

# THE 2° TARGET REVISITED: CLIMATE-ECOLOGICAL ASSESSMENT LOOP AND CONCEPTUAL FOUNDATION FOR AIR TRANSPORTATION SYSTEM RE-ENGINEERING

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## ABSTRACT

Climatologists around Meinshausen [1] calculated in a probabilistic approach that for a given probability to stay below 2° global warming, there is a certain budget of CO<sub>2</sub> emissions worldwide, which must not be exceeded. If this is true, the air transportation system as a part of the overall global industrial system needs to be renovated in order to achieve the 2° target. The research question is: How big is the responsibility for the aviation industry and what consequences for the ATS and aircraft design emerge out of the carbon budget considerations? Quantitative scenarios as a part of a climate-ecological assessment loop and an ATS re-engineering model are developed to gain insight in necessary technology decisions in order to achieve a certain climate target and to analyze implications of different zero emission aircraft entry into service patterns using forward and backward oriented scenario methods. The main goal of this paper is to close the conceptual gap between a global climate target, climate-ecological assessment in aviation and climate related requirements deduction for future aircrafts.

## 1. POSSIBLE CONSEQUENCES OF NOT REACHING THE 2° TARGET

The recent report "Turn Down the Heat" for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics [2] says that without strategic changes, in an BAU<sup>1</sup>-scenario, CO<sub>2</sub> emissions will result in a global warming of 3.5 to 4 °C by the end of the century. It also states that "the 4 °C scenarios are devastating". The report paints a picture resulting in major risks for fresh water supply, extreme weather events and food production, thus life quality. Scientists agree more or less that this scenario of an unwanted future of "too dangerous" climate change impacts can be avoided by staying below 2 °C global warming.

The report further says: "If [the current mitigation commitments] are not met, a warming of 4 °C could occur as early as the 2060s." The forthcoming Fifth Assessment Report of the IPCC in 2013/14 is supposed to provide more comprehensive scientific assessments and climate change impact scenarios. Climate change will lead to environmental pressures on the "water-food-energy nexus" as explained in the Global Risks 2011 Report. [3] Hansen et al. 2008 [4] state that "there is a danger that human-made forcings could drive the climate system beyond tipping points such that change proceeds out of our control". The 2° target has been adopted by the European Council in 2005 [5] and it was noted that "that there is increasing scientific evidence that the benefits of limiting overall global annual mean surface temperature increase to 2 °C above pre-industrial levels outweigh the costs of abatement policies".

The International Energy Agency states in its latest special report that currently "[...] global action is not yet sufficient to limit the global temperature rise to 2 °C [...]" and that "[...] the long-term average temperature increase is more likely to be between 3.6 °C and 5.3 °C." [6]

Secretary-General of the UN Security Council, Ban Ki-moon,

points out that "climate change is real and accelerating in a dangerous manner". He underlines that climate change "not only exacerbates threats to international peace and security; it is a threat to international peace and security." [7]

Further, Hansen et al. [8] suggest that even limiting global warming to 2 °C compared to pre-industrial levels is maybe not sufficient due to nonlinear effects and reinforcing feedbacks of the climate system.

Even though, there are deviating perspectives about climate change and the contribution of mankind, this study builds upon prevalent research as in [1] and [9]. The hypothesis for this paper is that 2° is a suitable target and that there is a carbon budget for humanity related to that target.

## 2. APPROACH

Whereas previous research in aviation science was mainly focused on calculating the climate impact of aviation, estimating the potential savings by different mitigation procedures and building fuel consumption scenarios, this study aims to integrate these findings plus a potential global climate target into one model in order to develop a model-based quantitative approach to build scenarios. The purpose of the scenario methodology is not to present the most accurate results possible, but to enhance the contextual awareness about how things are related to each other and what decision would lead to what kind of consequence in the future.

The usefulness of the method presented here is given by the clarification quantified scenarios can give in order to specify the degree of radicality (evolutionary vs. revolutionary aircraft concepts) to which decisions have to be made in order to achieve a certain climate target.

First, out of the illustrative default graph of the probabilistic carbon budget analysis of Meinshausen et al. [1], parametric civil aviation carbon budget cases are built (see FIG 1). The civil aviation carbon expense is then contrasted with the budget cases using scenario analysis. As all forecasting

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<sup>1</sup> business as usual

scenarios showed an inevitable budget overrun sooner or later, backcasting techniques are applied to find out under which conditions a determined climate target can be attained. The backcasting techniques aim to model a transition of the world fleet over time by simulating different zero emission aircraft introduction patterns (see FIG 4). This is realized by using the FFWD<sup>2</sup>-model [10] because it is able to decompose the world fleet of civil passenger aircrafts over time into seat categories and aircraft types that have a capacity of 50 pax and more. Since a great part of the climate impact caused by civil aviation is from non-CO<sub>2</sub> agents, it is necessary to develop a general model which allows a climate-ecological assessment of different future aircraft designs including revolutionary propulsion systems. A general approach allows assessing very different means to mitigate the climate impact of civil aviation, always in relation to a determined climate target. These can range from operational procedures of flying lower and slower to future aircrafts with revolutionary propulsion systems such as hybrid electric aircrafts (HEAC) or zero emission aircrafts (ZEAC) as in [12] [13]. A general model of climate-ecological assessment further allows assessing any combination of mitigating procedures, new aircrafts and demand growth. Because it is necessary to rethink the overall ATS in order to achieve a climate target, the climate-ecological assessment loop model needs to be complemented with an ATS re-engineering model (see FIG 6). This study is entirely theoretical and aims to explore possible fossil fuel phase-out scenarios.

### 3. CARBON BUDGET

#### 3.1. Introduction to Carbon Budget Thinking

In a probabilistic approach climatologists calculated with which probability the 2° target can be achieved in dependence of the amount of CO<sub>2</sub> emitted in the time period between 2000 and 2049. The estimation states that if less than 886 GtCO<sub>2</sub> are released globally during that period the chances are 80% that global warming will stay below 2 °C. [1] It has been estimated that in the years 2000 to 2010 already approximately 321 GtCO<sub>2</sub> including land use change have been emitted. [14] This may leave 565 GtCO<sub>2</sub> for the period 2011-2049. The transfer function between future CO<sub>2</sub> emissions and the probability of exceeding 2 °C is depicted in FIG 1.

