

# Air traffic growth jeopardises European aviation's climate mitigation despite substantial potential of hydrogen

Corresponding Author: Mr Thomas Arblaster

**This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.**

**Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.**

Version 0:

Decision Letter:

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Dear Mr Arblaster,

Your manuscript titled "Decarbonising aviation does not imply successful climate change mitigation" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

To meet the editorial threshold in the revised manuscript, it is recommended that novel, well-substantiated insights into decarbonization and hydrogen's role in sustainable aviation in Europe be presented, grounded in clearly defined study objectives. Additionally, detail the data and methodology, describe selected scenarios and assumptions, clarify technology readiness and scalability, and include a sensitivity analysis.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

**When resubmitting, please provide a point-by-point response to the reviewers' comments.** Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Pallav Purohit, PhD  
Editorial Board Member  
Communications Earth & Environment  
[orcid.org/0000-0002-7265-6960](https://orcid.org/0000-0002-7265-6960)

Martina Grecequet, PhD  
Senior Editor  
Communications Earth & Environment

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## REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

### 1. General feedback

This paper offers an original and rather novel approach using pLCA for assessing the sustainability of aviation decarbonisation scenarios. It addresses several mitigation levers including alternative aviation fuels (AAF). The paper offers a clear introduction with a consistent state of the art. The results and discussions are interesting and appropriate. A comprehensive method section allows a good understanding of the methodological choices, assumptions made, and models used.

I thank the authors for the quality of the paper. I only provide minor comments for improving the paper and answering to some questions. As a consequence, I recommend to the editor a publication of this paper in Nature Communications Earth & Environment after these small modifications.

### 2. Major comments

No major comments.

### 3. Minor comments

Abstract

- L9: "unprecedented" could be replaced by "novel" (or something else) because other papers already used similar approaches (e.g. Sacchi et al.).

Introduction

- L52: I think the following reference is appropriate in the context of pLCA and aviation feel free to include it or not (just for information): Pollet, F., Planès, T., & Delbecq, S. (2024, September). A Comprehensive Methodology for Performing Prospective Life Cycle Assessments of Future Air Transport Scenarios. In 34th Congress of the International Council of the Aeronautical Sciences.

- L57: I don't understand why you put on the same level offsetting and narrow technological solutions, the latter seems to me to be on the same level as AAF (promising but uncertain).

- L60: you should mention that you will limit your LCA to climate change indicator in the main paper.

#### Results

- L92: the 70% reduction is not clear (in particular when air traffic is compared in Figure 2).

- The reading of the Results – Climate impacts section can be complex because the scenarios are introduced after the results. I think you should invert Figure 1 and Figure 2 (and associated text) for allowing a clear structure (first the presentation of the scenarios, then the results from a climate point of view).

- Figure 3a: why do you use a little bit more fossil kerosene in ReFuelEU with H2 aircraft than in ReFuelEU without H2 aircraft?

- L117: the terms “low-end” and “high-end” are not clear for identifying the scenarios.

- L142: I think you should rephrase the sentence for mentioning the CO<sub>2</sub>-response only.

- L144: the offsetting of the overshoot should be detailed (not so easy to compare cumulative radiative forcing).

#### Discussion

- L165: probably bad reference for the figure (1a instead of 3a).

- L167: probably bad reference for the figure (1b instead of 3b).

- L171: probably bad reference for the figure (1b instead of 3b).

- L183: I do not understand how you demonstrate your fact using Supplementary Figure 7.

- L171: probably bad reference for the figure (3 instead of 2).

- L190: I disagree with the fact that biofuel would likely increase the climate impact, indeed it depends on a lot of factors (biofuel feedstock, biofuel pathway, electricity for e-fuels...). I would rather suggest that the impact of biofuel on climate is also uncertain.

- L199-203: feel free to also cite or not (just for information) the following reference already used in your report which deals with your discussion: Delbecq, S., Fontane, J., Gourdain, N., Planès, T., & Simatos, F. (2023). Sustainable aviation in the context of the Paris Agreement: A review of prospective scenarios and their technological mitigation levers. *Progress in Aerospace Sciences*, 141, 100920.

#### Methods

- L223: feel free to cite or not (just for information) these two recent papers using a pLCA method such as your paper and Sacchi et al.

o Pollet, F., Planès, T., & Delbecq, S. (2024, September). A Comprehensive Methodology for Performing Prospective Life Cycle Assessments of Future Air Transport Scenarios. In 34th Congress of the International Council of the Aeronautical Sciences.

o Planès, T., Salgas, A., Pollet, F., & Delbecq, S. Simulation and analyses of ICAO transition scenarios using the AeroMAPS open-source framework. In *Towards Sustainable Aviation Summit 2025*.

- L245: probably bad reference for the figure (1a instead of 3a).

- L247: probably bad reference for the figure (1b instead of 3b).

- L284-L289: Table 1 rather than Table 2?

- L290: “optimistic”, the current load factor is higher than 80%, I would use another term than optimistic.

- L297: it could be nice to add a kind of compound annual growth rate for the two air traffic forecast from EUROCONTROL.

- L313+: probably other mistakes on Figures and Tables...

- L464: why didn't you split the NO<sub>x</sub> emissions into two terms (short-term ozone and long-term methane) for using two different durations?

#### Others

- The supplementary information provides a comprehensive in-depth study and the open source code is worthy to note.

- Figure 6: I'm surprised by the low impact of NO<sub>x</sub> emissions, do you have an explanation?

#### Reviewer #2 (Remarks to the Author):

Please, see attached comments.

#### Reviewer #3 (Remarks to the Author):

The manuscript examines the role of hydrogen in enabling commercial aviation to align with European aviation climate targets. This is a timely and relevant topic with substantial societal implications, as hydrogen will likely play an important role in fueling aviation in climate-compatible ways. The introduction nicely frames the importance of these technologies towards reaching climate-compatible aviation. The utilization of a ‘light’ climate model to evaluate the impacts of these scenarios constitute an advantage over the status quo. In general, the model is constructed dutifully and with attention to plenty of details.

However, the scenario choice is quite confusing and badly explained and justified in the main text, which leads to some confusions in interpreting the results and extracting valuable insights on the impacts of different aviation pathways. All details can be found in the file attached.

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Decision Letter:

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Dear Mr Arblaster,

Your manuscript titled "Decarbonising aviation does not imply successful climate change mitigation" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Pallav Purohit, PhD  
Editorial Board Member  
Communications Earth & Environment

Martina Grecequet, PhD  
Senior Editor,  
Communications Earth & Environment  
Consulting Editor  
Communications Sustainability

#### REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for your detailed responses and updates to the paper. I believe it will be a valuable addition to the community. I recommend its publication.

Reviewer #2 (Remarks to the Author):

(Also attached)

COMMSENV-25-0747A  
Decarbonising aviation does not imply successful climate change mitigation

I appreciate the changes to the original manuscript, and the responses to reviewers' comments! The manuscript reads much smoother now, and I have only two concerns remaining, and some smaller comments.

##### 1. Title not supported by findings:

One concern relates to the title, which I think (while catchy) does not fully represent the authors' findings. If aviation used net-zero fuels, then its climate impacts would be minimal to none (depending on the non-CO2 effects of AAF). It is not that decarbonizing aviation does not achieve climate change mitigation, but rather that the ReFuelEU scheme is not enough to meet net-zero in the short term. In the abstract, the authors state "Although alternative fuels can greatly reduce CO2 emissions and non-CO2 impacts—with hydrogen-powered aircraft yielding the largest reductions—persistent air traffic growth drives the near-term use of fossil resources and the long-term scale of non-CO2 effects." So decarbonizing aviation does contribute to climate change mitigation, it is just not enough to meet net-zero targets from IATA in the short-term because demand is growing fast and we are not scaling these fuels fast enough—even in the ReFuelEU mandates the scaleup takes decades. So, I find the title to be too general and misleading. Another suggestion could be something like: "Hydrogen is not enough to meet net-zero aviation targets in Europe", or "ReFuelEU implementation would still lead to high emissions from aviation in the short-term", or something that's more specific to the authors' analysis. The authors are free to pick the title they prefer, but the current one I think is misleading.

##### 2. Authors' suggestion in discussion for demand reduction:

The second concern relates to the authors' suggestion that the solution is to reduce demand for aviation. While it is true that in their scenarios only degrowth meets CORSIA, a different policy suggestion derived from this study could be to more aggressively deploy AAFs, which would reduce the carbon intensity of the fleet, and thus potentially meet climate targets. What the authors are finding is that the current ReFuelEU scheme is not compatible with other CORSIA-IATA net-zero targets—but not necessarily that demand must decrease. Again, this feels like an opinion of the authors, which I can agree with, but it is not supported by their findings (but rather a scenario choice). Maybe on line 416 the authors could say "in light of these considerations and in absence of any modification to the ReFuelEU program, the adoption of measures to limit or reduce air travel could be effective in reducing...". The authors could also highlight alternatives (like trains), and bring in the importance of these services to be lower cost to aviation, and as efficient as possible (the authors never mention any alternative to flying).

##### Smaller comments

- Line 114: air traffic volumes "derived from NNNN". This may be a good place for authors to note what they assume future aviation demand is (which the methods state as EUROCONTROL, I think).
- Figure 1: why does the schematic include 3 air traffic volume scenarios (high, low, degrowth) but the figure includes four (adding base growth)? This is confusing, so if base growth is not used in their analysis I suggest the authors drop it.
- Line 145: Do you mean to eliminate fossil kerosene by 2050? Shouldn't it be 2060? By 2050 you have reduced it by 70%, and then you assume that by 2060 you have reduced fossil kerosene by 100% (at least that's what I see in Figure 1c).
- Line 211-212: "We assume that the initial introduction of hydrogen-powered aircraft is limited to narrow-body aircraft

servicing intra-European flights”: Maybe the authors here could just put what percent of European flights are “intra-European” and which ones are extra-European? I think it would be helpful to see the split, as it matters for fleet composition. (I see comes later in the Methods on Table 2, but it may be useful to add the percentages in this instance so that the reader has a general idea of the split).

- Line 231: I recommend the authors use the “non-drop-in AAF” in panel b, as this is easier to follow than “excluding drop in AAF”. Are the lighter shades in panel b in Figure 3 showing the amounts to hydrogen used to power hydrogen-planes? I think so, so just saying “non-drop-in hydrogen” or something like this is more intuitive.

- How do the authors estimate temperature impacts? It may be worth noting when authors introduce their results on line 270 “Climate impacts”. The authors explain in their methods the use of GWP, maybe they can add a simple sentence in line 270 to note this.

- There is some formatting issue in page 10 of the supplementary material (below supplementary figure 8), and some figures are hard to read (as if the resolution was not good enough. I am not sure if this was just happening to the version I opened, but it is worth double checking).

- There are also issues with the references at the bottom of SI.

#### Reviewer #3 (Remarks to the Author):

I would first like to thank the authors for carefully addressing the (plentiful) comments they received and for not shying away from substantial revisions to the manuscript. I think the changes they implemented have done a great deal in advancing the quality of the manuscript. In particular, the stepwise description of the scenarios increased the readability and clarity of the manuscript, and the results and important conclusions are now clearer both in the abstract and throughout the manuscript. The discussion is also well written and has a broad width of considerations, including justice. I also thank the authors for the kind explanations whenever I misunderstood the original intentions of the manuscript.

Below, I make some small editing suggestions:

Abstract – line 10: I would flip the sentence to emphasize a bit more the takeaway “We find that the adoption of alternative fuels alone does not guarantee abiding with climate targets, since their contribution to temperature change can widely vary (2.2 ...) and they can exceed CO<sub>2</sub>-based targets.”

Introduction – line 33-34: Here the discussion revolves only around offsets, without differentiating between traditional carbon offsets and carbon removals. I acknowledge the response to my comment 9 and the decision to not tackle in detail the shortcomings of offsets. But since the manuscript completely dismisses offsets AND carbon removals, it needs a short justification of why. I would argue here that the main argument against offsetting is not just that it does not deliver the promised reductions in atmospheric GHGs, but that we need a paradigm of true compensation of the climate impacts of aviation. This is guaranteed only by permanent carbon removals, and not by offset credits from emission avoidance or reduction projects. If the case against carbon removal is rooted, as argued in the response to Comment 10 of Reviewer 2, in avoiding the risk of locking the aviation sector into a path that depends on fossil fuels and heavily uses resources, then I would explicitly mention this in the text to legitimize the exclusion of this option from the scenarios explored. If you don't want to go into each of the mitigation options possible and argue why you exclude them, I would then argue as follow: due to its focus on ReFuelEU, this paper focuses on AAFs and excludes other mitigation options such as offsetting, CDR, and contrail avoidance.

Lines 99-109 – This section is great, but I wonder whether is best placed at the end of the introduction. It reads to me more like a conclusion section. I also suggest integrating the numbers in line 100-102 into the abstract (in the sentence “-with hydrogen-powered aircraft yielding the largest reductions-”) as it is a novel and very interesting result which will likely increase the number of citations if flagged already in the abstract.

Figure 1 – It is a bit confusing that in panel a there are three drivers of air traffic volume, but then in panel b) there is an additional air traffic volume scenario (base growth). If base growth is the extrapolation of current growth levels, I suggest either including it as one of the air traffic volume scenarios assessed (e.g., in Figure 2, 3, etc.), or just show it as a dashed grey line in panel (b) and not describe it as a scenario in line 135.

L. 138 – explicitly mention the label of the additional trajectory (I guess it is ‘degrowth’?) to avoid confusion.

L. 140 – briefly explain the difference between ‘optimistic’ and ‘breakthrough’ scenarios of efficiency,

L. 144-145 – It is not quite clear to me, from Figure 1c vs. the text, whether the additional measures are taken after 2050 to eliminate fossil fuels by 2060 (as the orange line in Figure 1c seems to suggest) or the measures are taken by 2050 but the elimination of fossil fuels only is completed by 2060.

L. 243 – I think it would be beneficial early on to explain what is the driver of this difference between the breakthrough and the optimism scenarios – do I understand it correctly that is both the energy demand of and the share of H<sub>2</sub> AC, which is also driven by demand?

Figure 4 and lines 280-295 – I am missing here a paragraph commenting on the air volume growth and efficiency impacts.

From how I read the figure, there are three important take-aways to highlight in this initial section: 1) high growth is always associated with the highest climate impacts, despite having the highest degree of innovation/efficiency; 2) ReFuelEU is preferable to limiting aviation growth in terms of CO2 emissions, but not really in terms of temperature change including non-CO2 effects; 3) H2 AC are preferable to no H2 AC.

L. 322 – “could reduce in ..” I think here was meant either “reduce the impacts” or “results in lower impacts”

Discussion – opening

L. 409 – I think the argument here is not about intergenerational equality, but rather about historical responsibility as well as ‘ability to abate’. Europe has arguably a) a higher historical responsibility in causing aviation-related climate impacts and b) a higher ability to pay for more costly AAFs, which is why it should pursue this strategy rather than plucking low-hanging fruits and prevent developing countries to later access these cheaper solutions.

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# Response to reviewers

Dear reviewers,

We thank you for your feedback. We have carefully reviewed your comments and improved the work accordingly, which has benefited its overall quality. In line with the advice of the editor, this revision includes the following:

- We expanded the introduction to more clearly outline our research objectives. This includes highlighting our focus on ReFuelEU and how we evaluate it against definitions of successful climate change mitigation considering a variety of factors. This framing is extended to how the results are presented and discussed.
- In the 'Methods' section, we now give an overview of modelling requirements which stem from our research objectives. Additionally, we compare these aspects of our work to previous studies. This illustrates the novelty of our work and serves as a summary of key features in terms of its scope and assumptions.
- We have extensively reworked how our model and its results are introduced to the reader. Before, we introduced the scenarios by first discussing their climate impacts. Now, we first explain the concrete meaning of scenario parameters. We make it clear how these are combined into scenarios by giving results for the aviation fleet, then showing how this translates to fuel demands, and finally presenting the results on climate impacts. With this build-up, we give the reader a more comprehensive understanding of our model, its assumptions, and implications for the sector, while still maintaining a consistent narrative.
- An additional sensitivity analysis was performed to contextualise our assumption that alternative fuels reduce the impact of aviation-induced cloudiness. This sensitivity analysis is included in the Supplementary Information alongside our other sensitivity analyses and we refer to it in the main text.
- Following the reviewers' recommendations, several updates were made to the model itself. We updated our air traffic projections according to EUROCONTROL's latest releases, meaning that 2024 is now a 'historic' starting year, rather than starting with prospective traffic. We also adjusted how we perform impact assessment, including splitting NO<sub>x</sub> into its long-term and short-term impacts.

On the following pages are our replies to each of the reviewers' comments. Changes we made to the text are marked in red. This does not cover all changes made, for which the attached document should be consulted.

