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The impact of revolutionary aircraft designs on global aviation emissions

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ABSTRACT

The discussion about the environmental impact caused by aviation has gained greater prominence due to the increased demand for this sector and, consequently, the increase in the number of flights. Environmental concerns have stimulated the development of novel approaches to reduce pollutants and CO_2 emissions. This study aims to assess the impact of disruptive concepts on commercial aircraft by reducing CO_2 emissions by 50% by 2050. In this regard the fleet system dynamics model is used to assess the effects of technological progress on future air transport systems. It accounts for the manufacturer's production capabilities and current projections and forecasts on the needs and evolution of global air transport, as well as their expected entry into service. The main factors reported were production capacity, year of entry of the technology/concept, and the transport capacity and range of aircraft. The sensitivity study on the production capacity of new aircraft/concepts showed that with a 15% increase, emissions can be reduced between 1 and 2.6%, depending on the case and scenario. On the other hand, increasing the aircraft production capacity could lead to a problem of overcapacity.

1. Introduction

The aeronautical sector has constantly sought new and improved aircraft designs towards well-defined and clear goals such as drag reduction or payload increase. These goals are defined as the results of external and geopolitical factors such as the oil shock recession in the 1970s, the Gulf War, or the current need to mitigate environmental impacts. In the early 1970s, with the oil crisis, efforts to increase aircraft efficiency led to the development of very large aircraft (VLA), such as the Boeing 747–100 put into service by Pan American World Airways in January 1970, with a fuel consumption of 33% lower than its predecessor, increasing the number of passengers carried on each flight. Moreover, the oil crisis led to the development of advanced technologies in the aeronautical sector, such as supercritical airfoils designed to operate at transonic conditions, reducing the onset of wave drag encountered as recently as in the Airbus A-320 Neo, and advanced composite materials that would ultimately replace metal alloy-based structural components in the Airbus A-380 and Boeing 787 designs, as well as laminar flow control techniques.

Natural disasters' frequency and intensity increase as a consequence of global warming due to human action, which has increased society's awareness, paving the way for a technological revolution aiming at reducing the impact of climate change.

The environmental impact of aviation is fundamentally divided into effects related to aircraft noise and due to exhaust gas emissions. The different pollutants emitted from aircraft engines have an impact on the local air quality and the global atmosphere. Even though aircraft have become less noisy in recent years, forecasted air transportation growth could lead to an increasing population percentage affected by noise, which could limit airport expansion and development leading to policy change and mounting costs. On the other hand, the global transportation sector holds substantial responsibility for the emission of greenhouse gases and other pollutants, such as nitrogen oxides NOx and sulfur oxides SOx [1]. According to the European Environment Agency's (EEA) Report No. 2/2022 on Transport and Environment for 2021, the transportation sector is a major contributor to these emissions. Globally, it is responsible for a staggering 28% of carbon dioxide CO_2 emissions [2,3]. Here, the aeronautical sector has been at the forefront of climate impact mitigation, researching new and improved technologies [4] ranging from improved engine configurations such as ultra-high bypass ratio [5,6] to distinct aircraft configurations [7–9] and fuels [10–12].

These strategies are viewed as potential game-changers in efforts to reduce the environmental impact of air travel. If successful, novel aircraft designs have the potential to reduce fuel consumption and

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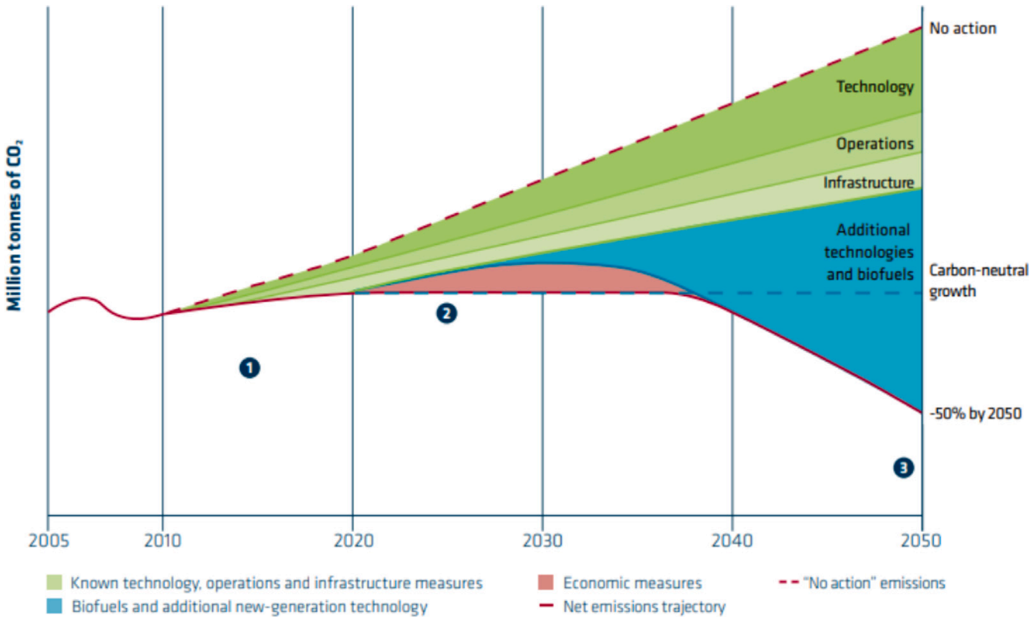

Fig. 1. Air transport emissions reduction goals [20].

emissions. Alternative fuels, such as sustainable aviation fuels (SAFs), have the advantage of being more environmentally friendly [13–16], providing an alternative to traditional fossil fuels. However, it is not consensual that marginal improvements in engine performance, aerodynamic efficiency, and the use of superior materials would be sufficient to meet current sustainability goals. Instead, disruptive designs would be needed as alternatives to or complementary to established and conventional designs. Some argue that disruptive and revolutionary designs are necessary, either as alternatives or complementary solutions to conventional aircraft designs. These disruptive designs could have a transformative effect on the environmental and cost aspects of air travel, addressing concerns at both global and European Union levels. However, their feasibility, cost-effectiveness, and the need for long-term policies to support their development remain subjects of ongoing discussion and analysis [17–19]. These are fundamentally based on three pillars: economic, social, and environmental development framed in the context of the sustainable development goals set by the United Nations 2030 Agenda for Sustainable Development, in particular, Goals 7, "Affordable and Clean Energy", 9, "Industry, Innovation and Infrastructure" and 13, "Climate Action". Coupled they represent the present work's core, combining a technological revolution with alternative energy sources towards improving humankind's quality of life. This is highlighted in Fig. 1, quantifying changes needed to reduced CO_2 emissions by 50% until 2050, with a focus on alternative fuels and technologies.