The total remaining fossil fuel reserves may be equivalent to approximately 2795 GtCO<sub>2</sub> and therefore higher than the remaining carbon budget in order to stay below 2 °C global warming. [14] The difference between the corresponding CO<sub>2</sub> emissions of all proven reserves and the carbon budget are technically unburnable in order not to exceed 2° global warming. This is why this difference is called "unburnable fuel" or "unburnable reserves". To achieve the climate target crude oil and other fossil energy reserves would have to be left under the earth surface or mustn't be burned without carbon capture and storage technologies (CCS). For this study the illustrative default case of [1] has been used.

That means that the climate target is maybe a much harder constraint to mobility and aviation than the peak of fossil

fuel considering the relatively small remaining carbon budget compared to the total physical fossil fuel reserves.

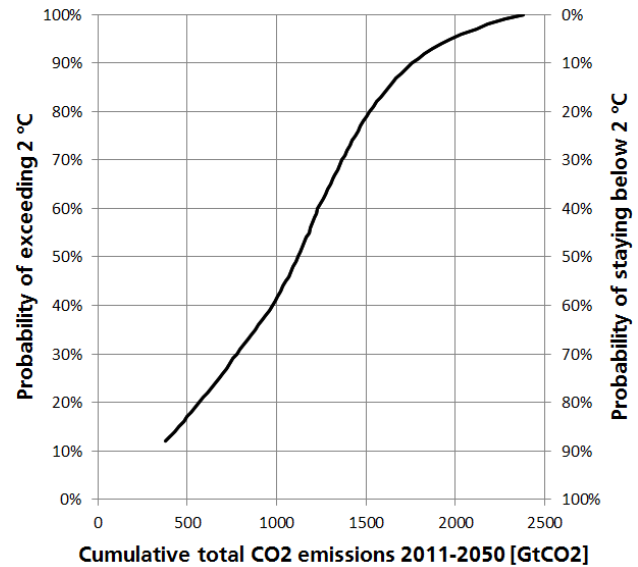


FIG 1. Total remaining carbon budget to limit global warming to 2°C (illustrative default of [1])

To get a better overview over the world total remaining carbon budget from 2011 until 2050, 3 cases are listed in TAB 1. [1]

Case No.	Probability of staying below 2°	Emitting period	Remaining carbon budget 2011-2049
1	80%	2011-2049	565 GtCO <sub>2</sub>
2	75%	2011-2049	679 GtCO <sub>2</sub>
3	60%	2011-2049	979 GtCO <sub>2</sub>

TAB 1. Total carbon budget cases for the 2011-2049 period

In [15] it is stated that "[...] emissions after 2050 also matter for global temperatures." The models used to estimate the carbon budgets run beyond 2050 as can be seen in [16]. This means that there are implications concerning the remaining carbon budget in the period from 2050 to 2100. It is estimated that post-2050 carbon budget for a 80% probability of staying below the threshold of 2 °C warming will then be approximately 75 GtCO<sub>2</sub>. The post-2050 budget is that small because the cumulative effect of the emissions in the pre-2050 period will still be existent. [15] This results in an estimated total remaining budget from 2011 until 2100 of about 640 GtCO<sub>2</sub>.

#### 3.2. Remaining Aviation Carbon Budget

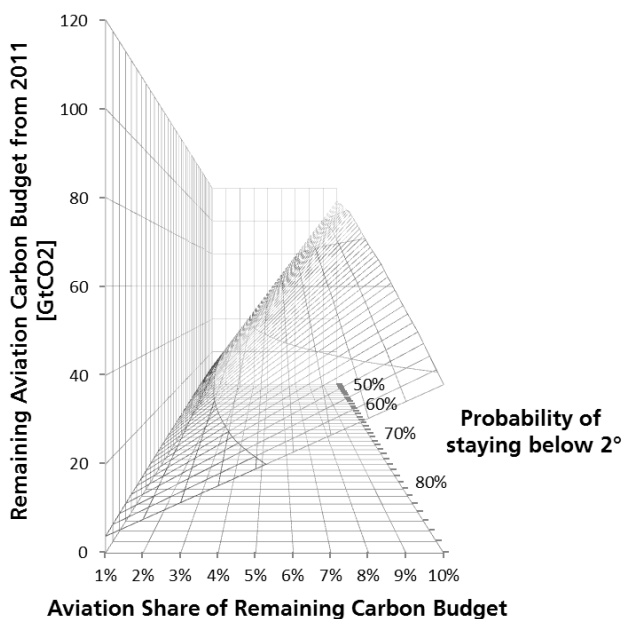
From the general carbon budget for entire humanity the share for civil aviation would have to be elaborated. At the moment aviation accounts for about 2 to 3% of the global CO<sub>2</sub> emissions, but may contribute between 3-8% [17] to anthropogenic global warming because of greater impacts caused by non-CO<sub>2</sub> climate change agents emitted in higher altitudes. The total economic impact of the air transport industry including direct, indirect, induced and tourism catalytic effects was estimated in 2011 by the Air Transportation Action Group (ATAG) at 3.5% of the global GDP. [18] The numbers shall only serve as a point of

<sup>2</sup> Fast-Forward: world fleet forecasting model

reference. It has to be kept in mind that these numbers are not natural constants and therefore the aviation share of total carbon budget is rather to be negotiated than calculated. The basic question is: How much is humanity willing to “invest” out of its fixed remaining carbon budget for aviation? This is not a question that can be resolved scientifically. Therefore a parametric study is conducted at this point. The values for a 1% to 10% share of the total budget are graphically displayed in FIG 2. The parametric study depicted in FIG 2 shows the estimated remaining carbon budget for civil aviation from 2011 to 2049 as a function of the probability of staying below 2 °C global warming and the percentage share of the remaining carbon budget that is conceded to aviation.