## Reviewer #1

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### Abstract

Comment 1: L9: “unprecedented” could be replaced by “novel” (or something else) because other papers already used similar approaches (e.g. Sacchi et al.).

Reply: Thank you for addressing this point. In order to avoid hyperbole, we have rephrased this sentence:

‘Our analysis considers the role of hydrogen in decarbonising the aviation system **while incorporating diverse** environmental and socio-technical dimensions.’

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### Introduction

Comment 2: L52: I think the following reference is appropriate in the context of pLCA and aviation feel free to include it or not (just for information): Pollet, F., Planès, T., & Delbecq, S. (2024, September). A Comprehensive Methodology for Performing Prospective Life Cycle Assessments of Future Air Transport Scenarios. In 34th Congress of the International Council of the Aeronautical Sciences.

Reply: Thank you for bringing this work to our attention. We agree that it is relevant to our work and have included a reference to it in our introduction.

Comment 3: L57: I don’t understand why you put on the same level offsetting and narrow technological solutions, the latter seems to me to be on the same level as AAF (promising but uncertain).

Reply: The sentence you’re referring to follows two paragraphs: one introducing the sector’s focus on offsetting and another introducing the sector’s focus on ‘alternative aviation fuels (AAF) and energy efficiency’. It is this second paragraph that we refer to with the term ‘narrow technological solutions’. So indeed, AAF are included in this term.

However, after restructuring the introduction, this sentence was removed in favour of discussing our immediate research objectives.

Comment 4: L60: you should mention that you will limit your LCA to climate change indicator in the main paper.

Reply: The line you’re referring to states that we ‘[quantify] the climate impacts of future European aviation’, without explicitly referring to other impact categories.

It is true that we do quantify other environmental impacts (see Supplementary Figure 9, formerly Supplementary Figure 8). These are briefly included in the discussion and the methods (‘System boundary’). Because our research question centres on climate change specifically, we made the choice to only briefly touch on other environmental concerns, which we believe is made clear in the introduction.

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We hope that you find our reasoning acceptable.

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## Results

Comment 5: L92: the 70% reduction is not clear (in particular when air traffic is compared in Figure 2).

Reply: Thank you for pointing out this confusing statement. We erroneously describe the reduction in yearly RPK to 70% of the 2019 value as a '70% reduction'. After amending this error, the sentence reads:

'[...] air traffic from 2035 onwards remains constant at 70% of the 2019 demand (Figure 1b).'

Comment 6: The reading of the Results – Climate impacts section can be complex because the scenarios are introduced after the results. I think you should invert Figure 1 and Figure 2 (and associated text) for allowing a clear structure (first the presentation of the scenarios, then the results from a climate point of view).

Reply: Multiple reviewers expressed dissatisfaction with the flow and detail with which the scenarios are introduced. We acknowledge these shortcomings and have accordingly reworked the build-up and order in which results are presented. The results now consist of two sections, following your recommendation.

Comment 7: Figure 3a: why do you use a little bit more fossil kerosene in ReFuelEU with H2 aircraft than in ReFuelEU without H2 aircraft?

Reply: Our implementation of ReFuelEU implies that, each year, a certain share of the total fuel demand (in terms of energy content) is satisfied by AAF. Since H<sub>2</sub> aircraft in the BAU and optimistic scenarios have a higher energy demand than contemporary hydrocarbon aircraft (Table 6), their introduction increases the total fuel consumed. This is why both the fossil kerosene consumed (Figure 3a) and the sum of AAF consumed (Figure 3b) are higher in these scenarios. The reverse effect can be seen in scenarios with breakthrough technology, since these scenarios assume that H<sub>2</sub> aircraft require slightly less energy than contemporary hydrocarbon aircraft.

We have considerably expanded this section in order to address such modelling choices and their results. The section now includes:

'[...] introducing hydrogen aircraft increases the total fuel demand. Since ReFuelEU defines a share of AAF, such changes to the total fuel demand influence how much fossil kerosene can be used (Figure 3a).'

Comment 8: L117: the terms "low-end" and "high-end" are not clear for identifying the scenarios.

Reply: You are correct in pointing out that we introduce new terms without adequately explaining them to the reader. We previously referred to the scenario parameter being discussed here as 'technology fuel efficiency' with the values 'breakthrough', 'optimistic', and 'business as usual'. Using these terms to replace the unclear terms, the text now reads:

'This shows that demand plays a significant role in the short term, while the contrast in fuel efficiency of aircraft technology (Table 6) becomes more influential over time. The business-as-usual scenario stabilises fuel use with 0% demand growth, while the breakthrough scenario stabilises fuel use with a year-on-year growth of 2.2%.'

Note that this section diverges from the original in other ways too, following your previous comment and comment 5 by reviewer 3.

Comment 9: L142: I think you should rephrase the sentence for mentioning the CO<sub>2</sub>-response only.

Reply: We want to make it as clear as possible when we refer to all climate forcers considered and when we refer to CO<sub>2</sub> alone. We agree with you that this could be improved in this section. Therefore, we have included clarifications at the start of the section and in the line you referenced. The section now reads:

'We combine the ICAO and IATA targets mentioned earlier into a single annual CO<sub>2</sub> limit (Figure 4a), which does not consider other climate forcers (see 'Methods').'

Comment 10: L144: the offsetting of the overshoot should be detailed (not so easy to compare cumulative radiative forcing).

Reply: Following your suggestion, we have expanded this section to specify the year in which scenarios exceed the budget. We have also included the value of the overshoot by 2070 in the new Supplementary Table 1. The section now reads:

'Figure 4 shows that both the low-growth and high-growth scenarios consistently exceed the combined ICAO/IATA target, overshooting the budget in 2043 and 2038, respectively. In contrast, AAF-powered degrowth scenarios stay below the annual CO<sub>2</sub> target for several decades, helping to offset the overshoot seen between 2045 and 2070 (Figure 4a). As a result, the degrowth scenarios with and without hydrogen-powered aircraft reach the budget in 2067 and after 2070, respectively.'

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## Discussion

Comment 11: L165: probably bad reference for the figure (1a instead of 3a).  
L167: probably bad reference for the figure (1b instead of 3b).  
L171: probably bad reference for the figure (1b instead of 3b).  
L171: probably bad reference for the figure (3 instead of 2).  
L245: probably bad reference for the figure (1a instead of 3a).  
L247: probably bad reference for the figure (1b instead of 3b).  
L284-L289: Table 1 rather than Table 2?  
L313+: probably other mistakes on Figures and Tables...

Reply: You are correct on all counts. Rearranging figures and tables lead to incorrect references, which we apologise for.

With this revision, additional changes have been made to the numbering of figures and tables. All references have been updated to refer to the correct numbering.

Comment 12: L183: I do not understand how you demonstrate your fact using Supplementary Figure 7.

Reply: Supplementary Figure 8 (formerly Supplementary Figure 7) shows a large range of scenarios which assume that the hydrogen used is not purely generated with electrolysis, but through an estimated market mix of technologies, following SSP2 with climate policy in line with the Paris Agreement (Pkbudg1550).

From this figure, one can deduce that the observations made about the scenarios presented in the main text do not hold here, e.g., fewer scenarios achieve the definition of 'climate neutral' used and the CO<sub>2</sub>-exclusive limit is exceeded to a higher degree.

Following your comment, we realise that this interpretation is not obvious to the reader. Therefore, we have rephrased our claim to be more straightforward and refer the reader to comparing two similar figures, rather than assuming they would intuitively know how compare Supplementary Figure 8 to the main text:

'If hydrogen is produced through electrolysis powered by fossil fuels or via steam methane reforming, even with carbon capture and storage, **there is a much smaller reduction in climate impact (compare Supplementary Figure 7 to Supplementary Figure 8)**'

Comment 13: L190: I disagree with the fact that biofuel would likely increase the climate impact, indeed it depends on a lot of factors (biofuel feedstock, biofuel pathway, electricity for e-fuels...). I would rather suggest that the impact of biofuel on climate is also uncertain.

Reply: Thank you for bringing this point to our attention. After reviewing the assumptions on which we based the claim you're referring to, we have come to realise our error and we have rewritten the text accordingly.

The particular claim we initially made—that bio-based AAF are expected to have a higher climate impact than the modelled fuels—was based on comparisons which show that e-fuels from a decarbonised energy system have a moderately lower impact than some bio-based fuels (see e.g. [https://doi.org/10.1007/978-3-030-50519-6\\_4](https://doi.org/10.1007/978-3-030-50519-6_4)). However, on reviewing the literature again, it is clear that bio-based AAF can have a similar or lower impact when considering that these too benefit from decarbonising the energy system (see e.g. <https://doi.org/10.1021/es500191g> and <https://doi.org/10.1016/j.fuel.2022.127316>).

The point we aimed to make is that, across scenarios presented in the main text, the climate impact caused by AAF production is very low (due to the assumptions made) and that we consider it unlikely that introducing bio-based AAF could reduce this much further. We have

therefore updated this part of the text to reflect this aim while more accurately portraying the relative impact of bio-fuels compared to e-fuels.

‘Depending on the particular feedstocks and fuel production pathways, e-fuels and bio-fuels can have similarly low climate impacts once fossil fuels are largely phased out<sup>25,47,62</sup>. We therefore expect that the exclusion of bio-based AAF from our analysis has a limited influence on the discussion of overall climate impacts.’

Comment 14: L199-203: feel free to also cite or not (just for information) the following reference already used in your report which deals with your discussion:

- Delbecq, S., Fontane, J., Gourdain, N., Planès, T., & Simatos, F. (2023). Sustainable aviation in the context of the Paris Agreement: A review of prospective scenarios and their technological mitigation levers. *Progress in Aerospace Sciences*, 141, 100920.

L223: feel free to cite or not (just for information) these two recent papers using a pLCA method such as your paper and Sacchi et al.

- Pollet, F., Planès, T., & Delbecq, S. (2024, September). A Comprehensive Methodology for Performing Prospective Life Cycle Assessments of Future Air Transport Scenarios. In 34th Congress of the International Council of the Aeronautical Sciences.
- Planès, T., Salgas, A., Pollet, F., & Delbecq, S. Simulation and analyses of ICAO transition scenarios using the AeroMAPS open-source framework. In *Towards Sustainable Aviation Summit 2025*.

Reply: Thank you for sharing this informative work. We have included references to it where appropriate, including the expanded ‘Modelling requirements and comparison to previous work’ section (see our reply to comment 12 by reviewer 3).

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## Methods

Comment 15: L290: “optimistic”, the current load factor is higher than 80%, I would use another term than optimistic.

Reply: Thank you for pointing this out. We have corrected the line in question:

‘A generic seat occupancy of 80% is assumed. This value is **in line with historic trends**<sup>69</sup> but **below aspiration goals**<sup>16</sup>.’

Comment 16: L297: it could be nice to add a kind of compound annual growth rate for the two air traffic forecast from EUROCONTROL.

Reply: Following this recommendation and comment 22 by reviewer 3, we now directly mention these values when first introducing the various demand trajectories:

‘We combine EUROCONTROL’s seven-year forecast (up to 2031)<sup>48</sup> and the long-term forecast (up to 2050)<sup>49</sup>. We assume that the long-term year-on-year growth remain representative until 2070, i.e., ‘low growth’ of 0.7%, ‘base growth’ of 1.6%, and ‘high growth’ of 2.2%.’

Comment 17: The supplementary information provides a comprehensive in-depth study and the open source code is worthy to note.

Reply: Thank you for this positive comment.

Comment 18: L464: why didn't you split the NO<sub>x</sub> emissions into two terms (short-term ozone and long-term methane) for using two different durations?

Figure 6: I'm surprised by the low impact of NO<sub>x</sub> emissions, do you have an explanation?

Reply: Thank you for bringing this to our attention. Indeed, our approach to impact assessment resulted in a very low contribution of NO<sub>x</sub> when compared to literature using other methods. We have therefore switched to a different approach, which we describe in the updated 'Impact assessment' section of the 'Methods'. Following this approach (which splits NO<sub>x</sub> into short-term and long-term effects), the impacts are more in line with their expected contributions.

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## Reviewer #2

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### Clarity

I think the authors could improve the clarity of their paper by:

1. Changing the order of the figures (and referring to them correctly)
2. Introducing the nine scenarios before the results (as well as its numerical assumptions)
3. Better explaining the methodology—both briefly in the introduction and more thoroughly in the methods section.

Overall, the introduction is written well, though the last paragraph can use some work to better explain the goals of the manuscript, include the description of scenarios, and shortly explain the methods.

|            |                                                                                  |
|------------|----------------------------------------------------------------------------------|
| Comment 1: | Goals: The two goals of the study (page 3 rows 69-71) are not clearly expressed. |
|------------|----------------------------------------------------------------------------------|

|       |                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Reply | <p>Thank you for your feedback. Accordingly, we have expanded and reworked the introduction to highlight our research objectives. This encompasses the latter half of the introduction, starting from:</p> <p><b>‘We do not yet know how the climate impact of future aviation will develop under influences such as ReFuelEU Aviation, nor how this future will compare to other targets for climate mitigation.’</b></p> |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

|            |                                                                                                                                                                           |
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| Comment 2: | Scenarios: The authors need to explain their scenarios earlier on. Right now, figure 1 has results for scenarios that are only explained in figure 2, which is confusing. |
|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

|       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
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| Reply | <p>Multiple reviewers expressed dissatisfaction with the flow and detail with which the scenarios are introduced. We acknowledge these shortcomings and have accordingly reworked the build-up and order in which results are presented.</p> <p>In doing so, we created a new section between the introduction and the climate impact results, which we carefully structured in order to clearly and transparently introduce the reader to how our scenarios are constructed and what they represent.</p> <p>This section starts with the scenario structure (Figure 1; formerly Figure 2) and how we select the nine future scenarios presented in subsequent figures. Next, we include a new figure about the evolution of the fleet composition under various demand trajectories and the share of H<sub>2</sub> aircraft (Figure 2), followed by the figure on fuel demands (Figure 3). The results shown in both of these latter figures are introduced with a focus on the modelling approach and implications for the sector, including possible limitations.</p> |
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|            |                                                                                                                                                                                                                                                                                                                                                                                        |
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| Comment 3: | Methods: The authors need to explain earlier on how they do their analysis, and also what forms on hydrogen they consider (as an e fuel and as a liquid) and when they get deployed. These assumptions are important, and only come in some fragments of the methods (for example, only in page 13 line 358 the authors specify that they assume hydrogen planes use liquid hydrogen). |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Reply See our reply to your comment 2.

Comment 4: Additionally, the authors describe figure 1, then shortly figure 2, then figure 3, but then the paragraph on CO2 emissions on page 7 row 137 goes back to figure 1. This back and forth is confusing. I suggest resorting figures and to address them in order.

Reply: Following your advice, we have reordered how the results are presented. Figure 1 of the initial submission is now Figure 4 and accompanies all direct discussion of this figure.

Comment 5: In the discussion section the authors keep referring to figure 3 for emissions, when I think they mean figure 1, as figure 3 has fuel consumption amounts.

Reply: We indeed meant to refer to a different figure here. With this revision, additional changes have been made to the numbering of figures and tables. All references have been updated to refer to the correct numbering.

Comment 6: The methodology part is also not clear, and it is hard to understand how the authors get to the results they do. They document their assumptions quite well, but they do not really explain how they use them to create emission trajectories and radiative forcing.

Reply: See our reply to your comment 2.

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## Hydrogen-focus

Comment 7: Focusing solely on hydrogen while ignoring biomass-based fuels may be overly simplistic. It is more likely that a mix of technologies—including biomass-based fuels—will be used to decarbonize aviation. These fuels are more advanced and currently cheaper to produce than hydrogen-powered aircraft or synthetic fuels. Also, it is misleading to state that biomass feedstock is “limited”. The real concern is sustainability, particularly because of its competition for land with food crops, which constraints how much should be used.

Reply: We are aware that our exclusion of bio-based fuels is a limitation. We have expanded our discussion of this limitation in the text and made it more precise (see our reply to comment 13 by reviewer 1):

‘If part of the AAF mix in the presented scenarios were bio-based fuels, hydrogen consumption would decrease. Depending on the particular feedstocks and fuel production pathways, e-fuels and bio-fuels can have similarly low climate impacts once fossil fuels are largely phased out<sup>25,47,62</sup>. We therefore expect that the exclusion of bio-based AAF from our analysis has a limited influence on the discussion of overall climate impact.’

In the second part of your comment, you point out that the main concern regarding the supply of biomass is sustainability. This is correct, and something that should be stated explicitly in the text:

‘Currently, most production methods are based on biomass feedstocks<sup>18</sup>, but the scale at which these feedstocks can be supplied sustainably is limited<sup>20</sup>.’

