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# Eco-efficiency in aviation

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**Abstract**

Air traffic guarantees mobility and serves the needs of society to travel over long distances in a decent time. But aviation also contributes to climate change. Here, we present various mitigation options, based on technological and operational measures and present a framework to compare the different mitigation options by taking into account aspects, such as changes in operational costs, climate impact reduction, eco-efficiency, possible starting point of the mitigation option and the investment costs. We show that it is not possible to directly rank these options because of the different requirements and framework conditions. Instead, we introduce two different presentations that take into account these different aspects and serve as a framework for intercomparison.

**Keywords:** WeCare project, climate impact, air traffic

## 1 Introduction

Mobility is important to our society and aviation is providing fast transportation over long distances. However, aviation also contributes to climate change. Aviation emissions of carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), water vapour ($H_2O$), particles, such as sulphates and soot, and the formation of contrails lead to a considerably larger climate impact than the $CO_2$ emissions alone. Estimates for the climate impact from aviation for the year 2005 amount to roughly 5 % of all anthropogenic effects (LEE et al., 2010). In addition, aviation is a growing sector with increasing emissions.

New aviation technologies and operational measures are suggested to reduce the climate impact of aviation (EUROPEAN COMMISION, 2011). Commonly, reductions in $CO_2$ emissions are regarded as an indicator for reducing the climate impact from aviation. Whilst this is generally not plainly false, its use as an indicator for climate impact of individual aviation technologies or air traffic management procedures may largely be misleading. Non-$CO_2$ effects are far too large to be ignored and changes in $CO_2$ emissions may not be taken as indicator for changes in non-$CO_2$ effects. For example, a higher cruise altitude might be beneficial for fuel efficiency and may also reduce the $NO_x$ emissions, but a higher ozone production efficiency at higher cruise altitudes might outweigh the positive effect on climate from higher fuel efficiencies (GREWE et al., 2002; FRÖMMING et al., 2012).

Only recently, a number of studies were published which investigate different options for air traffic routings, as well as aircraft and engine designs, taking into account $CO_2$ and the majority of non-$CO_2$ effects (GREWE et al., 2014; GREWE et al., 2017a). In Section 2 we briefly present technological and operational measures and put them in a broader perspective. Note that there is a broad spectrum of measures in the literature. A complete overview is beyond the scope. We concentrate on those studies, especially in Section 3, which gave an indication of the overall potential to reduce the climate impact from aviation as well as the related costs, i.e. which addressed their eco-efficiency. (Here we define eco-efficiency as the ratio of climate impact changes to cost increases.) In addition, also the different requirements and investments associated with the measure are briefly discussed. In Section 4, we suggest some key parameters which are important with respect to substantially contributing to a 2° target. They form a suitable basis for a common framework which guarantees a more consistent intercomparability of results on eco-efficiency of future aviation technologies, than only comparing emission reductions or climate impact reduction of a mitigation option. Some abbreviations, which are commonly used, are given in Table 1.

## 2 Approaches to reduce the climate impact from aviation

### 2.1 Technical and technological measures

On the technological side the climate impact of aviation can be mainly reduced through improvements in fuel efficiency, e.g. by increasing engine efficiencies, by reducing the aircraft structural mass using e.g. new materials

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**Table 1:** Commonly used abbreviations.

| Abbrev. | Explanation |
|---|---|
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATR | Average Temperature Response |
| ATS | Air Traffic System |
| CI | Cost Index |
| DOC | Direct Operating Cost |
| GWP | Global Warming Potential |
| ISO | Intermediate-Stop Operations |
| NextGen | Next Generation Air Transportation System (American) |
| SESAR | Single European Sky ATM Research Programme (European) |
| SPK | Synthetic Paraffinic Kerosene |
| TBO | Trajectory Based Operations |
| TOW | Take-Off Weight |

or lighter aircraft subsystems and by improved aerodynamics. A large spectrum of concepts and analyses are published (see e.g. IPCC, 1999; Green, 2003; Green, 2005; Maynard et al., 2015, for further information). However, only a few also investigate the climate impact of new technologies (IPCC, 1999; Grewe et al., 2007; Grewe et al., 2010; Grewe et al., 2016). Work is also ongoing to develop new combustor technologies specifically for the reduction of nitrogen oxide emissions. Results from the EU-project AHEAD are one example for a combination of a new combustor technology with an unconventional airframe, i.e. a blended wing body (Rao et al., 2014). In a first combustion chamber liquid hydrogen or liquid natural gas is burnt followed by a flameless combustion of bio kerosene in a second combustion chamber. The concept leads to low $CO_2$, $NO_x$ and particle emissions and to a smaller climate impact compared to conventional technologies (Grewe et al., 2016).

