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Climate impact of German air traffic: A scenario approach

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ABSTRACT

Transport is considered to be a major contributor to emissions, resulting in a deterioration of local air quality and contributing to global climate change. The present paper focuses on how passenger flights departing from German airports contribute to global climate change. We describe in detail, how traffic forecasts for three scenarios entitled Reference, Free Play and Regulated Shift have been developed and how the resultant emissions have been quantified. Subsequently, we applied a climate model, providing insights into the very long-term climate effects under different assumptions on emissions up to the year 2100. The modelling framework shows that the development of emissions results from complex interactions of demand development and supply decisions, which highly influence the climate impact. With this paper, we show that an integrated, multi-disciplinary analysis can create valuable indicators and advice for transport policy decisions.

1. Introduction

Although air traffic contributed only 2.6% to global anthropogenic CO_2 emissions in 2004 (Lee et al., 2010) and 4.9% to global anthropogenic radiative forcing in 2005 (Lee et al., 2009), the role and climate relevant performance of the air transport mode is subject to intensive political debates. Further traffic growth will increase the relative contribution of aviation in the long run. Means to reduce CO_2 emissions of air traffic are discussed and pursued by industry and politics, not only at the global, but also at national levels. The present paper focuses on how passenger flights departing from German airports contribute to global climate change and how effective preconceived measures are in terms of influencing both the demand and supply side in order to achieve climate relevant objectives. We developed scenarios of the German air traffic and quantified the resultant emissions and their climate impact. These scenarios are part of national transport scenarios for Germany entitled Reference (Ref), Free Play (FP) and Regulated Shift (RS), which were developed in the research project "VEU – Transport and the Environment" (Seum et al., 2017a, 2017b; Henning et al., 2015) and provide scenario specific measures for the air transport sector of Germany.

The objective of this paper is to describe the method and results of the scenario dependent development of air passenger demand and flight volumes of Germany for the year 2040, the resultant emissions and their impact on climate change. Thereby we have analyzed the future development of emissions per passenger-kilometer and have conceived this parameter as one of complex background, depending on technological progress in aviation, load factor of flights and aircraft seat capacity. These factors depend again on political measures and their influence on airline and passenger demand behavior and development.

To quantify future air traffic emissions and their potential scenario responsive reductions and subsequent effects on climate

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change we have focused on commercial air passenger traffic with flights originating in Germany. The approach follows thus the logic that emissions of the fuel sold in a particular country should be attributed to the respective country; this allocation scheme corresponds with the United Nations Framework Convention on Climate Change (UNFCCC) for the reporting of emissions originating from international bunker fuels.

The presented analysis of emissions of flights departing from Germany and their contribution to global climate change fills a gap in the existing literature. So far, studies on the climate impact of aviation either concentrate on global effects (e.g. Lee et al., 2009, 2010; Dessens et al., 2014; IPCC, 1999) or address the contribution of individual flights (e.g. Grewe et al., 2017; Niklaß et al., 2019).

The three scenarios mentioned above are described by Seum et al. (2017a, 2017b) and form the framework of different future paths of air transport demand and flight volumes. This paper provides in Section 2 a description of the transport endogenous scenario assumptions regarding factors which influence passenger demand, in particular travel times, cost and travel behavior, and traffic flows like aircraft fleets and energy availability. Section 3 gives an overview on the input data behind the scenario assumptions, the modelling approaches of the demand and flight forecast, and of the development of specific CO_2 and NO_x emissions per revenue passenger kilometer (RPK) and the climate impact. In Section 4 we present and comment scenario specific results of the air passenger and flight forecast, the specific and total emissions and the climate impact. Finally we discuss the forecast results in the light of political and technological means to reduce emissions and mitigate the climate impact.

2. Context scenarios and specific scenario assumptions influencing air travel demand

2.1. Context scenarios

For our analysis we derived aviation-specific scenario assumptions that are embedded in the scenarios of the “VEU – Transport and the Environment” project (Seum et al., 2017a, 2017b). There three different development pathways until 2040 have been compiled for Germany from which three scenarios of the German transport system have been derived, entitled Reference, Free Play and Regulated Shift. The objective was to identify and assess the effect of regulatory, instrumental and behavioral factors that can be influenced by regional, national or European policy decisions. Therefore a scenario approach was chosen which belongs to the family of explorative scenarios with open endpoints in contrast to goal scenarios with fixed end points. Furthermore framing conditions, i.e. the paths of macro factors such as GDP, crude oil prices and overall population development do not vary among the scenarios in order to avoid that these parameters cover the effects achieved by other, particularly regionally driven policy measures. The scenarios were created in 2016 and thus represent the policy and planning status of this year. The year 2010 was chosen as the base year and 2040 as the time horizon. This time period includes the commitment year for concrete greenhouse gas reductions in Germany in 2030. The scenarios are considered as equally possible. Achieving climate targets is one of several aspects that drive the setting of the policy and behavior options.

The transport system in the Reference scenario is the result of a moderate continuation of currently existing trends and policy goals. Transport regulations and taxation schemes follow patterns known and applied so far. The quality of traffic infrastructure is maintained over all modes and transport technology is further developed without strong incentives favoring a specific mode. In the Free Play scenario society follows a liberal market-economic logic, hence the transport system is developing with a minimum of regulations to foster free market solutions. Infrastructure investments follow demand oriented transport politics. In the Regulated Shift scenario politics pursue contrasting ways with the main objective to mitigate environmental and climate effects of transportation, mobility is redirected by tax regulation and infrastructure policy to become less energy consuming.

It is a special feature of the scenarios that framing conditions, in particular the macro parameters gross domestic product, crude oil prices, and overall population development do not vary among them. The assumptions of the Federal Transport Infrastructure Plan of Germany (BMVI, 2014) were adopted; they include a moderate 1.14% annual increase in GDP, the rise of the crude oil price to 125 US$ per barrel and a declining German population to 76.8 million in 2040. Further details about the methodological approach and the scenario storylines can be found in Seum et al. (2017a, 2017b).

Table 1
Key assumptions concerning air travel times, travel costs and holiday travel behavior.

	Regulated Shift	Reference	Free Play
Travel times	Travel times by air do not significantly vary among scenarios.		
Travel costs	Fares rise significantly, in relation to other transport modes	Fare levels rise like travel costs of other transport modes; hardly any change in price differences between modes.	Fares decline marginally, in relation to other transport modes
Holiday travel behavior	More conscious holiday travel behavior due to awareness of environmental issues. The trend to prefer the plane will be less accentuated	Continuation of growing travel propensity. Growing preference for the plane, as in the past.	Continuation of growing travel propensity. Stronger preference for the air mode due to falling air fares

2.2. Assumptions concerning air travel times, travel costs and travel behavior

Table 1 provides an overview of the key aviation-specific assumptions concerning travel times, travel costs and holiday travel behavior.

By definition, the fare rise in the Regulated Shift scenario is caused by an environmental policy with a direct effect on prices. Examples for fiscal and environmental measures are air transport taxes, a kerosene tax, CO_2 charges or emission related take-off and landing fees. Such measures affect the cost structure of airlines.

In the Regulated Shift scenario the fare increase compared to the other modes will particularly cause modal changes in the German intercity transport system and thereby affect domestic air transport demand. Also, border crossing short-stay personal journeys by air will be influenced. However, scenario-dependent price changes have only a small effect on border crossing business trips by plane. This is because the decision to make a business trip to another country is in most instances a simultaneous decision in favor of choosing the air mode, since the plane offers travel time advantages which are more important than travel cost advantages by slower ground modes. Due to the high time value of business travelers the demand for business travel is very price inelastic (Brons et al., 2002).

Changes in holiday trip making take place mainly in the long run and are not only affected by economic factors, but also by personal preferences and by conditions of daily life like the presence of children in the household. Since the economic development is the same in all scenarios and living conditions related to demography do not vary between scenarios, personal preferences are the decisive element causing differences in holiday trip making in the three scenarios.

In the Regulated Shift scenario, increasing awareness of environmental issues is leading to more conscious holiday travel behavior. However, according to the philosophy of the Regulated Shift scenario the group of “Post materialists” (Kroh, 2008) in the population will continue to grow. This group has an above average interest in holiday making. In addition, the young ones and young adults develop more and more a pragmatic relationship towards environmental and consumption issues (Hurrelmann and Albrecht, 2014). The trend to prefer the plane will be less accentuated, since the air mode will become more expensive due to an increase of the air traffic tax or of CO_2 charges.

The Free Play scenario is rather characterized by traditional materialistic orientations, so that people will prefer holiday trips to destinations that are accessible without great expenses. An even stronger preference for the air mode than in the Reference scenario will be assumed due to the price effect (assumption on falling air fares).

2.3. Assumptions concerning the development of aircraft fleets and energy availability

Table 2 provides an overview of the assumptions concerning the development of fuel efficiency, size of aircraft used, load factors, and energy availability in Germany.

