demonstrated this vulnerability, leading to a significant decrease in air traffic operations. Comparative analysis of passenger data between 2019 and 2020 revealed a reduction of 50%, while a comparable assessment for the years 2019 and 2021 indicated a 40% decline in passengers flown [1].

The repercussions of the COVID-19 pandemic disproportionately affected international flights in contrast to their domestic counterparts, inflicting greater financial strain on conventional air carriers compared to low-cost carriers. Nevertheless, the resurgence of the airline industry at the onset of 2021 encountered impediments with the emergence of a new COVID-19 variant, which contributed to a deceleration in recovery. Globally, countries reintroduced travel restrictions as a precautionary measure to impede the transmission of the infection. Despite these restrictive measures, the overall travel demand exhibited a resurgence in 2021, propelled by passengers' motivations for travel, particularly for familial and recreational purposes, and a heightened proportion of vaccinated individuals [1].

Once the first instance of COVID-19 was identified in Europe in January 2020, well-known European airlines began to decrease and eventually stop their operations in China by the end of that month. Following that, in the subsequent months, all prominent European airlines extensively halted their operations, mostly in response to travel restrictions that were enforced. Although domestic and intra-European flights quickly rebounded during the summer, intercontinental flights saw a slower recovery. In September, there was a decrease in air traffic once more, which was caused by airlines adjusting their schedules in reaction to the second surge of the COVID-19 epidemic. A significant obstacle faced by air travelers in Europe was the extensive array of national legislation that governed quarantine and testing requirements [1].

In 2021, European airlines commenced a gradual increment in the number of flights. Notably, this augmentation in flight frequency did not align with a corresponding surge in passenger numbers, leading to an average global passenger load factor of approximately 70%. This figure falls below the pre-pandemic levels surpassing 80%. The discernible escalation in flight operations, despite a lack of evident demand recovery, is conjectured to be influenced by the imperative to retain valuable slot rights [1].

4.2 Influence of COVID-19 pandemic on airports

The global ramifications of the COVID-19 pandemic were profoundly felt by airports in terms of both passenger volume and financial revenues throughout the years 2020 and 2021. This impact was a consequence of airline service reductions, border closures, travel restrictions, quarantine protocols, and the concomitant decline in demand. Governments enforced airport closures as a strategic tactic to minimize the transmission of the virus. During the first two years of the pandemic, the COVID-19 epidemic caused a decrease of 11.3 billion in global airport passenger traffic. In 2021, despite more people becoming vaccinated and some foreign travel restrictions being lifted, the total number of passengers did not show any noticeable indications of recovery. There were 4.4 billion travelers, which is 48.3% lower than the number of passengers in 2019 [1].

In the first half of 2021, international passenger traffic showed a slow pace trend, with a slight improvement towards the end of the year, mainly due to the growing number of people becoming vaccinated. In contrast, domestic passenger traffic demonstrated a swifter recovery than its international counterpart in 2021, particularly evident in key markets such as the United States. The recovery in the U.S. commenced in 2020 and gained momentum in 2021 [1].

Airborne activities within the European aviation sector transpired during the years 2020 and 2021, albeit at a subdued pace and considerably beneath the benchmarks established in 2019. In 2021, the number of aircraft movements increased by 23.3% compared to the previous year but decreased by 48% compared to the levels before the pandemic in European airports. Smaller provincial airports in the European Union, which heavily depend on tourism, were significantly affected by the COVID-19 pandemic. These airports experienced a sharp decrease in air traffic, exacerbating the impact on their operations [1].

4.3 Influence of the COVID-19 pandemic on the CORSIA program

The Committee on Aviation Environmental Protection developed three separate recovery scenarios in response to the significant decrease in CO_2 emissions throughout the year 2020. These scenarios were based on aviation traffic predictions and were developed through collaborative talks with the International Civil Aviation Organization's (ICAO) Aviation Data and Analysis Panel. The three projected scenarios outline different paths for the recovery rates of international aviation CO_2 emissions, based on the levels recorded in the baseline year of 2019. The latest version of these recovery scenarios, which started in November 2021, forms the fundamental basis for the informational framework given to the council in March 2022 [9].

