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COVID-19 and pathways to low-carbon air transport until 2050

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Abstract

The COVID-19 pandemic has led to an unprecedented decline in global air transport and associated reduction in CO_2 emissions. The International Civil Aviation Organization (ICAO) reacted by weakening its own CO_2-offsetting rules. Here we investigate whether the pandemic can be an opportunity to bring the sector on a reliable low-carbon trajectory, with a starting point in the observed reduction in air transport demand. We model a COVID-19 recovery based on a feed-in quota for non-biogenic synthetic fuels that will decarbonize fuels by 2050, as well as a carbon price to account for negative externalities and as an incentive to increase fuel efficiency. Results suggest that until 2050, air transport demand will continue to grow, albeit slower than in ICAO's recovery scenarios, exceeding 2018 demand by 3.7–10.3 trillion RPK. Results show that synthetic fuels, produced by 14–20 EJ of photovoltaic energy, would make it possible to completely phase out fossil fuels and to avoid emissions of up to 26.5 Gt CO_2 over the period 2022–2050.

1. Introduction

Aviation accounted for an estimated 2.8% of global emissions of carbon dioxide (CO_2) in 2018 (le Quéré *et al* 2020). Together with its other emissions, in particular nitrous oxides (NO_x) and water (H_2O) emitted at flight altitude, air transport was responsible for 3.5% of the net anthropogenic effective radiative forcing in 2011 (Lee *et al* 2021). Aviation has also been characterized by rapid growth in emissions that increased by a factor 6.8 over the period 1960–2018 (ibid.) and is one of the fastest growing sources of emissions in a global economy striving to decarbonize until 2050 (IPCC 2018).

As a result of the COVID-19 pandemic, flight operations decreased by an estimated −75% in April 2020 (compared to the same month in 2019) and aviation saw the largest decline in CO_2 emissions of any economic sector (−60%, or −1.7 Mt CO_2 d^{-1}) (le Quéré *et al* 2020). In June 2020, aviation started to rebound, at the time still with expectations that the recovery to 2019 air transport levels would take until 2022–2024 (ICAO 2020a). While this implies a significant reduction in emissions compared to the growth trajectory expected prior to COVID-19, it remains a likely scenario that emissions from air transport will double or triple between 2020 and 2050 (ICAO 2020a) (figure 1). Aircraft manufacturers anticipate, for example, that COVID-19 will delay growth by several years, with Boeing (2020) expecting about 18 680 billion revenue passenger kilometres (RPKs) in 2039 (Boeing 2020).

Under the Kyoto Protocol, 'limiting or reducing' emissions from international aviation falls under the remit of the International Civil Aviation Organization (ICAO) (UNFCCC 2018). In 2016, ICAO presented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA; ICAO 2020b). CORSIA seeks to offset a share of future emissions of CO_2 from international commercial aviation. The scheme ignores military and private flights, and does not cover domestic air traffic at all (UNFCCC 2018). CORSIA does not account for non-CO_2 warming, and is thus inadequate to address aviation's contribution to climate change (Gössling and Humpe 2020). CORSIA has also been criticized for its focus on offsetting and partially voluntary character (Lyle 2018, Scheelhaase *et al* 2018, Larsson *et al* 2019, Maertens *et al* 2019), while its fuel efficiency assumptions of 2% yr^{-1} until 2050 have been called unattainable by ICAO's own Committee on Aviation Environmental Protection (CAEP 2013). More importantly, there is