In the Reference scenario we assume that the average improvement in fuel efficiency will continue as in the past (see Section 3.3), but the average annual improvement will be smaller. The reason for this is that particularly the aircraft types used for long-haul flights are already relatively new on average, hence the potentials for improvement are comparably smaller in the future. It also becomes increasingly difficult for aircraft manufacturers to achieve further efficiency improvements. Policy measures included in the Reference scenario assumptions are the introduction of a worldwide CO_2-standard for novel aircraft types from 2020 on, and for aircraft types already being produced at present from 2023 on (EASA, 2017). In addition, the emission trading scheme for flights between airports of the European Economic Area will be retained, however, with a higher level of stringency than today (greater scarcity of certificates).

In the Regulated Shift scenario, higher rates of annual fuel efficiency improvement are assumed. The assumptions leading to the higher rate of annual fuel efficiency improvement include a more stringent worldwide CO_2-standard, the introduction of a global emission trading scheme for all flights and a scrapping premium combined with a ban of all aircraft with overly high specific fuel consumption, leading to a higher rate of fleet replacement.

In the Free Play scenario we assume that airlines have a smaller incentive to renew their fleets. Hence, in contrast to the previous scenario, older and less fuel efficient aircraft will be operated over a longer period of time. However, some gains in fuel efficiency will be realized through new aircraft being added to the fleet. The European emission trading scheme for aircraft emissions will remain active, with the same level of stringency as today.

In considering the future fleet composition further assumptions about changes in aircraft size and seat capacity per flight respectively have been made. For forecasting future aircraft emissions we have assumed that the trend of using larger aircraft will continue, however, with a slower pace than in the past (Airbus, 2018; Boeing, 2018). Equally we have assumed that average load

Table 2
Key assumptions about the development of aircraft fleets and energy availability.

	Regulated Shift	Reference	Free Play
Fuel efficiency	Higher rates of annual fuel efficiency improvement.	Improvement in fuel efficiency will continue, but at a lower rate than in the past.	Lower rates of annual fuel efficiency improvement
Aircraft size	Trend of using larger aircraft will continue, however, with a slower pace than in the past.		
Load factor	Average load factors by route type will further grow, however rather limited.		
Energy availability	Fossil kerosene will be the main energy source. Rather small shares of jet fuel from renewable sources will be used.		

factors by route type will grow further. However, since carriers have reached already high average load factors of around 80% and higher, here too, the further growth potential is rather limited. Based on the assumptions on fuel burn efficiency gain due to technology improvements of aircraft and engines, and on the development of average seat capacity and load factor growth, scenario dependent development parameters of fuel burn (g CO_2) per revenue passenger kilometer (RPK) have been derived for modelling future emissions. The detailed assumptions will be described and commented further in the context of the future development of specific aircraft emissions (see Section 3.3).

In all scenarios fossil kerosene will be the main energy source. Rather small shares of jet fuel from renewable sources will be used, but will have only a very limited effect on fuel consumption and overall fuel burn efficiency (Wolters et al., 2012).

As a prime objective of this study is to demonstrate the effect of different development paths of aviation on emissions and climate change, we assumed for reasons of methodological restrictions sufficient capacity of airport infrastructure in all scenarios so that the forecast demand can be satisfied.

3. Input data, empirical models and intermediate results

3.1. Overview

In order to assess the climate impact of future air transport of Germany, type and quantity of gaseous emissions from future aircraft movements have to be estimated. For some emissions, e.g. NO_x, not only the total mass, but also time and location of emissions are relevant for the climate impact. Hence, one would prefer to model each single flight of an aircraft including all factors relevant for the production of emissions like actual flight trajectory, weight of passengers and freight on board, engine type, weather conditions etc. However, this has been regarded as too cumbersome and time consuming in the context of our scenario analysis. To simplify, we have adopted an approach being based on the relationship:

$$E_{i,t} = \sum_{k} RPK_{k,t} \cdot e_{i,k,t}$$

where $E_{i,t}$ is the total mass of species i (e.g. CO_2) in year t, $RPK_{k,t}$ represents the revenue passenger kilometers in traffic region k, and $e_{i,k,t}$ is the specific emissions per revenue passenger kilometer of species i in the traffic region k. Thereby, we distinguish three traffic regions, i.e. domestic, intra-European and intercontinental flights, because each traffic region has its own specifics. By applying this approach, we assume that the geographical distribution of emissions within each traffic region remains constant over time. This method is advantageous in particular for a scenario analysis because it delivers results in the right range by covering the most important influencing factors at reasonable expense.

The major task of the emission forecast is to estimate RPKs and emissions per RPK by taking into account interdependencies which exist between demand and supply. As demand changes, other combinations of aircraft size and flight frequency may be advantageous in order to meet the demand while ensuring profitability of the airline industry at the same time. Besides aircraft size, technological progress and seat load factor also influence the specific emissions per RPK. These and others factors, in particular flight frequency, have developed steadily in the past. Therefore, we have based our scenarios on extrapolations of these trends thereby ensuring the trends to be consistent with each other and with scenario assumptions.

The forecast method we have developed consists of five stages (Fig. 1). Stage 1 sets the overall level of demand in terms of air trips generated, origin-destination passengers (OD-passengers) and the subsequent number of enplaned passengers. Based on these results, we estimate in stage 2 RPKs by using average flight distances for each traffic region. Furthermore representative values for aircraft size and seat load factors are extrapolated, taking into account expected future saturation effects and the interdependencies inherent to the air transport system in order to achieve a consistent set of results. In addition, numbers of flights are derived. In stage 3 the amount of emissions per RPK is estimated by taking into account the scenario assumptions concerning the development of the aircraft fleets and their technology. In stage 4, RPKs and emissions per RPK yield the total amount of emissions and their global distribution, which are input for climate impact modelling in stage 5.

3.2. Forecasting air travel demand and passenger-kilometers performed

The scenario forecasting is based on the DLR method of forecasting air transport demand in Germany (Pak et al., 2005). Total air passenger demand for Germany, depending on the framework data of the VEU-scenarios is forecast by market segment. The particularity of the model is given by a travel purpose specific segmentation of demand, which accounts for differing relations between purpose dependent behavior and factors influencing demand such as age, income or economic development. The demand segments are the following trip purpose specific groups:

- Domestic air journeys
- Border crossing business journeys by air
- Border crossing holiday journeys by air
- Border crossing short-stay personal journeys by air.

The segment specific method requires many data, which is cumbersome to maintain and use. Other methods with less input parameters and variables are meanwhile available (e.g. Gelhausen et al., 2018). However, due to the detailed description of the future

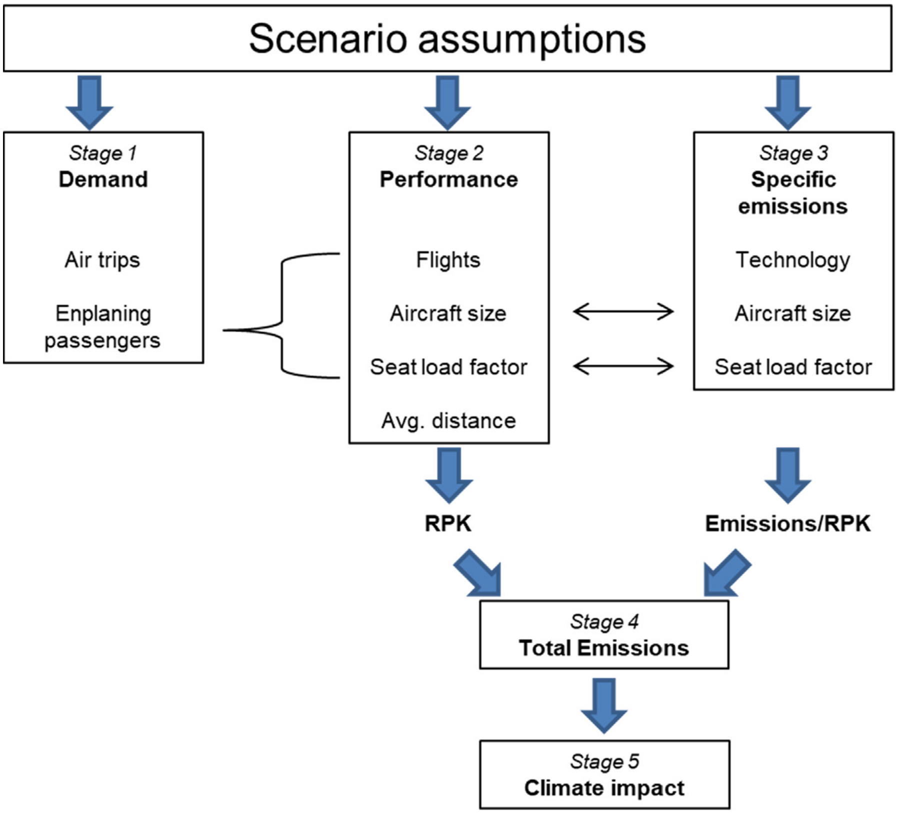

Fig. 1. Schematic overview of the modelling system.

air transport demand, the method applied here seems to be better suited for scenario analyses, since it offers the opportunity to transparently map the change of travel behavior in accordance with the framework data of the scenarios.