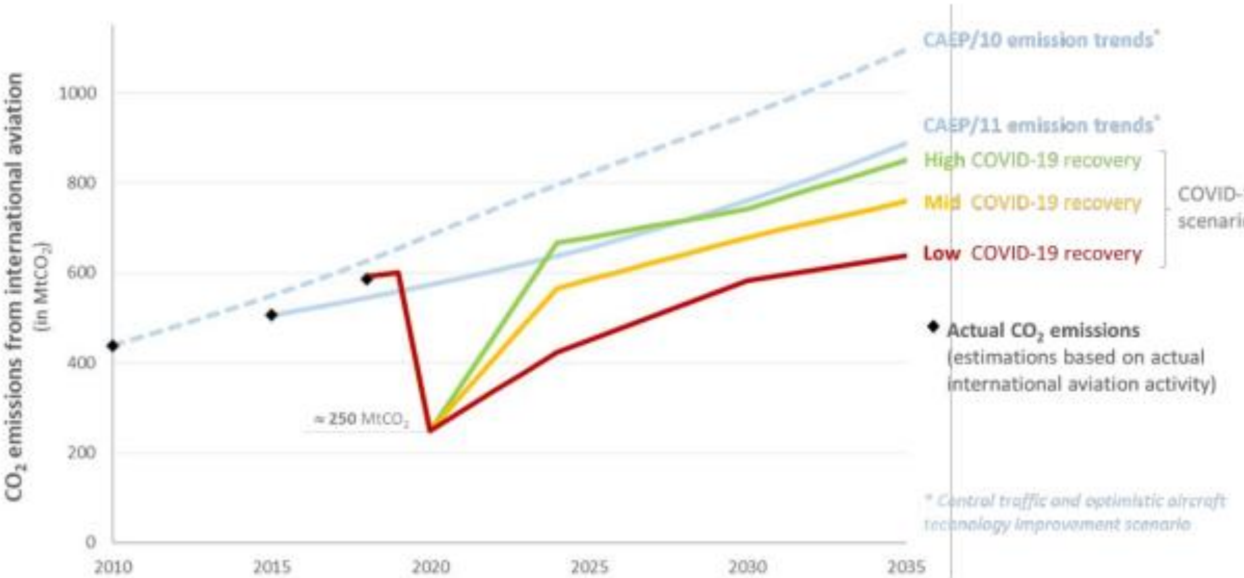


Fig. 2. Three scenarios of CO_2 emissions for recovery from COVID-19 [9]

Figure 2. The three scenarios depicting carbon dioxide emissions post-recovery from the COVID-19 pandemic are juxtaposed with the envisaged emissions trend. The green line delineates the most substantial recovery in terms of

emissions, closely aligned with the CAEP/11 emissions trend. Actual CO_2 emissions exhibited a decline in 2022, serving as the basis for projecting three distinct scenarios to calculate post-pandemic CO_2 emissions. Notably, the CAEP/11 emission trends markedly deviate downward compared to the previously established CAEP/10 emissions trend. CAEP utilized three COVID-19 recovery scenarios to predict the years in which international aviation could return to pre-COVID-19 levels in terms of CO_2 emissions.

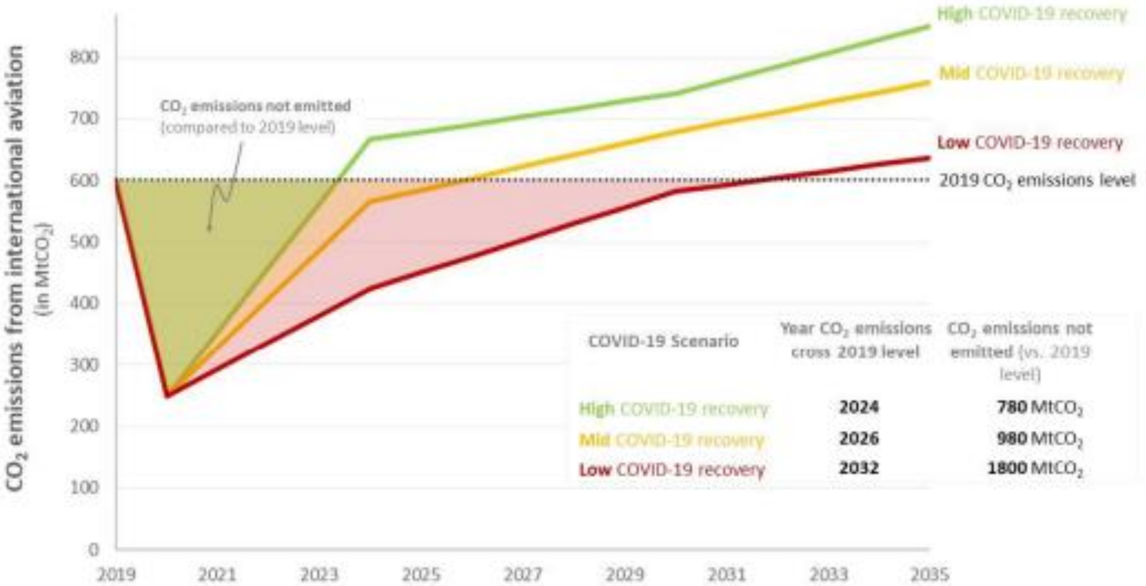


Fig. 3. Return of pre-pandemic CO_2 emissions levels [9]

Figure 3. presents a graphical representation delineating, across multiple scenarios, the anticipated temporal manifestation of emissions returning to pre-COVID-19 pandemic levels. The analysis reveals that the apex of recovery is prognosticated for the year 2024, followed by a medium-level recovery in 2026, and a more protracted recuperation trajectory leading to the attainment of pre-pandemic emission levels by 2032.

