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# Net-zero aviation: Time for a new business model?

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ABSTRACT

Recent years have seen vivid debate on decarbonizing aviation. Carbon-neutral flight is characterized by various barriers, however: Key transition technologies are in early stages of technology readiness, their scalability is uncertain, and airlines are not profitable. The replacement of fossil fuels will demand drop-in quota legislation at a global scale. This paper discusses the implications of continued growth in light of the sector's financial situation. It models the cost of biomass-based and non-biogenic synthetic (electric) fuels in combination with carbon taxes. Findings serve as a basis for the assessment of aviation's likelihood of achieving net-zero emissions without addressing growth. If the current business model – volume growth with very small profit margins – is continued, it is likely that aviation's contribution to climate change will grow, due to constraints in biofuel production, cost, and an increase in non-$CO_2$ warming. To stay within 1.5 °C warming, the sector has to reassess capacity and its relationship with profitability; and to possibly embrace an altogether different business model.

## 1. Introduction

In its most recent report, the Intergovernmental Panel on Climate Change (IPCC et al., 2021: no page) emphasizes that "every tonne of $CO_2$ emissions adds to global warming". To limit warming to 2 °C, or the more desirable maximum of 1.5 °C as agreed upon in the Paris Agreement (UNFCCC 2022), will require very significant year-on-year emission reductions. The remaining "carbon budget" that can be emitted before reaching 1.5 °C is 400 Gt $CO_2$ (67% chance of staying within temperature threshold; IPCC et al., 2021: 29). Aviation is a carbon-intense human activity. The sector currently emits about 1 Gt $CO_2$ per year, and is poised to deplete an increasing share of the remaining carbon budget under scenarios of continued growth. Importantly, the sector is also responsible for effective radiative forcing three times the warming caused by $CO_2$, i.e. its overall contribution to global warming is considerably greater than $CO_2$ alone suggests (Lee et al., 2021).

While this is now acknowledged in principle by the aviation sector, and covered politically by some jurisdictions such as the European Union, overall emissions from aviation continue to grow. The COVID-19 pandemic reduced air transport demand (Dube et al., 2021), but there is an expectation of rebound and return to the pre-pandemic growth model, potentially leading to a three-fold increase in air transport demand until 2050 (IATA 2022). To align this expected growth with net-zero ambitions is a challenge, as the sector's emissions have to decline against a growth trajectory. Technologies have to be introduced and upscaled at unprecedented scale, at a very significant cost, and in the absence of markets (Klöwer et al., 2021; Dray et al., 2022). This is complicated by global airlines' economic situation, which is characterized by low profitability and new debt accumulated during the pandemic. Against this background, the paper discusses the complexity of the environmental and economic environment characterizing aviation, to then model the cost of new fuels (biogenic/non-biogenic), and to finally analyze the implications for an aviation system that is seeking to deliver both net-zero emissions and economic profitability.

## 2. Theoretical background

### 2.1. Environment and economics

Responsibility for overseeing emission reductions in aviation was given to ICAO in 1997. Over a period of 20 years, ICAO moved through a series of negotiations, identifying (and discarding) various strategies for mitigation (Scott et al., 2012). In 2016, the organization presented its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which has since been criticized for its low reliability and

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credibility (Dray and Schäfer 2021; Gössling and Lyle 2021; Lyle 2018; Scheelhaase and Maertens 2020; Warnecke et al., 2019). Under the scheme, "baseline" emissions equal to those emitted in 2019 will not be considered, while non-$CO_2$ warming is ignored. CORSIA is legally non-binding. There is a focus on (forest) offsets, which are questionable given a growing prevalence of wildfires (Pausas and Keeley 2021). Offset-based strategies also omit that there is a need to transition to new technologies or fuels that will decarbonize the sector. The evidence is that aviation will continue to grow in its emissions, unless politically forced to decarbonize. In Harbison's (2021: no page) words, aviation "is a supreme case of a failed regulatory structure – and everyone knows it". This has led some observers to conclude that ICAO's plans will have to be seconded by national regulation if the sector is to engage on a low-carbon trajectory (Lyle 2018).

Against this background, it is of interest to note that green narratives are widespread in aviation, with the goal of creating a public understanding of progress on mitigation, obfuscating a reality of continuous emission growth. Examples include technology myths (Peeters et al., 2016), misleading communication (Guix et al., 2022), and 'aspirational', unattained decarbonization goals (Possible 2022). The sector is simultaneously focused on volume growth with low profitability, as evident in bargain marketing strategies (Higham et al., 2022). These marketing strategies are designed to increase demand growth, while discursively embracing future low carbon technologies (that do not exist as yet). Industry narratives of technology solutions are also problematic because they create an understanding that it is the system, not the individual, that needs to change; with evidence that air travelers do not see responsibility for reducing emissions with themselves (Gössling et al., 2009). This suggests that decarbonization in aviation is hampered by the combination of green narratives created by the aviation sector, public notions that decarbonization can and should be achieved through technology, and an absence of policies forcing the sector to adopt new technologies and air travelers to pay for them.