The methodological approaches of forecasting the demand segments differ: Methods for segments related to business travel are of econometric nature and those of private travel demand are less functional and consist more of extrapolations of trip characteristics, like trip intensity or frequency by travel group.

Various survey and statistical data sources (IFAK, 2016; Statistisches Bundesamt 2018) have been analyzed to obtain sufficient information not only on the actual volume of air trips, but also about trip purpose, trip origin and type of travel route (or relation). Fig. 2 shows the development of the demand segments of German air travel from 1991 to 2015. In the year 2015, about 90% of all air journeys in German origin to destination (O-D) travel either had a trip origin or destination in a foreign country.

Domestic O-D journeys by air (not counting passengers transferring at German airports) form a segment, which consists mainly of business travelers and competes with high-speed ground modes. Domestic air travel forms only a small part of the total air transport demand and became less important in the last years, also due to the competition with high speed trains. For forecasting the domestic air transport demand we can rely on an empirically verified econometric function. The function yields the propensity to fly, as expressed by the number of journeys in domestic O-D travel per inhabitant, in relation to the macro-economic productivity, expressed by the gross domestic product (GDP) per capita.

Almost a quarter of total air travel demand is border-crossing business travel. This segment has been subdivided into origin travel (mainly by Germans) and destination travel (mainly by foreigners). For years, the ratio has been about 55:45 varying only marginally over time. The demand for international business travel by air results mainly from the economic activities of industry and services, and from international relations between public and private institutions. Since border-crossing business travel is a necessary pre-requisite for realizing foreign trade a functional relationship has been formulated between total business travel demand and foreign trade of goods and services of Germany. Regarding the split between origin and destination travel demand, the ratio of 55:45 was maintained.

The biggest segment of air travel demand is the group of border-crossing holiday travelers. According to international statistics, holiday trips are defined as private trips with duration of five and more days. Due to the heterogeneous structure, this segment has been subdivided further into the group of travelers with trip origin in Germany (primarily German travelers) and those with trip destination in Germany (mainly foreigners visiting Germany). The origin segment is relatively large compared to the destination segment, about 85% of all holiday journeys by air are currently generated in Germany.

For originating cross-border holiday air travel, the model includes holiday travel behavior as explicit input variable and takes into account demographic changes of the German population in terms of size number and age structure. We use category analysis with age

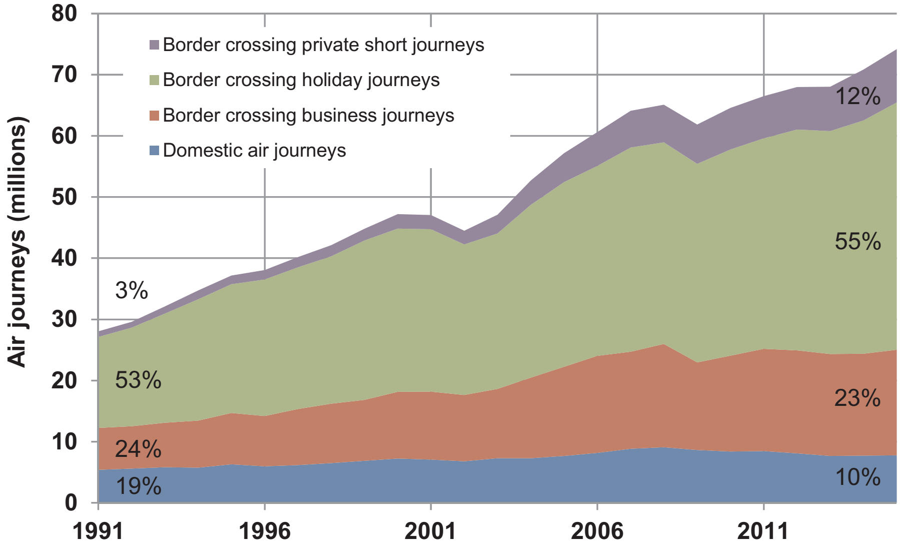

Fig. 2. Development of air transport demand of Germany by trip purpose segment (Source: own calculations based on IFAK (2016) and Statistisches Bundesamt (2018)).

as category, since age can be used as proxy variable for personal attributes like phase of life, position in the family and age-specific mobility. Travel decisions, travel destination choice, and choice of transport mode depend on these personal attributes and, therefore, may be correlated with age (Lohmann and Aderhold, 2009). Age-specific travel behavior is deducted empirically, based on travel survey data (Forschungsgemeinschaft Urlaub und Reisen F.U.R., 2012) and extrapolated into the future. The volume of holiday air travel of the German population is estimated for eight age-groups using intensity of travel (percentage of population that take a holiday), travel frequency (number of journeys per year per traveler), travel destination and mode choice as parameters. For incoming cross-border holidays, long time series are available and can be extrapolated directly by using time series projections.

The fourth and smallest segment, short-stay personal travel is characterized by duration of less than five days. This segment comprises journeys with a large variety of private purposes, like recreation, sightseeing tours or visiting friends and relatives. Especially in this segment, an expansion of the range of destinations of low-cost carriers was observed in the past, which led to a sharp increase in demand in the middle of the first decade of this century. For two reasons, extrapolations are applied to forecast private short stay trips in incoming and outgoing border crossing traffic. First, in contrast to business related journeys, “soft” factors play a more import role for private travelling and make it difficult to develop satisfactory econometric models. Second, potential travelers are very heterogeneous in their social background and travel decisions. This makes it difficult and cumbersome to collect the data necessary to estimate more sophisticated models.

The demand forecast framework described above is applied in the context of the VEU-scenario analysis. As the macro parameters do not vary among VEU scenarios, this approach enables the scenarios to demonstrate the effects of policy measures and specific societal developments that lead to different transport pathways.

Whereas business travel demand by air is rather price-inelastic, private air transport demand reacts more strongly to changes in travel costs influenced by policy measures like the air transport tax levied by the German State, CO_2-charges or emission trading. In order to capture these varying reactions, travel behavior and travel demand, respectively, are extrapolated for each of the three scenarios reflecting their main features. In the Reference scenario the positive trend of growing demand for short stay personal trips will continue, however, with a tendency towards saturation. In the Regulated Shift scenario we assume a slower demand growth than in the Reference scenario because of environmentally based travel cost increases, primarily caused by a strong rise of the air traffic tax and, should the occasion arise, through additional measures like the CO_2 charge. In the Free Play scenario demand growth will be somewhat higher than in the Reference scenario due the assumption that travel cost will not be raised as much, e. g. through an abolishment of the air traffic tax. However, the tendency of demand to move towards saturation will remain here as well.

Based on the number of air trips and OD-passengers, the number of enplaned passengers at German airports is estimated. The passenger volume exceeds the number of OD-passengers due to travelers transferring between flights on their way from or to a German airport and between international flights as well. An analysis of air traffic statistics shows that the ratio between OD-passengers and total passengers has been around 75% for years. This ratio is assumed to slightly go down in future because foreign demand is expected to grow faster than the German demand causing the share of passengers transferring between international flights to increase.

With the number of enplaned passengers and average flight distances the revenue passenger kilometers can be derived, which form a key input variable for estimating emissions of the German air traffic. Average flight distances will change marginally in the domestic traffic region. We slightly increased the average flight distance for the intra-European and intercontinental traffic region in accordance with the trend of the last years.

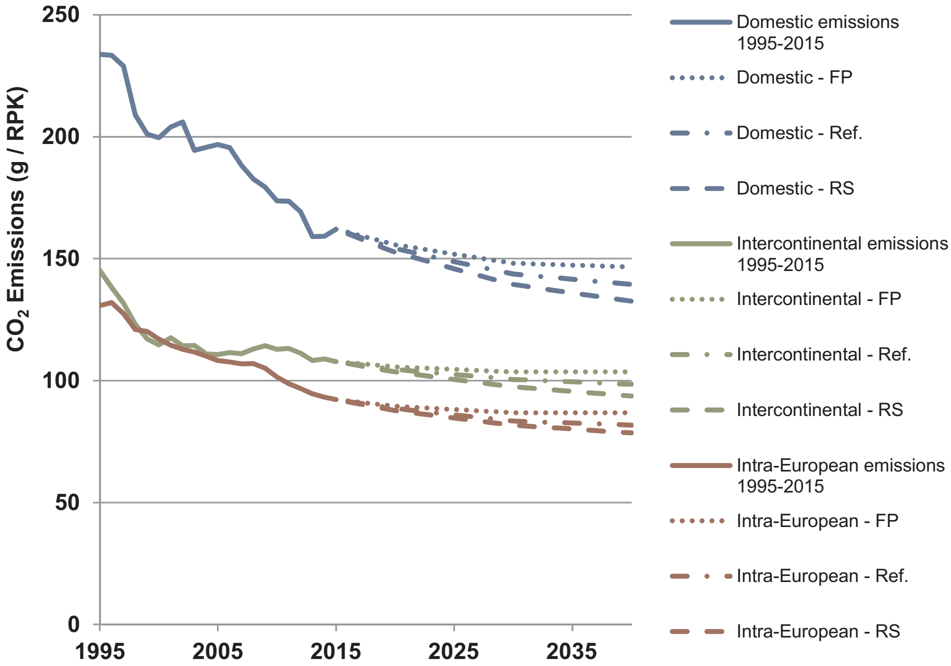

Fig. 3. Development 1995–2015 and projection of specific CO_2 emissions based on passenger flights departing from German airports (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

3.3. Modelling of specific emissions

For the projection of future emissions, specific CO_2 and NO_x emissions per RPK from historical emissions inventories are extrapolated and multiplied by the revenue passenger kilometers of the forecast year, resulting from the passenger traffic forecast. The modelling of emissions is conducted for passenger flights departing from German airports only, following the logic that emissions from the fuel sold in a particular country should be attributed to the respective country.

