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CO2 Reduction Measures in the Aviation Industry: Current Measures and Outlook

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To protect our global climate, the climate conference of the United Nations defined the so-called Paris Agreement in 2015 in Paris, which postulates that global warming should stay under 2° Celsius. In addition, further efforts should be made for a temperature increase limit of 1.5° Celsius (EU, 2020a).

This article focuses exclusively on CO_2 emissions. As the interaction of CO_2 with the climate is the best investigated pollutant, the quantity of available data is very high. Therefore, this paper determines which CO_2 reduction measures exist or will exist in the global aviation industry and discusses their effectiveness.

According to the International Energy Agency (IEA, 2020), the aviation industry alone produced 2.8% of global CO_2 emissions from fossil fuel burning in 2019. To reduce the emitted 915 Mt of CO_2 by the worldwide aviation industry (IATA, 2019), the International Air Transport Association (IATA, 2020a) proclaimed to halve the net CO_2 emissions by 2050 relative to 2005, which amounted to 416 Mt of CO_2 (Macintosh and Wallace, 2008). However, the emissions rate has already grown by 120% since 2005. Nevertheless, since 1990, reduction measures implemented in the aviation industry, such as new technologies, improved operational measures, and more efficient infrastructures, have reduced CO_2 emissions by 8.5 Gt (Boyd, 2020).

Every kilogram of fuel burned produces 3.16 kg of CO_2 (EASA, 2019). With a usual seat load factor of 80% and an average flight speed of 800 km/h, the consumption value per passenger is around 3.3 liters of kerosene per 100 flight kilometers, including increased consumption due to baggage and cargo in the belly (BAZL, 2015). The density of kerosene leads to emissions of 8.34 kg of CO_2 per passenger for every 100 flight kilometers. Therefore, another objective is to stabilize the net CO_2 emission at the level of 2020 with a decarbonized growth. However, the goals explained at the beginning to halve the net CO_2 emissions by 2050 could not be achieved by just reducing emissions (Rogelj et al., 2018). Additionally, not all mankind contributes to the CO_2 emissions of aviation, as only 2% to 4% of the global population flew internationally in 2018, and only 1% of the world population is responsible for 50% of CO_2 from commercial aviation (Gössling & Humpe, 2020). In addition, long-haul flights are estimated to account for 79% of all CO_2 emissions, even though the passenger volume is only 22%; whereas short-haul flights account for 78% of the passenger volume, with emissions of just 21% (Brülhart et al., 2020).

For reasons of clarity and to achieve the previously mentioned goals, IATA (2020a) has implemented a four-pillar strategy, which allows us to categorize the improvements and reduction measures into four areas: technology, operations, infrastructure, and market-based measures/political aspects.

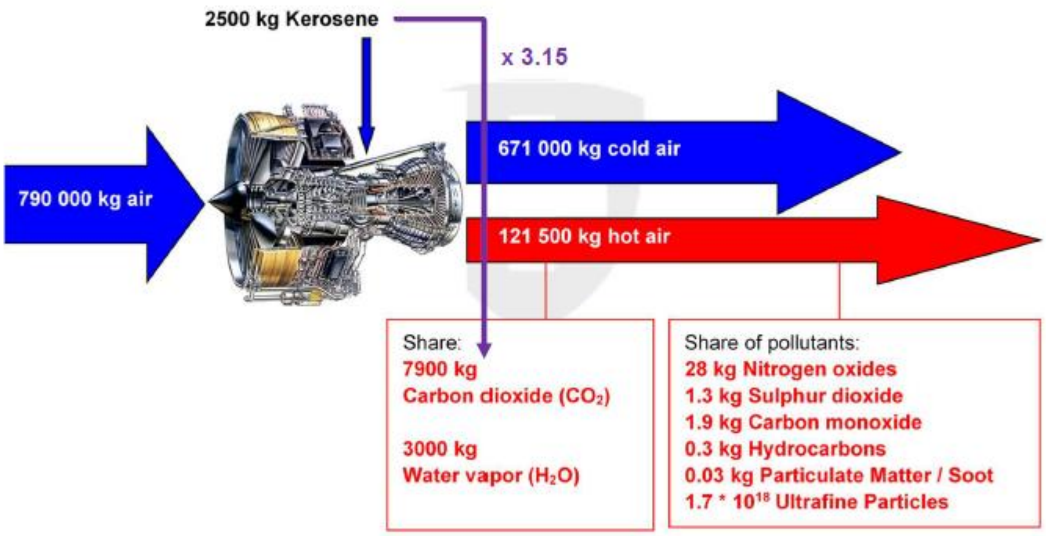
This article merges and evaluates the fragmented solution approaches of stakeholders for proposed reduction measures into a clearly structured overview. To reach this objective, an extensive literature review and personal interviews with experts are conducted. The solutions for sustainable aviation must on the one hand reduce the CO_2 emissions and on the other hand be technically feasible, safe, certifiable, accepted by passengers, and possess a positive cost-benefit ratio.

