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Net-zero aviation: Transition barriers and radical climate policy design implications

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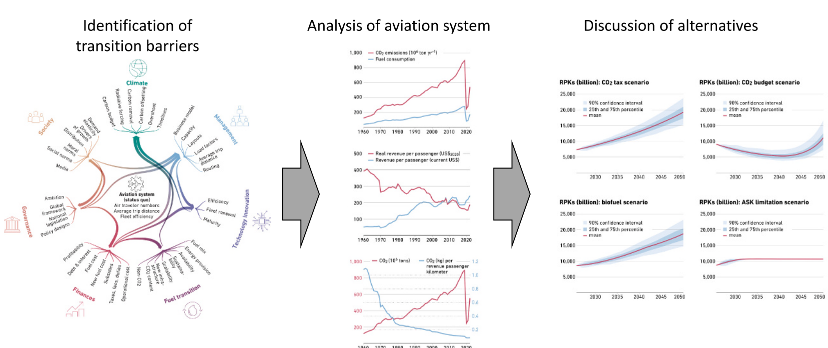
HIGHLIGHTS

- Identifies and structures barriers to the net-zero transition in aviation
- Analyzes performance indicators for air transport for the period 1978–2022
- Finds that it is very unlikely that aviation will reduce emissions in line with goals
- Provides four alternative scenarios for air transport futures, founded in limitations
- Reveals that volume growth is not necessarily the most profitable business model

GRAPHICAL ABSTRACT



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ABSTRACT

While air transport decarbonization is theoretically feasible, less attention has been paid to the complexity incurred in various ‘transition barriers’ that act as roadblocks to net-zero goals. A total of 40 barriers related to mitigation, management, technology and fuel transition, finance, and governance are identified. As these make decarbonization uncertain, the paper analyzes air transport system’s growth, revenue, and profitability. Over the period 1978–2022, global aviation has generated marginal profits of US$$_{2020}$0.94 per passenger, or US$$_{2020}$82 billion in total. Low profitability makes it unlikely that the sector can finance the fuel transition cost, at US $0.5–2.1 trillion (Dray et al. 2022). Four radical policy scenarios for air transport futures are developed. All are characterized by “limitations”, such as CO_2 taxes, a carbon budget, alternative fuel obligations, or available capacity. Scenario runs suggest that all policy scenarios will more reliably lead to net-zero than the continued volume growth model pursued by airlines.

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1. Introduction

It is generally acknowledged that to reduce aviation's contribution to global warming is technically challenging and costly (Bergero et al., 2023; Dray et al., 2022; Gonzalez-Garay et al., 2022; Gössling et al., 2021; Grewe et al., 2021). Scenario studies have concluded that air transport can significantly reduce emissions from aviation, with optimistic runs allowing for CO_2 reductions by >90 % to 2050, under a 2–3-fold increase in demand (Dray et al., 2022). However, this will require considerable change in the aviation system, including continued gains in fuel efficiency and a switch to alternative fuels (Bergero et al., 2023; Dray et al., 2022; Gössling et al., 2021; Ueckerdt et al., 2021), as well as carbon removal if aviation is to become "warming neutral" (Sacchi et al., 2023: 2). Given various uncertainties, such as the low level of maturity of proposed technologies and fuels, upscaling challenges, availability of biomass-based fuels, or the scale of necessary fuel production investments (Becken et al., 2023; Bergero et al., 2023; Brazzola et al., 2022; Dray et al., 2022; Gössling et al., 2021; Grewe et al., 2021; Ueckerdt et al., 2021), it has also been concluded that to *reliably* decarbonize the sector, demand growth rates will have to fall (Åkerman et al., 2021; Bergero et al., 2023; Brazzola et al., 2022; Gössling et al., 2021; Hassan et al., 2018; Sharmina et al., 2021; Skowron et al., 2021).

While there is thus a body of literature that analyzes the technology innovation potential of the sector (Bergero et al., 2023; Dray et al., 2022; Grewe et al., 2021), wider socio-economic-political complexities of net-zero goals have remained ignored. Yet, the understanding of interrelationships between management, technology and fuel transition, finance, and the role of governance is highly relevant for the reliability of net-zero strategies. Currently, growth rates as projected by industry serve as demand guidelines (Becken and Carmignani, 2020), which are then used to determine future fuel needs defining the transition challenge (Dray et al., 2022; Gössling et al., 2021; Grewe et al., 2021). However, transitions are characterized by great complexity that involve technologies, infrastructures, organizations, markets, regulations, and user practices (Geels et al., 2017), and, in the context of aviation, a wide range of uncertainties that in the past have consistently revealed "solutions" to represent "technology myths" (Peeters et al., 2016).

Against this background, the paper has three purposes. It presents an overview of transition barriers and their interrelationships that serve as a basis for the understanding of the complexity inherent to the system. The paper then goes on to analyze the current structure of the global aviation system in regard to various parameters, such as demand (passengers and distances flown), capacity growth, fuel consumption, emissions of CO_2, as well as different measures of profitability. The analysis illustrates that it is unlikely that continued volume growth can be aligned with net-zero goals. Based on this finding, four different scenarios for alternative air transport business models are developed that will reduce emissions more reliably. All scenarios have a starting point in limitations and may thus be considered "radical", including CO_2 taxation, a CO_2 budget, biofuel mandates, and capacity limits. The paper concludes with a discussion of the results.

2. Method

2.1. Transition barriers

A wide range of factors represent potential or factual barriers to the net-zero transition of the air transport system, with a status quo that can be described based on air traveler numbers, average trip distances, and fleet efficiency. Depending on changes in this system, effective radiative forcing – the measure describing air transport's total contribution to global warming (Lee et al., 2021) – increases or declines.

Net-zero transition challenges are framed as "transition barriers". Barriers are structured into seven categories related to climate, management, technology innovation, fuel transition, finances, governance, and society. In total, 40 different individual aspects with relevance for the net-zero transition are identified under these categories (for details see Supplement). The list is not necessarily exhaustive and serves the main purpose of providing a preliminary overview of complexities, challenges, and interrelationships.

As an example, there is no political consensus on timelines for net-zero aviation. Should aviation seek to be net-zero by mid-century, i.e. in line with wider ambitions for the world economy, or should the sector be given more time? Should the definition of 'net-zero' for aviation focus on CO_2 from fuel combustion; lifecycle emissions from oil extraction, refining, crude oil and fuel logistics (Dray et al., 2022); or even include the warming effects of other greenhouse gases at flight altitude (Lee et al., 2021) - to the point where all of aviation's climate impacts to 2050 are considered (Sacchi et al., 2023)? As global warming is largely determined by the build-up of CO_2 in the atmosphere, should there also be a total budget for emissions of CO_2 from air transport, which would potentially require more significant decarbonization efforts in the near future? These are examples of unresolved issues that act as potential barriers to the net-zero transition, as necessary changes in the system will be determined by the definition of goals.

2.2. Historical development of air transport, 1960–2021

The global air transport system, including domestic and international flights, has developed in specific ways between 1960 and 2021. Various parameters are analyzed to better understand this development, for instance in regard to revenue passenger kilometers (RPK), available seat kilometers (ASK), revenue ton kilometers (RTK), passenger numbers, fuel use, emissions, load factors, revenue, and profitability. The paper does provide the first longitudinal overview of these parameters with a view to understand weaknesses in the system, such as the sector's low profitability (Doganis, 2005). Longitudinal data is based on the following data sources and assumptions:

- Data for RPK, ASK, RTK, passenger numbers and load factors for the period 1960–2021 is retrieved from Airlines (2023).
- Aviation fuel consumption data for the period 1940–1970 is based on Sausen and Schumann (2000) and for the period 1970-2021on International Energy Agency (IEA, 2022a, 2022b). CO_2 emissions are calculated based on a conversion factor of 3.16 kg CO_2 per kg of fuel (IATA, 2022).
- Data for operating revenues and profits in US$ is derived from Airlines (2023). Real operating revenues and profits in USD_{2020} are calculated by dividing operating revenues and profits by the consumer price index normalized to 1 in 2020 (U.S. Bureau of Labor Statistics, 2023).