Inventories of CO_2 and NO_x emissions were created for the years 1995–2015 for all passenger flights (scheduled and non-scheduled) departing from German airports. For this purpose, DLR has developed the emissions inventory tool 4D-RACE (4-Dimensional Distribution of Aircraft Emissions), using the EUROCONTROL Base of Aircraft Data (BADA, EUROCONTROL, 2015) and the commercial flight performance software Piano-X (Lissys, 2008). For subsequent climate impact modelling, CO_2 and NO_x emissions are globally distributed in a four dimensional grid taking into account longitude, latitude, altitude and time of the emissions' origin. A detailed explanation of the approach used by 4D-RACE can be found in Grimme and Jung (2018).

Based on the historical emissions inventories, time series over two decades for specific emissions per RPK were deduced for domestic, intra-European and intercontinental flights. The extrapolation of specific emissions is conducted for each scenario taking into account factors compatible to the storyline of each scenario. Fig. 3 and Fig. 4 show the results of the specific emissions modelling with historical emissions and the extrapolation up to the year 2040 for both the CO_2 and NO_x emissions per RPK. We have to note that the total emissions are solely attributed to the revenue passenger kilometers. This means that emissions originating from belly cargo are also attributed to passengers. For this reason, specific emissions for intercontinental flights, which have a relatively high share of belly cargo, are higher than for intra-European flights. The chosen methodology also implies that the relation of belly cargo and passenger transport remains constant over time.

As we can see, specific CO_2 emissions have been considerably reduced over the timeframe from 1995 to 2015, although the long-term trend in fuel burn and the reduction of specific CO_2 emissions is declining, as it becomes increasingly difficult to realize further efficiency potentials (Kharina and Rutherford, 2015). In the last 20 years, NO_x emissions per RPK have declined, but at a smaller rate than specific CO_2 emissions. The main reason for the higher reduction in specific CO_2 emissions lies in a tradeoff between CO_2 and NO_x. Aircraft engines with a higher fuel efficiency, which have entered into service recently, have tended to produce more NO_x emissions, e.g. due to higher combustion temperatures (Freeman et al., 2018).

The future trajectories of specific CO_2 and NO_x emissions follow a degressive trend for several reasons. One reason is that the aircraft fleet used at German airports is already relatively modern and it is increasingly difficult to achieve further major efficiency improvements. In the past the efficiency improvement in specific CO_2 emissions from aircraft technology alone was in the order of 0.7% per year. This trend is expected to continue initially, but it is assumed that improvements in the longer term future become increasingly smaller.

Other factors that considerably influence specific CO_2 and NO_x emissions are the average aircraft size and seat load factors. As far as the average aircraft size is concerned, a strong upward trend could be observed for the short- and medium-haul market over the

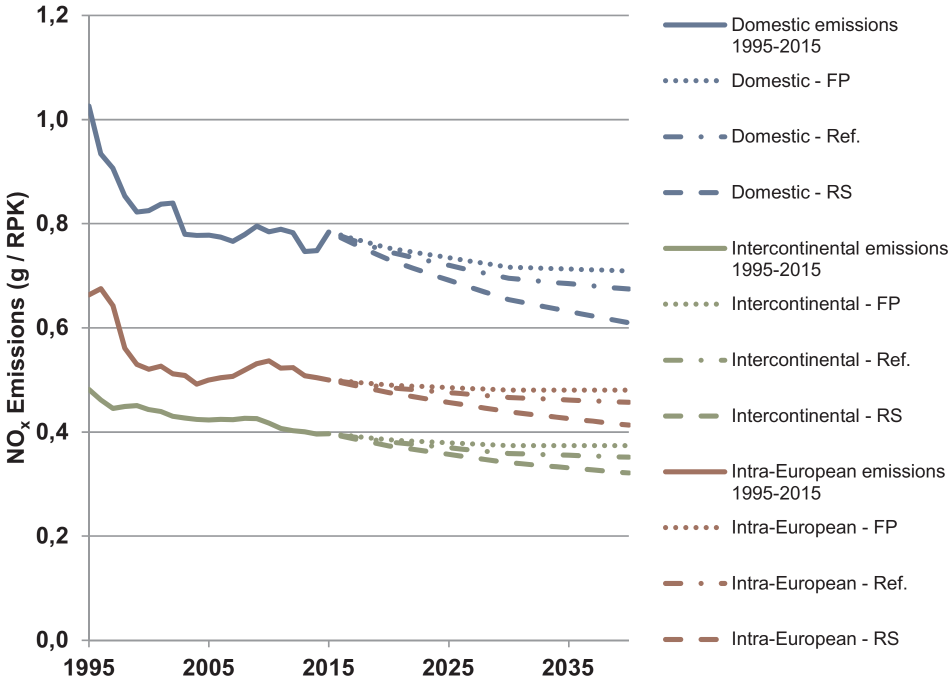

Fig. 4. Development 1995–2015 and projection of specific NO_x emissions based on passenger flights departing from German airports (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

past two decades, largely driven by the growth of the low cost carriers. This trend is likely to slow down, but not yet in the near future. In the long-haul market, even a reverse trend can be observed: Besides large wide body aircraft, which are more efficient on the basis of emissions per RPK, new single aisle aircraft with higher maximum ranges are introduced in order to offer new direct services on routes, where the demand does not allow the operation of larger aircraft. As a consequence, airlines do not exploit the theoretical advantage of using larger aircraft to the full extent in the long-haul market, so specific emissions CO_2 are likely to improve at a lower rate than the above mentioned 0.7% p.a. (Table 3).

The seat load factor has been significantly increased from around 72% in the mid-1990s to around 80% in the current decade. However, the increase in average seat load factors has leveled off at 80–81% for several years now, so the assumption in the scenarios is that saturation has already occurred and no further increases are to be expected.

For the future development of NO_x emissions, Schaefer (2012) has shown a trend with the emissions index for NO_x emissions in g per kg of fuel consumed ($EINO_x$) decreasing slightly under moderate technology trend assumptions. In this study we keep the $EINO_x$ constant in the Reference and Free Play scenarios, so that CO_2 and NO_x emissions will develop simultaneously. For the Regulated Shift scenario, where more stringent regulatory measures are assumed (e.g. higher NO_x-related airport charges), we assume a modest reduction of 5% for the $EINO_x$ until 2040.

For the estimation of CO_2 and NO_x emissions per RPK for the year 2040, improvement rates are derived from the previous two figures for the periods 2016 to 2020, 2021 to 2030 and 2031 to 2040 and for domestic, European, and intercontinental routes (Table 3). These rates vary throughout the three scenarios and include the effects coming from an increase in seat load factor, aircraft size and aircraft technology. In the Regulated Shift scenario stronger regulatory measures are introduced, so that airlines have an incentive to introduce more efficient aircraft at a faster pace, resulting in slightly higher annual efficiency improvements than in the

Table 3
Annual improvement rates [%] of specific CO2 and NOx emissions per revenue passenger kilometer.

		Regulated Shift			Reference			Free Play		
		domestic	intra-European	inter-continental	domestic	intra-European	inter-continental	domestic	intra-European	inter-continental
CO_2 per RPK	2016–2020	−1.2	−1.0	−0.8	−1.0	−0.8	−0.6	−0.8	−0.6	−0.4
	2021–2030	−0.9	−0.7	−0.6	−0.7	−0.6	−0.4	−0.5	−0.3	−0.2
	2031–2040	−0.5	−0.4	−0.4	−0.3	−0.2	−0.2	−0.1	0.0	0.0
NO_x per RPK	2016–2020	−1.4	−1.2	−1.0	−1.0	−0.8	−0.6	−0.8	−0.6	−0.4
	2021–2030	−1.1	−0.9	−0.8	−0.7	−0.6	−0.4	−0.5	−0.3	−0.2
	2031–2040	−0.7	−0.6	−0.6	−0.3	−0.2	−0.2	−0.1	0.0	0.0

Reference and Free Play scenarios.

