ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The wide range of possible aviation demand futures after the COVID-19 pandemic

To cite this article: Sebastian Franz *et al* 2022 *Environ. Res. Lett.* **17** 064009

IOP Publishing Environ. Res. Lett. 17 (2022) 064009 https://doi.org/10.1088/1748-9326/ac65a4

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
6 August 2021

REVISED
5 April 2022

ACCEPTED FOR PUBLICATION
8 April 2022

PUBLISHED
17 May 2022

LETTER

The wide range of possible aviation demand futures after the COVID-19 pandemic

Sebastian Franz[1,2,*], **Marianna Rottoli**[2] **and Christoph Bertram**[2]

[1] Technical University of Denmark (DTU), Department of Technology, Management and Economics, Lyngby, Denmark
[2] Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: semfr@dtu.dk

Keywords: integrated assessment modelling, transport modelling, energy demand, COVID-19, aviation, shared socioeconomic pathways (SSPs)

Supplementary material for this article is available online

Abstract

Aviation has been identified as one of the crucial hard-to-abate sectors, as long-range aviation in particular will continue to depend on liquid fuels for the foreseeable future. The sector was also one of the fastest growing emitters of fossil CO_2 emissions until 2019 but experienced sharply reduced demand during the COVID-19 pandemic, making future demand outlooks more uncertain. While past studies have looked at the variation in future aviation demands due to variations in demographics, income levels, and pricing policies, an exploration of potentially more sustainable demand futures does not yet exist. Here we use an open-source model with a detailed representation of country-level aviation demand per international/domestic and business/leisure segments to analyze a range of scenarios based on a consistent and comprehensive interpretation of the qualitative narratives related to behavioural aspects as well as the socioeconomic data from different shared socioeconomic pathways (SSPs). Our results show a potential stabilization of global aviation demand at roughly twice the 2019 level in an SSP1 scenario, a weakened growth for an SSP2 scenario, while an SSP5 scenario projects an aviation future virtually unaffected by the COVID-19 shock, resulting in continued high growth rates. Further results show that without specific interventions that change the past demand growth patterns, the aviation sector could grow to levels that are very challenging to defossilize in a sustainable manner. Therefore, policies aiming at less frequent flying seem to be an important component of long-term decarbonisation strategies, and decisions regarding airport extensions should carefully assess the risk of stranded infrastructure.

1. Introduction

Reducing emissions from the aviation sector is crucial to meeting the Paris agreement targets. However, due to the specific technical requirements and safety standards, the decarbonization of the sector presents unique challenges [1–3]. In addition, the demand for aviation is expected to grow in the future due to the expected income increase and the associated expansion in aviation activity [2, 4–6], especially in developing countries with currently low aviation demands. As of today, aviation represents the biggest share of the carbon footprint for specific high-income consumer groups [7], illustrating the sector's potential to dominate emissions in the future. Yet, the COVID-19 pandemic and the resulting extensive reduction in aviation activity challenged the entire industry and presented the opportunity to envisage a future with more sustainable air travel patterns. During the COVID-19 pandemic, the seat capacity available in the aviation industry declined by 67% year-on-year in 2020 [8], while the occupancy rate also decreased. This led to even more substantial losses of revenue, which resulted in aviation being one of the economic sectors most affected by the pandemic.

There are two different approaches to the current research on aviation demand projections. Among others, Gössling *et al* [1–3] adopt a top-down approach based on industry estimates for growth in demand for aviation and identify possible challenges for a sustainable aviation industry after the COVID pandemic. In parallel to such top-down studies, bottom-up studies are used. In Dray *et al* [9], the authors apply a very detailed origin and destination modeling approach to the aviation integrated model (AIM), calculating the demand between different geographic areas.

The exploration of economy-wide climate mitigation pathways makes use of increasingly detailed subsectoral modelling [2] and thus will require detailed assumptions about aviation demand. Given the prominence of the framework of shared socioeconomic pathways (SSPs) for global modeling studies, a readily usable, transparent, and documented set of aviation demand pathways along SSPs is a significant gap. Previous studies that looked into SSP variations of aviation [3, 10] have only used 'single elements of SSPs (such as gross domestic product (GDP) or population growth)' [11] and thus fail to capture the narratives behind different SSPs comprehensively.

This work further details the aviation sector representation in the transport model energy demand generator-transport (EDGE-T) [12] to project civil passenger aviation in three SSPs. In doing so, our main research question regarding possible aviation demand futures after the COVID-19 pandemic is being tackled. This is of broad importance as the future scale of this hard-to-abate sector [13] is a key determinant for broader decarbonisation and sustainability challenges related to its fuel supply. Our scenarios span a set of potential recoveries of the aviation sector after the COVID-19 shock, exploring a range of potential long-term impacts of the pandemic on different segments of civil aviation. Our model features aviation demand projections at a country level, capturing the key submarkets (international/domestic and business/leisure) and differentiating between three different pathways (namely SSPs 1, 2, and 5) with varying challenges to mitigation [14].

With this approach, we go beyond the existing literature [3, 9, 10], as our approach not only considers GDP and population as key drivers of the aviation demand but estimates SSP-specific behavioral effects. The additional set of parameters that shape the income elasticity, which due to the lack of country-specific data starts from the same initial value for all countries and diverges after that based on the respective GDP and activity trajectories, allows us to model the country-specific consumer behavior for both leisure and business trip purposes. The consistent interpretation of SSP narratives by differentiated income elasticity developments across SSPs, as well as sectoral recovery from COVID-19 activity reductions, is a novel way of modelling future aviation demand. We thus fill the existing research gap of a holistic approach towards SSP-specific aviation demand projections.

1.1. Understanding SSP narratives

The SSP-specific projections in this work are subject to the underlying narratives. In table 1, we present a comparison based on key differentiating aspects for the underlying SSP narratives, highlighting that a differentiation beyond GDP and population is key for consistently representing the narratives, especially with regards to consumption and lifestyle patterns and environmental regulation.

2. Methods

We use a sectoral, country-specific, and yearly model of the aviation industry to project the demand for civil aviation in three different SSPs with differentiated challenges for mitigation. We explore the COVID-19 shock and the long-term impact of the pandemic on civil aviation. The workflow of the model features three main steps, schematized in figure 1 and described in detail in the following paragraphs.

2.1. Preparation of disaggregated historical data

The first step deals with the preparation of disaggregated historical data. A set of data sources are collected, allowing a sectoral and trip purpose-related classification of historical demand [8, 15, 16]. We start with the EDGE-T historical data set [12], which provides data up to 2010. The country-specific historical dataset from the International Council on Clean Transportation is used for the 2018 data-points [17]. Based on the latter, the historical demand values are interpolated between 2010 and 2018. The historical demand is divided into international and domestic aviation based on country/regional data on current shares for these segments [18]. Finally, we divide the historical demand into different trip purposes on the basis of a 2017-based survey located in the US, used as a proxy for the rest of the world [16].