### 2.2. Aviation economics

More complexity is implied in aviation's global business model. The current market situation is characterized by additional debt, demand reductions, uncertainty, and bankruptcies (Dube et al., 2021). Aviation is a recipient of a wide range of subsidies (Gössling et al., 2017), with evidence that these, in combination with VAT-exemptions on international flights, the absence of a carbon price, and aircraft manufacturers' growth strategy, have been instrumental in generating overcapacities (Becken and Carmignani 2020; Chow et al., 2021; Forsyth and Guiomard 2019). Market deregulation and the introduction of wide-bodied aircraft created overcapacities and caused airfares to fall significantly over time, also reducing the sector's profitability (IATA 2018). In the post-pandemic recovery, Harbison (2021:6) notes that "simply servicing the additional debt [accumulated under the pandemic] will cost more than the industry has on average generated annually in profits". Fig. 1 illustrates this for the past 44 years, in which aviation has operated at a loss in 18 years, with marginal real profits per passenger. Any change in cost structures is likely to affect global airlines' business model, and has raised questions regarding the introduction of costly sustainable fuels, which airlines are unlikely to use unless forced (Fontanet-Pérez et al., 2022; Kallbekken and Victor 2022).

### 2.3. Technology readiness and scalability

Remaining carbon budgets for staying within 1.5 °C, 1.7 °C and 2.0 °C are 400 Gt $CO_2$, 700 Gt $CO_2$ and 1150 Gt $CO_2$ (67% chance; IPCC et al., 2021: 29). Aviation emits approximately 2.5% of global $CO_2$ (Lee et al., 2021), though its share in global warming is higher (Lee et al., 2021; Klöwer et al., 2021). The sector's share in the remaining carbon budget to 1.5 °C is in the order of 10 Gt $CO_2$, or 28.75 Gt $CO_2$ to 2.0 °C, assuming that the budget is shared between all economic sectors. Unless emissions are reduced from current levels of approximately 1 Gt $CO_2$ per year, aviation will deplete its remaining 2.0 °C budget in 2050. Notably, this steady-emission scenario implies that demand growth is balanced with efficiency gains, which is unlikely as expected growth rates in emissions exceed 3% per year. Hence, emission reductions have to be achieved through new technologies and sustainable aviation fuels.

Various technologies are currently under consideration as replacements of conventional fuel combustion technology (Dahal et al., 2021). Battery-electric aircraft may become relevant for short-haul flights (Epstein and O'Flarity, 2019), though battery energy-density will have to increase: Current battery technology can accommodate just a small percentage of the gravimetric energy density of aviation fuel (Viswanathan and Knapp 2019). While energy-efficient in principle, as no energy-conversion is implied in its use, infrastructures at airports would have to be revisited, also with a view to recharging times. This is a relatively uncertain field of progress, and it is unclear whether electric aircraft will make a significant contribution to air passenger transport until midcentury.

A second technology is hydrogen propulsion, with first commercial aircraft being expected by 2035 (Airbus 2021). This 'solution' is very

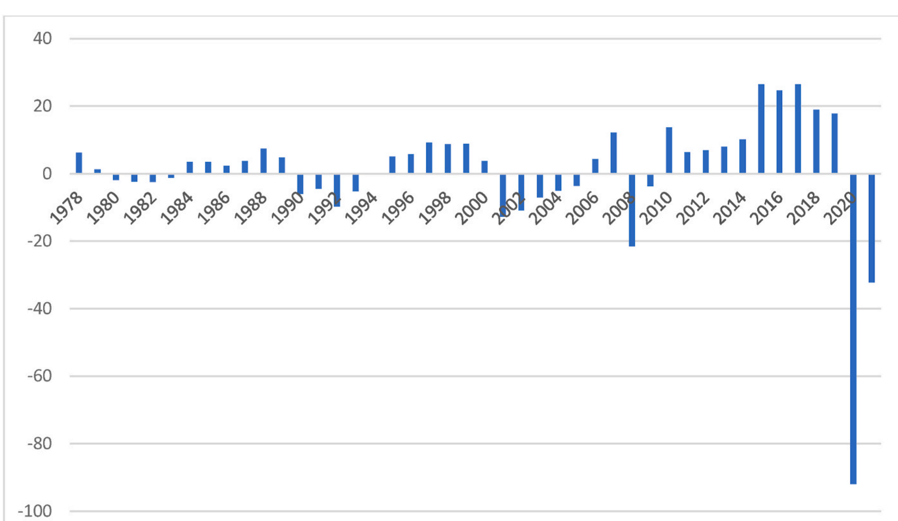


**Fig. 1.** Real net commercial airline profits, in billion US$$_{2000}$.
Source: IATA (2022); ICAO (Statistical Yearbook, 1978–2002); ICAO (Annual Report of the Council, 2011–2020); Jiang and Hansman (2006).