3.4. Modelling climate impact

The impact of aviation's emission on climate depends both on the emission strength and on emission location. Contrails for example only form in cold and humid regions and the impact of NO_x emissions on ozone and climate strongly increases with altitude (e.g. Grewe and Stenke, 2008; Frömming et al., 2012). Therefore the climate impact of aviation emissions cannot be analyzed by global emissions only, but 3 dimensional (longitude, latitude, altitude) emission inventories and region dependent climate simulations are needed. Additionally the impact of different species has significantly different lifetimes. While contrails only exist for some hours the emitted CO_2 stays in the atmosphere for several hundred years. Therefore we use the climate response model AirClim in this study (Grewe and Stenke, 2008; Dahlmann, 2012; Dahlmann et al., 2016). AirClim is a climate response model, i.e. it uses the relation between emissions and their impacts on atmospheric composition resulting in an estimate in near surface temperature change, which is presumed to be a reasonable indicator for climate change. AirClim is designed to be applicable to aircraft technology and mitigation options, including the climate agents CO_2, H_2O, CH_4 and O_3 (latter two resulting from NO_x-emissions) and contrail cirrus. A complex process model (climate chemistry model ECHAM) is used to produce a large set of relations between an emission at a particular location and its effect on climate (emission–effect relations). The climate response model combines these previous calculated atmospheric data with aircraft emission data and atmospheric perturbation life times to obtain the temporal evolution of atmospheric concentration changes, radiative forcing and temperature changes.

Additional benefit of using a climate response model is that the simulation can be performed over a large time horizon. The large climate impact of CO_2 emissions is due to the long lifetime and the accumulation during this time in the atmosphere. Therefore the differences in climate impact for the different emission scenarios develop over time and a simulation until 2100 is meaningful. As the detailed scenario projections end in 2040 we use different emission developments of German air traffic until 2100: decreasing emissions following a Gompertz function (Gomp), zero emissions after 2040 (Zero), constant emissions at the level of 2040 until 2100 (Const), increasing emissions with constant growth rates (KoWaRa) and linear increasing emissions (LinWa, Fig. 5). Furthermore it is assumed that emissions from global air traffic will develop similarly to emissions from German air traffic over time.

4. Results

4.1. Air transport and emissions

In the following we comment on the transport and emission results of the three scenarios which are summarized in Table 4a and 4b.

The air transport demand of Germany is expected to grow further in each scenario (see also Fig. 6). Until 2040, the number of OD-passengers will increase from 73 million in 2010 by 38% to 101 million in the Reference scenario. Demand will grow less by 25% in the Regulated Shift scenario and more by 47% in the Free Play scenario. In case of Germany, about one quarter of the OD-passengers travel within Germany, and three quarters travel abroad.

In contrast to other forecasts of the aviation industry (Airbus, 2018; Boeing, 2018) and institutions (ICAO, 2016) the demand growth estimated here is relatively low. This is primarily due to the relative small economic growth and the shrinking population in Germany assumed in all scenarios. The low growth of air travel is regarded as of minor relevance here since the objective of the study was not primarily to forecast the absolute level of demand, but rather to forecast and compare the relative impact of different policy measures on technology and operations and in consequence on air traffic emissions and climate effect in the three scenarios.

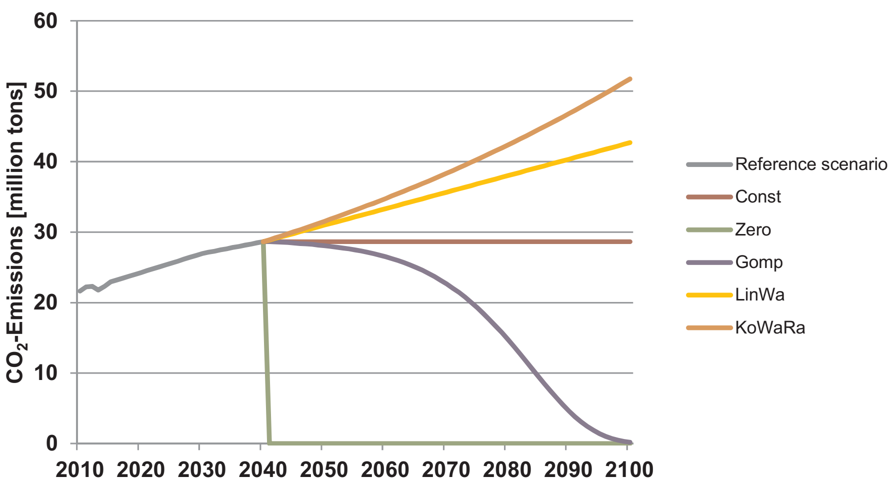

Fig. 5. Five emission scenarios of German air traffic for the period after 2040 using the example of the Reference scenario.

Table 4a
Summary of passenger, flight and emission forecast results 2040 for the three scenarios.

	Base year 2010	Regulated Shift	Reference	Free Play
OD-passengers [million]	73.0	91.3 (+25.0%)	100.5 (+37.7%)	107.4 (+47.1%)
Passengers [million]	96.5	121.7 (+26.4%)	134.7 (+39.6%)	147.3 (+52.7%)
Flights [thousand]	933.6	963.0 (+3.2%)	1041.3 (+11.5%)	1094.3 (+17.2%)
Passenger per flight	103.3	126.4 (+22.3%)	129.3 (+25.2%)	134.6 (+30.3%)
Revenue passenger kilometers [billion]	192.7	277.8 (+44.2%)	304.4 (+57.9%)	327.6 (+70.0%)
CO_2 [g] per revenue passenger kilometer	112.2	89.6 (−20.1%)	94.1 (−16.1%)	98.9 (−11.9%)
CO_2 [million t]	21.6	24.9 (+15.1%)	28.6 (+32.5%)	32.4 (+49.8%)
NO_x [g] per revenue passenger kilometer	0.508	0.387 (−23.7%)	0.428 (−15.7%)	0.449 (−11.6%)
NO_x [thousand t]	97.9	107.6 (+9.9%)	130.3 (+33.1%)	147.1 (+50.3%)

Corresponding with the OD-demand, the number of enplaned passengers at German airports is also expected to increase in each scenario, however, slightly more than the number of OD-passengers. This is due to a growing number of passengers transferring between domestic and/for international flights at German airports (mainly Frankfurt and Munich). The number of enplaned passengers will grow from 97 million in 2010 by 40% to 135 million in the Reference scenario, by 26% in the Regulated Shift scenario and by 53% in the Free Play scenario. For all scenarios the regional breakdown of passengers by traffic region is very similar. 60% of the passengers are on flights to European destinations. The shares of passengers on domestic and on intercontinental flights (OD- plus transfer passengers) amount to 20% each in 2040. Due to the trend towards more direct international flights from secondary airports in Germany the share of passengers on intra-European and intercontinental flights grows further, while the share of domestic passengers decreases.

To meet the growing air transport demand, additional flights will be supplied, however, to different degrees in each traffic region as well as in each scenario. In the Regulated Shift scenario, the number of flights will almost not grow (+3%) from 2010 to 2040, while in the Free Play scenario the number of flights will increase by 17%. With +12%, the Reference scenario is in between. The share of domestic flights will decrease from 30% in 2010 to about 23% in 2040, while both intra-European and intercontinental flights gain market shares. The share of flights to European destinations increases from 60% to almost two thirds, and the share of intercontinental flights from 9% to 12% of the flights in all scenarios.

With regard to passenger and flight volumes, the European market is the main traffic region of German air traffic, however, concerning revenue passenger kilometers and subsequent emissions the intercontinental market accounts with around 60% for most of the RPKs due to significant larger travel distances (Table 4b, Fig. 7). The corresponding RPK share to European destinations is about 35%. Domestic flights account for just 5% of the RPKs. While the breakdown of RPKs according to destinations does not change considerably, the total amount of RPKs grows significantly. In addition, RPKs increase more than the passenger volume due to a rise in average travel distance. While in the Regulated Shift scenario revenue passenger kilometers increase by 44% from 2010 to 2040, in the Free Play scenario, revenue passenger kilometers are expected to grow most by 70%. With +58% the Reference scenario is in between.

CO_2 and NO_x emissions increase in each scenario, however, less than the revenue passenger kilometers according to the scenario assumptions concerning aircraft technology, aircraft size and occupancy. CO_2 emissions grow from 22 million tons in 2010 by 33% to 29 million tons in the Reference scenario, by 15% in the Regulated Shift scenario and by 50% in the Free Play scenario (Fig. 8). This means an overall improvement of CO_2 emissions per RPK by 0.75%, 0.58% and 0.42% per year for the Regulated Shift, Reference and Free Play Scenario, respectively. Considering traffic regions, in each scenario CO_2 emissions increase for intra-European and intercontinental traffic and decrease for domestic traffic.

Unlike CO_2, NO_x emissions are not coupled directly to the fuel burned but depend on the technology used. Hence, NO_x emissions change differently than the CO_2 emissions (Fig. 9). According to the assumptions in the Regulated Shift scenario, NO_x emissions will rise only slightly by 10% from 2010 to 2040. In the Reference and Free Play scenario NO_x emissions rise similarly to the corresponding CO_2 emissions by 33% and 50%, respectively. Overall, NO_x emissions per RPK improve by 0.90%, 0.57% and 0.41% per year for the Regulated Shift, Reference and Free Play Scenario, respectively, thereby in the Regulated Shift scenario much more than the CO_2 emissions.