Technology Measures

To understand how technology affects aircraft emissions, the interaction between the four forces of flight should be kept in mind. For example, improving the aerodynamics of an aircraft produces less drag, and as a result, less thrust is necessary, which leads to fewer CO_2 emissions. Simply stated, improving aerodynamics will increase thrust and lift and decrease drag and weight. The place of action that causes emissions is the jet engines. How many emissions a twin-engine aircraft produces during one flight hour in cruise is shown in Figure 1. Other greenhouse gases and pollutants are also emitted, apart from CO_2.

Figure 1

Emissions of a Typical Passenger Aircraft During One Hour in Cruise (Rindlisbacher, 2020)



The fossil fuel consumption of today's commercial aircrafts is already around 70% less than it was 30 years ago (BAZL, 2015). However, the cost-benefit ratio for further progress with the current technology is gradually being exhausted.

Efficiency of Current Aircraft Models

The main objective of the functions in aircraft design is to decrease fuel consumption with economically appropriate technologies. According to Clean Sky (2020), an airline aircraft has a lifetime of 15–20 years, necessitating renewal of the fleet from time to time, with the most fuel-efficient aircraft. An aircraft also deteriorates over time and causes a fuel bias of 1% per 6,000 hours (Wild, 2018).

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Notably, the aircraft and engine are manufactured by separate companies, and compatibility between aircraft and engine is produced through close collaboration.

The efficiency improvement shows the efficiency of the entire aircraft system, which means the updates consist of aerodynamic improvements, such as winglets and more efficient jet engines. A detailed list of current efficiency improvements for short-haul and long-haul aircraft is available from IATA (2020b).

As a rule of thumb, engine improvements increase by 1% each year (P. Wild, personal communication, October 06, 2020). Considering the lifetime of an aircraft, the latest steps of this technology generation have led to around 20% more efficiency (L. Weibel, personal communication, November 04, 2020). One of the most important developments in engine technologies in the last decade is the geared turbofan. In a conventional turbofan, the fan and the low-pressure shaft are directly connected; however, in the geared turbofan, there is a gear located between them, which allows both components to rotate at their different optimal speeds, thus leading to a higher degree of efficiency. This technology step alone reduces fuel consumption by 35% compared to the conventional turbofan from 2000 (Sieber, 2020).

An observable trend for long-haul, wide-body aircrafts is that airlines no are longer purchasing four-engine aircrafts like the A380 from Airbus or the Boeing 747. One reason for this change is that the high passenger capacity is not exploited, which turns, for instance, the A380 from being one of the most fuel-efficient aircrafts to one of the worst (Rutherford, 2018).

Another reason why twin-engine aircraft have gained popularity for long-haul transoceanic flights is the higher range of extended-range twin-engine operational performance standards (ETOPS) due to the higher safety standard. ETOPS is a certification that allows twin-engine aircrafts to fly routes where an alternative airport for emergency cases is further than 60 minutes away (Sheffield, 2020). ETOPS is not applied to quad-engine aircraft because if one engine fails, the aircraft is still able to continue the flight safely with three engines running. A higher ETOPS range, combined with enough belly freight capacity, enables the aircraft to replace four-engine aircrafts, even for trans-pacific flights (Rutherford, 2018).

Future Aircraft Aerodynamics and Propulsion Design

To break down the technological improvements for the next decades, it makes sense to split them according to the categories of evolutionary and revolutionary aircraft technologies (IATA, 2020c). Evolutionary technologies are those that can be adapted to classical tube and wing aircrafts with jet-fuel engines, including the advanced turbofan engine, natural/hybrid laminar flow, and new engine core concepts. It is estimated that evolutionary upgrades will produce CO_2 emission savings of up to 30% by 2035. By contrast, revolutionary technologies use completely new technologies and design concepts. From the propulsion perspective, there are open rotor engines, hybrid-electric aircrafts, and fully electric aircrafts. From an aerodynamic perspective, improvements can be achieved by developing blended-wing body aircrafts or strut-braced wings.