Case No.	Probability of staying below 2°	Civil aviation share of global budget 2011-2049	Remaining civil aviation carbon budget 2011-2049
1.1	80%	2%	11.3 GtCO <sub>2</sub>
1.2		4%	22.6 GtCO <sub>2</sub>
1.3		6%	33.9 GtCO <sub>2</sub>
1.4		8%	45.2 GtCO <sub>2</sub>
1.5		10%	56.5 GtCO <sub>2</sub>
2.1	75%	2%	13.6 GtCO <sub>2</sub>
2.2		4%	27.2 GtCO <sub>2</sub>
2.3		6%	40.7 GtCO <sub>2</sub>
2.4		8%	54.3 GtCO <sub>2</sub>
2.5		10%	67.9 GtCO <sub>2</sub>
3.1	60%	2%	19.6 GtCO <sub>2</sub>
3.2		4%	39.2 GtCO <sub>2</sub>
3.3		6%	58.7 GtCO <sub>2</sub>
3.4		8%	78.3 GtCO <sub>2</sub>
3.5		10%	97.9 GtCO <sub>2</sub>

**TAB 2.** Aviation carbon budget cases for the emitting period 2011-2049



**FIG 2.** Parametric remaining civil aviation carbon budget

As post-2050 emissions also matter for not exceeding the temperature threshold, the carbon budget for the second half of the 21<sup>st</sup> century has to be incorporated in a methodology to assess climate mitigation technologies in aviation.

Case No.	Probability of staying below 2°	Civil aviation share of total budget 2011-2100	Remaining civil aviation carbon budget 2011-2100
1.1	80%	2%	12.8 GtCO <sub>2</sub>
1.2		4%	25.6 GtCO <sub>2</sub>
1.3		6%	38.4 GtCO <sub>2</sub>
1.4		8%	51.2 GtCO <sub>2</sub>
1.5		10%	64.0 GtCO <sub>2</sub>

**TAB 3.** Aviation carbon budget cases for the emitting period 2011-2100: pre-2050 [1] and post-2050 [15]

#### 4. CONSUMPTION SCENARIOS

In the previous section the carbon budget side has been discussed. In this section global aviation fuel consumption scenarios and corresponding CO<sub>2</sub> emissions will be analyzed. Eventually we will need to model the CO<sub>2</sub> emissions of the world fleet over the next decades against the backdrop of a global climate target in order to deduce requirements for future aircrafts. In a first step, with the determination of a BAU-scenario a reference has to be set. The goal, in a second step, is to estimate when the remaining carbon budget will be exhausted depending on what share of the total carbon budget will be allocated to scheduled civil aviation in the first place. Thereafter, a “2° backcasting scenario family” is built, consisting of 3 scenarios. The backcasting scenario family is designed to explore how the 2° target could be achieved, assuming that a certain carbon budget is allocated to scheduled civil aviation. This is realized by simulating the hypothetical introduction of ZEAC over discrete seat categories at a future time, thus a fossil-fuel phase-out. Because of the great uncertainties throughout the analysis chain and the extensive time horizon, scenarios are the instrument of choice. [19] The backcasting scenario family is calibrated with inventory results by Martin Schaefer of the year 2011. [20] In the consumption scenarios only-CO<sub>2</sub> emissions are considered.

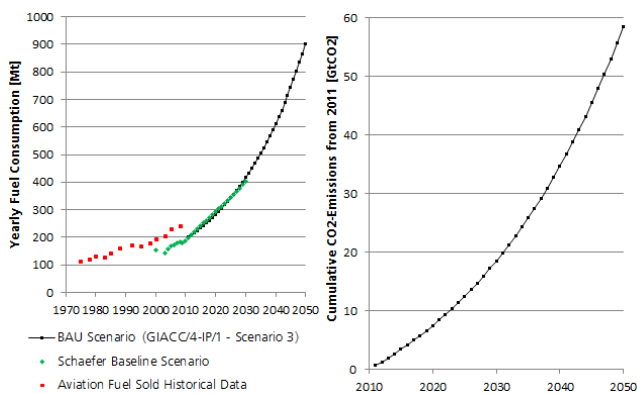
##### 4.1. Business as usual scenario

The selected reference scenario or BAU-Scenario is one of the scenarios presented by the Group on International Aviation and Climate Change (GIACC) in its information paper “Global aviation CO<sub>2</sub> emissions projections to 2050”. Scenario 3 of that report is assumed to be the most suitable base case. [21] Further, it matches well until 2030 with the baseline scenario developed by Martin Schaefer (see FIG 3). [20]

The BAU-Scenario is characterized by conventional fossil-fuel powered aircrafts that are getting constantly more efficient. With this scenario the academic question is explored when a potential budget would be exceeded, well knowing that we do not know what exact budget would be allotted to scheduled civil aviation or if that will ever happen.

Any different BAU-Scenario could be treated the same way. BAU-Scenarios distinguish themselves from one another only by varying assumptions concerning traffic growth, technology advancements in fuel consumption of new aircrafts and the EIS of these aircrafts.

The GIACC recognized in its 2009 final report that, in a BAU-scenario, projected growth of air traffic will overcompensate evolutionary fuel efficiency improvements leading to a yearly increase of total aviation burn. Referring to the report, these evolutionary improvements should be 2% per year of the overall ATS.<sup>3</sup> Further it is stated that this would "require a significant investment in technological development". [22] However, this can only be considered as a BAU-Scenario. To analyze the meaning of the CO2 emissions projections to 2050 by the GIACC one median projection (Scenario 3) of this publication is held against possible aviation carbon budget cases.



**FIG 3.** Selected fuel burn and emissions projections for parametric out-of-budget estimations

A first parameter variation reveals possible time horizons when civil aviation would approximately run out of budget under current assumptions in the given BAU-scenario. First estimations of out-of-budget cases are depicted in TAB 4.