For both types of emissions, the breakdown according to domestic, intra-European and intercontinental flights is similar to the revenue passenger kilometers. Intercontinental flights account for almost two thirds of the emissions. 30% of the emissions have to be assigned to intra-European flights. Domestic flights account for about 6% of the emissions.

In the current context of climate change mitigation policies, the forecast development of air transport emissions has to be seen against the background of national emission reduction targets. In 2010, Germany emitted 942.5 million tons of CO_{2eq}[1] (Federal Environmental Agency, 2020), while the CO_2 emissions of passenger flights from Germany amounted to 21.6 million tons or 2.3% of Germany's total emissions.

Germany as a Member of the European Union is part of the effort sharing in order to achieve the EU's joint nationally determined contribution (NDC) target of a greenhouse gas reduction of at least 40% in 2030 compared to 1990. In addition, Germany has defined

[1] Due to reporting standards and the attribution of emissions from international transport, CO_2 emissions from international bunker fuels are neither part of national climate objectives nor NDCs.

Table 4b
Detailed passenger, flight and emission forecast results 2040 for the three scenarios.

Base year 2010			Regulated Shift			Reference			Free Play		
domestic	intra-European	inter-continental	domestic	intra-European	inter-continental	domestic	intra-European	inter-continental	domestic	intra-European	inter-continental
OD-passengers [million]											
16.8	6.2		21.0 (+25.0%)	70.3 (+25.0%)		23.1 (+37.7%)	77.4 (+37.7%)		24.7 (+47.1%)	82.7 (+47.1%)	
Passengers [million]											
24.7	54.3	17.4	23.3 (−6.0%)	73.6 (+35.5%)	24.9 (+42.9%)	27.7 (+12.0%)	79.7 (+46.6%)	27.3 (+56.9)	28.5 m (+15.2%)	90.2 m (+66.0%)	28.6 m (+64.2%)
Flights [thousand]											
284.4	565.3	83.9	221.4 (−22.1%)	628.4 (+11.2%)	113.2 (+34.9%)	251.7 (−11.5%)	666.0 (+17.8)	123.6 (+47.3%)	242.4 (−14.8%)	724.0 (+28.1%)	127.9 (+52.4%)
Passenger per flight											
86.9	96.1	207.6	104.9 (+20.8%)	117.1 (+21.8%)	219.9 (+5.9%)	109.9 (+26.5%)	119.6 (+24.4%)	221.2 (+6.5%)	117.4 (+35.2%)	124.6 (+29.6%)	223.7 (+7.7%)
Revenue passenger kilometers [billion]											
10.8	68.8	113.2	9.9 (−8.4%)	100.0 (+45.4%)	168.0 (+48.4%)	11.8 (+9.1%)	108.2 (+57.4%)	184.4 (+62.9%)	12.1 (+12.3%)	122.6 (+78.2%)	193.0 (+70.5%)
CO_2 [g] per revenue passenger kilometer											
173.7	101.5	112.9	132.6 (−23.7%)	78.5 (−22.6%)	93.7 (−17.0%)	139.5 (−19.7%)	81.8 (−19.4%)	98.5 (−12.7%)	146.6 (−15.6%)	86.8 (−14.4%)	103.6 (−8.3%)
CO_2 [million t]											
1.9	7.0	12.8	1.3 (−30.1%)	7.9 (+12.5%)	15.7 (+23.2%)	1.6 (−12.4%)	8.8 (+26.8%)	18.2 (+42.2%)	1.8 (−5.3%)	10.6 (+52.5%)	20.0 (+56.5%)
NO_x [g] per revenue passenger kilometer											
0.785	0.417	0.537	0.610 (−22.3%)	0.321 (−22.9%)	0.413 (−23.0%)	0.675 (−14.0%)	0.352 (−15.6%)	0.457 (−14.8%)	0.709 (−9.6%)	0.374 (−10.4%)	0.480 (−10.5%)
NO_x [thousand t]											
8.5	28.7	60.7	6.0 (−28.8%)	32.1 (+12.0%)	69.4 (+14.3%)	7.9 (−6.2%)	38.1 (32.8%)	84.3 (+38.8%)	8.6 (+1.5%)	45.8 (+59.7%)	92.7 (+52.7%)

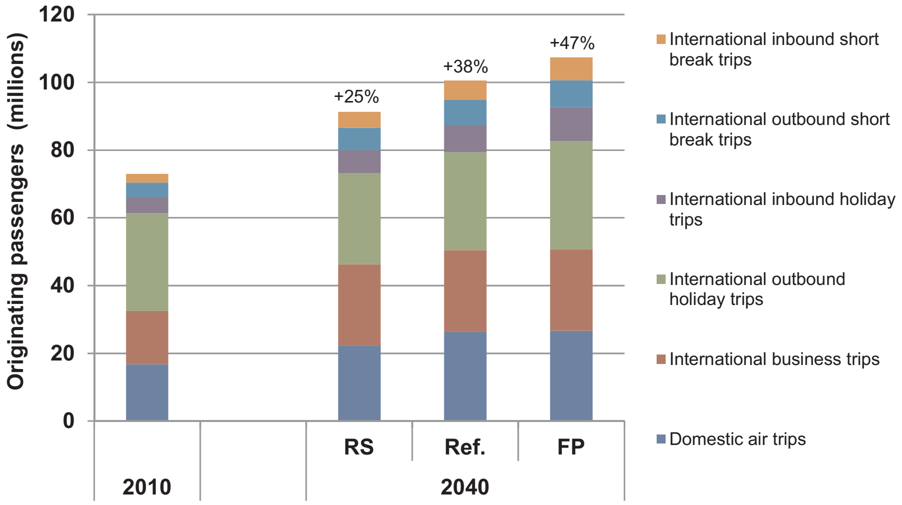

Fig. 6. Passengers originating from German airports (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

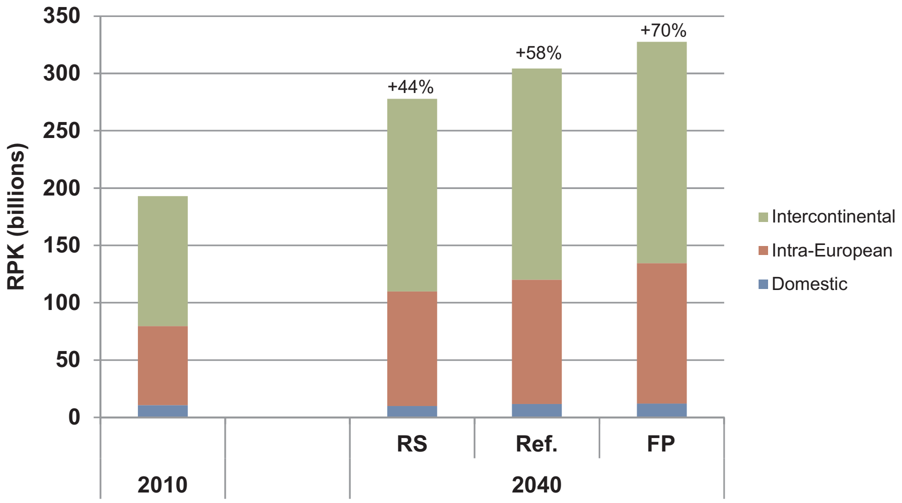

Fig. 7. Revenue passenger kilometers of flights departing from German airports. (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

its own climate action plan (Federal Ministry for the Environment, 2016), which aims at a reduction of at least 55% in greenhouse gas emissions in 2030 compared to 1990. The achievement of this goal would result in total domestic greenhouse gas emissions of 562 million tons CO_{2eq}, while aviation emissions for flights departing German airports based on the three scenarios presented here are expected to increase to 24.7–29.0 million tons CO_2 in 2030. Hence, the share of aviation emissions is expected to more than double from 2.3% in 2010 to 4.4–5.3%, depending on the scenario under consideration.

4.2. Climate impact

In 2010, the climate impact of emissions of passenger flights departing from German airports in terms of temperature increase compared to the world with no aviation is about 1.1 millikelvin (mK) (Table 5 and Fig. 10). The temperature change increases for the Reference scenario to 2.4 mK in 2040. The Regulated Shift scenario causes a 4.5% lower climate impact than the Reference scenario, while the Free Play scenario causes a 3.6% larger climate impact compared to the Reference scenario. Assuming constant emissions after 2040 leads to a temperature change of 3.7 mK in 2100 for the Reference scenario. The Regulated Shift scenario provides a 10% lower and the Free Play scenario an about 8% larger climate impact compared to the Reference scenario. Assuming decreasing (Gomp) or zero emissions after 2040 results in a significantly smaller temperature increase in 2100, but relative differences between the scenarios stay similar (Table 5). On the other hand increasing emissions (LinWa, KoWaRa) lead to significantly larger climate impact in 2100 and also to larger differences between the scenarios (up to 20%).