Comment 8: Furthermore, assuming that hydrogen-based fuels have no other climate impacts, especially in terms of contrails, is an oversimplification. This area is poorly understood and hard to quantify. To be conservative, the authors should assume hydrogen-fueled aircraft have similar non-CO<sub>2</sub> impacts as fossil jet fuel, or at least test this assumption in a scenario (e.g., assuming non-CO<sub>2</sub> impacts are the same vs. lower). See for, for example, Lee et al. 2023 (<https://doi.org/10.1039/d3ea00091e>)  
“Pure bio-based and synthetic SAF have low aromatic content and zero sulphur content. Such fuels would reduce soot number concentrations in the plume (high confidence) and may reduce contrail ERF (very low confidence).”

Reply: Thank you for your constructive comment, but want to point out that we do not assume the non-CO<sub>2</sub> impact of hydrogen-based fuels to be zero. As detailed in the ‘Impact assessment’ section of the methods, we assume that synthetic fuels (including liquid hydrogen) can reduce contrail ERF by up to 65.95%. We also state that this effect is uncertain and that our assumption is relatively optimistic compared to other estimated found in literature.

That being said, your suggestion to include additional scenarios to test the effect of this assumption is excellent. We have included this in Supplementary Figure 6, Supplementary Figure 7, and Supplementary Figure 8. We have added multiple references to this sensitivity analysis in the main text, including:

‘However, when discarding the assumption that AAF reduce contrail impacts, temperature change follows traffic trajectory past 2050 (Supplementary Figure 6).’

Comment 9: This also matters for offsets: how do the authors propose mitigating non-CO<sub>2</sub> impacts of aviation? It is true that offsets have not worked well in the past, but that is not sufficient reason to assume they will not work in the future, especially with technologies like direct air capture, which the authors assume will be fully scalable and operational.

Reply: We directly address contrail avoidance in the ‘Impact assessment’ section of the methods: ‘It must be stressed that the AIC impact of future fuels is a subject of ongoing research, with additional uncertainty added by the possibility of contrail avoidance strategies, which are not covered in this work.’

Furthermore, while non-CO<sub>2</sub> effects have a large impact, they are short-lived, they do not require the same permanent mitigation as CO<sub>2</sub>. We have made additions to the discussion section to reflect this:

‘Still, when understanding the impact of NO<sub>x</sub> and contrails as closely linked with total fuel use and distance flown respectively, there is a limit to the yearly provisioning of AAF-powered air transport within a given sectoral climate budget.’

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We do not claim that it is impossible to offset impacts with carbon removal technologies. Our discussion centres around the conceptual shortcomings of adopting this as the standard solution to climate mitigation. We expand on this in our reply to your following comment.

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### Conclusion (Page 8 line 196)

Comment 10: I believe that both offsetting and fuel switching in European aviation are justified and should even be incentivized. Europe, a wealthier region, would pay more to develop a technology that everyone would benefit from. For example, Germany did this with wind and solar in the early 2000s. While I understand the moral argument for reducing aviation demand when possible (especially for short trips with existing alternatives), I believe the core issue is reliance on fossil fuels. If richer, more developed societies developed (and paid for) the technologies to address this issue, then the developing world would benefit as well (especially since it is in those regions where aviation is growing the fastest).

Reply: We agree with you that the core issue is a reliance on fossil fuels. This is why we consider fuel switching to be indispensable. We also agree that it makes sense for Europe to pioneer this technology. However, since carbon removal technologies do not reduce the reliance on fossil fuels, and require limited resources (e.g., underground space to reliably store CO<sub>2</sub>) to utilise, we do not believe that carbon removal should be a standard component of aviation's climate mitigation strategy in Europe. This does not mean that we argue against its use as a whole, but that we argue for sector-specific targets in Europe which can be achieved without necessarily having to rely on carbon removal. Accordingly, we have made the following addition to the introduction:

'First, the European scope matters. Understanding that access to aviation is distributed highly unequally<sup>38</sup>, we argue that a just transition towards sustainable aviation should be understood differently across regions. To illustrate, Åkerman et al.<sup>27</sup> present a scenario where, within their definition of successful climate mitigation, per capita air travel is around 3,000 km in 2060. Compared to the levels before the COVID-19 pandemic, this represents a tripling of global air travel, yet at the same time almost halving it for the Swedish population<sup>27</sup>. Assuming that commercial aviation will evolve differently across regions, we avoid describing the sector in terms of global trends.'

Comment 11: Also note that the issue with offsets has been their permanence. If permanent removals were used, as well as sustainable aviation fuels, then mitigation climate impacts of aviation would be possible without necessarily changing demand patterns much (see for example (<https://doi.org/10.1038/s41893-022-01046-9>)).

Reply: While we model European aviation without permanent carbon removal, this does not exclude its use. However, as we explain in our previous reply, we argue against targets which presume its use.

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### Other comments

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## Introduction

Comment 12: Page 2 line 36: why use “alternative aviation fuels (AAF)” as opposed to “sustainable aviation fuels (SAF)” which is more common? If the authors prefer AAF they should at least also include SAF – unless they mean something different. Sometimes introducing new terminology makes the debate more confusing.

Reply: We do not use the term SAF because it needlessly confuses the discussion. Our main arguments for this are that:

1. some definitions of SAF include all alternative fuels, while other definitions (such as the one used in ReFuelEU Aviation) define SAF as strictly drop-in alternatives;
2. some definitions of SAF set no requirements for what makes an alternative fuel sustainable, while one would assume that a fuel labelled ‘sustainable’ should be, by some measure, sustainable;
3. definitions of SAF which do set requirements for sustainability are inevitably contentious, as understandings of ‘sustainability’ differ over time and across disciplines – knowing the production and composition of a fuel might not be enough to determine whether it can be labelled as SAF or not, and furthermore, whether the reader agrees with this definition of sustainability.

In contrast, AAF is much less susceptible to alternative interpretation, given that ‘conventional’ aviation fuel is intuitively understood to be fossil kerosene, and that any alternative to that would therefore be an AAF. AAF is also already an established term in the literature (see, for example <https://doi.org/10.1039/C9SE00788A>, <https://doi.org/10.1016/j.scitotenv.2022.153233> , and the even broader concept of ‘Alternative Energy Carrier’ used in <https://doi.org/10.1016/j.paerosci.2023.100920>).

We agree with you that this terminological choice should be clarified to the reader as well. We have therefore rewritten part of the introduction to make it clear that AAF describes aviation fuels other than fossil kerosene, covering both drop-in and non-drop-in alternatives. We also expanded on how ReFuelEU Aviation is introduced in order to clarify how (the EU’s definition of) SAF fits into the picture. The related parts of the introduction now read:

‘In addition to offsetting, aviation industry roadmaps focus on measures centred around energy efficiency **and substituting fossil kerosene with alternative aviation fuels (AAF)**<sup>13–16</sup>. [...] [The] European Union formalised **legal requirements in 2023**, under the so-called ReFuelEU Aviation initiative<sup>17</sup>. **Following this regulation, EU airports must meet a minimum share of AAF in the fuel they supply, increasing from 2% in 2025 to 70% in 2050. This minimum can be met with sustainable aviation fuels (SAF), defined in the EU as drop-in fuels which meet certain sustainability requirements, or with select non-drop-in alternatives to fossil kerosene.**’

Comment 13: Page 2 line 39: briefly explain what ReFuelEU intends to do, what are the targets? (This comes later, but I think it makes more sense at this point).

Reply: See our reply to your previous comment.

Comment 14: As mentioned above, the authors need to include a short description of the scenarios in their last paragraph of the introduction, or at least in the first paragraph of the results (before introducing the results). In Page 4 line 89 the authors briefly state what the assumptions for scenarios are, but do not really explain them. I would add quantifications on the assumptions for energy intensity. Otherwise, it is hard to understand figure 1 when the scenarios have not been introduced.

Reply: We address this in relation to your comment 2.

Comment 15: It is also not clear at the beginning that the authors are analyzing hydrogen as both liquid fuel in synthetic form and as a liquid itself. This was only clear to me after reading the methods.

Reply: We address this in relation to your comment 2.

Comment 16: The authors could also include one sentence on the global aviation sector, just to put the European context into the global picture.

Reply: We now elaborate further on the European context of this study (see our replies to your comment 10 and comment 12).

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## Results

Comment 17: In general, it would be better to include more numerical descriptions when analyzing results

- e.g. "The CO2 emissions from fossil-powered scenarios are comparable to those of AAF-powered scenarios"... by how much? The same applies to other instances

Reply: Following your suggestion, we have added multiple instances of numerical descriptions to the 'Results' section. For example:

'From 2050 to 2070, temperature change reduces by 13-20% for the AAF-powered degrowth scenarios and by 11-18% for those with low growth.'

Comment 18: Figure 1

- Why do all lines start at different values? Shouldn't the historical values all start at the same level, and only diverge in future modeled trajectories?

Reply: Initially, we started all scenarios in 2024, thereby already including diverging results in the first year, since 2024 wasn't in the past yet. We agree with you that a shared starting point is more intuitive to the reader. We have therefore updated our inputs with the historical data for 2024.

Comment 19: - How was the IATA/ICAO line created? Aren't they two different organizations that are not really related to each other programmatically? Why is there just one line?

Reply: You are correct: IATA and ICAO are two different organizations, with different aims and membership. However, both have a vision for how the global aviation sector should meet the Paris Agreement. They are broadly

aligned on the 'climate-neutral growth' concept of CORSIA towards 2035, which IATA has expressed should be followed by a trajectory towards 'net zero' by 2050.

The reader is first introduced to some of these ideas in the Introduction. We then give a detailed description of how our IATA/ICAO line is created in the 'Aviation climate targets' section of the methods. Initially, we did not refer the reader to this section when discussing Figure 4 (formally Figure 1), but we have now amended this (see our reply to comment 9 by reviewer 1).

Comment 20: Figure 2  
- It is also not clear why the first year varies? Shouldn't all scenarios have the same starting historical point?

Reply: See our reply to your comment 18.

Comment 21: Page 5 line 121: how much higher?

Reply: See our reply to your comment 2.

Comment 22: Figure 3:  
- In panel c the dashed lines are confusing. Is "European production" and "EU supply" the same?

Reply: We have clarified the meaning of these lines in the figure's caption:

'This panel also indicates 20% of the European Union's 2030 target hydrogen supply (the total consisting of 10 million tonnes production and 10 million tonnes import)<sup>58</sup> and 20% of European hydrogen production in 2050, following a 'net-zero emissions' scenario (the total being 44 million tonnes)<sup>21</sup>.'

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## Discussion

Comment 23: Page 7 line 165 and line 171: authors point to figure 3, but I think they mean figure 1 for CO<sub>2</sub> emissions

Reply: You are correct. All references have been updated to use the correct numbers.

Comment 24: Page 7 line 166: is it climate neutral or carbon neutral? If the authors are talking about CO<sub>2</sub> wouldn't it be more accurate to refer to it as carbon neutral?

Reply: The line you're referring to concerns climate neutrality and discusses CO<sub>2</sub> emissions within that context of climate neutrality.

Comment 25: Page 8 line 189: how much hydrogen production is projected in Europe? It would be good to have this number in EJ in the sentence, as well as the percentage.

Reply: We have included this in the caption of the figure being referred to in this line. See our reply to your comment 22.

Comment 26: Something missing in the discussion section relates to the challenges of scaling the hydrogen industry, as well as the direct air capture industry, which would make synthetic fuels possible. And another important issue also omitted related to the challenges of replacing infrastructure – going from our current fleet to a fleet powered by hydrogen. What percent of planes by 2070 are powered by what fuels? What would this mean for airport infrastructure? These would be important numbers to pull from the study.

Reply: The questions you raise are important. We have therefore included the corresponding results (see our reply to comment 2 by this reviewer) with the addition of a new figure. The corresponding additions to the text include:

‘Because hydrogen-powered aircraft are introduced to the extent required to meet demand, only a fraction of European airports require hydrogen infrastructure in 2035. However, we do assume that this can extend to all European airports as time goes on, as well as some extra-European destinations after 2050. With these ambitious assumptions, the share of air traffic powered by hydrogen rapidly grows from around 10% in 2040 to over 60% in 2070 (Figure 2).’

Comment 27: Another key missing aspect relates to costs, which the authors should discuss. Currently hydrogen-based synthetic fuels are very expensive and liquid-hydrogen planes are not fully deployed. In their scenarios the authors assume that both of these technologies are fully available, and that may be unrealistic.

Reply: In addition to our discussion of hydrogen-powered aircraft not existing yet and the challenges to their introduction (see also our reply to your previous comment), we now mention the costs of AAF in the results:

‘Some argue that, with projected growth, the energy demand of aviation could become incompatible with the available energy resources<sup>29,36</sup>. Others argue that the higher cost associated with AAF will somewhat slow growth but that further limitations would delay the sector’s sustainability transition by diverting financial resources<sup>13,14</sup>.’

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## Methods

Comment 28: It is unclear whether the authors use 2019 as their last historical period, or 2024. The main text seems to imply it is 2024, but the methods use 2019 (page 10 line 279).

Reply: The section of the methods you’re referring to describes how flight data for 2024-2070 is estimated based on detailed figures for 2019. We have clarified this in the methods:

‘The volume of air transport is estimated by processing flight data<sup>71</sup> from 2019 and **scaling this according to the demand for 2024-2070**.’

Comment 29: The authors could better explain their stock-and-flow model. Do authors assume certain future demand, and then let a model decide which aircrafts fly for how many kilometers, and based on emission factors get

total emissions for aviation? I know they are explaining this process on page 8 row 214, but this was not very clear from reading the paragraph.

Reply: We have included a more detailed description of the model in the results section. See our reply to your comment 2.

Comment 30: Page 8 line 217: what is LWE? This acronym is only explained later, and it is the method the authors use. They need to explain this early on.

Reply: Thank you for pointing out this oversight. However, with this revision we have switched how we conduct impact assessment, so this acronym is no longer used (see our reply to comment 18 by reviewer 1).

Comment 31: Page 9 line 218: regarding previous work, we did a very similar study varying the same parameters than the authors' are varying (namely demand, energy intensity, carbon intensity) which I think the authors could cite, as their study uses a very similar framework but to the European context. (<https://doi.org/10.1038/s41893-022-01046-9>)

Reply: We agree with the relevance of your work. We have included it in our overview of previous work in the section 'Modelling requirements and comparison to previous work' under 'Methods'.

Comment 32: Page 10 line 268: these are not limited measures with little impact. For example, research has found that simply rerouting planes to avoid contrail prone areas would reduce its climate impact. While it is ok not to include these in your modeling, at least acknowledging that these actions could be beneficial is important (for example: <https://doi.org/10.3390/aerospace7090121>)

Reply: We did not mean to imply that contrail avoidance was included among the measures we exclude due to 'limited influence'. We specifically discuss that contrail avoidance could bring considerable benefits:

'It must be stressed that the AIC impact of future fuels is a subject of ongoing research, with additional uncertainty added by the possibility of contrail avoidance strategies, which are not covered in this work.'

To avoid such confusion, we have simplified the line you're referring:

'Several other **possible** measures were not quantified here, **including** increased aircraft replacement rates, improved air traffic management, and the introduction of electric aircraft.'

Comment 33: How about freight aviation? Did the authors include this as well? Or did they just analyze passenger aviation?

Reply: As stated in the 'European aviation and air transport demand' section of the methods: 'To evaluate commercial aviation, the scope is limited to the most common types of flight, being passenger transport on scheduled flights. It can, therefore, be described in terms of revenue passenger-kilometres (RPK).'

Meaning that we use flight data for scheduled passenger flights to approximate the sector, as this covers the vast majority of flight

movements and distance travelled. There will be some quantity of freight being transported on such flights as well, but we choose to describe them entirely in terms of RPK, since this is the main purpose of these flights and a conceptually approachable metric.

Comment 34: Page 11 line 294: What do the authors use to assume hydrogen conversion potential in Table 1? I am not sure this numbers make sense, especially for longer distance flights.

Reply: These numbers are intentionally optimistic (see also our reply to your comment 26). We include a value for extra-European flights based on the theory that wide-body aircraft could be adapted to include hydrogen storage more efficiently than narrow-body aircraft (see e.g. <https://doi.org/10.1016/j.paerosci.2023.100922>).

Comment 35: Also, I think there may be some issues with table numbers. For example, page 10 line 84 should refer to Table 1? Same for Pag 11 line 321 I think (as it refers to share of aircraft with H2 conversion potential)

Reply: You are correct. All references have been updated to use the correct numbers.

Comment 36: Page 13 line 357: do authors assume that hydrogen in planes is liquified? Isn't this very challenging today given the low temperatures needed? I think the authors should touch on this in their discussion section, and write early on which forms of hydrogen they consider in their modeling.