As part of the Committee on Aviation Environmental Protection's (CAEP) assessment of the effects of COVID-19 on the CORSIA, a detailed investigation was carried out to examine how it has affected the measurable amount of CORSIA compensation claims. Three prominent factors have been identified in this context:

- The noticeable decrease in carbon dioxide (CO2) emissions from 2019 to 2020;
- The path showing the recovery of the aviation sector, indicating its restoration to the levels of activity seen before the epidemic;
- The determination of the CORSIA baseline following the initial stage of the program's implementation.

5 COMPARISON BETWEEN CO_2 EMISSIONS DURING THE COVID-19 PANDEMIC AND EMISSIONS REDUCTION DUE TO TECHNOLOGICAL INNOVATIONS IN AVIATION

For the fulfillment of the objectives established by the 2015 Paris Agreement, the transition to clean energy must effectuate a rapid and comprehensive reduction of greenhouse gas emissions to net zero over the ensuing decades. The Paris Agreement endeavors to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels." The agreement also promotes the goal of reaching the highest point of greenhouse gas emissions as soon as possible, and then rapidly reducing them to achieve a state where there are no net emissions in the second half of this century. In order to achieve net-zero emissions, it is necessary to fully compensate for any remaining human-caused emissions by methods such as changing land-use patterns, extracting carbon dioxide through bioenergy with carbon capture and storage, or capturing and storing carbon dioxide directly from the air [5].

In 2019, just before the start of the COVID-19 pandemic, the combined carbon dioxide emissions from both domestic and international aviation were roughly equal to the total CO_2 emissions produced by Japan as a result of energy consumption. This accounted for around 3% of the global CO_2 emissions caused by energy consumption. Within OECD nations, this proportion reached 5%, demonstrating a significant upward trend mostly driven by the development of international air travel in recent decades [10].

The COVID-19 pandemic had a disproportionate influence on air transport, resulting in a 75% decrease in activity and global CO2 emissions during April-May 2020 compared to the same period in 2019. Since March 2021, carbon dioxide emissions from domestic aircraft have returned to the levels seen before the pandemic. However, emissions from foreign flights in December 2021 were still around 45% lower compared to pre-pandemic levels [10]. Nevertheless, the International Transport Forum has forecasted that if technical developments are not accelerated and more aggressive policy measures are not implemented, CO_2 emissions from aviation might increase by 2.5 times between 2015 and 2050, mostly due to international air travel. This situation closely corresponds to predictions made before the epidemic, highlighting the crucial importance of technological advancements and legislative measures in reducing carbon dioxide emissions from air travel [10].

The OECD has created a database since 2013 that tracks CO2 emissions related to aviation in most countries, providing up-to-date information. This database utilizes air traffic statistics sourced from the International Civil Aviation Organization and a CO_2 emission calculation given by the European Organization for the Safety of Air Navigation. The objective is to simplify the monitoring of CO2 emissions in the post-COVID-19 pandemic recovery period, evaluate the effects of technical advancements on the operational aircraft fleet, and measure the impact of environmental policies like carbon taxes. The nations listed in the OECD member list are Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, and Japan [11].

Figure 4 illustrates the cumulative shares of domestic and international aviation contributing to the overall OECD share of aviation CO_2 emissions, denoted by the orange line. Examining Figure 4, spanning the period from 1971 to 2019, reveals that domestic aviation exhibited a higher percentage of CO_2 emissions than international aviation until around 2003. Subsequently, from 2003 onward, CO_2 emissions from international aviation surpassed those emanating from domestic aviation, attributable to the escalating volume of international flights and routes. Additionally, it is noteworthy that in 2019, CO_2 emissions reached a percentage of 5%.