A reason for the larger differences between the scenarios in 2100 compared to 2040 is on the one hand the lifetimes of the species, which cause accumulation effects over a longer time period and on the other hand the thermal inertia of the atmosphere, which

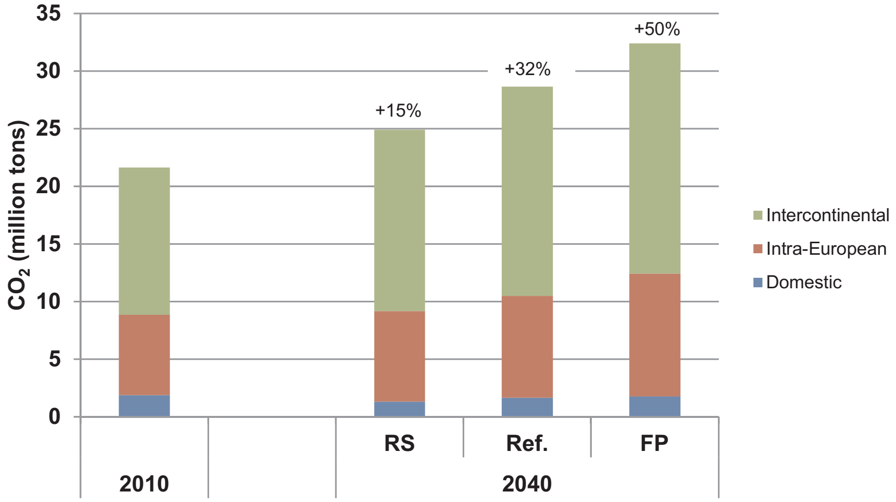

Fig. 8. CO_2 emissions of passenger flights departing from German airports. (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

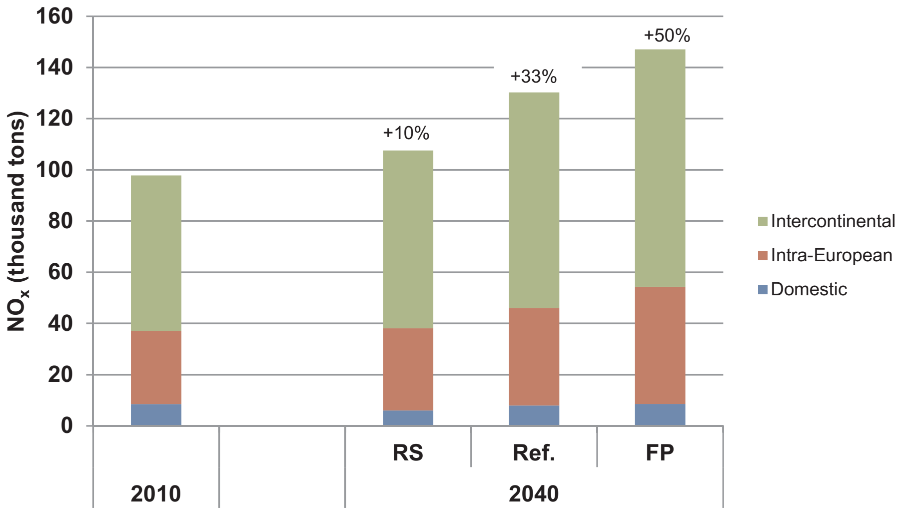

Fig. 9. NO_x emissions of passenger flights departing from German airports. (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

Table 5

Temperature change due to aviation. Values of 2010 result from historical data, values of 2100 depend on the assumed emission development after 2040. (RS: Regulated Shift, Ref.: Reference, FP: Free Play).

		Total temperature change ΔT [mK]			Change relative to Ref. [%]	
		RS	Ref.	FP	RS	FP
2010		1.13	1.13	1.13		
2040		2.28	2.38	2.47	−4.5	3.6
2100	const	3.37	3.75	4.04	−10.0	7.9
	Gomp	2.09	2.32	2.50	−9.5	8.1
	zero	0.75	0.81	0.87	−7.4	7.4
	KoWaRa	3.84	4.81	5.81	−20.2	20.8
	LinWA	3.72	4.44	5.03	−16.2	13.3

causes a delay in temperature change of about 30 years. Both can be seen in the temporal development of the temperature change when we assume that emissions follow a Gompertz function after 2040 (Fig. 10). While the emissions peak in 2040 and decreases to zero in 2100, the temperature change peaks in 2070 and decreases until 2100 only to 75% of the maximum value. The total climate impact of German air traffic largely depends on the assumed development after 2040 (Fig. 10). Nevertheless the relative changes in

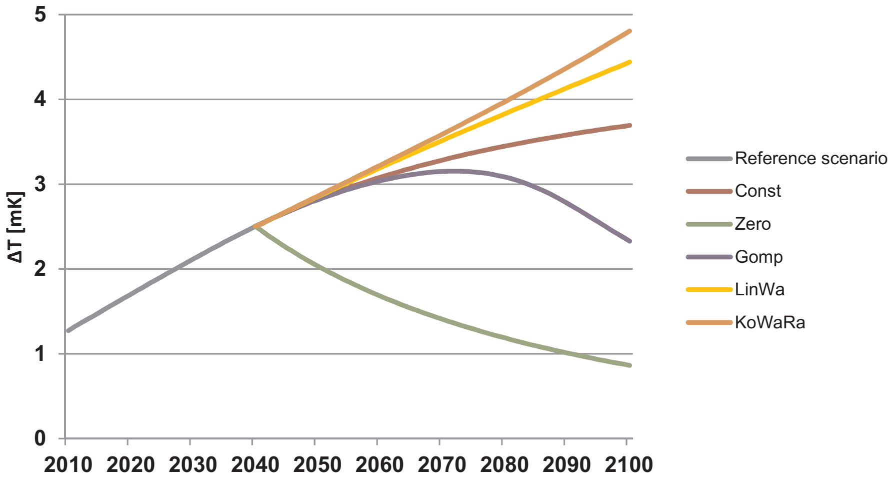

Fig. 10. Development of temperature change for the Reference scenario for the different developments of German air traffic emissions after 2040.

climate impact due to the three scenarios are quite similar. The same was shown in Dahlmann et al. (2016).

Regarding the climate impact of German aviation with respect to the three traffic regions, we can conclude that intercontinental flights contribute nearly two thirds to the total mean temperature change in all three scenarios (Fig. 11).

The contribution of non-CO_2 effects (e.g. NO_x, contrails, water vapor) to the total climate impact differs more for each traffic region than for each scenario (Fig. 12). While the non-CO_2 effects contribute to 76–78% to the total climate impact in terms of temperature change in 2100 (constant emissions after 2040) for intra-European and intercontinental flights, the contribution for domestic flights is only about 50%. Compared to intra-European and intercontinental flights the contribution of non-CO_2 effects of domestic flights is smaller since they are generally operated at lower altitudes, where the impact of aviation on contrails and ozone is smaller than in higher altitudes. Thus the contribution of domestic flights to the total climate impact is only 4%, although the contribution to the emissions is 6% for constant emissions after 2040.

5. Discussion and conclusion

In each scenario passenger volume, revenue passenger kilometers and associated emissions increase (Fig. 13). However, the development of CO_2 emissions is decoupled from the rise of RPKs, which is due to the combined effect of better aircraft technology, further deployment of larger aircraft and higher utilization. Our study shows that the developments of both the specific and absolute emissions result from complex interactions of demand development and supply decisions, which highly influence the climate impact. The improvement in specific emissions varies between the domestic and intra-European traffic on the one hand, and the intercontinental traffic on the other. This is derived from the fact that airlines in the past initially concentrated on reducing specific fuel

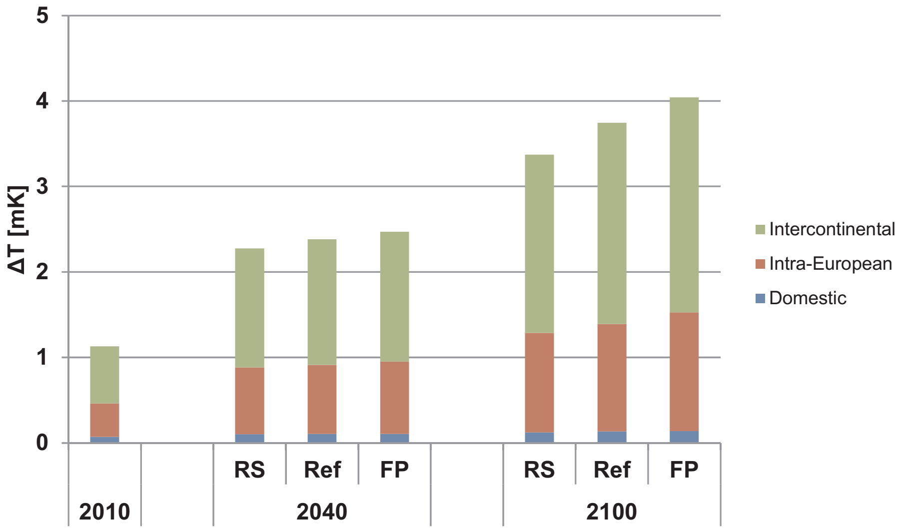

Fig. 11. Temperature change due to emissions of passenger flights departing from German airports for constant emissions after 2040.