The data allows for the development of integrated indicators. For example, real revenues and real net profits can be divided by the number of passengers to understand developments in revenue vis-a-vis profitability. Emissions can also be divided by real operating revenues and RPK to determine developments in fuel efficiency.

2.3. Model description and scenarios

The paper's purpose is to develop alternative scenarios for aviation that compare a business-as-usual baseline for RPK, emission growth, and revenue for the period 2025–2050 with futures that are characterized by different forms of limitations. Scenario runs explore the effects of CO_2 taxation, a CO_2 budget, biofuel obligations, and a no-growth capacity limit. The aviation demand growth model used in the paper was originally presented by Gössling et al. (2021) to understand future energy and land requirements for synthetic fuel production. Several adjustments are made to the original model to increase its reliability; the adjusted model also uses new data derived from calculations as detailed in Section 2.2.

2.3.1. Baseline model

In a first step, a baseline scenario for RPK growth to 2050 is developed. In the original model (Gössling et al., 2021), the average long-term air traffic demand growth expected by Airbus (2022) and Boeing (2022) was 4.45 % per year, with a post-pandemic recovery transport demand of 8860 billion RPK in 2022. Passenger air traffic demand growth was thus expressed as:

$$RPK_t = 8860*1.0445^t \quad (1)$$

Demand projections in Gössling et al. (2021) to 2050 were based on $t = 0$ for the year 2022 and $t = 28$ for the year 2050. The updated model sets the recovery year to 2025 and growth rates to 4.61 %, based on the latest estimates by Airbus (2022) and Boeing (2022) for commercial aviation. To also distinguish cargo from passenger transport, RPKs are converted to RTKs. RPKs are multiplied by a factor 0.1 to derive RTK equivalents, i.e. calculated as the ratio of RTK (cargo) to RTK equivalents (passenger weight), at an average 100 kg per passenger. While lower values have been used by Dray et al. (2022) at 90 kg per passenger, ICAO (2022a, 2022b) points to 100 kg per passenger, a value that is also used by the European Union to calculate emission allowances in the EU ETS (EU, 2009). All calculations of RPK do not consider empty space (ratio of ASK to RPK) or seat weight. To estimate total RTKs for the aviation sector (domestic and international), passenger RTK-equivalents are added to RTKs. This is necessary to model the growth of the entire system, and to compare this data to revenue (which is not available for cargo in comparison to passenger shares).

A weakness of the original Gössling et al. (2021) model is that it relies on a deterministic approach (fixed growth rates). The updated model uses a stochastic approach, based on bootstrapping. Moving block bootstrapping (MBB), as originally developed by Künsch (1989) and Liu and Singh (1992), can be used with general dependent time series data (Li and Maddala, 1996) to consider serial correlation in air transport demand (Dantas et al., 2017). Moving block bootstrapping has the advantage of not requiring a fitting of data into parametric form, making it possible to use empirical distribution directly (Li and Maddala, 1996). Given a sequence of stationary m-dependent random variables $X_1, \ldots, X_n$, the moving blocks bootstrap method resamples from moving blocks $B_1, \ldots, B_{n-b+1}$ with the size of the block b and the block of b consecutive observations starting at Xj donated B_j (Liu and Singh, 1992). Instead of using the same growth rate of 4.61 % for every year for the 2025–2050 period, demand projections consider historic characteristics of air traffic growth (skew, standard deviation, kurtosis). Draws are then re-scaled to a mean of industry-expected growth. The rationale for this approach is that aviation is characterized by business cycles (Doganis, 2005): bootstrapping makes it possible to consider future fluctuations in growth rates, and to increase the robustness of the scenarios.

The bootstrapping model is based on using moving blocks B_j with a size n of five years from (historic) RTK growth rates $R_i + 1$ between 1980 and 2019. This period is used as the aviation industry experienced considerable growth during the 1960s and 1970s, from low levels. The years 2020–2022 were characterized by the pandemic. Both periods do not adequately represent longer-term developments, hence the focus on 1980–2019. Five years approximates an average business cycle length in aviation (Doganis, 2005), and the model is based on:

$$B_j = \prod_{i=1}^{5}(R_i + 1) \quad (2)$$

In this approach, the constant growth rate is replaced with random draws from the historic growth rate distribution. From the distribution of moving blocks B_j we draw five times randomly with replacement. The procedure is repeated one million times and the consecutive five draws in each run are used to generate a forecast for air traffic demand in 2050:

$$RTK_{2050} = RTK_{2025}*\prod_{j=1}^{5} B_j \quad (3)$$

The upgraded model of air traffic demand is now stochastic, and confidence intervals, as well as means and modes can be calculated. To adjust the historic distribution (1980–2019) of air demand growth (5.41 %) to industry-expected growth rates, we re-scale the empirical historical distribution of growth rates to a mean of 4.61 %. Fig. 1 shows the distribution of RTK estimates in 2050 in a comparison of historical growth rates (BAU) and re-scaled growth distribution with industry-expected growth rates.

According to ICAO data (1980–2019, as detailed in 2.2), air transport has grown by 5.41 % per year. Extrapolating 2019 demand (1103 billion RTKs; cargo and passengers) to 2050 suggests that demand will reach 4204 billion RTKs (25th percentile: 3797 billion; 75th percentile: 4570 billion; mode: 4165 billion RTK). The RPK share of passenger transport (79 %) is 33,212 billion RPK (25th percentile: 29,996 billion, 75th percentile: 36,103 billion, mode: 32,904 billion RPKs). In comparison, Airbus (2022) and Boeing (2022) expectations of a 4.61 % growth rate per year to 2040 (and extrapolated to 2050), yields a mean estimate of 3471 billion RTK (25th percentile: 3135 billion; 75th percentile: 3773 billion; mode 3439 RTKs); and a corresponding value of 27,421 billion RTK for passenger transport (25th percentile at 24,767 billion, 75th percentile at 29,807 billion and mode at 27,168 billion RPKs). Here we use the lower values to reflect on industry expectations.

To estimate CO_2 emissions for the period 2025–2050, efficiency improvements need to be considered, based on annual changes in fuel consumption per RTK. The forecast uses data for the period 1980 and 2019. The scenario run starts in 2025 ($t = 0$) and ends in 2050 ($t = 25$),

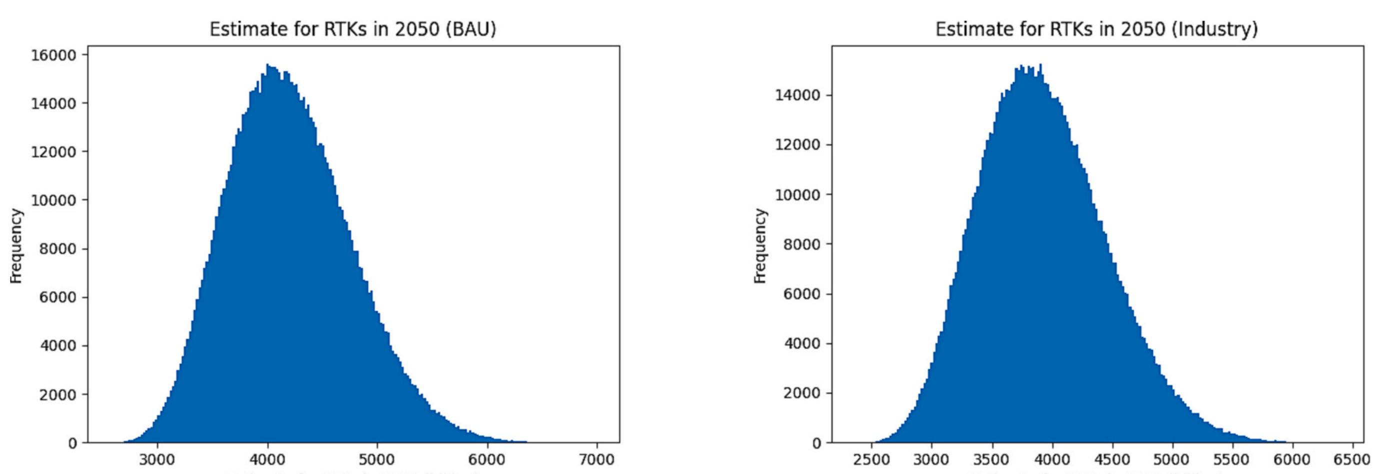

Fig. 1. 2050 air transport demand, 1980–2019 growth vis-a-vis industry expectations.

using a conversion rate of 3.16 kg CO_2 per kg fuel:

$$CO_{2_t} = RTK_t{*}(1 - efficiency\ gain)_t{*}0.300\ \frac{kg}{RTK}{*}3.16\ \frac{CO_2}{kg} \tag{4}$$

The analysis of data for this paper suggests that historical efficiency gains have been 2.5 % per year between 1980 and 2019. Air transport efficiency gains depend on changes in various parameters, such as (higher) load factors, or engine and airframe improvements, but as the system optimizes, it also approaches physical limits. Future efficiency gain estimates are thus lower, at an estimated 1.3 % per year (Dray et al., 2022). Following procedures as outlined in (3), historical distribution is re-scaled to derive an estimate for CO_2 emissions in 2050. Again, this is an improvement of the original model (Gössling et al., 2021) that considered constant efficiency gains of 1 % per year.