unlikely to bring aviation on a trajectory aligned with 1.5 °C or 2.0 °C goals, as a commercial service entry is deemed unlikely before 2050 (Waddington et al., 2021). Further challenges arise out of the need to store hydrogen in fluid form in high-pressure tanks, with implications for aircraft seize and available space (Huete et al., 2021). The technology has advantages, such as the comparably low conversion losses from electricity to hydrogen (electrolysis), which are significantly higher in the case of synthetic fuels (Schemme et al., 2020; Schmidt et al., 2018; Yao et al., 2020). However, major disadvantages are the need to redesign all types of aircraft, and to build new, additional infrastructures for production, distribution, and bunkering. Hydrogen may thus be seen as a longer-term option for reducing emissions. This is equally true for hydrogen-electric aircraft (Nicolay et al., 2021), though these aircraft would also reduce non-$CO_2$ emissions.

Sustainable aviation fuels (SAF) are a third option. SAF are particularly suitable for the transition, because they can replace conventional jet fuels without requiring new infrastructure (airports and aircraft). For various SAF, it is feasible and legal to blend these with conventional jet-fuel. SAF potentially comprise a wide range of fuels, including biogenic (biomass-based) fuels derived from plants, and non-biogenic synthetic fuels that are chemically engineered (Dahal et al., 2021). Sustainability implications of biomass-based fuels are complex (Darda et al., 2019; Nazari et al., 2021): biomass-based fuels appear to reduce non-$CO_2$ effects (Grewe et al., 2021), but they are far from net-zero in terms of $CO_2$. Synthetic fuels have a lower carbon content, if electricity is sourced from renewable sources. Yet, synthetic fuels also require a greater electricity input and are not currently available in more than experimental stages. They are produced through a process involving electrolysis converting water and $CO_2$ into syngas and jet fuel through Fischer-Tropsch synthesis and refinery (Dahal et al., 2021). The process uses atmospheric or captured $CO_2$, and is carbon neutral if carbon-free electricity is used. All alternative fuels will require new production infrastructure, but can feed into existing distillation, distribution and storage. Production cost is a major barrier, with estimates of direct operating costs for biomass-based fuels being 15%–500% higher than for conventional jet fuel (Dahal et al., 2021). The lowest cost has been found for wheat grain, forestry residues and wheat straw. For non-biogenic synthetic fuels, market entry prices are expected to be two and up to six times higher than conventional jet fuel (Schmidt et al., 2018).

There is consequently considerable debate regarding new technologies, low-carbon fuels, and their cost. While some scenarios suggest that emission reductions can be achieved in principle, barriers have been acknowledged: Klöwer et al. (2021) find that zero-carbon fuels have to replace conventional fuels at 5.8% per year, if emissions are to be reduced by 90% by 2050 under a continued growth scenario. Gössling et al. (2021) discuss the implications of fully replacing fossil fuels with non-biogenic synthetic fuels in a scenario combining a 3% per annum feed-in quota requirement with a carbon tax. They show that technology scalability represents a major barrier to synthetic fuels. This is in principle acknowledged by Dray et al. (2022), who run different combined pathway scenarios (biofuels and hydrogen/power-to-liquid), concluding that production will require a significant expansion of (zero carbon) power sources, with power-to-liquid and hydrogen having a very limited scale-up potential before the 2030s. Dray et al. (2022) conclude that efficiency gains and contrail avoidance could reduce lifecycle $CO_2$ emissions by 89–94% to mid-century, notably accommodating a 2–3 fold growth in demand between 2019 and 2050. Even though Dray et al. (2022) estimate production investment costs to be up to US$_{2020}$1.8 trillion in the period 2025–2050, the cost of airfares is expected to increase by only 15%. In Grewe et al. (2021), changes in load factors, seat density, operational efficiencies in combination with scenario runs including “current technology”, “late technology advancements”, and “continuous technology advancements” achieve a reduction to continuous $CO_2$ emissions of about 1 Gt $CO_2$ annually. How these are going to be eliminated is unclear, as reference to the European Union’s Flight Path 2050 (EC, 2012) is unspecific on strategies.

A general conclusion in this line of research is that aviation will not meet its climate goals unless very significant barriers of technology adoption and fuel transition are overcome. Legislation is required as airlines will not invest in sustainable aviation fuels, as long as these represent an additional cost in a highly competitive market. This legislation will not be presented by ICAO, and depends on national policy initiatives that are unlikely. Even though Dray et al. (2022) find the difference in the cost of alternative fuels to be small in 2050, these are initially far more expensive (10–20 times in 2020). The only significant policy initiative at this point is the European Union’s Refuel initiative outlining a 6% SAF target in 2030, which is too little in view of the remaining carbon budget, yet perhaps even too ambitious in production-upscaling terms. Overall, this suggests major roadblocks to optimistic scenarios (e.g. Dray et al., 2022).