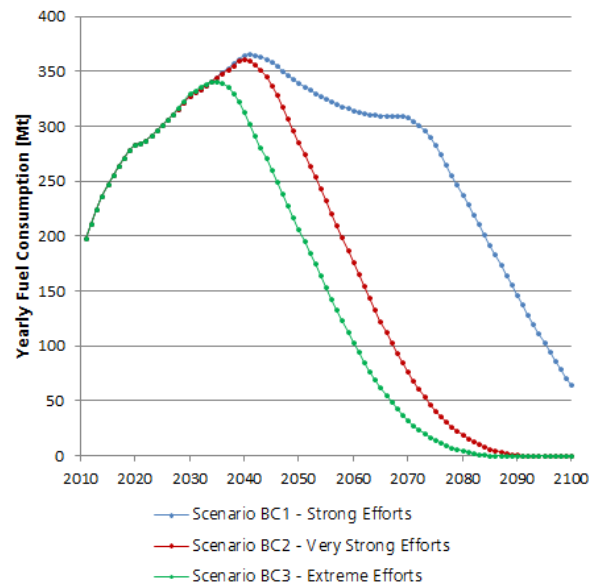
Case No.	Probability of staying below 2°	Civil aviation share of total budget	Out-of-budget estimated in
1.1	80%	2%	2024
1.2		4%	2033
1.3		6%	2040
1.4		8%	2045
1.5		10%	2050
2.1	75%	2%	2026
2.2		4%	2036
2.3		6%	2043
2.4		8%	2049
3.1	60%	2%	2031
3.2		4%	2043
3.3		6%	2050

**TAB 4.** Estimated out-of-budget cases with underlying GIACC global aviation emissions predictions to 2050

<sup>3</sup> Efficiency is defined as fuel used per revenue ton kilometer performed.

## 4.2. 2°C Backcasting Scenario Family

Three different backcasting scenarios (BC) are displayed in FIG 4, but any other scenario of new aircraft introduction patterns - conventional, hybrid electric or zero-emission - into the world fleet can be modeled. The three scenarios selected here intend to achieve the greatest strategic contextual awareness possible and not to predict a certain development. The selected scenarios are meant to show what decisions today will lead to what effect in the future in a quantitative way. Here, the focus is sketching a phase-out model of fossil fuel based technologies in civil aviation by introducing revolutionary new aircrafts like HEACs and ZEACs against the backdrop of a global climate target. Projected air traffic growth is a necessary input value. For the backcasting scenario family in this study average yearly growth rates had been assumed to be 4% in the decade 2010-2020 and then decreasing each decade by -0.2%. Relative to Boeing and Airbus forecasts this is a low growth scenario. Here, a simple basic value method analogous to [23] analyzing falling historic growth rates from decade to decade had been applied. A comprehensive analysis of near term aircraft programs can be found in [10], which also has been reflected in the generic aircraft timeline backcasting scenario family. More modeling background information is provided in [24].



**FIG 4.** Backcasting scenarios overview: civil world fleet fuel consumption (scheduled traffic), modeled introduction of zero emission aircraft

### 4.2.1. BC1 – Hybrid Electric 2035, ZEAC 2065

In BC1 it is assumed that for aircrafts in the seat range 401-650, successors are introduced in 2025 with a fuel consumption improvement of -15%. 10 years later, in 2035 very fuel efficient hybrid electric aircrafts are introduced in the segment 51-210 seats, followed by an introduction of that type of aircrafts in the segment 211-650 seats in 2040. The hypothetical ultra-green aircraft [12] is assumed to be -70% more fuel efficient than the reference aircraft. In this scenario the aircraft programs of the N+2 generation are active for 30 years leading to an entry into service (EIS) of

the ZEACs in 2065 and 2070, respectively. Ramp-up time is modeled to be 7 years for both the N+2 and N+3 generation. The simulated introduction pattern is depicted in TAB 5.

Seat Category	Reference Aircrafts	Fossil Fuel Consumption Technology Assumptions					
		N+1	Entry	Full Market	N+2	Entry	Full Market
51-100	AT76/CRJ9	-15%	2013	2022	-70%	2035	2042
101-150	A320/B737	-15%	2014	2021	-70%	2035	2042
151-210	A320/B738	-15%	2014	2021	-70%	2035	2042
211-300	B763	-20%	2012	2015	-70%	2040	2047
301-400	A333/B773	-20%	2012	2021	-70%	2040	2047
401-500	A388/B748	-15%	2025	2032	-70%	2040	2047
501-600	A388/B748	-15%	2025	2032	-70%	2040	2047
601-650	A388	-15%	2025	2032	-70%	2040	2047

Seat Category	Reference Aircrafts	N+3	Entry	Full Market		
51-100	AT76/CRJ9	-100%	2065	2072		
101-150	A320/B737	-100%	2065	2072		
151-210	A320/B738	-100%	2065	2072		
211-300	B763	-100%	2070	2077		
301-400	A333/B773	-100%	2070	2077		
401-500	A388/B748	-100%	2070	2077		
501-600	A388/B748	-100%	2070	2077		
601-650	A388	-100%	2070	2077		

**TAB 5.** BC1 - strong efforts: Hybrid electric aircrafts from 2035, zero emission aircrafts from 2065

#### 4.2.2. BC2 – no HEAC, direct ZEAC in 2035/2040

In BC2 as in BC1, in the seat range 401-650, an improved successor is introduced in 2025 with a fuel consumption improvement of -15%. BC2 simulates accumulated emissions if in 2035 ZEACs are introduced in the segment 51-210 seats, followed by an introduction of ZEACs in the segment 211-650 seats in 2040. The difference between scenario BC2 and BC1 is that there is no intermediate aircraft program on the way to a full zero emission aircraft.

Seat Category	Reference Aircrafts	Fossil Fuel Consumption Technology Assumptions					
		N+1	Entry	Full Market	N+2	Entry	Full Market
51-100	AT76/CRJ9	-15%	2013	2022	-100%	2035	2042
101-150	A320/B737	-15%	2014	2021	-100%	2035	2042
151-210	A320/B738	-15%	2014	2021	-100%	2035	2042
211-300	B763	-20%	2012	2015	-100%	2040	2047
301-400	A333/B773	-20%	2012	2021	-100%	2040	2047
401-500	A388/B748	-15%	2025	2030	-100%	2040	2047
501-600	A388/B748	-15%	2025	2030	-100%	2040	2047
601-650	A388	-15%	2025	2030	-100%	2040	2047