Furthermore, alternative fuels, based on non-fossil sources and following the Jet A1 specification, are promising, in particular to reduce $CO_2$ emissions in the aviation sector (IPCC, 1999). In the European project "Sustainable Way for Alternative Fuels and Energy in Aviation" (SWAFEA) different alternative fuels serving as kerosene substitute were subjected to a life-cycle assessment. Global emission distributions were calculated based on Airbus Global Market Forecast for 2026 both for a conventional kerosene-driven air traffic scenario and a Synthetic Paraffinic Kerosene (SPK) scenario. In the latter one the SPK is assumed to be produced from biomass together with conventional Jet A1 fuel in equal shares. It was found that due to the higher energy content of SPK compared to normal fuel, in general fuel consumption could be reduced leading to less $CO_2$, $H_2O$ and $NO_x$ emissions (Novelli et al., 2011).

## 2.2 Operational measures

### 2.2.1 Reducing the take-off weight (TOW) and increasing aircraft utilization

One way to increase the fuel efficiency of aircraft is to avoid all unnecessary weight during flight, e.g. by an accurate and optimized fuel planning. Also concepts such as the Electronic Flight Bag which eliminates the need for heavy operating manuals on board contribute to reducing the TOW. IPCC (1999) estimated a maximum possible fuel savings of 1–2 % by these measures. However, assuming a given passenger demand for air transport, a payload specific fuel efficiency can also be achieved by better using the aircraft's available capacity, i.e. increasing its load factor. Although this initially seems contradictory to the above statements, in this way the fuel consumption per passenger will be cut down. This may lead to a climate impact reduction as long as the number of flights is reduced consequently (Linke, 2016). Aircraft operators typically try to optimize the vertical profile of a flight as this affects the fuel burn. On long-haul flights, this is particularly true for the cruise phase as this phase is very long compared to climb and descent phases. The altitude at which an aircraft with a given weight and Mach number achieves its maximum specific range is considered as optimum altitude. The optimum altitude increases, with decreasing weight, which results from continuous fuel burn. Therefore pilots perform so called step climbs to adjust to the optimum profile. If the TOW is reduced, the optimum altitude is consequently increased, which may lead to a higher cruise flight profile depending on the TOW reduction. Therefore, besides the fuel saving potential of a TOW reduction measure it has to be noticed that emissions would be released at higher flight levels where, e.g. $NO_x$ emissions have a more severe impact on the climate (Grewe and Stenke, 2008; Köhler et al., 2008; Frömming et al., 2012).

One measure, which is based on the idea of reducing the TOW, is the reduction of the actual fuel quantity required for the trip. For a given transport performance, however, this is possible only if the aircraft is refueled during the mission. For this purpose there are two different approaches: In the civil air-to-air refueling, the aircraft is refueled in-flight at a selected point by a tanker aircraft, which departs from a tanker base nearby. In this concept, the flight time is hardly affected by the refueling process, as it does not require an interruption of the flight; however, due to the additional coordination effort between tankers and users, the concept is not immediately feasible. Nangia (2008) estimates the theoretical fuel savings based on aircraft design considerations by 30–50 % for missions of 6000 nm and 9000 nm length when using an aircraft optimized for a 3000 nm range. These savings already include the fuel consumption of the tanker aircraft. The actual values strongly depend on the ratio between the fuel provided by the tanker and the mission fuel of the tanker itself. Savings of more than 30 % can be achieved, if this ratio is greater than or equal to 2. Analyses in the EU project RECREATE have shown that in a transatlantic traffic scenario in which realistic and optimal tanker bases are considered only about 10 % of fuel may be saved by air-to-air refueling operationally (Morschek, 2014). Implications of that concept to the climate have not been investigated so far.