It is also worth noting that with the exception of Gössling et al. (2021), none of the scenarios presented by e.g. Dray et al. (2022) or Grewe et al. (2021) includes a $CO_2$ price. $CO_2$ represents a cost that should be internalized (Stern and Stiglitz 2021). A carbon price will also limit growth rates (Fageda and Teixidó 2022; Falk and Hagsten 2019), which is of importance considering the significant share of flights made simply because they are cheap (Gössling et al., 2019). A carbon price has the added effect of narrowing the cost gap between Jet A and SAF, making their market introduction more attractive (Teusch and Ribansky 2021). This paper does for this reason provide a combined approach, i.e. it calculates the cost of replacement fuels in combination with taxation.

## 3. Method

### 3.1. Context

Calculations focus on fuels that can immediately replace Jet A, i.e. biomass-based fuels (used cooking oil, agricultural or forest residues) as well as non-biogenic synthetic fuels. The latter are a technologically basically feasible option, though there apparently exists no running pilot plant at the time of writing (October 2022), and the technology’s upscaling potential remains uncertain. Both fuels may replace Jet A as drop-in fuels, as these become available. The paper uses an established model for air transport fuel transitions (Gössling et al., 2021), and compares a mix of low-carbon biomass-based fuels (based on Graver et al., 2022) with synthetic fuels derived from different energy sources (nuclear, solar, wind). As the production of synthetic fuels requires very significant amounts of electricity, electricity generated from coal or gas is not considered: the carbon content of these sources would exceed the amount of $CO_2$ that can be avoided by using synthetic fuels. Nuclear, solar, and wind are all considered low-carbon electricity sources. Wind has a cost similar to solar, though the cost of solar is anticipated to fall faster in the future (Roser 2021).

Given current uncertainties regarding the rebound in aviation after the pandemic, the model has a starting point in 2025, at which a return to 2019 demand (in revenue passenger kilometers, RPK) is assumed. In reality, this rebound may occur sooner or later, but it only affects the model in the sense that results shift in time by a year or two. The model should be understood as an attempt to identify barriers to the low-carbon transition, and to explore possible net-zero pathways. Should pressure increase on aviation to reduce its emissions, future aviation may use a combination of technologies, as also anticipated by Dray et al. (2022). Irrespective of real-world developments, any technology will face difficulties of market introduction for reasons of prohibitive costs. For this reason, the SAF scenarios presented in this paper illustrate the issue of cost and upscaling barriers. The discussion also considers the carbon budget risks implied in later vis-à-vis earlier reductions, and implications for remaining carbon budgets.

As earlier sections have highlighted, a carbon cost will make alternative fuels more competitive, as these will be exempt from taxation. It will also make flying more expensive, bringing down growth rates (Gössling et al., 2021). The model consequently considers a carbon price for $CO_2$ as well as for non-$CO_2$ emissions, the latter to account for additional radiative forcing with a warming effect that is here considered equal to $CO_2$ (a conservative approximation; Lee et al., 2021). The transition to 100% SAF is integrated over the model period of 25 years, effectively requiring a drop-in quota increasing by about 4% per year to complete the transition by 2050. $CO_2$ price and the cost of SAF production increase the cost of flying, while efficiency gains reduce the cost. The model considers both. Price elasticity assumptions and efficiency gain expectations are derived from industry.

As indicated, the purpose of the model is not to accurately depict the future development of air transport demand, which will depend on a wide range of factors, such as global and national air transport policies (for instance, in regard to a $CO_2$ price), the introduction of drop-in quotas, upscaling feasibility, the mix of technologies employed, global fleet renewal rates, efficiency gains, changes in load factors, aircraft layouts (seat density), the development of business travel demand, as well as overall available seat capacity in the market. All of these influence the cost of air travel, and hence demand; a complexity that is not considered in any of the studies on net zero aviation. The model presented here consequently provides additional insight into the challenges and complexities of the net-zero transition with relevance for industry and policymakers.

