CO_2 reduction measures in the aviation industry - Current state and outlook / Political aspects

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Abbreviations

ACARS = Aircraft Communications Addressing and Reporting System
AHV/OASI = Alters- und Hinterlassenenversicherung /Old-Age and Survivors's Insurance)
ANS = Air Navigation Services
APU = Auxiliary Power Unit
ATM = Air Traffic Management
BLADE = Breakthrough Laminar Aircraft Demonstrator in Europe
BPR = Bypass Ratio
CORSIA = Carbon Offsetting and Reduction Scheme for International Aviation
DME = Distance Measuring Equipment
EASA = European Union Aviation Safety Agency
EGNOS = European Geostationary Navigation Overlay Service
ESG = Environmental, Social, Governance
ETOPS = Extended-range Twin-engine Operational Performance Standards
EU ETS = European Emission Trading System
FIR = Flight Information Region
FLEX = Flexible temperature
FOCA = Federal Office of Civil Aviation
FRA = Free Route Airspaces
GNSS = Global Navigation Satellite System
GPS = Global Positioning System
GPU = Ground Power Unit
IATA = International Air Transport Association
ICAO = International Civil Aviation Organization
ILS = Instrument Landing System
MTOW = Maximum Take Off Weight
NDB = Non-Directional Beacon
PEM = Proton-Exchanged Membrane
SAF = Sustainable Aviation Fuel
SBB = Schweizerische Bundesbahnen / Swiss federal railways
SESAR = Single European Sky ATM Research
VAT = Value Added Tax
VOR = Very high frequency Omnidirectional Radio range

Project work MSc Civil Engineering

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Abstract

This thesis deals with the numerous CO_2 reduction measures in the aviation industry and is giving a holistic overview of already introduced reduction measures and analyses which are feasible in the future and their effectiveness. To achieve the objectives of the Paris Agreement, the aviation industry needs to implement reduction measures because of its forecasted growth and its contribution to the global warming. The focus is set on CO_2 reduction measures, categorized in technology, operations, infrastructure / ATM and market-based measures. Additional for the latter one, a non-representative online survey is conducted to check the passenger acceptance of a Swiss flight tax and the travel behaviour around COVID-19.

The most promising long-term technologies to reduce CO_2 emissions are hydrogen powered aircrafts and SAF. In terms of operations, it is all about weight savings either from fuel or payload. For every additional ton on board of an aircraft, extra fuel of 3 – 25 % is necessary, depending on the route distance. From an infrastructure / ATM perspective, the goal is to decrease the flight time and avoid holdings, because every kg of fuel burnt produces 3.16 kg CO_2 emissions. Market-based measures have a low impact as a reduction measure, but revenues may be used to accelerate research and development of more promising reduction measures. The current limitation of the Swiss flight tax will not massively influence the travel behaviour of the surveyed participants, also as long as the average limit is not 3.5 – 5 times higher. The implementation of just one reduction measure is not reasonable. A global approach with reasonable incentives to support CO_2 reduction measures are preferable.

Key words

Aviation, CO_2 reduction measures, Swiss flight tax

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Short facts

Table 1 Short facts

Fact	Chapter (page)	Source
2.8 % of global CO_2 emissions of fossil fuel burning is originating from the aviation industry	1 (4)	IEA (2020)
905 Mt CO_2 emissions for 2018 **915 Mt CO_2** emissions for 2019 **936 Mt CO_2** emissions for 2020 for worldwide airline industry	1 (4)	IATA (2019)
8.5 Gt of CO_2 emission has been avoided since 1990	1 (4)	Boyd (2020)
3.16 kg CO_2 emissions for every kg of fuel burnt (pure combustion)	1 (4)	EASA (2019)
1 % of world population emits **50 % of CO_2** from commercial aviation User of a private aircraft can emit up to **7'500 t CO_2** per year	1 (5)	Gössling and Humpe (2020)
Share of emissions and passenger volume: Short haul: **21 % emissions** and **78 % passenger volume** Long haul: **79 % emissions** and **22 % passenger volume**	1 (5)	Brülhart et al. (2020)
Energy density of a battery **0.25 kWh per kg**	2.2 (14)	Sieber (2020)
Energy densities per mass and volume: Hydrogen (liquid): **33.3 kWh/kg and 2.3 kWh/l** Jet fuel (Kerosene): **12 kWh/kg and 9.4 kWh/l**	2.3 (15)	IPCC (2020)
Current power density of fuel cells: **1 – 2 kW/kg**	2.3 (15)	Sieber (2020)
SAF production forecast: 2020: **43 million liters** / 2025: **7 billion liters**	2.4 (18)	IATA (2020c)
Production costs of fuels: Fossil jet fuel **0.50 CHF/l** Synthetic jet fuel **2.00 CHF/l**	2.4 (18)	Patt (2019)
Additional ton of weight on board, requires **3 – 10 %** additional fuel for short-haul flights **20 – 25 %** additional fuel for long-haul flights	3.2 (25)	Wild (2018)
Specific CO_2 emissions short/long-haul aircraft: APU **337 / 758 kg CO_2/h** Diesel GPU **19.1 / 38.2 kg CO_2/h** Fixed electricity **0.7 / 1.2 kg CO_2/h**	3.3 (28)	Fleuti and Ruf (2018)
10 % CO_2 emission savings with SESAR	4 (31)	SESAR (2020a)

1 Introduction

For the protection of our global climate, the climate conference of the United Nations defined 2015 in Paris the so-called Paris Agreement, which postulates that the 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).

Main driver of global warming are in compliance with Umweltbundesamt (2020) greenhouse gases like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) as well as fluorinated gases (HFCs, PFCs, SF_6, NF_3). In addition, several other pollutants like nitrogen oxides (NO_x), steam, sulphur dioxide (SO_2) and black carbon have a big impact on the climate (Neu, 2020). The influence of black carbon particle number emission in the vicinity of an airport is described in Zhang et al. (2019). Especially in air layers close to the ground, do SO_2, NO_x and black carbon have direct effects on the health and environment.

How does the global aviation industry contribute to the climate effects? First, during the combustion of jet fuel, emissions such as CO_2, NO_x and H_2O are produced, where the latter is under certain conditions visible for the human eye as condensation trails. Second, emissions of CO_2 from cruise flights are warming up the climate by similar amounts as on the ground. Third, NO_x causes at cruise altitude ozone in the troposphere and is accelerating the climate effects more compared to the same emissions on the ground (Schumann, 2008).

But for this thesis, because of the high diversity of environmental pollutants, the focus will be exclusively on CO_2 emissions. Besides, the interaction of CO_2 with the climate is the best-investigated pollutant and consequently the quantity of available data is very high. Therefore, this thesis deals with the question of which CO_2 reduction measures exist or will exist in the global aviation industry and what are their effectiveness.

According to IEA (2020), the aviation industry alone produced in 2019 2.8 % of global CO_2 emissions from fossil fuel burning. To reduce the emitted 915 Mt of CO_2 by the worldwide aviation industry (IATA, 2019), in IATA (2020a) they proclaimed for instance to halve the net CO_2 emissions for the year 2050 in comparison to 2005, which amounted to 416 Mt of CO_2 (Macintosh and Wallace, 2008). That means that the growth of emissions is already at 120%. But since 1990, already 8.5 Gt of CO_2 emission has been avoided in the aviation industry due to reduction measures, like new technologies, improved operational measures and more efficient infrastructures (Boyd, 2020).

With every kilogram of burnt fuel, 3.16 kg of CO_2 is produced (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 litres of kerosene per 100 flight kilometres. The increased consumption due to baggage and cargo in the belly is included (BAZL, 2015). In regard of the density of kerosene, this leads to an emission of 8.34 kg of CO_2 per passenger and 100 flight kilometres. Another objective is to stabilize the net CO_2 emission at the level of 2020 with a decarbonized growth. But in general, by just reducing the emissions, the goals explained at the beginning could not be achieved (Rogelj et al., 2018). One must also be aware that not the whole mankind contributes to the CO_2 emissions of aviation. It is just 2 % to 4 % the of global population who flew internationally in 2018 and that 1 % of world population is responsible for 50 % of CO_2 from commercial aviation (Gössling and Humpe, 2020). Besides, the emissions of long-haul flights are estimated to 79 % although the passenger volume is only 22 %. Whereas short-haul flights account 78 % of the passenger volume with emissions of just 21 % (Brülhart et al., 2020).

The Swiss Government or more precisely the Federal Council goes with the objectives of CO_2 emissions one step further. They defined in the energy strategy that until 2050, that the greenhouse gas emissions should be reduced to net-zero (BFE, 2020). The Swiss population endorsed this strategy in a popular vote with a majority of 58.2% (BFE, 2018). In comparison to the global emissions, the share of CO_2 emissions from the air traffic in Switzerland is higher and amounts to 12 % with an absolute value of 5 Mt (PB, 2019).

For clarity reasons and to achieve the previous mentioned goals, a four pillars strategy, as shown in Figure 2, is implemented by IATA. This allows to categorize the improvements and reductions measures. The schema of four pillars is also transmitted to this thesis, with only small adaptations. In some cases, several pillars are affected, for instance some more efficient procedures in an aircraft can be only be applied if the existing infrastructure is laid out for that.

Figure 2 IATA's four pillars strategy

Source: CAPA (2020)

One pillar describes the progress of technology which is explained in chapter 2. This includes new developments of aircrafts with respect to the general design, propulsion, engine and sustainable fuels. The introduction and realisation of new technology takes time because of the protracted certification.
The pillar operations cover measurements, which are feasible with the current stand in technology, can be found in chapter 3. This concern, as the term operation already suggests, operator or user like airlines which are able to optimize the flight planning and their procedures in accordance to their operations manual. Furthermore, an airline can control carrying along unnecessary ballast in their daily operations.
The characteristic of category infrastructure deviates in this thesis compared to the definition of IATA, because the ground infrastructure like airports are neglected. For that, the focus in chapter 4 is set on possible measurements from the view of air traffic management like navigation or traffic flow management.
Finally, market-based measures and political interventions or policies are represented in chapter 5, which should be compatible with the so-called ESG factors (environmental, social and governance). Topics like offsetting emissions (CORSIA), personal compensation are considered globally in contrast to political aspects where the main focus is on Switzerland.

A further aspect, which is neglected for the most parts due to a long-term view, is the influence of the current status with the pandemic COVID-19. But it is trivial that with the restrictions of all governments the global travel behaviour has been reduced. Especially the aviation business has been hit hard due to its vulnerability and missing resilience to crisis (Gössling, 2020). As a result, the CO_2 emissions in the aviation sector decreased by 60 % or an average of 1.7 Mt CO_2 per day however it has had only an impact of about 10 % on the decline of global emissions. In former crisis namely financial or pandemic, the decrease of emissions has been temporary whereas after the crisis the development of emissions recovered to the pre-crisis level (Le Quéré et al., 2020).

Besides the literature research to collect information about CO_2 emissions in various aviation sectors, personal conversations with experts from different stakeholders like Aerospace Project Development Group, Bauhaus Luftfahrt, Climeworks, Lufthansa Group, Skyguide, Swiss and Synhelion are held. In addition, a non-representative survey (n = 237, filled out completely) about market-based measures and possible influence of the pandemic to the travel behaviour is conducted.
The goal of this thesis is to merge and evaluate the fragmented solution approaches of stakeholders for reduction measures into a clearly structured overview. Different options and challenges are discussed, and the reduction measures are evaluated as objectively as possible with the criteria potential and necessary duration to realisation for market lunch. The solutions for

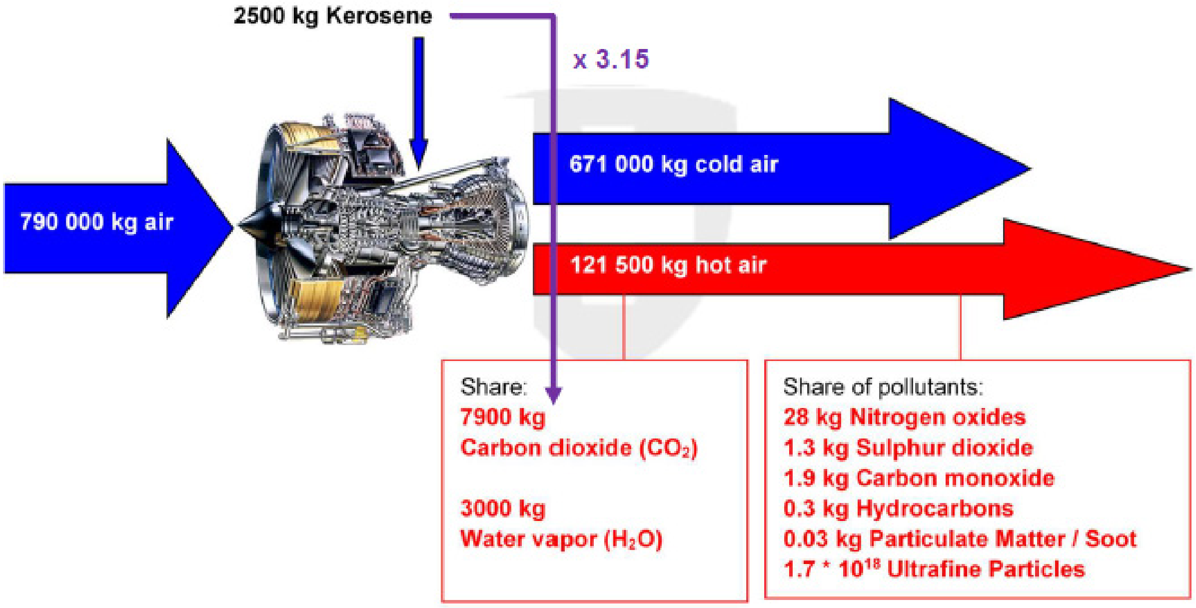
sustainable aviation must on one hand reduce the CO_2 emissions and on the other hand be technically feasible, safe, able to certificate, passenger accepted and possess a positive cost benefit ratio.

2 Technology

A clear and easy approach to understand how technology affects the emissions of an aircraft, the interaction between the four forces of flight should be kept in mind. These are on one hand thrust in flight direction and drag against the flight direction, on the other hand, perpendicular and upwards to the flight direction acts the lift whereas the weight has a downward effect. For example, if the aerodynamics of an aircraft is improved, it produces less drag and as a result less thrust is necessary which leads to less CO_2 emissions. Simply stated, thrust and lift shall be increased and on the contrary drag and weight shall be decreased. Also experiments implemented in general aviation with small aircrafts and mostly with propeller propulsion are not transferable to bigger commercial aircrafts due to scale effects.

The place of action which causes emissions are the jet engines. How much emissions a twin-engine aircraft produces during one flight hour in cruise is shown in Figure 3. It is also evident that apart from CO_2, other greenhouse gases and pollutants are emitted.

Figure 3 Emissions of a typical passenger aircraft during one hour in cruise



Source: Rindlisbacher (2020)

Twin-engine aircrafts are due to safety reasons generally "overpowered", because the aircraft should be able to take off even if one engine fails after the decision speed. Thus, four-engine aircrafts own smaller jet engines because they have still enough power with three engines to continue the climb (Weibel, 2020).

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

2.1 Efficiency of current aircraft models

The main objective function in aircraft design already is to decrease fuel consumption with economically appropriate technologies. According to Clean Sky (2020), the lifetime of an airline aircraft is between 15 and 20 years. Therefore, a fleet renewal is required from time to time, where the most fuel-efficient aircraft is chosen for their needs. Table 2 shows some examples of fleet renewals with the replaced and the successor aircraft model in the last years. The efficiency improvement shows the efficiency of the entire aircraft system. That means the updates consist of aerodynamic improvements like winglets and more efficient jet engines. An aircraft also deteriorates with the time and causes a fuel bias of 1 % per 6'000 hours (Wild, 2018). Important to know is that the aircraft itself and engine are manufactured by separate companies. But through close collaboration, a compatibility between aircraft and engine is produced.

Table 2 Efficiency improvement with fleet renewal for typical short-haul aircrafts

Aircraft Model	Successor model	Efficiency improvement [%]
Airbus 319	Airbus 319 neo	20[1]
Airbus 319	Airbus 220 (C-Series)	20[2]
Airbus 320	Airbus 320 neo	up to 20[3]
Boeing 737	Boeing 737 Max	14[4]
Embraer 190-E1	Embraer 190-E2	17.3[5]

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[1] https://www.airbus.com/aircraft/passenger-aircraft/a320-family/a319neo.html

[2] Successor model of Swiss Airlines, according to Weibel (2020)

[3] https://www.swiss.com/ch/DE/fliegen/flotte/airbus-kurzstrecke#t-page=pane2

[4] https://www.boeing.com/commercial/737max/by-design/#/cultivate-sustainability

[5] https://embraer.com/global/en/news?slug=7130-e190-e2-flight-test-results-confirm-e2-as-most-efficient-single-aisle-jet

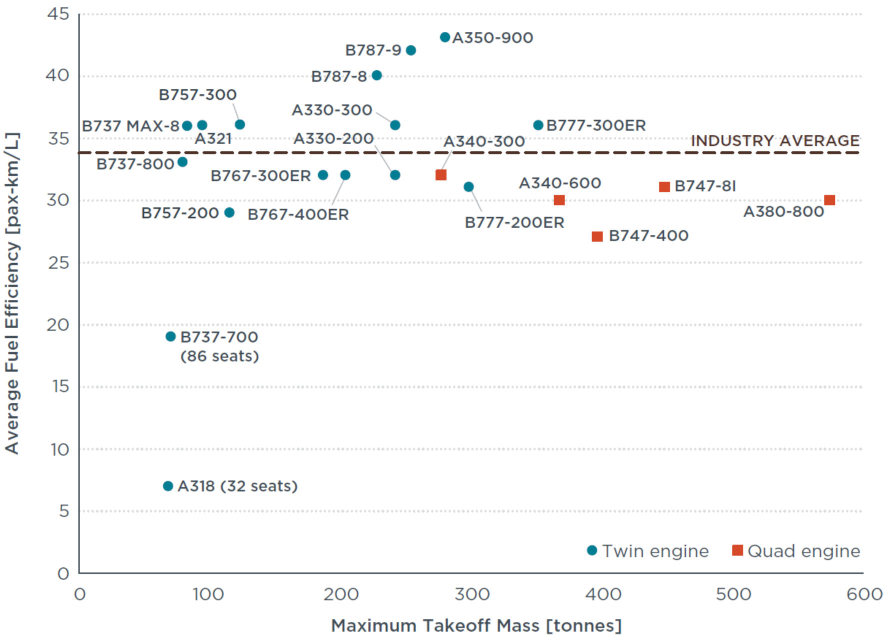
The efficiency improvements are ranged between 14 % and 20 %, which are in concordance with BAZL (2015) and IATA (2020b). A detailed list of current efficiency improvements for long-haul aircrafts (wide-bodies) is available in IATA (2020b).

As a rule of thumb, the engine improvements are increasing each year by 1 % (Wild, 2020a). Considering the lifetime of an aircraft, the latest steps of this technology generation led to around 20 % more efficiency (Weibel, 2020). One of the most important new developments in engine technologies of the last decade is the geared turbofan. While in a conventional turbofan the fan and the low-pressure shaft are directly connected together, in the geared turbofan there is a gear between. Thereby both components could rotate at their different optimal speed which leads to a higher degree of efficiency. This technology step alone reduces the fuel consumption by 35 % comparing to the conventional turbofan from 2000 (Sieber, 2020).

On traditional aircrafts, the on-board electrical and pneumatic systems are not fed with electricity from a battery, but from generators driven by the engines. To power aircraft systems like the hydraulics, the pneumatic system bleeds air off the engines. Hence, not the full power of an engine can be used as thrust. A way to remove this air loss is to replace it with an electric system, why this technology is called "no-bleed" system. This leads to more efficient power generation and due to weight savings to better fuel efficiency and less drag (Boeing, 2020).

An observable trend for long-haul, wide body aircrafts is that airlines no longer purchase four-engine aircrafts like the A380 from Airbus or the Boeing 747. One reason is that the high passenger capacity is not exploited, which turns for instance the A380 from one of the most fuel-efficient aircrafts to one of the worst (Rutherford, 2018), like in Figure 4 illustrated.

Figure 4 Fuel efficiency of aircraft types used on transatlantic routes 2017



Source: Graver and Rutherford (2018)

According to the transatlantic route analysis from Graver and Rutherford (2018), twin-engine wide body aircrafts are more fuel efficient. For example, the A350-900 has an average fuel efficiency of 43 passenger kilometres per liter. In contrary the A380-800 with 30 passenger kilometres per liter which is 40 % less efficient in this case. Generally, all quad-engine aircrafts that are used in transatlantic flights, have an average fuel efficiency under the industry average of 35 passenger kilometres per liter. The special cases or outliers B737-700 and A318 should not be taken into account for the discussion on fuel efficiency because these are not regularly flown by an airline operator.

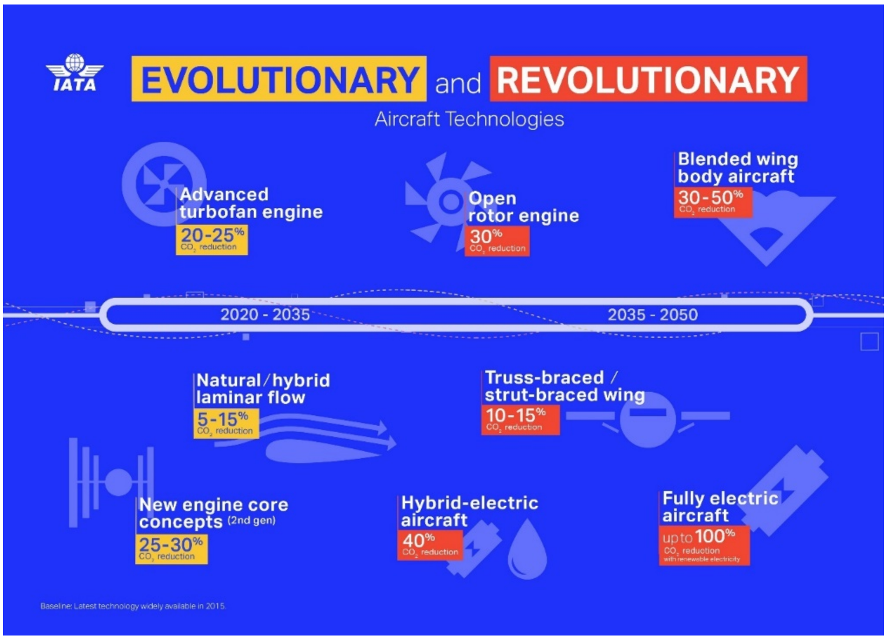
Another reason why twin-engine aircrafts are gaining popularity for long-haul transoceanic flights are the higher ETOPS ranges due to the higher safety standard. ETOPS is a certification that allows twin-engine aircrafts to fly routes where an alternate airport for emergency cases is further away than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

2.2 Future aircraft aerodynamics and propulsion design

This chapter of future aircraft aerodynamics and propulsion design summarizes the IATA Aircraft Technology Roadmap to 2050 (IATA. 2020b). The hydrogen technology in propulsion design, which is currently the most promising long-term technology, is presented separately in chapter 2.3.