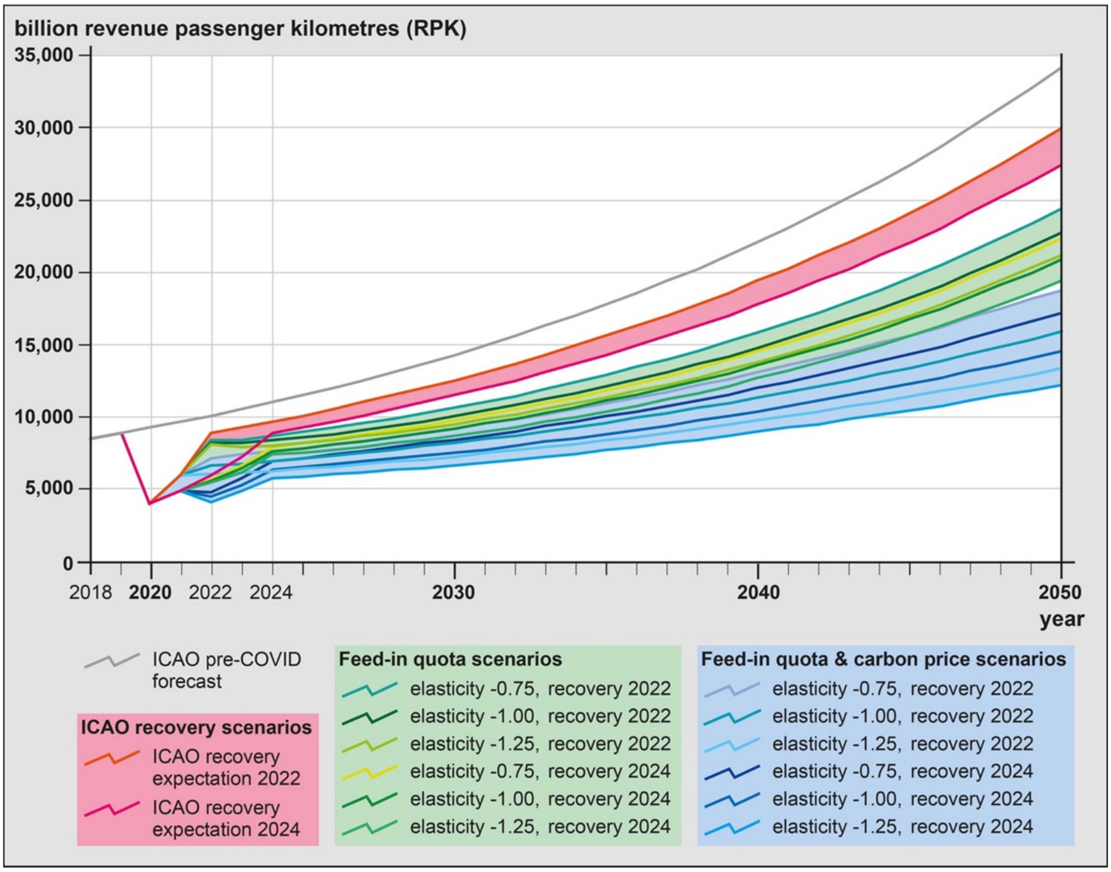

Figure 1. RPK development under different price elasticity of demand assumptions.

no market basis under CORSIA for the introduction of new technologies to replace fossil fuels. This raises the question how the aviation sector can be reliably decarbonized until 2050. The purpose of this paper is to explore one potential low-carbon pathway, and to highlight its challenges and implications.

Two major low-carbon technologies have been discussed in the literature, i.e. electric flight (Schäfer *et al* 2019) and sustainable alternative fuels, the latter including very different options such as hydrogen, biomass-derived fuels, or e-fuels (also described as power-to-liquid or non-biogenic synthetic fuels) (Herz *et al* 2018, Perner and Bothe 2018, Schmidt *et al* 2018). Each alternative fuel has specific disadvantages in comparison to conventional jet fuel, because of differences in energy density, weight, storage volumes, land or water requirements, or greenhouse gas avoidance potential (Herz *et al* 2018, Perner and Bothe 2018, Schmidt *et al* 2018). A consensus seems to be emerging that batteries will be too heavy for longer flights in the foreseeable future; hydrogen, including hybrid-electric, will depend on different aircraft designs due to its lower energy-density and significantly greater space requirements; sustainable alternative biofuels will reduce only a share of CO_2 emissions (Herz *et al* 2018, Perner and Bothe 2018, Schmidt *et al* 2018, Schäfer *et al* 2019). This leaves drop-in non-biogenic synthetic fuels as the technically most viable option to replace jet fuel (IEA 2019a). These fuels have for years had a high level of technology readiness (German Environment Agency 2016), but they require a vast renewable energy input for their production, and are expected to be two to three times more costly than conventional fuel, depending on fossil fuel price developments as well as technological progress in synthetic fuel production (German Environment Agency 2016, IEA 2019a).

Technological change depends on the emergence of new competitive technologies, but also on the substitution of fossil fuels (Davidson 2019). This paper seeks to assess whether a slower COVID-19 recovery represents an opportunity to advance the decarbonization of global aviation. This is because the current decline in demand represents an opportunity for system change, as the amount of alternative fuels needed is currently lower, making replacement needs easier to achieve. This is considered on the basis of a feed-in quota obligation, forcing airlines to use an annually growing share of synthetic fuels, as well as a price for CO_2 as well as on non-CO_2 radiative forcing to internalize the future cost of climate change (Nordhaus 1994, Lee *et al* 2021; for details see section 4). Both feed-in quota and carbon price significantly increase the cost of air transport, with concomitant negative repercussions for demand. The price increase may however be seen against industry growth since 2000, which has been accelerated by capacity growth, efficiency gains, deregulation, and subsidies, all of which have contributed to the observed decline in the real cost of air travel by 60% between 1998 and 2018 (IATA 2019). As various studies suggest, the low price of air travel has induced rapid growth in air travel (Kantenbacher *et al* 2018, Falk and Hagsten 2019, Gössling and Humpe 2020). COVID-19 itself has also changed patterns of demand, as videoconferencing has gained ground (Suau-Sanchez *et al* 2020).

While other regulatory options exist (Larsson *et al* 2018, 2019) as well as more diversified technology transformations, involving, for instance, a share of electric aircraft, we suggest that a feed-in quota obligation in combination with a carbon price is the most reliable and least disruptive mechanism for a technology/fuel transition. A constantly increasing feed-in quota reliably phases out fossil fuels. Carbon pricing encourages an increase in fuel efficiency and reflects the cost of climate change (Stiglitz *et al* 2017).