### 3.2. Model assumptions

To lower the barrier to a market introduction of sustainable aviation fuels, and given that $CO_2$ represents an environmental cost, conventional fuels can be taxed. As aviation causes warming related to $CO_2$ and non-$CO_2$, the model foresees a price on Jet A that increases from US$50 in 2025 to US$400 in 2050 per ton of $CO_2$. To approximate the warming related to emissions of $NO_X$ and $H_2O$ (non-$CO_2$ effects), the cost is doubled (i.e., the price is US$100 in 2025 and US$800 in 2050) (Gössling et al., 2021). This is likely a significant underestimate of warming effects in comparison to $CO_2$ (Lee et al., 2021). For synthetic and biomass-based fuels, the model only considers non-$CO_2$ effects, as the fuel burn does not generate more $CO_2$ than was already removed from the atmosphere for production. For biomass-based fuels, this balances likely lower contributions to non-$CO_2$ effects (Grewe et al., 2021) and higher carbon content (Capaz et al., 2021). A limitation is that lifecycle and supply chain emissions are ignored, as infrastructures and distribution cannot be assumed to be zero-carbon. The $CO_2$ tax on sustainable aviation fuels (both synthetic and biomass-based) is US$50 in 2025 and US$400 in 2050 per ton of $CO_2$"-equivalent".

Synthetic fuel production entails a cost of electricity, production itself, transport and refinery, which translates into a "total cost" of production. Each of these depends on various factors, such as power source, scale of production, grid-dependence, or transport distances. Three principal power sources can be used, nuclear, wind, and solar. Nuclear power is a stable, reliable power source; wind is the least reliable; sun is reliable in specific locations, but only during day time. Nuclear capacity takes at least a decade to install, wind power several years, solar less than a year. Nuclear is the most expensive power source (US$155/MWh in 2019), followed by onshore-wind (US$41/MWh, no data for offshore available) and solar (US$40/MWh) (Roser 2021). This acknowledges that there remains considerable uncertainty regarding the future cost of production. There is also a trade-off in that wind and solar energy are expected to become cheaper, while nuclear will become more expensive (Roser 2021). In the scenario runs, the cost of the three electricity sources is US$ 0.168 per kWh (nuclear in 2025), US$ 0.038/kWh (onshore wind) and US$ 0.035/kWh (solar). This will increase/decrease to US$ 0.233/kWh (nuclear in 2050), US$ 0.029/kWh (onshore wind) and US$ 0.020/kWh (solar). Note that as a result of the Ukraine war and climate change mitigation efforts, electricity demand is expected to increase substantially globally. Some countries, including France, seek to address this situation by investing in nuclear power. As it may take decades until this power is available, electricity cost may be volatile and increase rather than decrease in the near future. In all scenarios presented in this paper, except business-as-usual, synthetic fuels are introduced in 2024, and their share in total fuel consumption increases by 4% per year.

The initial electricity requirement for producing one kg of synthetic crude is set at 45 kWh (for details see Gössling et al., 2021). The energy input is expected to decline over time, in line with expectations voiced in the literature (Schemme et al., 2020; Schmidt et al., 2018; Yao et al., 2020). The model assumes an electricity requirement of 40 kWh per kg of synthetic fuel in 2025, and 25 kWh in 2050. The total production cost per kg of synthetic crude is US$ 8.46 per kg (nuclear in 2025), US$ 3.29 per kg (onshore wind) and US$ 3.16 per kg (solar); this will decrease to US$ 8.08 per kg (nuclear in 2050), US$ 2.98 per kg (onshore wind) and US$ 2.76 per kg (solar). This considers a $CO_2$ price as outlined. For fossil fuel bunkers, the cost of US$ 0.65 per kg is assumed to be constant, though the $CO_2$ price will increase the overall cost of this fuel from US$ 0.97 per kg in 2025 to US$ 3.18 per kg in 2050. For biomass-based fuels, the average cost for production is derived from the International Council on Clean Transportation (ICCT; Graver et al., 2022). The organization provides a cost estimate for a mix of biofuels including used cooking oil HEFA, and gasified agricultural residues, forest residues and municipal solid waste, for 2030 (US$2.53/kg), 2040 (US$2.27/kg) and 2050 (US $3.03/kg).

General assumptions for the four scenarios include a growth rate in air transport of 4.45% per year (ICAO, 2022), and a demand elasticity of −1 (for details and justification see Gössling et al., 2021). The fuel efficiency is assumed to improve by 1% per year, and a fuel cost projected to represent 24.5% of the operational cost in 2024. All changes are linear in the model, following industry sources. As a limitation, it is acknowledged that demand elasticities are dynamic. For instance, a significant share of air travelers is wealthy, and for some travel (e.g. visiting family), high premiums may be paid.

## 4. Results

Table 1 shows how the aviation system would perform under the outlined assumptions. If the system recovers and continues to grow, commercial aviation will emit 722 Mt $CO_2$ in 2025, and 1.7 Gt $CO_2$ by 2050 (Fig. 2). If a $CO_2$/non-$CO_2$ price is introduced, starting at US$100 per ton and rising to US$800 per ton in 2050, emission growth will be limited to 607 Mt $CO_2$ in 2025, and 780 Mt $CO_2$ in 2050, illustrating the effect of significant taxes on demand. In all scenarios, $CO_2$ emissions fall to zero due to the mandated drop-in quota of 4% per year to fully replace Jet A by midcentury. There is a secondary demand-reducing effect associated with the higher price of fuels. Nuclear power will increase airfares the most, by a factor 3.8, compared to solar, as the cheapest power source, by a factor 1.8.