Reply: In the introduction, we state: 'However, the relatively low volumetric energy density of hydrogen, even in liquid form, presents a challenge for aviation<sup>22,23</sup>. New technologies are needed to adapt aircraft accordingly, with the market entry of narrow-body hydrogen-powered aircraft expected for 2035<sup>24</sup>.'

However, we have also expanded how the scenarios are introduced (see our reply to your comment 2). Early in the results we now include:

**'In our scenarios, the alternatives to fossil kerosene are drop-in e-fuel and non-drop-in liquid hydrogen.'**

Comment 37: Page 15 line 411: probable the scenario design should come earlier in the explanations, as it is core to understanding the results.

Reply: See our reply to your comment 2.

Comment 38: Page 16 line 444: the use of REMIND is not clear to me. Which parameters did the authors use? Why do they need an integrated assessment model if they are performing a life cycle analysis?

Reply: LCA uses background databases to represent those economic activities which the practitioner does not directly model themselves. In order to align this background with the rapid decarbonisation of societal energy systems, we conduct transformations following the SSP2-PkBudg1150 pathway as generated by REMIND (see <https://doi.org/10.1016/j.rser.2022.112311>). The core parameters used here concern the electricity mix of IAM regions at each time step.

Comment 39: Why did the authors use Allen et al (DOI 10.1088/1748-9326/abfcf9) as opposed to Lee et al (<https://doi.org/10.1016/j.atmosenv.2020.117834>) which is directly measuring aviation non-CO<sub>2</sub>

Reply: We originally did use factors from Lee et al. to model aviation non-CO<sub>2</sub> impacts. However, our implementation following Allen et al. introduced some inaccuracies in calculating warming-equivalent emissions of non-CO<sub>2</sub> effects. We have now updated our approach to these calculations (see our reply to comment 18 by reviewer 1).

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## Reviewer #3

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### Major comments

Comment 1: The manuscript would highly benefit from a more extensive explanation of the choice of scenarios. Especially unclear is the extent to which AAFs vs. H2 aircraft are deployed in the different scenarios. This is crucial to interpreting the results and in drawing the key insights from the results.

Reply: We have significantly altered how the scenarios are introduced and discussed. This includes additional sections which elaborate on how the scenarios are created. We support these sections with additional results which we added following your recommendations and which aim to give the reader a robust understanding of how to interpret the results overall.

We elaborate further on the specific adjustments made according to your related comments below.

Comment 2: I also wonder whether this study would not have benefitted to a comparison of the impacts of AAFs and H2 AC in a 'vacuum' setting – namely looking only at the climate impacts over time (considering LCA aspects) of two 'pure pathways' looking at these two technologies. This could also be added as an initial figure, and then the other 'megatrends' such as policies, air traffic volumes, breakthroughs in AC could be added in following figures.

Reply: The kind of results you're referring to falls outside of the scope of our analysis, as we generate fleets of aircraft and fuel infrastructure to work together—these cannot be disentangled into a static value for a given technology. However, we do agree that we should do more to discuss hydrogen-powered aircraft and the effect of introducing them to the fleet. For example:

'In the scenarios following our extended version of ReFuelEU, the required AAF share (Figure 1c) is achieved by introducing hydrogen-powered aircraft and by replacing fossil kerosene by e-fuel. The combined AAF used across scenarios with or without hydrogen-powered aircraft is therefore similar (Figure 3b), with some divergence emerging due to differences in the energy demand for hydrogen-powered and hydrocarbon-powered aircraft. Hydrogen-powered aircraft could require less energy per available seat-kilometer (ASK) than their contemporary hydrocarbon-powered counterparts (Table 6)<sup>57</sup>. This is why the introduction of hydrogen-powered aircraft reduces the total demand for aviation fuel when assuming 'breakthrough' future technology. In other scenarios, this is not the case, and introducing hydrogen aircraft increases the total fuel demand. Since ReFuelEU defines a share of AAF, such changes to the total fuel demand influence how much fossil kerosene can be used (Figure 3a).'

In line with your comment, we have also included an additional figure (Supplementary Figure 4), which includes how scenarios compare in terms of MJ/RPK and gCO<sub>2</sub>/RPK.

Comment 3: The introduction needs to introduce the ‘megatrends’ that are then a core part of the scenarios assessed (AC efficiency, air traffic volume and the presence of ReFuelEU as a climate policy driver).

Reply: We acknowledge that a clearer overview of what you call ‘megatrends’ was needed. We have therefore restructured the results section, which now opens with a more thorough overview of how the scenarios are generated and what these ‘megatrends’ entail:

‘A stock-and-flow model generates fleets of aircraft and fuel infrastructure in order to meet the imposed air traffic volumes (Figure 1a). Characteristics of the aircraft and fuels introduced are governed by two additional scenario parameters: the advancement of aircraft technology and the evolution of AAF use. The resulting flows are used to scale technology-level LCA data, covering both direct aircraft emissions and emissions across the lifecycles of aircraft and fuel infrastructure. Figure 1 provides an overview of the key parameters, parameter values, and the system boundary. We briefly elaborate on this in the following paragraphs. Detailed descriptions are given the corresponding parts of the ‘Methods’ section.’

The introduction has also been updated: we further expanded on how ReFuelEU is introduced and describe how our scenario parameters interact with our research objectives. For example:

‘In addition to offsetting, aviation industry roadmaps focus on measures centred around energy efficiency and substituting fossil kerosene with alternative aviation fuels (AAF)<sup>13–16</sup>. [...] [The] European Union formalised legal requirements in 2023, under the so-called ReFuelEU Aviation initiative<sup>17</sup>. Following this regulation, EU airports must meet a minimum share of AAF in the fuel they supply, increasing from 2% in 2025 to 70% in 2050. This minimum can be met with sustainable aviation fuels (SAF), defined in the EU as drop-in fuels which meet certain sustainability requirements, or with select non-drop-in alternatives to fossil kerosene.’

And later:

‘[...] the analysis of mitigation pathways is inherently tied to how these pathways are conceptualised and understood. For example, we assume that the introduction of AAF—including the potential deployment hydrogen-powered aircraft—is driven by ReFuelEU, with additional measures to eliminate the use of fossil kerosene by 2060. Other studies consider different logic for the adoption of AAF (see Table 1 in ‘Methods’).’

Comment 4: There’s an overstatement in the kind of novelty brought by due to the promise of a comprehensiveness in the assessment of H2 scenarios. Yet, scenarios are really coarsely picked based on very broad ‘megatrends’, which leads to a bundling of a lot of possible technologies together – with potentially important differences in terms of LCA. I think this is not per se a problem, but definitely it tampers the scientific advance brought by with this study (which should then not be overstated throughout the manuscript).

Reply: We have reworked our framing of the scientific novelty in the abstract (see our reply to your comment 7) and in the introduction, discussion, and literature review (see our replies to your comment 13 and comment 26).

Comment 5: The introduction promises a focus on hydrogen, which then does not perfectly match back to the results, since in the results hydrogen is considered very bimodally (in a 'on off' kind of design), without investigating in the different technologies, and its effects are co-founded by other important trends such as air traffic volumes, efficiency increases and different blending quotas. I think the premise of the introduction is very interesting and should be better developed throughout the results and discussion by adding more in-depth analyses of the role of hydrogen.

Reply: We have addressed this comment with multiple changes.

First, the final paragraphs of the introduction now frame the research differently. One of our aims with these changes was to avoid giving readers the impression that our focus is on hydrogen itself. See also our reply to your comment 3.

Secondly, the restructured results section (which we've touched on in several replies above) now includes additional results which help untangle how the different parameters affect the scenarios' outcomes.

Comment 6: Overall, it's unclear why the exclusion of H2 aircraft has such a small impact in the amounts of AAFs deployed. Is this due to assumptions in the scenario design (if so, I think a sensitivity analysis for higher H2 aircraft shares is needed) or due to the incapacity to increase H2 aircraft in the fleet at higher rates (due to the lifetime of the fleet)?

Reply: We believe that your comment might stem from a misunderstanding of what we mean with AAF: this term includes both drop-in and non-drop-in fuels. We have aimed to clarify what we mean with AAF (see our reply to your comment 10).

Additional changes we made should further help readers in understanding our results and how they are obtained. In particular, see our reply to comment 7 by reviewer 1.

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### Minor comments

Comment 7: p. 1 l. 9 – This sounds a bit overstated.

Reply: Thank you for addressing this point. In order to avoid hyperbole, we have rephrased this sentence:

'Our analysis considers the role of hydrogen in decarbonising the aviation system **while incorporating diverse** environmental and socio-technical dimensions.'

Comment 8: p. 1 – Abstract: I find it hard to match the premise (the promise of identifying the conditions under which hydrogen-based aviation can comply with European climate targets) with the results actually expressed in the abstract, namely the different levels of stabilizations. It would be

good here to pinpoint directly at the most important conditions identified in the study which help attaining an appropriate level of warming (but I guess the problem is also that in the EU we don't have a sectorial, or even regional, breakdown of temperature targets). I'd highlight the novelties of this study already in the abstract, otherwise it reads like something we knew already from previous studies (namely that the trajectory before 2050 will influence the level of warming in 2050).

Reply: We agree that this part of the abstract doesn't adequately reflect our work. We have reworded this to align with the research objectives we set out in the introduction:

'With the recent adoption of ReFuelEU Aviation, the use of alternative aviation fuels is set to increase. We explore how this affects the climate impact of European aviation and its alignment with notions of successful climate change mitigation.'

We now also more directly highlight our contribution in the abstract:

'Although alternative fuels can greatly reduce CO<sub>2</sub> emissions and non-CO<sub>2</sub> impacts—with hydrogen-powered aircraft yielding the largest reductions—persistent air traffic growth drives the near-term use of fossil resources and the long-term scale of non-CO<sub>2</sub> effects.'

Furthermore, we can indeed not determine what a 'appropriate' level of warming exactly implies. This is something we highlight as a requirement to guiding effect climate mitigation:

'Therefore, we recommend reassessing aviation climate targets, including the consideration of non-CO<sub>2</sub> effects in budget-based targets and stronger incentives to reduce near-term fossil kerosene use.'

See also our reply to your comment 13.

Comment 9: p. 2 l. 18-34 – Here it would be important to mention not only the lack of quality of offsets (in terms of delivering less emission reductions than promised), but also generally their non-compatibility with a truthful concept of net-zero, where long-lived CO<sub>2</sub> emissions need to be compensated by equally durable CO<sub>2</sub> removals. This could be implemented (in theory), but today's offsets are almost all emissions avoidance, emissions reductions, or biogenic, non-durable CO<sub>2</sub> removals (e.g., in trees).

Reply: While we fully agree with your statement, we faced a trade-off in how to address the shortcomings you highlight. These are the options we considered:

1. Each shortcoming is introduced in a way that is accessible to readers, in which case the introduction would have to be considerably expanded.
2. Alternatively, we could mentioned these shortcomings by name only (non-permanence, double counting, lack of additionality, etc.).

3. Finally, we could not elaborate on concrete shortcomings at all, instead broadly explaining what the intended effect of offsets is and stating that in practise, they often fall short.

We excluded option 1 in order to keep the introduction targeted and within an acceptable length. Option 2 we excluded because it does not benefit readers who are not familiar with these terms, nor does it benefit readers who were already aware of these shortcomings to begin with. This is why we chose option 3.

This being said, our initial word choice ('emission reduction') does not accurately describe all offset mechanisms we aimed to address with this line. We have therefore changed this to 'reduction of atmospheric GHGs'.

We hope that you find our response acceptable.

Comment 10: p. 2 l. 35-36 – Is there a specific reason for calling them AAF instead of, as mostly common, SAFs? I would refrain from introducing a non-common acronym in order to improve clarity for readers that quickly skim through the manuscript.

Reply: Please see our reply to comment 12 by reviewer 2.

In brief, AAF, while less common, is already an established term and avoids the ambiguity of SAF, which has multiple definitions, many of which are not interchangeable with our use of AAF. We have made adjustments to the text in order to clarify this point.

Comment 11: p. 2 l. 37 – 'but have not been met': unclear that it refers to the ambitious targets. Add 'these targets have ...'

Reply: Thank you for pointing this out. The sentence has been improved with the suggested addition.

Comment 12: p. 2 l. 37 – 'These voluntary targets': unclear before that these targets are voluntary and hard to establish the parallel with the ReFuelEU. I would reshape the first 3 sentences of this paragraph to enhance clarity and explain that, while most voluntary targets were ambitious, they also have been largely ignored in practice – but the situation with ReFuelEU should be different (why? Are there any guardrails in place to ensure the targets will be met?).

Reply: Thank you for your constructive feedback. We have addressed your remarks in the new version of this section:

'In addition to offsetting, aviation industry roadmaps focus on measures centred around energy efficiency and substituting fossil kerosene with alternative aviation fuels (AAF)<sup>12–15</sup>. Industry actors have set ambitious non-binding targets for these two measures in past decades, but these targets have not been met<sup>16</sup>. In contrast to these voluntary targets, the European Union formalised legal requirements in 2023, under the so-called ReFuelEU Aviation initiative<sup>17</sup>. Following this regulation, EU airports must meet a minimum share of AAF in the fuel they supply, increasing from 2% in 2025 to 70% in 2050. This minimum can be met

with sustainable aviation fuels (SAF), defined in the EU as drop-in fuels which meet certain sustainability requirements, or with select non-drop-in alternatives to fossil kerosene.'

Comment 13: p. 2 l. 56 ff. – I find this transition to the significance of the study a bit weak, resulting in an unclear picture of how this study will advance the current state of knowledge. The introduction well highlights the different pathways to reduce aviation's emissions and the issue with offsets (even though the potentially very important role of CDR is left out). But here I don't understand what is exactly the gap that this study is contributing too. I think what's missing is a little review of the literature comparing these pathways, which should highlight that a comprehensive comparison has never been done (even though I know of several studies that have attempted at a comprehensive assessment of pathways, such as Bergero et al., 2023; Dray et al., 2022; ...). Also, I think it should be justified more why pLCA is the appropriate approach – a focus on the different LCA dimensions still neglects the economic component, so this should be justified a bit more thoroughly (by stating more explicitly the contribution to the literature, which has either examined broadly costs and pathways without looking at the LCA in depth – e.g., Dray et al., 2022 – or has looked at these aspects but only for a very narrow selection of technologies – e.g., Sacchi et al., 2023; Brazzola et al., 2025). I'd also argue that a in-depth inclusion and comparison of hydrogen aircraft to AAFs is missing in the literature, especially with an pLCA perspective.

Reply: We have taken your recommendations to heart and considerably reworked this part of the introduction to highlight our research objectives and novelty. This encompasses the latter half of the introduction, starting from:

'We do not yet know how the climate impact of future aviation will develop under influences such as ReFuelEU Aviation, nor how this future will compare to other targets for climate mitigation.'

We have also reworked our discussion of previous work in the 'Methods' section. This section is now called 'Modelling requirements and comparison to previous work' and includes:

'As outlined in the introduction, we conducted this work in order to understand the implications of ReFuelEU for the climate impact of European aviation. When quantifying and discussing this climate impact, ongoing academic and societal discussions of how to define successful climate change mitigation for aviation must be considered (see 'Aviation climate targets', below). For our assessment of the sector to be robust, it should consider diverse trends for air traffic demand and improvements to aircraft technology. Within these trends, it is relevant to consider the possibility of hydrogen-powered aircraft, given the European focus on hydrogen<sup>13,59</sup>.

[...]

We also reviewed related aspects in previous works which discuss aviation climate mitigation pathways (Table 1). These articles provide insightful perspectives on the future of aviation's impact on climate change, although none meet all of our requirements. This is natural, considering differences in research objective.'

Comment 14: p. 3 l. 75 ff. – Here, you jump straight into the figures without first guiding the reader through a description of the scenarios represented. I suggest adding a small first section where the scenarios are explained in detail, including a modified version of Figure 2 better tracking back to the different scenarios shown in Figure 1, as a first thing, in order to lay the basics for understanding the results to follow. For example, for me it's not clear how to interpret the trade-off between hydrogen aircraft and AAFs from Figure 1. The text introducing Figure 1 also mentions fossil fuels, but I'm not fully sure how these map to the figure (I guess we talk here about the red line, but then again, would the ReFuelEU with H2 aircraft also apply here?). Also, there's no mention of the European focus in the introduction – as a result, this focus comes through as an (unjustified) surprise.

Reply: Thank you for your constructive recommendations. We have taken them to heart. The results are now introduced in a very different way, including more details on how scenarios are constructed, how fuel mixes and aircraft fleets are modelled, and how these affect the scenarios.