Another approach is to conduct a stopover at a suitable airport to refuel the aircraft. This concept is also known as "Intermediate Stop Operations" (ISO). Due to the additional landing and take-off as well as a taxiing and refueling phase on the ground there is a flight time penalty, which is even exacerbated by not optimally located airports. However, in contrast to other concepts it is possible to implement ISO instantly without further action. In a recent study, Linke (2016) have quantified the short-term fuel saving potential of ISO by 4.8 % globally taking into account real-world long-haul flight routes and airport locations. Furthermore, the effect of wind was considered. It was found, that due to the significant reduction of the aircraft's TOW on the first leg of the stopover mission, the optimum altitude shifts up considerably. Assuming that aircraft operators try to follow the optimum altitude profile as long as ATM constraints permit, there is a global shift of cruise emissions up by 4000–6000 ft on average. A quantification of the corresponding climate impact using a climate response model revealed that this leads to an increase of the Average Temperature Response over the next 100 years (ATR100) by 2.3 % through ISO compared to the reference direct flight scenario. The warming effects caused mainly by ozone and water vapour concentration perturbations dominate the impact from other radiative forcing agents, i.e. cooling from less $CO_2$ and contrails.

### 2.2.2 Variation of air speed

The choice of cruise speed influences the direct operating cost (DOC) of a flight as it affects flight time and fuel consumption. The cruise Mach number, which leads to minimum cruise costs, $M_{ECON}$, which plays a crucial role in flight planning processes today is, depending on the Cost Index (CI) set by the aircraft operator, above the Mach number the maximum range can be achieved with, $M_{MRC}$. The CI is defined as the ratio between time-related cost per minute of flight and the cost of fuel per kg and provides flexibility to the operator to control fuel burn and flight time based on operational priorities. A reduction of the speed, down to a minimum fuel consumption results in $M_{MRC}$ on the mission and thus leads to the lowest release of engine exhaust gases, such as $CO_2$ and $NO_x$. However, with a $CI > 0$, DOC will inevitably increase. Moreover, it has to be noticed that in doing so the productivity, i.e. payload times speed, of the airline's fleet is reduced. According to Bonnefoy and Hansman (2010), this could be compensated for by minor adjustments in the flight plan, therefore a reduced cruise speed may become more attractive for aircraft operators in a scenario with rising fuel prices and environmental fees. While with new aircraft designed for lower speeds, the fuel consumption could be reduced by approximately 40 % (Bonnefoy and Hansman, 2010, speed reduction by 5–10 %). The study refers to a next generation subsonic jet aircraft and the reduction results from a 14 % structural weight reduction, 38 % increase of L/D and 6 % thrust specific fuel consumption of the engines. Higher benefits may be achieved in case of Turboprop configurations. The potential savings for existing aircraft only amount to 1–2 % for a speed reduction of 3–5 % (Airbus Customer Services, 2004; IPCC, 1999).

### 2.2.3 Variation of altitude

There have been various studies on the influence of altitude on emissions and climate impact of aviation (e.g. Fichter et al., 2005; Fichter, 2009; Schwartz Dallara et al., 2011; Koch, 2013). For a purely operational change of typical cruise altitudes without any structural adjustments to the aircraft design the TRADEOFF project (Frömming et al., 2012) is referenced. In summary, it was found that there is a reduction in the global coverage of line-shaped contrails if cruise altitude is lowered; flying higher accordingly leads to increased contrail formation. Frömming et al. (2012) did not investigate contrail-cirrus, but newer studies support this finding also for contrail-cirrus (U. Burkhardt personal communication; see also Dahlmann et al., 2016, supplement). The total ozone contribution of aviation can also be reduced by choosing lower altitudes; higher altitudes cause an increase in the ozone concentration. The methane lifetime increases slightly at higher flight levels and can be reduced at lower altitudes. Due to the increased fuel consumption at lower altitude caused by an inefficient operating point there is an additional release of carbon dioxide, which leads to a long-term increase in global $CO_2$ concentration due to its long atmospheric lifetime. The increasing $H_2O$ emissions at lower flight levels remain less long in the atmosphere, leading to lower mass mixing ratios (= mass of water vapour per mass of dry air, also known as specific humidity) than at higher cruising altitudes. In total, for a cruise altitude reduction these effects eventually lead to a short-term radiative forcing reduction as well as to a reduced average temperature change in the long-term.