To breakdown the technology improvements for the next decades, it makes sense to split them into the categories evolutionary and revolutionary aircraft technologies, as illustrated in Figure 5. Evolutionary technologies are those which can be adapted on classical tube and wing aircrafts with jet-fuel engines including the advanced turbofan engine, natural/hybrid laminar flow and new engine core concepts. The CO_2 emission savings with evolutionary upgrades can be estimated up to 30 % until 2035. In contrary, revolutionary technologies are using 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 reached with blended wing body aircrafts or strut-braced wings.

Figure 5 Overview of evolutionary & revolutionary aircraft technologies



Source: IATA (2020c)

The goal of natural laminar flow is to reduce the drag of a wing. Laminar flow describes how turbulent the air passes over the wings. If a lot of turbulence is generated, less laminar flow is produced and consequently more drag occurs (Cummins, 2020). Therefore, Airbus built a test demonstrator aircraft under the program BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe) to investigate this effect in respect to fuel efficiency (BLADE, 2017). The new design results in 50 % less friction drag and overall aircraft drag reduction by 8 % (Cummins, 2020), as well as the fuel efficiency improvement for the test flight being at 4.6 % (IATA 2020c).

The improvements in the 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 between 5:1 and 6:1 (IATA, 2020c). With the newer engine generation like the "GE9X" on the Boeing 777X, a BPR of 10:1 together with a fuel consumption reduction of 10 % is possible (MTU, 2020). Also, the engine "Advance" from Rolls-Royce allows a higher BPR of 11:1 and thus results in an improvement of fuel burn of 20 % and correspondingly less emissions. The "UltraFan" engine is based on the Advance engine and will have a BPR of 15:1 with an even higher fuel burn improvement of 25 % (Rolls-Royce, 2020).

A further breakdown and listing of less efficient evolutionary technology is available in Table 7 of Appendix 9.1

A not so well-known potential way to increase fuel efficiency is to use Fuel Matrix, which is demonstrated in a small-scale experiment in KingTech (2020). With the addition of Fuel Matrix in kerosene, the dispersion and intermolecular forces are changed. Consequently, the mixed fuel is able to dissolve higher oxygen concentrations, which in turn improves the combustion process. Already a dosage ratio of 1:10’000 with Fuel Matrix allows a 12.8 % higher fuel economy. But the feasibility in practice has to be verified.

The blended wing body aircraft represents a completely different approach to aircraft design. This type of aircraft is actually a large wing, where the passenger cabin and cargo load are positioned in the middle section. Due to the form of the aircraft, the fuselage and wings are just one element, making the whole aircraft generate lift. Thus, the fuel efficiency improvements are forecasted at around 27 – 50 %. Further benefits are shorter turnaround times, less noise and larger available cargo volume. In contrast, big challenges are that the infrastructure needs changes, high uncertainties in the design process and high investments (IATA, 2020c). In addition, the passenger acceptance is questionable and how the aircraft should be evacuated is not clarified (Immer, 2020).

In the strut-braced aircraft design, an additional strut connects the fuselage with the wing. The support with the strut enables to design the wing slender (IATA, 2020c). Therefore, the aerodynamic efficiency measuring aspect ratio, which specifies the ratio between wingspan and mean width of the wing, is higher (Immer, 2020) and consequently less thrust is needed. A configuration with advanced turbo-fan engine could have up to 29 % better fuel burn rates. (IATA, 2020c)

The open rotor engine is a mix of propeller and a turbofan engine with two counter-rotating fans. The fans are not surrounded with a housing. The reduction of fuel burn could be around 30 %. Downsides to the open rotor technology are the higher noise level, lower cruise speed, and higher cabin noise, why the research is not further pushed (IATA, 2020c)

Electric propulsion with an efficiency degree of 95 % (Rindlisbacher, 2020) offers, no matter if the energy comes from batteries (fully electric aircraft) or from a gas engine (hybrid-electric aircraft), new degrees of design freedom (Moore and Fredericks, 2014) especially in the number of engines, for example aircrafts with more than four engines. Battery-electric propulsion produces no emissions during flight, particularly when the batteries are charged with renewable energy. Although the degree of efficiency for electric propulsion is twice as much as of a gas turbine, the potential of commercialising 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 and thus the turnaround times too. With the high amount of load cycles, the battery lifetime is very limited (Rindlisbacher, 2020).
To conclude, only small aircrafts from the general aviation or urban-mobility concepts (2020 – 2025) up to commuter (until 2030) or regional jets (until 2045) can be operated with pure battery-electric propulsion (Sieber, 2020).
The potential of using electric propulsion in a hybrid-electrical aircraft with a hydrogen fuel cell is described in the next section.

2.3 Hydrogen technology in propulsion design

Already back in 1988, the Soviet Union tested with the aircraft Tupolev Tu-155 a propulsion system with hydrogen and natural gas. The classical tube-wing-aircraft with three engines and the hydrogen tanks located in the rear, took off to around 100 test flights, although the engines were tested only during 5 flights with pure hydrogen. The research program was not continued with the collapse of the Soviet Union (Stoffels, 2020).

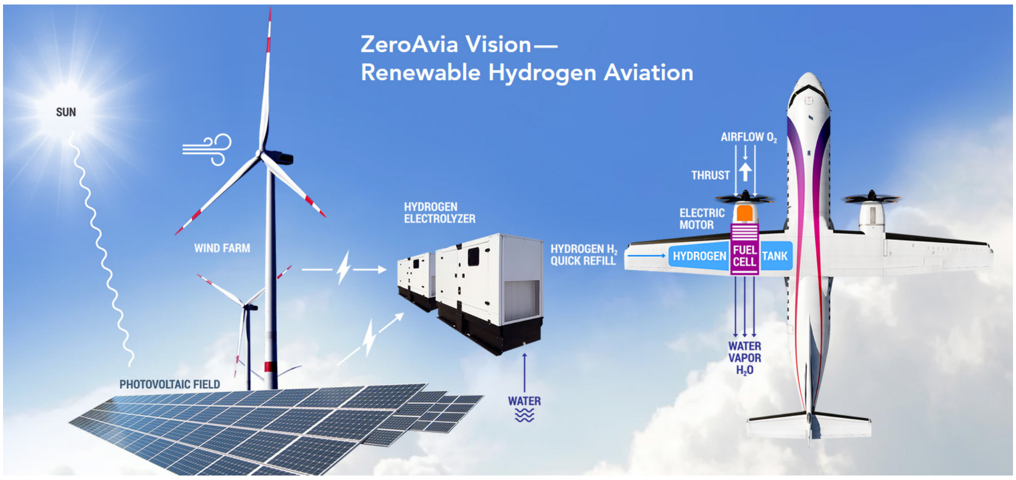
The combustion of hydrogen is a carbon-free process that emits mainly water vapor. Hydrogen as a propulsion method can be used as a fuel for aircrafts when it is combusted directly in a hydrogen burning engine like in a conventional jet engine or reacts in a fuel cell powering electric motor (Clean Sky, 2020). The liquid hydrogen energy density per mass is with 33.3 kWh/kg around three times higher than kerosene but the volumetric density is with 2.3 kWh/l four times smaller (IPCC, 2020). In order to decrease the volume of gaseous hydrogen to liquid hydrogen, a lot of energy is needed to cool down the liquid hydrogen to -253° Celsius. Nevertheless, large tanks, which should be safe, are needed on board of an aircraft which significantly increases the operating weight (Clean Sky, 2020). This plays a particularly important role for long-haul flights, because it is assumed that the empty weight of the hydrogen tanks is higher compared to the tanks for kerosene-based systems.

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

In a hydrogen powered aircraft, the fuel cell converts the hydrogen into electric energy which powers an electric motor, as illustrated in Figure 6. The process with the highest potential in the aviation sector are low temperature proton-exchanged membrane fuel cells (PEM fuel cells) (Clean Sky, 2020). The current power density of fuel cells is between 1 – 2 kW/kg (Sieber, 2020), but for an efficient usage in an aircraft, it requires a two to three times higher power density (Clean Sky, 2020).

Figure 6 also shows a possible cycle of a renewable hydrogen aviation. The hydrogen production, where water is split into hydrogen and oxygen, is delivered with energy from a wind farm or a photovoltaic field. The produced hydrogen is then transported to the airport where the aircrafts are fuelled. To produce thrust, the fuel cell converts hydrogen into electricity and drives the electric motor which spins a propeller. As a result, only water vapor is emitted.

Figure 6 Fuel cell with renewable energy



Source: ZeroAvia (2020a)

The industry relies on hydrogen powered aircrafts. For instance, in September 2020 ZeroAvia (2020b) conducted in a Piper M-class the world's first hydrogen fuel cell powered flight containing a full traffic pattern. Furthermore, DLR (2020) is developing a twin-engine Dornier 228 demonstrator with hydrogen fuel cell and electric propeller propulsion. The maiden flight is planned for 2026. Figure 7 represents illustrations from the hydrogen concept of Airbus' "Zero emission" program. On the left side of the figure, three different concepts consisting of a "Turboprop", "Blended-Wing Body" and a "Turbofan" are shown, which are either powered with hybrid turboprop engines or with hybrid turbofan engines. The passenger load and the range are lower for the turboprop aircraft. The tanks for the liquid hydrogen for the classical tube and wing aircrafts are placed behind the rear pressure bulkhead. The storage of liquid hydrogen for the revolutionary design of the "Blended-Wing Body" is located underneath the wings. The turbofan engines are placed in the top rear of the aircraft (AIRBUS, 2020a). On the right side of the figure, the newest publication with six engines ("pods") is illustrated. Besides the number of engines, other differences to the types on the left side are that the "pods" are removable and that the propellers are driven by electric motors. The electricity comes from the hydrogen fuel cells (AIRBUS, 2020b). The ambitious goal of Airbus is to bring the first commercial aircraft with hydrogen propulsion until 2035 onto the market (AIRBUS, 2020a).

Figure 7 Insights of Airbus' hydrogen projects

Source: AIRBUS (2020a) / AIRBUS (2020b)

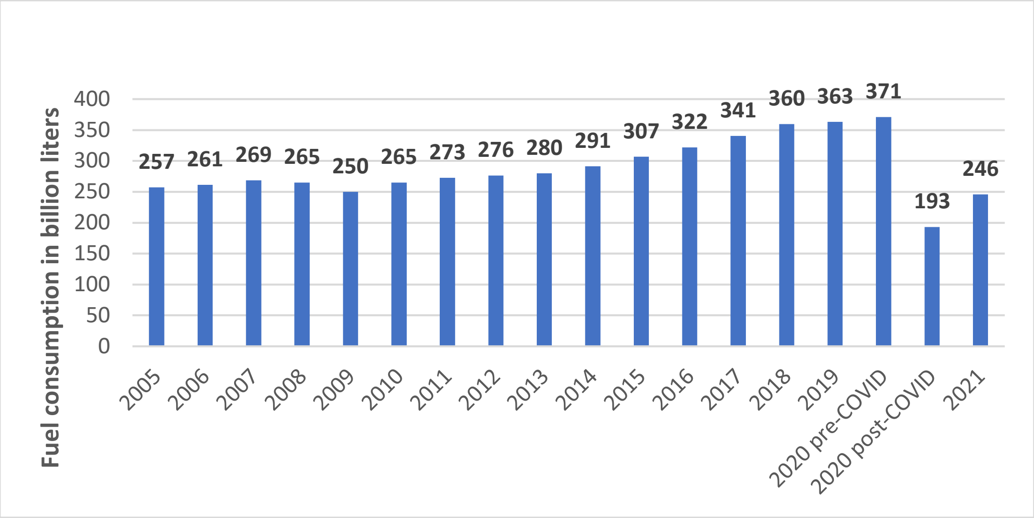
Additional benefits of hydrogen powered aircrafts are that the maintenance activities for electric motors are less frequent and less costly compared to combustion engines. Also the aircraft design from already existing aircrafts could be used (IATA, 2020c). In contrast, the turnaround times on ground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

2.4 Sustainable Aviation Fuels (SAF)

Due to the fact that the implementation of revolutionary technologies requires time for development and therefore a carbon neutral growth is not yet possible, another solution like SAF needs to step in, which can be implemented more quickly. SAF is the generic term for bio-fuels, alternative fuels and synthetic fuels. Instead of emitting new CO_2 in the atmosphere with fossil fuel from crude oil, SAFs are a way to close the CO_2 cycle. The CO_2 will be stored in organic materials and with approved production processes, the material is converted into SAF which releases again CO_2 when is burnt. Hence, the lifecycle emission of CO_2 can be reduced up to 80% (IATA, 2020c). SAF can be produced for instances from household waste, used cooking oil or halophytes which are growing in saltwater. If the production of SAF should conflict the food production, destroy forests or consume too much fresh water, the SAF are not any more sustainable but destructive (IATA, 2020d). Using the sun to liquid process from chapter 2.4.1 or power to liquid process from chapter 2.4.2 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, nowadays over 250’000 flights from 40 airlines are conducted with SAF (IATA, 2020d). Considering the total fuel consumption from Figure 8, the fraction of SAF is undoubtedly negligible. But the demand of SAF is rising and is forecasted for 2020 to 43 million liters. As the growth of demand is exponential and the production factories could produce on a bigger scale, the market could be served with 7 billion liters until 2025 (IATA, 2020c) which would be around 2 % of the total fuel consumption in 2019.

Figure 8 Total fuel consumption of commercial airlines worldwide between 2005 and 2021



Source: Mazareanu (2020)

According to ATAG (2020b), the use of SAF is constrained with a blending limit, which is dependent from the production processes like Fischer-Tropsch or Alcohol-to-Jet. That means that the SAF could only be mixed in with the fossil kerosene. The blending limit from the two mentioned production process are the highest with up to 50 %. The blending limit was implemented because in the conventional jet fuel, there are components like sulphur which swells and prevent leaks. The newer engine technology is not affected with this issue and also military aircrafts were tested with an admixture of 100 %. In the near future, a cancellation of the blend limit is expected.

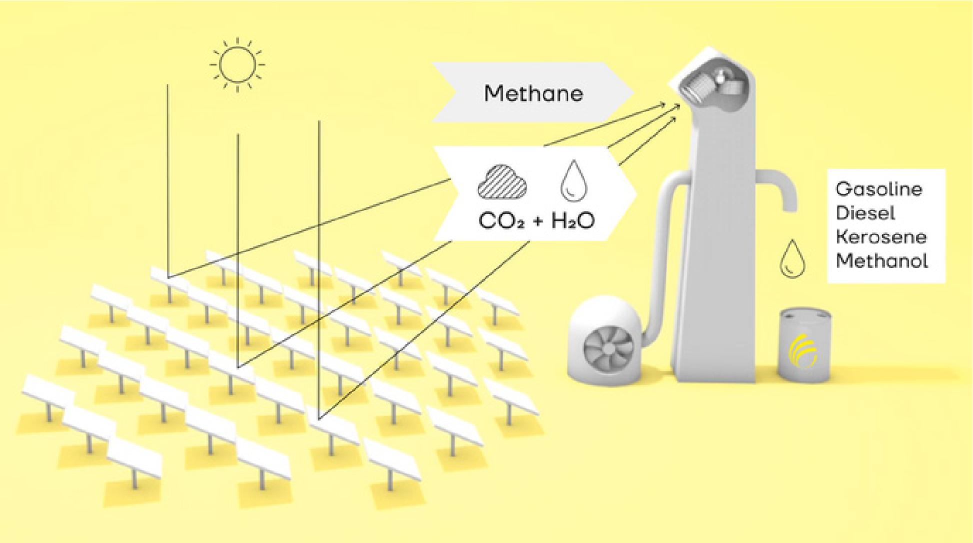
The current major challenge of SAF is that the amount of production is small and the price for a liter of SAF is still too high. For an airline, the main cost factor is today the fuel cost, making up to 40 % of the budget (Wild, 2020b). With the current price of SAF, which is between three times (Compensaid,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

The benefits of SAF are besides low CO_2 emissions that the aircraft design needs no adaptions, the existing infrastructure can be used and the turnaround times for an aircraft stays the same as before (Clean Sky, 2020).

2.4.1 Sustainable solar fuels (Sun to liquid)

Like in Figure 9 illustrated, a possible production process for solar fuels is, that with solar collector the energy of the sun is collected and directed to the head of a solar tower. In this tower head the actual transformation process happens. First, in the solar receiver the ambient air acts a heat transfer fluid and is heated up to 1’500° Celsius with the collected solar radiation. In a second step the heat transfer fluid transforms within a thermochemical reactor to syngas which can be further used for the production of kerosene (Romero and Steinfeld, 2012).

Figure 9 Scheme for solar fuels production



Source: Synhelion (2020)

For an efficient and commercial production of solar fuels, regions with high solar irradiation are favoured. A possible scale-up location in Europe could be South of Spain, where for instance Synhelion (Murer, 2020) could build up until 2025 a capacity of 1500 t/year with a field size of 8000 m^2. With the installation of bigger stations, a ramp-up to a capacity of 1 Mt/year and a fuel price of 1 Euro/l Kerosene until 2030 is targeted. Until 2040 the capacity could reach 40 Mt/year and a fuel price of 0.5 - 1 Euro/l kerosene is possible, which made up about 14% of the fuel consumption in 2019 (Mazareanu, 2020).

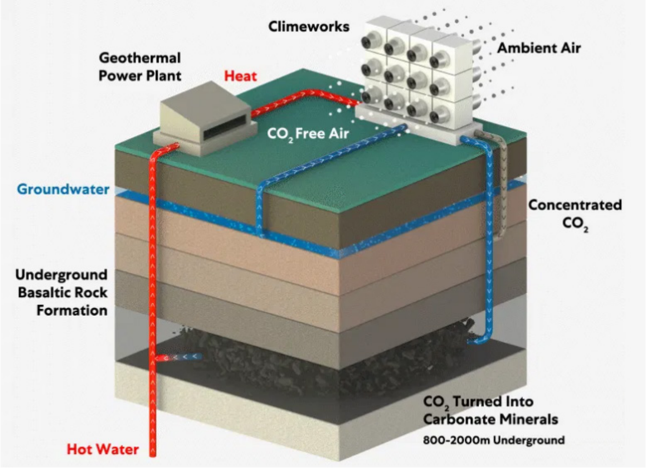
A faster way to step in the market of synfuels until 2023 is to add external methane from biomass or natural gas to the chemical reaction together with CO_2 and water, because this process is based on industrial reforming technology and needs a lower heat of 800 – 1'200 °C. As a consequence, this synfuel would be competitive with fossil fuels and the savings of net CO_2 emission would be up to 50 % if natural gas is used, and up to 80 % if biogas is used. An even faster development is not possible as the construction of customised prototypes to build the first industrial-scale fuel plant takes time (Murer, 2020).

2.4.2 Removal / Direct air capture (Power to liquid)

According to Rogelj et al. (2018), just the reduction of CO_2 emission is not enough to reach the objectives of the Paris Agreement. Therefore, a removal of about 8 billion tons of CO_2 is necessary in 2020. The amount of CO_2 which needs to be removed, is increasing in the next years to 10 – 15 billion tons (Egger, 2020).

A possible way to remove CO_2 from the air is schematic shown in Figure 10. In this process, the ambient air which contains CO_2, streams in the collectors where the CO_2 is chemically bound to the filter. The output from the collector is nearly CO_2 free air. In a second step, when the filter is saturated with CO_2, the filter is heated up to 100° Celsius while the CO_2 is released and pumped out. The concentrated CO_2 is then collected in a tank and can be further either stored in the underground (DACS, 2020) or be reused for example to produce synthetic fuels with external hydrogen and renewable energy in a power to liquid process (Rindlisbacher, 2020).

Figure 10 Scheme for a direct air capture process



Source: Climeworks (2020)

Together with sustainable energy as a main energy source, the modular CO_2 collectors are able to capture air and remove CO_2 with an efficiency of around 90% (Climeworks, 2020).
The costs for capturing one ton of CO_2 are currently around 600 – 800 USD (Egger, 2020). With a possible scale-up roadmap for Climeworks, which is illustrated in Table 3, the costs of removing CO_2 should decrease to 100 USD per ton after 2030 (Egger, 2020).