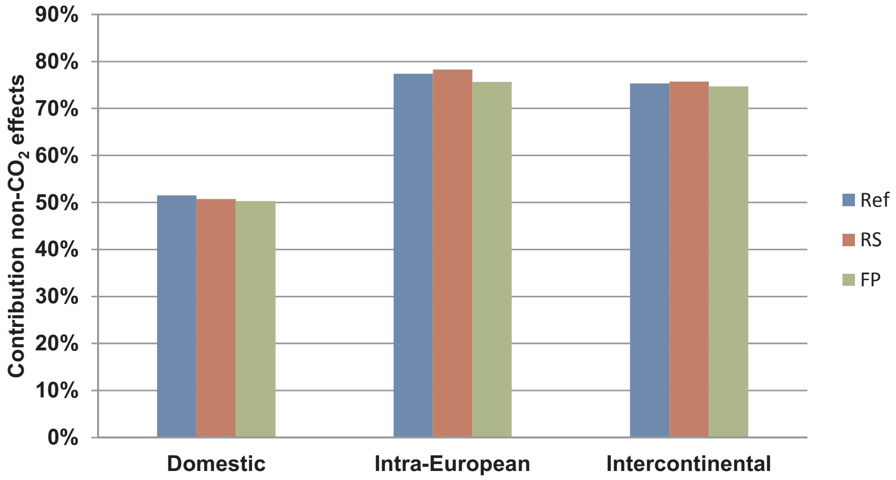

Fig. 12. Contribution of non-CO_2 effect to the temperature change in 2100 for domestic, intra-European, and intercontinental traffic departing from German airports for the three scenarios with constant emissions after 2040.

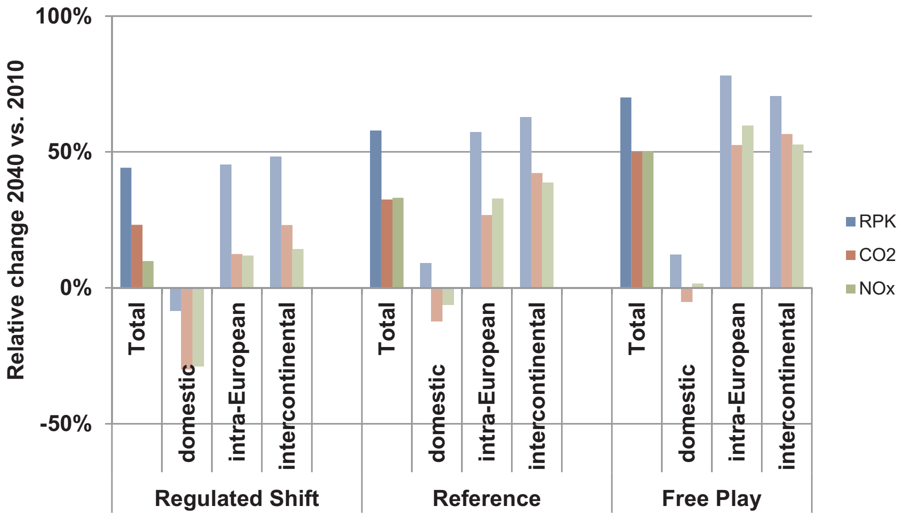

Fig. 13. Relative change of revenue passenger kilometers and emissions of passenger flights departing from German airports from 2010 to 2040.

consumption on long-haul routes, so that the potential for further efficiency gains is lower in this traffic sector. In contrast, specific fuel consumption on short- and medium-haul routes can be reduced much more. As a result, CO_2 emissions of domestic air traffic are dropping, even though air traffic demand is rising in the Reference and Free Play scenarios. In the Regulated Shift scenario, a reduction in air traffic demand fosters the decline of CO_2 emissions. Regarding border crossing air traffic, CO_2 emissions of intra-European air traffic are rising less than the emissions of intercontinental air traffic. This becomes particularly obvious in the Regulated Shift scenario. There, the CO_2 emissions of the intercontinental air traffic grow twice as much as the emissions of the intra-European air traffic while the revenue passenger kilometers increase approximately similarly (Fig. 13).

NO_x emissions are not directly linked to the fuel consumption, but depend on engine technology. Aircraft engines with higher fuel efficiency have higher combustion temperatures and, hence, tend to produce more NO_x-emissions. The total amount of NO_x grows considerably less in the Regulated Shift scenario because NO_x-reducing measures will be implemented. But in the other two scenarios, NO_x emissions increase approximately in line with the CO_2 emissions, because there is no specific incentive to reduce NO_x emissions. Therefore the NO_x emissions increase for the Free Play scenario by about 50% from 2010 to 2040, while the NO_x emissions increases only by 10% in the Regulated shift scenario.

Our results on the development of specific emissions per RPK show much smaller improvements than stated by industry or policy goals. For instance, Flightpath 2050 aims at reducing CO_2 emissions per RPK by 75% and NO_x emissions per RPK by 90% in 2050 compared to the technological level of the year 2000 (European Commission, 2011). This is on the one hand probably more ambitious than technology can reasonably achieve (Graham et al., 2014). On the other hand, even if in 2050 aircraft and engine technology is able to reach the ambitious goals, it would take further two to three decades until this technology has diffused to a reasonably high share in the global fleet. The relatively conservative efficiency improvements in this study are also a result of the near saturation of load factors, decreasing technological progress with regard to a simultaneous reduction in emissions and energy consumption (with current technology, a reduction in NO_x results in a fuel burn penalty, Freeman et al. 2018) and longer service life of aircraft currently in production. Further research should be undertaken to identify the individual contribution of each of the involved factors in emissions development, e.g. load factor, technology level and aircraft size.

Although air traffic grows rather moderately in all three scenarios as compared with traffic growth in industry forecasts, the envisaged improvements in specific CO_2 and NO_x emissions per RPK are not sufficient to absolutely reduce these emissions. A reduction of total emissions is intended by the German climate action plan (Federal Ministry for the Environment, 2016) for all economic sectors. We therefore have to conclude that further mitigation efforts are necessary to reduce the climate impact of aviation. Further regulatory and technological measures will be needed, and a main focus should be the intercontinental air traffic because of the high contribution of this segment to total emissions and climate change.

Power-to-liquid (PtL) fuels constitute a potential for reducing net carbon emissions in aviation. While on the one hand these fuels are currently significantly more expensive than petroleum-based jet fuel, they on the other hand can be blended with traditional jet fuel, which makes a gradual increase of their use possible, when production capacities will be built up over time (Scheelhaase et al., 2019). A gradual introduction, supported by adequate policy measures (e.g. blending quota) is likely not to overstress the aviation sector when it comes to fuel costs. PtL fuels can be almost carbon neutral, in case CO_2 from the atmosphere is captured for their production. However, considerable challenges are associated with the large scale production of PtL fuels, namely the cost-efficient implementation of electrolysis, carbon capture and provision of green electrical power, which is likely to be realized only in a longer timeframe and with a high capital expenditure (Zech et al., 2016). Regarding non-CO_2-effects of aviation, PtL fuels are likely to reduce the amount of soot, due to a lower content of ring-shaped hydrocarbons (Saffaripour et al., 2011). However, concerning NO_x emissions, the reduction potential of PtL fuels is limited, as NO_x creation depends on engine technology rather than fuel properties. At least for short-haul flights with small regional aircraft, progress in (hybrid-)electric aircraft concepts (e.g. Atanasov et al., 2019) can provide further opportunities for emissions reductions, both in CO_2 and NO_x, when significant portions of shorter flights can be conducted with electric propulsion. The electricity consumed by hybrid or full electric aircraft must be generated from renewable sources in order to achieve carbon neutrality. However, this would affect only a relatively small share of transport demand and emissions. Hence, the reduction potentials are limited.

A scenario approach as presented in this paper is supposed to be applicable also for further research on the long term air transport development on a system level, for instance with respect to the impacts of introducing synthetic fuels for aviation or aircraft with innovative propulsion technologies. The focus should be laid on the impact of technological innovations (e.g. hybrid-electric aircraft with hydrogen fuel cells or batteries) and policy instruments (e.g. blending quotas or green certificates for synthetic fuels) on air transport demand and supply and the subsequent impacts on climate change mitigation. Finally, we would like to state that the scenario specific results of the future development of aviation emissions and climate impact refer to Germany and reflect in particular Germany's geographic situation, its role in the world economy and the touristic travel behavior of its population. As such these results are not directly applicable for other countries. However, basic trends, in particular the development of specific emissions per RPK, bear some validity for other countries as well and can be used for scenario analyses for similar transport and environment issues.

CRediT authorship contribution statement

Michael Hepting: Conceptualization, Methodology, Validation, Writing - original draft. **Henry Pak:** Methodology, Investigation, Validation, Formal analysis, Writing - original draft. **Wolfgang Grimme:** Methodology, Investigation, Formal analysis, Writing - original draft. **Katrin Dahlmann:** Investigation, Formal analysis, Writing - original draft. **Martin Jung:** Formal analysis. **Dieter Wilken:** Validation, Writing - review & editing.

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