This study aims to assess the impact of disruptive concepts on commercial aircraft by reducing CO_2 emissions by 50% by 2050. It accounts for the manufacturer's production capabilities and current projections and forecasts on the needs and evolution of global air transport, as well as their expected entry into service. Accordingly, several revolutionary technologies are reviewed in Section 2, followed by several scenarios supported by distinct technological processes and macroeconomic effects in Section 3. Then, the modeling strategy used is explained in Section 4, on which the forecasts in Section 5 are based. Lastly, the main conclusions are presented in Section 6.

2. Revolutionary technologies

The reduction of global net aviation CO_2 emissions in 50% by 2050 in relation to 2005 emissions implies a reduction of CO_2 emissions by 80% [21]. In this sense, the aeronautical industry is striving to improve already available concepts and develop new ones aimed at increased fuel efficiency and lower emissions.

2.1. Blended wing body

The blended wing body (BWB) configuration was introduced at the concept study level in the late 1980s and further analyzed in the 1990s [22]. It is a flying wing with a payload area within its center section. The shape of the center body and the outer wings are smoothly blended. The aerodynamic shape allows generating lift by the entire aircraft, which is significantly higher compared to conventional tube-and-wing configurations [21]. Several BWB concepts have been introduced by research centers such as the Deutsches Zentrum für Luft und Raumfahrt, with a capacity of 500 seats and an estimated entry-into-service of 2040 [23]. Further examples are currently in development as NASA's X-Plane [24], Boeing's concept based on the X-48 experimental aircraft [25], or Lockheed Martin's hybrid wing body (HWB) combining features of BWB and tube-and-wing configurations [26]. Fuel efficiency projections for the various BWB concepts range from 27% to around 50% compared to aircraft of similar size and range [27]. According to Page et al. [28], the new small BWB design allows fuel savings estimated to be around 30% compared to current reference aircraft. Nevertheless, several challenges need to be overcome [29] in terms of stability, control, cabin pressurization, and aircraft handling qualities.

2.2. Strut-braced Wing

The concepts of structurally optimized aircraft, such as the Strut-braced Wing (SBW), have been widely studied in the scientific community [21,22]. The concept of SBW consists of using wing support to increase wingspans without increases in structural weight, leading to lower induced drag. Another advantage of this concept is that the high wing arrangement allows for bigger engine sizes, such as open rotors. Boeing, in the Subsonic Ultra Green Aircraft Research (SUGAR), designed a high aspect-ratio, low induced-drag SBW aircraft with a capacity of 154 seats [21]. This concept is about 29% more efficient over a 900 nmi mission (design range of 3500 nmi) than a Boeing 737–800 with CFM56 engines. According to Bradley and Droney [30], the SBW concept combined with an open rotor could potentially lead to a block fuel saving of up to 53% compared to the evolutionary baseline

Table 1
Overview of technology concepts (2020–2050).

Group	Concept	Fuel Efficieny	Reference
New Aircraft Concept	Blended Wing Body	27% to 50%	[27]
	Small BWB	27%	[28]
	Strut-Braced Wing	29%	[36]
	Double Bubble Fuselage	20%	[21]
	Strut-Braced Wing with Open Rotor	53%	[30]
	Boundary Layer Ingestion	11%	[32]
Propulsion Technology	Advanced Turbofan	20%	[37]
	Ultrafan	25%	[37]
	Open Rotor	30%	[21]
Electric Aircraft	Zunum Aero 50	80%	[21]
	Zunum Aero 100	80%	[21]
	ATR 72 Fully Electric[a]	100%[b]	[21]
	Embraer 190 Fully Electric[a]	100%[b]	[21]
Aerodynamics Technology	Natural Laminar Flow	4.6%	[38]

[a] To analyze the influence that fully electric aircraft can have on global CO_2 emissions, the ATR 72 Fully Electric and the Embraer 190 Fully Electric were considered, with a capacity for 50 and 100 passengers, respectively.

[b] Assuming that energy does not come from fossil fuels.

fleet. Its EIS could be possible around 2040. The Strut-braced wing configuration has been gaining attention [31] due to lower induced drag and higher aerodynamic efficiency during the cruise. However, it can result in aeroelastic instabilities and constraints related to engine positioning under the wings and limitations related to airport gates, possibly requiring changes to the airport structures.

2.3. *Boundary Layer Ingestion*

Boundary Layer Ingestion (BLI), presented as the Propulsive Fuselage Concept (PFC), allows the entire fuselage to produce thrust. The concept of BLI has been investigated in various projects, including the NASA FuseFan, the Bauhaus Luftfahrt Claire Liner, the MIT D8 concept, and NASA's STRAC-ABL [21]. In BLI technology, the engines are located near the aircraft's rear so that air flowing over the aircraft body becomes part of the mix of air going into the engine. According to NASA [32], the BLI technology is capable of reducing aircraft fuel burn by 8.5% compared to aircraft operating today. BLI concept aircraft is further being developed in the framework of the Horizon 2020 Programme under the CENTRELINE project [33], aiming at maximizing the benefits of aft-fuselage wake filling under real systems design and operating conditions. The main objectives are to achieve a Technology Readiness Level (TRL) of 3 and 4 for the PFC concept at the end of the project and to achieve an 11% reduction in CO_2 emissions compared to current aircraft. This concept has a potential entry into service in 2035 [21,34]. To ingest the boundary layer, the engine intake should be attached to the fuselage surface, either in the circular form encircling the fuselage cross-section or in linear form on top of a flattened fuselage. Difficulties in integrating an encircling intake and its associated fan at the rear fuselage, flow distortion, and loss of thrust are disadvantages of this configuration [35].

2.4. *Double-bubble fuselage*

In NASA's X-plane project [24], Aurora Flight Sciences designed the Double-bubble fuselage, also called the D8 aircraft. The main feature of this concept is a fuselage that can be thought of as consisting of two blended side-by-side tubes. The wide flattened fuselage body generates additional lift, allowing the wings to be smaller and lighter, resulting in a significant reduction in fuel burn compared to conventional configurations. Another advantage of this concept is that the engines are attached at the rear of the fuselage, allowing the air to flow over the aircraft's top and move through the engines, reducing drag. However, since the fuselage section is not circular, it is subjected to higher stress loads.