Table 3 Capacity trend

	2017	2021	approx. 2023	approx. 2025
Capacity [kt/year]	1	4	>50	>500

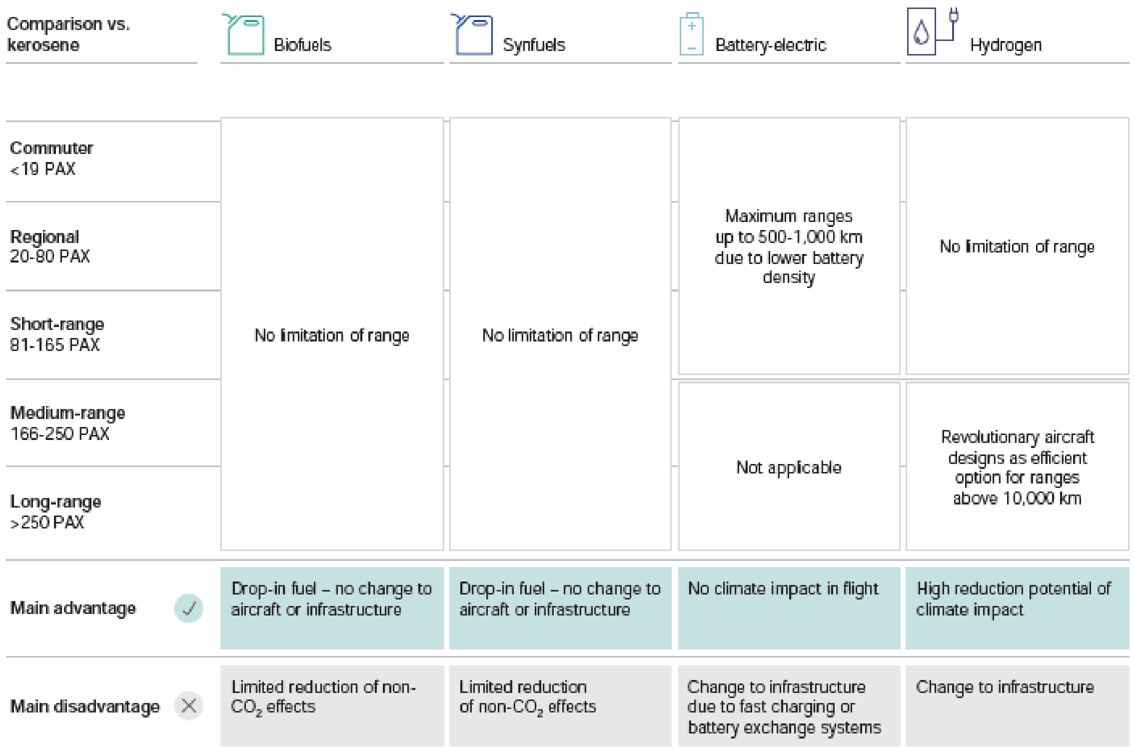
Source: DACS (2020)

It is expected that with optimising processes and further gain of experiences, the industrial learning curve with doubling the production volume and a cost reduction of 20 % - 30 % can be applied.

2.5 Comparison of new technologies with SAF

As every technology has its particular benefits, challenges and optimal operation ranges, it is worth to compare the technologies regarding these aspects. One technology alone is not able to decarbonise the whole aviation sector. An overview for comparing SAF like bio-fuels, synthetic fuels and revolutionary propulsion technology is represented in Figure 11. Bio-fuels, synthetic fuels and hydrogen propulsion have no limitation in range whereas battery-electric aircrafts are limited to a range of approx. 1’000 km due to the low energy density in the batteries. The hydrogen propulsion is strongly dependant on revolutionary technology. The main advantage of sustainable fuels is that it does not require to replace the aircraft or infrastructure but after combustion CO_2 is still emitted. On the contrary, battery-electric and hydrogen propulsion have at least a high reduction potential of climate impact but require a change in infrastructure. The production of hydrogen needs less energy than the production of SAF, even if both are produced with renewable energy (Clean Sky, 2020). Thereby, the chicken-egg problem exists. A reliable cost comparison is dependant from the chosen scenario and advantage the preferred technology and disadvantage the other technology. Therefore, it is omitted in this thesis.

Figure 11 Comparison of new technology and sustainable aviation fuels



Comparison vs. kerosene	Biofuels	Synfuels	Battery-electric	Hydrogen
Commuter <19 PAX	No limitation of range	No limitation of range	Maximum ranges up to 500-1,000 km due to lower battery density	No limitation of range
Regional 20-80 PAX				
Short-range 81-165 PAX				
Medium-range 166-250 PAX			Not applicable	Revolutionary aircraft designs as efficient option for ranges above 10,000 km
Long-range >250 PAX				
Main advantage ✓	Drop-in fuel – no change to aircraft or infrastructure	Drop-in fuel – no change to aircraft or infrastructure	No climate impact in flight	High reduction potential of climate impact
Main disadvantage ×	Limited reduction of non-CO_2 effects	Limited reduction of non-CO_2 effects	Change to infrastructure due to fast charging or battery exchange systems	Change to infrastructure

Source: Clean Sky (2020)

As previously seen, the hydrogen technology is more promising to succeed over the battery-electric aircraft due to less limitations in range. The participation of revolutionary technology in regards of 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 are a suitable bridging solution to already allow a carbon neutral growth.

3 Operations

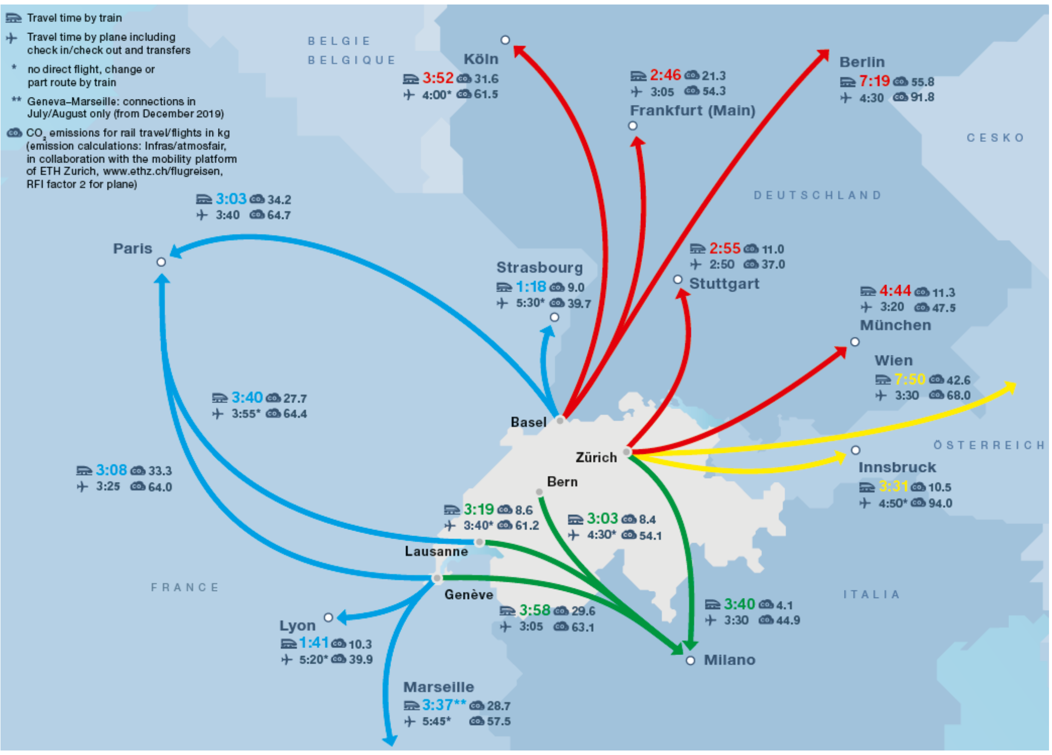
Operations reduction measures are feasible with the current stand in technology. Operators or users like airlines are able to optimize their process and procedures regarding CO_2 emissions in their daily business operations.

3.1 Intermodal traffic / mode shift

An acceptable CO_2 reduction measure is to change the mode of transport for domestic travels or travels in adjacent countries to a more ecological transport mode, for instance train travels replacing short-haul flights. Figure 12 shows an overview, where a plane/train comparison with the parameter travel time and CO_2 emission are made. In the figure, travels from Swiss cities to cities in the nearby regions abroad are illustrated. It is evident that travels by train produce at least two times less CO_2 than by an aircraft. If the train is operating with electricity from renewable energy options, the effect of mode shift is even higher. Also, the travel times are comparable except to further away capital cities like Berlin and Vienna, where currently no high-speed trains are operating. The price component is not shown in this figure, but it is a relevant decision factor for passengers.

The airlines SWISS and Lufthansa are already offering programs like airtrain (SWISS, 2020) or Rail&Fly (Lufthansa, 2020). The idea is to reduce domestic travels by an aircraft. The passenger is either able to use it from Basel SBB or Lugano to Zurich Airport or as a complement to the existing flight connections between Geneva and Zurich. The train ticket is included in the flight ticket (SWISS, 2020). Lufthansa is offering a travel from or to their international flights from all train stations in Germany with a flat surcharge (Lufthansa, 2020).

Figure 12 Plane/Train comparison with travel time and CO_2 emissions



Source: ETHZ (2020)

3.2 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 up to 20 – 25 % of extra fuel (Wild, 2018). In Table 4, there are different weight reduction measures listed with the savings per aircraft if not further specified. Considering only one single measure, the savings are not immense. But remembering that an aircraft flies several times a day, a big scale effect occurs.

Table 4 Weight reduction measures

Measure	Savings [kg]
New trolley materials and design; per trolley	9 – 12
Thinner, carbon-fibre seats; per seat	4 – 5
Economy/Business class divider	> 20
Cleaned carpets, holds and interior	10 – 50
Newer external paintings	100 – 200
Not often used cabin materials like wheelchairs, camping chairs, baby cradles	25
Excess customer service items like books, magazines, headsets	20 – 160
Excess catering supplies (25 % were unused) on narrow body / widebody aircraft	365 / 970
Limited duty-free sales (online pre-ordering) on short / long-haul	48 / 60
Potable water (not at full capacity if it is unnecessary)	50 – 650
Zonal dryer (moisture between insulation blankets near the skin)	250 – 2000
Excessive movable first-aid oxygen bottles	6 – 60
Single chamber life vests	9 – 21
Electronic libraries for crew (already mostly implemented)	4
Uniform cargo load devices	Up to 240
Overfueling due natural safety tendency from pilots / fueller	0 – 200
Replace classical inflight entertainment with installations for passengers "own device" or an airline entertainment app	-
Carbon brakes instead of steel brakes	250
Composite parts (carbon- and glass-fibre)	Up to 20 %

Source: Wild (2018)

3.3 Flight planning and fuel calculation / aircraft procedures

The flight planning should be optimised by the aircraft operator with respect to the optimal flight route, altitude, speed and payload. The goal of an optimised flight profile is to reach the cruise altitude fast and leave this altitude as late as possible for the approach (Immer, 2020). With the use of the optimal operating point according to the ratio of payload and range, an aircraft could be operated more efficient. For example, an Airbus A320 is used for too short

short-haul flights (Immer, 2020). But it is obvious, that an operator uses an aircraft which is already available in his versatile fleet. As mentioned in chapter 2.1, airlines invest from time to time in new, more efficient aircrafts. The current pandemic situation postpones the high investments. But the situation acts a "catalyst for prioritisation" (Weibel, 2020), because due to the smaller number of flights, only the most efficient aircrafts in the fleet are used. Also taking out inefficient aircrafts earlier out of service is conceivable (Weibel, 2020).

Reliable planning should contain statistical evaluation tools, flight level optimisation, precise weights, precise performance data for each aircraft, integrated track optimisation and cost index optimisations. This leads to savings between 1 – 2 % (Wild, 2018). The guideline for general improvements is cost effective but at least on the same safety level as the previous technology (Weibel, 2020). The cost index optimisations should also consider the emission footprint. From an ecological perspective, a route planning like illustrated in Figure 13 should be avoided. It shows a flight from Warsaw (Poland) to Rome (Italy) where it is cheaper for an operator to fly a detour (red line) with burning 115 kg more fuel than the shorter fuel optimised routing (green line) with higher route charge of 109 Euros (EUROCONTROL, 2020a).

Figure 13 Comparison of flight routes from Warsaw to Rome

Source: EUROCONTROL (2020a)

For inflight communications, pilots are using, besides the normal radio communication, ACARS as well for data exchange with air traffic control, aeronautical operational control or airline administrative control (airline dispatch or maintenance). This ACARS system originated in 1978, but the data volume is limited even though it has developed further (Skybrary, 2020). In contrast, passengers in the back are able to use Wi-Fi for communications. With the usage of Wi-Fi, the cockpits members are able to look further ahead during the flight. Further benefits are for example, that they have live information about the traffic situation and could adapt their speed instead of holding in the air in the vicinity of their arrival airport. Also current weather forecasts could be faster transmitted en-route to avoid turbulences or dangerous weather conditions and the crew is overall more flexible to make inflight route changes.

What also applies for the fuel calculation is, that with every additional ton of fuel on board, additional fuel is needed. The fuel policy boundaries are given by EASA. The main improvements in fuel calculation could be done 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 95th quantile of extra fuel amount of all flights to a destination within one year is considered (Wild, 2018). But it is not so easy to conduct such a statistical evaluation due to data protection regulations concerning cockpit members (Weibel, 2020). With a new regulation regarding contingency fuel, a fuel reduction 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. Due to less weight on board from the passenger and baggage, less fuel is necessary. This improvement has a bigger impact on long-haul flights than on short-haul (Wild, 2018)

If the engines of an aircraft are not running, the APU powers the aircraft with external power. Although today's APU is further developed and more efficient (Wild, 2018), the usage of Diesel GPU or fixed energy systems produces less CO_2 emissions by a factor of 17 (GPU) or 480 (fixed energy system) (Fleuti and Ruf, 2018). Using the GPU as a procedure requires the necessary infrastructure and reduces besides the emission also the maintenance cost of the APU (Weibel, 2020).

By using the procedure of reduced engine taxiing or single engine taxiing, fuel savings of 40 – 100 kg per aircraft are possible. The taxiing after landing is less problematic than before take-off due to the required warm-up time. In inappropriate situations like winter operations or runway crossings, this procedure should be renounced (Wild, 2018).

During the procedure of take-off, the bleed configuration is set to "pack off" and not to "APU only". This leads to savings of 2 – 10 kg of fuel during each take off. With the adapted configuration of flaps to the runway lengths, weights, etc., fuel savings in the 1 – 50 kg are possible dependent of aircraft and selected configuration. Together with a derated or FLEX (flexible temperature) thrust setting according to the conditions, the savings are even higher (Wild, 2018). An early retraction of gear and flaps are also reducing the CO_2 emissions (Immer, 2020), but the noise abatement procedures of the departure airport have to be still considered. Airport authorities publish in certain cases different noise abatement procedures, which lead to different emissions. But some airlines are using their fixed procedure for all airports. If changing to a more flexible procedure, saving about 30 – 180 kg for each take-off is possible.

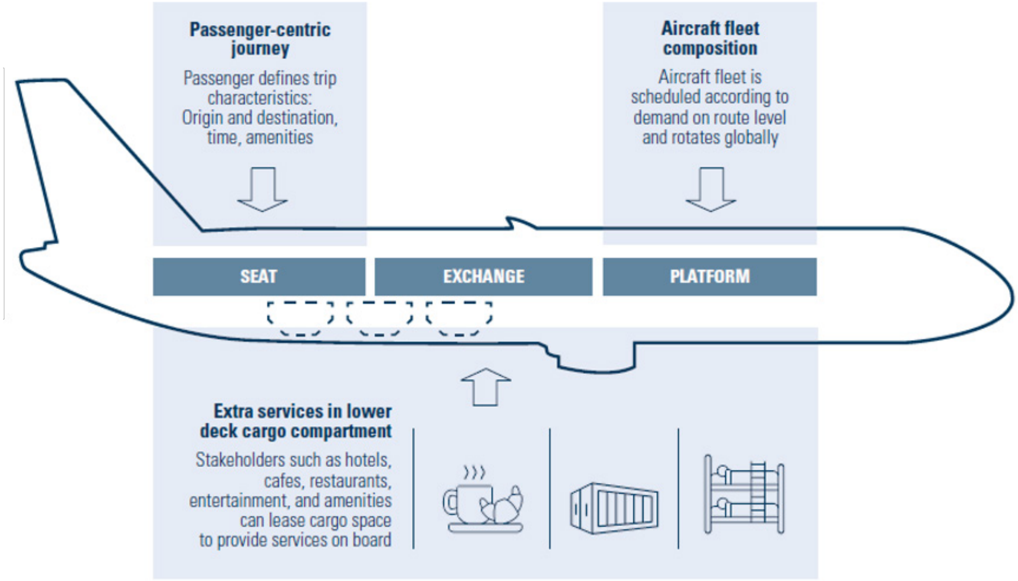
A late flaps and gear extension in the approach is reducing the CO_2 emissions (Immer, 2020). A more ecological procedure in the braking phase on the runway is to use idle reverse thrust (IATA, 2020e) instead of full reverse, if the boundary conditions allow it.

3.4 Different operational model for long-haul flights

A new futuristic operational model to reduce emissions for long-haul flights is proposed by Bauhaus (2019). It is called "ShAirline" and contains an open "Seat Exchange Platform", where single seats are leased by companies from different industries and finally offered to the passenger. Because it is a demand-oriented supply which requires a high seat load factor, the excessive capacities are avoided and more direct routes instead of intermediate stops are possible. With the dropped intermediate stops, the travel speed could be decreased without losing time on the total travel time (Bauhaus, 2019). Figure 14 illustrates additionally, that the passenger can expect extra services, e.g., entertainments, restaurants etc. on board of the aircraft. This would lead to a possible higher productivity from passenger perspective (Kluge, 2020).

The challenges for this different operational model are the passenger acceptance, the contradiction with weight reduction and the question if this concept is more financially rewarding at all than the classical airline concept.

Figure 14 "ShAirline" concept

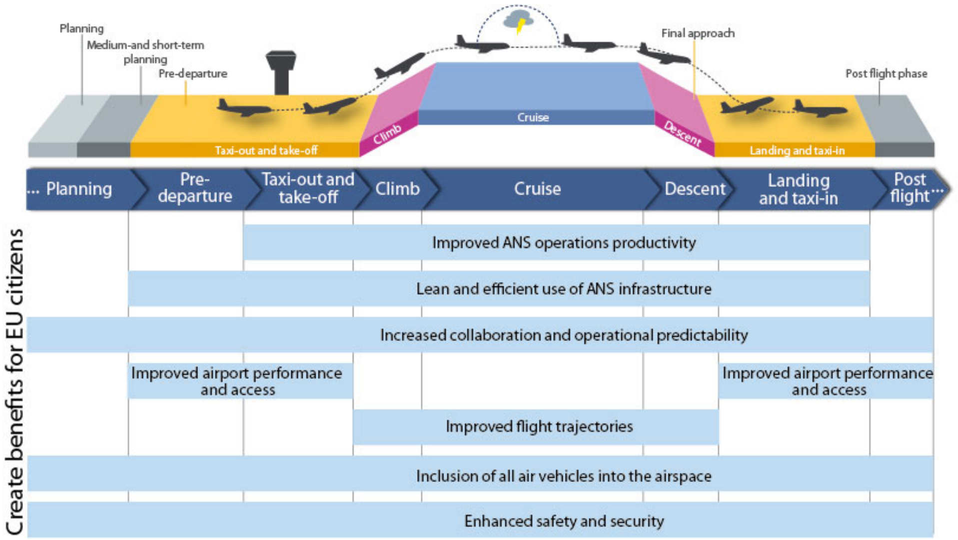


Source: Greune (2019)

4 Infrastructure / ATM

In this chapter about infrastructure measures, only the role of ATM with navigational improvements and more efficient use of airspaces to reduce the total flight times is considered. To modernise the European airspace, especially to reorganize the fragmented airspaces, the EU commission developed together with the European air traffic controller EUROCONTROL an initiative called "Single European Sky ATM research program (SESAR)". The main goal is to merge the large number of airspaces together to reduce at least 10 % of CO_2 emissions (SESAR, 2020a). Thereby, the average fuel reduction per flight is estimated at 250 – 500 kg (SESAR, 2020b). According to Figure 15, improvements on ground also creates benefits for the environmental impact and hence for citizens. With more efficient taxi operations, fuel savings of 38 – 75 kg per flight (relative reduction 30 %) are targeted (SESAR, 2020b).
The equivalent modernisation process for the US airspace is called NextGen (FAA, 2020).

Figure 15 Benefits of SESAR



Source: SESAR (2020a)

Focussing on Switzerland, with the program AVISTRAT-CH a holistic restructuring of the detailed airspace based on a clean sheet approach is planned. The goals are a higher safety, more performance and less environmental impacts (AVISTRAT, 2019). As a model example for the goals of SESAR with defragmenting airspaces, the Swiss air traffic provider Skyguide is about to digitally merge the two area control centres Zurich and Geneva into one "Virtual Centre" (Truffer, 2020). The physical equipment is still at the same locations but the data, applications and air navigation services (ANS) are independent from the geographical locations (Skyguide, 2020a). The COVID-19 situation with less air traffic favoured the implementation (Truffer, 2020).

In the following, some components to reach the CO_2 reduction goal of 10 % are presented. Especially a lean and efficient use of ANS together with increased collaboration and operational predictability with improved flight trajectories is introduced.

The concept of 4D Navigation, which uses the three spatial dimensions and the time dimension, allows to introduce a trajectory of a flight. With overlaying trajectories of different flights, conflicts and holdings could be noticed earlier, respectively could be prevented entirely, so that every aircraft is able to fly their optimal trajectory at the preferred cruise level as long as possible, like illustrated in Figure 16. As a result, the emission is reduced due to the decreased flight time. The challenges are that ANS provider and aircrafts need new technical equipment. Also, the controller must be aware of what impact an influencing factor has to the whole trajectory. This is particularly difficult when the equipment fails and could lead to a work-overload for the controller (Skybrary, 2017).