Similarly, in the project CATS the climate impact reduction potential by an optimization of flight profiles was examined. In a fleet-wide analysis including all flights operated by A330-200 aircraft it was found that lowering the mean initial cruise altitude from 37,000 ft to about 26,000 ft a reduction of the mission-specific 100 year Average Temperature Response by roughly 40 % would be possible. However, this change goes hand in hand with a 10 % increase in DOC and also requires a reduction in the cruise Mach number from 0.81 to 0.71 (Koch, 2013; Dahlmann et al., 2016). Note that cruise altitude and speed changes are not performed uniformly as in TRADEOFF, but an altitude and speed change is determined for each individual flight of the route network considered.

## 2.3 More efficient and environmentally friendly routing

As part of the ongoing harmonization of the European and U.S. ATM systems in SESAR and NextGen

**Table 2:** Overview on research projects on eco-efficiency (eco-efficiency figures given as ratios of possible relative reduction in climate impact and relative cost increase).

| Scope | Project | favourable | maximum | start | Requirements | Comment | reference |
|---|---|---|---|---|---|---|---|
| | | eco-efficiency | | | | | |
| General cruise altitude changes | TRADEOFF | 16 % : 5 % | 22 % : 6 % | 2015 | None | | Frömming et al. (2012) |
| Route-adapted cruise altitude changes | CATS | 31 % : 5 % | 64 % : 32 % | 2015 | None | | Koch (2013);<br>Dahlmann (2012) |
| Route-adapted cruise altitude changes with aircraft re-design | CATS-Redesign | 46 % : 5 % | 66 % : 29 % | 2025 | Aircraft re-design | 32 % : 0 % also feasible | Koch (2013);<br>Dahlmann (2012) |
| Intermediate Stop Operations with today's aircraft | WeCare-ISO | eco-efficient on select routes only | | 2015 | Infrastructure at some affected airports | | Linke (2016) |
| Intermediate Stop Operations with aircraft re-design | single studies (ISO-Redesign) | 13 % : −8 % | – : – | 2025 | Aircraft re-design and airport infrastructure | Generic mission analysis; GWP: NPV (20 years); cost reduction | Creemers and Slingerland (2007);<br>Langhans et al. (2013) |
| Weather adapted routing | REACT4C | 25 % : 0.5 % | 60 % : 15 % | 2025 | Forecast of climate sensitive regions | Case study; Impact on ATC | Grewe et al. (2014) |
| Closing Airspace (climate sensitive regions) | WeCare-CAS | 20 % : 0.5 % | – : – | 2020 | Forecast of climate sensitive regions | Only scoping study | Niklass et al. (2015) |
| Multi-fuel blended wing body | AHEAD | – | 25 % | 2050 | new engine and aircraft design | | Rao et al. (2014);<br>Grewe et al. (2016) |

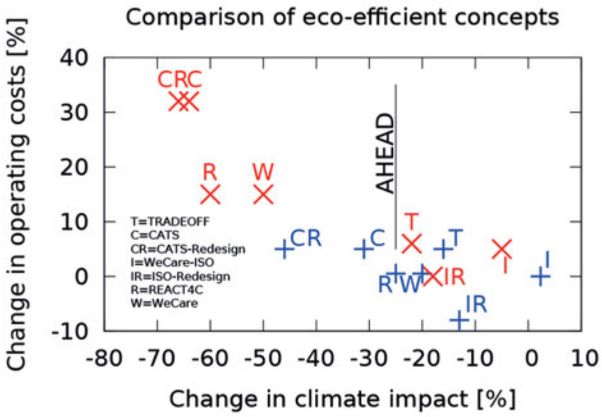

**Figure 1:** Intercomparison of different eco-efficient concepts. Details are given in Table 2. Blue crosses indicate favourable eco-efficient relations and red crosses maximum possible climate impact reductions. For ISO not all data are available. Hence we estimated values for the maximum possible climate impact (I, red) based on a most promising subset of the trajectories analysed in Linke (2016). The ratio between those two values is also taken to estimate the respective value for the ISO-Redesign case (IR, red).