2.5. *Open rotor*

Engine architectures in the past decades have suffered several changes to increase engine efficiency. One of the most promising engine architectures is the Counter-rotating Open Rotor (CROR). It consists of a hybrid system between a propeller and a turbofan engine, characterized by two counter-rotating, unshrouded fans, which allows a reduction of fuel burn and CO_2 emissions of typically 30% compared to conventional turbofan engines, such as the CFM56 [39]. The open rotor concept began to be developed in the 80 s, although its development has been slow due to difficulties in reducing noise levels which are higher compared to turbofan engines, improving in recent years due to advances in computational fluid dynamics and blade design [40]. Manufacturers expect this concept to go into service around 2030 [21].

2.6. *Electric aircraft*

Electric and hybrid propulsion systems are rapidly evolving and occupying an ever-greater market share. In the aeronautical sector, electric propulsion has been explored for its environmental advantages [21,22,41]. Electric engines do not produce emissions during operations, making them a fundamental technological element in achieving environmental goals for 2050. However, it must be considered that electric power generation is not currently produced without emissions, as fossil fuels are still used in many countries for electric power generation. Although electric energy production is not emission-free, electric propulsion could contribute to a considerable decrease in emissions by 2050 due to the investment in renewable energies in all sectors of the global economy. Another advantage of electric propulsion over conventional propulsion is that it requires less maintenance when compared to combustion engines (lubrication is absent), resulting in cost benefits for airlines. In this sense, Airbus, Rolls-Royce, and Siemens formed a partnership in 2017 to develop and build a hybrid-electric aircraft called E-Fan X, characterized by containing hybrid electrical technology in series to power a 2-megawatt electric motor. The main long-term objective is to build a commercial aircraft equipped with E-Fan X technology with a capacity for 50–100 passengers and a range capable of making regional flights. The expected EIS is around 2035 [21]. Furthermore, Boeing HorizonX and JetBlue Technology Ventures have supported and invested in Zunum Aero, which aims to develop the first commercial hybrid-electric aircraft. Zunum plans to introduce one aircraft in 2027 with a capacity of 50 passengers and a range of 1000 nmi. Zunum is also planning to develop an aircraft with a capacity of 100 passengers and a range of 1500 nm. This aircraft will reduce emissions by 80%, and the estimated year of entry into service is 2030 [21]. The main challenge associated with electrification is the development of storage devices, such as batteries, which would supply the propulsive system with the necessary power output requirements.

Table 2
Aircraft operational profile.

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

3. Scenario planning

The disruptive nature of the aircraft designs analyzed insofar has the potential of introducing fundamental changes into air transportation. Usually, aircraft or engine manufacturers compare the efficiency of these potentially disruptive technologies with existing concepts. However, it is still necessary to understand how much emissions, such as CO2, will be effectively reduced by introducing these technologies into the world's airline fleet. In order to attempt to shed some light on the issue, several scenarios are used and looked into for a quantitative emission assessment.

The quantitative scenarios created constitute a solid basis for inferring multiple futures. These scenarios have been created according to parameters such as entry year, type of aircraft configuration, and technology readiness level. An overview of technology concepts is given in Table 1.

Passenger and cargo capacity were defined during the simulations by taking into account the reference aircraft considered. These are listed in Table 2.

Several scenarios were considered in the present study as follows:

- Scenario Business As Usual - BAU: it assumes that there is no introduction of new technology into the simulation. This scenario represents a conservative case in which manufacturers continue to produce aircraft with more relevance in transport capacity without the development of new vehicle types.
- Scenario 1 - New aircraft programs introduced by 2020: it aims at assessing the most efficient aircraft programs introduced in the world fleet so far. The aircraft introduced are the Boeing 747–800, Embraer 190 E–2, Boeing 747–8F, ATR advanced, Airbus A330neo, Airbus A350–900, and Airbus A320neo.
- Scenario 2 - Imminent new technologies: It represents the technological evolution of aircraft until 2025. Therefore in this scenario aircraft and technologies expected in the aeronautical sector until 2025 are considered, including the Boeing 777X aircraft, Rolls Royce engines (Advanced Turbofan and Ultrafan), and Natural Laminar Flow.
- Scenario 3 - New aircraft configurations (BAD): it introduces the analysis of three new aircraft configurations: the Blended Wing Body with a fuel efficiency of 27% compared to the Boeing 747–400, the Small Blended Wing Body and the Boundary Layer Ingestion configurations.
- Scenario 4 - New aircraft configurations (BEST): it groups the concepts with the highest emissions reduction. Small BWB, Strut-Braced Wing, and Double-Bubble Fuselage configurations are considered.
- Scenario 5 - Radically newer propulsive designs: it examines the ability that the introduction of new engine configurations could have in reducing CO_2 emissions. An aircraft (Open Rotor C2) with a fuel efficiency of 30% compared to the Boeing 747–00 is considered.
- Scenario 6 - Towards electrification: it represents the future of aviation towards electric propulsion, using both hybrid and electric propulsion. Aircraft such as the Zunum Aero 50 and Zunum Aero 100 using hybrid propulsion are introduced, as well as the ATR 72 Fully Electric and the Embraer 190 Fully Electric to assess the influence of fully electric aircraft.

Scenarios 3 and 4 detail two distinct levels of fuel consumption reduction, depending on technology implementation. While Scenario 3 groups the configurations with the lowest fuel efficiency, in Scenario 4, the most efficient configurations are considered. Moreover, Scenarios 1 and 2 represent baselines [10] against which some comparisons are carried out. Lastly, recognizing the importance of the entry year and the manufacturer's production capacity, several analyses were carried out:

- **Case 1** - The technologies introduced up to the year 2020 are constant for all scenarios, except for scenario BAU;
- **Case 2** - The technologies introduced up to the year 2025 are constant for all scenarios, except scenario BAU;
- **Case 3** - Increase of 15% in aircraft production capacity, in relation to case 1;
- **Case 4** - Increase of 15% in aircraft production capacity, about case 2.