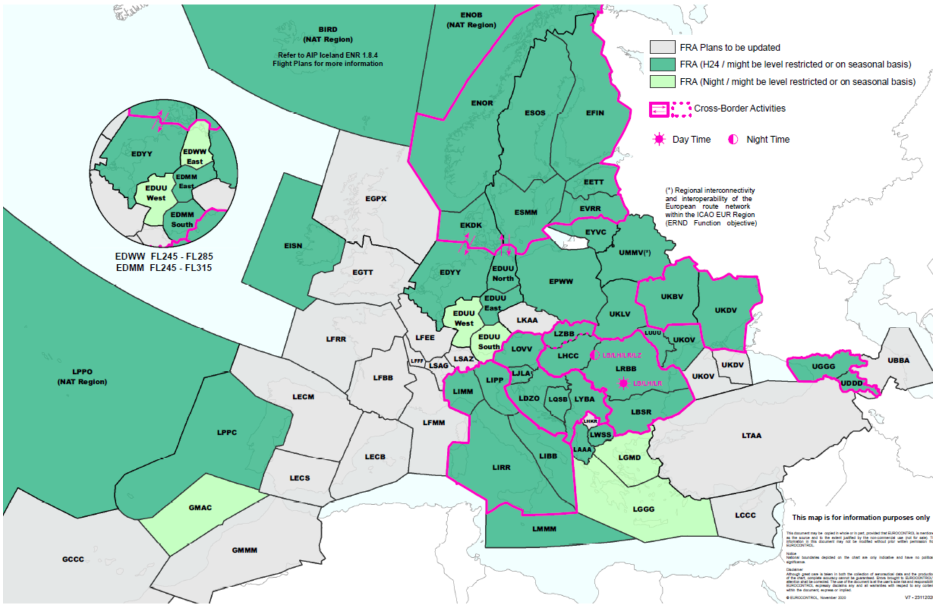
Figure 16 Optimal flight trajectory

Source: NATS (2020)

With an improvement of vertical navigation like 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 of optimised departure and approach operations is up to 1.1 million tonnes of CO_2 per year (Skyguide, 2020b). 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 resulted although in an increased capacity of 14 %, but the aircraft is able to fly more on its optimized altitude which reduces its CO_2 emissions. Therefore, any holdings should conduct on the highest reasonable altitude or even better to reduce the speed to avoid holdings. But in the longest flight phase of cruise, the optimum altitude should be targeted where the lift drag ratio is at maximum for the chosen speed. Consequently, this is a reason for changing the altitude during the cruise because flying lower or higher uses more fuel and hence the aircraft produces more CO_2 emissions (Wild, 2018).

The improvements in the horizontal navigation can be reached with free route airspaces (FRA), which leads 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 the free airspaces, flights are still under air traffic control. The horizontal limits exist regardless of FIR or country borders and the vertical level limit is dependent from the particular FRA (Todorov, 2019).
Figure 17 illustrates the still fragmented European airspaces (FIRs) as well as the current progress of the FRA implementation. The green coloured areas already implemented the concept of FRA by end of 2020. The objective is that all FIRs have implemented the FRA until 2024 (Todorov, 2019). A need to catch up exists especially in parts of France, Spain, Switzerland and in South East Europe.

Figure 17 Free Route Airspace Implementation – Status End 2020



Source: EUROCONTROL (2020b)

The average en-route fuel savings amounts 50 – 100 kg per flight, which represents a relative reduction up to 2.5 % (SESAR, 2020b)

Today’s aircraft navigation still relies on ground-based systems like ILS, VOR, DME or NDB. Especially NDB and VOR, whose accuracy is not anymore state of the art and are expensive to maintain, are taken out of service from time to time. But by using satellite-based navigation (GNSS), improved and more efficient procedures like performance-based navigation (PBN) are possible. In Switzerland from a GNSS navigational perspective, currently only GPS and EGNOS are approved for operational use. This is a specification from FOCA. Skyguide continuously monitors the performance of the system (Truffer, 2020). EGNOS is improving the performance of GNSSs like accuracy and reliability of the position information (GSA 2020a). For example, during the GNSS final approach of a flight, the pilots of an aircraft do not need a visual contact to ground until reaching an altitude of 200 ft above the runway (GSA 2020b). The pure DME navigation is a legally assessed backup for PBN, if GPS/EGNOS is jammed or out of service. In this case, at least two DME stations are needed to receive. The range and accuracy of DME stations are high so that an en-route horizontal separation of 1 NM instead of 5 NM is possible (Truffer, 2020).
The benefits of satellite-based navigation are more efficient air traffic handling, lower fuel consumption leading to less CO_2 emissions and less noise emissions (Skyguide, 2020c).

An early trial to defragment the European airspaces in nine functional airspace blocks has failed. The reasons were that "a ’lack of commitment on the part of the member states’, which want to ‘preserve sovereignty, the legacy of national air navigation service providers’, revenues and workforce" (Tani, 2017). A collaboration between the European countries is with a standardisation of data and radar data technically feasible. Financial and political aspects are a hurdle in this process (Truffer, 2020).

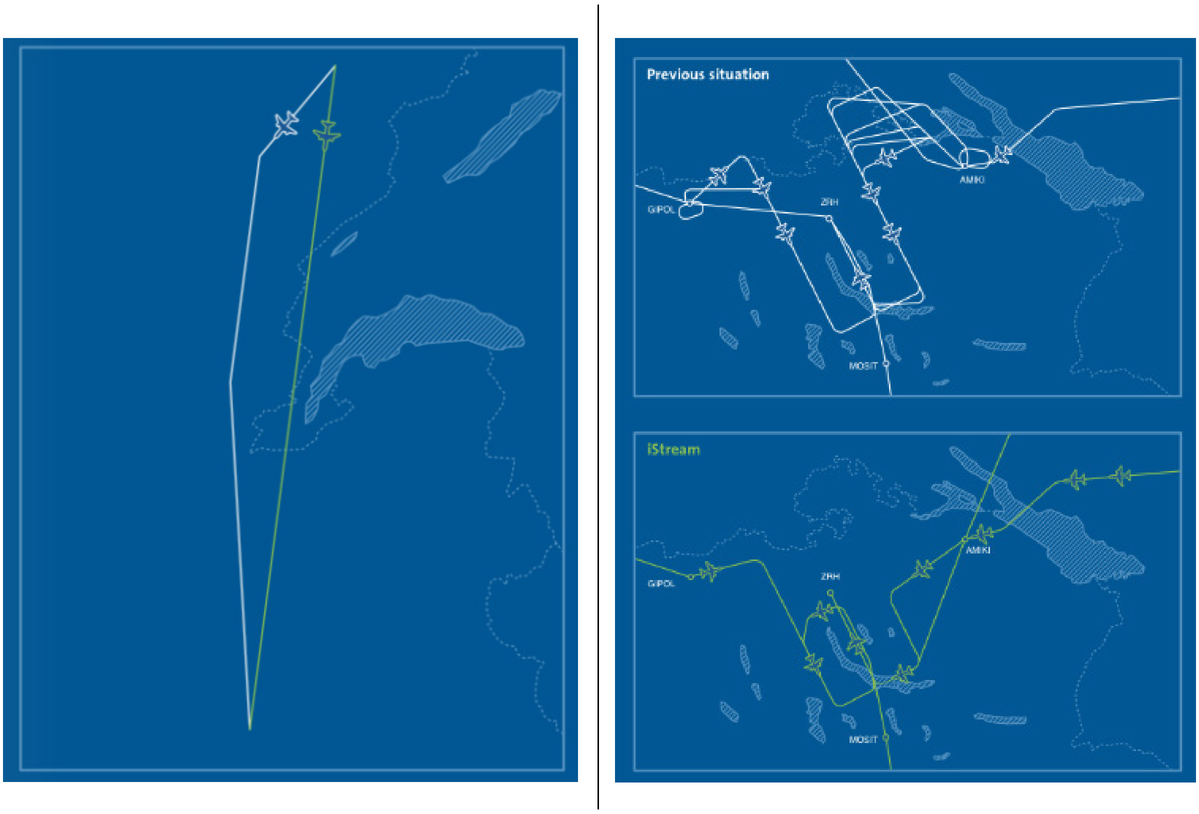
With the future technological development, the work of an air traffic controller shall be converted to the work as an air traffic manager, who is monitoring the working process. This reduces the cognitive workload for the controller and enables safer and more efficient actions, which also results in more economical and ecological actions (Truffer, 2020).
To sum up, a reduction of CO_2 emission is possible with more continuous climb and descent operations, more direct routes, reduction of holdings in the air and better collaboration with neighboured air traffic controllers.

4.1 Applied examples from Swiss airspace

In this section, three specific examples of CO_2 reduction measures from Skyguide as a part of SESAR are illustrated. The savings for each case are small but if similar improvements are made for other airspaces, a big scale effect occurs.

On the left side of Figure 18, there is an example of direct routes. For this case, the route from Pontarlier (Switzerland) to Chambéry (France) is optimised in time and fuel savings. The CO_2 emissions savings are estimated to 1.7 kt/year (Skyguide, 2020b).
In contrast on the right side of Figure 18, the assigning arrival slot mechanism "iStream" for Zurich Airport is shown. In the previous situation, where the inbound long-haul flights approached uncoordinated in the morning right after the airport opened, the aircraft had to wait and hold before it could land. Nowadays, the pilots are updating their time of arrival when reaching the top of climb during flight while sending an ACARS message to the operation centre in Zurich. The employee in Zurich is collecting all updated times, creating an arrival ranking and sends the information with the targeted arrival time back to the pilots. Afterwards the pilots are able to select the speed according to their assigned time. Comparing to the previous situation, a more efficient traffic management with increasing flight efficiency and punctuality is possible (Istream, 2016). With the implementation of "iStream" and the collaboration between SWISS Airlines, Airport Zurich and Skyguide, the holding times are decreased by 90 % and is saving 2.1 kt CO_2 emissions per year (Skyguide, 2020b).

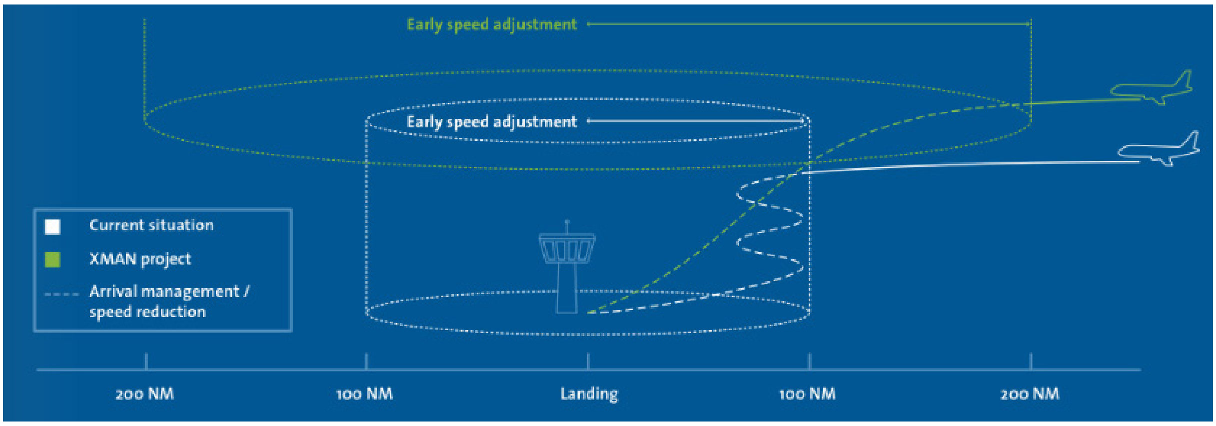
Figure 18	Direct routes / iStream



Source: Skyguide (2020b)

Figure 19 presents an extended arrival management system, which optimises the arrival sequences. With this mechanism, the air traffic controller informs the approaching aircraft, which is still in the neighboured airspace, to reduce the speed for a coordinated arrival. Thereby, the pilots are able to descent later with a continuous descent from high altitude without following a holding pattern. Currently the actions radius is 160 km, which will extend to 360 km by 2023. The CO_2 emission savings are estimated to 33.5 kt/year (Skyguide, 2020b).

Figure 19 Optimised arrival sequences



Source: Skyguide (2020b)

5 Market-based measures / Political aspects

This chapter outlines market-based measures with positive economic measures and their incentives including area-wide compensation systems, flight taxes, using tax revenues for technology support and voluntary private compensation.

Not paying fuel tax or VAT on commercial international flights is a relic of the past. This rule goes back to the foundation of the ICAO (Chicago convention, Article 24) in 1944 (ICAO, 1944) to promote civil aviation as well as because the aviation industry payer their infrastructure mostly by themselves (BDL, 2020a). For example, the mineral oil tax for diesel amounts in Switzerland to 75.9 Swiss cents (EZV, 2020) whereas the resource price for one liter kerosene has been over the last years on average around 52 Swiss cents (Indexmundi, 2020). According to the model of Faber et al. (2019), without these tax exemptions the average ticket price increases 10 % and the passenger demand deceases 11 %. Consequently, besides the emissions decline of 11 %, it causes a negative impact on employment in the aviation sector but the higher fiscal revenue is offsetting this impact. At the end, a negligible effect on employment and GDP (Gross Domestic Product) is observable.

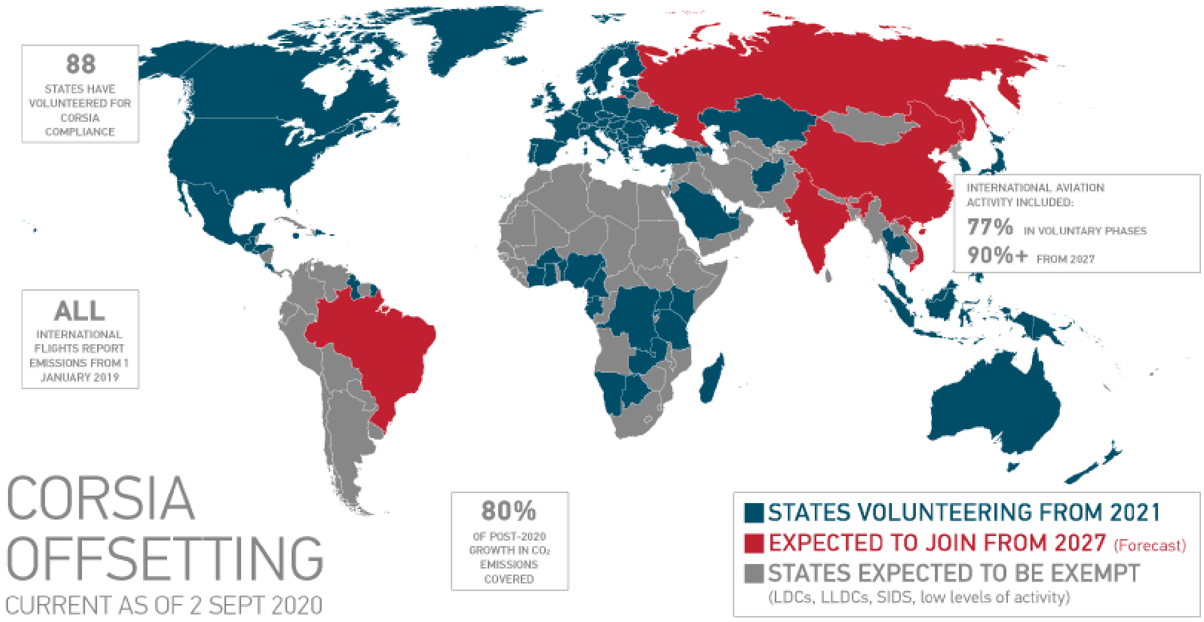
The aviation industry is a global business. Therefore, competition boundaries like political boundaries or public awareness should be treated globally in a similar way for every operator. A fair competition without a distortion is a main motivation for the acceptance of market-based measures (Lee, 2020).

5.1 Area-wide compensation systems (EU ETS / CORSIA)

Area-wide compensation systems are acting under the principle of "The polluter pays". The EU ETS is an emission trading system, which is already active since 2005 as the first major carbon market, and is constrained to Europe. It is still the biggest carbon market and the mechanism is a Cap & Trade system, which concerns companies with high CO_2 emissions and other pollutants like heavy energy-using installations, and since 2012 airlines as well. 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 be then traded with other companies to cover all their emissions. If a company has not enough certificates after each year, a big fine is distributed. The goal is that companies 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 was fluctuating between 5 to 30 Euros per ton CO_2 (Vollebergh and Brink, 2020). To achieve the objective of the Paris Agreement, a price 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, ICAO resolved in 2016 a compensation system called Carbon Offsetting and Reduction Scheme for International Aviation or short CORSIA. Compared to the EU ETS, CORSIA is only focused on the international air transport and it is the first globally active climate protection instrument in the transport and economy sector. The CORSIA program provides 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 exceptions shown in Figure 20. The program is so far running until 2035 (ICAO, 2020a).

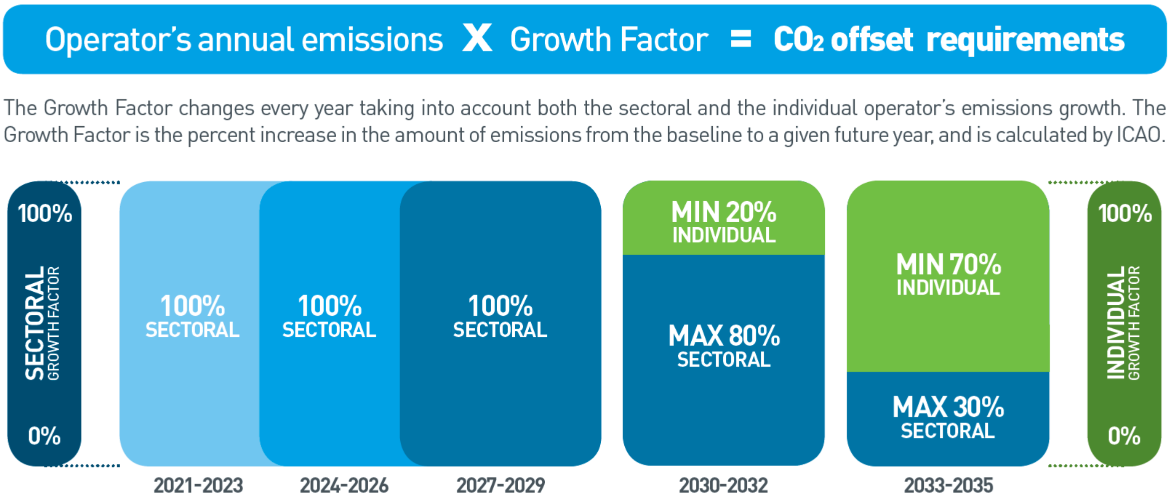
Figure 20 CORSIA offsetting countries



Source: ATAG (2020b)

How is the CORSIA mechanism working? According to BDL (2020b), the aircraft operator firstly needs to monitor the CO_2 emission from their fleet since January 2019 and report the values to the government yearly. For this, the route-based approach is applied, where only flights between countries, which are participating CORSIA, are counted. Secondly, the governments are verifying the reports through independent institutions to the offsetting requirements and informs the aircraft operator how much CO_2 emissions they should compensate. The CO_2 offsetting requirement is calculated as a multiplication of the operator's annual emissions and the growth factor. The growth factor is set by ICAO and the composition over the years is illustrated in Figure 21, which provides the sectoral and individual operator's emission growth.

Figure 21 CORSIA CO_2 offset requirements



Source: ICAO (2020b)

This compensation happens via acquiring eligible emission units from CO_2 offsets of climate protection projects in other sectors like renewable energy projects. The climate protection projects are certified and examined after international standards. Especially projects in emerging and developing countries, which have a big potential to reduce CO_2 emissions, are taken into account.

To put it simple, from 2021 on, an aircraft operator in Switzerland who emits more than 10'000 tons of CO_2 per year on international flights is obligated to compensate a part of their emissions by purchasing emission units. A possible way to merge EU ETS and CORSIA is yet unknown (BAZL, 2020). The funding for climate projects with CORSIA is forecasted to 40 billion USD and offsets 2.6 billion tonnes of CO_2 between 2021 and 2035 (ICC, 2019).

5.2 Flight taxes

Within this thesis, the term "flight tax" refers to a ticket tax, which is charged from the departure destination. The objective of a flight tax is to use the demand elasticity in the aviation sector. With a higher ticket price, less people would fly and therefore an overall reduction of flights and their emissions occurs. As specified in Faber et al. (2019), already 14 countries in Europe and 19 countries outside of Europe use a flight tax on domestic and international flights. The average burden per passenger in Europe is at around 15 Euro with a range between of 40 Euro (United Kingdom) and 1 Euro (Croatia). The effects of flight tax only on the aviation CO_2 emissions is investigated in EUROCONTROL (2020c). The influence of a ticket tax in countries like United Kingdom, Germany and Italy has shown that the implementation of a ticket tax has only a limited effect in decreasing emissions. In relation to the total growth of the aviation sector in particular countries for the years 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 (Wild, 2020). In addition, the impact on the seat load factor is not high enough to change the operations to a smaller aircraft.

With revision of the CO_2 law (CO_2-Gesetz, BBI 2020; 7847) in Switzerland and its expected implementation in 2022, a flight tax (BBI 2020, Art. 42 – 48) and a levy for general aviation (BBI 2020, Art. 49 – 52) is charged. The purpose of the law is explicitly mentioned in Art. 1 (BBI 2020) and has the same objectives as defined by the Paris Agreement. The flight tax amounts for short-haul flights up to 30 CHF and for long-haul flights up to 120 CHF depending on the booking class. The levy for general aviation ensures that departures from aircrafts over 5’700 kg MTOW, which are not captured by the flight tax, are generally charged. The costs are at least 500 CHF and maximum 3’000 CHF per departure, depending on MTOW, the travel distance and the competitiveness of the airport. The revenues of this tax and levy go to a climate fund, where less than half of the revenue is used for reduction measures of greenhouse gases (BBI 2020, Art. 53, §2). Especially an appropriate support for research and innovation in the aviation sector from the climate fund should be ensured (BBI 2020, Art. 53, §4).

Estimated effects on demand with the implementation of the above-mentioned Swiss flight tax is described in Brülhart et al., (2020). In general, a passenger is more price sensitive if the passenger is more flexible, especially for short-haul flights and for economy-class flights. Together with other demand elasticities, different scenarios are simulated. This results to air traffic reductions down to 20 % and the greenhouse gas emissions decreased down to 10 %. With that mitigation, Switzerland’s total global warming impact decreases down to 2 %. But with the demand growth of the aviation sector, this positive impact regarding emission saving would be offset within three years. The revenues of this flight tax are estimated to be up to 1 billion CHF per year.