Our low-carbon transition model shows how demand growth and CO_2 emissions will develop until 2050, considering the parameters carbon price, feed-in quota, efficiency gains, and price elasticity (IATA 2020). The model purposefully includes only these key dimensions to avoid vulnerabilities arising out of multiple parameter feedback-loop complexity (for details see section 4). Growth projections are based on industry market forecasts. While industry growth scenarios are always ambiguous in that they have self-serving purposes (Becken and Carmignani 2020), they allow for an assessment of the cost and inter-linkages of system transformations under industry assumptions of desirable transport futures. Industry scenarios are also widely accepted by stakeholders and policymakers. Results as presented in this paper are explicitly not intended to represent accurate scenarios of future transport demand. Rather, the paper explores principle challenges of technology change transformations in relation to cost/price and demand, providing general insights of importance for the low-carbon transition (Rosenbloom *et al* 2020).

2. Results

Figure 1 shows ICAO's pre-pandemic forecast as well as the organization's recovery scenarios in comparison to the scenarios for low-carbon aviation presented in this paper (based on ICCT 2019 data). The latter include the effect of a feed-in quota, as well as the combination of a feed-in quota and a carbon price, on air transport demand growth (RPK) for the period 2022/24–2050. Reference scenarios are ICAO (2016) non-pandemic demand trajectory, and ICAO (2020a) 2022/2024 recovery scenarios, with an averaged 4.45% annual growth in consecutive years. As the scenario runs show, COVID-19 has significantly affected the industry's demand growth expectations. Depending on the rebound year (i.e. the return to 2019 levels by 2022 or later), the difference between the non-pandemic (34.2 trillion RPK) and ICAO's 2024 recovery scenario (27.5 trillion RPK) may be more than 6.6 trillion RPK in 2050. While the great recession in 2008/2009 led to only temporal decline, compensated by higher growth rates in 2010 (Peters *et al* 2012), we expect that COVID-19 has a longer-lasting effect.

A feed-in quota would further reduce demand due to the higher cost of flying (see section 4). To illustrate the effect, we model the cost of synthetic fuel production against three different price elasticities for 2 recovery years (2022/2024), showing that the quota will reduce demand growth to a total of 19.5–24.4 trillion RPK by 2050. Even though representing a reduction in demand, this is still two to three times the number of RPK flown in 2018. Adding a carbon price that starts at \$100 t^{-1} CO_2 in 2022 and increases to \$800 t^{-1} CO_2 in 2050 (see section 4), further reduces demand to between 12.2 and 18.8 trillion RPK by 2050. Even the most demand-reducing scenario would consequently imply further growth in air transport compared to 2018, by at least 3.7 trillion and up to 10.3 trillion RPK in 2050. Although air transport's growth expectation is significantly lower than in the ICAO baseline scenario, the sector would continue to accommodate demand in both the feed-in quota as well as the feed-in quota and carbon price scenario.

Significantly lower growth rates also reduce the sector's contribution to radiative forcing. This is illustrated in figure 2, which shows the difference in CO_2 emissions between the pathways. In the most conservative ICAO recovery scenario, emissions will grow by almost 140%, with efficiency gains already considered (see section 4). In comparison, both the feed-in quota scenario and the combined feed-in quota and carbon price scenario lead to near zero CO_2 emissions by 2050, following steeper or more moderate reduction curves. The ICAO recovery and the modelled low-carbon trajectories have very different implications for total emissions: the cumulative amount of 'avoided' emissions from aviation between 2022 and 2050 is 26.5 Gt CO_2, if comparing the ICAO 2022 recovery scenario (35.8 Gt CO_2 between 2022 and 2050) with the 2022 feed-in quota and carbon price scenario (9.3 Gt CO_2 between 2022 and 2050).

A significant contribution to radiative forcing is also made by contrail cirrus and nitrous oxides (Lee *et al* 2021). Even under a scenario of a full switch to synthetic fuels, non-CO_2 warming cannot be avoided. Concerns over this issue have been raised two decades ago, as growth in air transport with concomitant increases in CO_2 emissions that are partially offset does incur an overall increase in radiative forcing (Lee and Sausen 2000). Recent research has opened up for

