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Pathways towards 90% decarbonization of aviation by 2050

Demand for aviation will increase by 2–3-fold by 2050. Nonetheless, 90% decarbonization compared with 2019 can be achieved by continued efficiency gains in aircraft and operations, and by the use of ultra-green fuels derived from biomass or clean electricity. Achieving this decarbonization goal will require an increase in airfares of up to approximately 15%.

This is a summary of:
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The problem

In 2019, global aviation generated approximately 1 billion tonnes of CO_2, or 2.7% of all energy-related CO_2 emissions, which is nearly twice the amount released by the entire UK economy. Furthermore, warming from contrails is of similar magnitude to that from aviation CO_2 emissions, and thus greatly increases the climate impact of aviation[1]. Reducing the climate impact of this sector is particularly challenging owing to its high growth rate and long-lived assets, as well as the importance of non-CO_2 climate impacts and the absence of commercially available, scalable zero-carbon or carbon-neutral technology. Despite these challenges, aviation, along with other sectors, needs to decarbonize by mid-century to keep the global average temperature increase to below 2 °C, as required by the Paris Agreement.

The solution

We attributed the greenhouse gas emissions of the aviation sector to their key determinants — that is, aviation demand, the energy intensity of the air transportation system and the climate impact of aviation fuel supply and combustion — and explored the techno-economic characteristics of the mitigation options that might become available before 2050. These options include improvements in aircraft fuel efficiency, enhancements in air traffic control, operational measures[2], alternative fuels with low lifecycle CO_2 emissions[3] and contrail avoidance[4]. To evaluate these mitigation options, we used an integrated aviation systems model with nine aircraft size classes that simulates traffic between 1,169 airports, the associated flight schedules, technology uptake, local and global emissions, and other attributes, while considering the impact of changing airfares on demand[5].

Our projections indicate that market forces will continue to have an important role. Baseline 2050 CO_2 emissions will be reduced by approximately 30% through the introduction of more fuel-efficient aircraft and operational practices. These reductions will happen in the absence of CO_2 mitigation policies because they are cost effective under today's economic conditions. Additionally, 2050 CO_2 emissions would need to be reduced by approximately 50% through the use of synthetic fuels, initially biofuels, and later complemented by power-to-liquids (PTL) or liquid hydrogen. Because these fuels will remain more expensive than crude-oil-based jet fuel, investment incentives will be needed. The remaining 10–20% of 2050 CO_2 emissions would be reduced through a decrease in demand associated with higher airfares due to the synthetic fuels. These measures mitigate approximately 90% of CO_2 emissions, compared with 2019 levels, but contrail avoidance would also be required to avert the other half of the warming from aviation (Fig. 1a).

The implications

Because less than three decades remain for developing the alternative-fuel infrastructure, policies are needed now to stimulate the vast investments required for commercializing and building commercial-scale synthetic-fuel plants and the underlying renewable-power-generation system (Fig. 1b). To fund the transition towards a net-zero-carbon aviation system, ticket prices would ultimately need to increase by up to approximately 15%. Nonetheless, the aviation sector will continue to grow in a net-zero world, albeit at slightly lower rates than it would do otherwise. Although CO_2 emissions can be nearly eliminated by efficiency gains and synthetic fuels, contrail avoidance is key to controlling most of the non-CO_2 effects. Studies are ongoing to investigate this aspect, with some indicating the potential to eliminate most contrail-related warming in exchange for a 1–2% increase in fuel burn[4]. (We applied a conservative approach that focused on the introduction of synthetic fuels.) As most of the remaining climate impacts are due to contrails, this area needs considerable research with respect to both improving the scientific understanding of contrail and contrail-cirrus formation, particularly for liquid hydrogen aircraft and alternative fuels, and demonstrating and quantifying the costs and benefits of contrail avoidance.

The next steps in our research will address the opportunities and challenges of contrail avoidance and aim to reduce the uncertainties in technology costs, particularly in direct air capture, which is needed for PTL production. Moreover, we plan to better understand changes in consumer behaviour and the willingness to pay for green aviation, particularly in rapidly developing economies, to model the aviation sector with increased heterogeneity to explore niche markets for the uptake and scale-up of disruptive zero-carbon technology, and to explore the most promising emissions mitigation policy regimes.