5.3 Using tax revenues for technology support

As in the previous section mentioned, a share of the Swiss flight tax and the levy for general aviation is used for technology support, with a partly warranty for the aviation sector. Another

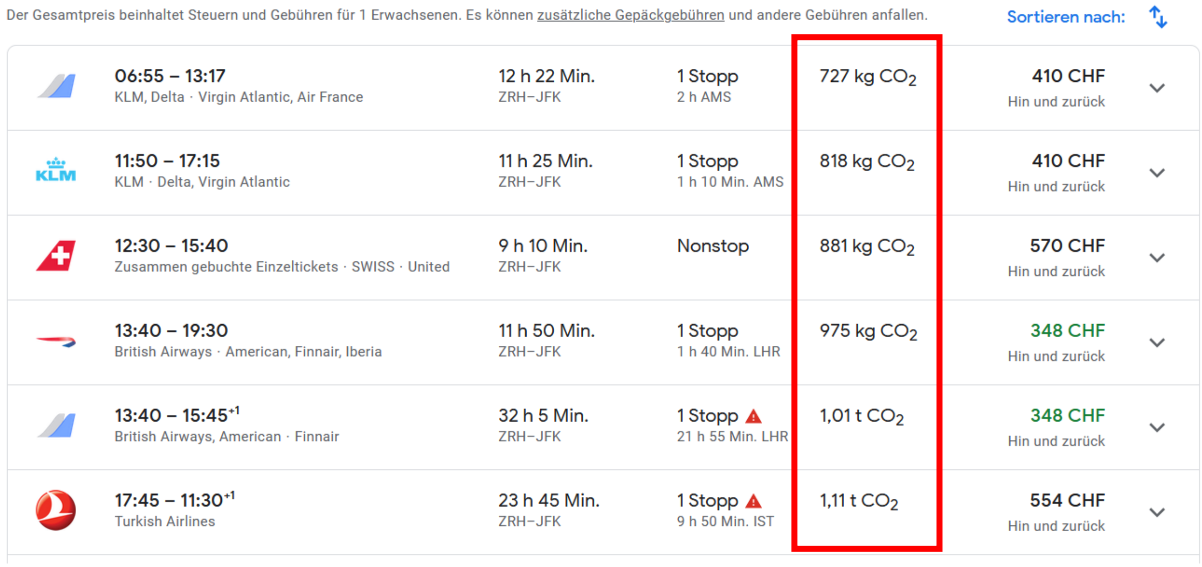
approach to use tax revenues for technology support is explained in Patt (2019) and has already been successfully implemented in the support of the photovoltaic sector. To bring the product of synthetic fuels to customers, three actions for a government policy in Switzerland are suggested. First, generate an initial demand, then stimulate the investments and transfer the additional costs of synthetic fuel to consumers in an adequate manner. A possible scenario is that the government obligate fuel suppliers might mix in synthetic fuel with a share of below 1 % of total fuel volume to increase the share every year. The emerged additional costs can be carried for example by an initial tax of 5 Swiss cents per litre on kerosene which would lead to an increase of 3 % in ticket prices. Due to the fact that the share of synthetic fuel increases with this measure, the tax is also rising to cover the volume. But with increasing capacity, the production cost for synthetic fuel is decreasing. At the end, the cost of a liter kerosene of synthetic fuel drops down to 1 CHF. Until 2050, a full decarbonization of the aviation sector may be possible with progressively rising ticket prices, which are almost not recognizable.
A further remark from Patt (2020) is that market-based measures are not effective enough, when the revenues are not reinvested in technology support to reduce the costs of their production in an economically meaningful way.

5.4 Voluntary compensation

A possible way to offset self-induced CO_2 emission on a journey is to compensate the emission voluntarily and on a private basis on climate compensation platforms. In order to do so, the produced emissions are estimated and the price for the CO_2 compensation is calculated. The current price per ton CO_2 is on average 28.40 CHF (Appendix 9.2) and the revenues are used for certified climate protection projects (Myclimate, 2020). The compensation payments are tax-deductible in Switzerland and Germany.
These climate protection projects are often conducted in developing countries because the emission reduction is mostly very cost effective. But with the offset mechanism the aviation sector is only indirectly more sustainable. Another option to make the aviation sector directly more sustainable is to compensate the flight using platform, which supports project in the section of sustainable aviation fuels (Compensaid, 2020).

To raise passenger awareness on how much CO_2 emissions their journey produces, the amount of emissions should be considered and sorted by in the booking process as illustrated in Figure 22 for a flight from Zurich to New York in January 2021. The calculation includes the European Environment agency algorithmic model from 2019, where the CO2 estimation is dependent from the point of departure, the destination, aircraft type and the amount seats per booking class on the particular aircraft (Travel Help, 2020).

Figure 22 Visibility of CO_2 emissions for a flight Zurich – New York



Der Gesamtpreis beinhaltet Steuern und Gebühren für 1 Erwachsenen. Es können zusätzliche Gepäckgebühren und andere Gebühren anfallen. Sortieren nach:

06:55 – 13:17 KLM, Delta · Virgin Atlantic, Air France	12 h 22 Min. ZRH–JFK	1 Stopp 2 h AMS	727 kg CO_2	410 CHF Hin und zurück
11:50 – 17:15 KLM · Delta, Virgin Atlantic	11 h 25 Min. ZRH–JFK	1 Stopp 1 h 10 Min. AMS	818 kg CO_2	410 CHF Hin und zurück
12:30 – 15:40 Zusammen gebuchte Einzeltickets · SWISS · United	9 h 10 Min. ZRH–JFK	Nonstop	881 kg CO_2	570 CHF Hin und zurück
13:40 – 19:30 British Airways · American, Finnair, Iberia	11 h 50 Min. ZRH–JFK	1 Stopp 1 h 40 Min. LHR	975 kg CO_2	348 CHF Hin und zurück
13:40 – 15:45^{+1} British Airways, American · Finnair	32 h 5 Min. ZRH–JFK	1 Stopp ⚠ 21 h 55 Min. LHR	1,01 t CO_2	348 CHF Hin und zurück
17:45 – 11:30^{+1} Turkish Airlines	23 h 45 Min. ZRH–JFK	1 Stopp ⚠ 9 h 50 Min. IST	1,11 t CO_2	554 CHF Hin und zurück

Source: Google Flights

An airline could also use the commitment for a sustainable aviation as a marketing strategy. For example, Easyjet (2020) is compensating every flight without any extra cost to the passenger.

6 Survey about market-based measures and travel behaviour during COVID-19

To check the benefit and acceptance of the previous mentioned market-based measures, a non-representative online survey is conducted for this thesis. The access to the survey occurred via an email link. Some participants shared the link on the platform twitter and their own homepage too. The online survey was created with findmind, a platform where data is transferred encrypted and hosted on Swiss servers. In total, 374 people opened the survey within two and a half weeks. 237 participants, mainly from the associations Aerosuisse and Economiesuisse, filled out the survey completely. It is assumed that the participant group travels more than an average citizen due to their business activities.
In addition, the influence of the pandemic to the travel behaviour of the respondents was evaluated. The questionnaire and the results in raw state are attached in the appendix 9.3 and 9.4.

6.1 Evaluation process, results and discussion

The data is directly collected and illustrated with the online tool. But for some instances, the data had to be cleaned in Excel, because some of the participants misunderstood the answer masks. For example, when the requested answer was a number, some answered with a comment which was not answering the question. To bring together as many people as possible from different language regions, and in regard of the probability for translation errors, the survey was only conducted in English. The participants also had the opportunity to skip questions or to add a comment in some questions. The results are shown in pie charts with their relative frequencies. The respective number of answers is given in the parentheses of the figure designation.

Figure 23, Figure 24 and Figure 25 represent the travel behaviour of the participants before, during and after the pandemic situation. To be more precisely, they show the number of flights of a participants per month. A roundtrip with outward and return flight counts as two flights. The number of flights after COVID-19 is obviously an estimate of the surveyed.
Before COVID-19, 49 % of the participants flew less than once per month and 29 % flew between one and two times. During COVID-19 the fraction of flying less than once per month increases to 83 %. In contrary, the number of participants flying more than three times per month decreases significantly from 22 % to only 4 %. The main reasons for this decline are in descending order: The quarantine list for risk countries, more virtual meetings and meetings that are cancelled. Just every eighth person specified, that the risk of infection is too high during travelling. Other reasons are that people are temporarily not reliant on flying with the high unpredictability of flight cancellations or their business had collapsed.

Figure 23 Flights per month before COVID-19 (n = 278)

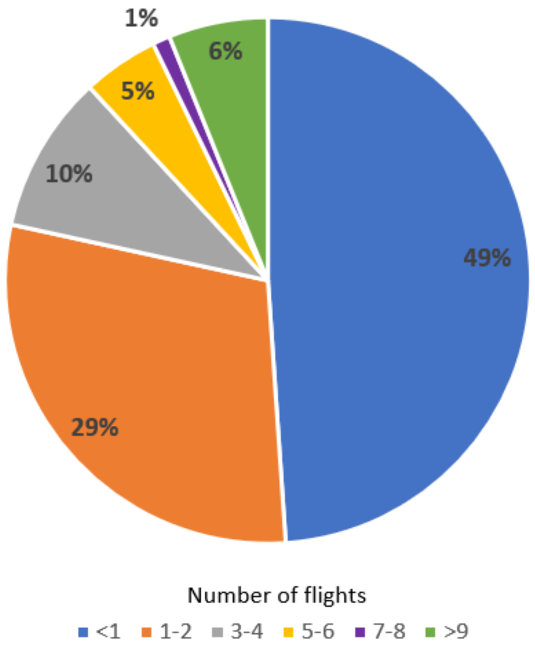


Figure 24 Flights per month during COVID-19 (n = 278)

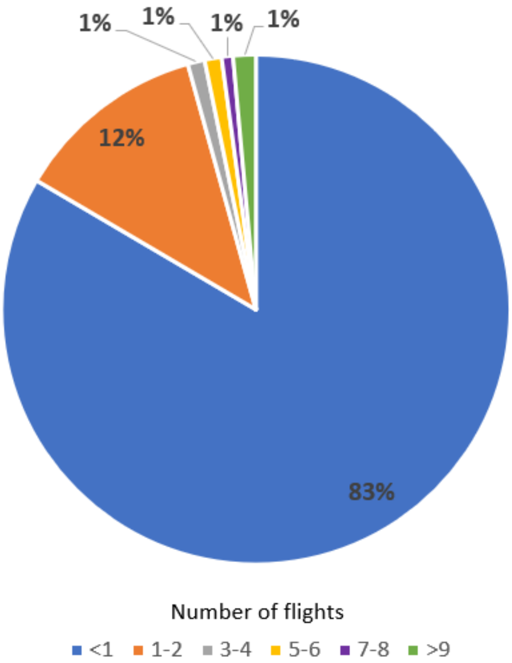
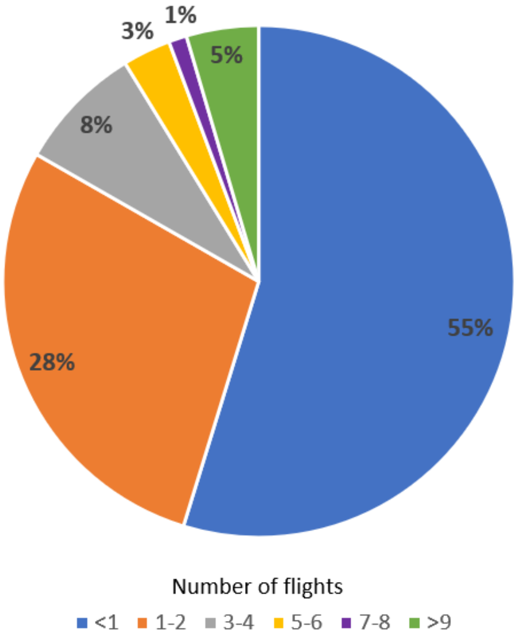


Figure 25 Flights per month after COVID-19 (n = 264)



As shown in Table 5, the average of flights decreases from 2.34 to 0.59 per month.
The maximum number of flights from a participant is limited to 30. Any flights more than 30 are considered as an outlier because that would mean that a participant travels for example as a commuter with making a roundtrip every second day per month.
In the pre-COVID phase 18 % of the participants are responsible for 75 % of the flights while during COVID-19 restrictions, only 6 % of the participants are responsible for the same share.

Table 5 Key figures travel behaviour

	Before COVID-19	During COVID-19	After COVID-19
Average flights per month	2.34	0.59	1.99
Total amount flights	649	164	525
Maximum amount flights from a participant	30	20	30
50 % Share of flights	6 %	2 %	5 %
75 % Share of flights	18 %	6 %	16 %

When comparing the survey numbers from before COVID-19 and after COVID-19, a full recovery is not expected. The average of flights per month falls from 2.34 down to 1.99 because the participants are intending to fly less and the catch-up effect because of missed travel is small. The main reason for this is that more virtual meetings are conducted instead of flying to a meeting. Almost every third person want to fly less due to environmental reasons.

According to Myclimate (2020), an economy class flight produces less CO_2 emissions than a business class flight due to less required space and weight per passenger seat. Therefore, the share of the different booking classes as selected by the surveyed, are illustrated for short-haul flights in Figure 26 and for long-haul flights in Figure 27. The option of flying first class is for almost each airline exclusively a booking class for long-haul flights. The fraction of economy class bookings is for short-haul flights dominant with around 81 % whereas for long-haul trips the share of business and economy bookings are similar.

Figure 26 Booking class short-haul flight (n = 229)

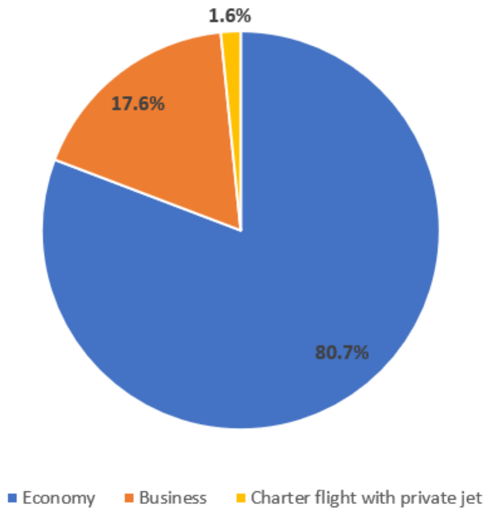


Figure 27 Booking class long-haul flight (n = 223)

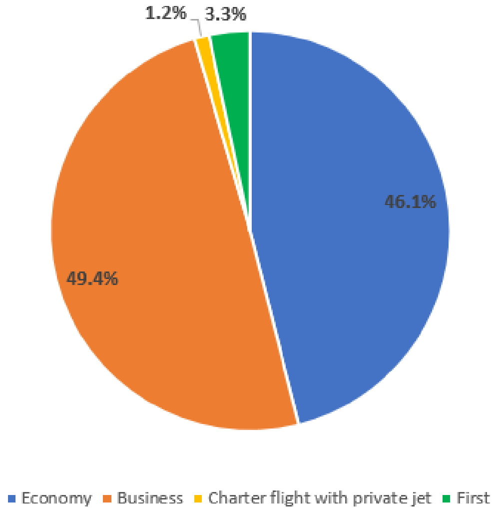


Figure 28 shows that around 60 % of the participants of the survey would support an environmental tax in Switzerland, but only a quarter (Figure 29) thinks that the introduction of a Swiss flight tax at the amount of maximum 30 CHF, respectively 120 CHF, would have an influence on their travel behaviour or would fly less. A possible explanation could be that the surveyed are rather wealthier.

Figure 28 Support environmental tax (n = 252)

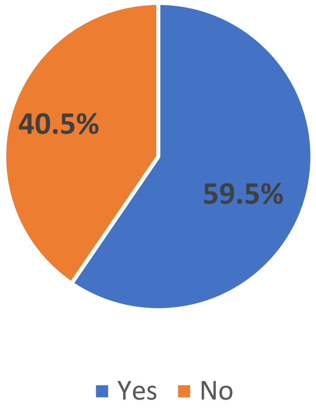
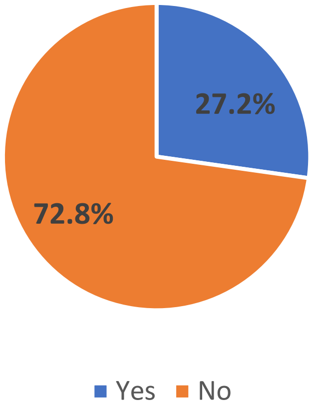


Figure 29 Influence of initiating Swiss flight tax (n = 246)



Mentioned changes in travel behaviour are, besides flying less, adjusting the mode of transport to the cheapest or to avoid the Swiss flight tax by flying from airports in closer abroad, where a tax is not implemented or not that high. This would be undoubtedly a wrong incentive.

As seen in Figure 29, for three quarters of the participants the limit of the Swiss flight tax will not influence their travel behaviour. In Figure 30, more than 80 % of the surveyed believe that for short-haul flights, a higher Swiss flight tax of 30 CHF would influence their travel behaviour. For long-haul it does not look much different with around 70 %, according to Figure 31. The average limit for the flight tax on short-haul flight is 159 CHF, which is approx. five times higher than the maximum intended legal amount. For a long-haul flight, the average limit is 412 CHF, but the difference is smaller and still 3.5 time higher than the politically accepted solution.

The evaluated medians for short-haul are at 100 CHF, respectively 250 CHF for long-haul. The big difference between average limit and median limit occurs because participants submitted a value lower than provided in the CO2 law. This contradicts the asked question which was: "If the flight tax mentioned has no influence on your travel behaviour, what would be your limit on taxes for short-haul flights?".

Figure 30 Limit flight tax short-haul (n = 189)

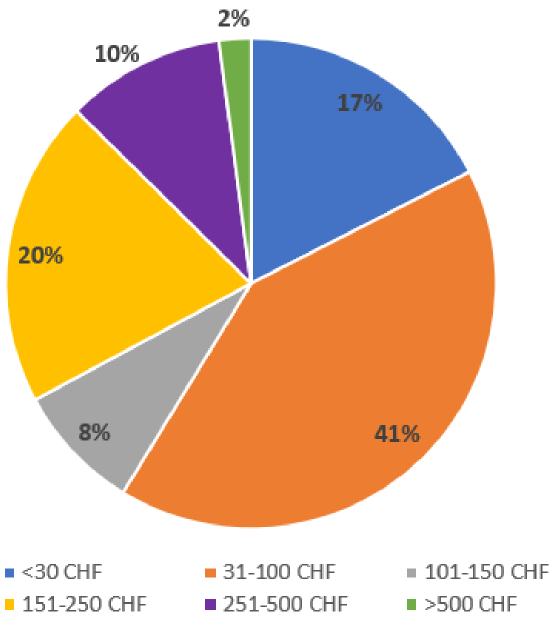
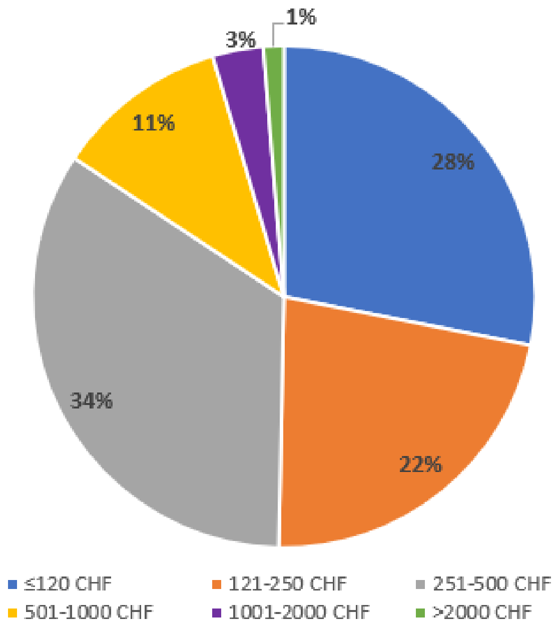


Figure 31 Limit flight tax long-haul (n = 196)



Due to the current pandemic situation, the overall economic situation is very difficult. Especially the aviation sector is affected, as explained in chapter 1. Thereby, a delay of implementing the flight tax to stimulate the Swiss aviation industry can be considered. As seen in Figure 32, no clear majority is emphasised. Some are in favour of implementing the flight tax immediately, some want to abolish it right away.

Figure 32 Support delay of flight tax implementation (n = 243)

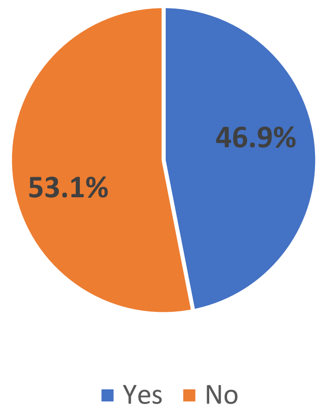


Figure 33 Minimum ticket fare (n = 222)

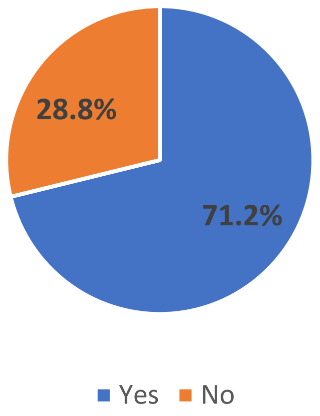


Figure 33 shows the result of a fictional scenario. The participants were asked if they would pay a minimum ticket fare per flight (for example on a short-haul flight 150 CHF) if the difference (50 CHF) of revenue (150 CHF) and costs (100 CHF) is used for sustainable technology support in aviation. Approx. 70 % of the surveyed agreed with the idea of a surcharge, if it is used directly from where it comes. This effect is comparable with the food organic label, where people are willing to pay more for sustainable products.

Another fictional scenario is the implementation of a flight contingent. The main principle of a flight contingent is that a person in Switzerland has a certain amount of flight miles available within a specific period, for example two short-haul flights and one long-haul flight per year. If you fly more than this contingent, then a charge is raised. Figure 34 reflects that the flight tax has a high acceptance with 68 %, whereas the flight contingent just gets an approval with 28 %. That might be related with a high bureaucracy and as well as the freedom of mobility being partly constricted.