2.2. Construction of baseline scenarios

Based on the historical values determined in step 1, we build a baseline case for the different SSPs. Equation (1) represents the demand regression function adopted in this study:

$$D_{c,t} = \mathrm{D}_c \left(\frac{g_{c,t}}{g_{c,t-1}}\right)^{\alpha} \left(\frac{p_{c,t}}{p_{c,t-1}}\right)^{\beta} \left(\frac{Q_{c,t}}{Q_{c,t-1}}\right) \qquad (1)$$

where $D_{c,t}$ is the energy services demand for time t and country c, D_c represents the last historical value of the demand in the base year (2019), α is income elasticity, β price elasticity, $g_{c,t}$ is GDP per capita, $Q_{c,t}$ is population and $p_{c,t}$ is transport price. Required inputs are the price and assumptions on the socioeconomic developments (i.e. population and GDP), from today until 2100. In this study, we purposely only explored changes induced by the income elasticity and thus set the price elasticity β to 0, equivalent to assuming constant prices over time and across scenarios.

Table 1. Comparison of SSP1, SSP2 and SSP5 by certain categories. Adapted from Kriegler *et al* [15]. Elements that motivate differentiation of behavioural parameters for aviation are highlighted in bold italics. Reprinted from [15], Copyright (2017), with permission from Elsevier. CC BY 4.0.

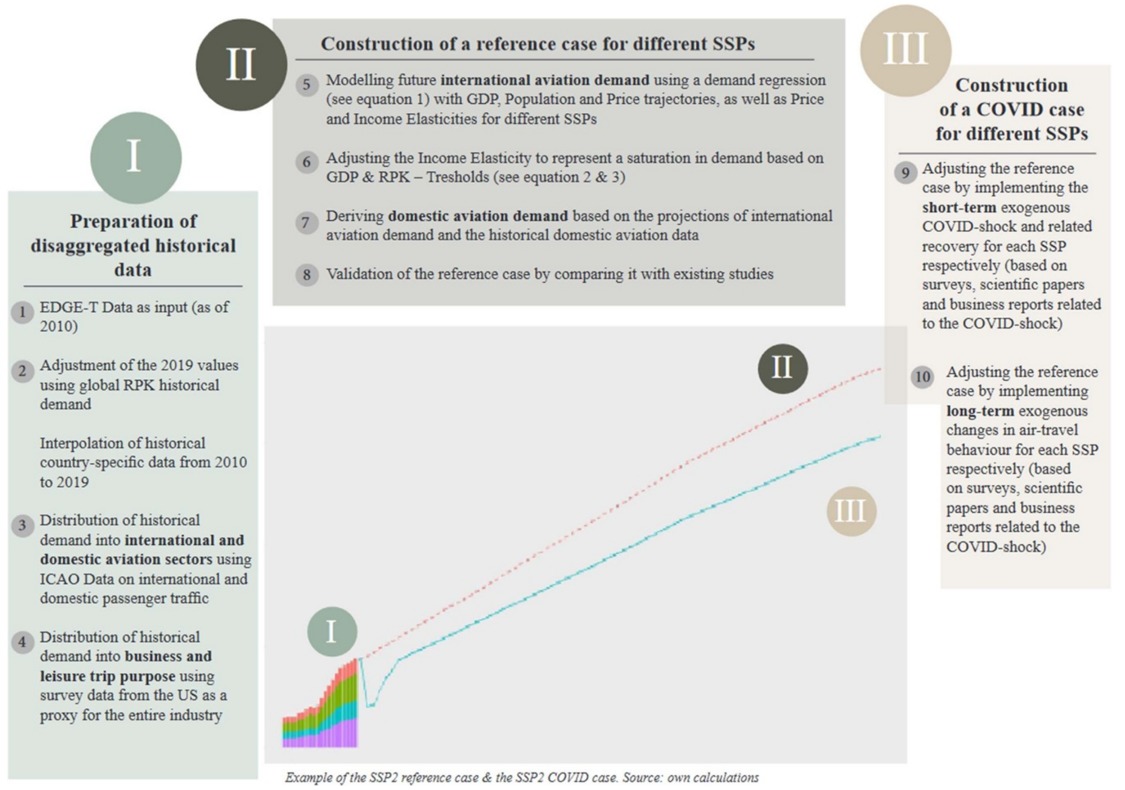
Indicator	SSP1	SSP2	SSP5
Demographics			
Population growth	Low	Medium	Low
Migration	Medium	Medium	High
Economy and lifestyle			
GDP growth	High	Medium, uneven	High
Inequality	Reduced	Uneven, reduced moderately	Strongly reduced
Globalization	Connected markets	Semi-open global economy	Strong
International Trade	Moderate	Moderate	High
Consumption	***Low material consumption***	***Material intensive***	***Materialism, status consumption, high mobility***
Diet	Low meat diets	Medium meat consumption	Meat-rich diets
Technology			
Development	Rapid	Medium, uneven	Rapid
Energy technology change	Directed away from fossil fuels toward efficiency, renewables	Some investment in renewables, continued reliance on fossil fuels	Directed toward fossil fuels; alternative sources not actively pursued
Environment and resources			
Fossil constraints	Preferences shift away from fossil fuels	No reluctance to use unconventional resources	None
Land use	Strong regulations to avoid environmental trade-offs	Medium regulations lead to slow decline in the rate of deforestation	Medium regulations lead to slow decline in the rate of deforestation
Agriculture	Improvements in agriculture productivity; rapid diffusion of best practices	Medium pace of tech change in agriculture sector; entry barriers to agriculture markets reduced slowly	Highly managed, resource-intensive, rapid increase in productivity
Policies and instruments			
International cooperation	Effective	Relatively weak	Effective for development, limited for environment
Environmental policy	***Improved management of local and global issues; tighter regulation of pollutants***	***Concern for local pollutants but only moderate success in implementation***	***Focus on local environment, little concern with global problems***

In addition to the SSP-specific GDP and population, income elasticity (IE) plays a key role in the modeling process as this is the one parameter used to account for behavioral differences across SSPs. The IE starts at 1.55 and evolves over time based on a hybrid threshold model differentiated by SSP. In this work, we only consider SSP1, −2, and −5 pathways as we are interested in the different challenges towards mitigation rather than adaptation [15, 19, 20]. In line with the storylines of these SSPs, IE decreases fastest in SSP1 and slowest in SSP5, with SSP2 in between (see figures S1 and S2 of the SI available online at stacks.iop.org/ERL/17/064009/mmedia). In each SSP scenario, an income elasticity decreases both with increasing GDP per capita and with increasing revenue-per-passenger kilometers (RPK) per capita (see equation (2)). This leads to saturation in demand at levels differentiated by SSP:

$$\alpha_{c,t} = \alpha_{c,t-1} * \varepsilon_{c,t} * \theta_{c,t} \tag{2}$$

where:

- $\alpha_{c,t}$ = Income elasticity for country c in time step t
- $\varepsilon_{c,t}$ = RPK-based decay rate (between 0.85 and 0.95 depending on SSP scenario)
  For all countries, c and time steps t where $\frac{\text{RPK}}{\text{cap}}_{c,t} > \text{RPK threshold}_{c,t}$, else = 1 in all other cases
- $\theta_{c,t}$ = GDP-based decay rate (between 0.95 and 0.99 depending on SSP scenario)
  For all countries, c and time steps t where $\text{GDP/cap}_{c,t} > \text{GDP threshold}_{c,t}$, else = 1 in all other cases
- $\alpha_{c,t=2019}$ = Initial income elasticity of 1.55 [21]
- $\text{GDP/cap}_{c,t}$ = GDP per capita for country c and time step t
- $\text{RPK/cap}_{c,t}$ = RPK per capita for country c and time step t