The difference in the nuclear vis-à-vis the business-as-usual scenario in accumulated $CO_2$ emissions is 25.1 Gt $CO_2$ in the period 2025–2050. This is equivalent to 87% of aviation's remaining carbon budget to 2.0 °C, and underlines the implications of net-zero pathway designs that allow for continued growth, while ignoring taxation. There is an added uncertainty in non-$CO_2$ warming. Should these remain unavoidable for synthetic fuels – and synthetic fuels be used at scale –, effective radiative forcing will continue to increase even though fuels become carbon neutral. Unless ways are found to avoid non-$CO_2$ effects, for instance through flight path alterations (Teoh et al., 2020), costly carbon removal technologies would have to be developed. Biomass-based fuels may make lower contributions to non-$CO_2$ warming (Dray et al., 2022; Grewe et al., 2021), but their availability may be limited and compete with other uses.

Fuel demand can be translated into revenue passenger kilometers (RPK), assuming no changes in average fuel use and aircraft layout, such as reductions in premium class seating to increase seat density. Here, the nuclear power use transition scenario is the costliest option, reducing demand to 4852 billion RPK in 2050, i.e. just a fraction of the 26,312

**Table 1**
Scenario run results.

| | | 2025 | 2035 | 2045 | 2050 |
|---|---|---|---|---|---|
| **Tax** | $CO_2$/non-$CO_2$ tax, US $100 in 2025, US$800 in 2050 (per ton $CO_2$) | 0.32 | 0.73 | 1.67 | 2.53 |
| | Bunker fuel cost (constant at US$0.65 per kg) | 0.65 | 0.65 | 0.65 | 0.65 |
| **Electricity** | Nuclear US$/kWh | 0.168 | 0.191 | 0.218 | 0.233 |
| | Onshore wind US$/kWh | 0.038 | 0.034 | 0.030 | 0.029 |
| | Solar US$/kWh | 0.035 | 0.028 | 0.022 | 0.020 |
| | Synthetic fuel transport, production, margin per US$/kWh | 0.04 | 0.04 | 0.04 | 0.04 |
| | kWh/kg synthetic fuel | 40.00 | 33.14 | 27.46 | 25.00 |
| **Total cost** | Cost 1 kg synthetic fuel nuclear | 8.46 | 8.02 | 7.91 | 8.08 |
| | Cost 1 kg synthetic fuel wind | 3.29 | 2.82 | 2.77 | 2.98 |
| | Cost 1 kg synthetic fuel solar | 3.16 | 2.62 | 2.55 | 2.76 |
| | Cost 1 kg bunker fuel including $CO_2$ tax | 0.97 | 1.38 | 2.32 | 3.18 |
| | Cost 1 kg biofuel | 2.45 | 2.35 | 2.58 | 3.03 |
| **RPKs** | RPKs (billion) BAU recovery 2025 | 8860 | 13,694 | 21,165 | 26,312 |
| | RPKs (billion) synthetic fuel from nuclear | 5688 | 4208 | 4470 | 4852 |
| | RPKs (billion) synthetic fuel from wind | 6954 | 8086 | 10,592 | 12,358 |
| | RPKs (billion) synthetic fuel from solar | 6983 | 8306 | 11,077 | 13,001 |
| | RPKs (billion) bunker (tax) | 7459 | 10,080 | 12,020 | 12,313 |
| | RPKs (billion) biofuel | 7141 | 8690 | 11,157 | 12,428 |
| **$CO_2$ emissions** | $CO_2$ emissions (Mt) BAU recovery 2025 | 722 | 1009 | 1410 | 1667 |
| | $CO_2$ emissions (Mt) synthetic fuel from nuclear | 445 | 179 | 57 | 0 |
| | $CO_2$ emissions (Mt) synthetic fuel from wind | 545 | 344 | 136 | 0 |
| | $CO_2$ emissions (Mt) synthetic fuel from solar | 547 | 353 | 142 | 0 |
| | $CO_2$ emissions (Mt) bunker (tax) | 607 | 742 | 801 | 780 |
| | $CO_2$ emissions (Mt) biofuel | 559 | 369 | 143 | 0 |
| **Airfare** | Ticket price index BAU recovery 2025 | 100 | 100 | 100 | 100 |
| | Ticket price index synthetic fuel from nuclear | 123 | 233 | 333 | 380 |
| | Ticket price index synthetic fuel from wind | 115 | 150 | 177 | 188 |
| | Ticket price index synthetic fuel from solar | 115 | 147 | 170 | 180 |
| | Ticket price index bunker fuel with tax | 112 | 127 | 163 | 195 |
| | Ticket price index biofuel | 114 | 143 | 171 | 190 |
| **Fuel** | Bunker consumption (Mt) BAU | 228 | 319 | 446 | 527 |
| | Synthetic fuel consumption (Mt) nuclear | 6 | 41 | 76 | 97 |
| | Synthetic fuel consumption (Mt) wind | 7 | 80 | 180 | 248 |
| | Synthetic fuel consumption (Mt) solar | 7 | 82 | 189 | 261 |
| | Synthetic fuel consumption (Mt) bunker fuel with tax | 192 | 235 | 253 | 247 |
| | Biofuel consumption (Mt) | 7 | 86 | 190 | 249 |
| **non-$CO_2$ emissions** | non-$CO_2$ emissions (Mt) BAU recovery 2025 | 722 | 1009 | 1410 | 1667 |
| | non-$CO_2$ emissions (Mt) synthetic fuel from nuclear | 463 | 310 | 298 | 307 |
| | non-$CO_2$emissions (Mt) synthetic fuel from wind | 566 | 596 | 706 | 783 |
| | non-$CO_2$ emissions (Mt) synthetic fuel from solar | 569 | 612 | 738 | 824 |
| | non-$CO_2$ emissions (Mt) bunker (with tax) | 607 | 742 | 801 | 780 |
| | non-$CO_2$ emissions (Mt) biofuel | 582 | 640 | 743 | 787 |