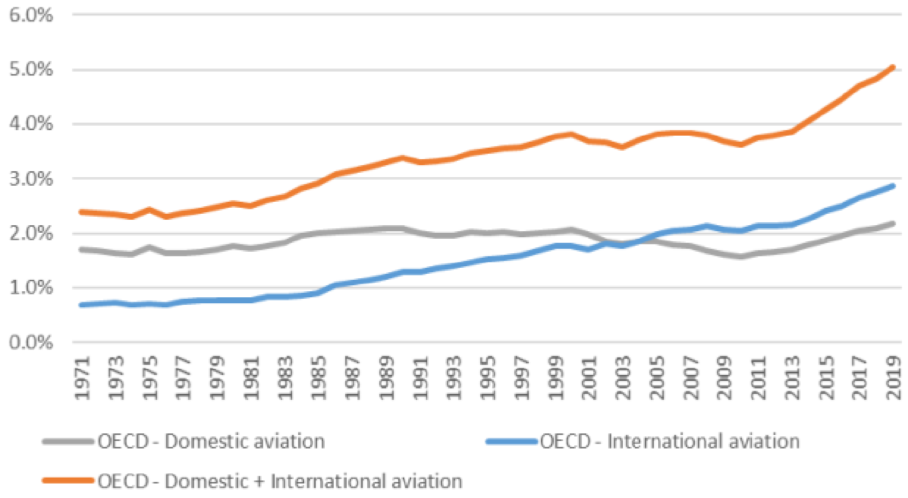


Fig. 4. Share of domestic and international aviation in total energy-related CO_2 emissions, OECD countries, 1971-2019 [10]

As pointed out in this thesis, the projected path of air transport expansion was expected to be strong prior to the emergence of the COVID-19 pandemic. The International Civil Aviation Organization's projections indicate that without technical and operational improvements, carbon dioxide emissions are expected to triple by 2050 compared to the levels recorded in 2019.

Figure 5 illustrates the discernible impact of the COVID-19 pandemic on air transport. In April-May 2020, a notable reduction in the number of flights ensued, leading to a consequential 75% reduction in CO_2 emissions. From May 2020 to December 2021, fluctuations in CO_2 emissions occurred due to varied restrictions imposed by countries in response to the pandemic. Notably, a comparison of CO_2 emissions in November 2020 and November 2021 reveals an approximate 30% difference.

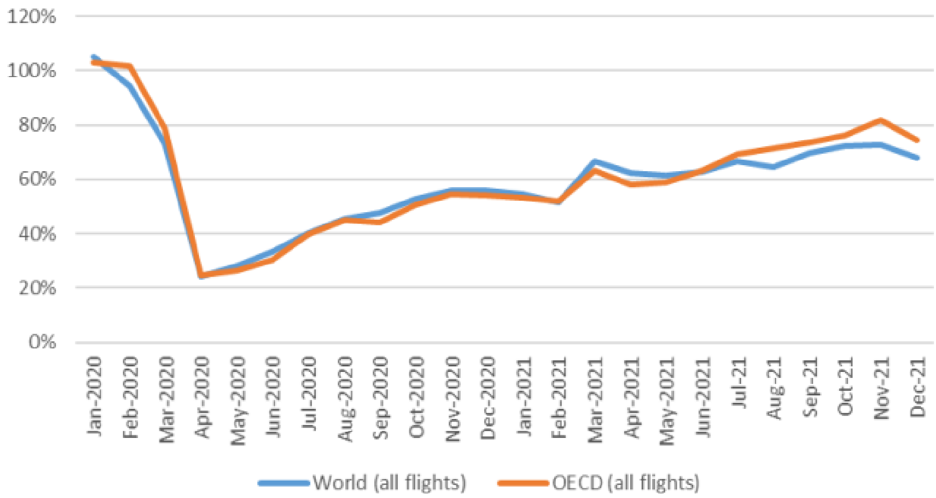


Fig. 5. CO_2 emissions relative to the same month of 2019, World and OECD countries, January 2020 – December 2021 [10]

Figure 6 provides an evaluation of the influence of innovation on CO_2 emissions. Innovations encompass the utilization of sustainable aviation fuels, biofuels, fuels incorporating a specified percentage of hydrogen, electric aircraft, and enhancements in aircraft operations. The absence of innovation is prognosticated to perpetuate a rise in CO_2 emissions. Notably, the most efficacious impacts are attributed to the utilization of sustainable aviation fuels, the integration of novel aircraft technology, and the transition to electrically powered aircraft.

The introduction of new technologies holds the potential for a regression of CO_2 emissions to pre-2020 levels. With each iteration of innovation implementation, a concomitant reduction in CO_2 emissions is observed.