new technologies and solutions are being implemented, which aim at increasing the efficiency of air transport. The potential to reduce fuel consumption through improvements in ATM was estimated by IPCC (1999) with globally 6–12 % per flight citing studies by EUROCONTROL, the FAA and ICAO. CANSO (Civil Air Navigation Services Organization) indicated inefficiency for Europe, the U.S. and Australia in 2007 of about 6–8 % (CANSO, 2012), which can be mainly attributed to the existing rigid ATM infrastructure and fixed ATS routes. In the long term concepts such as Direct Routing, Free Routing as well as Trajectory Based Operations (TBO) will allow for the stepwise approximation of planned and realistic trajectories to the optimal trajectories. TBO will be based on a decoupling of the flight path from the rigid physical ATM/CNS infrastructure (e.g. radio navigational aids). However, an essential prerequisite for the realization of optimal trajectories is a precise and continuously adapted flight planning process which requires accurate meteorological data (in particular weather forecasts) as well as System Wide Information Management (SWIM) and data link technologies providing means for the transmission of data between ground stations and the flight deck.

The term "optimal trajectory" may be defined differently based on the routing strategy of the individual aircraft operator. Besides the present-day economic flight planning (minimization of DOC) it is conceivable that in the future also routes with reduced climate impact will be important. Based on this assumption, the potential for reducing the climate impact of aviation by an altered routing strategy was examined in the project REACT4C (www.react4c.eu). A possibility of reducing the climate impact by 25 % in terms of the Absolute Global Warming Potential (over the period of 100 years) on westbound flights was found for one specific winter weather situation (Grewe et al., 2014). Eastbound flight showed, for this weather situation, smaller climate impact reductions since those flights take advantage of the tail winds of the jet stream. The additional operating costs for this re-routing options were found to be in the order of 0.5 %. Larger reduction in climate impact of around 60 % were feasible, however at much larger costs of around 15 %. Within the project WeCare (Grewe et al., 2017b), a scoping study showed that a large part of this climate impact reduction potential can be raised by closing airspace, which is very climate sensitive (Niklass et al., 2015).

### 2.4 Combination of operational and technological measures

It should be noticed that the above mentioned operational mitigation options have been discussed assuming that changes are applied solely to the way the aircraft is operated, but no design changes were made to the vehicles themselves. It can be expected that by adapting the aircraft design to new operating conditions (e.g. lower cruise altitude, lower cruise mach number, reduced range) the achievable benefits could even be augmented. In the ISO case (similar for air-to-air refueling), there is unnecessary structural weight carried along the mission as much of the fuel tank volume is not required any longer. Redesigning the aircraft for shorter ranges could lead to fuel savings between 13 % and 23 % (e.g., Green, 2006; Hahn, 2007; Poll, 2011; Langhans et al., 2013) on one-stopover missions benefiting from snowball effects. Until now, the implications from ISO on global emissions and climate using optimized aircraft have not been analyzed system-wide. However, Creemers and Slingerland (2007) have estimated the Global Warming Potential (GWP) caused by an aircraft redesigned for ISO using a simplified altitude-dependent emission-climate model. According to the authors, an aircraft designed for a 3600 nm range operated in ISO mode may reduce the GWP on generic missions with ideal stopover locations by 13 %. For a similar design, in a separate study by Langhans et al. (2013) it was found that over an aircraft's life-cycle of 20 years the net present value (NPV) at the end would increase by approximately 8 % due to ISO although initial investments for the introduction are necessary. NPV is a financial measurement that considers incoming and outgoing cash flows over a period of time, e.g. the life-cycle of an aircraft, and hence allows for a comparison of investments. Therefore, in contrast to other mentioned eco-efficient concepts that are characterized by climate impact reduction potentials at the expense of costs, ISO with redesigned aircraft could both reduce climate impact and operational costs.

The adaptation of the aircraft vehicle to climate-optimized cruise operating conditions (reduced cruise altitude and mach number) was investigated in the project CATS, showing that the adaptation of the aircraft design to a slightly lower cruise speed and altitude leads to a slightly larger reduction in climate impact, however at largely reduced costs of operation (Koch et al., 2011; Koch, 2013; Dahlmann et al., 2016).

## 3 Summary of eco-efficient mitigation options

From the last section it becomes clear that numerous options were discussed to reduce aviation's climate impact. Table 2 summarises those findings, which include a climate impact analysis and Figure 1 summarises the relation between climate impact reduction and cost increase. Note that aircraft type and operation, as well as the climate metric selected, differ. Results from the TRADEOFF and CATS projects (see Section 2.2.3), show climate impact reduction of 15 to 30 % at a cost increase of 5 % for general altitude changes. In principle, these procedures could be implemented today without any further requirements, such as investments for re-design, etc. Still, incentives would be necessary to cope with cost increases and air space capacities have to be considered. However, this is beyond the scope of our study. Here we concentrate on how to compare on a theoretical basis the different mitigation options.