Additionally, to further clarify the European focus to the reader, we have named the first sub-header of the results 'Future European aviation'.

Comment 15: p. 3 l. 89 ff – Here, we find out suddenly that the different scenarios are not only looking at the different technologies, but also at 'megatrends' in aviation, including air traffic volumes and different variations of ReFuelEU – of which no mention was made in the introduction. Also, multiple variable vary at the same within different scenario, which makes it hard to disentangle the effect of single variables (e.g., air traffic volumes and efficiency breakthroughs). In particular, it is unclear to which extent the AC breakthroughs impact the amount of H2 AC present in the mix (and what happens if we have great AC breakthroughs but no H2 AC?). This calls for a more extensive scenario-description section before diving into the results – otherwise readers are confused to why we are having these different scenarios and what we should take out of them.

Reply: As we've said above, the scenarios are now introduced much more extensively. This includes additional sections explaining the meaning of scenario parameters and how these are used to construct scenarios. For example:

'Nine scenarios are selected by combining the three sets of demand-technology pairs with three distinct fuel mix scenario values (Figure 1a). These fuel mixes consist of (1) a baseline, where the share of AAF is not increased, (2) the implementation of an extended version of ReFuelEU Aviation (Figure 1c), but with no commercial introduction of hydrogen-powered aircraft, meaning that all AAF is modelled as e-fuel, and (3) the extended version of ReFuelEU Aviation, also featuring commercial

hydrogen-powered aircraft in future generations, meaning that the share of AAF is met through a combination of liquid hydrogen and e-fuel.'

Furthermore, we now build up the results by first showing fleet compositions (Figure 2) and fuel use (Figure 3), and only then presenting climate impacts (Figure 4).

Comment 16: Figure 1 – Personally, after reading the introduction, I'm mostly curious to clearly see the effect in climate impacts of H<sub>2</sub> hydrogen vs. AAFs. Yet, because the 'megatrends' of AC breakthrough, ReFuelEU absence and air traffic volumes seem to be more important, the differences between H<sub>2</sub> aircraft and AAFs are very hard to read. While it's nice that you are able to visually display such a diverse range of scenarios on one figure, I wonder whether it would not be better to pick fewer 'megatrends' and reduce the number of scenarios such to focus more strongly on figuring out the contribution of H<sub>2</sub> aircraft. Other scenarios could be added in a second part of the paper or in the supplementary information.

Reply: With this revision, we spend much more time on pointing out the differences between scenarios with and without H<sub>2</sub> aircraft. This includes the 'Fuel demand' section:

'In the scenarios following our extended version of ReFuelEU, the required AAF share (Figure 1c) is achieved by introducing hydrogen-powered aircraft and by replacing fossil kerosene by e-fuel. The combined AAF used across scenarios with or without hydrogen-powered aircraft is therefore similar (Figure 3b), with some divergence emerging due to differences in the energy demand for hydrogen-powered and hydrocarbon-powered aircraft. Hydrogen-powered aircraft could require less energy per available seat-kilometer (ASK) than their contemporary hydrocarbon-powered counterparts (Table 6). This is why the introduction of hydrogen-powered aircraft reduces the total demand for aviation fuel when assuming 'breakthrough' future technology. In other scenarios, this is not the case, and introducing hydrogen aircraft increases the total fuel demand. Since ReFuelEU defines a share of AAF, such changes to the total fuel demand influence how much fossil kerosene can be used (Figure 3a).'

And the 'Climate impacts' section:

'AAF scenarios with hydrogen-powered aircraft emit 23-32% less CO<sub>2</sub> annually than those without, but this reduction is modest compared to the reduction of roughly 80% relative to scenarios without ReFuelEU (Figure 4a). Differences such as the diverging hydrogen demand (Figure 3c) are limited in their influence on climate change, since we assume that AAF value chains are largely free of fossil resources by the time that hydrogen-powered aircraft enter the fleet. The difference in temperature change is more noticeable: we assume that a turbine burning hydrogen produces 90% less NO<sub>x</sub> emissions in cruise than one burning the same energy content in hydrocarbons<sup>61</sup>, leading to a distinct change in NO<sub>x</sub> impacts (Supplementary Figure 6). However, such assumptions about the non-CO<sub>2</sub> effects of AAF are highly uncertain (see 'Methods').'

Readers who want to additional insight regarding how scenarios with and without H<sub>2</sub> aircraft compare can consult the supplementary information, which shows, for example, that introducing low-performance H<sub>2</sub> aircraft already causes a small decrease in the CO<sub>2</sub> emissions accumulated by 2070 across all scenarios (Supplementary Figure 7), which is larger if H<sub>2</sub> aircraft perform better or the impact of H<sub>2</sub> production increases (Supplementary Figure 8), but smaller if drop-in e-fuel is produced more efficiently (Supplementary Figure 10).

Comment 17: Figure 1 – Why are the emissions in 2020 so different among the ‘megatrend’ scenarios? It looks like different growth trajectory take place already in the past. This makes it very hard to compare scenarios as apparently they also start on different historical premises. I would make sure to homogenize these premises such to isolate the impacts of pathways post 2020.

Reply: Initially, we started all scenarios in 2024, thereby already including diverging results in the first year, since 2024 wasn’t in the past yet. We agree with you that a shared starting point is more intuitive to the reader. We have therefore updated our inputs with the historical data for 2024.

Comment 18: Figure 1b – Why are the non-CO<sub>2</sub> impacts differences among with/no H<sub>2</sub> AC scenarios so little? I would expect the effects of H<sub>2</sub> AC on non-CO<sub>2</sub> mitigation to be substantially higher than those of AAFs. Is that due to the fact that H<sub>2</sub> AC are only present in very small shares?

Reply: This is a consequence of how we model the non-CO<sub>2</sub> effects of alternative fuels. We acknowledge that this is a highly uncertain area and have therefore added additional discussion and sensitivity analyses on this topic (see our reply to comment 8 by reviewer 2). Furthermore, by improving how we perform impact assessment, the influence of H<sub>2</sub> aircraft on reducing NO<sub>x</sub> emissions has become more clear in the results. For example:

‘AAF scenarios with hydrogen-powered aircraft emit 23-32% less CO<sub>2</sub> annually than those without, but this reduction is modest compared to the reduction of roughly 80% relative to scenarios without ReFuelEU (Figure 4a). Differences such as the diverging hydrogen demand (Figure 3c) are limited in their influence on climate change, since we assume that AAF value chains are largely free of fossil resources by the time that hydrogen-powered aircraft enter the fleet. The difference in temperature change is more noticeable: we assume that a turbine burning hydrogen produces 90% less NO<sub>x</sub> emissions in cruise than one burning the same energy content in hydrocarbons<sup>61</sup>, leading to a distinct change in NO<sub>x</sub> impacts (Supplementary Figure 6). However, such assumptions about the non-CO<sub>2</sub> effects of AAF are highly uncertain (see ‘Methods’).’

Comment 19: Figure 2 – To also tackle my comment above, I would add a third panel to Figure 2 showing the share of H<sub>2</sub> Aircraft under the different scenarios.

Reply: Your recommendation is highly appreciated. We have included the composition of aircraft fleets in a new figure (Figure 2) and explicitly discuss the share of H<sub>2</sub> aircraft:

‘In scenarios featuring hydrogen-powered aircraft, these are introduced with consideration for the aircraft type and flight destination. We assume that the initial introduction of hydrogen-powered aircraft is limited to narrow-body aircraft servicing intra-European flights (see Table 2 and Table 3, as well as associated text, in ‘Methods’). Because hydrogen-powered aircraft are introduced to the extent required to meet demand, only a fraction of European airports require hydrogen infrastructure in 2035. However, we do assume that this can extend to all European airports as time goes on, as well as some extra-European destinations after 2050. With these ambitious assumptions, the share of air traffic powered by hydrogen rapidly grows from around 10% in 2040 to over 60% in 2070 (Figure 2).’

Comment 20: Figure 2c – Why do we have a ReFuelEU ‘as-is’ scenario, if it actually is never shown in the other figures?

Reply: ReFuelEU Aviation extends to 2050, but not beyond. In order to extend our modelling to 2070, we make the assumption that additional efforts are made in order to phase out fossil aviation fuels entirely. To highlight that this is an additional assumption we have to make, we call this parameter value ‘ReFuelEU Aviation extended’ (or ‘ReFuelEU extended’, for short).

Results for the scenarios featuring ‘ReFuelEU Aviation as-is’ are included in the supplementary information, but since we do not consider these scenarios to be particularly insightful or narratively coherent, they are excluded from the main text.

However, following other suggestions by you and the other reviewers, we have significantly adjusted the way in which the scenarios are introduced and presented (see your comments 1). As a result, we now elaborate on the above in the section ‘Future European aviation’:

‘The fuel supply follows the ReFuelEU Aviation initiative, aiming to reduce fossil kerosene to 30% of the fuel supply by 2050. Although ReFuelEU does not extend past 2050, we consider an ‘extended’ version of ReFuelEU, in which additional measures are taken to eliminate fossil kerosene by 2050 (Figure 1c). In our scenarios, the alternatives to fossil kerosene are drop-in e-fuel and non-drop-in liquid hydrogen.’

Comment 21: Figure 3 – What drives reductions in fossil kerosene use when we don’t have ReFuelEU? Is that the ‘disentangled effect’ of growth and efficiency? How does efficiency trace-back to H2 aircraft deployment? Why is the difference in AAF use so little between scenarios with H2 aircraft and without? Answers should be findable in the main text and easily understandable from the figures (thanks to a clear explanation of the scenarios).

Reply: The section titled ‘Total fuel demand’ addresses these questions.

- Fossil kerosene use without ReFuelEU: The behaviour seen in Figure 3 is discussed in the first paragraph, distinguishing between the effects of demand and aircraft technology:

‘In the baseline scenarios—where AAF is not scaled up—total fuel demand initially diverges but then stabilises around 2035 with the introduction of future aircraft (Figure 3a). This shows that demand plays a significant role in the short term, while the contrast in fuel efficiency of aircraft technology (Table 6) becomes more influential over time.’

- Effect of H<sub>2</sub> aircraft efficiency & comparison to e-fuel only: The effect of introducing H<sub>2</sub> aircraft and the influence of their efficiency is discussed in the second paragraph, which we’ve rewritten as follows:

‘In the scenarios following our extended version of ReFuelEU, the required AAF share (Figure 1c) is achieved by introducing hydrogen-powered aircraft and by replacing fossil kerosene by e-fuel. The combined AAF used across scenarios with or without hydrogen-powered aircraft is therefore similar (Figure 3b), with some divergence emerging due to differences in the energy demand for hydrogen-powered and hydrocarbon-powered aircraft. Hydrogen-powered aircraft could require less energy per available seat-kilometer (ASK) than their contemporary hydrocarbon-powered counterparts (Table 6). This is why the introduction of hydrogen-powered aircraft reduces the total demand for aviation fuel when assuming ‘breakthrough’ future technology. In other scenarios, this is not the case, and introducing hydrogen aircraft increases the total fuel demand. Since ReFuelEU defines a share of AAF, such changes to the total fuel demand influence how much fossil kerosene can be used (Figure 3a).’

As you point out, the improvements we’ve made to the way the scenarios are introduced and presented (with the new ‘Future scenarios’ and ‘Aircraft fleets’ sections) already help in making the ‘Total fuel demand’ section more intuitive to the reader. An additional change we have made is that Figure 3b now shows what share of the AAF use is liquid hydrogen.

Comment 22: p. 5 l. 117-119 – This is the kind of very useful information on the characteristics of scenarios that should come up earlier (and maybe be put systematically in a tabular form, so that we can clearly read out all the different assumptions driving the different scenarios and heavily impacting the results).

Reply: These lines refer to the air traffic demand scenario parameter being described in terms of year-on-year growth. We agree that this is a useful description to add, supplementing the values of yearly RPK given in the supplementary files and shown in Figure 1b (formerly, Figure 2b). Therefore, we now mention these values when first introducing the various demand trajectories:

‘We combine EUROCONTROL’s seven-year forecast (up to 2031)<sup>48</sup> and the long-term forecast (up to 2050)<sup>49</sup>. We assume that the long-term year-on-year growth remain representative until 2070, i.e., ‘low growth’ of 0.7%, ‘base growth’ of 1.6%, and ‘high growth’ of 2.2%.’

Comment 23: p. 7 l. 137 – I find it very confusing that this little section referring to Figure 1 is placed here. I think overall the whole results section needs some

serious restructuring in order to 1) ensure scenarios are clear at the beginning, 2) ensure that each figure provides insights that are then explained in the text immediately preceding/following it.

Reply: The restructuring of the results we did address this comment as well. All discussion of climate impacts is now grouped into the section 'Climate impacts'.

Comment 24: General comment - Scenario naming: I strongly recommend changing the names of the scenarios represented by dashed, dotted lines etc. by having a 'fossil jet fuels' scenario vs. a 'ReFuelEU' and a 'ReFuelEU + H2 aircraft'.

Reply: We appreciate your suggestion, but we have chosen not to rename the scenarios, given that H<sub>2</sub> aircraft are not introduced as a pure addition to ReFuelEU, but as one of the ways in which the ReFuelEU requirements can be met, thereby displacing e-fuel.

The changes made to how aircraft fleets and fuel mixes are introduced clarify this (see our replies to your other comments, such as 14, 20, and 21).

Comment 25: p. 7 l. 165 – “This suggests...” I would argue that here the logical link is flawed. You first say that emissions are down to a fifth of those with fossil fuels, and then claim that based on this climate-neutral aviation is possible. But actually climate neutrality strongly depends on the baseline relative to which aviation is considered neutral. CO<sub>2</sub> neutrality, on the other hand, never gets reached based on Figure 1a.

Reply: Indeed, what it means to be 'climate-neutral aviation' varies a lot across scenarios. This is an inherent feature of the definition of being 'climate-neutral' we use. We do not claim that this covers 'CO<sub>2</sub> neutrality'. However, we include criticism of this definition which also applies to targets such as 'CO<sub>2</sub> neutrality by 2050':

'Aside from the uncertainty of AAF non-CO<sub>2</sub> impacts, the fact that climate neutrality as defined here can be achieved under any growth scenario, despite large differences in impact, suggests that this is not a robust measure of successful climate mitigation. Because this definition of climate neutrality defines success with respect to a future reference year, it neglects the harmful effect of emissions which occurred prior to this reference year. A more meaningful measure of success requires a budget-based target.'

Furthermore, we have now included additional discussion of climate neutrality and the role CO<sub>2</sub> plays in the discussion:

'Provided that low-impact AAF replace fossil kerosene at scale, our analysis indicates that, by 2060, net CO<sub>2</sub> emissions are less than one-fifth of those from an equivalent fossil-fueled scenario (Figure 4a). This suggests that achieving a 'climate-neutral' aviation sector is feasible, with the temperature change caused by aviation reaching a (temporary) peak before 2050 (Figure 4b). This conclusion is based on the assumption that alternative fuels reduce the impact of contrail formation, thereby

compensating for the remaining CO<sub>2</sub> emissions. However, because the requirements of ReFuelEU scale with the fuel supply, emission targets set by ICAO and IATA are likely to be exceeded unless accompanied by short-term demand reduction (Figure 4b). Therefore, achieving climate neutrality by 2050 is not an accurate indicator of aviation's contribution to climate change, for which a measure reflecting its total impact is necessary.

[...]

Still, when understanding the impact of NO<sub>x</sub> and contrails as closely linked with total fuel use and distance flown respectively, there is a limit to the yearly provisioning of AAF-powered air transport within a given sectoral climate budget. In this context, CO<sub>2</sub> is primarily a concern to the extent that its accumulation (driven by fossil fuel use) limits how much of the total budget remains in the future.'

Finally, readers can also identify to what extent scenarios can be considered 'CO<sub>2</sub> neutral' (i.e., how much CO<sub>2</sub> emissions occur after 2050) by referring to Supplementary Figure 7.

Comment 26: p. 7 l. 164 ff. – I feel like these conclusions miss the novelty of the whole paper. We already knew from multiple studies (the above mentioned) that pathways to climate neutral aviation are in principle possible. But what's the contribution of H2 aircraft compared to AAFs to do so? And what should happen to align the sector to climate targets? To answer this, I believe you would need to change the scenarios a little bit. Especially, it would be interesting to have scenarios that can get to the ICAO targets eventually (by having more H2 aircraft earlier on, for example), and that show the contribution of H2 aircraft vs. AAFs more clearly. Finally, I think it would be nice to deduct some sort of 'threshold' for climate neutrality that should be reached. I know it's extremely hard to do so (we only have a global temperature target), but you could for example use the mean of the European aviation RF from IAMs ensembles that manage to limit 1.5-2°C by 2100 and add these as horizontal lines in your Figure 1.