**TAB 6.** BC2 - very strong efforts: zero emission aircrafts from 2035

#### 4.2.3. BC3 – Extreme Efforts, ZEAC in 2030/2035

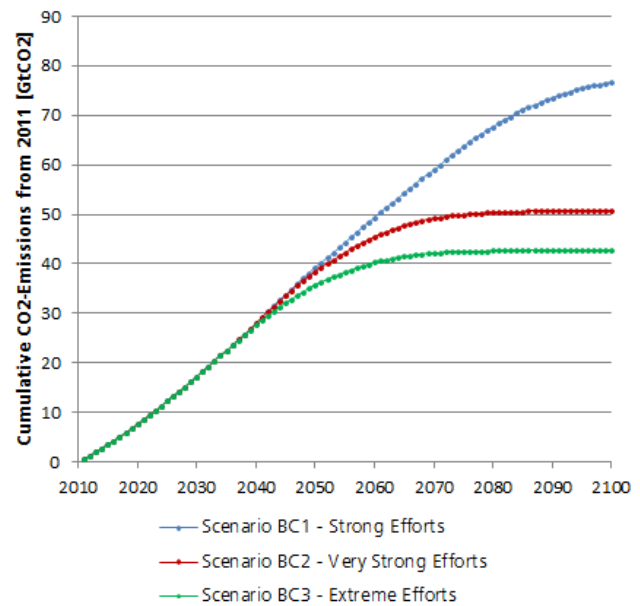
Backcasting scenario 3 is meant to be the most extreme scenario. Here it is simulated what would happen if per hypothetical global policies and extreme efforts, from 2040 only ZEAC are delivered. EIS is simulated to be in 2035 with a shortened ramp-up time of 5 years.

Seat Category	Reference Aircrafts	Fossil Fuel Consumption Technology Assumptions					
		N+1	Entry	Full Market	N+2	Entry	Full Market
51-100	AT76/CRJ9	-15%	2013	2022	-100%	2030	2035
101-150	A320/B737	-15%	2014	2021	-100%	2030	2035
151-210	A320/B738	-15%	2014	2021	-100%	2030	2035
211-300	B763	-20%	2012	2015	-100%	2035	2040
301-400	A333/B773	-20%	2012	2021	-100%	2035	2040
401-500	A388/B748	-100%	2035	2040			
501-600	A388/B748	-100%	2035	2040			
601-650	A388	-100%	2035	2040			

**TAB 7.** BC3 - Extreme efforts: zero emission aircrafts from 2030

#### 4.2.4. Analysis of cumulative CO2 emissions

For a given pre-2050 carbon budget the sensitivities of different scenarios are relatively low. The cumulative emissions until 2100 in FIG 5 show that major differences between the scenarios do not become apparent until after 2050.



**FIG 5.** Cumulative emissions of backcasting scenarios throughout the 21st century: Apparent differences in the post-2050 period

Scenario	Cumulative CO2 emissions from 2011 until 2049	Probability of staying below 2°	Required civil aviation share of budget 2011-2049
BC1	39.5 GtCO2	5%	2%
		34%	3%
		60%	4%
		69%	5%
		76%	6%
		80%	7%
		83%	8%
		85%	9%
		87%	10%
		BC2	38.6 GtCO2
37%	3%		
61%	4%		
70%	5%		
77%	6%		
81%	7%		
84%	8%		
86%	9%		
88%	10%		
BC3	35.9 GtCO2		
		44%	3%
		64%	4%
		73%	5%
		79%	6%
		82%	7%
		85%	8%
		87%	9%

**TAB 8.** 2° Target backcasting scenario family: estimation of the required share of global budget versus probability for given scenario to stay below 2°C without post-2050 carbon budget consideration

Only in combination with the post-2050 carbon budget the advantage of one scenario over the other becomes obvious.

Scenario	Cumulative CO2 emissions from 2011 until 2100	Probability of staying below 2°	Required civil aviation share of budget 2011-2100
BC1	77 GtCO2		12%
BC2	51 GtCO2	80%	8%
BC3	43 GtCO2		7%

**TAB 9.** Estimation of the required share of global carbon budget for an 80% probability of staying below 2 °C warming including post-2050 budget and emissions

## 5. CARBON DIOXIDE EQUIVALENCY

The carbon budget approach with the consideration of only-CO2 emissions is a simplification, especially concerning the ATS. It doesn't consider the emission of diverse non-CO2 agents. Non-CO2 emissions in higher layers of the atmosphere have a greater effect than emissions on the surface. The climate impact depends on the species, amount, altitude and latitude of emission. Nevertheless, the simplifications allow becoming capable of acting and deriving a logical chain of thought from a political climate target of staying below 2° - over an intermediate step of quantitative world fleet scenarios - to future aircraft design attributes. In future research, the effects of species, amount, altitude and latitude have to be included which would be a refinement of the chain of thought. Here, an idea of how it could be done shall be outlined. A pragmatic approach would be to calculate CO2 equivalents (CO2eq) and to use it as a common metric. CO2 equivalents in the context of carbon budget thinking stand for a certain budget of all different kinds of climate change agents released into the atmosphere in different amounts, altitudes and latitudes converted into a single manageable metric with the unit GtCO2eq. In the context of this study, CO2 equivalents mean the flow of a mixture of greenhouse gases into the atmosphere.

If a certain carbon budget was conceded to civil aviation, it will have to be simulated, how the ATS could be re-engineered in order to not exceed a to be defined budget and how the impact of CO2 and non-CO2 agents emitted over time use up that budget. In order to boil the complex topic of climate change and mitigation ambitions down to a set of manageable design attributes for the ATS and future aircraft design, simplifications have to be made. A range of diverse climate change agents exist with strong differences in radiative forcing. The climate change agents are gases, aerosols, particle matter and induced cloudiness. [25] As CO2 is emitted in great abundance into the atmosphere by the global industrial system and as it causes the greatest radiative forcing, CO2 reasonable reference gas. [26]

Uncertainties concerning the real climate change impact of civil aviation are propagated into the estimation of the aviation carbon budget depletion rate. In section 4.2, for a first estimation when zero emission aircrafts would have to be introduced into the fleet in order to achieve the 2° target, only-CO2 emissions which are directly dependent of fossil fuel burn have been considered. Other climate change agents have a spatial-dependent global warming potential (GWP). In total, those effects are most likely resulting in higher yearly aviation carbon expense than the modeled only-CO2 emissions from aviation fuel burn scenarios.