The improvements in advanced turbofan engine technology go hand-in-hand with the new engine core concepts. A characteristic measurement to show the improvements is the bypass ratio (BPR), which specifies the amount of air that bypasses the engine core with the air streaming through the core of the engine, respectively, the combustion chamber. Earlier engines had a BPR ranging from 5:1 to 6:1 (IATA, 2020c). With the newer engine generation like the "GE9X" on the Boeing 777X, a BPR of 10:1 is possible, with a reduced fuel consumption of 10% (MTU, 2020).

The blended wing body aircraft represents a completely different approach to aircraft design. This type of aircraft is a large wing, with the passenger cabin and cargo load positioned in the middle section. The fuselage and wings are just one element of the aircraft that makes the whole aircraft generate lift. Thus, the fuel efficiency improvements are forecasted at around 27%–50%. Further benefits include shorter turnaround times, less noise, and larger available cargo volume. However, developing these aircraft requires changes to the current infrastructure and high investments, and high uncertainties in the design process need to be overcome (IATA, 2020c). In addition, the passenger acceptance is questionable, and how the aircraft should be evacuated has not yet been clarified (M. Immer, personal communication, October 28, 2020).

Electric propulsion with an efficiency degree of 95% (Rindlisbacher, 2020) offers new degrees of design freedom (Moore & Fredericks, 2014), whether the energy comes from batteries (fully electric aircraft) or from a gas engine (hybrid-electric aircraft), especially in the number of engines, meaning aircrafts with more than four engines could be developed. Battery-electric propulsion produces no emissions during flight, particularly when batteries are charged with renewable energy. Although the degree of efficiency for electric propulsion is twice that of a gas turbine, the potential for commercializing battery-electric aircraft is low due to the small energy density of the battery with 0.25 kWh/kg (Sieber, 2020) compared to the 12 kWh/kg (IPCC, 2020) from conventional jet fuel. In addition, the charging time for a short-haul aircraft would be long, thus lengthening turnaround times. With the high number of load cycles, the battery lifetime is very limited (Rindlisbacher, 2020).

Hydrogen Technology in Propulsion Design

The combustion of hydrogen is a carbon-free process that emits mainly water vapor. Hydrogen as a propulsion method can be used as a fuel for aircrafts when it is combusted directly in a hydrogen burning engine, as in a conventional jet engine, or reacts in a fuel cell powering electric motor (Clean Sky, 2020). The liquid hydrogen energy density per mass is 33.3 kWh/kg, around three times higher

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than kerosene, but the volumetric density is 2.3 kWh/l, four times smaller (IPCC, 2020). To decrease the volume of gaseous hydrogen to liquid hydrogen, a lot of energy is needed to cool the liquid hydrogen to -253°C. Nevertheless, large tanks, which should be safe, are needed on board an aircraft, which significantly increases the operating weight (Clean Sky, 2020). However, the empty weight of the hydrogen tanks is thought to be higher than that of the tanks for kerosene-based systems, making them particularly unsuitable for long-haul flights.

As hydrogen propulsion emits water vapor instead of CO_2, other inflight emissions and effects like NO_x and contrails are also reduced compared to kerosene powered aviation. In particular, fuel cells emit less NO_x and leave fewer contrails compared to the hydrogen turbine, because the latter still produces some NO_x, and the water vapor from a fuel cell is cooler and more controllable. With the new development of fuel cells to a two to three times higher power density, the efficiency of fuel cells is better than that of hydrogen-burning engines regarding the lower heating value (Clean Sky, 2020).

In a hydrogen-powered aircraft, the fuel cell converts hydrogen into electric energy, which powers an electric motor. The process with the highest potential in the aviation sector is low-temperature proton-exchanged membrane fuel cells (PEM fuel cells) (Clean Sky, 2020). The current power density of fuel cells is between 1 and 2 kW/kg (Sieber, 2020), but for efficient usage in an aircraft, it requires a two to three times higher power density (Clean Sky, 2020).