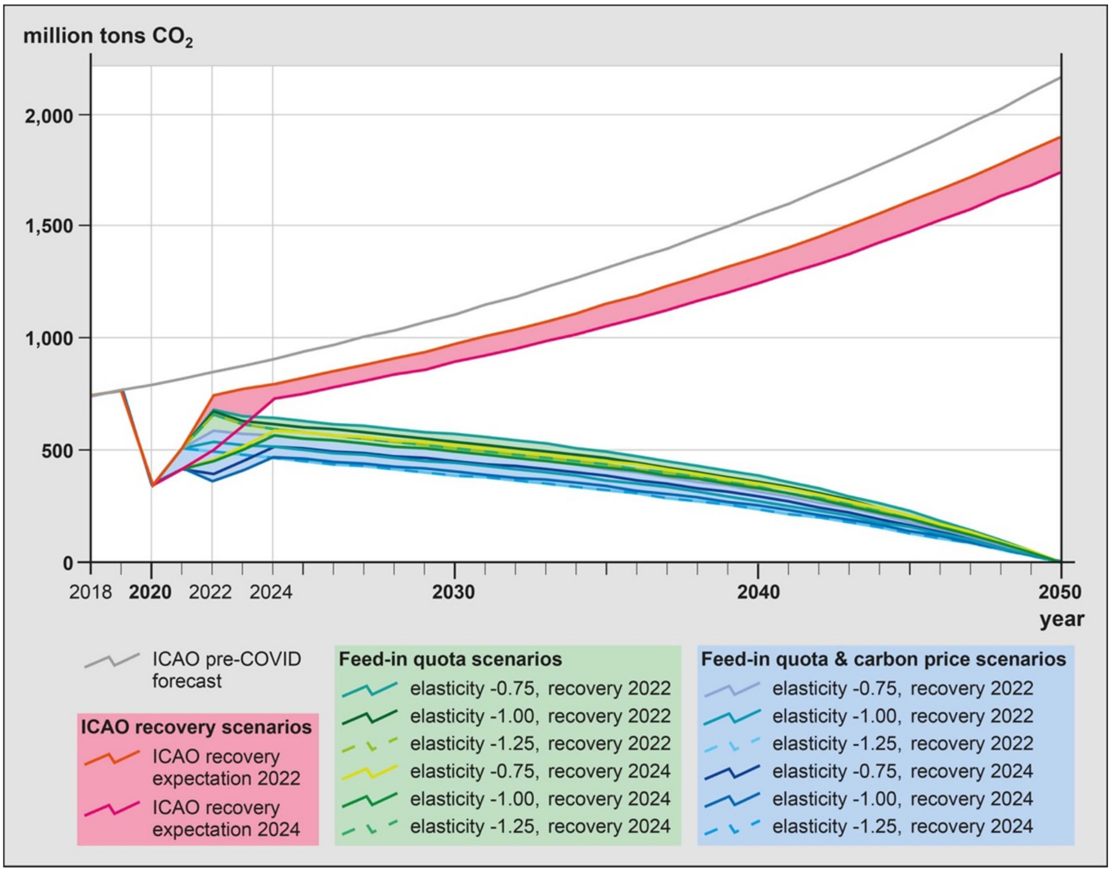

Figure 2. Development of CO_2 emissions under business-as-usual and feed-in scenarios.

chemically purer synthetic fuels to add lower amounts of soot (Burkhardt *et al* 2018), which may reduce forcing by 15% (Bock and Burkhardt 2019). Teoh *et al* (2020) also demonstrated that altering a small share of flight paths may significantly reduce radiative forcing, at a small additional fuel cost. Yet, it is premature to evaluate the future potential and feasibility of flight path changes to reduce radiative forcing, and reduced growth rates in combination with a feed-in quota thus appear to be the most reliable and least risky pathway for mitigating aviation's contribution to global warming.

Fuel requirement calculations can be used to estimate the size of the area needed for the production of synthetic fuels (for details see section 4). In the medium elasticity scenario with a recovery in 2022, continued demand growth would lead to global fuel consumption of 456 Mt in 2050 in the feed-in quota scenario and 319 Mt in the combined feed-in quota and CO_2 price scenario (medium demand elasticity of −1.0). To calculate area use, we assume a more optimistic synthetic fuel production efficiency of 1000 GJ ha^{-1} yr^{-1} from utility scale photovoltaic in combination with a CO_2 source (German Environment Agency 2016). Solar is currently the cheapest and most space-efficient option. Wind power requires larger areas of land, while other options (hydroelectric dams, nuclear reactors, thermal plants) are costlier (German Environment Agency 2016, Ram *et al* 2018). At an energy density of about 44 MJ kg^{-1} (Vera-Morales and Schäfer 2009: 6), one ha of land yielding 1000 GJ can be used to produce about 22.75 t of synthetic fuel per year. To produce 456 Mt of fuel will consequently require about 200 000 km^2 (approximately the size of Uganda), while 319 Mt still require 140 000 km^2 (approximately the size of Nepal) (table 1).

Table 1. Area requirement for renewable energy production in the feed-in quota and carbon price scenario, with a recovery in 2022.

Scenario	Demand 2050 (trillion RPK)	Fuel use 2050 (Mt)	Area for solar electric energy production (km^2)
Business-as-usual	30.0	601.0	264 000
Demand elasticity −0.75	18.8	376.8	166 000
Demand elasticity −1	15.9	318.8	140 000
Demand elasticity −1.25	13.4	267.7	118 000

Assumptions: 1000 GJ ha^{-1} yr^{-1}; 8.5 trillion RPK in 2018; specific fuel use 0.035 l per RPK in 2018, in 2050: 0.0254 l per RPK.

Photovoltaics are expected to provide 30–70 TW capacity by 2050 (Haegel *et al* 2019), which would produce 170–400 EJ annually. In the medium demand elasticity scenarios specified above, 20 EJ and 14 EJ of energy would be required respectively, i.e. a fraction 4%–11% of potential technical photovoltaic capacity. However, the high demand of land required, a scarce resource at global scale (Creutzig 2017), also motivates a lower demand growth scenario.