CO2 equivalents as a function of altitude, latitude and mass of emissions need to be calculated for a specific year and each climate change agent. CO2 equivalents are calculated by multiplying the GWP of an agent with the amount emitted of that agent both being a function of altitude and latitude:

$$(1) \quad CO2eq_{agent\ i} = \int_{-90}^{+90} \int_0^{ALT} GWP_{agent\ i}(alt, lat) \times \dot{m}_{agent\ i}(alt, lat) \, dalt \, dlat$$

In the above mentioned equation  $\dot{m}_{agent\ i} = f(altitude, latitude)$  is the cumulative mass flow of climate change agent  $i$  over the period of one year emitted in a certain altitude and latitude in the year  $t$  by the whole ATS. Therefore,  $\dot{m}_{agent\ i}$  has the unit Gt/a. The total CO2eq emitted of  $n$  agents is summarized to a global number of CO2eq emitted by the ATS per year:

$$(2) \quad CO2eq_{global} = \sum_{i=1}^n CO2eq_{agent\ i}$$

$CO2eq_{global} = f(t)$  is mainly driven by air traffic growth and the introduction of new technologies. Total aviation carbon expense until 2100 would have to be harmonized with a remaining Aviation Carbon Budget in order to achieve the 2° target with a certain probability. The aviation carbon budget is a function of the targeted probability to stay below 2 °C global warming and the share of the worldwide budget that is allocated as described in section 3.2:

$$(3) \quad \text{Aviation Carbon Budget}_{2011-2100} =$$

$$\sum_{i=1}^n \int_{2011}^{2100} \int_{-90}^{+90} \int_0^{ALT} GWP_{agent\ i}(alt, lat) \times \dot{m}_{agent\ i}(alt, lat) \, dalt \, dlat \, dt$$

Yet, the world carbon budget in terms of CO2 equivalents is higher than the only-CO2 budget. Meinshausen et al. [1] estimate the cumulative Kyoto-gas budget from 2000-2049 at 1,356 GtCO2eq for an 80% probability of staying below 2 °C global warming (illustrative default case). In the UNEP 2012 Report<sup>4</sup> it is stated indirectly that between 2000 and 2010 about 454 GtCO2eq have been used, leaving approximately 900 GtCO2eq for the period 2011-2049. [26] For the period after 2050 cumulative Kyoto-gas budget in terms of CO2eq could not be found in literature. For the ATS re-engineering approach described in the following section, it will be necessary to know as well the post-2050 Kyoto-gas budget.

<sup>4</sup> UNEP 2012, p. 29

## 6. CLIMATE-ECOLOGICAL ASSESSMENT LOOP & ATS RE-ENGINEERING MODEL

From a climate-ecological point of view, there is a need to renovate the ATS. Scenario methods show that the current development is not in line with meta-level political climate goals. The term re-engineering is selected since the existing system needs to be changed. The change needed is fundamental because the problems are systemic. Synonymously the term renovation is used. The reasoning why the existing system needs to be altered is derived by a scenario development process with backcasting techniques in a quantitative way. Only a quantitative non-linear climate-ecological assessment, hence loop, can trigger a subsequent renovation process.

### 6.1. Climate-ecological assessment loop

The climate-ecological assessment loop is adapted and further developed from Lee et al. [30] It is necessary not only to understand climatological effects of the existing world fleet with current aircraft technology, but also to have the ability to react to the insights of climate research. New strategies, concepts and technologies need to be assessed against the backdrop of a climate target of limiting global warming to 2 °C. It does not seem enough to relatively assess new aircraft technologies by comparing mitigation potentials with each other. What really is needed, is a compelling narrative, a "desirable scenario" how and which new concepts, technologies and policy measures can be arranged to achieve the target. Therefore, one has to know what effect will be produced not only by today's concepts, but also by tomorrow's. The climate-ecological assessment loop aims to contribute to the mutual understanding of very different disciplines of policy making, atmospheric research, systems analysis, aircraft design and disciplinary technological research.

The schema of Lee et al. depicting the atmospheric processes (right side downward arrows of FIG 6) caused by aircraft operations is extended by schema which explains the conceptual foundation needed to deduce requirements for the design of future aircrafts. Climate impact research and atmospheric research are quantifying anthropogenic global warming and the impact of aviation related emissions. With each step from aircraft development to climate change induced damages, the relevance for policy increases. If these damages were to be limited to an "acceptable" level, there would be a corresponding maximum surface temperature increase compared to the pre-industrial level. If this was 2°C, there would be an according remaining carbon budget. If there was a remaining carbon budget, civil aviation would get a percentage of the whole remaining carbon budget. If civil aviation was given a remaining carbon budget, a thorough systems analysis including quantitative scenarios would have to be built in order to elaborate how not to exceed the budget. Out of a scenario package, a desirable scenario would have to be chosen and the ATS accordingly renovated. This would include a wide range of aeronautical research fields, where the systems boundary can no longer be the aircraft alone. That means that, if the ATS needed to be renovated, an ATS re-engineering model would be useful.

### 6.2. ATS re-engineering model

The ATS re-engineering model is developed from the pyramid re-engineering model by Byrne. [4] Here, only the main differences between the Byrne pyramid and the ATS re-engineering rhombus model will be pointed out in detail. While the forward engineering branch of the rhombus model (FIG 6) is exactly in line with the definitions of Byrne, there are essential differences regarding the backward engineering branch. For the rhombus model, the reverse engineering branch of original pyramid model by Byrne has been replaced with a backward engineering branch in order to cope with the problem of re-engineering the ATS. This distinction is necessary in order to adjust the Byrne re-engineering model to a problem-deduced scenario process. Two properties of the backward engineering model are similar to the reverse engineering model:

- **Levels of Abstraction:** From bottom upwards the level of abstraction increases.
- **Separation of Concerns:** "Each level of abstraction defines a different set of characteristics."

The other properties of the *backward engineering* branch are directly *opposite* compared to reverse engineering as follows:

- **Information Inclusion:** Information on lower abstraction levels influence information on higher abstraction levels. Further, there is generally a one-to-many relationship from one information within one level and information at higher levels being derived from it.
- **Creation of Characteristics:** More "external" concept relevant information is included from other disciplines within each abstraction level towards a more holistic system. Successively systems characteristics are created in each abstraction level that influence the creation of characteristics on the next higher abstraction level.
- **Information Volume:** There is an increasing amount of contextual information from lower to higher abstraction level (Therefore the rhombus shape.)