Andreas W. Schäfer[1] and Steven R. H. Barrett[2]
[1]University College London, London, UK.
[2]Massachusetts Institute of Technology, Cambridge, MA, USA.

EXPERT OPINION

"This is indeed a very relevant, well written and interesting paper. Few previous studies include both different fuel pathways and non-CO_2 impacts. It provides an image of a technologically possible future that combines increasing air travel with reaching the climate targets; however, it would require a global regulatory framework, which does not yet show any sign of materializing." **Jörgen Larsson, Chalmers University of Technology, Gothenburg, Sweden.**

FIGURE

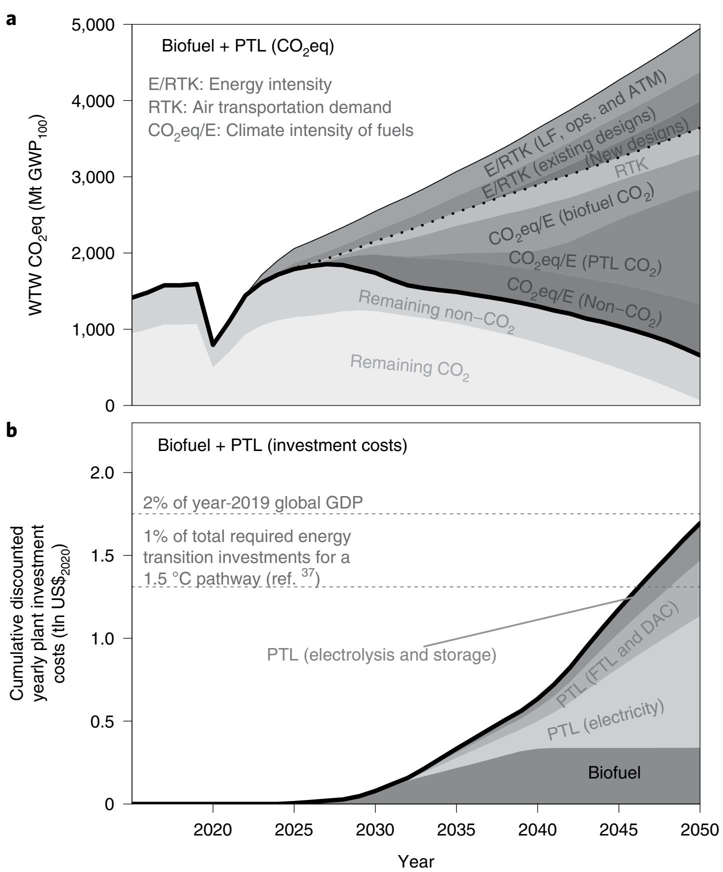

Fig. 1 | Model outputs for the combined biofuels + PTL pathway towards net-zero climate impact in 2050. **a**, Reduction in emissions in terms of CO2 equivalents (CO_2eq) derived using GWP100 by type of mitigation strategy. **b**, Cumulative discounted plant investment costs. (See linked paper for details of ref. [37].) ATM, air traffic management; DAC, direct air capture; E, energy; FTL, Fischer–Tropsch liquids; LF, load factor; ops, operational mitigation measures; RTK, revenue tonne-kilometres; WTW, well-to-wake. © 2022, Dray, L. et al.

BEHIND THE PAPER

Although not completely unexpected, the vast scale of global air transportation becomes apparent when trying to identify synthetic fuels that could potentially substitute crude-oil-based jet fuel. Replacing the amount of jet fuel consumed in 2019 with either liquid hydrogen or PTL would require around a quarter of the total electricity produced globally in 2020 to produce the synthetic fuel. And this percentage is only going to grow with the projected strong increase in aviation demand. The enormous scale of this task evidences the need for drastic improvements in the fuel efficiency of the air transportation system. **A.W.S. and S.R.H.B.**

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   This paper presents the integrated aviation model used in our study.

FROM THE EDITOR

"This paper provides a comprehensive analysis of the feasible mitigation pathways for the aviation sector, which is an important aspect of future decarbonization. This work stands out, with the help of an integrated aviation systems model, because it incorporates various factors, from socio-economic change to technological progress, that could impact the emissions of the aviation sector. Furthermore, it examines the potential non-CO_2 impacts together with different pathways, which is novel in the field." **Editorial Team, *Nature Climate Change*.**