The CATS-Redesign (Table 2 and Figure 1) clearly enhances the climate impact reduction from 30 % to 40 % at the same cost increase of 5 %. However, it also requires investments in the redesign and hence can be implemented only at a much later stage than without a change of the aircraft design. Similarly, for the other studies, such as REACT4C, WeCare and AHEAD, we find different general frameworks. The mitigation options differ in

1. climate impact reduction potential,
2. change in operating costs,
3. eco-efficiency: relation between climate impact reduction and change in operating costs,
4. earliest date of implementation, and
5. additional costs, such as enhanced controllers work load, investments in re-design, extra infrastructure.

A straight forward intercomparison of the climate impact reduction potentials and operating costs as in Figure 1, neglects these different aspects and strongly limits the information value.

## 4 A framework for assessing eco-efficiency

In this Section, we now present in Figure 2 and 3 the mitigation options listed in Table 2, in two different designs. They include all five aspects raised in the last Section, which are abbreviated with “Eco-efficiency”, “Climate”, “Operating costs”, “Starting Time”, and “Investments” in Figure 2. The individual axes are scaled in a way that the most promising value is always at the end point of either axis, for example the axis “Climate” indicates the further away from the center, the larger is the climate impact reduction, or for “Investments”, the further away from the center, the smaller is the investment (see inlay in Figure 2). These parameters form the basis of the common framework.

Hence, the area the net spans gives a first indication on the quality of a mitigation option. However, comparing different options requires further information. Clearly, the different mitigation options span very different areas. Some are more located in the lower left,

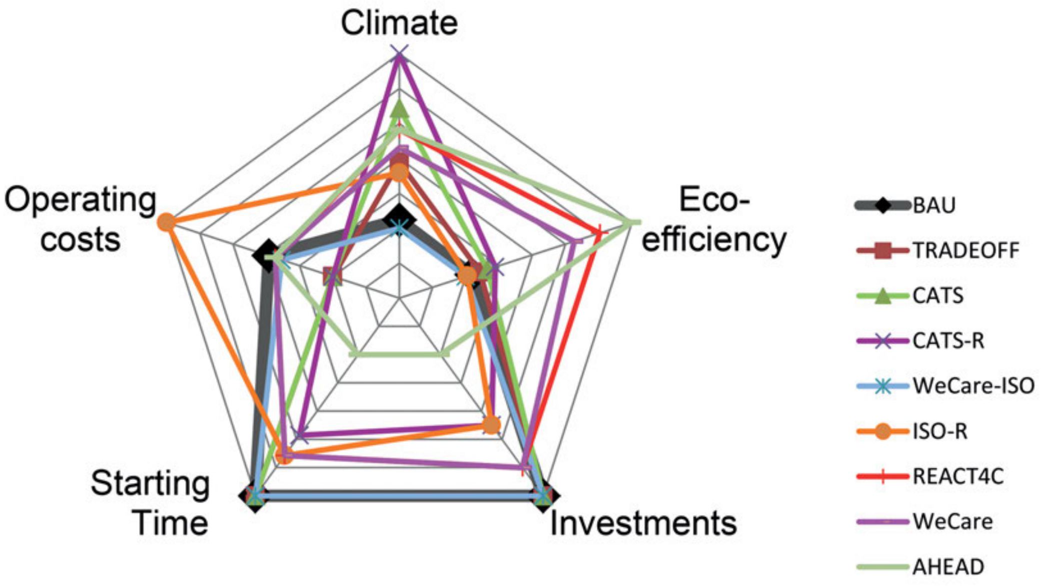

**Figure 2:** Multi-dimensional presentation of different mitigation options. Each axis is scaled such that the most desirable effect is on the outer edge (see inlay). Here most desirable are: Large climate impact reduction, low operational and investment costs, large eco-efficiency (ratio of climate impact reduction and costs increase), and early starting point of the mitigation option, i.e. time of implementation. The thick black line shows a business-as-usual (BAU) reference situation. For the AHEAD results, we have assumed low additional operational costs, i.e., the operational costs of such an aircraft are similar to those of a conventional aircraft.