Additional insights regarding the implications of continued growth can be gained from a regional analysis (figure 3). Extrapolations of industry expectations (Airbus 2019, Boeing 2019) adjusted to the 2022 recovery scenario suggest that RPKs demand will grow by more than 140% in North America and more than 360% in the Asia-Pacific (2018–2050). By 2050, North America and Europe will together account for about one third of RPK (34.8%), while almost half of the world's air traffic (42.9% of RPK) will take place in the Asia-Pacific region. From the viewpoint of individual contributions, North America remains the most mobile region, with about 12 400 RPK per capita and year in 2050, while the Asia-Pacific region is expected to grow to an annual per capita transport demand of 2600 RPK. Demand remains low in Africa at 290 RPK per capita and year in 2050. In comparison, the 2018 annual per capita world average is 1100 RPK.

Regional emission responsibilities will be influenced by these developments (table 2). For example, North Americans will continue to be the most mobile population on a per capita basis, flying 40 times more than Africans. Although Africa is expected to be the home of 25% of the world population by 2050, it will only account for 2.4% of RPK demand and emissions of CO_2. By 2050, annual per capita CO_2 emissions from aviation will be about 785 kg in North America, 170 kg in the Asia-Pacific, and less than 20 kg in Africa. Given the distribution of the global population by 2050, the Asia-Pacific would however account for almost 43% of global emissions of CO_2 from aviation. These calculations show the implications of industry growth expectations under a business-as-usual recovery scenario.

3. Discussion

Scenario runs illustrate the difference between ICAO (2020a) recovery scenarios and an alternative growth model based on a feed-in quota for non-biogenic synthetic fuels and a carbon price to reliably decarbonize the sector. This alternative strategy would avoid emissions of up to 26.5 Gt CO_2 until 2050, and hence help 'preserving' a significant share of the remaining carbon budget (Rogelj *et al* 2019). Considering three different price elasticities of demand, RPK growth would be in the order of 57%–187% between 2018 and 2050, compared to 250% growth in the 2022 recovery scenario (feed-in quota only: 21.2 - 24.4 trillion RPK; feed-in quota & carbon price: 13.4 - 18.8 trillion RPK, in 2050, with a recovery in 2022). The combined effect of the feed-in quota and CO_2-price is one of moderated growth that simultaneously represents a climatically viable transition policy (Rosenbloom *et al* 2020). Following an unmitigated growth trajectory, emissions from aviation would significantly increase, with the Asia-Pacific region alone accounting for more CO_2 by 2050 than aviation did globally in 2018 (figure 4).

Notably, even in the moderate growth scenario, the technology challenge is formidable. As calculations show, to produce sufficient amounts of non-biogenic synthetic fuels, solar electric utilities would have to expand by more than 6000 km^2 yr^{-1} until 2050. Lands for production may be primarily found in desert areas, leading to other complexities such as the transportation of fuels, or socioeconomic and political stability. There are no antecedents of similar large-scale projects, even though synthetic fuel production could imply new economic opportunities for emerging economies. In light of these difficulties, alternatives for decarbonizing aviation, such as electric propulsion should be pursued simultaneously. Electric propulsion may be feasible on shorter distances and for limited passenger numbers (Schäfer *et al* 2019), and could fully avoid emissions at flight altitude, resolving the issue of non-CO_2 warming. As a caveat, we note that none of these strategies is zero-carbon on a lifecycle basis.

The speed at which the transition to sustainable alternative fuels needs to happen highlights the need to immediately begin and upscale synthetic fuel production, as there exist no significant production capacities at the moment. The COVID-19 pandemic may be seen as an opportunity in this regard, as the crisis offers a window of opportunity to rethink aviation under more modest growth rate scenarios. Notably, calculations of fuel requirements as presented in this paper only include commercial air passenger transport, omitting cargo, private and military flight. Other sectors such as the maritime industry also look into non-biogenic synthetic fuels to replace marine diesel oil or heavy fuel oil. Agriculture will likely have to switch to synthetic fuels as well. As the world economy becomes increasingly electrified, there will also be issues of competition over renewable energy. The findings presented in this article illustrate the challenges implied in reducing the sector's contribution to global warming without embracing a far-reaching technology transition, and implicitly underline the need for a 'green' pandemic recovery with a starting point in mitigation.

4. Materials and methods

4.1. Model description

A model was built to assess global aviation's growth for the period 2022–2050 under the assumption of a