5 Modelling future **international aviation demand** using a demand regression (see equation 1) with GDP, Population and Price trajectories, as well as Price and Income Elasticities for different SSPs

6 Adjusting the Income Elasticity to represent a saturation in demand based on GDP & RPK – Tresholds (see equation 2 & 3)

7 Deriving **domestic aviation demand** based on the projections of international aviation demand and the historical domestic aviation data

8 Validation of the reference case by comparing it with existing studies

1 EDGE-T Data as input (as of 2010)

2 Adjustment of the 2019 values using global RPK historical demand

Interpolation of historical country-specific data from 2010 to 2019

3 Distribution of historical demand into **international and domestic aviation sectors** using ICAO Data on international and domestic passenger traffic

4 Distribution of historical demand into **business and leisure trip purpose** using survey data from the US as a proxy for the entire industry

9 Adjusting the reference case by implementing the **short-term** exogenous COVID-shock and related recovery for each SSP respectively (based on surveys, scientific papers and business reports related to the COVID-shock)

10 Adjusting the reference case by implementing **long-term** exogenous changes in air-travel behaviour for each SSP respectively (based on surveys, scientific papers and business reports related to the COVID-shock)

Example of the SSP2 reference case & the SSP2 COVID case. Source: own calculations

Figure 1. Three-step methodology of the entire modeling process—preparation of historical data—building a baseline scenario and building the COVID scenarios.

- GDP $\text{threshold}_{c,t} = 40000\ \text{USD}^{/\text{cap}}$
- RPK $\text{threshold}_{c,t} =$ between 2000 and 6000 km cap^{-1} depending on SSP-scenario.

Table 2. RPK thresholds for different SSPs.

Scenario	Threshold value in RPK	Decay rate for IE Decay in %
SSP1	2000	15
SSP2	4000	10
SSP5	6000	5

Table 3. GDP thresholds for different SSPs.

Scenario	Threshold value in USD	Decay rate for IE Decay in %
SSP1	40 000	5
SSP2	40 000	2.5
SSP5	40 000	1

When working with income elasticities, recognizing that they are not universally valid is essential. There is undoubtedly a clear relationship between increased income and demand for air travel for impoverished countries. However, people will not fly more even though they have more income at a certain point. This is because the monetary budget constraint at a certain income level is not binding anymore, but other constraints, like limited vacation time or interest in international travel, become dominant, which can be mimicked by a decreasing income elasticity for civil air travel [22]. Similarly, once a higher amount of demand in this sector is already achieved, the essential long-distance mobility service is already fulfilled, and the link to income will become weaker. We, therefore, assume income elasticity starts decreasing as a function of RPK per capita and GDP per capita after SSP-specific thresholds in both variables are reached (see equation (2)).

The threshold in RPK (revenue per capita threshold, see table 2) defines the onset of a relatively fast decay in income elasticity and thus is the core driver for saturated per-capita demand levels. The other threshold is the GDP per capita threshold (see table 3), which defines the onset of relatively slow decay in income elasticity at per-capita GDP levels of relatively rich countries as of today, and makes sure that some differentiation of per-capita RPK levels is maintained primarily in SSP5, reflecting current RPK differences of countries with similar per-capita GDP levels. An initial income elasticity of 1.55 for all countries may seem too high, especially for developed countries, yet due to the saturation process of income elasticity based on the shown parameters in tables 2 and 3, this high initial income elasticity will decline rapidly for developed countries while it will remain high for developing countries. Thus this high initial income elasticity helps to draw a realistic picture

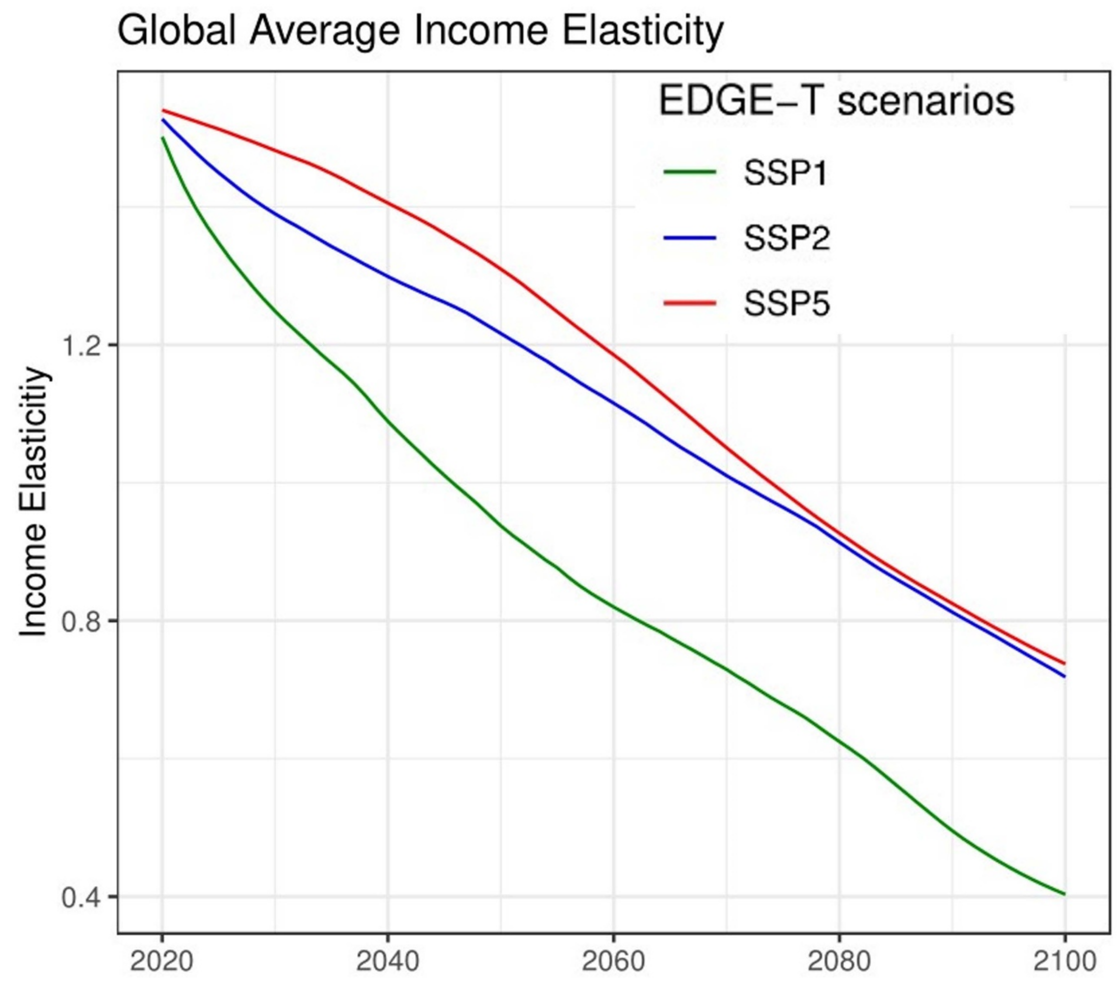


Figure 2. Global average income elasticity for different SSPs.

across different countries. The resulting heterogeneity in income elasticity is shown in figure 2 for global average values and S1 in the SI for regional values.