The MBB simulation for the entire aviation system (cargo and passenger transport) suggests mean 2050-CO_2 emissions of 2.37 Gt (25th percentile: 1.90 Gt CO_2; 75th percentile: 2.77 Gt CO_2; mode 2.31 Gt CO_2). The share of passenger traffic is 1.87 Gt CO_2 in 2050 (25th percentile: 1.50 Gt CO_2, 75th percentile: 2.19 Gt CO_2; mode: 1.82 Gt CO_2). This is the default business-as-usual scenario against which alternative scenarios can be assessed.

For these scenarios, economic data is needed (see details in 2.2). Historical data does not allow for a split of RTK to RPK profitability, and we calculate proportional RPK to RPK profit ratios (10 RPK representing one RTK). This overestimates profitability in passenger air travel as cargo is more profitable (IATA and McKinsey, 2022). Profitability for passenger air travel should thus be seen as an upper bound estimate. All assumptions for the baseline model are detailed in Table 1.

For the four scenarios, the following equations become relevant: the effect of taxation on the price elasticity of demand is calculated by:

$$\varepsilon_{RPK(fuel\ price)} = \frac{log(RPK_t) - log(RPK_{t-1})}{log(fuel\ price_t) - log(fuel\ price_{t-1})} \tag{5}$$

With a price elasticity of demand $\varepsilon_{\mathrm{RPK(ticket\ price)}}$ air transport demand is given by:

$$\mathrm{RPK_t} = \mathrm{RPK_{(t-1)}}{*}(\mathrm{R_i}+1){*}\left(\left(log\left(\frac{\mathrm{USD}}{\mathrm{KG}}\mathrm{fuel_t}\right) - log\left(\frac{\mathrm{USD}}{\mathrm{KG}}\mathrm{fuel_{t-1}}\right)\right){*}\varepsilon_{\mathrm{RPK(ticket\ price)}}{*}\mathrm{fuel\ cost\ share}+1\right)$$

The price elasticity function is applied to model the effect of price increases on air transport demand. This is done in the CO_2 tax scenario and the biofuel blending obligation scenario (approach c). For the CO_2 budget (scenario b) and ASK limitation (scenario d), air transport demand is limited, and we make use of the price elasticity of demand function to calculate the price increase level that will limit growth to a predefined level (here zero growth, once RPK equal ASK, implying that every available seat kilometer is sold).

Table 1
Overview of baseline model assumptions.

Assumption	Value	Source
Long-term demand growth expectation	4.61 % per year	Airbus (2022), Boeing (2022)
Expected long-term efficiency gains.	1.3 % per year	Dray et al. (2022)
Fuel consumption in 2025	0.3 kg/RTK	IEA, Airlines (2023)
CO_2 emissions per kg fuel	3.16 kg CO_2	IATA (2022)
Jet A1 price in 2025	0.65 US$ per kg	Gössling et al. (2021)
Fuel cost share in 2025	24.5 %	Gössling et al. (2021)
Baseline RTKs in 2025	1103 billion	Airlines (2023)
Baseline ATKs in 2025	1338 billion	Airlines (2023)
Cost per RTK in 2025	0.73 US$	Airlines (2023)
Revenue per RTK in 2025	0.77 US$	Airlines (2023)

The cost of fuel in the blending obligation scenario is calculated based on a linear increase in the feed-in quota of biofuels from 0 % in 2024 to 100 % in 2050. This scenario presupposes that biofuels become available at scale and would lead to a reduction in air transport supply if not. A decline in the production cost of biofuel by 50 % between 2025 and 2050 is incorporated in the model:

$$US\$\ per\ kg\ fuel_t = C_K\ US\${*}\left(1-\frac{t+1}{26}\right) + C_B\ US\${*}(1-C_d)^{\left(\frac{t+2}{27}\right)}{*}\left(\frac{t+1}{26}\right) \tag{6}$$

with C_K being the cost of kerosene; C_B the cost of biofuel; and C_d a biofuel production cost decline (50 % cost reduction, with $C_d = 0.5$).

The CO_2 tax for kerosene in the CO_2 tax scenario a), is based on:

$$US\$\ per\ kg\ fuel_t = \left(C_K\ US\$ + \left((C_{CO2}){*}\frac{3.16}{1000}\right){*}4^{\left(\frac{t+1}{26}\right)}\right){*}\left(1-\frac{t+1}{26}\right) + \left(C_B\ US\${*}(1-C_d)^{\left(\frac{t+2}{27}\right)}{*}\left(\frac{t+1}{26}\right)\right) \tag{7}$$

2.3.2. Approach a): CO_2 taxation

This scenario illustrates the effects of differential tax levels for RPK growth/decline and revenue generation under the assumption that no new technology becomes available. We use different tax levels for CO_2 as well as CO_2-equivalent emissions that consider system-wide effective radiative forcing at three times the forcing caused by CO_2 (Lee et al., 2021). Taxation starts in 2025 and continues to 2050, with inflation ranging between 0 % to 5 %. Elasticities are affected by factors such as traveler segment, flight class, and flight distance (Brons et al., 2002; Gillen et al., 2008; Falk and Hagsten, 2019). Demand price elasticities have been found to range between −0.27 and − 1.52 (Gillen et al., 2008). We use three price elasticity values (−0.75, −1.0, and − 1.25) that represent a range across all market segments, noting that calculations as detailed in Section 2.2 point to a long-term historical price elasticity of demand of −1. Tax levels are set at US$100 ($CO_2$) and US $300 ($CO_2$-equivalent) per ton in 2025. These rise linearly to US$400 ($CO_2$) and US$1200 (CO_2-equivalent) in 2050. This is within the range of current social cost of carbon assessments (Tol 2023). The tax is only imposed on fossil fuels, and based on the assumption that fossil fuels continue to be used over the next 30 years.

2.3.3. Approach b): CO_2 budget

In this approach, aviation is allocated a CO_2 (carbon) budget based on a sectoral distribution of the remaining global carbon budget to 1.5 °C of 500 Gt CO_2. For aviation, the share is 2.4 % (Lee et al., 2021) or about 12.5 Gt CO_2, corresponding to the sector's current contribution to emissions of CO_2. Once this budget is depleted, aviation's "license to operate" depends on net-zero technology (electric, hydrogen, biomass-based or e-fuels). In the scenario, aviation emits 1 Gt CO_2 in 2025, with emissions falling by ~6.3 % per year until the budget is depleted in 2050, when 12.5 Gt CO_2 have been emitted in a linear scenario. The scenario considers efficiency gains (Dray et al., 2022) and is likely assigning a too large share of the shrinking carbon budget (Lamboll et al., 2023) to aviation. As fossil fuel usage declines, the introduction of biofuels will begin, commencing with a volume of 1 Mt in 2025 (ICAO, 2023). As the scalability of fuels is unclear, pathways vary between an annual growth rate of in between 5 % and 25 %. RPK development under this approach is a function of fuel availability/use.