4. Air transport system modeling

The effect of putting into service the revolutionary technologies described in Section 2 will be estimated considering the scenarios defined in Section 3. However, to estimate and quantify fuel burn and the corresponding emission of the global airline fleet, one needs to go beyond a technology performance comparison. In this sense, to infer

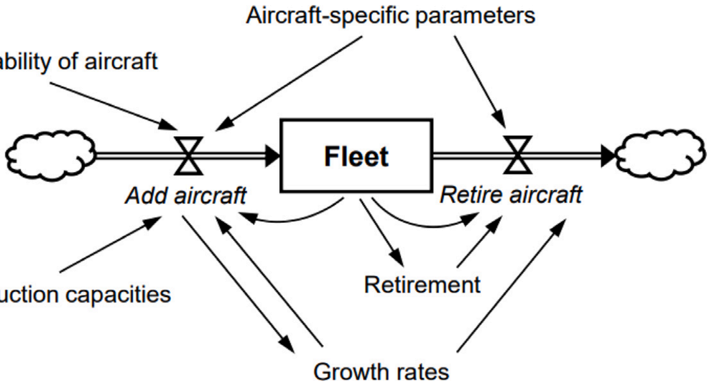

Fig. 2. Functional scheme of the FSDM based on the system dynamics philosophy [42].

Table 3
Characteristics and metrics of the global air transport fleet [42].

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

the CO_2 emissions resulting from introducing new technologies, the fleet system dynamics model (FSDM) developed at the Institute of Aircraft Design of TU Munich was used. It was developed to quantitatively assess the effects of technological progress on the future performance of the air transport system, as described by Randt [42], to where the reader is referred to.

The air transport system is considered to be a system of aircraft operating on a specific network of air routes. Airports are not included and air traffic management authorities are only taken into account considering the influence they have on aircraft legally operated. The characteristics and metrics employed are listed in Table 3.

One of the equally crucial tasks related to fleet planning, especially in the long term, is the modeling of the retirement of aircraft in service. In the context of the model, it corresponds to the outflow, where the aircraft is considered retired from service when it does not resume long-term operations. To represent the decisions that are taken by airlines to retire their aircraft from service, the FSDM has a module that approximates the retirement of aircraft through an age-related function of the aircraft. For this purpose, survival curves describe the percentage of aircraft that remain in the fleet depending on their respective age.

The total time an aircraft needs to perform a flight is defined as utilization hours (UHs). These comprise the following three subcategories: block hours (BHs), the number of hours an aircraft requires to perform a flight mission; turn-around hours (THs), the number of hours an aircraft requires to be ready for the next flight mission; maintenance hours (MHs), the number of hours an aircraft requires to maintain airworthiness [42,43].

After determining the number of aircraft that are retired during each year of the simulation, it is necessary to evaluate the capacity gap to define how many aircraft have to be added to the fleet in the following year to meet operational requirements. New aircraft are introduced minimizing the global fleet's total fuel consumption. Furthermore, aircraft manufacturers obviously cannot deliver an unlimited number of aircraft of a specific type in a certain period, especially when new aircraft programs are introduced. Therefore, the unlimited supply of aircraft cannot be guaranteed by the manufacturer, since first it still needs to prepare the necessary facilities for the production of new models model. To be able to represent fleet simulations more realistically, the FSDM allows limiting the number of aircraft that are available to be added in each year of the simulation. Similarly, it is also necessary to define which aircraft type and how many of them are needed to operate a given flight route and schedule. Once again, the FSDM tackles this problem with the intent of minimizing fuel consumption (see Fig. 2).

Several model assumptions and limitations were imposed on the simulation to simplify the air transport system complexities. These include airline competition, fleet allocation, simulation time interval, representation of the global fleet, and route network. In this regard, it is assumed that a single airline is capable of fulfilling global passenger and cargo demand. As such, no profit maximization is sought, instead the fleet assignment problem is solved by aiming at fuel consumption reduction. Simulations can be carried out for a minimum period of one year starting in 2008. Several aircraft categories are defined to reduce complexity while also maintaining model complexity, with the same procedure being done with the route network through the definition of six global routes, namely Europe, North America, Latin America, Africa, Middle East and Africa.

Lastly, aircraft performance is evaluated through the Base of Aircraft Data (BADA), considered to be the standard in the performance assessment of civil aircraft [44]. It allows us to determine the fuel consumption of the global fleet and the amount of CO_2 emissions.

5. Results and discussion

The impact of implementing disruptive concepts on civil aircraft is quantified, taking into account the manufacturer's production capabilities and the aircraft type, either single- or twin-aisle. Moreover, it is necessary to include the COVID-19 pandemic's effect on the air transportation system. Fig. 3 depicts three different predictions on the air transport evolution, based on the BAU scenario described in Section 3 to a time-frame until 2050 and the corresponding CO_2 emissions projection.

The first option is the "Optimistic Growth" variation of the BAU scenario, where a continuous annual 5% and 4.7% increase in passenger and cargo are considered, respectively. Similarly, we also define a "Pessimistic Growth" with a 1.5% annual air traffic growth. Lastly, Fig. 3 also highlights the Air Transportation Action Group (ATAG) forecast, taking into account the unprecedented effect of the COVID-19 pandemic, exhibiting a similar trend as the "Pessimistic Growth".

The projected scenarios will be combined with the two cases, accounting for the technology's entry into service and the manufacturer's production capacity.

5.1. Case 2 – Entry into service

Case 2 is defined by hypothesizing that the technologies introduced up to 2025 are constant for all the projected scenarios except scenario

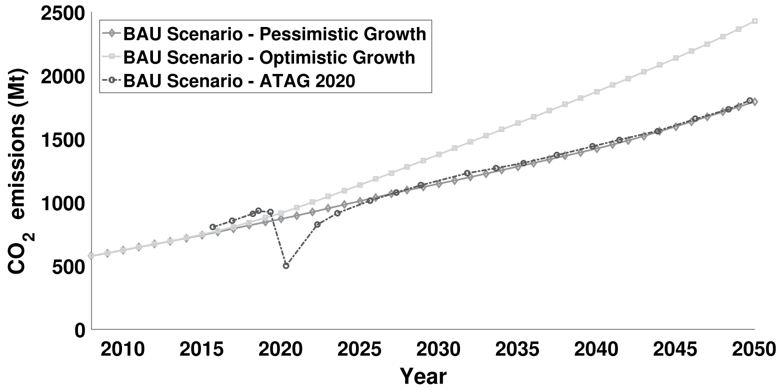

Fig. 3. CO_2 emissions evolution for different growth rates of aviation market.