billion RPK in the business-as-usual recovery scenario. Nuclear power use is thus the best option to degrow air transport. More growth can be expected in scenarios sourcing electricity from wind (12,358 billion RPK in 2050) or solar (13,001 billion RPK in 2050) (Fig. 3). The cheapest energy source, solar power, would allow aviation transport supply to grow by about 47% over 2019 levels, to about 13,000 billion RPK. In this least costly scenario, airfares will increase by 80% over 2025 in 2050, mostly as an effect of taxation. Figs. 2 and 3 compare differences in growth for $CO_2$ and RPK for the different scenarios, and implications for carbon budgets and global air transport demand.

## 5. Discussion

Findings illustrate complexities in the transition to sustainable aviation. They support the results presented in other papers that biomass-based fuels may at least partially replace Jet A, though there are implications. Given considerable uncertainties regarding the availability and scalability of biofuel and/or synthetic fuels over time, this paper highlights in particular the issue of total fuel demand growth: According to IEA (2022), biomass-based fuel production capacity will be 1.5 Mt in 2023, which can be compared to the sector's 2025 energy demand of 228 Mt (our model). There are also uncertainties in regard to contrail avoidance and non-$CO_2$ warming. Whether total fuel demand increases, remains constant or decreases, will have relevance for net-zero pathways as well as the remaining carbon budgets to 1.5 °C and 2.0 °C. The paper thus does not share the optimism of replacing Jet A under continued growth scenarios as adumbrated by Dray et al. (2022).

An important related question is whether air transport demand is induced or 'real': Proponents of unlimited growth, specifically the manufacturers of aircraft, highlight aviation's economic benefits, equating travel wants with travel needs. COVID-19 has illustrated that this notion is not necessarily correct. Global business continued even when air travel was severely restricted, while global tourism found new equilibria with domestic and inter-regional travel (e.g. Plzáková and Smeral 2022; Wang et al., 2022). The pandemic has also underlined the economic vulnerability of in particular small islands and developing states arising out of the reliance on long-haul tourist arrivals. These issues are not currently discussed, while aviation benefits in particular a small group of frequent fliers (Gössling and Humpe 2020), with very low airfares of the low-cost carriers having limited importance for social equality (Banister 2018).

Findings suggest that progress on transitioning to low-carbon propulsion is unlikely because of the absence of markets for alternative fuels, and a business side of air transport that is characterized by overcapacities, low profitability and debt, in what is an overall financially questionable business model. As the introduction of new fuels – and new technology – will imply a higher cost for air transport that the sector cannot pass on to travelers without degrowing the system, it is difficult to see how the sector will transition under a continuation of the current growth model. For airlines, a model with different supply-demand ratios would seem desirable, as profitability will increase where growing demand meets a stable supply.