The industry relies on hydrogen powered aircrafts. For instance, in September 2020, ZeroAvia (2020) conducted the world's first hydrogen fuel cell-powered flight containing a full traffic pattern in a Piper M-class. Furthermore, DLR (2020) is developing twin-engine Dornier 228 demonstrators with hydrogen fuel cells and electric propellor propulsion, and the maiden flight is planned for 2026. The hydrogen concept of Airbus's "Zero emissions" program consists of three different concepts: "Turboprop," "Blended-Wing Body," and "Turbofan," which are either powered with hybrid turboprop engines or with hybrid turbofan engines (Airbus, 2020a). The newest "Turboprop" concept intends six removable engines, the so-called "pods," with the propellors driven by electric motors. The electricity comes from hydrogen fuel cells (Airbus, 2020b). This ambitious goal of Airbus is to bring the first commercial aircraft with hydrogen propulsion onto the market by 2035 (Airbus, 2020a).

Additional benefits of hydrogen-powered aircrafts are that the maintenance activities for electric motors are less frequent and less costly compared to combustion engines. The aircraft design from existing aircrafts could also be used (IATA, 2020c). However, the turnaround times on the ground are longer due to the longer refueling process (Clean Sky, 2020). The biggest challenges for hydrogen-powered aircraft are hydrogen storage in the aircraft and the introduction of a new hydrogen infrastructure on the ground (Sieber, 2020).

Sustainable Aviation Fuels (SAF)

Since the implementation of revolutionary technologies requires time for development and therefore carbon-neutral growth is not yet possible, another solution like SAF is needed, which can be implemented more quickly. SAF is a generic term for biofuels, alternative fuels, and synthetic fuels. Instead of emitting new CO_2 into the atmosphere with fossil fuels from crude oil, SAFs are a way to close the CO_2 cycle. The CO_2 is stored in organic materials, and with approved production processes, the material is converted into SAF, which releases CO_2 when it is burned. Hence, the lifecycle emissions of CO_2 can be reduced by up to 80% (IATA, 2020c). SAF can be produced, for instance, from household waste, cooking oil, or halophytes that are growing in saltwater. If the production of SAF conflicts with food production, destroys forests, or consumes too much fresh water, SAF is no longer sustainable but destructive (IATA, 2020d). Using the sun-to-liquid process or the power-to-liquid process, the production of SAF is possible with a net zero of CO_2 emissions.

The aviation sector already uses SAF for their operations. Starting in 2015, with a volume of 0.5 million liters, over 250,000 flights from 40 airlines have been conducted with SAF (IATA, 2020d). Considering the total fuel consumption of 363 billion liters in 2019 (Mazarenau, 2020), the usage of SAF is undoubtedly negligible. But the demand for SAF is rising and is forecasted to reach 43 million liters by 2020. As the growth of demand is exponential and production factories could produce SAF on a bigger scale, the market could be served with seven billion liters by 2025 (IATA, 2020c), which would be around 2% of the total fuel consumption in 2019.

The current major challenge of SAF is that the amount of production is small, and the price of a liter of SAF is still too high. For an airline, the main cost factor today is the fuel cost, making up to 40% of the budget (Wild, 2020). With the current price of SAF, which is between three (Compensaid, 2020) and four times (Patt, 2019) higher than fossil fuels, it makes no sense to use it from an economical perspective. However, with a larger-scale deployment due to the decreased price, the usage of SAF becomes more feasible, affordable, and available. With conductive projects from the public sector, together with regularities, incentives, or subsidies, as is already conducted with wind and photovoltaic energy, a faster way to build more efficient production factories is possible (IATA, 2020c). Hence, the demand for SAF can be saturated with a price at the level of conventional jet fuel.

The participation of revolutionary technology regarding the goals of 2050 is very late, especially if considering the long certification procedure, which lasts around 10 years in the aviation sector due to safety reasons. Therefore, SAF is a suitable bridging solution to allow carbon-neutral growth.

Operations Measures

Operations reduction measures are feasible with the current stand-in technology. Operators or users, such as airlines, are able to optimize their processes and procedures regarding CO_2 emissions in their daily business operations.