Figure 34 Flight tax or flight contingent (n = 222)

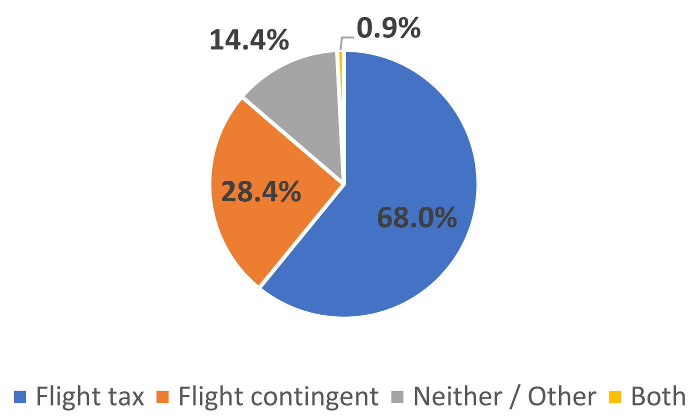
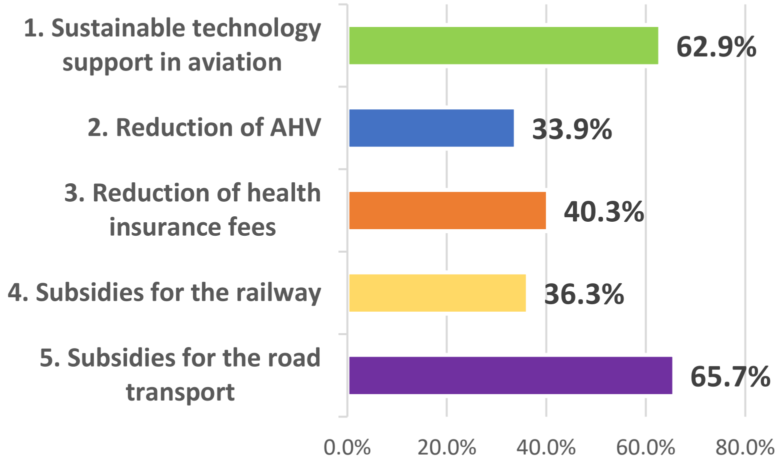


Figure 35 represents a ranking on personal expense preferences for revenues from flight tax, flight contingent or minimum ticket fare. Almost 63 % of the participants agreed that the first place to spend the revenues is sustainable technology support in aviation, followed by reduction of AHV (old-age and survivors's insurance; OASI) and reduction of health insurance fees. A majority of the surveyed agrees, that subsidies for other modes of transport have less priority. Around 66 % of the participants ranked the option "subsidies for the road transport" as number five. According to Patt (2019), an example for cross-financing is the revenue of the heating oil levy, which is used for the reduction of AHV and health insurance fees.

Figure 35 Expenses of revenues (n = 248)



Insights on whether the participants already voluntarily compensate their business or private travels according to chapter 5.4, are presented in Figure 36 and Figure 37. The fraction for both compensations, sustainable fuels and the option "not selectable on the booking site" are similar for business and private travels. In contrast, a small shift from business travels climate compensation to no compensation in private travels occurs. It must also be considered that the availability of sustainable fuels, respectively nowadays it is just bio-fuels, is very small. Reasons for the high fraction of no compensation are, that the participant's employer is already compensating or offsetting the emissions and that the participants are part of a higher social standing. It is important not to forget that the compensation is still voluntary and not mandatory.

Figure 36 Compensation business travels (n = 216)

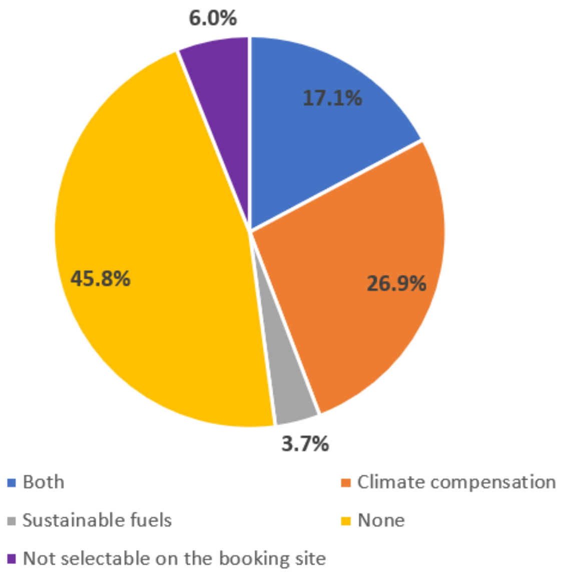


Figure 37 Compensation private travels (n = 220)

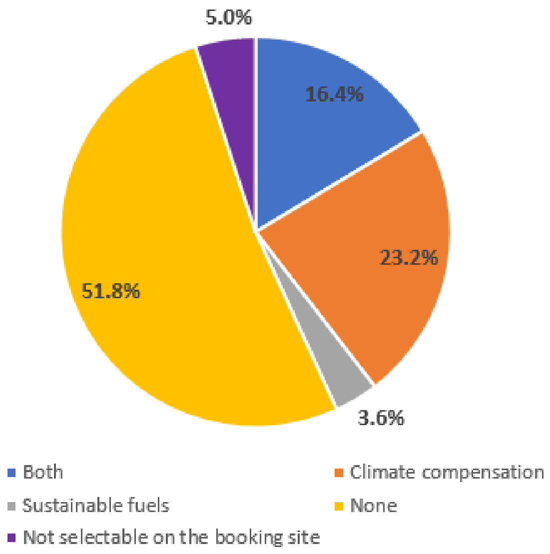
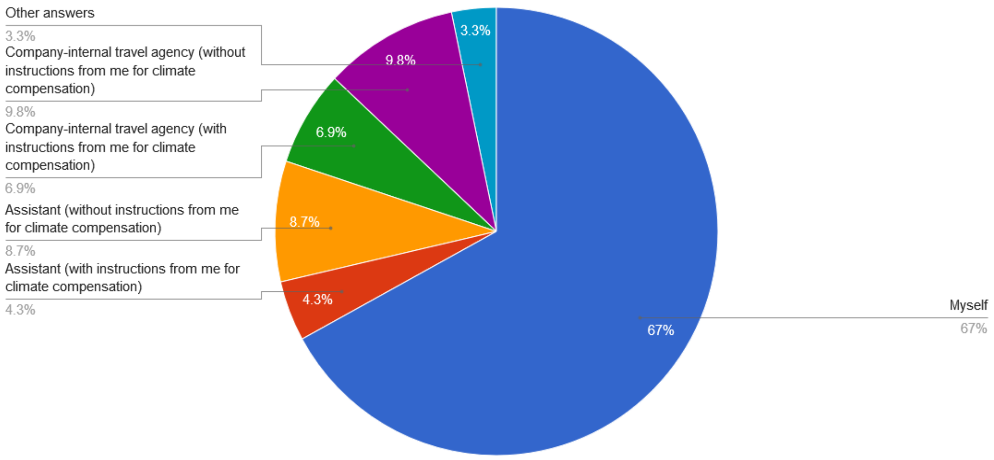


Figure 38 indicates if the participants have the choice to select climate compensation options for their business travels. At least two third are booking the flight by themselves. Nevertheless, for one third of the participants, the booking process for their business travels is conducted by another person, from an assistant or a company-internal travel agency.

Figure 38 Booking person (n = 249)



On the subject of flight tax two antagonistic views meet each other. On one hand, there's people who are generally against taxes and designate it as a competition distortion. On the other hand, there's people who are greeting the flight tax, but think that the amount is not high enough and that it will not be introduced more quickly. A broad consensus is, that a unilateral way with a "Swiss solution" is not conducive because the mechanism with a traffic redirection to the close abroad destinations will be inserted.

It is noticeable that the solution is plausible for the majority. But is it effective enough to reach the climate goals? Certainly, this survey shows that the amount of the flight tax is too low to influence the travel behaviour of the participants. But the customer awareness for environmental topics is existent and also the flight tax reminds people about the environmental impact of flying. The amount of already compensated participants is higher than expected. The idea behind sustainable fuels are not evident for every participant.

The survey also made it clear that the participants fly less after the COVID-19, compared to the pre-COVID phase. A shift within the customer segment could also occur because meetings are no longer just held on-site but relocated to virtual rooms.

7 Conclusion

The aviation industry produced in 2019 2.8 % of global CO_2 emissions by burning fossil fuel. To achieve the objectives of the Paris Agreement, IATA proclaimed to halve the net CO_2 emissions for the year 2050 in comparison 2005 despite of a forecasted growth in the aviation sector. Hence, the growth should happen decarbonized and for the moment be stabilized at the forecasted pre pandemic CO_2 emissions level of 2020. This thesis investigates the various current and future CO_2 reduction measures in the global aviation industry and shows their effectiveness. The reduction measures are superordinate categorized in technology, operational, infrastructural / ATM and market-based measures. A holistic evaluation with the mitigation measures in a time period/potential matrix is illustrated in Table 6. In horizontal direction, the potential or impact of a reduction measure is shown. The time period in vertical direction represents when the reduction measure would be implemented.

A continuous development of the conventional jet engines, aerodynamics and getting rid of quad engines aircrafts are a first step to reduce CO_2 emissions. The implementation of this fuel efficiency optimisation measures takes time until a 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 very exhausted and therefore the potential is low. On the contrary, advanced turbofan and new engine core concepts as evolutionary engine improvements have a medium potential because the development of jet engines with higher BPRs are still with a reasonable expenditure possible. The potential for revolutionary aircraft designs like open rotor engines and strut-braced wings is low. The former due to its immense noise emissions and the latter because of the only small reduction of emissions. 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 operations weight. Hydrogen technology is also more scalable, energy-efficient and the more economic option. The potential of hydrogen powered aircrafts and "blended wing boy" aircrafts are for long-haul flights associated with high uncertainties and as a result just medium. In general, the participation of revolutionary technology in regards of the goals of 2050 is very late. Also, conflicting objectives and effects like the reduction of CO_2 emissions and non-CO_2-emissions should be further investigated and not neglected. For instance, with hydrogen, where less CO_2 is produced but more water vapor and NO_x is created.

The potential of synthetic fuels and direct air capture are in short-term low due to its small production capacity. But today’s use of bio-fuels as blending has until 2025 a medium potential because the production growth is on the exponential path. From 2025, SAF have a high potential and impact as CO_2 reduction measure. A comparison of economic efficiency between hydrogen and SAF is omitted because it is strongly dependent from the chosen scenario and the assumptions of further development of both technologies. To sum up, the most promising long-term technologies to reduce CO_2 emissions are hydrogen powered aircrafts and SAF. But the advantages of SAF and hydrogen powered aircraft outweigh only when the used energy for production is renewable.

A mode shift from flying to taking the train is a reasonable reduction measure for travels to adjacent countries with good train accessibilities. The travels by train produces at least two times less CO_2 than by an aircraft and even less when the train is operating with electricity from renewable energies. Operation measures like weight reduction and flight planning, fuel calculation have a medium potential in a short-term because they are easy to realise and due to the big scale effect. With every weight savings either from fuel or payload, an avoidance of carrying additional fuel is possible. Because with every further ton on board of an aircraft, is additional fuel in the amount of 3 – 10 % for short-haul and 20 – 25 % for long-haul flights necessary. Different operational models have a high uncertainty regarding financial rewarding and therefore a low potential.

The objectives of reduction measures from an infrastructure / ATM perspective are to decrease the flight time and avoid holdings because every kg of fuel burnt produces 3.16 kg CO_2 emissions. The implementation of more efficient airspaces and flight routes in Europe is achieved by SESAR. The goal is to reduce at least 10 % of CO_2 emissions. This is done with the introduction of 4D Navigation, free route airspaces and performance-based navigation. Further ATM procedures like continuous climb and descent operations, more direct routes, assigned arrival slots and extended arrival management systems are mitigating just a small number of emissions. But with implementing these improvements area-wide, a big scale effect occurs. Therefore, the impact is first just low but with increasing time it rises to medium.

Regulations in a free market are necessary, when nobody feels responsible to pay the cost for damage like climate warming. With applying "the polluter pays" principle, it might be possible to stop such market failures. This includes market-based measures as area-wide compensation systems like EU ETS, CORISA and taxes like the Swiss flight tax. Studies confirms that market-based measures have a low impact as a reduction measure because the prices are too low to obtain a significant reduction. With today’s offsetting of CO_2, the problem is not solved at the root. The revenues may be used better to invest in research and development of more promising reduction measures, as for example the Swiss law also provides it partially for the Swiss flight tax. This will also raise the acceptance to pay such a market-based measures and provide new jobs. To support CO_2 reduction measures, a global approach with standardized rules and reasonable incentives are useful regarding to the distortion of competition. A unilateral "Swiss solution" is not conducive. But the implementation of market-based measures is connected with conflict of interest regarding ecological, economic, political and social goals.

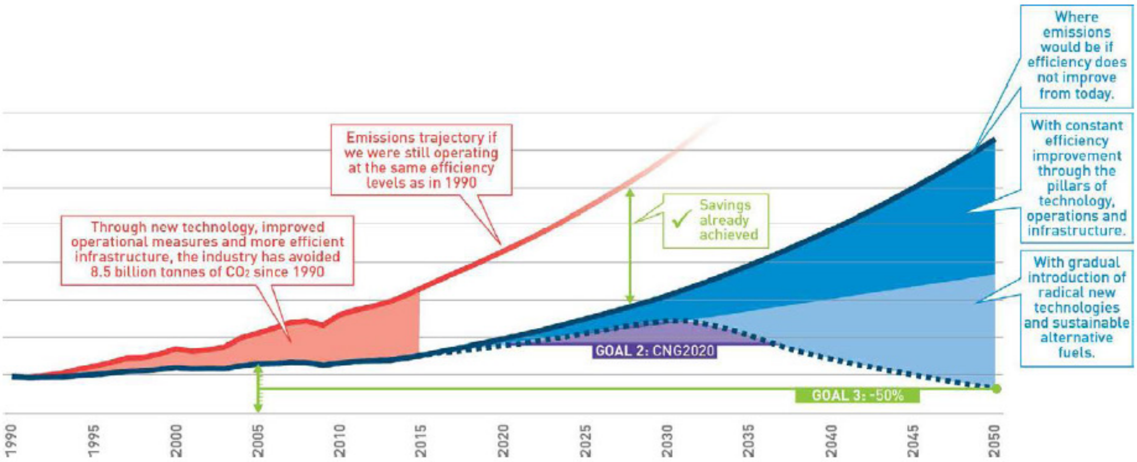
The non-representative online survey was filled out by 237 participants completely. Their average flight frequency per month before COVID-19 amounts to 2.34. With the pandemic situation the average number of flights per month decreased to 0.59. The main reasons for this decline are the quarantine list for risk countries, more virtual meetings and cancelled meetings in-person. After COVID-19, the participants' average number of flights per month is 1.99 and a full recovery to pre-COVID-19 levels is not expected. The reasons for intending to fly less for the participants are with 45 % agreement more virtual meetings and 33 % due to environmental reasons. It is assumed that the participant groups of mainly Aerosuisse and Economiesuisse travel more than an average citizen due to their business activities. The majority of around 60 % of the participants are for the support of an environmental tax. 63 % ranked on a first place, that the revenues from a levy should be used for sustainable technology support in aviation. Followed in descending order by reduction of AHV/OASI, reduction of health insurance fees, subsidies for the railway and subsidies for the road transport. The current Swiss flight tax limit of max. 30 CHF for short-haul flights and max. 120 CHF for long-haul flights has an influence only for 27 % of the participants. For the other participants an average limit of 159 CHF on short-haul and 412 CHF on long-haul flight is necessary to change their travel behaviour. On average, about 45 % of the participants are already voluntarily compensating their business and private travels. A further incentive to voluntarily compensate the emissions would be to deduct the compensated amount from the tax up to a maximum limit. Or for a passenger to be able to replace the flight tax with a voluntarily compensation in the same amount. But a twin-track strategy with flight tax and voluntarily compensation would be not useful. Due to the high number of participants, the comments and the sharing of links via third platforms, it is concluded that the topic is trending and widely discussed.

Table 6 Evaluation matrix

SH = Short-haul LH = Long-haul		**Potential / Impact**		
		Low	Medium	High
Time period	Short-term until 2025	• Synthetic fuels & Direct air capture • 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 • Different operational model • EU ETS / CORSIA / Flight tax	• Evolutionary engine improvements • Procedures of ATM	• SAF
	Long-term from 2040	• Open rotor engine / Strut-braced wings • EU ETS / CORSIA / Flight tax	• SH: Electric aircraft • LH: Hydrogen aircraft / Blended wing body aircraft	• SH: Hydrogen aircraft • SAF

Figure 39 sums up the roadmap of CO_2 reduction measures for reaching the two goals of carbon neutral growth from 2020 on together with launching the influence of the market-based measure CORSIA. The further objective is to halve the CO_2 emissions from 2005 by 2050. Since 1990, already 8.5 Gt of CO_2 emissions has been avoided in the aviation industry due to reduction measures, like new technologies, improved operational measures and more efficient infrastructures.

Figure 39 Influence of past, current and future reduction measures



Source: Boyd (2020)

It is obvious that the implementation of just one reduction measure is not purposeful. SAF and radical new technologies are expected to account for around 50 % of CO_2 savings by 2050. But especially for long-haul flights only SAF are a likely solution as a reduction measure.

CO_2 reduction measures are a hot topic where monthly technological progress is made. This thesis shows just a time segment and further development will occur over time, because big companies and political institutions are investing in new ideas. With investing into new technology measures nowadays, the leverage factor for the return of investment is higher. The pandemic situation could be used as a chance for innovation.

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9 Appendix

9.1 Detailed overview of evolutionary technologies

Table 7 Evolutionary technologies and their fuel efficiency improvements

Group	Concept	Fuel efficiency improvements
Aerodynamics	Variable Camber	1 – 2 %
	Riblets	1 %
	Raked Wingtip	3 – 6 %
	Winglets	3 – 6 %
	Natural Laminar Flow	5 – 10 %
	Hybrid Laminar Flow	10 – 15 %
	Variable Camber with New Control Surfaces	5 – 10 %
	Spiroid Windtip	2 – 6 %
Advanced Engine Components	Fan Component Improvement	2 – 6 %
	Very High BPR Fan	2 – 6 %
	Advanced Combustor	5 – 10 %
	Zero Hub Fan	2 – 4 %
New Engine Architecture	Advance Turbofan	20 %
	Ultrafan	25 %
	GE9X	10 %
	Counter Rotating Fan	15 – 20 %
	Ultra-High Bypass Ratio Engine	20 – 25 %
Cabin	Lightweight Cabin Interior	1 – 5 %

Engine Cycle	Adaptive/Active Flow Control	10 – 20 %
	Ubiquitous Composites (2nd Gen)	10 – 15 %
Material & Structure	Advanced Materials	1 – 3 %
	Active Load Alleviation	1 – 5 %
	Composite Primary Structures	1 – 3 %
	Composite Secondary Structures	< 1 %
Systems	Adjustable Landing Gear	1 – 3 %
	Taxi Bot	1 – 4 %
	Advanced Fly-by-Wire	1 – 3 %
	Structural Health Monitoring	1 – 4 %
	Electric taxiing system with Auto Transformer Rectifier Unit	3 %
	Fuel Cells	1 – 5 %

Source: IATA (2020c)

9.2 Calculation CO_2 compensation myclimate

Destination	Arrival	Booking Class	Distance in NM	tonnes CO2	CHF	CHF / ton CO2
ZRH	SFO	Economy	18'800	3.1	88	28.39
ZRH	SFO	Business	18'800	5.9	169	28.64
ZRH	SFO	First	18'800	9.2	262	28.48
ZRH	JFK	Economy	12'600	2	58	29.00
ZRH	JFK	Business	12'600	3.9	112	28.72
ZRH	JFK	First	12'600	6.1	174	28.52
ZRH	LIS	Economy	3'500	0.635	18	28.35
ZRH	LIS	Business	3'500	0.947	27	28.51
ZRH	LIS	First	3'500	1.7	47	27.65
ZRH	GVA	Economy	500	0.224	6	26.79
ZRH	GVA	Business	500	0.286	8	27.97
ZRH	GVA	First	500	0.524	15	28.63
Source: (Myclimate, 2020)					**Average**	**28.4**

9.3 Question catalogue survey

1. - How often did you fly per month in the time before COVID-19?

*Time **before** COVID-19*

(Roundtrip with outward and return flight counts as two flights)

Enter a number

---

2 - How often do you fly per month in the time during COVID-19?

*Time **during** COVID-19*

(Roundtrip with outward and return flight counts as two flights)

Enter a number

---

3 - If you fly less during COVID-19 than before, why?

☐ More virtual meetings

☐ Meetings cancelled

☐ Risk of infection too high

☐ Quarantine list for risk countries

☐ Smaller supply of flights

Other reasons

---

4 - How often do you intend to fly per month in the time after COVID-19?

*Time **after** COVID-19*

(Roundtrip with outward and return flight counts as two flights)

Enter a number

---

5 - If you intend to fly after COVID-19 less than before or during, why?

☐ More virtual meetings

☐ Too high risk of infection

☐ Environmental reasons

Other reasons

---

6 - Do you book your flight by yourself or via other people?

☐ Myself

☐ Assistant (with instructions from me for climate compensation)

☐ Assistant (without instructions from me for climate compensation)

☐ Company-internal travel agency (with instructions from me for climate compensation)

☐ Company-internal travel agency (without instructions from me for climate compensation)

Other answers

---

7 - For business travels: In which booking class do you fly on a short haul flight?

☐ Economy

☐ Business

☐ Charter flight with private jet

---

8 - For business travels: In which booking class do you fly on a long haul flight?

☐ Economy

☐ Business

☐ First

☐ Charter flight with private jet

---

9 - Do you support the idea of an environmental tax as a climate change policy in Switzerland?

○ Yes

○ No

Can you elaborate why yes/no?

---

10 - Due to the revision of the CO2-law, from the 01.01.2022 on, a flight tax of min. 30 CHF on short haul flights and max. 120 CHF on long haul flights is collected. Do you think this will have an influence on your travel behaviour?

○ Yes

○ No

Can you elaborate why yes/no?

---

11 - If the flight tax mentioned above has no influence on your travel behaviour, what would be your limit on taxes for short haul flights?

Enter a number in CHF

---

12 - If the flight tax mentioned above has no influence on your travel behaviour, what would be your limit on taxes for long haul flights?

Enter a number in CHF

---

13 - Would you support the delay of implementing the flight tax to stimulate the Swiss aviation industry?

○ Yes

○ No

It depends on...

---

14 - As an alternative to the flight tax a flight contingent could be implemented. Which option do you prefer?

The main priciple of a flight contingent is that a person in Switzerland has a certain amount of flight miles available, for example two short haul flights and one long haul flight per year. If you fly more than this contingent, then a charge is raised.

☐ Flight tax

☐ Flight contingent

Others / Reasons?