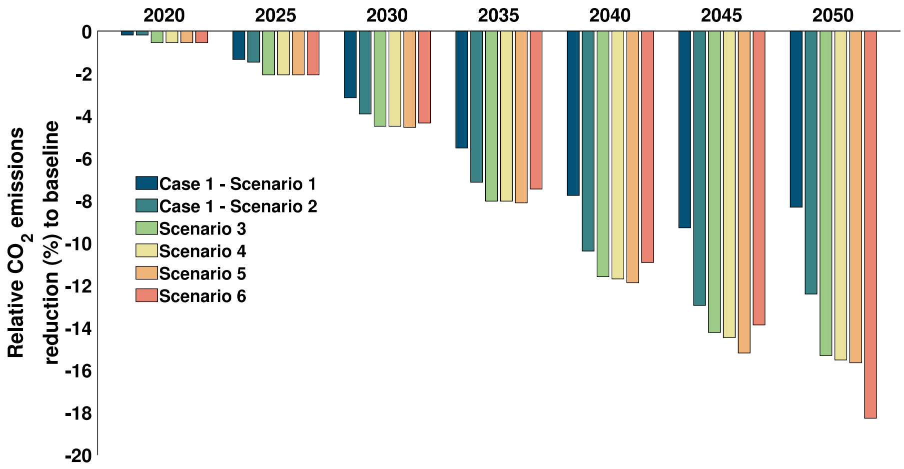

Fig. 4. Fleet-level CO_2 emissions reduction from 2020 to 2050 of Case 2 relative to baseline.

BAU. A sensitivity analysis accounts for the 2025 time frame to ascertain the level of CO_2 emissions since the scenario leading to the most emissions was Scenario 2, considering Case 1.

For Case 2, as shown in Fig. 4, it is possible to observe emissions reduction of CO_2 for Scenarios 3, 4, 5, and 6. In this case, considering the technologies introduced until 2025 in these four scenarios, they stand out for their potential reductions in fuel consumption. In Case 1, the reduction in fuel consumption was overcome by Scenario 2 because the EIS proved to be a factor in emissions reduction until 2050. The most prominent scenario in 2050 is Scenario 6, with a decrease of 18.38%. However, it became more prominent between 2045 and 2050 because electric propulsion is considered. Fully electric aircraft will be introduced in 2040, and hybrid aircraft in 2030. Until these aircraft enter the global fleet in sufficient numbers, it will not be possible to see their potential to reduce emissions. Another essential factor for the reductions not to be higher in this scenario is that electric aircraft have a limited capacity and range. These results agree with the results published by IATA [21], where it is shown that electric propulsion has a powerful impact on CO_2 emissions reduction.

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

Fig. 6 depicts the evolution of CO_2 emissions year after year for the global fleet. Under the defined conditions, the scenario that allows reducing the most emissions by 2047 is Scenario 5, which corresponds to new propulsion designs. However, from 2047 onward, Scenario 6 shows the lower emissions. This scenario, in 2050, registers 1465 Mt of CO_2, which is a reduction of 327 Mt compared to the BAU scenario.

5.2. *Case 4 – Manufacturer's production capacity*

Case 4 is similar to Case 2, except that the simulations performed for all four scenarios considered an increase of 15% in individual productions of all aircraft/concepts analyzed in the respective scenarios. Fig. 7 depicts the results of the CO_2 emissions reduction in the global fleet compared to the BAU scenario. Within all cases analyzed, Case 4 shows the highest emissions reduction. As Fig. 7 shows, technological progress in 2050 reaches 20% for Scenario 6. When comparing Case 2 with Case 4, it can be seen that for all the simulated scenarios, there is an increase in emissions reduction. Table 4 highlights the emissions reduction for Cases 2 and 4 compared to the BAU scenario.

These results are consistent with those published by Schilling et al. [22] and by Ploetner et al. [45]. According to Schilling et al. [22], the CO_2 reduction potential from radical aircraft concepts in 2050 can reach about 20% to 25% compared to the emissions in the baseline scenario. Additionally, Ploetner et al. [45] details that the new aircraft technologies with radical ramp-up timelines might lower global fleet fuel burn until the year 2050 between 17% to 27%. In the present work, the results for Case 4 can reach about 17% to 20% compared to the baseline scenario.

Fig. 8 shows the CO_2 performance until 2050 for Case 4. The scenario with a lower CO_2 performance is Scenario 5, proving once again

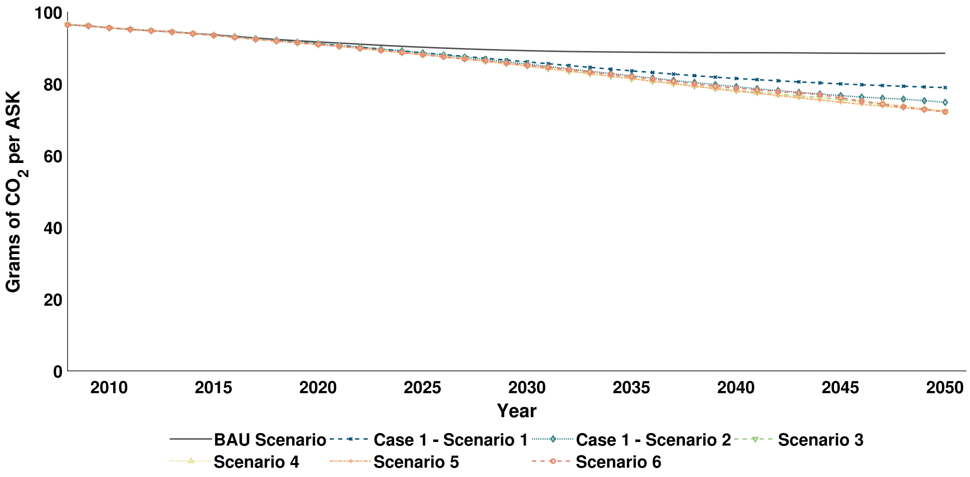

Fig. 5. CO_2 performance for Case 2.

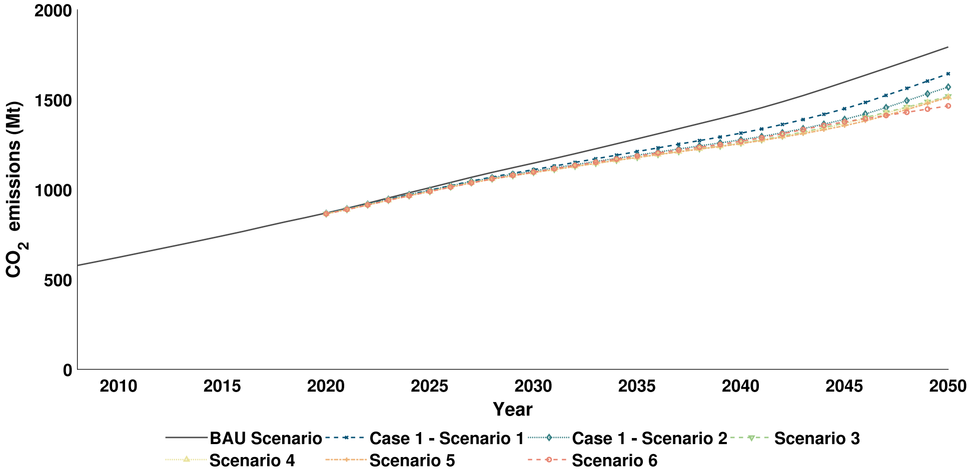

Fig. 6. Fleet-level CO_2 emissions from 2008 to 2050 of Case 2.