Intermodal Traffic/Mode Shift

An acceptable CO_2 reduction measure is to change the mode of transport for domestic travel or travel in adjacent countries to a more ecological transport mode, for instance, train travels replacing short-haul flights. A plane/train comparison made by ETHZ (2020) of the parameter travel time and CO_2 emissions from Switzerland to neighboring countries showed that travel by train produces at least two times less CO_2 than by an aircraft. If the train operates with electricity from renewable energy options, the effect of the mode shift is even higher. The travel times are also comparable, except to further away capital cities like Berlin and Vienna, where currently no high-speed trains are operating. The price component is not considered, but it is a relevant decision factor for passengers.

Weight Reduction

With every additional ton of weight on an aircraft, more fuel is necessary. For a short-haul flight, this amounts to between 3% and 10%, and for a long-haul flight, it amounts to 20%–25% of extra fuel (Wild, 2018).

Table **1** lists the different weight-reduction measures with the savings per aircraft. Considering only one single measure, the savings are not immense; however, given that an aircraft flies several times a day, these savings have a large-scale effect.

Table 1

Weight Reduction Measures

Measures	**Savings [kg]**
Newer external paintings	100–200
Excess customer service items like books, magazines, headsets	20–160
Thinner, carbon-fiber seats; per seat	4–5
Limited duty-free sales (online pre-ordering) on short/long-haul	48/60
Uniform cargo load devices	Up to 240

Note. Source: Wild (2018).

Flight Planning and Fuel Calculation/Aircraft Procedures

Flight planning should be optimized by the aircraft operator with respect to the optimal flight route, altitude, speed, and payload. The goal of an optimized flight profile is to reach cruise altitude quickly and leave this altitude as late as possible for the approach (M. Immer, personal communication, October 28, 2020). Using the optimal operating point according to the ratios of payload and range, an aircraft could be operated more efficiently.

Reliable planning should contain statistical evaluation tools, flight level optimization, precise weights, precise performance data for each aircraft, integrated track optimization, and cost index optimizations, leading to savings of between 1% and 2% (Wild, 2018). The guideline for general improvements is cost-effective, but at least on the same safety level as previous technology (L. Weibel, personal communication, November 04, 2020). The cost index optimizations should also consider the emission footprint. From an ecological perspective, route planning, as in the following example, should be avoided. In this specific case, for a flight from Warsaw (Poland) to Rome (Italy), it is cheaper for an operator to fly a detour with burning 115 kg more fuel than the shorter fuel optimized routing with a higher route charge of 109 euros (EUROCONTROL, 2020a).

What also applies to the fuel calculation is that, with every additional ton of fuel on board, additional fuel is needed. The fuel policy boundaries are set by the European Union Aviation Safety Agency (EASA). The main improvements in fuel calculations could be made with the contingency fuel and the extra fuel. A decision tool for the extra fuel amount is served by a statistical evaluation tool. Thereby, the 95^{th} quantile of the extra fuel amount of all flights to a destination within one year is considered (Wild, 2018), but it is not easy to conduct such a statistical evaluation due to data protection regulations concerning cockpit members (L. Weibel, personal communication, November 04, 2020). With a new regulation regarding contingency fuel, a fuel reduction of around 1% is possible. Another adjustment for the fuel calculation could be made according to the latest payload information because for commercial flights, “no-shows” of passengers can occur. With less weight onboard from the passenger and baggage, less fuel is necessary. This improvement has a greater impact on long-haul flights than on short-haul flights (Wild, 2018).

If the engines of an aircraft are not running, the auxiliary power unit (APU) powers the aircraft with external power. Although today’s APU is further developed and more efficient than the predecessors (Wild, 2018), the use of a diesel ground power unit (GPU) or fixed energy system produces fewer CO_2 emissions by a factor of 17 (GPU) or 480 (fixed energy system) (Fleuti & Ruf, 2018). Using the GPU as a procedure requires the necessary infrastructure and reduces, besides

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emissions, the maintenance cost of the APU (L. Weibel, personal communication, November 04, 2020).

Infrastructure/ATM

ATM contributes to navigational improvements and a more efficient use of airspaces to reduce total flight times. To modernize the European airspace, especially to reorganize the fragmented airspaces, the EU commission developed an initiative called "Single European Sky ATM research program (SESAR)" with the European air traffic controller EUROCONTROL. The main goal is to merge the large number of airspaces to reduce at least 10% of CO_2 emissions (SESAR, 2020a), thereby giving an average fuel reduction per flight estimated at 250–500 kg (SESAR, 2020b). With more efficient taxi operations, fuel savings of 38–75 kg per flight (relative reduction 30%) are targeted (SESAR, 2020b). The equivalent modernization process for US airspace is called NextGen (FAA, 2020).