Reply: We agree that the statement that climate-neutral aviation is in principle possible does not capture the novelty of our work. This observation has indeed already been robustly established in the literature.

Accordingly, we have reframed the novelty of our work in the introduction, in the 'Modelling requirements and comparison to previous work' section of the methods (see our reply to your comment 13). We have also rewritten the section itself you're referring to, as described in our reply above.

We consider the development of an absolute warming threshold for (European) aviation to be outside the scope of our work. We highlight how the absence of such a threshold risks excessive climate damage, but do not go beyond this.

Comment 27: General about the discussion – I feel like the discussion is erratically spanning across various themes while it fails to deliver a succinct summary of the main findings and their relevance to science and society.

Relative to my previous comment, I would in general reshape the study such to delivery clear take-aways instead of the current, general ones – which have already been largely delivered by existing studies. I think the modelling set-up of the study allows for these novel and important insights to be delivered.

Reply:

We have restructured the discussion to more directly tie in with the research objectives laid out in the introduction, to have a more natural narrative flow, and to embed our findings more clearly into the existing literature. A few take-aways we highlight:

- 'Hydrogen is used more efficiently when powering aircraft directly than in the production of hydrocarbon e-fuel'
- '[...] because the requirements of ReFuelEU scale with the fuel supply, emission targets set by ICAO and IATA are likely to be exceeded unless accompanied by short-term demand reduction'
- '[...] achieving climate neutrality by 2050 is not an accurate indicator of aviation's contribution to climate change, for which a measure reflecting its total impact is necessary [...] the notion of a sectoral climate budget becomes essential.'
- '[...] from a climate budget perspective, our current use of the aviation sector directly influences the ability of future generations to benefit from flight'
- 'In light of these considerations, we suggest that the adoption of measures to limit or reduce air travel could be effective in reducing both near-term use of fossil resources and the continuous impacts of non-CO<sub>2</sub> effects to the extent that existing measures risk falling short of the desired impact mitigation. These restrictions should effectively mitigate climate change while fostering an equitable society on a liveable planet.'

That being said, we acknowledge that there are still many different topics brought up in this section. Understanding the implications of our work requires understanding how our model compares to real-world conditions and the challenges faced in achieving these conditions, as well as understanding diverse aspects of aviation's climate impact. Even now, we do not elaborate on these aspects to the full extent that readers might require. For example, some aviation emissions are included in the EU ETS, which could be adapted to define a consistent sector-wide budget, but then brings additional challenges and limitations with it as well. Another example is discussing the costs of decarbonisation and how this burden is allocated, which is relevant to the discussion our work contributes to, but beyond the immediate scope of our results. We did our best to formulate a coherent and succinct discussion of our results while providing the necessary context.

Comment 28:

On this note, I would also revise the title such to place a major emphasis on the (novel) exploration of the role of hydrogen.

Reply:

As we explained in our other replies (the previous one, but also e.g., to your comment 5), our focus is not necessarily on hydrogen itself, but on decarbonising aviation following ReFuelEU and understanding what this implies for the sector's climate impacts. We have therefore not changed the title.

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# Response to reviewers

Dear reviewers,

Thank you for carefully reviewing our revised manuscript. The changes implemented include various additions and alterations to the text and figures. Notably:

- We changed the title from 'Decarbonising aviation does not imply successful climate change mitigation' to 'Air traffic growth jeopardises European aviation's climate mitigation despite substantial potential of hydrogen'.
- Figure 1 (including its caption) has been adjusted to more clearly exclude the 'base growth' and 'ReFuelEU as-is' scenario values from the results presented in the main text.
- The relevance of carbon removal and other offsetting to our work, and to aviation more broadly, is now discussed more thoroughly in the 'Introduction' and 'Discussion' sections.
- We now further contextualise our results and what it means to fly less in the 'Discussion' section.

We respond to each of your comments below.

## Reviewer #1

|            |                                                                                                                                                         |
|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| Comment 1: | Thank you for your detailed responses and updates to the paper. I believe it will be a valuable addition to the community. I recommend its publication. |
|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|

|        |            |
|--------|------------|
| Reply: | Thank you. |
|--------|------------|

## Reviewer #2

|            |                                                                                                                                                                                                           |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Comment 1: | I appreciate the changes to the original manuscript, and the responses to reviewers' comments! The manuscript reads much smoother now, and I have only two concerns remaining, and some smaller comments. |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

|        |                                                   |
|--------|---------------------------------------------------|
| Reply: | Thank you. We have addressed your comments below. |
|--------|---------------------------------------------------|

|            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Comment 2: | <p>1. Title not supported by findings:</p> <p>One concern relates to the title, which I think (while catchy) does not fully represent the authors' findings. If aviation used net-zero fuels, then its climate impacts would be minimal to none (depending on the non-CO2 effects of AAF). It is not that decarbonizing aviation does not achieve climate change mitigation, but rather that the ReFuelEU scheme is not enough to meet net-zero in the short term. In the abstract, the authors state "Although alternative fuels can greatly reduce CO2 emissions and non-CO2 impacts—with hydrogen-powered aircraft yielding the largest reductions—persistent air traffic growth drives the near-term use of fossil resources and the long-term scale of non-CO2 effects." So decarbonizing</p> |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

aviation does contribute to climate change mitigation, it is just not enough to meet net-zero targets from IATA in the short-term because demand is growing fast and we are not scaling these fuels fast enough—even in the ReFuelEU mandates the scaleup takes decades. So, I find the title to be too general and misleading. Another suggestion could be something like: “Hydrogen is not enough to meet net-zero aviation targets in Europe”, or “ReFuelEU implementation would still lead to high emissions from aviation in the short-term”, or something that’s more specific to the authors’ analysis. The authors are free to pick the title they prefer, but the current one I think is misleading.

Reply: When we say that decarbonisation ‘does not imply’ successful climate change mitigation, this should be understood as ‘not necessarily leading to’, rather than ‘not contributing to’. We also argue that near-term emissions are not be neglected when determining what ‘successful’ mitigation looks like, making ‘net zero’ (in isolation) an insufficient target.

We understand your argument for a title that more specifically reflects our work. Based on your recommendations and those of the editors, we have changed the title to:

**‘Air traffic growth jeopardises European aviation’s climate mitigation despite substantial potential of hydrogen’**

This conveys the important contribution which alternative fuels (in our case, non-drop-in hydrogen & hydrogen-based drop-in) could make to decarbonisation, but that the current mitigation trajectory in Europe will still result in excessive climate impacts if the role of air traffic growth is not considered.

Comment 3: 2. Authors’ suggestion in discussion for demand reduction:  
The second concern relates to the authors’ suggestion that the solution is to reduce demand for aviation. While it is true that in their scenarios only degrowth meets CORSIA, a different policy suggestion derived from this study could be to more aggressively deploy AAFs, which would reduce the carbon intensity of the fleet, and thus potentially meet climate targets. What the authors are finding is that the current ReFuelEU scheme is not compatible with other CORSIA-IATA net-zero targets—but not necessarily that demand must decrease. Again, this feels like an opinion of the authors, which I can agree with, but it is not supported by their findings (but rather a scenario choice). Maybe on line 416 the authors could say “in light of these considerations and in absence of any modification to the ReFuelEU program, the adoption of measures to limit or reduce air travel could be effective in reducing...”. The authors could also highlight alternatives (like trains), and bring in the importance of these services to be lower cost to aviation, and as efficient as possible (the authors never mention any alternative to flying).

Reply: We agree that it is reasonable to suggest that AAFs should be deployed more aggressively following our findings. We now more explicitly stress that the core challenge is phasing out fossil fuels, which more ambitious decarbonisation would contribute to:

‘Gössling and Humpe<sup>36</sup> model how global aviation might respond to a strictly enforced climate budget, concluding that the risk of exceeding climate targets can be greatly reduced by decreasing the near-term air traffic volume, but that traffic could increase again following successful decarbonisation. Our work supports this observation: after 2035, the influence of high year-on-year air traffic growth on climate impact can broadly be negated (Figure 4b), so reducing the overall demand prior to 2035 could lead to a similar temporary reduction. **Following our approach**, up to 8% of the CO<sub>2</sub>-based budget remains when combining degrowth with technological breakthroughs (Supplementary Figure 7), **allowing for additional air travel within the budget—which could increase further were decarbonisation to exceed the trajectory we assume here**. Still, when understanding the impact of NO<sub>x</sub> and contrails as closely linked with total fuel use and distance flown respectively, there is a limit to the yearly provisioning of AAF-powered air transport within a given sectoral climate budget. In this context, CO<sub>2</sub> is primarily a concern to the extent that its accumulation limits how much of the total budget remains in the future, **again highlighting the importance of phasing out fossil fuels**.’

The paragraph you refer with line 416 is not about providing a complete overview of possible policies, but a suggestion to start considering demand management as a serious option, rather than to continue with the assumption that a market-based distribution of supply and demand will suffice. However, we understand that by comparing this to ‘existing measures’, we imply that these ‘existing measures’ are static, rather than additional opportunities for change. We’ve improved this phrasing:

‘In light of these considerations, we suggest that the adoption of measures to limit or reduce air travel could be effective in reducing both near-term use of fossil resources and the continuous impacts of non-CO<sub>2</sub> effects to the extent that **other** measures risk falling short of the desired impact mitigation.’

We also appreciate the suggestion that we mention alternatives to flying. We agree that this forms a valuable part of the discussion of reducing future air travel:

**‘Various economic policies could facilitate a modal shift, e.g., from air to rail<sup>71</sup>, but it is evident that many flights have no feasible alternative. Reducing air travel also implies journeys not taken. While a journey doesn’t always have a clear necessity or benefit to the traveller<sup>72,73</sup>, this dimension is hard to access on a policy level. Restrictions to air travel should effectively mitigate climate change while fostering an equitable society on a liveable planet. The social and environmental realisation of these goals could be undermined by unintended incentives, e.g., by reinforcing current traffic patterns or encouraging additional long-distance flights.**’

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### Smaller comments

|            |                                                                                                                                                                                               |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Comment 4: | Line 114: air traffic volumes “derived from NNNN”. This may be a good place for authors to note what they assume future aviation demand is (which the methods state as EUROCONTROL, I think). |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Reply: We have chosen to keep the paragraph you're referring to succinct, but we inform the reader about the air traffic volumes in the following paragraph and distinguish between EUROCONTROL and the 'degrowth' trajectory:

'We combine EUROCONTROL's seven-year forecast (up to 2031)<sup>50</sup> and the long-term forecast (up to 2050)<sup>51</sup>. We assume that the long-term year-on-year growth remain representative until 2070, i.e., 'low growth' of 0.7%, 'base growth' of 1.6%, and 'high growth' of 2.2%. Following public support for suppression of commercial aviation as a climate mitigation strategy<sup>52–54</sup>, we also considered an additional 'degrowth' trajectory, in which air traffic from 2035 onwards remains constant at 70% of the 2019 demand (Figure 1b).'

We have also clarified this point in the caption of figure 1, as we explain in response to your following comment.

Comment 5: Figure 1: why does the schematic include 3 air traffic volume scenarios (high, low, degrowth) but the figure includes four (adding base growth)? This is confusing, so if base growth is not used in their analysis I suggest the authors drop it.

Reply: We believe that it is relevant for the reader to be aware that EUROCONTROL provides a 'base growth' scenario, even though we choose to exclude it in the scenarios presented in the main text.

Still, your criticism is valid, so we have chosen to make this line grey, as recommended by reviewer 3. We have also reworded the caption of this figure, which now reads:

**'b** The volume of air traffic in revenue passenger-kilometres (RPK) per year according to four trajectories: high growth (blue line), base growth (grey line, not included in the scenarios presented in the main text), and low growth (orange line), which are based on EUROCONTROL<sup>50,51</sup>, and degrowth (red line).'

Comment 6: Line 145: Do you mean to eliminate fossil kerosene by 2050? Shouldn't it be 2060? By 2050 you have reduced it by 70%, and then you assume that by 2060 you have reduced fossil kerosene by 100% (at least that's what I see in Figure 1c).

Reply: You are correct. We have amended this mistake and reduced ambiguity:

'Although ReFuelEU does not extend past 2050, we consider an extended version of ReFuelEU, in which additional measures lead to the elimination of fossil kerosene by 2060 (Figure 1c).'

Comment 7: Line 211-212: "We assume that the initial introduction of hydrogen-powered aircraft is limited to narrow-body aircraft servicing intra-European flights": Maybe the authors here could just put what percent of European flights are "intra-European" and which ones are extra-European? I think it would be helpful to see the split, as it matters for fleet composition. (I see comes later in the Methods on Table 2, but it may be

useful to add the percentages in this instance so that the reader has a general idea of the split).

Reply: We thank you for this recommendation and have chosen to adopt it. The text now reads:

‘We assume that the initial introduction of hydrogen-powered aircraft is limited to intra-European flights **serviced by narrow-body aircraft—a segment which represents 48% of air traffic in terms of revenue passenger-kilometres (RPK) (see Table 2 in ‘Methods’)**. Because hydrogen-powered aircraft are introduced to the extent required to meet demand, [...]’

Comment 8: Line 231: I recommend the authors use the “non-drop-in AAF” in panel b, as this is easier to follow than “excluding drop in AAF”. Are the lighter shades in panel b in Figure 3 showing the amounts to hydrogen used to power hydrogen-planes? I think so, so just saying “non-drop-in hydrogen” or something like this is more intuitive.

Reply: Based on your recommendation, we have changed the label in this panel from ‘excl. drop-in AAF’ to ‘non-drop-in H<sub>2</sub>’. We have also rephrased how these lines are included in the figure’s caption, which now reads:

**‘b AAF consumed by aircraft (saturated lines) and, for scenarios which include hydrogen-powered aircraft, the hydrogen consumed as non-drop-in AAF (desaturated lines).’**

Comment 9: How do the authors estimate temperature impacts? It may be worth noting when authors introduce their results on line 270 “Climate impacts”. The authors explain in their methods the use of GWP, maybe they can add a simple sentence in line 270 to note this.

Reply: Thank you for pointing this out. We seem to have neglected to explain how a temperature response is calculated based on warming-equivalent emissions. We have made the appropriate additions. In Results:

‘We **use** the computational framework of Smith et al.<sup>61</sup> **to express the combined impact of climate forcers as time-dependent warming-equivalent emissions, using** aviation-specific parameters based on Arriolabengoa et al.<sup>42</sup>. **These warming-equivalent emissions are multiplied by the transient climate response to cumulative CO<sub>2</sub> emissions<sup>62</sup>, thereby obtaining** the aviation system’s contribution to temperature change (Figure 4b).’

In Methods:

‘Quantifying climate impacts in terms of warming equivalence is useful in obtaining an impression of the temperature response within the temporal scope considered. **This temperature change is calculated by multiplying the warming-equivalent emissions with the transient climate response to cumulative CO<sub>2</sub> emissions (TCRE) factor. Likely, TCRE falls in the range of 0.27-0.63 K per 1000 Gton CO<sub>2</sub>—here, we use the best estimate of 0.45 K per 1000 Gton CO<sub>2</sub><sup>62</sup>. A drawback of expressing impact following**

warming equivalence is that climate forcing beyond the temporal scope at hand is obfuscated.'

Comment 10: There is some formatting issue in page 10 of the supplementary material (below supplementary figure 8), and some figures are hard to read (as if the resolution was not good enough. I am not sure if this was just happening to the version I opened, but it is worth double checking).

Reply: Indeed, thank you for pointing this out. We have amended this issue with this revision.

Comment 11: There are also issues with the references at the bottom of SI.

Reply: As above, we have amended this issue. Thank you for pointing it out.

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### Reviewer #3

Comment 1: I would first like to thank the authors for carefully addressing the (plentiful) comments they received and for not shying away from substantial revisions to the manuscript. I think the changes they implemented have done a great deal in advancing the quality of the manuscript. In particular, the stepwise description of the scenarios increased the readability and clarity of the manuscript, and the results and important conclusions are now clearer both in the abstract and throughout the manuscript. The discussion is also well written and has a broad width of considerations, including justice. I also thank the authors for the kind explanations whenever I misunderstood the original intentions of the manuscript.

Reply: Thank you. We are glad that you appreciate our revision.

Comment 2: Abstract – line 10: I would flip the sentence to emphasize a bit more the takeaway “We find that the adoption of alternative fuels alone does not guarantee abiding with climate targets, since their contribution to temperature change can widely vary (2.2 ...) and they can exceed CO<sub>2</sub>-based targets.”

Reply: Thank you for the suggestion. We have rephrased this sentence as:

‘We find that the adoption of alternative fuels alone does not guarantee successful mitigation, since the resulting temperature change can vary widely (2.2-8.9 mK estimated by 2070) and most scenarios exceed CO<sub>2</sub>-based targets.’