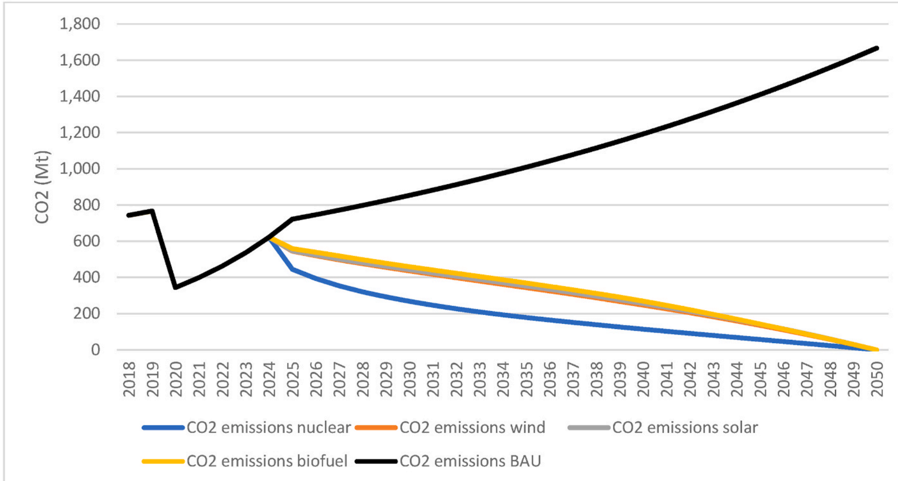


**Fig. 2.** Emissions of $CO_2$ under different scenarios.

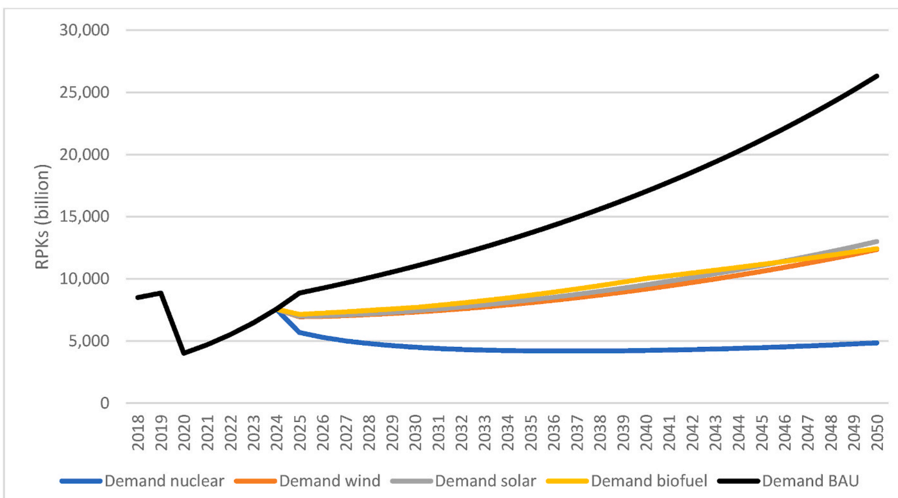


**Fig. 3.** RPK growth under different scenarios.

Apart from this central discussion point for climatically sustainable aviation, the model runs also point to the need to immediately invest in new fuels and technologies, as opposed to investments in carbon offsetting or carbon removal strategies. To achieve this, significant amounts of biomass and renewable electricity will have to be made available, and markets for new fuels be established. This will not happen without policy interventions, such as mandated drop-in quotas as under the European Union's Refuel initiative. Policy considerations of relevance have been discussed by Lyle (2018), Gössling and Lyle (2021) as well as Panoutsou et al. (2021).

Seen against these complexities, a different aviation model is warranted, characterized by lower transition risks due to lower growth rates, a more limited increase in fuel demand, a credible and reliable fuel transition, and improved efficiencies in the system. With regard to the latter, there seems very limited discussion of load factors or seat densities, for example. Increasing load factors reduces the gap between RPK and ASK; reducing premium class seat shares makes available capacity. The transition to a net-zero pathway is characterized by considerable complexity that remains unexplored, though it is in stark contrast to green narratives on sustainable aviation futures as spread by airlines (Guix et al., 2022).

## 6. Conclusions

This research is similar to other modelling in that it seeks to explore pathways to net-zero aviation. However, this paper has a starting point in the assumption that a transition to net-zero requires Jet A to be replaced with sustainable aviation fuels, as the only currently available option to reduce the sector's emissions within existing supply chains and infrastructures (airports and aircraft). In contrast to other papers, the implications of continued growth and the aviation sector's business model have been under specific scrutiny. In concluding that limiting growth is of relevance regarding the availability and scalability of alternative fuels, as well as the overall transition challenge in terms of fuel requirements, it is argued that a carbon tax reflecting on the cost of emissions needs to be introduced. The overall effect is that the transition to net zero becomes more credible and achievable, though it comes at the cost of curbing growth rates. This is not necessarily an issue, given that much air travel is characterized by wants rather than needs, induced by low and declining airfares, and concentrated in a small group of very frequent fliers. A new business model for aviation will lead to new equilibria in global travel, possibly aligning net-zero pathways with profitability for airlines.

## Author statement file with CRediT roles

Stefan Gössling: Conceptualization; Methodology; Formal analysis; Writing-Original draft preparation, Andreas Humpe: Conceptualization; Methodology; Data curation; Formal analysis; Visualization; Writing - review & editing.

## Declaration of competing interest

None.

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