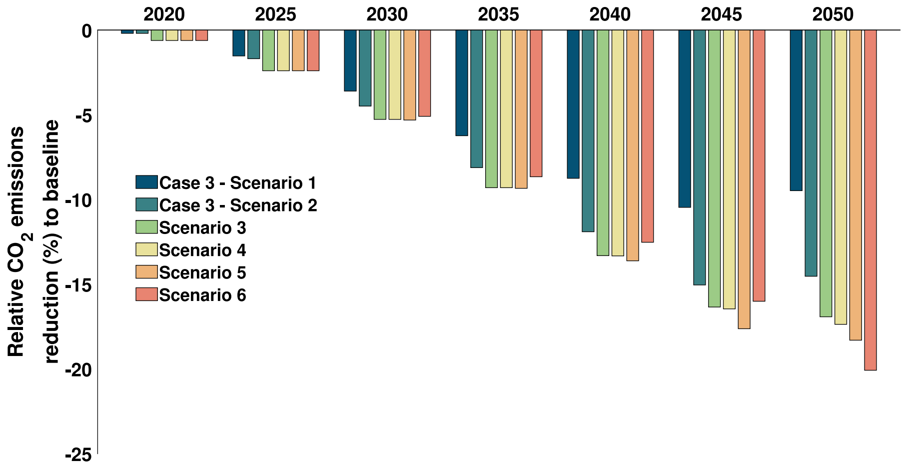

Fig. 7. Fleet-level CO_2 emissions reduction from 2020 to 2050 of Case 4 relative to baseline.

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

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

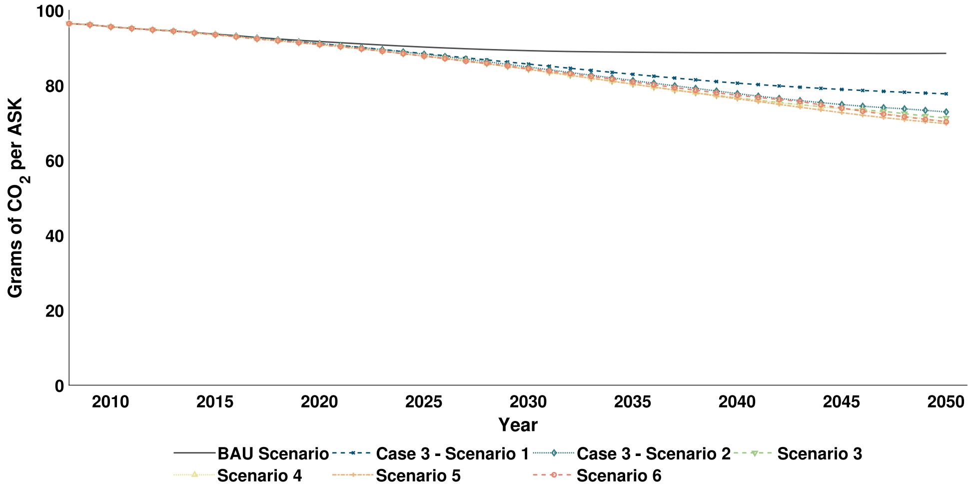

Fig. 8. CO_2 performance for Case 4.

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

Fig. 9 shows the evolution of CO_2 emissions until 2050. Scenario 6 from 2047 shows the lowest emissions, although its CO_2 performance is not as low as Scenario 5. The main reason is that although Scenario 5 has a lower CO_2 performance since a seat load factor of 83% is assumed, this means each aircraft goes with 83% of available seating capacity filled with passengers. If the seat load factor was 100%, Scenario 5 would reduce more emissions since it would have a higher ASK than Scenario 6 because the aircraft considered in Scenario 5 has more capacity than the aircraft considered in Scenario 6.

According to the results of the present work, these do not corroborate what Terekhov et al. [46] have shown. The authors reported that for the maximum technology assumptions, it is possible to have a near to CO_2 neutral growth from 2030 on. In the four cases under analysis, it has not been possible to achieve carbon-neutral growth with only technological improvements.

Given these case studies carried out, two factors are deemed relevant to implementing new technologies. The first is the entry into service (EIS) since if the technologies are implemented in the years before 2050, their effect will be residual. The other factor is the production capacity, determining whether market penetration will be fast or slow.

6. Conclusions

Aviation has a considerable contribution to the economic growth of the global economy. According to the various studies of the largest institutions associated with the commercial aviation industry, they predict that global demand for air transport will continue to increase. From an economic point of view, this development is considered a positive one. However, this vigorous growth of the aviation sector will hurt the environment, both locally (especially near airports) and globally, affecting the environment. Currently, the environmental impact because of this sector is already considerable, establishing about 2.4% of global CO_2 emissions.

The results of technological evolution have shown several points that need to be considered given their influence on reducing CO_2 emissions. The main factors reported were production capacity, year of entry of the technology/concept, and the transport capacity and range of aircraft. The sensitivity study on the production capacity of new aircraft/concepts showed that with a 15% increase, emissions can be reduced between 1 and 2.6%, depending on the case and scenario. On the other hand, increasing the aircraft production capacity could lead to a problem of overcapacity.

In Cases 2 and 4, the scenarios that allowed the highest reduction in fuel consumption were notably Scenarios 5 and 6. Scenario 5 represents the new engine configurations, whose results showed the importance of developing engine technologies, given that it was the scenario with the lowest value of CO_2 performance for Cases 2 and 4. Engine manufacturers in the past years have invested in technology to provide clean, quiet, affordable, reliable, and efficient power. Engine technologies are designed, tested, and implemented since they become mature. Electric propulsion has proven to be an essential approach to mitigating CO2 emissions. However, the results revealed that its ability to reduce emissions is limited. First, because of the transport capacity of the technologies considered, and second, because its range is small compared to other aircraft, being these technologies restricted only to regional flights.