The following paragraphs present some components to reach the CO_2 reduction goal of 10%, introducing, in particular, a lean and efficient use of air navigation services (ANS) with increased collaboration and operational predictability and improved flight trajectories.

The concept of 4D navigation, which uses the three spatial dimensions and the time dimension, allows the introduction of a trajectory of a flight. With overlaying trajectories of different flights, conflicts and holdings could be noticed earlier and could be prevented entirely so that every aircraft is able to fly their optimal trajectory at the preferred cruise level for as long as possible. As a result, emissions are reduced due to the decreased flight time. The challenge is that ANS providers and aircrafts need new technical equipment. Also, the controller must be aware of what impact an influencing factor has on the whole trajectory, which is particularly difficult when the equipment fails and could lead to a workload for the controller (Skybrary, 2017).

With improved vertical navigation, such as continuous climb and descent operations instead of climb step operations, a fuel reduction of 163–325 kg per flight (relative reduction 10%) is possible (SESAR, 2020b). In Europe alone, the potential for optimized departure and approach operations is up to 1.1 million tons of CO_2 per year (Skyguide, 2020). According to Wild (2018), the vertical separation minimum between FL290 and FL410 was reduced in 2002 from 2,000 ft to 1,000 ft due to more precise navigational equipment. This reduction resulted in an increased capacity of 14%, but the aircraft was able to fly more at its optimized altitude, which reduced its CO_2 emissions. Therefore, any holdings should be conducted at the highest reasonable altitude or even better to reduce speed and avoid holdings. However, in the longest flight phase of cruise, the optimum altitude should be targeted where the lift drag ratio is at a maximum for the chosen speed. Consequently, the altitude should be changed during the cruise because flying lower or higher uses more fuel and the aircraft produces more CO_2 emissions (Wild, 2018).

Improvements in horizontal navigation can be achieved with free route airspaces (FRA), leading to more direct routes. The concept provides that a user of an aircraft is able to plan a route freely with or without intermediate waypoints in a specific airspace while considering the boundaries of a defined entry and exit point. Inside free airspaces, flights are still under air traffic control. The horizontal limits exist regardless of Flight Information Region (FIR) or country borders, and the vertical-level limit is dependent on the particular FRA (Todorov, 2019). The average en-route fuel savings amount to 50–100 kg per flight, which represents a relative reduction up to 2.5% (SESAR, 2020b). An early trial to defragment the European airspaces in nine functional airspace blocks failed because of "a lack of commitment on the part of the member states to preserve sovereignty, the legacy of national air navigation service providers, revenues, and workforce" (Tani, 2017).
A collaboration between European countries is, with a standardization of data and radar data, technically feasible. Financial and political aspects are a hurdle in this process (P. Truffer, personal communication, November 11, 2020).

Market-based Measures/Political Aspects

Not paying fuel tax or VAT on commercial international flights is a rule that goes back to the foundation of the International Civil Aviation Organization (ICAO Chicago Convention, Article 24) in 1944 (ICAO, 1944) to promote civil aviation, and because the aviation industry pays for its infrastructure mostly by itself (BDL, 2020). According to the model developed by Faber et al. (2019), without tax exemptions, the average ticket price increases by 10%, and passenger demand decreases by 11%. Consequently, besides the emissions decline of 11%, the falling demand has a negative impact on employment in the aviation sector, but the higher fiscal revenue offsets this impact. In the end, a negligible effect on employment and gross domestic product (GDP) is observable.

The aviation industry is a global business. Therefore, competition boundaries, such as political boundaries or public awareness, should be treated in a similar way for every operator globally. A fair competition without distortion is a main motivation for accepting market-based measures (D.-H. Lee, personal communication, October 28, 2020).