The parameter differentiation displayed in tables 2 and 3 were initially motivated by the underlying SSP narratives [14] and the final choice of parameters was made so as to achieve a good match with other studies, especially in the SSP5 scenario [3, 10, 23]. All of these scenarios are a high-level representation of country-specific behavioral patterns determined by the underlying SSP narrative (e.g. flight shaming, general attitude towards sustainability within society, etc) [24, 25]. By allowing for this extensive income elasticity heterogeneity across different countries, this model differs to quite some extent from the original EDGE-T models, which only used GDP per capita as a dependent variable for income elasticity [12].

In this work, the entire demand modeling process is carried out specifically for international aviation. However, in order to represent the entire aviation industry, domestic aviation demand is derived from international aviation demand with the implementation of a diverging growth trend for domestic aviation given the competition for other transport modes (see section 2 of the SI for details). We first estimate the historical demand data for domestic aviation for the baseline year 2019 on the basis of historical values [26]. We further assume that the share of domestic passenger traffic decreases as compared to the international passenger traffic due to increasing competition of other transport modes in this segment and faster saturation of domestic demands [27].

Baseline trends of international and domestic aviation demand are validated comparing other state-of-the-art aviation demand projections [3, 10, 23]. Specifically, we find comparable results on a global scale when comparing our baseline projections to the bottom-up modeling approach of Dray *et al* [10] (see figure 7).

2.3. Construction of a COVID case for different SSPs

The actual short term shock in demand for air travel in 2020 and 2021 is modeled in the same way for all SSP scenarios. The only distinction being made is between domestic and international aviation. This distinction follows the actual figures of the impact of

Table 4. COVID-19 impact per year and segment for different SSPs in percent of noCOVID RPK value, motivated by [10, 27, 30–32]. The numbers show the effective multiplier for the respective COVID-19 impact.

SSPs	2020	2021	2022–2024	>2024
SSP1	Int. leisure: 24%	Int. leisure: 25.8%	Int. leisure: 30%–80%	Int. leisure: 100%
	Int. business: 24%	Int. business: 25.8%	Int. business: 30%–45%	Int. business: 50%
	Domestic leisure: 48.6%	Domestic leisure: 63%	Domestic leisure: 65%–90%	Domestic leisure: 100%
	Domestic business: 48.6%	Domestic business: 63%	Domestic business: 63%–51%	Domestic business: 50%
SSP2	Int. leisure: 24%	Int. leisure: 25.8%	Int. leisure: 30%–80%	Int. leisure: 100%
	Int. business: 24%	Int. business: 25.8%	Int. business: 30%–65%	Int. business: 70%
	Domestic leisure: 48.6%	Domestic leisure: 63%	Domestic leisure: 65%–90%	Domestic leisure: 100%
	Domestic business: 48.6%	Domestic business: 63%	Domestic business: 65%–69%	Domestic business: 70%
SSP5	Int. leisure: 24%	Int. leisure: 25.8%	Int. leisure: 30%–80%	Int. leisure: 100%
	Int. business: 24%	Int. business: 25.8%	Int. business: 30%–80%	Int. business: 90%
	Domestic leisure: 48.6%	Domestic leisure: 63%	Domestic leisure: 65%–90%	Domestic leisure: 100%
	Domestic business: 48.6%	Domestic business: 63%	Domestic business: 65%–85%	Domestic business: 90%

the pandemic on offered seat capacity in 2020 and 2021, which were collected by ICAO and used as a proxy for RPK data [28, 29]. This data can be seen in table 4 in detail.

For the recovery part, which starts from 2023 onwards, different levels of growth are modeled for the different SSP scenarios. These can be seen in table 4.

The behavioral changes triggered by the COVID-19 pandemic could significantly impact the future of air traffic [10, 27, 30, 31]. Above all, the business trip segment could feel lasting effects from the pandemic. With the rise of ICTs like different video-conferencing platforms, some long-haul trips that in the past were performed for business purposes will likely, at least in an environmentally aware SSP1 narrative, be replaced permanently by online means, given the immense time and money savings. For example, not the entire ten-person sales team could be flown to Asia for a sales pitch, but only the two sales executives, while the support staff, in particular, would then be connected digitally via continually improving communication platforms [32]. This line of reasoning is behind recent forecasts, which estimated up to 80% of business trip purpose-related air traffic worldwide would be eliminated [27, 31]. For this reason, there were significantly reduced long-term projections of the COVID-19 scenarios compared to the baseline scenarios without the COVID-19 shock and related implications, but with a differentiation across SSPs in line with the narratives. The long-term yearly reductions compared to the baseline scenario are shown in table 4, which are being motivated by the above-mentioned impacts and the underlying SSP narratives and projections by other researchers [10, 27, 30–32].

As can be seen from the selected recovery parameters in table 4, the different scenarios can be clearly distinguished from one another. This is because in a heterogeneous world with large uncertainties regarding the future behavior of people, as well as regulatory measures, it is important to calculate especially extreme developments in the model [33]. This is done in the framework of this work by the scenarios SSP1 and SSP5, while the SSP2 scenario serves as a baseline or middle-of-the-road scenario, though this does not imply that SSP2 necessarily is the most likely scenario. The exploration of these extremes offers the possibility of obtaining a framework in which the future demand for international aviation could vary. This is very existential when it comes to re-evaluating international climate policy. Furthermore, it can be seen that domestic aviation demand is recovering somewhat faster than international demand, which is suffering greatly from ongoing and partly persistent travel restrictions [8], but also from lower flexibility to profitably operate at reduced demand levels (due to less frequent flights in larger aircraft compared to domestic aviation).

3. Results

3.1. Wide range of demand projections after COVID-19

Based on our model and in line with previous research, aviation demand in the 21st century can expand almost ten-fold with respect to 2019 levels. Importantly, however, our results also show that they could also only double. Which future unfolds depends both on socioeconomic factors and, even more, on the emphasis on sustainability of societies and respective decision-making in politics, the private sector, and by individuals (figure 3). Compared to projections without the effect of COVID-19, the impact of reduced business travel after COVID-19 is especially profound for the SSP1 and 2 scenarios. Our pre-COVID projections (referred to as ‘SSPx_noCOVID’ in figure 3) do not fully align with the reference demand projections from the AIM model [9, 10], as the effect of higher demands in SSP1 is somewhat reduced in our projections, given that we include differentiation of income elasticities in line with SSP narratives, while the AIM scenarios only use population and GDP from SSPs. As shown below in figure 7 in the ‘Discussion’ section, our model, despite using a different modeling approach (top-down