---

15 - Would you pay a minimum ticket fare per flight if the difference of minimum ticket fare and lowest possible ticket price is used for sustainable technology support in aviation?

For example this initial situation for a fictional short haul flight:

*Lowest possible ticket price **100 CHF** (costs for airline or minimum of revenue an airline needs)*

*Minimum ticket fare **125 CHF** (determined by economy & politics)*

*Difference **25 CHF** (fund for sustainable technology in aviation)*

○ Yes

○ No

It depends on…

---

16 - What should happen with the revenues of flight tax / flight contingent / minimum ticket fare? Rank the possibilities based on your personal preferences.

____ Sustainable technology support in aviation

____ Reduction of AHV

____ Reduction of health insurance fees

____ Subsidies for the railway

____ Subsidies for the road transport

---

17 - Do you use the climate compensation or the option "Sustainable fuels" during the booking process of your business travels?

For business travels

Note: Not every airline is offering the option climate compensation or "Sustainable fuels".

○ Both

○ Climate compensation

○ Sustainable fuels

○ None

○ Climate compensation not selectable on the booking site

○ Sustainable fuels not selectable on the booking site

Reasons why / why not?

---

18 - Do you use the climate compensation or the option "Sustainable fuels" during the booking process of your private travels?

For private travels

Note: Not every airline is offering the option climate compensation or "Sustainable fuels".

○ Both

○ Climate compensation

○ Sustainable fuels

○ None

○ Climate compensation not selectable on the booking site

○ Sustainable fuels not selectable on the booking site

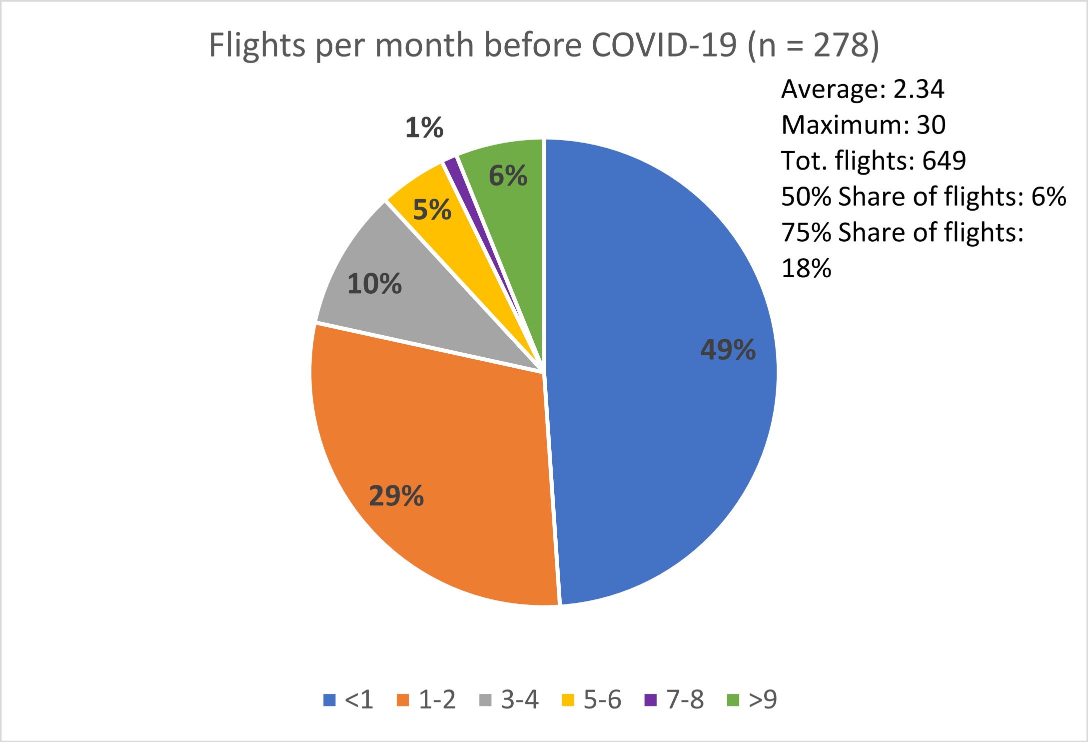
Reasons why / why not?

---

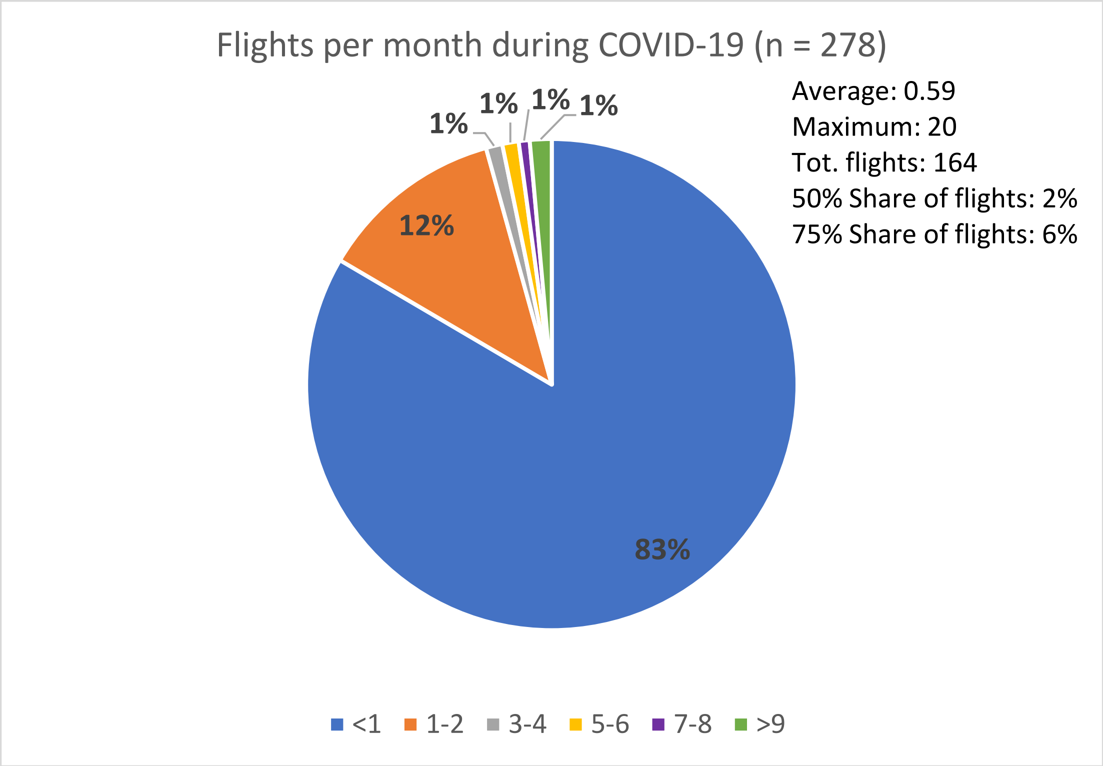
19 - Open field for ideas and comments

9.4 Evaluation of survey

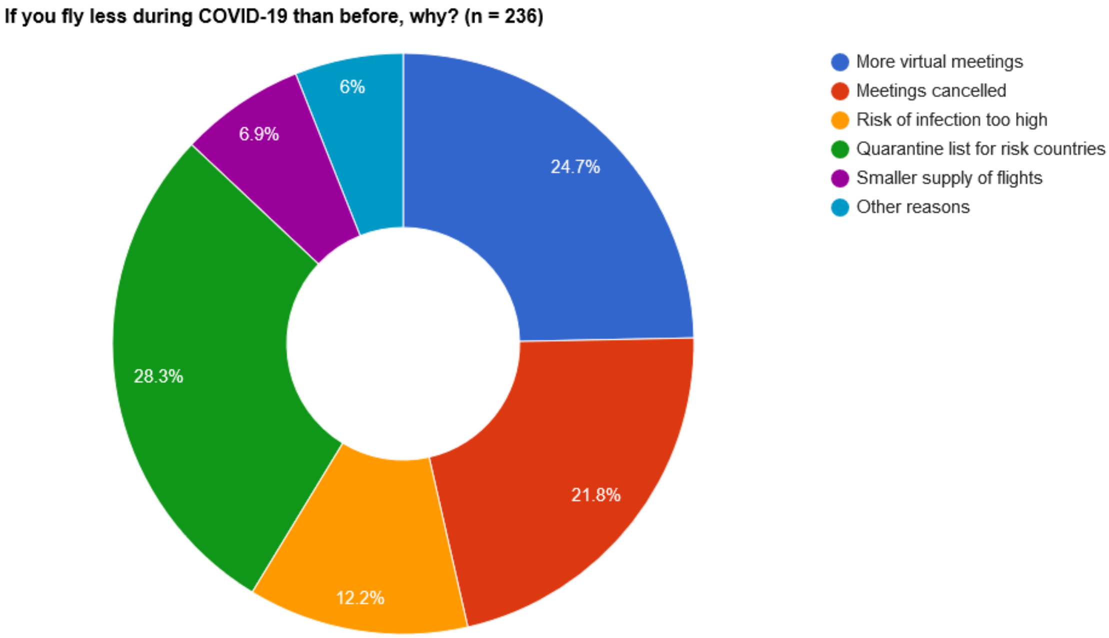
1 How often did you fly per month in the time before COVID-19?



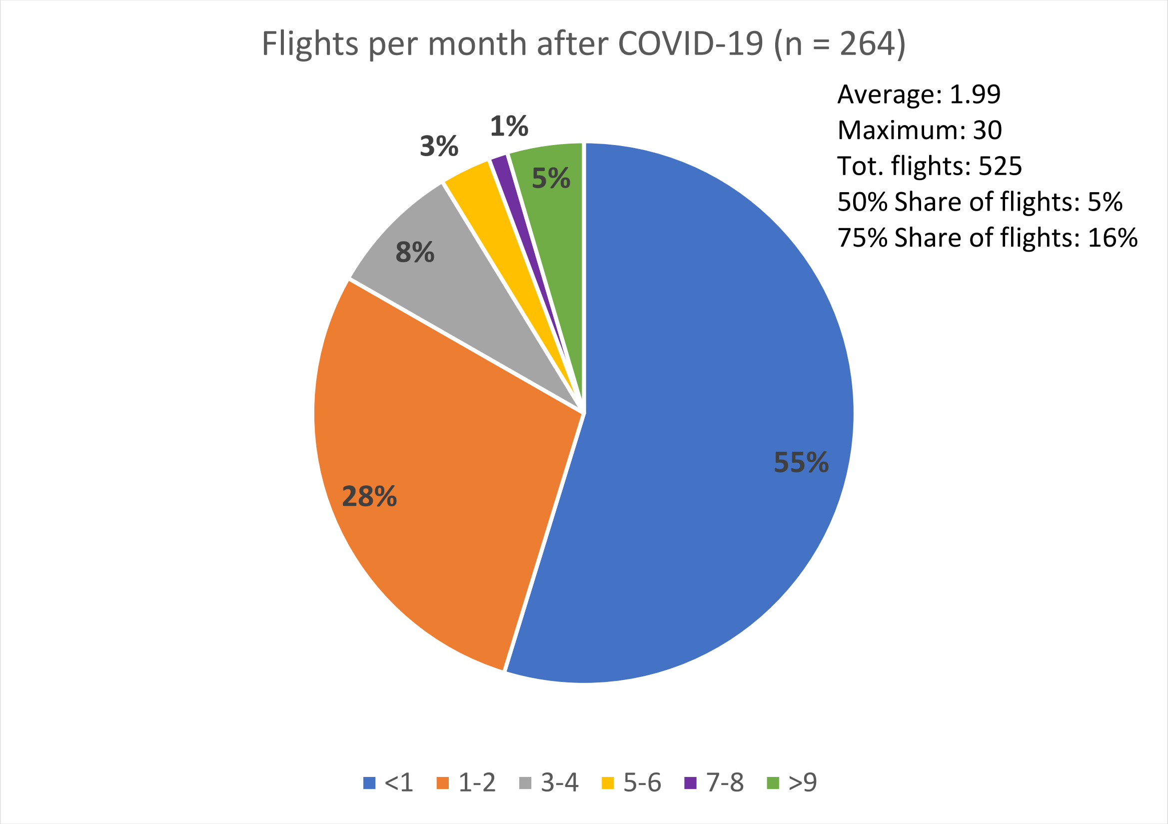
2 How often do you fly per month in the time during COVID-19?



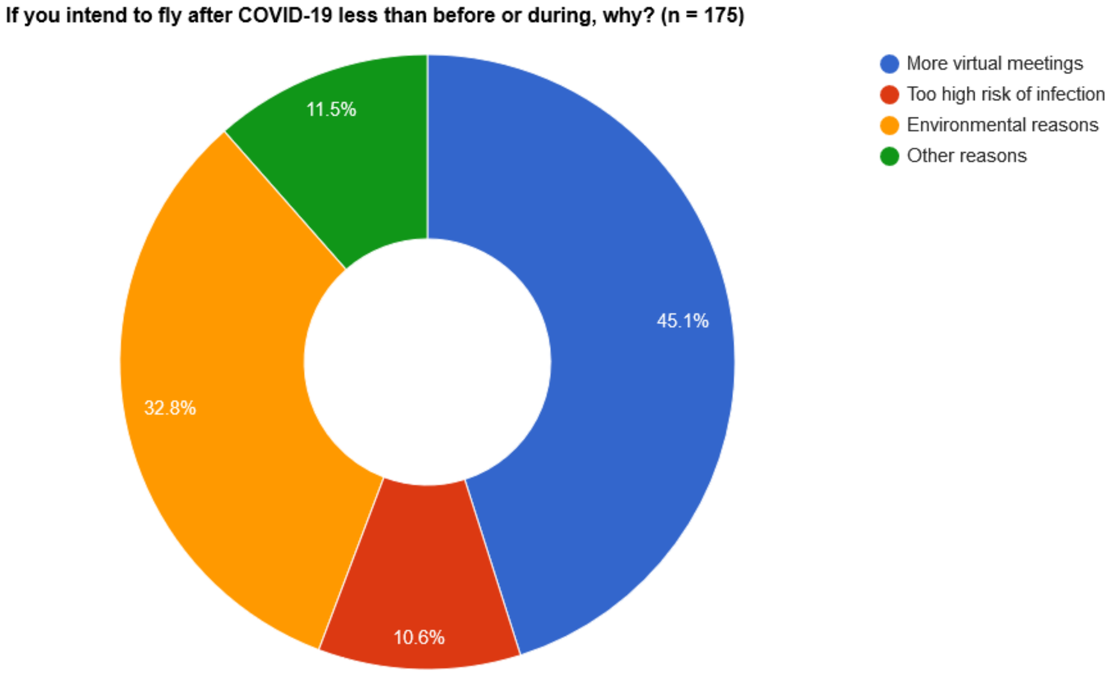
3 If you fly less during COVID-19 than before, why?



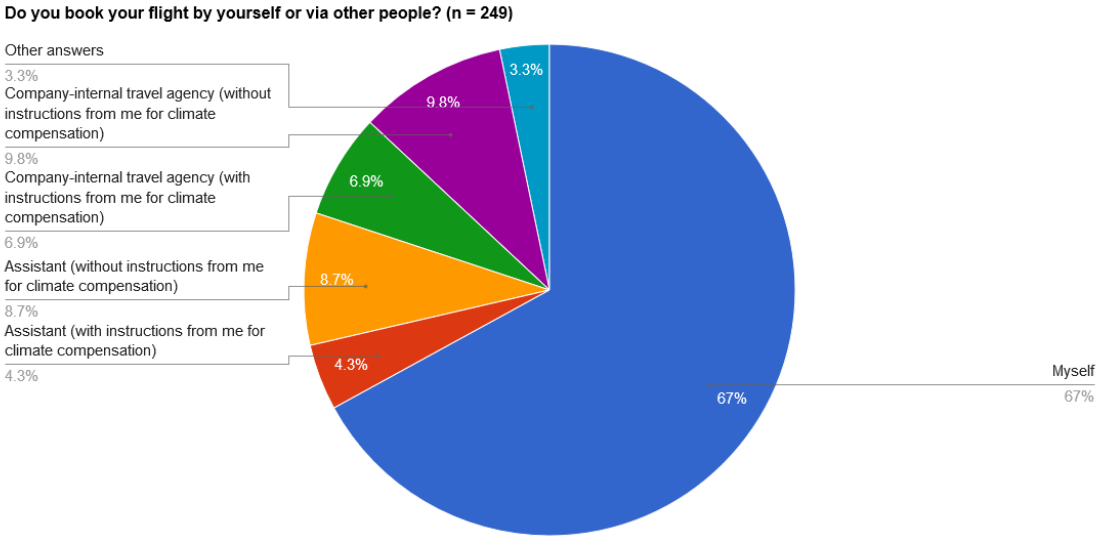
4 How often do you intend to fly per month in the time after COVID-19?



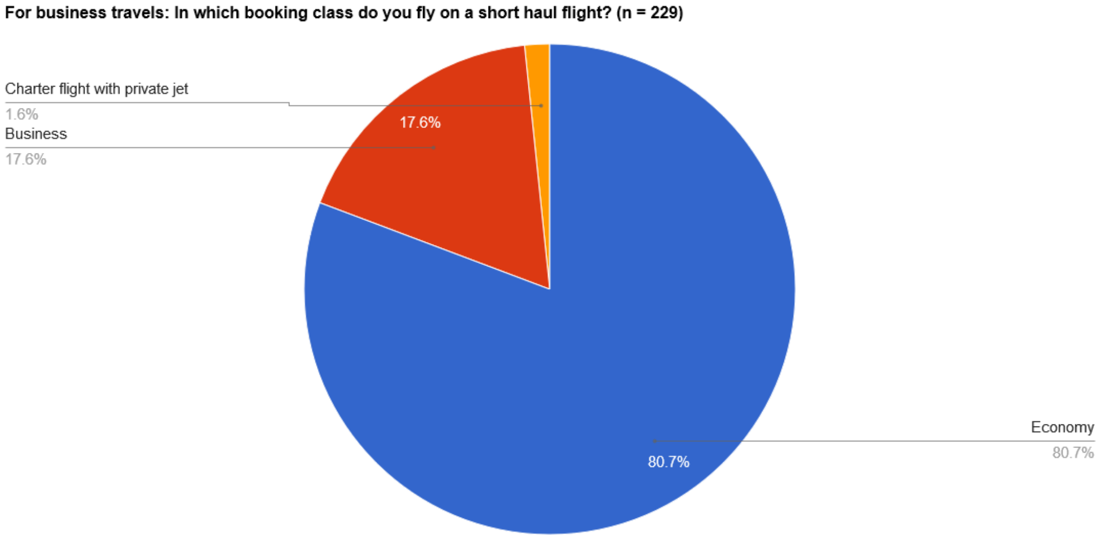
5 If you intend to fly after COVID-19 less than before or during, why?



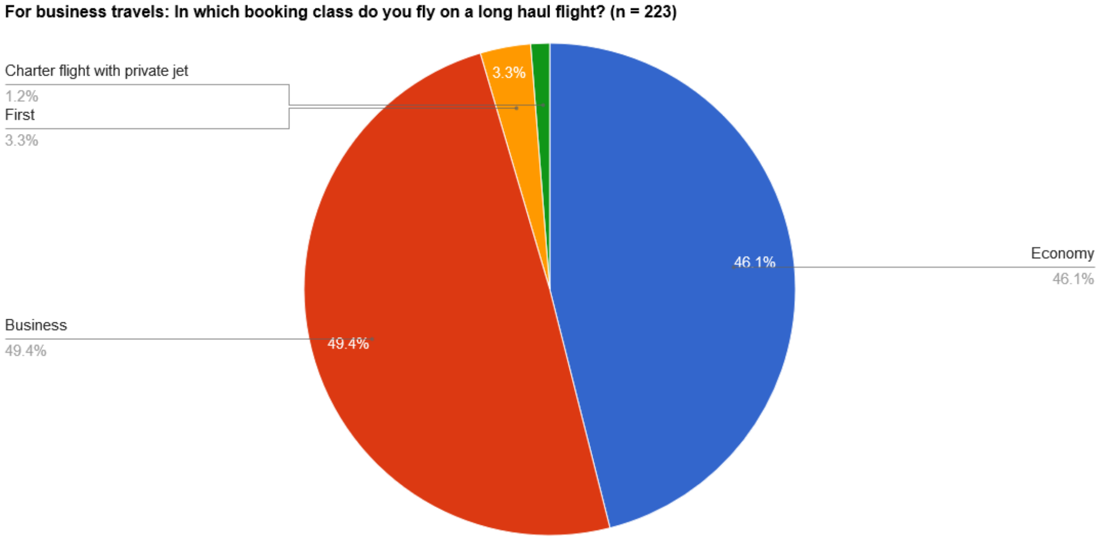
6 Do you book your flight by yourself or via other people?



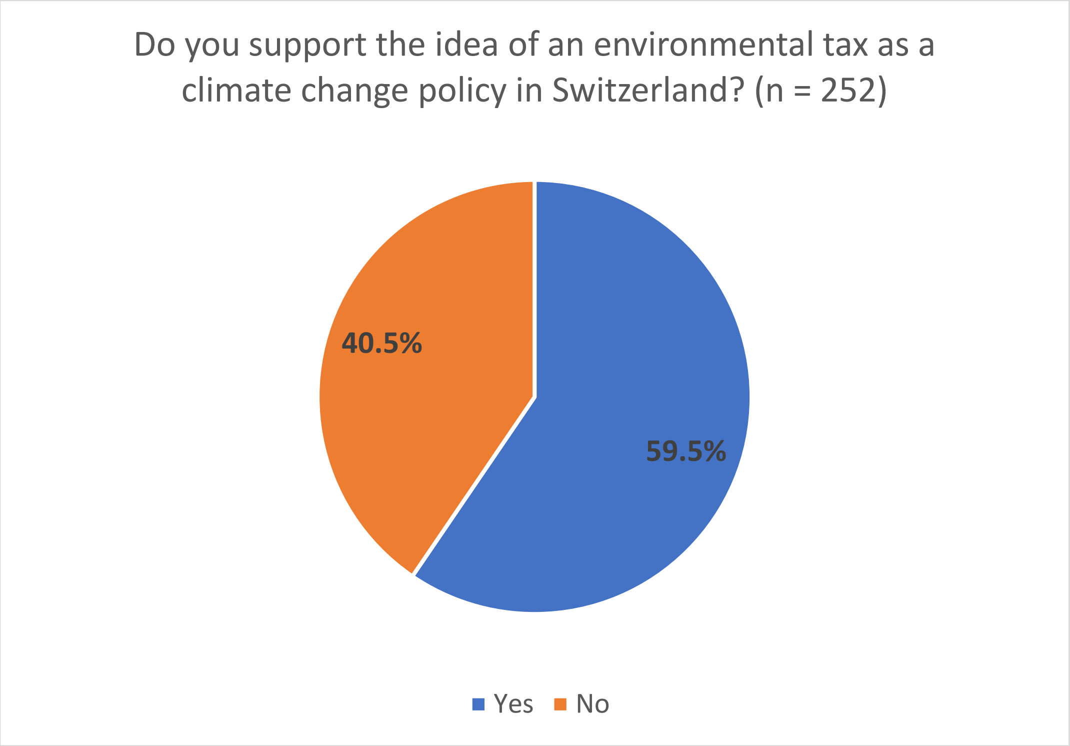
7 For business travels: In which booking class do you fly on a short haul flight?