Area-wide Compensation Systems (EU ETS/CORSIA)

Area-wide compensation systems act under the principle that "the polluter pays." The European Emission Trading System (EU ETS) is an emission trading system constrained to Europe that has been active since 2005 as the first major carbon market. It remains the biggest carbon market, and it uses a Cap & Trade system to monitor companies with high CO_2 emissions and other pollutants, such as heavy energy-using installations and, since 2012, airlines. Until the end of 2023, only flights in the European Economic Area will be affected. The cap is fixed on the total amount of emissions and will be decreased yearly. A polluter needs certificates as an allowance to emit, for instance, a ton of CO_2. These certificates can then be traded with other companies to cover all their emissions. If a company does not have enough certificates at the end of each year, a big fine is distributed. The goal is for companies to invest in clean, low-carbon technologies (EU, 2020b). The price for a carbon certificate from the EU ETS in the years between 2008 and 2019 fluctuated between 5 and 30 euros per ton CO_2 (Vollebergh & Brink, 2020). To achieve the objective of the Paris Agreement, a price of up to 100 USD per ton CO_2 is needed to reduce emissions with this mechanism (Rogelj et al. 2018).

Another market-based approach to reduce CO_2 emission is called "offsetting." For that reason, in 2016, ICAO resolved a compensation system called Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA for short. Compared to the EU ETS, CORSIA focuses solely on international air transport and is the first globally active climate protection instrument in the transport and economy sector. The CORSIA program comprises three phases, where the pilot phase (2021–2023) and the first phase (2024–2026) are voluntary for the member states, while the second phase (2027–2035) is mandatory for all 193 member states, with some exceptions. The program is running until 2035 (ICAO, 2020).

Companies receive compensation when they acquire eligible emission units from CO_2 offsets of climate protection projects in other sectors, such as renewable energy projects. The climate protection projects are certified and examined after international standards. Projects in emerging and developing countries, which have a large potential to reduce CO_2 emissions, are particularly taken into account. A possible way to merge the EU ETS and CORSIA is unknown (BAZL, 2020). The funding for climate projects with CORSIA is forecasted to be 40 billion USD and offsets 2.6 billion tons of CO_2 between 2021 and 2035 (ICC, 2019).

Flight Taxes

In this article, the term "flight tax" refers to a ticket tax that is charged from the departure destination. The objective of a flight tax is to use demand elasticity in the aviation sector. With a higher ticket price, fewer people would fly, and therefore, an overall reduction of flights and their emissions occurs. As specified by Faber et al. (2019), 14 countries in Europe and 19 countries outside of Europe already use a flight tax on domestic and international flights. The average burden per passenger in Europe is around 15 euros, with a range between 40 euros (United Kingdom) and 1 euro (Croatia). EUROCONTROL (2020b) investigated the effects of flight tax only on aviation CO_2 emissions and found that the implementation of a ticket tax in countries such as the United Kingdom, Germany, and Italy has shown only a limited effect in decreasing emissions. In relation to the total growth of the aviation sector in particular countries for 2010–2019, the effects of a flight tax are almost negligible. Further, the passenger number reduction per flight due to the flight tax is not significant enough to force an airline to not operate that flight (P. Wild, personal communication, October 06, 2020). In addition, the impact on the seat load factor is not high enough to change operations to smaller aircraft.

Estimated effects on demand with the implementation of a flight tax are based on the example of Switzerland in Brülhart et al. (2020). In general, passengers are more price sensitive if they are more flexible, especially for short-haul and economy-class flights. With other demand elasticities, different scenarios are simulated, resulting in air traffic reductions decreasing to 20% and greenhouse gas emissions decreasing to 10%. With this mitigation, Switzerland's total global warming impact decreases to 2%. However, with the demand growth of the aviation sector, this positive impact regarding emissions savings would be offset within three years. The revenues of this flight tax are estimated to be up to 0.9 billion USD per year.

Conclusion

IATA proclaimed to halve the net CO_2 emissions by 2050 compared to 2005, despite a forecasted growth in the aviation sector. Hence, the growth should be decarbonized and, for the moment, stabilized at the forecasted pre pandemic CO_2 emissions level of 2020. This paper investigates the various current and future CO_2 reduction measures in the global aviation industry and shows their effectiveness. Figure 2 illustrates a holistic evaluation of mitigation measures in a time period/potential matrix. The horizontal direction shows the potential or impact of a reduction measure. The time period in vertical direction represents when the reduction measure would be implemented.