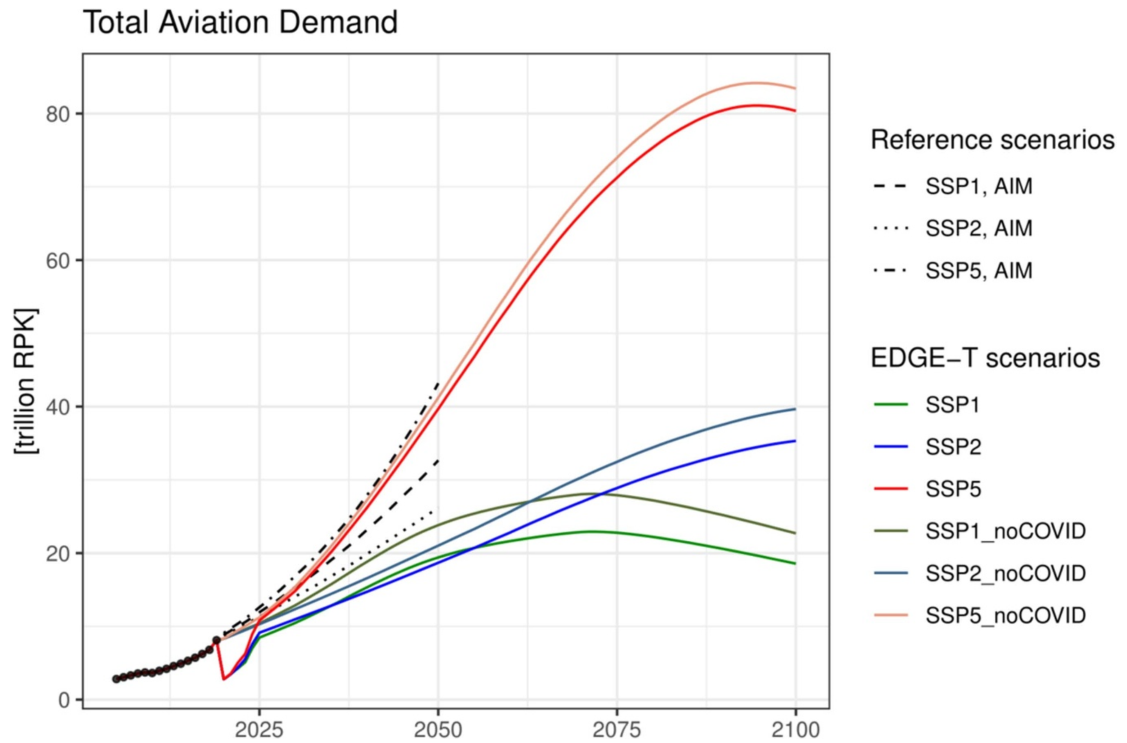


Figure 3. Global aviation demand for different SSPs. Baseline, COVID, and reference scenarios.

compared to AIM's bottom-up modeling), replicates well the AIM results if assuming SSP5 parameters except for population and GDP.

Due to the faster GDP growth and convergence, SSP1 initially generates more demand for civil air transport up to 2060 than the SSP2, especially in the absence of the COVID-specific effects. In our central SSP1 estimate, which includes both lower elasticities, and a stronger long-term reduction of business travel (see figure 2 and table 4), global demand, however, stays below, or temporarily only slightly above, the corresponding SSP2 scenario and reaches saturation in the second half.

The projections of the SSP2 scenario follow the narrative of the middle-of-the-road scenario [19], featuring a similar growth trend in the COVID-19 case as compared to the baseline case. The COVID-19 shock induces a strong decline in demand for civil aviation in the short term with long-term consequences. However, this scenario does not show any significant long-term saturation of demand, only a gradual flattening of the growth trend.

On the contrary, the SSP5 scenario, in line with our assumptions (see figure 2 and table 4), shows a significantly lower COVID-19 related reduction in demand for civil air transport. The demand recovers quickly from the COVID-19 shock, and by 2030 the growth trend continues closely in line with the pre-COVID-19 dynamics.

Given our assumed SSP-specific development, based on the underlying SSP narratives (see table 1), it seems very likely that overall demand will keep on growing for the next decades, though vastly different rates are possible. However, these global totals mask huge shifts across regions, and to a lesser extent, from business to leisure and from domestic to international.

3.2. Impacts on airport infrastructure investments and operations

The value of take-offs/landings estimated from RPK levels will not reach pre-COVID-19 values in an SSP1 and SSP2 future for certain regions like Europe, due to the reduction in demand, especially in domestic business travel (figure 4, see section 5 of the SI for details of calculation). This effect will be amplified by the shift from domestic to international aviation in the long-run, since an increase in international aviation demand leads to the overall slower growth of airport infrastructure operations (APO) as compared to a strong domestic aviation demand. However, we can still see a substantial increase in demand for take-offs/landings for developing regions like sub-Saharan Africa, illustrating continued infrastructure investment requirements. Note that the population in sub-Saharan Africa by 2070 reaches between [2.0–3.3] times the European population across the considered SSPs (see figures S1, S2 and S3 of the SI). The comparison across developing regions exemplifies the regionally dependent dynamics of our approach since the behavioral effects induced by the COVID-19 pandemic will be especially relevant for developed economies featuring high per-capita RPK and GDP levels.

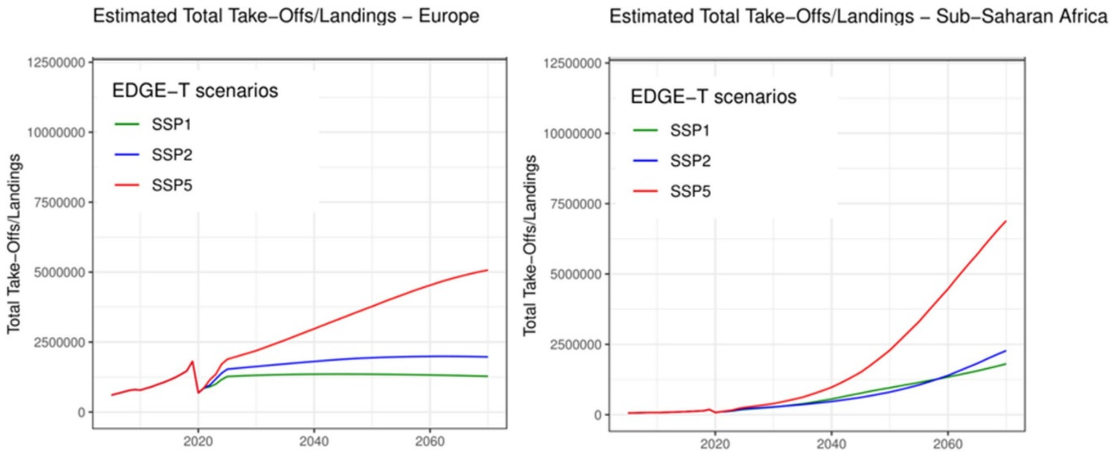


Figure 4. European (left-hand side) and sub-Saharan Africa (right-hand side) take-offs/landings based on RPKs differentiated by SSPs in time and in absolute numbers.