2.3.4. Approach c): Blending obligation

The blending obligation forces airlines to transition to biomass-based or synthetic fuels, and it only allows the sector to grow if alternative fuels become available. Only synthetic fuels are potentially CO_2-neutral, though it is currently unclear how relevant their non-CO_2 warming will remain in the future (Dray et al., 2022; Teoh et al., 2022). Unavoidable non-CO_2 effects will require carbon removal, at a scale that is currently unknown (Bergero et al., 2023) and with unclear feasibility. The scenario does not distinguish between fuel types, as this remains a contested issue (Becken et al., 2023). The scenario uses a cost gap for biofuels of US$1.12 per kg in 2025, in comparison to fossil fuels, and declines to US$0.56 per kg in 2050 (medium scenario; Graver et al., 2022). It is acknowledged that SAF use may be subsidized in the future, or that a very high oil price would make SAF cost-effective. There however is no current evidence for this at the global level.

2.3.5. Approach d): ASK limitation

In the ASK limitation scenario, the number of ASK in the system is kept constant at 2019 levels. This is a radical measure that is politically unlikely, with a global demand response that is difficult to anticipate. In this scenario, it assumed that RPK continue to grow until they become equal to ASK, leading to a (theoretical) load factor of 100 % in 2030. To determine the revenue becoming available to airlines under this approach, the price increase that reduces demand growth to zero is calculated. As outlined, data suggests a historical price elasticity of demand of −1.0. As demand continues to increase, the real price per RPK travelers are willing to pay rises with the growth rate of 4.6 %, assuming that capacity is kept constant. In this scenario, the price rises from its lowest point of US$$_{2020}$0.077 per RPK in 2024 to US$$_{2020}$0.12 per RPK in 2050. Complexities are acknowledged: for instance, short-haul and low-cost flights are likely more affected by price increases (Falk and Hagsten, 2019). Given such uncertainties, results are indicative.

3. Results

3.1. Transition barriers

Transition barriers are contested and unresolved issues that potentially undermine the success of net-zero strategies - beyond the challenge of sustainable fuel provisions. A total of 40 transition barriers in relation to climate change mitigation, management, technology innovation, fuel transition, finances, policies, and society are illustrated in Fig. 2; arrows depict relationships.

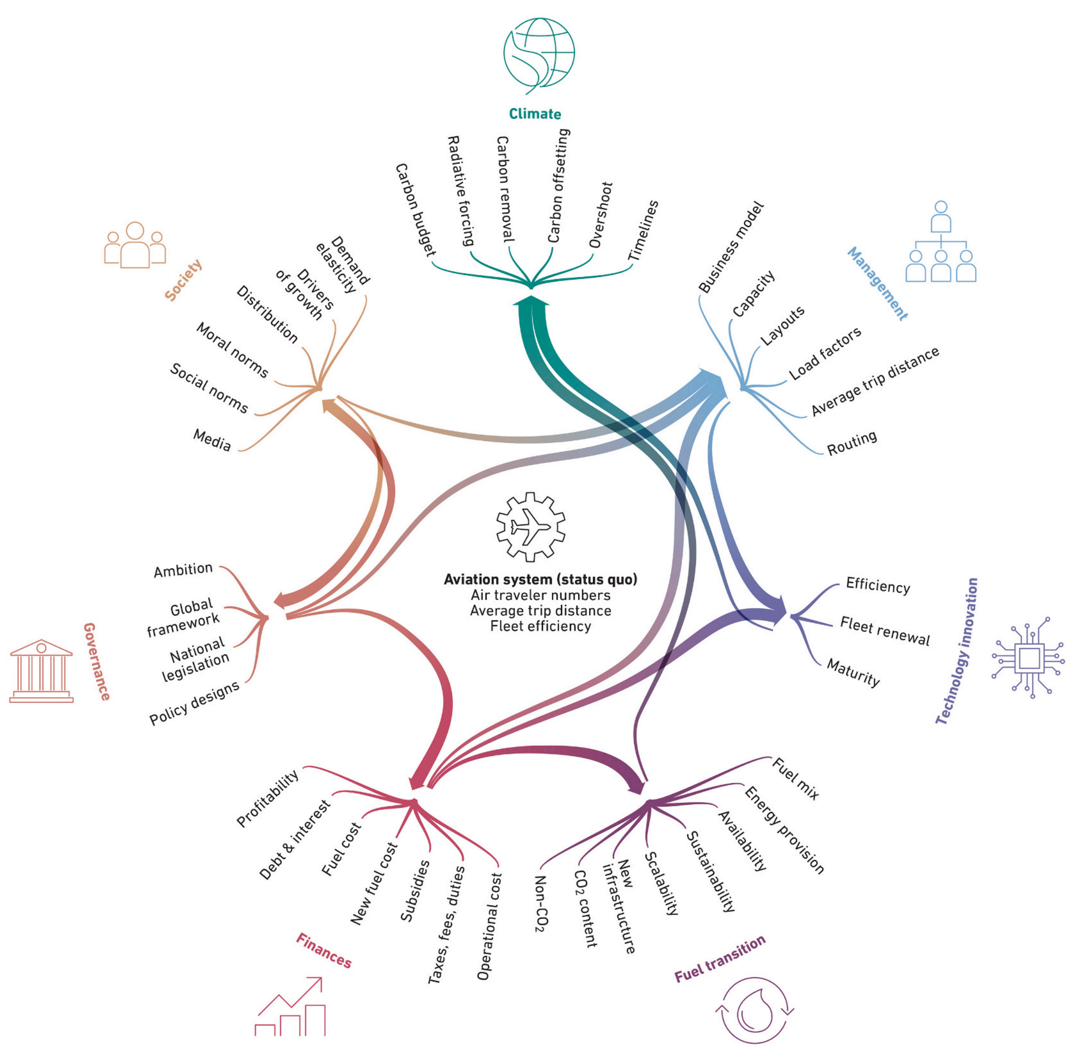

Fig. 2. Transition barriers to climatically sustainable aviation.

At the core of Fig. 2 is the current *aviation system* and its contribution to global warming, measured in effective radiative forcing. This system is made up of air traveler numbers, average trip distances, and efficiencies that determine energy demand and emissions. Efficiencies, i.e., the average amount of fuel needed per revenue passenger kilometer (RPK) or revenue ton kilometer (RTK), again depend on fleet composition (aircraft models with specific airframes and engines), load factors, and layouts (seat density, share of premium class seating, cargo shares) (Gössling and Humpe, 2020).

Climate change objectives for global aviation are uncertain, as "net-zero" remains insufficiently defined. For example, the remaining carbon budget for staying within the more ambitious 1.5 °C goal is 500 Gt CO_2 (2022–2050, >50 % chance; IPCC, 2022; though also see Lamboll et al., 2023). As aviation emits 2.5 % of global CO_2 (Lee et al., 2021), the sector's 'fair' share in the remaining carbon budget is about 12.5 Gt CO_2. At current emission rates of about 1 Gt CO_2 (Gössling and Humpe, 2020), this budget will be depleted before 2035. A related question concerns the acceptable future contribution of aviation to effective radiative forcing (Grewe et al., 2021), as non-CO_2 warming is anticipated to remain an issue even when new fuels are introduced (Dray et al., 2022). The role of carbon removal and offsetting (Bergero et al., 2023) thus needs to be defined, or whether emission overshoot is permissible. The identification of decarbonization milestones requires policy agreements. Uncertainty in regard to these aspects characterizes these transition barriers.

Air transport management is influenced by specific perspectives on growth and profitability. The current system is characterized by capacity growth, with expectations for passenger numbers to double to 2041 (Airbus, 2022). Aircraft have specific layouts, in which premium class seating occupies large shares of the available space (Gössling and Humpe, 2020). Much capacity is flown empty, while average trip distances have constantly increased. In the future, fuel burn may increase, as aircraft avoid supersaturated zones to reduce effective radiative forcing (Grewe et al., 2021).

Technology innovation refers to the future efficiency of new aircraft models (airframes and engines), as well as the speed at which fleet renewal takes place, as passenger aircraft are in service for about 25 years (SGI Aviation, 2018). A major unresolved question concerns the introduction of new technologies and fuels that are currently still unavailable – and may not become available within net-zero timeframes -, including electric, hydrogen, and e-fuel propulsion.