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

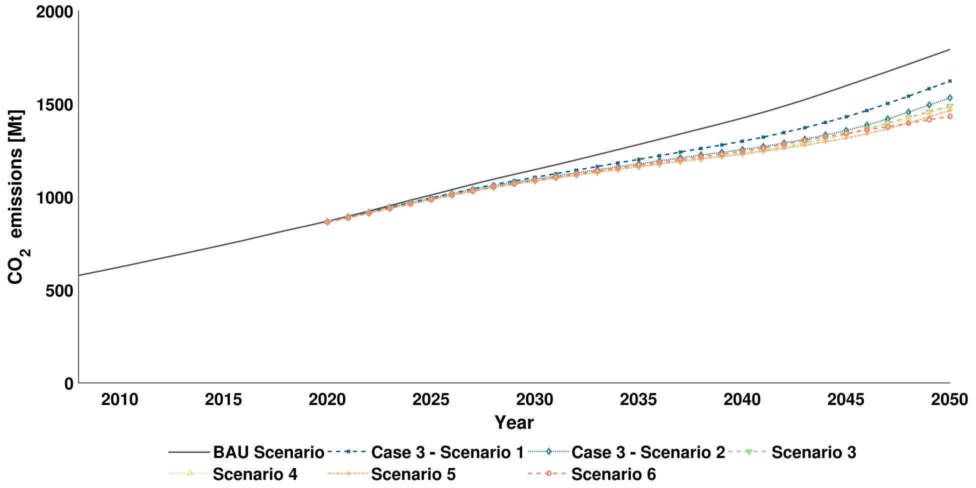

Fig. 9. Fleet-level CO_2 emissions from 2008 to 2050 of Case 4.

CRediT authorship contribution statement

Ivo Abrantes: Investigation, Visualization, Writing – original draft. **Ana F. Ferreira:** Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Leandro B. Magalhães:** Validation, Visualization, Writing – original draft, Writing – review & editing. **Mário Costa:** Conceptualization, Methodology, Supervision. **André Silva:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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References

[1] WHO, WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulphur Dioxide and Carbon Monoxide, Technical Report, World Health Organization, 2021.

[2] EEA, Decarbonising Road Transport - The Role of Vehicles, Fuels and Transport Demand, Technical Report, (02/2022) European Environment Agency, 2022.

[3] EASA, European Aviation Environmental Report 2022, European Aviation Safety Agency, 2022, http://dx.doi.org/10.2822/04357.

[4] J. Schneider, A. Strohmayer, Development process for preliminary aircraft sizing methods with regard to new technologies, Aircr. Eng. Aerosp. Technol. 95 (9) (2023) 1353–1362, http://dx.doi.org/10.1108/AEAT-10-2022-0277.

[5] R. Cavallaro, L. Demasi, Challenges, ideas, and innovations of joined-wing configurations: A concept from the past, an opportunity for the future, Prog. Aerosp. Sci. 87 (2016) 1–93, http://dx.doi.org/10.1016/j.paerosci.2016.07.002.

[6] F.C. Barbosa, Ultra high bypass ratio engine technology review - the efficiency frontier for the TurbofanPropulsion, 2022, SAE Technical Paper. http://dx.doi.org/10.4271/2021-36-0032.

[7] J.R.R.A. Martins, Aerodynamic design optimization: Challenges and perspectives, Comput. Fluids 239 (2022) 105391, http://dx.doi.org/10.1016/j.compfluid.2022.105391.

[8] P.D. Bravo-Mosquera, F.M. Catalano, D.W. Zingg, Unconventional aircraft for civil aviation: A review of concepts and design methodologies, Prog. Aerosp. Sci. 131 (2022) 100813, http://dx.doi.org/10.1016/j.paerosci.2022.100813.

[9] R. Nangia, L. Hyde, J. Cooper, Developing certifiable liquid hydrogen gondola airliner, design innovations and challenges, in: Aerospace Europe Conference Joint 10th EUCASS - 9th CEAS Conference, 2023.

[10] I. Abrantes, A.F. Ferreira, A. Silva, M. Costa, Sustainable aviation fuels and imminent technologies - CO2 emissions evolution towards 2050, J. Cleaner Prod. 313 (2021) 127937, http://dx.doi.org/10.1016/j.jclepro.2021.127937.

[11] F. Afonso, M. Sohst, C.M.A. Diogo, S.S. Rodrigues, A. Ferreira, I. Ribeiro, R. Marques, F.F.C. Rego, A. Sohouli, J. Portugal-Pereira, H. Policarpo, B. Soares, B. Ferreira, E.C. Fernandes, F. Lau, A. Suleman, Strategies towards a more sustainable aviation: A systematic review, Prog. Aerosp. Sci. 137 (2023) 100878, http://dx.doi.org/10.1016/j.paerosci.2022.100878.

[12] J. Eissele, S. Lafer, C.M. Burbano, J. Schließus, T. Wiedmann, J. Mangold, A. Strohmayer, Hydrogen-powered aviation—design of a hybrid-electric regional aircraft for entry into service in 2040, Aerospace 10 (3) (2023) 277, http://dx.doi.org/10.3390/aerospace10030277.

[13] K.F. Tzanetis, J.A. Posada, A. Ramirez, Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance, Renew. Energy 113 (2017) 1388–1398, http://dx.doi.org/10.1016/j.renene.2017.06.104.

[14] S.M. Rassoulinejad-Mousavi, Y. Mao, Y. Zhang, Reducing greenhouse gas emissions in sandia methane-air flame by using a biofuel, Renew. Energy 128 (2018) 313–323, http://dx.doi.org/10.1016/j.renene.2018.05.079.

[15] G. Szabados, A. Bereczky, Experimental investigation of physicochemical properties of diesel, biodiesel and TBK-biodiesel fuels and combustion and emission analysis in CI internal combustion engine, Renew. Energy 121 (2018) 568–578, http://dx.doi.org/10.1016/j.renene.2018.01.048.

[16] E. Emmanouilidou, S. Mitkidou, A. Agapiou, N.C. Kokkinos, Solid waste biomass as a potential feedstock for producing sustainable aviation fuel: A systematic review, Renew. Energ. 206 (2023) 897–907, http://dx.doi.org/10.1016/j.renene.2023.02.113.

[17] A. Abbas, J. de Vicente, E. Valero, Aerodynamic technologies to improve aircraft performance, Aerosp. Sci. Technol. 28 (1) (2013) 100–132, http://dx.doi.org/10.1016/j.ast.2012.10.008.