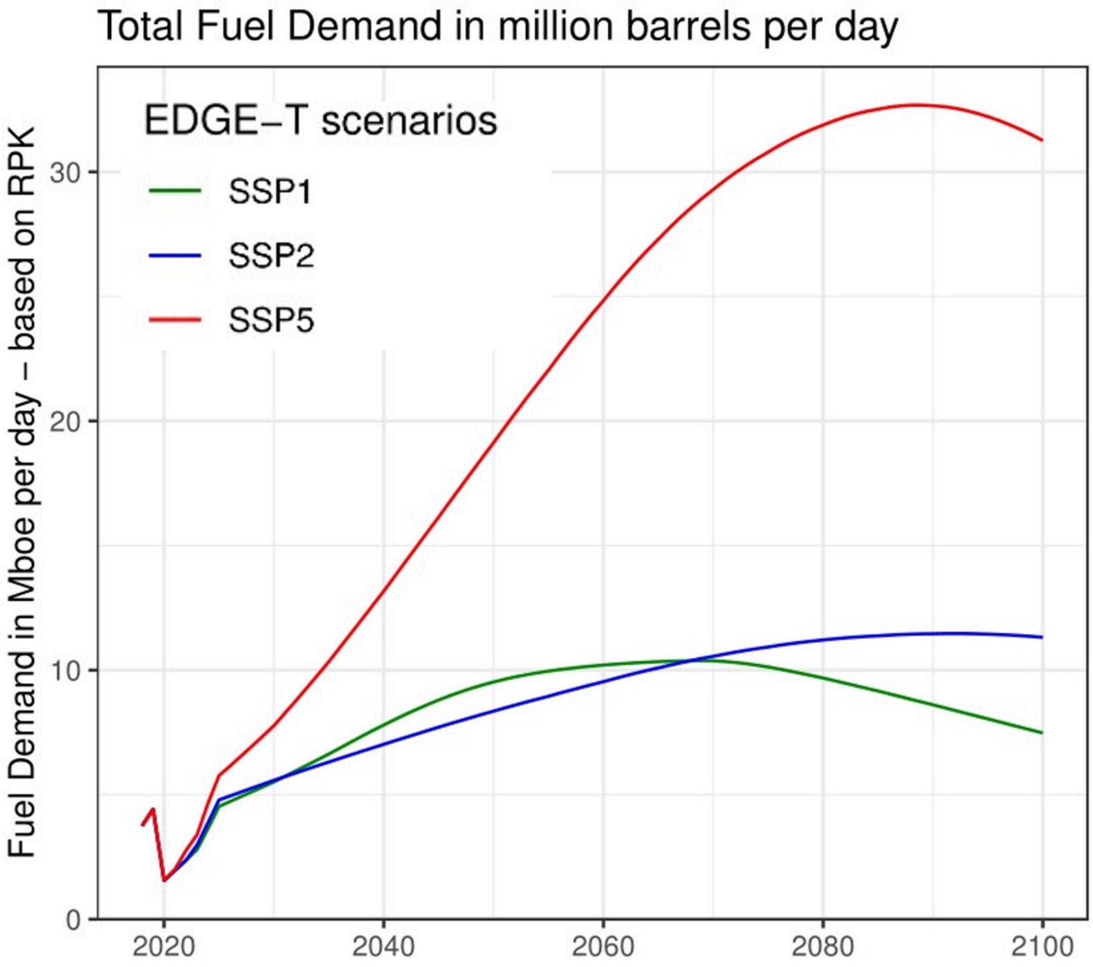


Figure 5. Total global fuel demand in a million barrels per day in time.

3.3. Impacts on fuel demand and mitigation challenges

Global fuel demand could either expand six-fold compared to 2019 values, or less than double, depending on the scenario (figure 5). Figure 5 presents the total fuel demand in a million barrels per day, based on the RPK projections for the respective SSP. These fuel demand projections are based on a SSP-differentiated estimate for the fuel efficiency (see section 4 of the SI, including a sensitivity analysis on the fuel efficiency projections). Demand for aviation fuels represented about 6% of total liquid fuel consumption in 2019 but could reach much higher shares in the future with mostly electrified industry [34] and land transport [17]. Aviation fuel demands in SSP5 would represent more than a third of today's oil industry in the second half of the century, making the provision of these amounts of sustainable fuels challenging if not impossible, given several other uses for liquid fuels even in broadly electrified energy systems, e.g. as feedstock in industry. Switching to low carbon fuels (biofuels/synthetic or electro fuels) to enable effective decarbonization of the aviation sector would hence be much easier to achieve in an SSP1 and SSP2 demand future. The same applies to the decarbonization via partial electrification of regional-range flights, whose actual mitigation impact would depend on the power generation mix and thus the demand for electricity based on the respective aviation demand [35].

4. Discussion and limitations

4.1. Uncertainties within demand projections

The underlying dynamics of RPK development across countries are highly sensitive to the underlying assumptions towards country-specific income elasticity development and expectations towards future COVID-19 impact.

In figure 6, we show the sensitivity of our main assumption towards income elasticity development across countries and expectations towards COVID-19 impacts. We compare our baseline results with both a high value (25% higher) and a low value (25% lower) for the respective assumptions. The most extensive sensitivity can be identified by modifying the initial income elasticity and thus the societies' willingness to pay additional income for mobility via aircraft. This high sensitivity leading to two-fold higher or lower demand values in SSP2 and SSP5 underlines the importance of a well-calibrated starting point. In this study, we used the same initial IE for all countries irrespective of their actual income level and RPK per capita. In further research, one could calibrate the initial IE for each country individually. We also investigated more extreme sensitivities with 50% lower and 50% higher values in the supplementary information (see SI section 6).

Another important sensitivity to mention is the underlying expectations towards the impact of the COVID-19 pandemic on people's behavior towards flying. Our assumptions are mainly based on expert interviews, other modeling studies, surveys [10, 27, 30–32] and so more evidence is required. This could come from large-scale surveys and ongoing observations about the effects of teleworking on business air travel and the effects of social awareness regarding climate change towards leisure air travel.

4.2. Endogenizing SSP narratives beyond GDP and population growth

Until now, global aviation demand projections have been driven by an SSP5 type of socioeconomic narrative such as the high social acceptance of abundant flying for industrialized nations, massive subsidies for airports [35], as well as tax exemptions for various fuel mobility services [36] and a lack of internalization of externalities like air pollution, noise or climate change. Therefore, we identify SSP5 as the baseline regarding socioeconomic narratives for the aviation sector. This means even though scenarios in previous studies [3, 9, 10, 37] have been labeled SSP1, SSP2, or SSP5, the socioeconomic behavioural aspect has been driven by an implicit SSP5 narrative, and thus the only differentiation across SSPs has been made via the use of different GDP and population projections. In this study, we overcome this weakness, as pointed out by O'Neill *et al* [11], by changing the underlying socioeconomic parameters driven by their actual SSP narrative and not by a uniform narrative that is in line with an SSP5 world but not with an SSP1 or SSP2 world.

In figure 7, we show the impact of the three-step modeling process. In the first step ('Initial Projection'), we model SSP-specific aviation demands purely driven by GDP and population, but with SSP5 thresholds and decay rates (see tables 2 and 3). As can be seen in the first step, our first step projections are well in line with the AIM projections for the respective SSPs, undermining the SSP5 base for socioeconomic parameters in these projections. The second step represents the 'noCOVID' scenarios in figure 3, labeled here 'Effect of SSP-specific thresholds and decline rates.' This reflects a consistent and comprehensive implementation of the respective SSP narratives prior to COVID. The third step is represented by 'Effect of COVID-19 implications': here, we show our final aviation demand projection incorporating both the consistent implementation of SSP full narratives and the COVID-19 impact. While it is clear that it is crucial to take the behavioral aspects into account for an entirely consistent SSP scenario, the exact quantification of the thresholds and decline rates we have used to represent this behavioral difference is uncertain. Similarly, the quantification of the additional permanent effect of COVID is uncertain, but structurally differentiating the two is an important innovation that allows for a more structured analysis and discussion.