8 For business travels: In which booking class do you fly on a long haul flight? (n = 223)



9 Do you support the idea of an environmental tax as a climate change policy in Switzerland?



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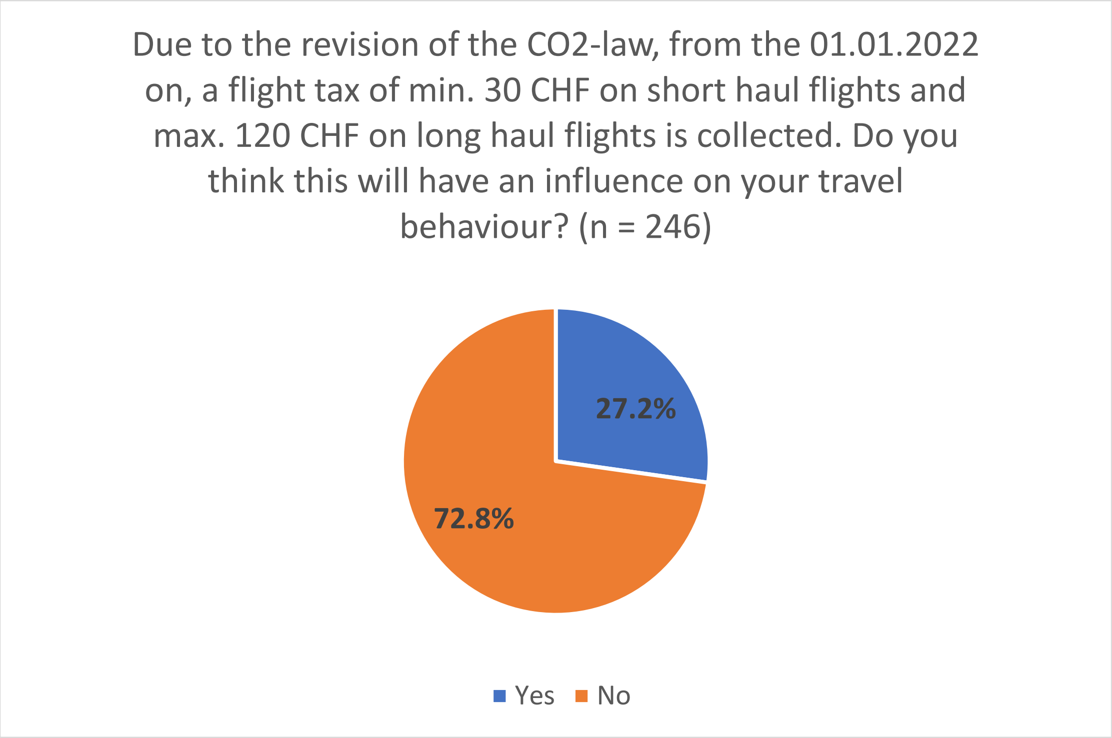

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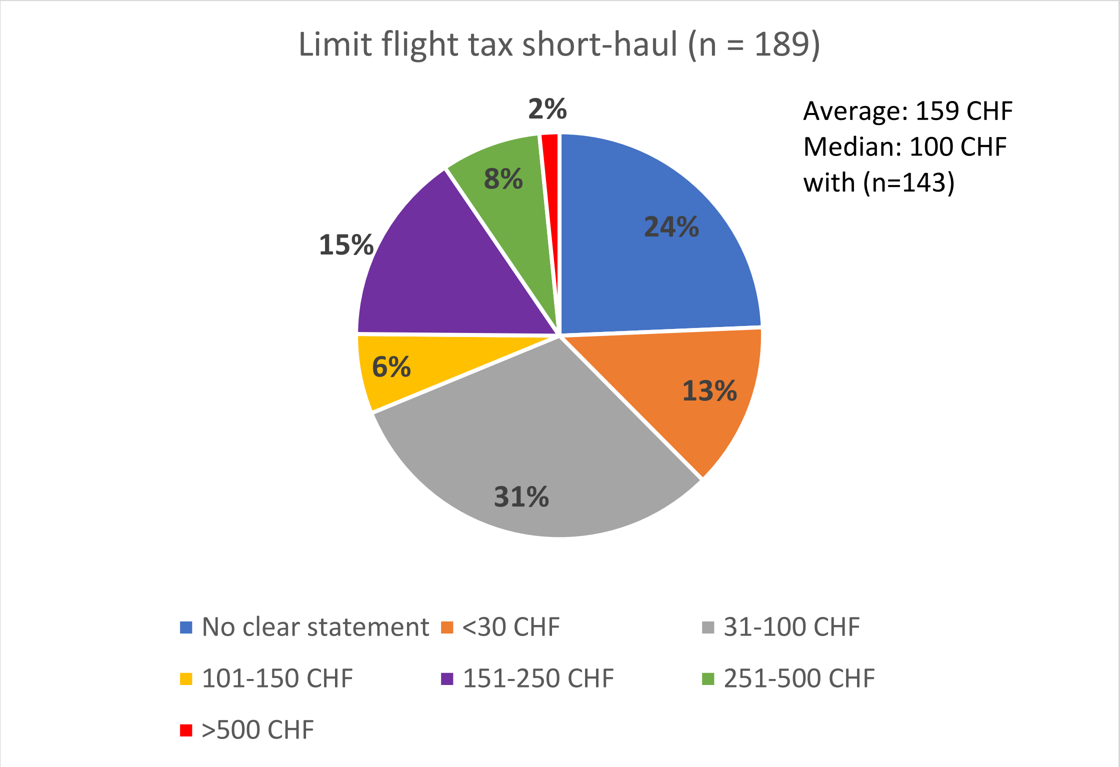
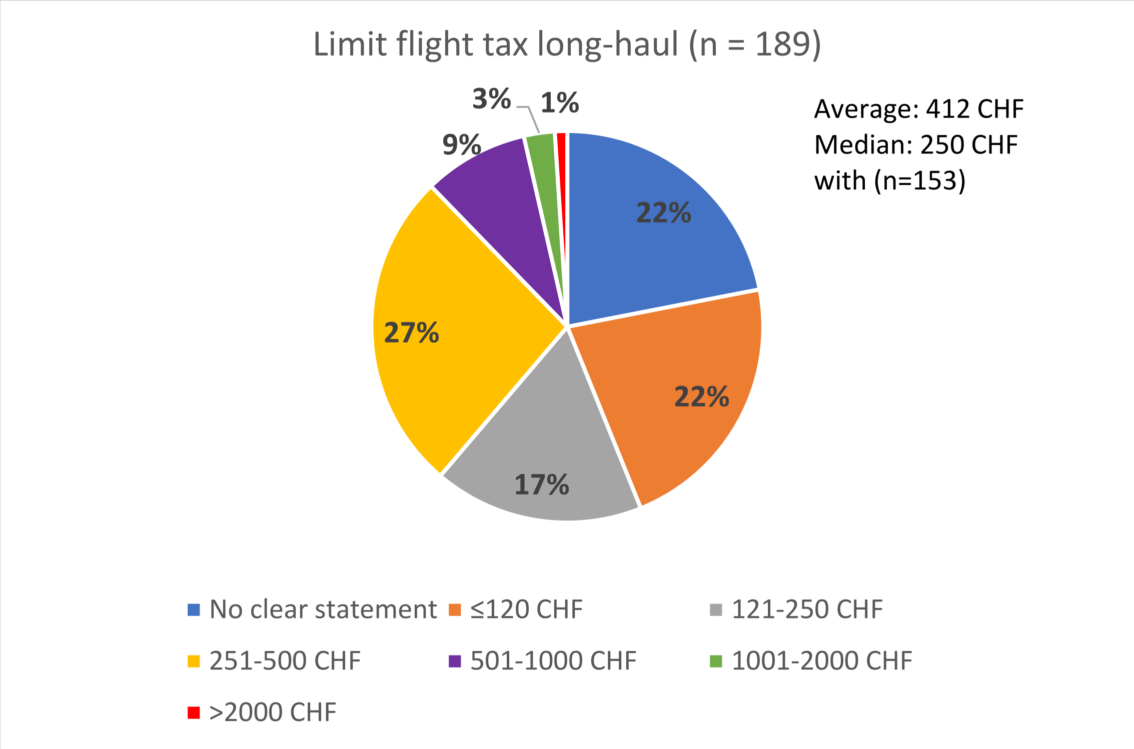
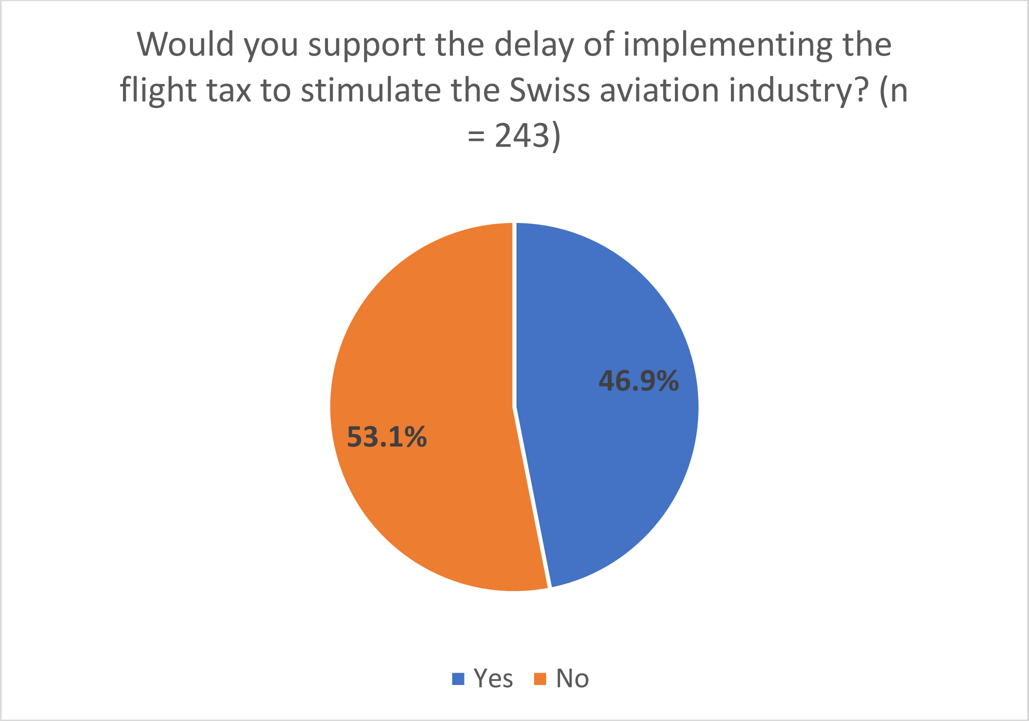


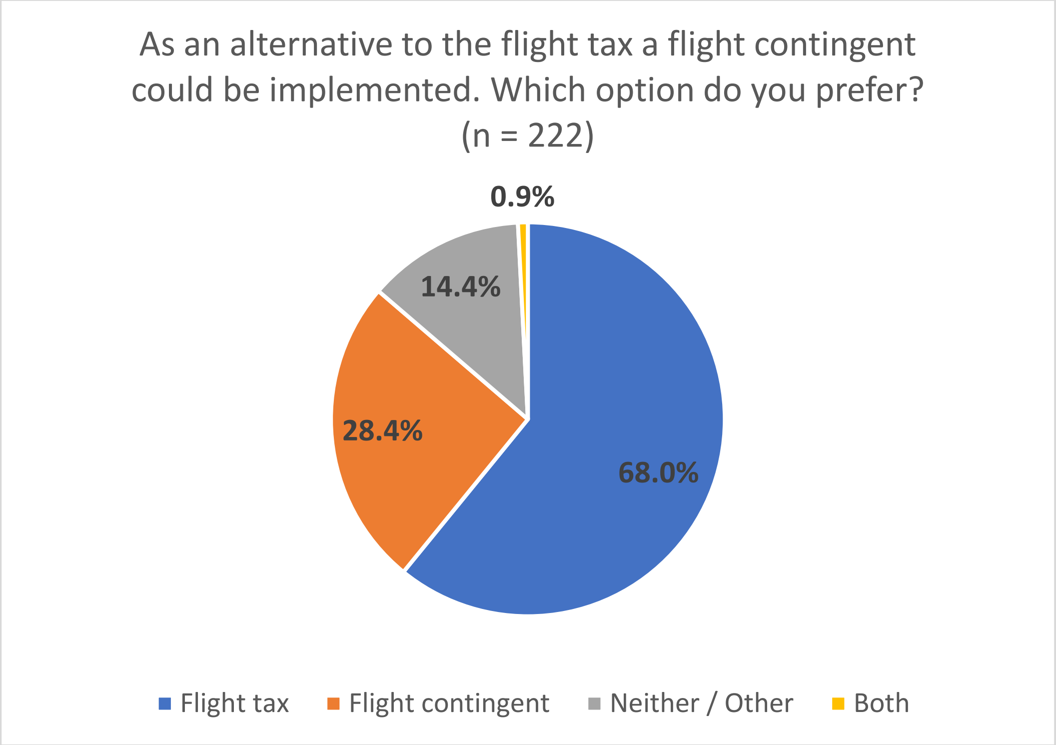
12 If the flight tax mentioned above has no influence on your travel behaviour, what would be your limit on taxes for long haul flights?



13 Would you support the delay of implementing the flight tax to stimulate the Swiss aviation industry?



14 As an alternative to the flight tax a flight contingent could be implemented. Which option do you prefer?



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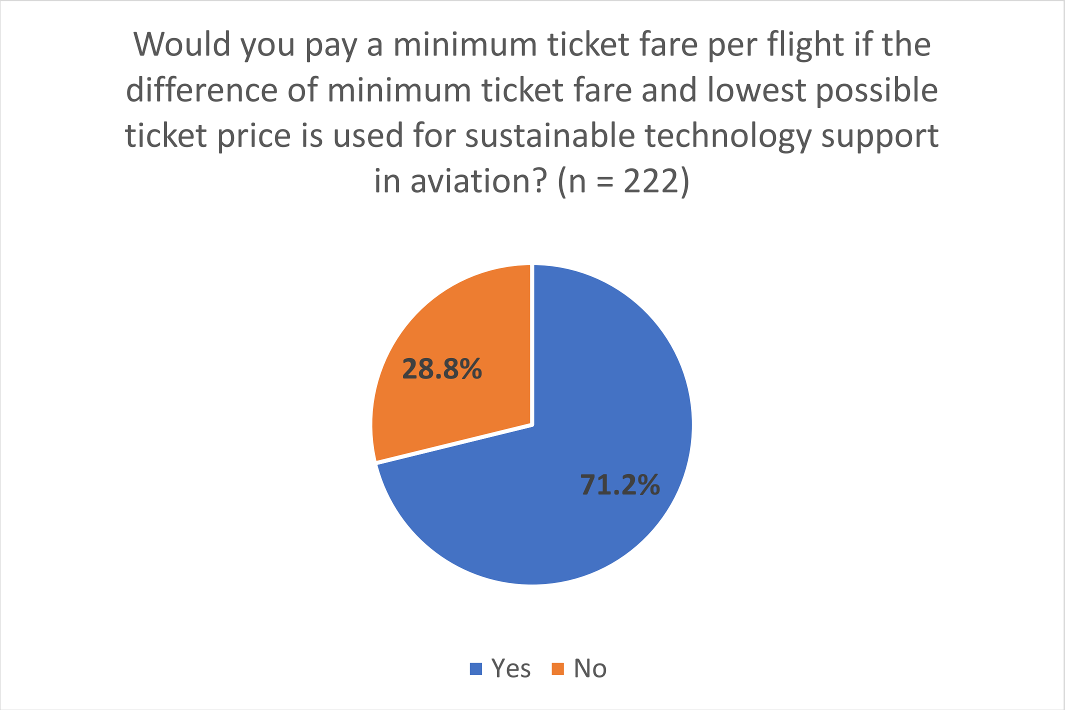
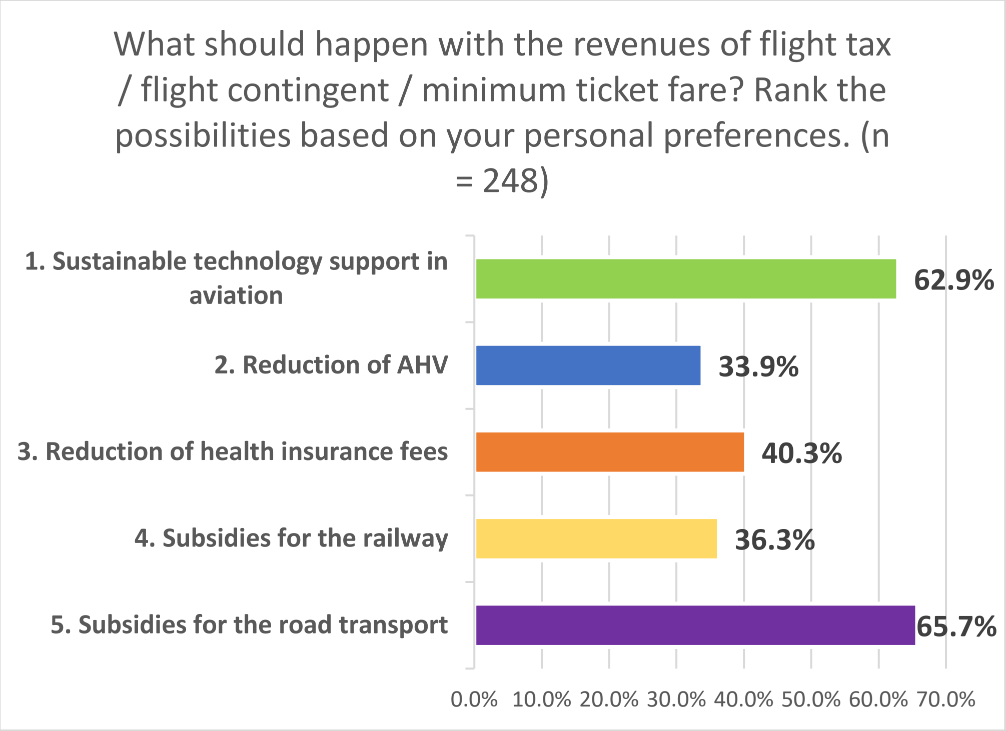


16 What should happen with the revenues of flight tax / flight contingent / minimum ticket fare? Rank the possibilities based on your personal preferences.



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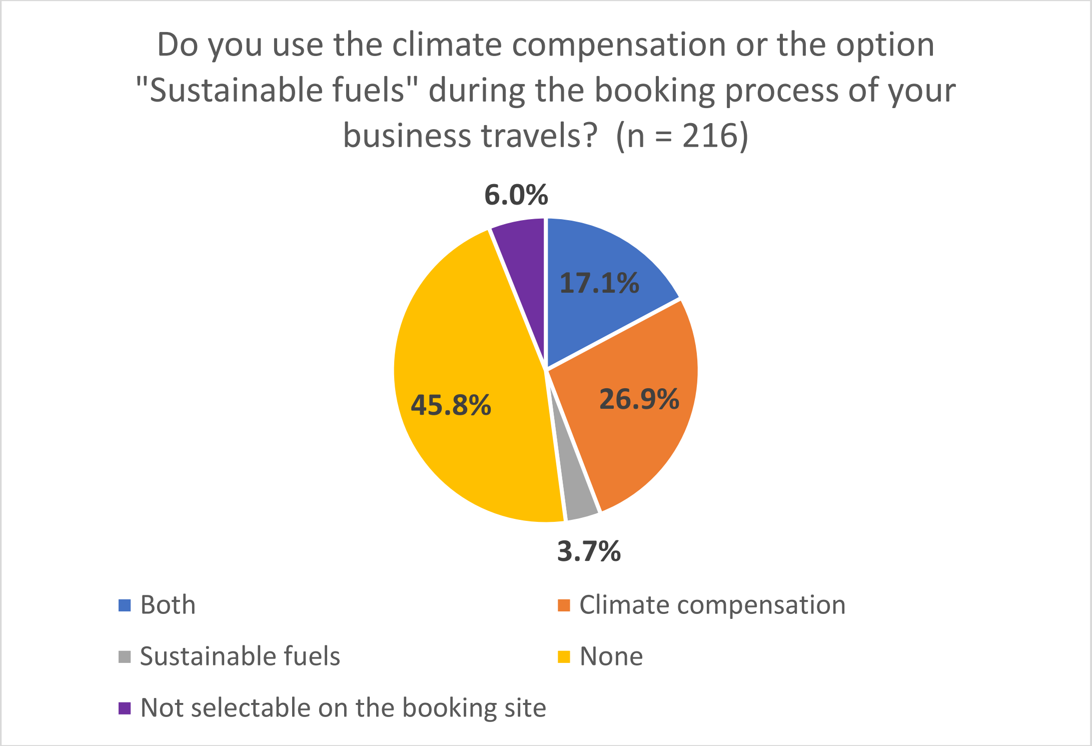

18 Do you use the climate compensation or the option "Sustainable fuels" during the booking process of your private travels?