The fuel transition itself is characterized by various complexities. This includes the future mix of fuels that determines energy demand and type (electricity, biomass); production limits and sustainability (biomass, renewable energy); the speed at which production of alternative fuels can be upscaled; infrastructure demands (charging, storage, distribution); as well as the CO_2 that is avoided in the lifecycle (oil extraction, refining, crude oil and fuel logistics), and how this compares to developments in non-CO_2 forcing from "soot, stratospheric water vapour, contrails and contrail cirrus, oxides of nitrogen and sulphur" emissions (Dray et al., 2022: 958; see also Becken et al., 2023; Bergero et al., 2023; Brazzola et al., 2022; Bullerdiek et al., 2021; Ueckerdt et al., 2021). *E*-fuels, which are part of many scenarios (Dray et al., 2022), are not currently available at even modest scale. Even though ICAO (2023) lists hundreds of production facilities on its dashboard for SAF and e-fuels, there is no data regarding production volumes or 'entry in service' years for many, and some are listed as being 'in service' even though they are not.

Financially, air passenger transport is unlucrative, as airlines operate at small profit margins or losses (IATA and McKinsey, 2022). Financial market conditions are affected by airline debt and interest rates; operational cost by changes in fossil fuel *vis-a-vis* alternative fuel cost developments. Currently, industry points at a fuel cost gap of US$1.4–1.8 per liter (Avinor et al., 2021). Other uncertainties concern the continuation of subsidies, as well as the introduction of taxes, fees, duties, or a CO_2 price (Falk and Hagsten, 2019). Operational cost may also be affected by bunkering/charging times (hydrogen/electric aircraft) and the average number of passengers or the cargo volume that can be transported (aircraft capacity in relation to battery/tank weight/volume).

Governance is imperative in system change. This starts with political perspectives on net-zero responsibilities, i.e. whether accountability lies with airlines, aircraft manufacturers, fuel providers, consumers, or governments. On the supranational level, ICAO continues to have a formal role in defining the sector's response, but its Carbon Offsetting and Reduction Scheme for International Aviation is widely considered unreliable (Dray and Schäfer, 2021; Lyle, 2018; Scheelhaase and Maertens, 2020; Warnecke et al., 2019). Progress on decarbonization requires national action (Lyle, 2018) that is currently unlikely to become a global effort. Several governments and jurisdictions such as the EU have included aviation in NDCs, with legislation including emission trading, blending obligations, CO_2 taxation, premium class duties, and initiatives such as short-haul bans (France) or slot reductions (Netherlands). To ensure a level playing field and to have transitional relevance, such policies need worldwide adoption. Open questions include subsidies for research & development and the closing of the fuel cost gap, with some organizations demanding government support as a transition requirement (Avinor et al., 2021).

Last, *societal developments* have considerable influence on net-zero goals. Demand elasticities determine the effect of price changes, which are known to vary by travel motivation (Brons et al., 2002). Private aviation and frequent fliers account for a large share of overall transport demand, underlining the relevance of distributional aspects (Gössling and Humpe, 2020). Moral norms reflect on societal views regarding aviation's contribution to climate change and have relevance for policy support. Social norms influence perspectives on the desirability of air travel and individual decisions to fly. Norms are affected by media reports and discourses on air transport, specifically regarding 'solutions' (Guix et al., 2022; Peeters et al., 2016).

3.2. Development of the aviation system

Preceding sections have discussed interrelated transition barriers that constitute net-zero transition risks. To better understand these risks, it is relevant to consider the system's development over time (Figs. 3a-i). Over the past 60 years (1960–2019), passenger air transport grew from a supply of 0.2 trillion ASK to approximately 10.5 trillion ASK, and cargo from 3 to 235 billion RTK. Passenger numbers increased from 0.1 billion to 4.5 billion, and the average distance flown almost doubled from 1028 km to 1931 km. Yet, air travel remains an elite activity. Distributional analyses show that only 2–4 % of the world population have flown internationally in 2018, while 1 % of the world population accounts for an estimated 50 % of emissions from commercial air transport (Gössling and Humpe, 2020).

The efficiency of air transport has significantly improved over time, as illustrated by air passenger transport data. Measured per RPK, emissions declined from 0.98 kg CO_2 in 1960 to 0.09 kg CO_2 in 2019, also because load factors increased from 59.2 % in 1960 to 82.4 % in 2019. Total fuel consumption grew from 34 Mt in 1960 to 260 Mt in 2019, with corresponding emissions of about 0.82 Gt CO_2 (Sausen and Schumann, 2000; IEA, 2022a, 2022b).

As air traveler numbers increased, operational revenues rose from US$_{2020}$ 38 billion in 1960 to US$_{2020}$670 billion in 2019. Real revenues per passenger declined from US$_{2020}$356.5 to US$_{2020}$149.0 in the same period (Airlines, 2023). Real net profits oscillated; averaged between 1960 and 2022, the global real net profit per passenger was US$_{2020}$1.19, corresponding to a 0.6 % net profit margin. Without the profitable 1960s and early 1970s, aviation operated at a profit of US$_{2020}$0.94 per passenger - or US$_{2020}$0.00053 per RPK -, equivalent to a 0.49 % net profit margin. This amounts to overall net profits of US$_{2020}$81.9 billion in the period 1978–2022. To generate a profit of 1 US$_{2020}$ in this period, an airline had to transport one person over 1901 km, generating emissions of 298.6 kg CO_2. While emissions per unit of revenue have constantly declined – from about 3.7 kg CO_2 in 1960 to about 1.2 kg CO_2 per US $\$_{2020}$ in 2019 –, the sector's overall emissions almost tripled between 1980 and 2019.

A central question is how the aviation system will continue to develop. Dray et al. (2022) expect direct energy use to grow from 13 EJ in 2019 to 17.7–29.4 EJ (fossil fuels) or 15.0–28.6 EJ (sustainable aviation fuels, i.e., biomass-based and e-fuels) in 2050. In the biomass/e-fuel scenario, a considerable share of this energy will have to be green liquid hydrogen, requiring large electricity inputs (Bergero et al., 2023; Dray et al., 2022). At the upper end of energy demand projections (28.6 EJ), electricity demand is equivalent to current global renewable power production, without accounting for conversion losses (8300 TWh in 2021; IEA, 2022a, 2022b). Competition for clean energy must be expected, as countries seek to electrify. While an energy transition is estimated to reduce lifecycle aviation CO_2 by up to 89–94 % in 2050 compared to 2019, non-CO_2 radiative forcing is projected to decline by only 46–69 % (Dray et al., 2022). This suggests that the sector will continue to remain a significant contributor to global warming beyond 2050 (Grewe et al., 2021), and that additional carbon removal is necessary. The cost of the fuel transition over the coming 30 years is estimated to be in the order of US\$0.5–2.1 trillion (Dray et al., 2022), or six to 25 times the profits made by the sector over >45 years (US$_{2020}$ 82 billion; 1978–2022). Even more notable is the external cost of carbon in comparison to profits: At €300 per ton CO_2-equivalent and emissions of 0.09 kg CO_2-equivalent per RPK, the current cost of carbon is >50 times higher than the sector's long-term profitability (€$_{2020}$0.027 carbon cost to US\$$_{2020}$0.00053 profit per RPK). This adds financial barriers to environmental and technical ones.