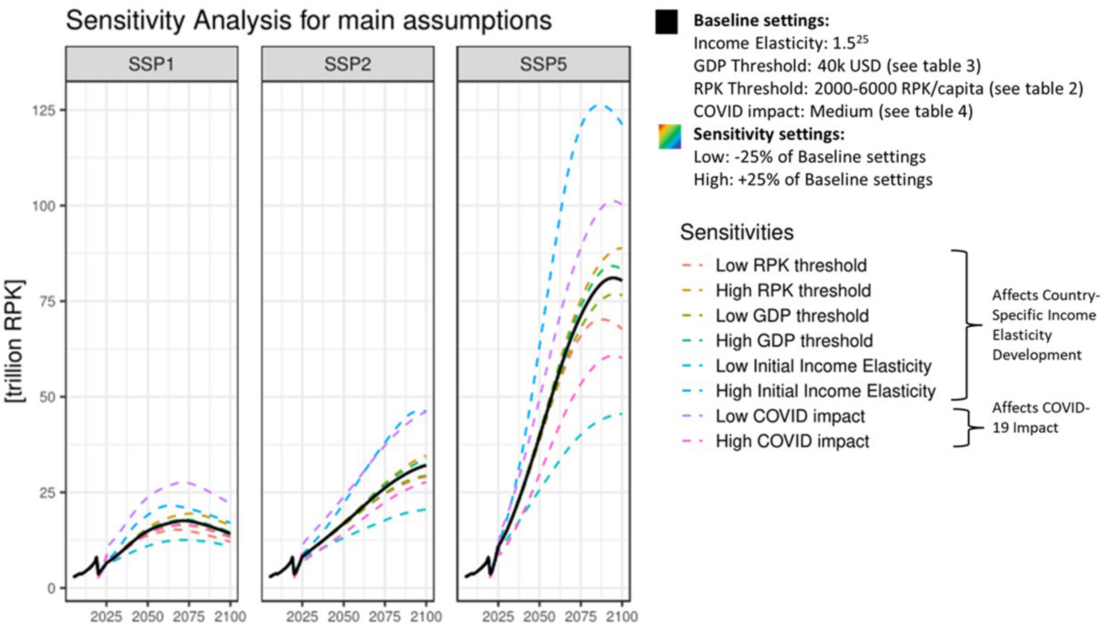


Figure 6. Sensitivities for SSP-specific aviation demand scenarios.

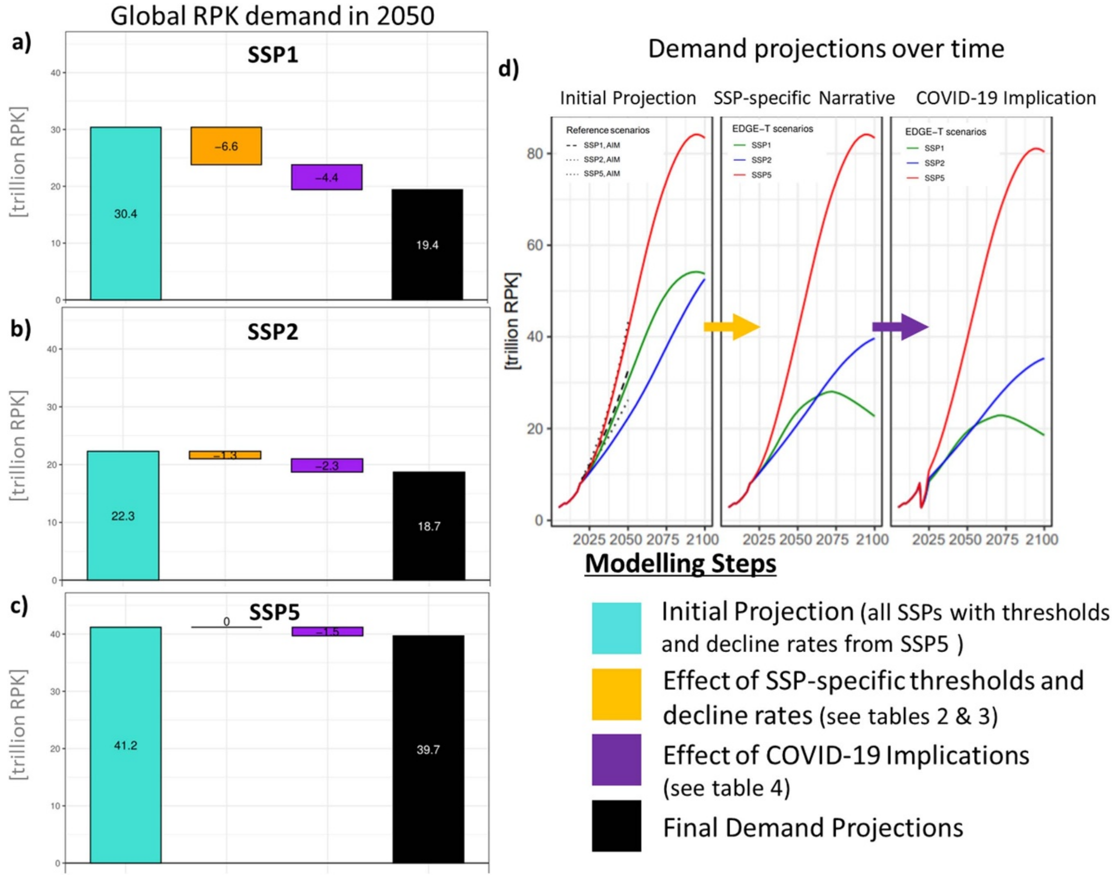


Figure 7. Impact of endogenizing SSP narratives and COVID-19 impact. (a) Global RPK development for our modeling steps in 2050 for an SSP1 scenario, (b) global RPK development for our modeling steps in 2050 for an SSP2 scenario, (c) global RPK development for our modeling steps in 2050 for an SSP5 scenario, (d) global RPK development for all analyzed SSP scenarios and years featuring our modeling steps (the second and third set of trajectories are identical to the noCOVID and default results in figure 3).

5. Conclusion

The COVID-19 pandemic changed the way we travel. It normalized new ways to communicate and work and thus illustrated the scope for reduced mobility, but also showed that some mobility is essential, as not all forms of personal interaction can be meaningfully achieved online.

We find that the SSP narrative-motivated changes towards the socioeconomic behavior of individuals induced by the COVID-19 pandemic could have a massive impact on RPK development. Due to our country-level-based modeling process and the consistent implementation of the underlying SSP narratives towards socioeconomic parameters such as passengers' behavior and COVID-recovery, and thus beyond GDP and population growth projections, we are able to analyse different country-specific dynamics within the aviation industry. This indicates that, depending on societal choices, even a decline in take-offs/landings for certain regions such as Europe in SSP1 is possible. Furthermore, we find future fuel demand to be highly dependent on the respective SSP, as well as the penetration of international passenger transport (see additional figures S2, S3 and S5 of the SI). Given the scarcities of the various potential decarbonized fuel routes that can satisfy the growing aviation demand, especially in the international aviation segment reliant on liquid fuels, a scenario with lower overall fuel demand seems to be significantly less challenging in terms of decarbonization effort. Furthermore, not only the aviation industry but also international shipping and the petrochemical industry are considered hard-to-abate sectors [13], and so intersectoral competition for the main commodities for a green transition, such as ecologically sustainable biomass for deriving bio-based fuels (e.g. bio-e-methanol, liquified biogas or pyrolysis oil), can be expected [38].