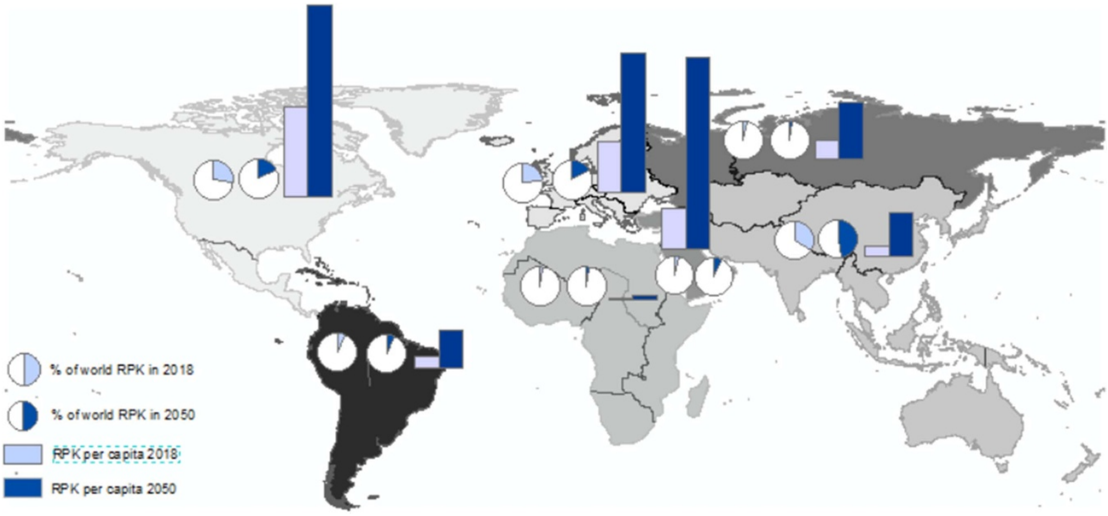

Figure 3. Map created using ArcGIS® by Esri, Global Mapping International, U.S. Central Intelligence Agency (The World Factbook) Expected development of RPK by region (% and RPK per capita).
Source: (Airbus 2019, ICCT 2019, UN DESA 2019).

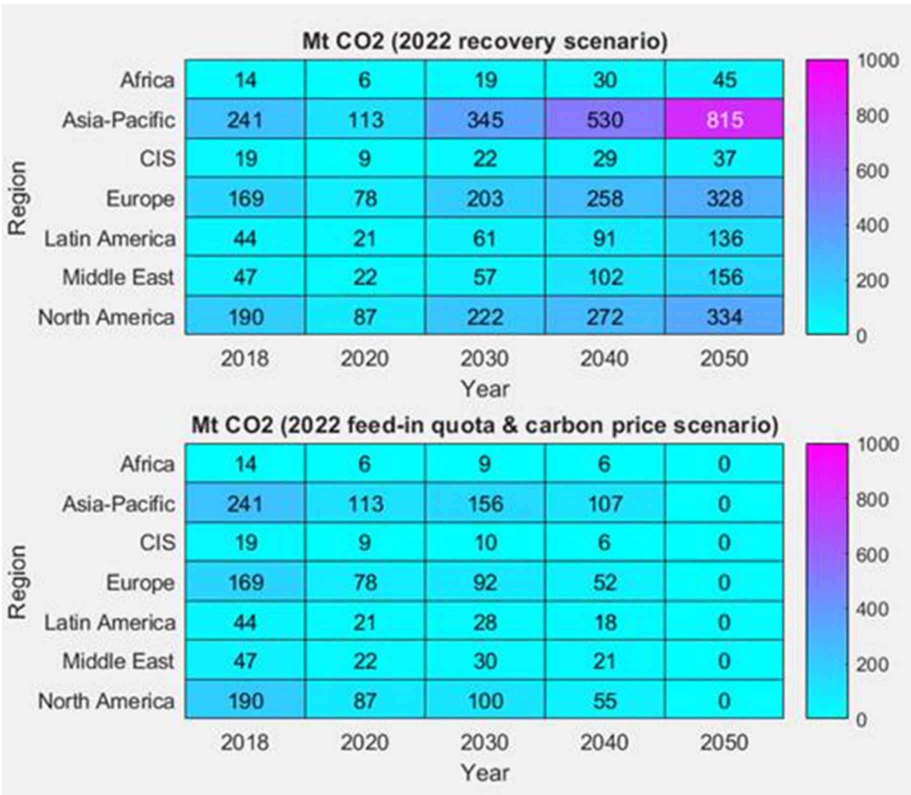

Figure 4. Heatmap of emission growth, ICAO, ICCT 2019 and model projections[a].
[a]ICAO scenario based on industry assumptions (Airbus 2019, Boeing 2019).

carbon price and a feed-in quota for synthetic fuels. The model is linear and based on industry projections, which implies that a wide range of assumptions have to be implicitly accepted. The purpose of this model is not to present an accurate understanding of aviation in 2050, rather than to illustrate the challenges of moving towards a climatically sustainable air transport system should there be a rebound and return to growth pathways as plotted by industry after the COVID-19 pandemic.

The model considers growth in air transport demand on the basis of a growth rate of 4.45% yr^{-1}. This is the major aircraft manufacturers' averaged annual growth rate of 4.3% (Airbus 2019) and 4.6%

Table 2. RPK and emissions by region, 2018 and 2050[a].