3.3. *Alternative aviation futures*

The historical analysis of the aviation system confirms transition risks, specifically in relation to the financing of new fuels. To mitigate this risk, four alternative aviation scenarios are developed and evaluated in regard to their potential to support the fuel/technology transition. This analysis focuses on passenger transport, which is the least profitable yet highest-emitting component of the aviation industry (Gössling and Humpe, 2020; IATA and McKinsey, 2022). The four alternative scenarios have a starting point in reducing growth rates, and include a) a CO_2 tax internalizing the cost of CO_2/non-CO_2, in a scenario assuming that biofuels will not become available at scale ; b) a 'fair burden sharing' CO_2 budget of 12.5 Gt CO_2 that limits the system's growth to its ability of introducing low-carbon biofuels (non-CO_2 warming is not considered); c) a blending obligation that mandates jet fuel replacement with sustainable biofuels or synthetic fuels, assuming these become available; d) a capacity constraint scenario, in which transport capacity is limited to 2019 levels, i.e., a capacity of 10.5 trillion ASK. This last scenario explores profitability under the assumption that demand continues to grow while the supply remains stable. If emission reductions are to be achieved in this scenario, these would have to be mandated. The assumption for all scenarios is that these are introduced globally and that the cost is passed on to passengers, who may forego trips when the price becomes too high, or, where feasible, prefer alternative transport

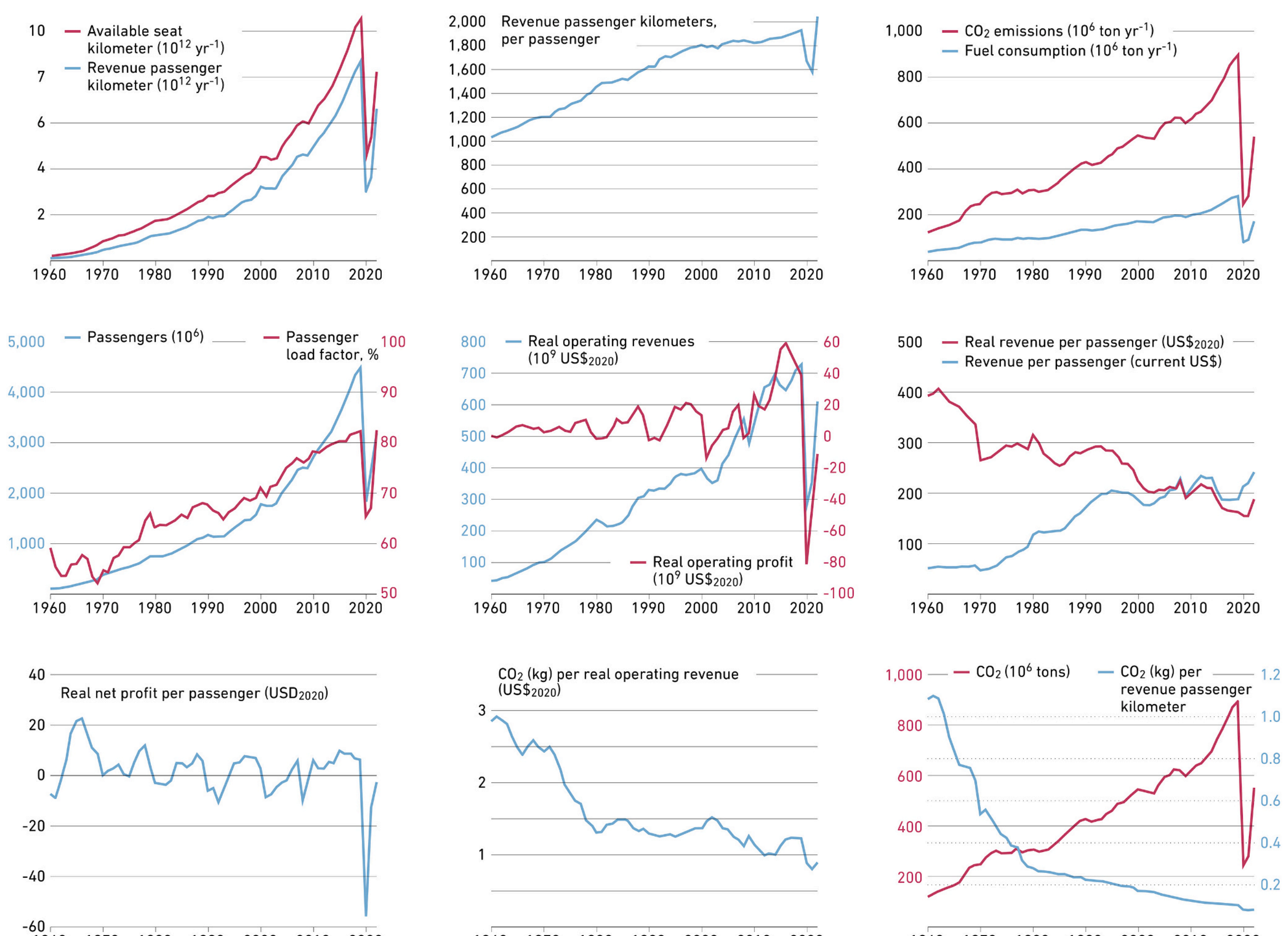

Fig. 3. a-i: Development of the aviation system (1960-2022).

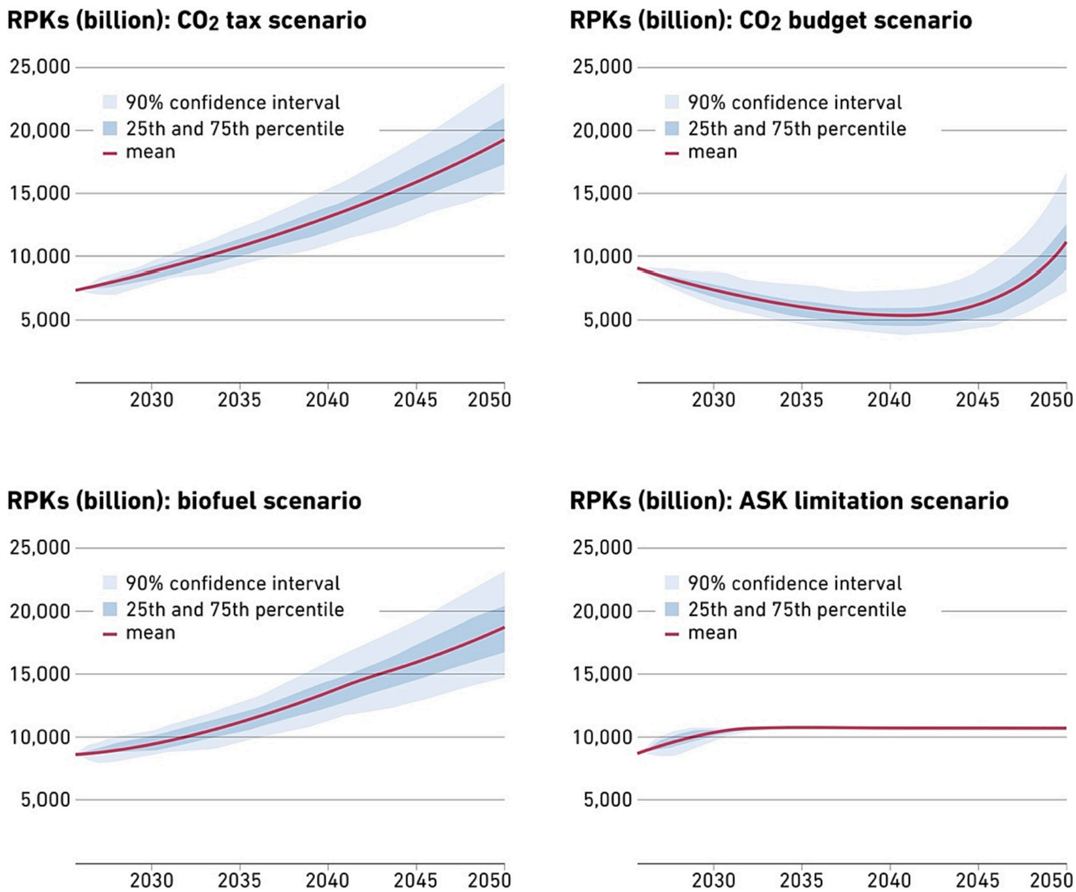

Fig. 4. a-d: Scenario results for RPK.

modes. Results are illustrated in Fig. 4a-d, which shows RPK development under the different scenarios, as well as 5a-d, depicting revenue/cost developments (see also Table 2).

Outcomes of a *CO_2 tax* depend on the scale of the tax (Fig. 4a, 5a, medium scenario), with higher taxes suppressing RPK growth with the benefit of a somewhat higher revenue to governments. Taxes increase the sector's interest in new fuels, as they reduce the fuel cost gap. To become profitable under this approach, airlines would have to

Table 2
Effect of CO_2 taxation on RKPs and government revenue, 2025–2050.