This backward engineering model was developed to depict the process needed to renovate the ATS as a result of the insight gained through the climate-ecological assessment loop with the integrated scenario development process. In essence, it is a problem-deduced or "scenario-pull" case leading to a forward engineering process. The backward engineering process closes the conceptual gap between results of the climate-ecological scenarios and the classical forward engineering process.

Whereas the forward engineering process is characterized by an ongoing refinement from an abstract task to a simulated product, the backward engineering process is characterized by an ongoing conceptualization from a simulated single characteristic of an aircraft (in this case being zero-emission) to a more holistic system. An overall vision of the ATS is including a consistent set of sub-solutions for aircraft, airport, ATM-system and airline design each with multiple characteristics all consistent to one another. The backward

engineering process gives the initial spark for alteration on the different abstraction levels to re-think, re-specify, re-design and re-simulate.

The Principle of Refinement is defined by Byrne:

*"The gradual decrease in the abstraction level of a system representation is caused by the successive replacement of existing system information with more detailed information."*

The Principle of Conceptualization is:

*The gradual increase in the abstraction level of a system representation is caused by the successive replacement of existing system information with more contextual information, new fitting aspects from diverse disciplines.*

Byrne states, referring to his pyramid model, that "[...] the higher the abstraction level the less information about a system there is to comprehend." In the rhombus model this is only true for the forward engineering branch. For the backward engineering branch representing the work of conceptualization, exactly the opposite is the case. While reverse engineering starts from an existing previously forward engineered system and attempts to re-build the initial thoughts, backward engineering starts from a needed performance (in this case zero emissions) deduced from a simulated implementation of a future system (in this case an aircraft). Backward engineering is about developing a concept that previously did not exist.

While refinement successively gives more precise information about the performance of a system, conceptualization successively gives more contextual information about how different pieces of a puzzle can shape a visionary system. Refinement is about analysis and specification. In contrast, conceptualization is about synthesis and composition.

The level of abstraction increases from simulating just one aircraft performance characteristic (in this case being zero emission) over design attributes to the vision of the overall ATS. Backward engineering and forward engineering are closely linked together in a non-linear way. At every point in time and at every abstraction level, alteration should be embraced. At each abstraction level a specific kind of alteration happens.

Forward engineering starts with a task leading to design principles, design attributes and requirements. Backward engineering on the contrary ends with that highest abstraction levels. Here, a fundamentally different mindset is needed than in a forward engineering process. This mindset is in literature referred to as "design thinking". [31]

In the context of the ATS re-engineering model it is important to note that abstraction mustn't be confused with virtuality. The specific performance of an aircraft - even if it is only the one characteristic of being zero emission - is still a detail. Higher abstraction means more generality and simplicity and less detail. Design Principles for example have a higher abstraction level than the potential specific fuel consumption of a future aircraft, yet both are virtual.

The time horizon can be more than 40 years from the first

idea to the last aircraft manufactured and delivered. The time horizon of an aircraft is about 20 years. "Because of the inertia of the ocean-atmosphere system, the earth surface temperature follows the radiative forcing with a delay of about 40 years." [32] This leads to cumulated time scale needed for a thorough systems analysis and concept design over multiple disciplines of roughly 100 years. At this time scale a sophisticated scenario method incorporated to a global air transportation systems design framework is needed.