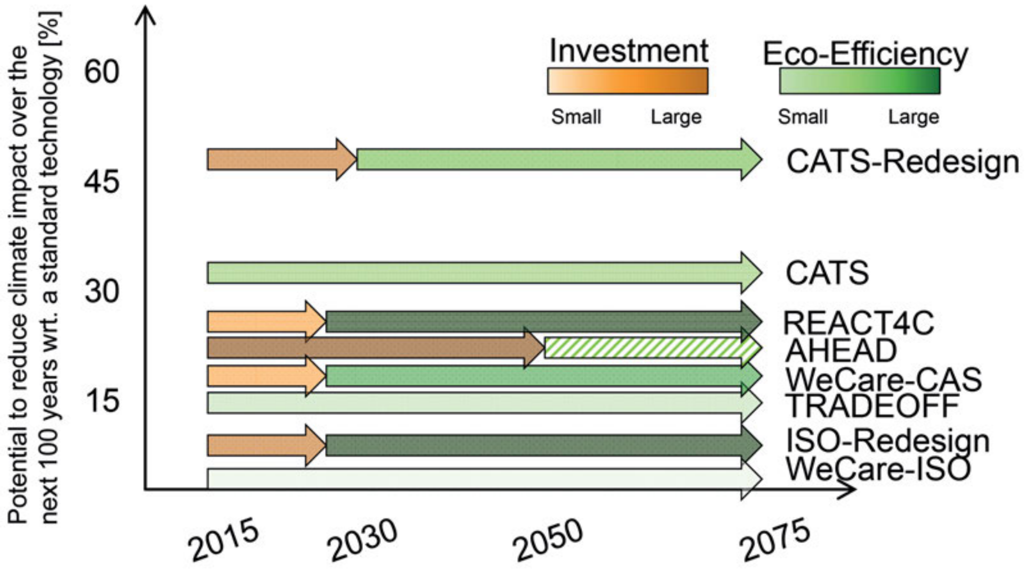

**Figure 3:** Multi-dimensional presentation of different mitigation options. By contrast to Figure 2, here we show the same kind of information on the different mitigation options, but more focusing on their starting point and climate impact reduction potential (*x*- and *y*-axis). The investment costs are indicated in brown colours, with light brown for low investment costs and dark brown for high costs. The eco-efficiency is indicated in green colours, with light green for low efficiency and dark green large eco-efficiency. Since no costs are quantified for AHEAD, we dashed the arrow to indicate an expectation.

with low investments, low operational costs, low climate impact reductions, but also characterized by an early possible starting point (TRADEOFF and CATS). In contrast, the AHEAD mitigation option spans more to the upper right with a high eco-efficiency, but large investments, and a late starting point. Figure 3 shows the same data, but focuses more on the time, when the individual mitigation option may become operational. The total climate impact reduction is presented on the *y*-axis, whereas the other aspects, such as costs of the investment and eco-efficiency are indicated by colours, brown and green, respectively. Clearly, both figures (2 and 3) show the complexity of comparing different mitigation options. A clear preference for one or another mitigation option, or even a ranking of mitigation options is not directly possible. However, these presentations offer the possibility to indicate the eco-efficiency and framework conditions of individual mitigation options. Note that we have limited the number of parameters to those which can be assessed based on existing literature. Other aspects, such as risk assessment, air space capacity, impacts on airports, ect. even may add more complexity.

## 5 Conclusion

We have presented a number of possibilities, which are suitable to reduce the climate impact of aviation. They comprise mainly operational measures, but also include a future aircraft technology. We are focusing on those studies, which include a considerable investigation of the climate impact, i.e., effects such as concentration changes of $CO_2$, ozone, methane, and contrail-cirrus.

It would be desirable to compare the individual mitigation options with respect to their eco-efficiency. However, we clearly show that the framing conditions, such as starting point of implementation, cost of investments for, e.g., redesign of an aircraft, additional controller's workload, and additional infrastructure, inhibit a clear comparison and ranking of mitigation options and measures.

In order to overcome this problem, we present two multi-dimensional diagrams, which include information on operational costs, climate impact reduction potential, eco-efficiency, investment costs and the possible starting point of the mitigation option. The presentations clearly show the different aspects of the individual mitigation options and can therefore serve as basis for decision-making.

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