Applied CO2 tax (US$ 100–400)		Inflation in %					
		0	1	2	3	4	5
RPKs (billion)							
Elasticity	−0.75	19,511.82	20,685.99	21,720.66	22,596.29	23,342.76	23,952.88
	−1	17,349.74	18,754.60	**20,021.60**	21,109.99	22,042.03	22,816.07
	−1.25	15,388.57	16,969.36	18,400.76	19,670.61	20,763.02	21,681.63
CO2 Tax (billion USD_{2020})							
Elasticity	−0.75	7623.26	5612.17	4161.70	3117.72	2367.97	1828.13
	−1	6973.69	5199.23	**3896.24**	2942.50	2248.71	1743.68
	−1.25	6366.86	4808.31	3638.76	2770.40	2130.41	1659.40

Applied CO2 tax (US$ 300–1200)		Inflation in %					
		0	1	2	3	4	5
RPKs (billion)							
Elasticity	−0.75	8959.31	10,024.71	11,065.61	12,058.88	12,982.31	13,807.07
	−1	5269.06	6124.40	**6992.84**	7846.36	8656.19	9399.58
	−1.25	2445.13	2953.65	3488.48	4029.16	4557.35	5051.34
CO2 Tax (billion USD_{2020})							
Elasticity	−0.75	11,442.04	8767.92	6732.08	5195.74	4044.17	3182.06
	−1	7148.95	5619.25	**4408.25**	3463.19	2733.24	2173.93
	−1.25	3532.60	2846.04	2280.49	1822.55	1458.74	1172.72

Table 3
Effect of CO_2 budget on RPKs and biofuel production cost, 2025–2050.

		Biofuel cost scenarios		
		ICCT	Dray (low)	Dray (high)
RPKs (billion)				
Production growth in %	5	2656.38	2656.30	2653.37
	10	2943.54	2943.37	2942.67
	15	3797.69	3797.14	3798.24
	20	6212.56	6215.09	6212.56
	25	12,757.08	12,761.11	12,752.65
Cost (billion USD)				
Production growth in %	5	49.91	26.56	59.46
	10	102.18	34.52	125.10
	15	223.65	76.07	278.31
	20	508.03	173.00	637.34
	25	3979.32	1170.84	14,734.22

Table 4
Effect of biofuel blending obligations on RPKs and production cost, 2025–2050.

		ICCT	Dray (low)	Dray (high)
RPKs (billion)				
Elasticity	−0.75	20,781.42	24,852.53	19,745.73
	−1.00	**18,927.85**	24,061.58	17,681.07
	−1.25	17,246.33	23,286.91	15,828.05
Biofuel costs (billion USD_{2020})				
Elasticity	−0.75	7281.13	2840.53	8637.72
	−1.00	**6788.90**	2769.34	7926.33
	−1.25	6333.48	2699.34	7276.11

significantly reduce capacity, as taxes suppress demand (Fageda and Teixidó, 2022). In the lower tax scenario (US$100 per ton in 2025), net-zero effects are uncertain as effective radiative forcing will continue to increase in the absence of measures. In the higher scenario (US$300 per ton in 2025), RPK demand is reduced below 2019 levels. Taxes will likely affect load factors and individuals' flight frequency (Kang et al., 2022). Should new fuels and technologies not become available, a CO_2 tax approach will be more aligned with climate stabilization goals. It also generates significant welfare effects, as revenue is collected by governments (Table 2). Results indicate considerable variation in RPKs and CO_2 tax volumes (Table 2, for 2050), with a medium pathway (inflation 2 %, elasticity −1) of 20.0 trillion RPK and $US\$_{2020}$ 3.9 trillion in tax revenue under taxation of US$100 per ton in 2025, and 7.0 trillion RPK and $US\$_{2020}$ 4.4 trillion in tax revenue under the US$300 per ton in 2025 scenario.

A *CO_2 budget* forces the sector to adopt biofuels or new propulsion technologies to remain operational. To not deplete >12.5 Gt CO_2, emissions would have to fall by 6.3 % per year between 2025 and 2050 (linear interpolation), requiring a proportional technology replacement and/or biofuel blend-in. The approach does not allow the sector to exceed the carbon budget, and has similarities with the EU ETS that leaves the future mix of technologies/fuels to the market. The EU ETS has already reduced growth rates, even though half of allowances were distributed for free (Efthymiou and Papatheodorou, 2019). Its impact has been mostly felt by low-cost carriers and on routes where aircraft compete with highspeed railway systems (Fageda and Teixidó, 2022). Such changes may also be expected under a CO_2 budget approach, which initially leads to a decline in RPK per year, as biofuels cannot be produced at scale (Teoh et al., 2022), to increase when these become available (the scenario assumes availability of 1 Mt of biofuels in 2025; and a production increase by 25 % per year to 2050) (Table 3).

The *blending obligation* forces airlines to fully replace fossil fuels, based on the assumption that these become available at scale (biomass-based or e-fuels). Under this scenario, air transport demand will grow to 18.9 trillion RPK in 2050, with an estimated cost of $US\$_{2020}$6.8 trillion (equivalent to revenue for alternative fuel providers). Airline profitability remains uncertain, as volume growth continues with small profit margins. A blending obligation replacing all fuels between 2025 and 2050 requires significant policy changes: In 2019, sustainable aviation fuel use was 0.05 % of global fuel use (Avinor et al., 2021). Currently, only Finland and Norway have significant blending obligations (30 % to 2030, Bullerdiek et al., 2021), while the EU discusses to replace 6 % of fuels in 2030, of which 0.7 % will fall under a synthetic share sub-obligation. The synthetic fuel sub-share is to be upscaled to 28 % of fuel use by 2050 (European Parliament, 2023). Considering that under continued growth scenarios, air transport will grow to 19 trillion RPK in 2050 (inflation rate: 2 %, elasticity: −1), fuel demand will grow to 450 Mt biofuels in 2050. The blending approach leads to a faster increase in biofuel use than the carbon budget approach if such fuels can be made available at scale (Table 4).

In the fourth scenario, ASK are limited at 2019 levels (10.5 trillion ASK). Growing demand for this limited supply of air miles would generate $US\$_{2020}$17.2 trillion in revenue to global airlines (2025–2050). This is likely more money than required to cover the cost of a mandated fuel transition, and thus the most profitable model for airlines. The MBB simulation yields an expected average revenue per RPK of $US_{2020}\$0.124$ (mode $US_{2020}\$$ 0.124) with the 25th percentile at $US_{2020}\$$ 0.116 and the 75th percentile at $US\$_{2020}$0.133 per RPK (2 % inflation scenario). Assuming that the cost per RPK will stay at $US\$_{2020}$0.073 and fall by 2 % per annum, cumulated profits for the aviation sector will amount to $US\$_{2020}$17.2 trillion over the period 2025–2050 (Table 5).

Results are summarized in figs (Figs. 4a-d; 5a-d), as well as in

Table 5
Effect of ASK limitation on RPKs and airline profits, 2025–2050.