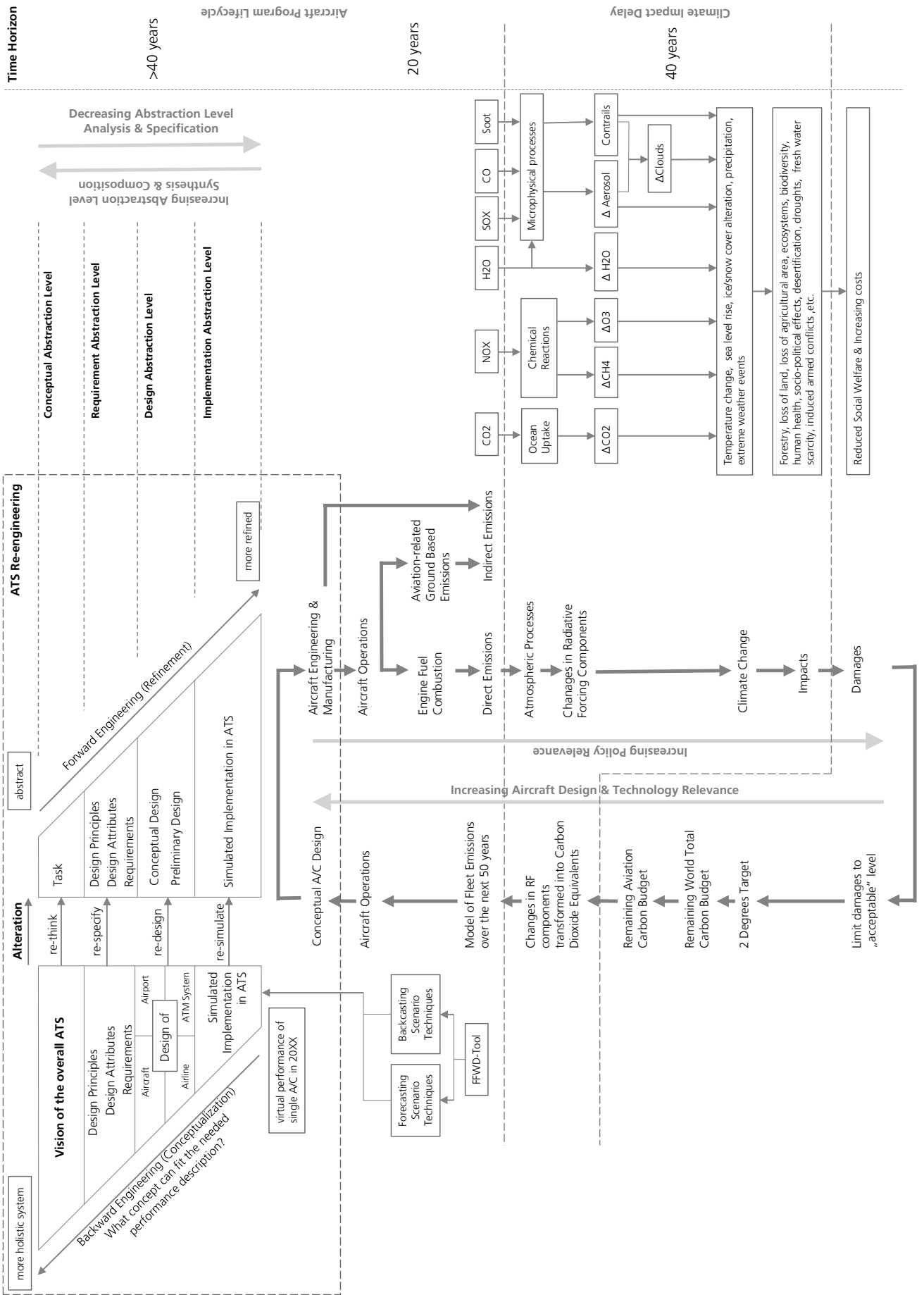


FIG 6. Climate-ecological assessment and ATS re-engineering model (Adapted and further developed from Prather et al. [28], Wuebbles et al. [29], Lee, D.S. et al. [30] and Byrne [27])

## CONCLUSION

Even very efficient conventional aircrafts are in great number adding huge amounts of yearly CO<sub>2</sub> emissions to the fleet. The cumulative study shows that despite more efficient aircrafts any possible commercial aviation carbon budget in order to achieve the 2° target will be overrun in a surprisingly near future if current climatologic assumptions on global warming remain valid. Ambitions for efficiency gains by large technology initiatives are in essence BAU-scenarios. Different technology improvements and growth forecasts lead to different points in time for predicted carbon budget overrun. Technology improvements postpone the time of overrun further into the future, but can't circumvent it. Backcasting techniques show that due to the longevity of aircrafts once added to the fleet, early strategic decisions have to be made in order to achieve the target with a certain probability. The scenario analysis also reveals that it is decisive to discuss how much of the remaining general carbon budget should be allocated to commercial aviation. It is especially important to consider post-2050 budgets. The sooner a decision is made, the greater is the room for maneuver. From a different perspective it can be deduced that for a certain introduction pattern of ZEAC over all seat categories - as shown in the backcasting scenario family - a respective smaller or greater share of the world carbon budget has to be allocated to aviation. The key question to be answered for strategic decision making is, how big this share to be conceded to civil aviation actually can be.

The research identifying and quantifying potentials to reduce the climate impact of aviation has advanced in the recent years. Nevertheless, it is important to underline the need to build a scenario capability in the area of climate-ecological assessment of aviation. This can be done with a general model which can simulate radical new aircraft concepts, promising technologies and operational procedures of any kind and in any combination. This general approach would also allow assessing if and by how much mitigating potentials of very different nature (new aircraft concept, biofuels, new procedures) can be stacked until an aspired climate budget is not exceeded. It will be necessary to model potential savings of CO<sub>2</sub>eq in a heterogeneous world fleet over the next decades. If for example alternatively fueled aircrafts with a hydrogen fueled gas turbine or a fuel cell hybrid propulsion system are introduced in 2025 [12] into the world fleet in great numbers, it will be necessary to be able to quantify the climate impact of such a revolutionary technology in terms of CO<sub>2</sub>eq emitted in combination with falling CO<sub>2</sub>eq emissions from slowly retiring fossil fuel powered conventional aircrafts.

Global GWP respond surfaces for each agent in combination with a spatial-dependent climate change agent emission model would allow a holistic simulation of different introduction scenarios of newly developed aircrafts and operational procedures. Thus, different technological solutions such as biofuel propelled conventional aircrafts, lower- and slower-flying old aircrafts, battery propelled electric new aircrafts, hydrogen propelled fuel cell aircrafts and hydrogen propelled gas turbine fuel cell hybrid aircrafts as well as any other conceivable variant could be climate-ecologically assessed. Using this methodology, the climate-ecological effectiveness of heterogenic combinations of new concepts (aircrafts, procedures, policy) can be simulated until

one "desirable scenario" is developed that aligns with the remaining carbon budget.

From a scenario-pull perspective the 2° target may lead to harder and earlier requirements for an action plan in aircraft design and airport design than the pure supply security perspective of fossil fuels. Hansen et al. [4] point out that from the climate arises a "necessity of finding an energy course beyond fossil fuels sooner than would otherwise have occurred." This may also be true for the ATS.

This paper describes the process and gives a first climate-ecological scenario analysis for the ATS. The main objective is to close the scientific gap between a climate target and requirements for future aircraft programs from a problem-deduced scenario-pull perspective. Further adjustments and refinement of the calculation is needed to minimize the large uncertainties. Results will also have to be modified with more precise results from climatologists, aviation growth forecasts, aviation emission inventories and impact assessment of non-CO<sub>2</sub> climate agents as research proceeds continuously and scientific understanding deepens. From a scientific point of view, it will also be necessary to quantitatively assess climate-ecological compensation mechanisms between traffic growth and technology advancement.

It is also important to keep in mind that flight related emissions account only for a to be quantified percentage of total air transportation system related emissions. Thus, aviation-related ground based emissions need to be incorporated in the analysis. In contrast to the propulsion of aircraft these ground based energy consumptions seem to be "relatively easy" substitutable by zero emission technologies.

In the context of the climate target to limit global warming to 2°, "market-based measures across national borders" [22] (e.g. CO<sub>2</sub>-Certificates) can only be effective, if the remaining carbon budget is reflected in such an approach. This means that there has to be an absolute limited number of CO<sub>2</sub>eq-Certificates until 2100 according to the remaining carbon budget to achieve the 2° target. For each kilogram of CO<sub>2</sub>eq emitted the respective Certificate would have to be voided (forever).

An introduction of aviation in a globally harmonized emission trading system, as Lee et al. [30] suggest, would enable the aviation industry to buy more allowances to emit CO<sub>2</sub> equivalents after which is a viable option as long as the world carbon budget is in total not exceeded.

It is important to note that early strategic decision making for the global ATS supported by decision scenarios is necessary because of the occurring "observation and acceptance delay" as well as of the "solution and implementation delay". [33]

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