This implies that a credible policy roadmap towards a decarbonized aviation industry should not only include the ramping up of green fuel production facilities via carbon pricing and carbon contracts for differences, fuelling standards, and massive investments towards fuel efficiency gains [2, 5]. Pushing for SSP1-type demand trends, e.g. by disincentivicing frequent flying, support for regional tourism, support for virtual work meetings and conferences, etc seems very important when it comes to reducing mitigation challenges and thus ensuring a reasonable chance of reaching reduction goals in line with the Paris Agreement while also taking additional sustainability concerns into account.

In this study, we purposely only explored differences in demand projections driven by income elasticities, so inherent demand, instead of only prices as in e.g. Goessling *et al* [3]. However, combining their approach with ours could be relevant for future research. On the one hand, driving up prices could lead to even more unequally distributed access to international mobility, but it also helps to lower overall demand and transform the supply side.

Finally, the restart of the aviation industry and international travel after the current COVID-19 pandemic offers a unique opportunity for policy makers to push the transportation sector onto a path encompassing reduced sustainability and mitigation challenges and enabling more equitable access to the key service of international mobility. Indeed, given the wide range of potential futures, early clear planning involving all relevant stakeholders seems to be essential to avoid carbon lock-ins and stranded assets in airport infrastructure.

Code availability statement

The code for a stand-alone run of the model is available on Github. The link to the Github repository can be found here: https://github.com/SebastianFra/Aviation_Demand_Projections

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/SebastianFra/Aviation_Demand_Projections.

Acknowledgments

S F and C B were supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 821471 (ENGAGE). M R was supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 821124 (NAVIGATE).

Contributions

S F and C B designed the study. S F performed the analysis, designed and produced the figures and wrote the manuscript, with input from all co-authors.

Conflict of interest

The authors declare no competing interests.

ORCID iDs

Sebastian Franz https://orcid.org/0000-0002-9243-8119
Marianna Rottoli https://orcid.org/0000-0001-7108-908X
Christoph Bertram https://orcid.org/0000-0002-0933-4395

References

[1] Gössling S and Lyle C 2021 Transition policies for climatically sustainable aviation *Transp. Rev.* **41** 643–58

[2] Sharmina M *et al* 2021 Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2 °C *Clim. Policy* **21** 455–74

[3] Gössling S, Humpe A, Fichert F and Creutzig F 2021 COVID-19 and pathways to low-carbon air transport until 2050 *Environ. Res. Lett.* **16** 034063

[4] European Federation for Transport and Environment AISB 2018 *Roadmap to decarbonising European aviation* European Federation for Transport and Environment AISB

[5] Bows-Larkin A, Mander S L, Traut M B, Anderson K L and Wood F R 2016 Aviation and climate change-the continuing challenge *Encyclopedia of Aerospace Engineering* (Hoboken, NJ: Wiley) pp 1–11

[6] ICAO 2016 Aviation and climate change *Environmental Report 2016*

[7] OXFAM 2020 *Confronting Carbon Inequality* OXFAM

[8] International Civil Aviation Organization 2021 *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis*

[9] Dray L, Krammer P, Doyme K, Wang B, Zayat K, O'Sullivan A and Schäfer A 2019 AIM2015: Validation and initial results from an open-source aviation systems model *Transport Policy* **79** 93–102

[10] Dray L and Schäfer A W 2021 Initial long-term scenarios for COVID-19's impact on aviation and implications for climate policy *Transp. Res. Rec.* 036119812110450

[11] O'Neill B C *et al* 2020 Achievements and needs for the climate change scenario framework *Nat. Clim. Change* **10** 1074–84

[12] Rottoli M, Dirnaichner A, Kyle P, Baumstark L, Pietzcker R and Luderer G 2021 Coupling a detailed transport model to the integrated assessment model REMIND *Environ. Model. Assess.* **26** 891–909

[13] Ueckerdt F, Bauer C, Dirnaichner A, Everall J, Sacchi R and Luderer G 2021 Potential and risks of hydrogen-based e-fuels in climate change mitigation *Nat. Clim. Change* **11** 384–93

[14] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

[15] Kriegler E *et al* 2017 Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century *Glob. Environ. Change* **42** 297–315

[16] IPSOS 2017 *Airlines for America—Poll*

[17] Zhang R and Fujimori S 2020 The role of transport electrification in global climate change mitigation scenarios *Environ. Res. Lett.* **15** 034019

[18] Graver B, Zhang K and Rutherford D 2018 *CO2 emissions from commercial aviation* International Council on Clean Transportation

[19] Fricko O *et al* 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century *Glob. Environ. Change* **42** 251–67

[20] van Vuuren D P *et al* 2017 Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm *Glob. Environ. Change* **42** 237–50

[21] Gallet C A and Doucouliagos H 2014 The income elasticity of air travel: a meta-analysis *Ann. Tour. Res.* **49** 141–55

[22] Moneta A and Chai A 2014 The evolution of engel curves and its implications for structural change theory *Cambridge J. Econ.* **38** 895–923

[23] Dray L M, Krammer P, Doyme K, Wang B, Al Zayat K, O'Sullivan A and Schäfer A W 2019 AIM2015: validation and initial results from an open-source aviation systems model *Transp. Policy* **79** 93–102

[24] Kikstra J S, Vinca A, Lovat F, Boza-Kiss B, van Ruijven B, Wilson C, Rogelj J, Zakeri B, Fricko O and Riahi K 2021 Climate mitigation scenarios with persistent COVID-19-related energy demand changes *Nat. Energy* **6** 1114–23

[25] Creutzig F *et al* 2022 Demand-side solutions to climate change mitigation consistent with high levels of well-being *Nat. Clim. Change* **12** 36–46

[26] EU Commision 2021 *Energy Datasheets: EU Countries*

[27] International Energy Agency 2020 *World Energy Outlook 2020*

[28] International Civil Aviation Organization 2021 *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis Air Transport Bureau Contents* International Civil Aviation Organization

[29] ICAO 2022 *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis*

[30] Kearney 2020 *The Future of Aviation: Could COVID-19 be the First and Final for Airlines?*

[31] Stoll C and Mehling M A 2020 COVID-19: clinching the climate opportunity *One Earth* **3** 400–4

[32] Havard Business Review 2021 *Looking to the Future of Air Travel*

[33] McCollum D L, Gambhir A, Rogelj J and Wilson C 2020 Energy modellers should explore extremes more systematically in scenarios *Nat. Energy* **5** 104–7

[34] Madeddu S, Ueckerdt F, Pehl M, Peterseim J, Lord M, Kumar K A, Krüger C and Luderer G 2020 The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat) *Environ. Res. Lett.* **15** 124004

[35] Gössling S, Fichert F and Forsyth P 2017 Subsidies in aviation *Sustainability* **9** 1295

[36] ICAO 1994 ICAO's policies on taxation in the field of international air transport

[37] Gössling S and Humpe A 2020 The global scale, distribution and growth of aviation: implications for climate change *Glob. Environ. Change* **65** 102194

[38] Franz S, Campion N, Shapiro-Bengtsen S, Backer M and Münster M 2021 *MarE-Fuel: ROADMAP for Sustainable Maritime Fuels* Technical University of Denmark