		RPK cost inflation in %			
RPKs (billion)		0	1	2	3
Elasticity	−0.75	10,578.1	10,578.1	10,578.1	10,578.1
	−1	10,578.1	10,578.1	10,578.1	10,578.1
	−1.25	10,578.1	10,578.1	10,578.1	10,578.1

		RTK cost inflation in %			
Profits (billion USD_{2020})		0	1	2	3
Elasticity	−0.75	20,802.97	23,118.83	25,099.88	26,793.26
	−1	12,867.06	15,177.27	**17,161.73**	18,856.85
	−1.25	9167.13	11,483.39	13,468.68	15,159.76

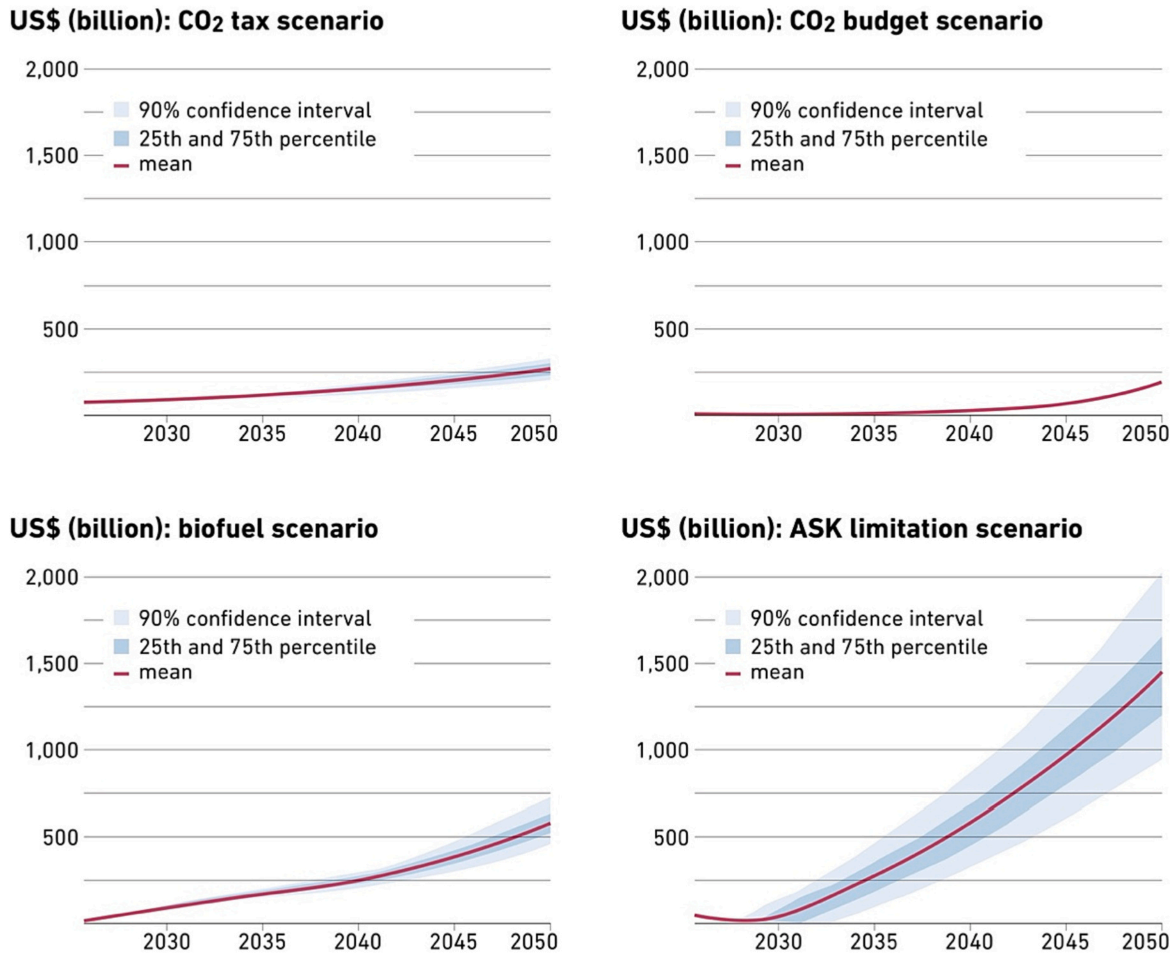

Fig. 5. a-d: Scenario results for revenue/cost.

Table 6
Alternative aviation scenarios, 2025–2050.[a]

Scenario	Transport demand	Revenue/cost/profit (US $_{2020}$)	Cumulative emissions (CO_2)	Recipient	Net-zero
Business-as-usual RPK growth rate 4.6 % per year	27.4 trillion RPK in 2050	0.2 trillion[b] (revenue)	32.9 Gt CO_2	Industry	Highly unlikely
CO_2 tax No AP, BF available	20.0 trillion RPK in 2050 (US$$_{2020}$100 per ton in 2025) 7.0 trillion RPK in 2050 (US$$_{2020}$300 per ton in 2025)	3.9 trillion (cost) 4.4 trillion (cost)	24.9 Gt CO_2 10.0 Gt CO_2	Government	Uncertain, only growth reduction
CO_2 budget Sectoral carbon budget, BF use	12.8 trillion RPK in 2050	1.2 trillion (cost)	12.5 Gt CO_2	AP, BF provider	More certain, as growth dependent on AP/BF introduction
Blending obligation Depending on BF availability	18.9 trillion RPK in 2050	6.8 trillion (cost)	14.5 Gt CO_2	AP, BF provider	Less certain, only if BF or AP become available.
ASK limitation	10.5 trillion RPK in 2050	17.2 trillion (profit)	21.4 Gt CO_2	Airlines	Uncertain, BF use needs to be mandated

AP = Alternative propulsion such as electric, hydrogen; BF = biofuels (biomass-based, e-fuels).
[a] 2 % inflation, elasticity −1.
[b] Calculated based on historical (1980–2019) profitability per RPK.

Table 6.

4. Discussion

Preceding sections have highlighted transition risks to net-zero aviation. Under continued growth scenarios, such risks increase, as there are uncertainties regarding alternative fuels (production, cost), and a lack of regulatory environments. While some countries have included emissions from international aviation in their NDCs, their ambitions for net-zero trajectories remain uncertain. The EU is the only jurisdiction in the world with two significant aviation emission reduction mechanisms, the EU ETS and the ReFuel blending obligation. However, in the EU ETS, the EU currently only considers intra-EU flights in an open emission trading scheme, while meeting ReFuel obligations will depend on technology innovations that do not currently exist. Even if alternative fuels can be provided at scale, it is uncertain whether this significantly reduces effective radiative forcing.

Against the backdrop of these uncertainties, as well as other transition barriers, historical analysis suggests that airlines are unlikely to become profitable under scenarios of continued volume growth. This constitutes the most significant barrier to the fuel transition. Four scenarios provide insight regarding possible alternatives, with a starting point in limitations. Results demonstrate that all approaches will reduce growth rates. This aligns with findings that growth rates must be brought down if the sector is to stand a realistic chance of meeting net-zero goals (Gössling et al., 2024). Depending on objective, each scenario reveals specific advantages, including government revenue generation via CO_2 taxes, 'certain' emission reductions through carbon budget or blending obligation, or industry profitability gains based on ASK limitation. Should new technologies and fuels not become available, all four options have critical roles in limiting the sector's climate impacts, as they reduce the sector's growth rates. If new fuels become available at scale, both carbon budget and blending obligation support growth harmonious with climate goals, though non-CO_2 warming remains an issue. The blending obligation would allow for faster growth in RPK, if production can be upscaled more rapidly. ASK limitation is the most desirable scenario for airlines, as it will generate profits that exceed the expected cost of the fuel/technology transition by a large margin. As all scenarios are built on industry assumptions and not considering potential dynamics, these may be developed further in the future to describe the range of possible outcomes. Here, they serve the main purpose to initiate a discussion of alternatives to the growth-maximizing air transport futures pursued by the aviation sector.

As the alternative scenarios for air transport futures will affect demand, it is important to consider social outcomes. As a rule, demand is a function of access and opportunity: in the early 2000s, the emergence of low-cost carriers led to a significant rise of air traveler numbers (Boonekamp et al., 2018). During the COVID pandemic, holiday patterns changed in favor of closer destinations, and teleconferencing replaced business trips. This suggests that air transport is to a considerable degree induced, and that new equilibria will be established in response to any of the four scenarios presented in this paper.

Currently, aviation policies are implemented in only a few countries, as well as the European Union, which may imply that demand is more affected in some regions than others. However, as the disruptive outcomes of climate change are increasingly felt, it is also possible that public support of more serious climate policies grows, and that currently "radical" scenarios become socially viable.

In anticipation of a future that is characterized by progress on aviation technology and alternative fuels, a mix of scenarios is likely to deliver the best outcome for industry and climate. For example, a combination of carbon budget/blending obligations and ASK limitation will reduce transition risks and increase airline profitability. While it is unlikely that any of the proposed scenarios, alone or in combination, will be introduced globally, findings do suggest that it is meaningful for aviation representatives and policy makers to discuss alternatives to volume growth business models.

CRediT authorship contribution statement

Stefan Gössling: Conceptualization, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Andreas Humpe:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169107.

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