Comment 3: Introduction – line 33-34: Here the discussion revolves only around offsets, without differentiating between traditional carbon offsets and carbon removals. I acknowledge the response to my comment 9 and the decision to not tackle in detail the shortcomings of offsets. But since the manuscript completely dismisses offsets AND carbon removals, it needs a short justification of why. I would argue here that the main argument against offsetting is not just that it does not deliver the promised reductions in atmospheric GHGs, but that we need a paradigm of true

compensation of the climate impacts of aviation. This is guaranteed only by permanent carbon removals, and not by offset credits from emission avoidance or reduction projects. If the case against carbon removal is rooted, as argued in the response to Comment 10 of Reviewer 2, in avoiding the risk of locking the aviation sector into a path that depends on fossil fuels and heavily uses resources, then I would explicitly mention this in the text to legitimize the exclusion of this option from the scenarios explored. If you don't want to go into each of the mitigation options possible and argue why you exclude them, I would then argue as follow: due to its focus on ReFuelEU, this paper focuses on AAFs and excludes other mitigation options such as offsetting, CDR, and contrail avoidance.

Reply: We introduce the term 'offsets' to also include carbon removals: 'In a net-zero scenario, any greenhouse gases emitted through human activities must be 'offset', i.e., balanced by an equivalent **reduction** of greenhouse gases.' (Bold added for clarity.) We do not specify that this 'reduction' can be implemented in a variety of ways, as we motivated previously.

We agree with you that our motivation to exclude these options should be stated explicitly. We have therefore expanded on this in the Introduction:

'Other studies consider different logic for the **deployment** of AAF (see Table 1 in Methods) **and further mitigation measures. Here, we focus on AAFs, air traffic volumes, and aircraft technology. We do not consider contrail avoidance, although it could be a viable mitigation strategy<sup>39</sup>. Following the challenges introduced above, we exclude carbon storage and other offsetting techniques, despite their prominence in sectoral roadmaps (see also Discussion). Beyond technical and social dimensions, coverage of environmental dimensions varies too. CO<sub>2</sub> is a common focus of aviation climate targets [...]**

We have also made changes to how we come back to this topic in the Discussion, as we explain in our reply to your comment 12.

Comment 4: Lines 99-109 – This section is great, but I wonder whether is best placed at the end of the introduction. It reads to me more like a conclusion section. I also suggest integrating the numbers in line 100-102 into the abstract (in the sentence " -with hydrogen-powered aircraft yielding the largest reductions-" ) as it is a novel and very interesting result which will likely increase the number of citations if flagged already in the abstract.

Reply: We have included this paragraph following the journal's instructions for the introduction:

'The background and rationale for the work. **The final paragraph should be a brief summary of the major results and conclusions.** The results of the current study must only be discussed in this final paragraph. Do not include subheadings.' (Bold added.)

We appreciate your suggestion to improve our abstract. Unfortunately, we weren't able to include more numbers in the abstract without exceeding the limit of 150 words.

Comment 5: Figure 1 – It is a bit confusing that in panel a there are three drivers of air traffic volume, but then in panel b) there is an additional air traffic volume scenario (base growth). If base growth is the extrapolation of current growth levels, I suggest either including it as one of the air traffic volume scenarios assessed (e.g., in Figure 2, 3, etc.), or just show it as a dashed grey line in panel (b) and not describe it as a scenario in line 135.

Reply: The 'base growth' air traffic trajectory is one of the three trajectories published by EUROCONTROL and we believe that it's relevant for the reader to be aware of it.

We appreciate your constructive criticism. We have made this line grey in figure 1b and rewrote its caption, which now reads:

'b The volume of air traffic in revenue passenger-kilometres (RPK) per year according to four trajectories: high growth (blue line), base growth (grey line, not included in the scenarios presented in the main text), and low growth (orange line), which are based on EUROCONTROL<sup>49,50</sup>, and degrowth (red line).'

Comment 6: L. 138 – explicitly mention the label of the additional trajectory (I guess it is 'degrowth'?) to avoid confusion.

Reply: Thank you for the suggestion. This part now reads:

'[...] we also considered an additional 'degrowth' trajectory [...]

Comment 7: L. 140 – briefly explain the difference between 'optimistic' and 'breakthrough' scenarios of efficiency,

Reply: Following your recommendation, we have expanded on this paragraph:

'Technological improvements in aircraft efficiency vary from a business-as-usual scenario, with progress following historic trends<sup>55</sup>, to scenarios that include substantial improvements, from 'optimistic' expert estimates<sup>30</sup>, to speculative 'breakthrough' advances<sup>55</sup>. Future hydrogen-powered aircraft are correlated to these general trends, having a lower efficiency under business as usual and a higher efficiency under breakthrough.'

Comment 8: L. 144-145 – It is not quite clear to me, from Figure 1c vs. the text, whether the additional measures are taken after 2050 to eliminate fossil fuels by 2060 (as the orange line in Figure 1c seems to suggest) or the measures are taken by 2050 but the elimination of fossil fuels only is completed by 2060.

Reply: We unfortunately made a mistake in this sentence: 2050 should have been 2060. We understand your concern regarding the potential ambiguity of phrasing of 'measures are taken [...] by 2060'. We have therefore adjusted this sentence as follows:

'Although ReFuelEU does not extend past 2050, we consider an extended version of ReFuelEU, in which additional measures lead to the elimination of fossil kerosene by 2060 (Figure 1c).'

Comment 9: L. 243 – I think it would be beneficial early on to explain what is the driver of this difference between the breakthrough and the optimism scenarios – do I understand it correctly that is both the energy demand of and the share of H2 AC, which is also driven by demand?

Reply: The primary driver for this difference is the difference in energy demand of hydrogen-powered aircraft between these scenarios. We have made this more explicit in the text:

‘Hydrogen-powered aircraft could require less energy per available seat-kilometre (ASK) than their contemporary hydrocarbon-powered counterparts (Table 6). This is why the introduction of hydrogen-powered aircraft reduces the total demand for aviation fuel when assuming ‘breakthrough’ future technology. In ‘optimistic’ and ‘business as usual’ scenarios, this is not the case, and introducing hydrogen aircraft increases the total fuel demand.’

There is indeed also an effect following from the share of hydrogen-powered aircraft, which follows from demand. We touch on this in the following paragraph.

Comment 10: Figure 4 and lines 280-295 – I am missing here a paragraph commenting on the air volume growth and efficiency impacts. From how I read the figure, there are three important take-aways to highlight in this initial section: 1) high growth is always associated with the highest climate impacts, despite having the highest degree of innovation/efficiency; 2) ReFuelEU is preferable to limiting aviation growth in terms of CO<sub>2</sub> emissions, but not really in terms of temperature change including non-CO<sub>2</sub> effects; 3) H2 AC are preferable to no H2 AC.

Reply: These are indeed all important points, the first two of which we do not explicitly highlight. After reflecting on this, we decided to add a paragraph to the section ‘CO<sub>2</sub> limit and air traffic volumes’:

‘It is notable that the fossil-powered degrowth scenario exceeds the CO<sub>2</sub> budget later (2050 versus 2038) and to a lesser degree (overshoot in 2070 of 1.3 versus 2.3-2.5 Gton CO<sub>2</sub>) than either of the AAF-powered high-growth scenarios. This is closely related to fossil kerosene use (compare Figure 4a to Figure 3a). As discussed above, the assumed differences in technological development can largely compensate for growth, but only beyond 2035, leading to these distinct differences in cumulative CO<sub>2</sub> emissions. This highlights the crucial influence of future air traffic on the resulting impacts. This influence is even more prominent when considering non-CO<sub>2</sub> effects, which we discuss in the following section.’

Comment 11: L. 322 – “could reduce in ..” I think here was meant either “reduce the impacts” or “results in lower impacts”

Reply: Thank you for pointing out this mistake. The text now reads:

‘[...] AAF could **result** in lower impacts from persistent contrails [...]’

Comment 12: Discussion – opening  
L. 409 – I think the argument here is not about intergenerational equality, but rather about historical responsibility as well as ‘ability to abate’. Europe has arguably a) a higher historical responsibility in causing aviation-related climate impacts and b) a higher ability to pay for more costly AAFs, which is why it should pursue this strategy rather than plucking low-hanging fruits and prevent developing countries to later access these cheaper solutions.

Reply: We agree that our argument here was not adequately developed. We have adjusted this part of the paragraph:

‘Techniques such as carbon removal could help return atmospheric CO<sub>2</sub> to pre-industrial levels. This requires compensating for past emissions—using it to extend the use of fossil resources is a secondary distraction<sup>67</sup>. To the extent that this latter application could be justifiably allocated to aviation, we argue that it should contribute to addressing economic and environmental inequality—for example, by benefitting regions less prepared for the large-scale development of AAF or with a relatively lower contribution to past emissions. Even within our analysis, climate targets were formulated based on the historical distribution of environmental burdens. This should not be mistaken for a fair or just distribution<sup>68,69</sup> and further highlights the normative issues at play in international aviation policy<sup>70</sup>.’

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**Decarbonizing aviation does not imply successful climate mitigation**

The authors analyze decarbonization for aviation in Europe, specifically analyzing the role of hydrogen in powering aviation. The authors do a prospective life cycle analysis for different scenarios varying assumptions on demand, aircraft efficiency, and carbon intensity. The topic is very relevant and timely; however, the manuscript is not very clear, the analysis of hydrogen only as the alternative fuel may be too simplistic, and the article's conclusion seems rather opinionated (reducing demand as the one solution to decarbonize aviation). I elaborate on this below.

**Clarity:**

I think the authors could improve the clarity of their paper by:

1. Changing the order of the figures (and referring to them correctly)
2. Introducing the nine scenarios before the results (as well as its numerical assumptions)
3. Better explaining the methodology—both briefly in the introduction and more thoroughly in the methods section.

Overall, the introduction is written well, though the last paragraph can use some work to better explain the goals of the manuscript, include the description of scenarios, and shortly explain the methods.

- Goals: The two goals of the study (page 3 rows 69-71) are not clearly expressed.
- Scenarios: The authors need to explain their scenarios earlier on. Right now, figure 1 has results for scenarios that are only explained in figure 2, which is confusing.
- Methods: The authors need to explain earlier on how they do their analysis, and also what forms on hydrogen they consider (as an e fuel and as a liquid) and when they get deployed. These assumptions are important, and only come in some fragments of the methods (for example, only in page 13 line 358 the authors specify that they assume hydrogen planes use liquid hydrogen).

Additionally, the authors describe figure 1, then shortly figure 2, then figure 3, but then the paragraph on CO<sub>2</sub> emissions on page 7 row 137 goes back to figure 1. This back and forth is confusing. I suggest resorting figures and to address them in order.

In the discussion section the authors keep referring to figure 3 for emissions, when I think they mean figure 1, as figure 3 has fuel consumption amounts.

The methodology part is also not clear, and it is hard to understand how the authors get to the results they do. They document their assumptions quite well, but they do not really explain how they use them to create emission trajectories and radiative forcing.

### **Hydrogen-focus:**

Focusing solely on hydrogen while ignoring biomass-based fuels may be overly simplistic. It is more likely that a mix of technologies—including biomass-based fuels—will be used to decarbonize aviation. These fuels are more advanced and currently cheaper to produce than hydrogen-powered aircraft or synthetic fuels. Also, it is misleading to state that biomass feedstock is “limited”. The real concern is sustainability, particularly because of its competition for land with food crops, which constraints how much should be used.

Furthermore, assuming that hydrogen-based fuels have no other climate impacts, especially in terms of contrails, is an oversimplification. This area is poorly understood and hard to quantify. To be conservative, the authors should assume hydrogen-fueled aircraft have similar non-CO<sub>2</sub> impacts as fossil jet fuel, or at least test this assumption in a scenario (e.g., assuming non-CO<sub>2</sub> impacts are the same vs. lower). See for, for example, Lee et al. 2023 (<https://doi.org/10.1039/d3ea00091e>)

“Pure bio-based and synthetic SAF have low aromatic content and zero sulphur content. Such fuels would reduce soot number concentrations in the plume (high confidence) and may reduce contrail ERF (very low confidence).”

This also matters for offsets: how do the authors propose mitigating non-CO<sub>2</sub> impacts of aviation? It is true that offsets have not worked well in the past, but that is not sufficient reason to assume they will not work in the future, especially with technologies like direct air capture, which the authors assume will be fully scalable and operational.

### **Conclusion** (Page 8 line 196):

I believe that both offsetting and fuel switching in European aviation are justified and should even be incentivized. Europe, a wealthier region, would pay more to develop a technology that everyone would benefit from. For example, Germany did this with wind and solar in the early 2000s. While I understand the moral argument for reducing aviation demand when possible (especially for short trips with existing alternatives), I believe the core issue is reliance on fossil fuels. If richer, more developed societies developed (and paid for) the technologies to address this issue, then the developing world would benefit as well (especially since it is in those regions where aviation is growing the fastest).

Also note that the issue with offsets has been their permanence. If permanent removals were used, as well as sustainable aviation fuels, then mitigation climate impacts of

aviation would be possible without necessarily changing demand patterns much (see for example (<https://doi.org/10.1038/s41893-022-01046-9>) ).

## **Other comments**

### **Introduction:**

- Page 2 line 36: why use “alternative aviation fuels (AAF)” as opposed to “sustainable aviation fuels (SAF)” which is more common? If the authors prefer AAF they should at least also include SAF – unless they mean something different. Sometimes introducing new terminology makes the debate more confusing.
- Page 2 line 39: briefly explain what ReFuelEU intends to do, what are the targets? (This comes later, but I think it makes more sense at this point).
- As mentioned above, the authors need to include a short description of the scenarios in their last paragraph of the introduction, or at least in the first paragraph of the results (before introducing the results). In Page 4 line 89 the authors briefly state what the assumptions for scenarios are, but do not really explain them. I would add quantifications on the assumptions for energy intensity. Otherwise, it is hard to understand figure 1 when the scenarios have not been introduced.
- It is also not clear at the beginning that the authors are analyzing hydrogen as both liquid fuel in synthetic form and as a liquid itself. This was only clear to me after reading the methods.
- The authors could also include one sentence on the global aviation sector, just to put the European context into the global picture.

### **Results:**

- In general, it would be better to include more numerical descriptions when analyzing results
  - o e.g. “The CO<sub>2</sub> emissions from fossil-powered scenarios are comparable to those of AAF-powered scenarios”... by how much? The same applies to other instances
- Figure 1
  - o Why do all lines start at different values? Shouldn't the historical values all start at the same level, and only diverge in future modeled trajectories?
  - o How was the IATA/ICAO line created? Aren't they two different organizations that are not really related to each other programmatically? Why is there just one line?
- Figure 2
  - o It is also not clear why the first year varies? Shouldn't all scenarios have the same starting historical point?

- Page 5 line 121: how much higher?
- Figure 3
  - o In panel c the dashed lines are confusing. Is “European production” and “EU supply” the same?

### **Discussion:**

- Page 7 line 165 and line 171: authors point to figure 3, but I think they mean figure 1 for CO<sub>2</sub> emissions
- Page 7 line 166: is it climate neutral or carbon neutral? If the authors are talking about CO<sub>2</sub> wouldn't it be more accurate to refer to it as carbon neutral?
- Page 8 line 189: how much hydrogen production is projected in Europe? It would be good to have this number in EJ in the sentence, as well as the percentage.
- Something missing in the discussion section relates to the challenges of scaling the hydrogen industry, as well as the direct air capture industry, which would make synthetic fuels possible. And another important issue also omitted related to the challenges of replacing infrastructure – going from our current fleet to a fleet powered by hydrogen. What percent of planes by 2070 are powered by what fuels? What would this mean for airport infrastructure? These would be important numbers to pull from the study.
- Another key missing aspect relates to costs, which the authors should discuss. Currently hydrogen-based synthetic fuels are very expensive and liquid-hydrogen planes are not fully deployed. In their scenarios the authors assume that both of these technologies are fully available, and that may be unrealistic.