Region	Growth rate per year (%)	RPK 2018 (billion)	RPK 2050 (billion)	RPK per capita 2018	RPK per capita 2050	RPK share 2050 (%)	CO_2 global (Mt, 2050)	CO_2 per capita (kg, 2050)
Africa	5.35	157	713	123	286	2.4	45	18
Asia-Pacific	5.45	2762	12 871	648	2641	42.9	815	167
CIS	3.50	213	578	894	2275	1.9	37	144
Europe	3.45	1934	5173	2867	7782	17.3	328	493
Latin America	5.10	507	2147	790	2816	7.2	136	178
Middle-East	5.35	543	2460	3181	9228	8.2	156	585
North America	3.10	2174	5269	5967	12 392	17.6	334	785
Rest of world	4.56	212	773	—	—	2.6	49	—
Total		8503	29 983	—	—	100	1.899	—

[a] Scenario based on industry assumptions (Airbus 2019, ICCT 2019, Boeing 2019); for details see section 4.

(Boeing 2019) over the period 2019–2038, and continued to 2050. The year 2022 is $t = 0$ and 2050 is $t = 28$. RPK development (in billion RPK) is given by:

$$\mathrm{RPK}_t = 8860 \times 1.0445^t.$$

The cost of a feed-in quota for non-biogenic synthetic fuels is based on a linear increase in synthetic fuel use from 0% in 2021 to 100% by 2050, and production cost decline from US\$2.88 kg^{-1} in 2020 to US\$1.44 kg^{-1} in 2050 (German Environment Agency 2016, IEA 2019a). The longer-term price for fossil fuel is US\$0.65 kg^{-1} (IATA 2018; note that, 2020 June projection is about US\$0.41 kg^{-1} for 2021). The development of the cost of fuel is given by:

$$\text{US\$ per kg fuel}_t = 0.65\ \text{US\$} \times \left(1 - \frac{t+1}{29}\right) + 2.88\ \text{US\$} \times 0.5^{\left(\frac{t+2}{30}\right)} \times \left(\frac{t+1}{29}\right).$$

It is acknowledged that the cost of fuel changes constantly. The model relies on industry projections, to stay within the general framework of industry assumptions (Airbus 2019, Boeing 2019, 2020, McKinsey 2020).

The model considers a carbon price of CO_2 for fossil fuel that starts at US\$50 t^{-1} CO_2 in 2022 and increases to US\$400 t^{-1} of CO_2 by 2050 (Rockström *et al* 2017). It includes an identical price for non-CO_2 emissions, to consider additional radiative forcing from aviation (Lee and Sausen 2000, Lee *et al* 2021), also starting at US\$50 t^{-1} CO_2 in 2022 and increasing to US\$400 t^{-1} of CO_2 by 2050 (a motivation for this approach is provided further down below). Emissions of greenhouse gases are calculated on the basis of the following assumptions: 1 l of jet fuel has a weight of 0.79 kg, with 1 kg of jet fuel burning to 3.16 kg of CO_2. This is given by:

$$\begin{aligned}\text{US\$ per kg fuel}_t &= \left(0.65\ \text{US\$} + \left((50+50) \times \frac{3.16}{1000}\right) \times 8^{\left(\frac{t+1}{29}\right)}\right) \\ &\quad \times \left(1 - \frac{t+1}{29}\right) + \left(2.88\ \text{US\$} \times 0.5^{\left(\frac{t+2}{30}\right)}\right. \\ &\quad \left. + \left(50 \times \frac{3.16}{1000}\right) \times 8^{\left(\frac{t+1}{29}\right)}\right) \times \left(\frac{t+1}{29}\right).\end{aligned}$$

Note that the carbon price is considered separately from the uptake of synthetic fuels, as this model's feed-in quota is mandatory. The carbon price impact is thus primarily one of reducing demand, i.e. working in tandem with the additional cost of introducing synthetic fuels. Estimates are aligned with recent industry reports (McKinsey & Company 2020).

Efficiency gains through the introduction of new technologies or improved air traffic management are considered at 1% yr^{-1}, leading to a specific fuel use of 3.36 l per 100 RPK in 2022, declining to 2.54 l per 100 RPK in 2050. The 1% yr^{-1} estimate is based on observed improvements in efficiencies in the last decade (Peeters *et al* 2016, IATA 2019). Growth in specific fuel use is given by:

$$\text{Fuel/RPK}_t = 0.0336\,\mathrm{l} \times 0.99^t.$$

Hence, considering fuel efficiency gains, CO_2 emission growth in the business-as-usual scenario is represented by:

$$CO_{2_t} = 8860 \times 1.0445^t \times 0.0336\,\mathrm{l} \times 0.99^t \times 0.79\frac{\mathrm{KG}}{\mathrm{l}} \times 3.16.$$