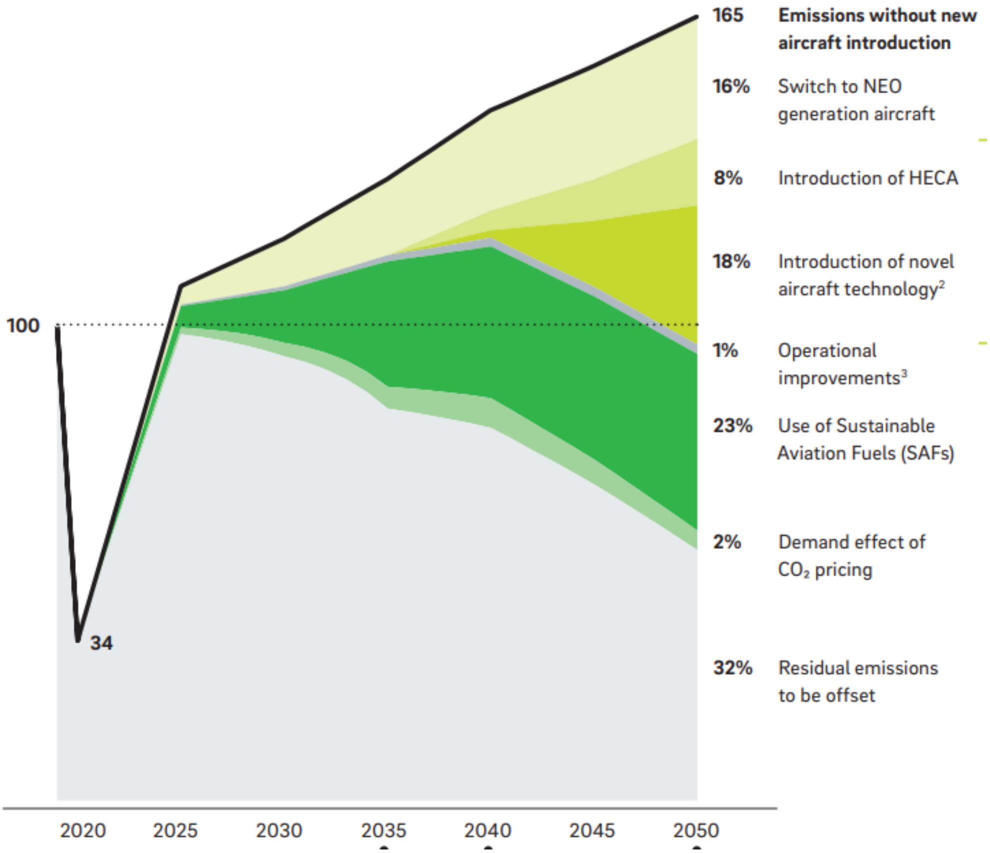


Fig. 6. Assessment of the impact of innovation on CO_2 emissions

6 CONCLUSIONS

The escalating volume of air traffic accentuates the imperative for innovations aimed at curtailing gas emissions, particularly carbon emissions. Innovations, in this context, represent advancements capable of mitigating the environmental impact of aviation. Despite the substantial environmental footprint of aviation, it is postulated that by 2050, appropriate measures could yield a 50% reduction in carbon emissions compared to the levels observed in 2019—a benchmark year considered one of the most successful in air transport.

Growing awareness within airlines and airports underscores the paramount importance of environmental conservation in aircraft operations for human life, terrestrial flora, and fauna. Consequently, various measures and recommended standards are being implemented to reduce carbon emissions at national, regional, and global levels.

This comprehensive study delves into innovations related to aircraft technologies, presenting designs anticipated for future application. Additionally, an innovation of sustainable aviation fuels, slated for imminent use, is elucidated. The incorporation of sustainable aviation fuels, blended with fossil fuels in specific proportions, is anticipated to yield a tangible reduction in carbon emissions.

One of the strategies aimed at reducing carbon emissions is the implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Global implementation of CORSIA has the potential to significantly increase the reduction of carbon emissions in the aviation industry. Although currently optional, member governments of the International Civil Aviation Organization (ICAO) have started to implement this measure, anticipating that it would eventually become compulsory worldwide.

Analysis of the presented data necessitates the acknowledgment that the reduction in flights during the COVID-19 pandemic resulted in substantial savings in CO_2 emissions. The multitude of restrictions and limitations imposed on travel and air travel significantly impacted airlines, airports, and passengers alike. It is pertinent to emphasize that the COVID-19 pandemic yielded greater savings in CO_2 emissions compared to the potential impact of new technological innovations. Furthermore, it is crucial to note that the implementation of technological innovations entails substantial investments and costs, encompassing equipment, policy formulation, regulatory frameworks, staff education, and prequalification, thereby posing financial challenges even if adopted.

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