[18] K. Dahlmann, A. Koch, F. Linke, B. Lührs, V. Grewe, T. Otten, D. Seider, V. Gollnick, U. Schumann, Climate-compatible air transport system—climate impact mitigation potential for actual and future aircraft, Aerospace 3 (4) (2016) 38, http://dx.doi.org/10.3390/aerospace3040038.

[19] F. Yin, A.G. Rao, A. Bhat, M. Chen, Performance assessment of a multi-fuel hybrid engine for future aircraft, Aerosp. Sci. Technol. 77 (2018) 217–227, http://dx.doi.org/10.1016/j.ast.2018.03.005.

[20] ATAG, Beginner's Guide to Aviation Efficiency, Technical Report, Air Transport Action Group (ATAG), 2010.

[21] IATA, Sustainable Aviation Fuel: Fact Sheet, Technical Report, International Air Transport Association, 2019.

[22] T. Schilling, T. Rötger, K. Wicke, Assessment of the impact of radically climate-friendly aviation technologies, in: Greener Aviation Conference 2016, No. 1, 2016, pp. 1–12.

[23] T. Schilling, AIRCAT - Assessment of the Impact of Radical Climate-Friendly Aviation Technologies, Technical Report, (IB 328-2016-17) Deutches Zentrum für Luft und Raumfahrt, 2016.

[24] NASA, Industry provides NASA with ideas for next X-Plane, 2018, https://www.nasa.gov/aero/industry-provides-nasa-with-ideas-for-next-x-plane. (Accessed 08 June 2020).

[25] NASA, X-48B blended wing body, 2010, https://www.nasa.gov/aeronautics/x-48b/. (Accessed 08 June 2020).

[26] J.R. Hooker, Design of a hybrid wing body for fuel efficient air mobility operations at transonic flight conditions, in: 52nd Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, 2014, http://dx.doi.org/10.2514/6.2014-1285.

[27] M. Marino, O. Siddique, R. Sabatini, Benefits of the blended wing body aircraft compared to current airliners, in: First International Symposium on Sustainable Aviation, ISSA 2015, 2015.

[28] M.A. Page, E.J. Smetak, S.L. Yang, Single-aisle airliner disruption with A single-deck blended-wing-body, in: 31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018, 2018.

[29] Z. Chen, M. Zhang, Y. Chen, W. Sang, Z. Tan, D. Li, B. Zhang, Assessment on critical technologies for conceptual design of blended-wing-body civil aircraft, Chin. J. Aeronaut. 32 (8) (2019) 1797–1827, http://dx.doi.org/10.1016/j.cja.2019.06.006.

[30] M.K. Bradley, C.K. Droney, Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development, techreport. NASA/CR-2012-217556, NASA, 2012.

[31] C.P. Szczyglowski, C. Howcroft, S. Neild, B.T. Titurus, J.Z. Jiang, J. Cooper, E. Coetzee, Strut-braced wing modelling with a reduced order beam model, in: 5th Aircraft Structural DesignConference Royal Aeronautical Society, 2016.

[32] NASA, Reduce fuel burn with a dose of BLI, 2017, URL: https://www.nasa.gov/aero/reduce-fuel-burn-with-a-dose-of-bli. (Accessed 09 June 2020).

[33] A.P. Castillo, B.D. Corte, S. Rau, A. Seitz, G. Wortmann, CENTRELINE - Concept Validation Study for Fuselage Wake-Filling Propulsionintegration, Technical Report, (Ares(2021)606991) European Union, 2021.

[34] A. Seitz1, F. Peter, J. Bijewitz1, A. Habermann1, Z. Goraj, M. Kowalski, A.C. Pardo, C. Hall, F. Meller, R. Merkler, O. Petit, S. Samuelsson, B.D. Corte, M. van Sluis, G. Wortmann, M. Dietz, Concept validation study for fuselage wake-filling propulsion integration, in: 31st Congress of the International Council of the Aeronautical Sciences, 2018, pp. 09–14.

[35] S. Hosseini, M.A. Vaziri-Zanjani, H.R. Ovesy, Conceptual design and analysis of an affordable truss-braced wing regional jet aircraft, Proc. Inst. Mech. Eng. G J. Aerosp. Eng. (2020) 0954410020923060, http://dx.doi.org/10.1177/095441002092306.

[36] FlightGlobal, Boeing unveils trussed wing capable of jet speeds, 2019, https://www.flightglobal.com/airframers/pictureboeingunveilstrussedwingcapableofjetspeeds/130914.article. (Accessed 13 June 2020).

[37] R. Royce, Future products, 2020, URL: https://www.rollsroyce.com/productsandservices/civilaerospace/futureproducts.aspx#/. (Accessed 12 June 2020).

[38] IATA, Aircraft Technology Roadmap to 2050, Technical Report, International Air Transport Association, 2019.

[39] O. Turan, Exergo-economic analysis of a CFM56-7B turbofan engine, Energy 259 (2022) 124936, http://dx.doi.org/10.1016/j.energy.2022.124936.

[40] J. Jupp, 21St century challenges for the design of passenger aircraft, in: 28th Congress of the International Council of the Aeronautical Sciences, 2012.

[41] J.L. Felder, NASA Electric Propulsion System Studies, Technical Report, NASA, 2015.

[42] N.P. Randt, Aircraft Technology Assessment Using Fleet-Level Metrics (Ph.D. thesis), TUM, 2016, p. 258.

[43] I. Tetzloff, W. Crossley, An allocation approach to investigate new aircraft concepts and technologies on fleet-level metrics, in: 9th AIAA Aviation Technology, Integration, and Operations Conference, ATIO, American Institute of Aeronautics and Astronautics, 2009, http://dx.doi.org/10.2514/6.2009-6979.

[44] A. Nuic, D. Poles, V. Mouillet, Bada: An advanced aircraft performance model for present and future ATM systems, Internat. J. Adapt. Control Signal Process. 24 (10) (2010) 850–866.

[45] K.O. Ploetner, R. Rothfeld, M. Urban, M. Hornung, G. Tay, O. Oguntona, Technological and operational scenarios on aircraft fleet-level towards ATAG and IATA 2050 emission targets, in: 17th AIAA Aviation Technology, Integration, and Operations Conference, No. June, American Institute of Aeronautics and Astronautics, 2017, pp. 1–13, http://dx.doi.org/10.2514/6.2017-3771,

[46] I. Terekhov, T. Schilling, M. Niklaß, R. Ghosh, Assessing the impact of new technologies in aviation using a global aircraft fleet forecasting model, in: AEGATS 2018, No. November, 2018, pp. 1–12,