4.2. Assessment of implications for demand

The increase in the cost of flying will lead to a decline in demand. We distinguish a price elasticity of demand and a fuel cost elasticity of demand. Carbon price and feed-in quota increase the cost of fuel, which represents about 24.5% of the cost of air transport (average 2014–2019; IATA 2019). This means that if the cost of fuel doubles, and the elasticity of demand is -1.0, then the fuel cost elasticity of demand is -0.245. In this example scenario of a 100% increase in the cost of fuel, demand for air transport will fall by 24.5%, the share by which the total cost of flying increases. Elasticities have been investigated in different contexts, with a general consensus that they depend on traveller segments, flight class, and flight distance (Brons *et al* 2002, Gillen *et al* 2008, Falk and Hagsten 2019). Studies have suggested price elasticities of demand ranging between -0.27 and -1.52 (Gillen *et al* 2008). To illustrate the implications of different price elasticity scenarios, we use three different high-level price elasticities of demand (-0.75; -1.0; $-1{,}25$), that are likely to represent the most reliable range over all market segments. Note that the global population of air travellers is limited (Gössling and Humpe 2020). This results in a fuel cost elasticity of demand of -0.184, -0.245, and -0.306. The effect of price elasticities of demand is given by:

$$\varepsilon_{\mathrm{RPK(fuel\ price)}} = \frac{\log(\mathrm{RPK}_t) - \log(\mathrm{RPK}_{t-1})}{\log(\text{fuel price}_t) - \log(\text{fuel price}_{t-1})}.$$

With a price elasticity of demand $\varepsilon_{\mathrm{RPK(ticket\ price)}}$ and RPK_0 8860 billion for 2022, RPK demand is given by:

$$\begin{aligned}\mathrm{RPK}_t &= \mathrm{RPK}_{(t-1)} \times 1.0445 \\ &\quad \times \left(\left(\log\left(\frac{\mathrm{USD}}{\mathrm{KG}}\text{fuel}_t\right) - \log\left(\frac{\mathrm{USD}}{\mathrm{KG}}\text{fuel}_{t-1}\right)\right)\right. \\ &\quad \left.\times\, \varepsilon_{\mathrm{RPK(ticket\ price)}} \times \text{fuel cost share} + 1\right).\end{aligned}$$

It is acknowledged that the model relies on industry assumptions that are based on demand change in different markets for different price/income-dependent elasticities. This is necessarily a simplification, because short, medium and long-haul markets and different traveller groups will react differently to price changes.

4.3. Motivation for parameter choices following industry growth projections

Industry projections are based on complex assumptions including economic and technological developments (Airbus 2019, Boeing 2019). These projections can be compared to other estimates. For example, ICAO (2016) projects demand to grow by 2.8–3.9 between 2010 and 2040. Lee *et al* (2009) estimate that fuel use will grow by a factor 2.7–3.9 between 2000 and 2050, while Chen and Gettleman (2016) suggest a factor 2.7–5.0 for the period 2006–2050. Owen *et al* (2010) postulate that CO_2 emissions could grow by up to 360% between 2000 and 2050. Estimates in the wider literature are thus broadly aligned with industry assumptions, which under its business-as-usual scenario projects fuel use and emissions to grow by an estimated factor three between 2018 and 2050. While the COVID-19 pandemic changes these assumptions, the overall understanding is that with the expected rebound of the aviation system, emissions will significantly grow.

4.4. Motivation for consideration of non-CO_2 emissions on the basis of CO_2

Long-lived CO_2 and short-lived non-CO_2 emissions are not comparable, though both contribute to changes in radiative forcing (IPCC 1999, Lee *et al* 2021). To ignore non-CO_2 effects in climate mitigation assessments is consequently an omission of a significant part of aviation's contribution to global warming. In this paper, we use a non-CO_2 price that approximates warming effects. This does not represent a scientifically valid integration: while it has been long acknowledged that short-lived emissions cause additional warming (Lee and Sausen 2000), there is no consensus how effects should be addressed in climate policies. Countries such Austria or Germany have included non-CO_2 emissions on the basis of emission weighting factors in national assessment of aviation impacts (Environment Agency Austria 2018, German Environment Agency 2018). The model follows this approach, equalling the contribution of CO_2 and non-CO_2 as an approximation of global warming potential, and assuming an identical price for both (Lee *et al* 2021). The price applies to both conventional and synthetic fuels, as both contribute to non-CO_2 warming. This is likely to represent an underestimation of the impacts of non-CO_2 emissions at flight altitude in comparison to CO_2 (Lee *et al* 2021). As conventional fuels are phased out and replaced with non-biogenic synthetic fuels, the cost of CO_2 declines to zero by 2050. The price for non-CO_2 emissions increases to US\$400 t^{-1} in 2050, as non-CO_2 warming effects persist (Burkhardt *et al* 2018, Bock and Burkhardt 2019), unless alternative flight pathways can be found (Teoh *et al* 2020).

4.5. Motivation for feed-in quota assumptions

The feed-in quota for synthetic fuels illustrates a linear transition to synthetic fuels. Here the paper follows the IPCC (2018) to pursue rapid decarbonization, i.e. to replace all fossil fuels within 30 years. To achieve this, the feed-in quota grows linearly from 0% in 2021 to 100% in 2050. As overall fuel consumption grows, this means that synthetic fuel production has to be scaled up over time. In the model, this upscaling is linear, though in reality, amounts produced initially would be small. Area calculations for synthetic fuel production are based on a fuel yield of 1000 GJ ha^{-1} and year, i.e. the upper range of estimates of 580–1070 GJ ha^{-1} and year presupposing high-yielding production locations and availability of a CO_2 source (German Environment Agency 2016).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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