### **Methods:**

- It is unclear whether the authors use 2019 as their last historical period, or 2024. The main text seems to imply it is 2024, but the methods use 2019 (page 10 line 279).
- The authors could better explain their stock-and-flow model. Do authors assume certain future demand, and then let a model decide which aircrafts fly for how many kilometers, and based on emission factors get total emissions for aviation? I know they are explaining this process on page 8 row 214, but this was not very clear from reading the paragraph.
- Page 8 line 217: what is LWE? This acronym is only explained later, and it is the method the authors use. They need to explain this early on.
- Page 9 line 218: regarding previous work, we did a very similar study varying the same parameters than the authors' are varying (namely demand, energy intensity, carbon intensity) which I think the authors could cite, as their study uses a very

similar framework but to the European context. (<https://doi.org/10.1038/s41893-022-01046-9>)

- Page 10 line 268: these are not limited measures with little impact. For example, research has found that simply rerouting planes to avoid contrail prone areas would reduce its climate impact. While it is ok not to include these in your modeling, at least acknowledging that these actions could be beneficial is important (for example: <https://doi.org/10.3390/aerospace7090121>)
- How about freight aviation? Did the authors include this as well? Or did they just analyze passenger aviation?
- Page 11 line 294: What do the authors use to assume hydrogen conversion potential in Table 1? I am not sure this numbers make sense, especially for longer distance flights.
- Also, I think there may be some issues with table numbers. For example, page 10 line 84 should refer to Table 1? Same for Pag 11 line 321 I think (as it refers to share of aircraft with H2 conversion potential)
- Page 13 line 357: do authors assume that hydrogen in planes is liquified? Isn't this very challenging today given the low temperatures needed? I think the authors should touch on this in their discussion section, and write early on which forms of hydrogen they consider in their modeling.
- Page 15 line 411: probable the scenario design should come earlier in the explanations, as it is core to understanding the results.
- Page 16 line 444: the use of REMIND is not clear to me. Which parameters did the authors use? Why do they need an integrated assessment model if they are performing a life cycle analysis?
- Why did the authors use Allen et al ([DOI 10.1088/1748-9326/abfcf9](https://doi.org/10.1088/1748-9326/abfcf9)) as opposed to Lee et al (<https://doi.org/10.1016/j.atmosenv.2020.117834>) which is directly measuring aviation non-CO2s?

# Decarbonising aviation does not imply successful climate change mitigation

## Short summary of contribution and overall appraisal

The manuscript examines the role of hydrogen in enabling commercial aviation to align with European aviation climate targets. This is a timely and relevant topic with substantial societal implications, as hydrogen will likely play an important role in fueling aviation in climate-compatible ways. The introduction nicely frames the importance of these technologies towards reaching climate-compatible aviation. The utilization of a 'light' climate model to evaluate the impacts of these scenarios constitute an advantage over the status quo. In general, the model is constructed dutifully and with attention to plenty of details.

However, the scenario choice is quite confusing and badly explained and justified in the main text, which leads to some confusions in interpreting the results and extracting valuable insights on the impacts of different aviation pathways. I summarize below the main points of critique, while detailing in the 'Minor comments' these critiques and suggesting avenues for improvement.

## Major comments (details can be found below in the minor comments)

1. The manuscript would highly benefit from a more extensive explanation of the choice of scenarios. Especially unclear is the extent to which AAFs vs. H2 aircraft are deployed in the different scenarios. This is crucial to interpreting the results and in drawing the key insights from the results. I also wonder whether this study would not have benefitted to a comparison of the impacts of AAFs and H2 AC in a 'vacuum' setting – namely looking only at the climate impacts over time (considering LCA aspects) of two 'pure pathways' looking at these two technologies. This could also be added as an initial figure, and then the other 'megatrends' such as policies, air traffic volumes, breakthroughs in AC could be added in following figures.
2. The introduction needs to introduce the 'megatrends' that are then a core part of the scenarios assessed (AC efficiency, air traffic volume and the presence of ReFuelEU as a climate policy driver).
3. There's an overstatement in the kind of novelty brought by due to the promise of a comprehensiveness in the assessment of H2 scenarios. Yet, scenarios are really coarsely picked based on very broad 'megatrends', which leads to a bundling of a lot of possible technologies together – with potentially important differences in terms of LCA. I think this is not per se a problem, but definitely it tampers the scientific advance brought by with this study (which should then not be overstated throughout the manuscript).
4. The introduction promises a focus on hydrogen, which then does not perfectly match back to the results, since in the results hydrogen is considered very bimodally (in a 'on off' kind of design), without investigating in the different technologies, and its effects are co-founded by other important trends such as air traffic volumes, efficiency increases and different blending quotas. I think the premise of the introduction is very interesting and should be better developed throughout the results and discussion by adding more in-depth analyses of the role of hydrogen.
5. Overall, it's unclear why the exclusion of H2 aircraft has such a small impact in the amounts of AAFs deployed. Is this due to assumptions in the scenario design (if so, I think a sensitivity

analysis for higher H2 aircraft shares is needed) or due to the incapacity to increase H2 aircraft in the fleet at higher rates (due to the lifetime of the fleet)?

#### **Minor comments**

p. 1 l. 9 – This sounds a bit overstated.

p. 1 – Abstract: I find it hard to match the premise (the promise of identifying the conditions under which hydrogen-based aviation can comply with European climate targets) with the results actually expressed in the abstract, namely the different levels of stabilizations. It would be good here to pinpoint directly at the most important conditions identified in the study which help attaining an appropriate level of warming (but I guess the problem is also that in the EU we don't have a sectorial, or even regional, breakdown of temperature targets). I'd highlight the novelties of this study already in the abstract, otherwise it reads like something we knew already from previous studies (namely that the trajectory before 2050 will influence the level of warming in 2050).

p. 2 l. 18-34 – Here it would be important to mention not only the lack of quality of offsets (in terms of delivering less emission reductions than promised), but also generally their non-compatibility with a truthful concept of net-zero, where long-lived CO2 emissions need to be compensated by equally durable CO2 removals. This could be implemented (in theory), but today's offsets are almost all emissions avoidance, emissions reductions, or biogenic, non-durable CO2 removals (e.g., in trees).

p. 2 l. 35-36 – Is there a specific reason for calling them AAF instead of, as mostly common, SAFs? I would refrain from introducing a non-common acronym in order to improve clarity for readers that quickly skim through the manuscript.

p. 2 l. 37 – 'but have not been met': unclear that it refers to the ambitious targets. Add 'these targets have ...'

p. 2 l. 37 – 'These voluntary targets': unclear before that these targets are voluntary and hard to establish the parallel with the ReFuelEU. I would reshape the first 3 sentences of this paragraph to enhance clarity and explain that, while most voluntary targets were ambitious, they also have been largely ignored in practice – but the situation with ReFuelEU should be different (why? Are there any guardrails in place to ensure the targets will be met?).

p. 2 l. 56 ff. – I find this transition to the significance of the study a bit weak, resulting in an unclear picture of how this study will advance the current state of knowledge. The introduction well highlights the different pathways to reduce aviation's emissions and the issue with offsets (even though the potentially very important role of CDR is left out). But here I don't understand what is exactly the gap that this study is contributing too. I think what's missing is a little review of the literature comparing these pathways, which should highlight that a comprehensive comparison has never been done (even though I know of several studies that have attempted at a comprehensive assessment of pathways, such as Bergero et al., 2023; Dray et al., 2022; ...). Also, I think it should be justified more why pLCA is the appropriate approach – a focus on the different LCA dimensions still neglects the economic component, so this should be justified a bit more thoroughly (by stating more explicitly the contribution to the literature, which has either examined broadly costs and pathways without looking at the LCA in depth – e.g., Dray et al., 2022 – or has looked at these aspects but only for a very narrow selection of technologies – e.g., Sacchi et al., 2023; Brazzola et al., 2025). I'd also argue that a in-depth inclusion and comparison of hydrogen aircraft to AAFs is missing in the literature, especially with an pLCA perspective.

p. 3 l. 75 ff. – Here, you jump straight into the figures without first guiding the reader through a description of the scenarios represented. I suggest adding a small first section where the scenarios

are explained in detail, including a modified version of Figure 2 better tracking back to the different scenarios shown in Figure 1, as a first thing, in order to lay the basics for understanding the results to follow. For example, for me it's not clear how to interpret the trade-off between hydrogen aircraft and AAFs from Figure 1. The text introducing Figure 1 also mentions fossil fuels, but I'm not fully sure how these map to the figure (I guess we talk here about the red line, but then again, would the ReFuelEU with H2 aircraft also apply here?). Also, there's no mention of the European focus in the introduction – as a result, this focus comes through as an (unjustified) surprise.

p. 3 l. 89 ff – Here, we find out suddenly that the different scenarios are not only looking at the different technologies, but also at 'megatrends' in aviation, including air traffic volumes and different variations of ReFuelEU – of which no mention was made in the introduction. Also, multiple variables vary at the same within different scenarios, which makes it hard to disentangle the effect of single variables (e.g., air traffic volumes and efficiency breakthroughs). In particular, it is unclear to which extent the AC breakthroughs impact the amount of H2 AC present in the mix (and what happens if we have great AC breakthroughs but no H2 AC?). This calls for a more extensive scenario-description section before diving into the results – otherwise readers are confused to why we are having these different scenarios and what we should take out of them.

Figure 1 – Personally, after reading the introduction, I'm mostly curious to clearly see the effect in climate impacts of H2 hydrogen vs. AAFs. Yet, because the 'megatrends' of AC breakthrough, ReFuelEU absence and air traffic volumes seem to be more important, the differences between H2 aircraft and AAFs are very hard to read. While it's nice that you are able to visually display such a diverse range of scenarios on one figure, I wonder whether it would not be better to pick fewer 'megatrends' and reduce the number of scenarios such to focus more strongly on figuring out the contribution of H2 aircraft. Other scenarios could be added in a second part of the paper or in the supplementary information.

Figure 1 – Why are the emissions in 2020 so different among the 'megatrend' scenarios? It looks like different growth trajectories take place already in the past. This makes it very hard to compare scenarios as apparently they also start on different historical premises. I would make sure to homogenize these premises such to isolate the impacts of pathways post 2020.

Figure 1b – Why are the non-CO2 impacts differences among with/no H2 AC scenarios so little? I would expect the effects of H2 AC on non-CO2 mitigation to be substantially higher than those of AAFs. Is that due to the fact that H2 AC are only present in very small shares?

Figure 2 – To also tackle my comment above, I would add a third panel to Figure 2 showing the share of H2 Aircraft under the different scenarios.

Figure 2c – Why do we have a ReFuelEU 'as-is' scenario, if it actually is never shown in the other figures?

Figure 3 – What drives reductions in fossil kerosene use when we don't have ReFuelEU? Is that the 'disentangled effect' of growth and efficiency? How does efficiency trace-back to H2 aircraft deployment? Why is the difference in AAF use so little between scenarios with H2 aircraft and without? Answers should be findable in the main text and easily understandable from the figures (thanks to a clear explanation of the scenarios).

p. 5 l. 117-119 – This is the kind of very useful information on the characteristics of scenarios that should come up earlier (and maybe be put systematically in a tabular form, so that we can clearly read out all the different assumptions driving the different scenarios and heavily impacting the results).

p. 7 l. 137 – I find it very confusing that this little section referring to Figure 1 is placed here. I think overall the whole results section needs some serious restructuring in order to 1) ensure scenarios are clear at the beginning, 2) ensure that each figure provides insights that are then explained in the text immediately preceding/following it.

General comment - Scenario naming: I strongly recommend changing the names of the scenarios represented by dashed, dotted lines etc. by having a 'fossil jet fuels' scenario vs. a 'ReFuelEU' and a 'ReFuelEU + H2 aircraft'.

p. 7 l. 165 – "This suggests..." I would argue that here the logical link is flawed. You first say that emissions are down to a fifth of those with fossil fuels, and then claim that based on this climate-neutral aviation is possible. But actually climate neutrality strongly depends on the baseline relative to which aviation is considered neutral. CO2 neutrality, on the other hand, never gets reached based on Figure 1a.

p. 7 l. 164 ff. – I feel like these conclusions miss the novelty of the whole paper. We already knew from multiple studies (the above mentioned) that pathways to climate neutral aviation are in principle possible. But what's the contribution of H2 aircraft compared to AAFs to do so? And what should happen to align the sector to climate targets? To answer this, I believe you would need to change the scenarios a little bit. Especially, it would be interesting to have scenarios that can get to the ICAO targets eventually (by having more H2 aircraft earlier on, for example), and that show the contribution of H2 aircraft vs. AAFs more clearly. Finally, I think it would be nice to deduct some sort of 'threshold' for climate neutrality that should be reached. I know it's extremely hard to do so (we only have a global temperature target), but you could for example use the mean of the European aviation RF from IAMs ensembles that manage to limit 1.5-2°C by 2100 and add these as horizontal lines in your Figure 1.

General about the discussion – I feel like the discussion is erratically spanning across various themes while it fails to deliver a succinct summary of the main findings and their relevance to science and society. Relative to my previous comment, I would in general reshape the study such to deliver clear take-aways instead of the current, general ones – which have already been largely delivered by existing studies. I think the modelling set-up of the study allows for these novel and important insights to be delivered.

On this note, I would also revise the title such to place a major emphasis on the (novel) exploration of the role of hydrogen.

## COMMSENV-25-0747A

Decarbonising aviation does not imply successful climate change mitigation

I appreciate the changes to the original manuscript, and the responses to reviewers' comments! The manuscript reads much smoother now, and I have only two concerns remaining, and some smaller comments.

### Title not supported by findings:

One concern relates to the title, which I think (while catchy) does not fully represent the authors' findings. If aviation used net-zero fuels, then its climate impacts would be minimal to none (depending on the non-CO2 effects of AAF). It is not that decarbonizing aviation does not achieve climate change mitigation, but rather that the ReFuelEU scheme is not enough to meet net-zero in the short term. In the abstract, the authors state "Although alternative fuels can greatly reduce CO2 emissions and non-CO2 impacts—with hydrogen-powered aircraft yielding the largest reductions—persistent air traffic growth drives the near-term use of fossil resources and the long-term scale of non-CO2 effects." So decarbonizing aviation does contribute to climate change mitigation, it is just not enough to meet net-zero targets from IATA in the short-term because demand is growing fast and we are not scaling these fuels fast enough—even in the ReFuelEU mandates the scaleup takes decades. So, I find the title to be too general and misleading. Another suggestion could be something like: "Hydrogen is not enough to meet net-zero aviation targets in Europe", or "ReFuelEU implementation would still lead to high emissions from aviation in the short-term", or something that's more specific to the authors' analysis. The authors are free to pick the title they prefer, but the current one I think is misleading.

### Authors' suggestion in discussion for demand reduction:

The second concern relates to the authors' suggestion that the solution is to reduce demand for aviation. While it is true that in their scenarios only degrowth meets CORSIA, a different policy suggestion derived from this study could be to more aggressively deploy AAFs, which would reduce the carbon intensity of the fleet, and thus potentially meet climate targets. What the authors are finding is that the current ReFuelEU scheme is not compatible with other CORSIA-IATA net-zero targets—but not necessarily that demand must decrease. Again, this feels like an opinion of the authors, which I can agree with, but it is not supported by their findings (but rather a scenario choice). Maybe on line 416 the authors could say "in light of these considerations **and in absence of any modification to the ReFuelEU program**, the adoption of measures to limit or reduce air travel could be effective in reducing...". The authors could also highlight alternatives (like trains), and bring in the importance of these services to be

lower cost to aviation, and as efficient as possible (the authors never mention any alternative to flying).

#### Smaller comments

- Line 114: air traffic volumes “derived from NNNN”. This may be a good place for authors to note what they assume future aviation demand is (which the methods state as EUROCONTROL, I think).
- Figure 1: why does the schematic include 3 air traffic volume scenarios (high, low, degrowth) but the figure includes four (adding base growth)? This is confusing, so if base growth is not used in their analysis I suggest the authors drop it.
- Line 145: Do you mean to eliminate fossil kerosene by 2050? Shouldn't it be 2060? By 2050 you have reduced it by 70%, and then you assume that by 2060 you have reduced fossil kerosene by 100% (at least that's what I see in Figure 1c).
- Line 211-212: “We assume that the initial introduction of hydrogen-powered aircraft is limited to narrow-body aircraft servicing intra-European flights”: Maybe the authors here could just put what percent of European flights are “intra-European” and which ones are extra-European? I think it would be helpful to see the split, as it matters for fleet composition. (I see comes later in the Methods on Table 2, but it may be useful to add the percentages in this instance so that the reader has a general idea of the split).
- Line 231: I recommend the authors use the “non-drop-in AAF” in panel b, as this is easier to follow than “excluding drop in AAF”. Are the lighter shades in panel b in Figure 3 showing the amounts to hydrogen used to power hydrogen-planes? I think so, so just saying “non-drop-in hydrogen” or something like this is more intuitive.
- How do the authors estimate temperature impacts? It may be worth noting when authors introduce their results on line 270 “Climate impacts”. The authors explain in their methods the use of GWP, maybe they can add a simple sentence in line 270 to note this.
- There is some formatting issue in page 10 of the supplementary material (below supplementary figure 8), and some figures are hard to read (as if the resolution was not good enough. I am not sure if this was just happening to the version I opened, but it is worth double checking).
- There are also issues with the references at the bottom of SI.