Figure 2
Evaluation Matrix

SH = Short-haul LH = Long-haul	Potential / Impact		
Time period	Low	Medium	High
Short-term until 2025	• Synthetic fuels • SH: Mode shift • Procedures of ATM • EU ETS / CORSIA / Flight tax	• Bio fuels as blending • Weight reduction • Flight planning and fuel calculation / aircraft procedures	
Mid-term 2025 – 2040	• Evolutionary aerodynamic improvements • SH: Electric / Hydrogen aircraft • EU ETS / CORSIA / Flight tax	• Evolutionary engine improvements • Procedures of ATM	• SAF
Long-term from 2040	• EU ETS / CORSIA / Flight tax	• SH: Electric aircraft • LH: Hydrogen aircraft / Blended wing body aircraft	• SH: Hydrogen aircraft • SAF

The implementation of fuel efficiency optimization measures takes time until fleet turnover is planned, especially when considering the long certification time of up to 10 years and the aircraft lifespan of about 15–20 years. Aerodynamic improvements for tube and wing aircrafts are already exhausted; therefore, the potential for further improvement is low. On the contrary, advanced turbofan and new engine core concepts as evolutionary engine improvements have medium potential because the development of jet engines with higher BPRs is still with reasonable expenditure possible. The introduction of an aircraft for short-haul commercial flights using electric motors is to be expected for mid-2030. The motors will be either powered by hydrogen fuel cells or electricity from batteries, whereby the storage of hydrogen is a step ahead regarding operation weight. Hydrogen technology is also more scalable and energy efficient and is the more economic option. Also, conflicting objectives and effects, such as the reduction of CO_2 emissions and non-CO_2-emissions should be further investigated and not neglected. For instance, with hydrogen, less CO_2 is produced, but more water vapor and NO_x are created. The potential of synthetic fuels is low in the short term due to their small production capacity. However, today's use of biofuels as blending has medium potential to be implemented by 2025 because production growth is on the exponential path. From 2025, SAF has a high potential and impact as CO_2 reduction measure. The most promising long-term technologies to reduce CO_2 emissions are hydrogen-powered aircrafts and SAF. However, the advantages of SAF and hydrogen-powered aircraft outweigh the other options only when the energy used for production is renewable.

A mode shift from flying to taking a train is a reasonable reduction measure for travel to adjacent countries with good train accessibilities. Operation measures, such as weight reduction, flight planning, and fuel calculation, have medium potential in the short term because they are easy to realize and have a big scale effect. With every weight saving, either from fuel or payload, an avoidance of carrying additional fuel is possible because with every further ton on board an aircraft, additional fuel amounting to 3%–10% for short-haul flights and 20%–25% for long-haul flights is needed.

The objectives of the reduction measure from an infrastructure/ATM perspective are to decrease flight times and avoid holdings because every kg of fuel burned produces 3.16 kg CO_2 emissions. The implementation of more efficient airspaces and flight routes in Europe can be achieved by SESAR to reduce at least 10% of CO_2 emissions. While these improvements mitigate only a few emissions, implementing these improvements area-wide create big scale effect. Therefore, the impact is low at first, but increases to medium with time.

Regulations in a free market are necessary when nobody feels responsible for paying the cost for damage like climate warming. By applying "the polluter pays" principle, it might be possible to stop such market failures by implementing market-based measures, such as area-wide compensation systems like EU ETS, CORSIA, and taxes. Studies confirm that market-based measures have a low impact as a reduction measure because prices are too low to obtain a significant reduction. However, with today's offsetting of CO_2, the problem is not solved at the root. Therefore, the revenues obtained through these systems may be used to invest in the research and development of more promising reduction measures. Doing so will also raise people's acceptance to pay such market-based measures and provide new jobs. To support CO_2 reduction measures, a global approach with standardized rules and reasonable incentives is useful regarding the distortion of competition. The implementation of market-based measures is connected with conflicts of interest regarding ecological, economic, political, and social goals.

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Abbreviations

ANS =	Air Navigation Services
APU =	Auxiliary Power Unit
ATM =	Air Traffic Management
BPR =	Bypass Ratio
CORSIA =	Carbon Offsetting andReduction Scheme for International Aviation
EASA =	European Union Aviation Safety Agency
ETOPS =	Extended-range Twin-engine Operational Performance Standards
EU ETS =	European Emission Trading System
FIR =	Flight Information Region
FRA =	Free Route Airspaces
GPU =	Ground Power Unit
IATA =	International Air Transport Association
ICAO =	International Civil Aviation Organization
PEM =	Proton-Exchanged Membrane
SAF =	Sustainable Aviation Fuel
SESAR =	Single European Sky ATM Research
VAT =	Value Added Tax