Non-CO_2 impacts of hydrogen:

A summary report for the Aviation Environment Federation

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Introduction

This briefing note summarises a review by the University of Leeds of the current state of knowledge on the non-CO_2 climate impacts ("non-CO_2 impacts") of hydrogen as an alternative aviation fuel.

Current aviation is almost completely dependent on fossil fuel kerosene or jet fuel. As well as carbon dioxide (CO_2), jet aircraft release into the atmosphere nitrogen oxides (NOx), aerosols, and water vapour, which leads to the formation of contrails. Combined, these emissions roughly triple the total climate impact of aviation compared to that from CO_2 alone.

Hydrogen is one of several low- or zero-carbon alternative aviation fuels that could replace fossil fuel kerosene (others include ammonia, synthetic or efuels and biofuels), but each of these has its own benefits and limitations.

Below, we review current knowledge on the use of hydrogen as an alternative aviation fuel, including that presented in the Aviation Impact Accelerator's RECCE tool. We find that, as well as zero CO_2 emissions, hydrogen-fuelled aircraft are likely to lead to less non-CO_2 warming than those fuelled by kerosene. However, further work is needed to better understand the non-CO_2 impacts of hydrogen, and so we also provide direction for future research if hydrogen is to become a viable alternative aviation fuel.

Current atmospheric science knowledge on the non-CO_2 impacts of hydrogen

Contrails and aviation-induced cirrus

A number of recent studies[1,2,3,4,5] have examined the effects of switching to hydrogen on contrail formation but the results remain inconclusive.

Hydrogen-fuelled combustion aircraft will almost certainly create contrails, but they will be different to those generated by kerosene due to the different exhaust temperatures plus changes to water vapour and soot emissions.

The higher exhaust temperatures of liquid hydrogen combustion aircraft reduce the likelihood of contrails forming, but the dominant effect is the substantial increase in water vapour emissions which means that overall contrails are more likely to form.

[1] https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-022-014854/MediaObjects/41558_2022_1485_MOESM1_ESM.pdf
[2] https://acp.copernicus.org/articles/23/287/2023/acp-23-287-2023.html
[3] https://www.nature.com/articles/s41612-018-0046-4
[4] https://pubs.acs.org/doi/10.1021/acs.est.9b05608
[5] https://elib.dlr.de/142742/1/Gierens-aerospace2021.FC-Contrails.pdf

Using hydrogen will also remove aerosol particles (e.g. soot) from emissions. This in turn will make contrail ice crystals larger and reduce their climate impact. Increasing ice crystal size might also reduce the contrail lifetime, reducing their climate impact still further.

However, any change in engine design that alters cruise altitude might have the largest impact on contrail formation, and this is hard to predict at present.

NOx

The net climate effect of NOx emissions depends on both the period considered and the balance of different warming and cooling effects. Lee et al. (2021)[6] estimate that the overall NOx impact from hydrogen would be warming in the current climate, but it could also be close to zero if nitrate aerosol formation is taken into account (Grobler et al., 2019[7]). The net NOx climate impact is expected to fall in future, but how NOx emissions change depends heavily on how engines develop.

Stratospheric water vapour

Water vapour released into the stratosphere warms the climate for several months. All things being equal this effect would increase by a factor of around 2.6 with hydrogen-powered aircraft, but this also depends on engine efficiency gains and how many hydrogen-powered flights there are. Overall, stratospheric water vapour is expected to lead to a small amount of warming under hydrogen-powered flight.

Particulates

The minimal amounts of sulphates and soot from hydrogen aircraft would immediately reduce their respective direct cooling and warming effects to zero. However, there could be indirect effects on non-contrail clouds (sulphates, and nitrates from NOx, are important cloud condensation nuclei) but these wider aerosol-cloud interactions represent a large scientific knowledge gap (see below).

Hydrogen leaks

As well as on the ground, hydrogen leaks could also occur in-flight. Although not a greenhouse gas, hydrogen alters atmospheric chemistry, affecting methane and stratospheric water vapour. A 2% leakage rate (as assumed in Dray et al., 2022[8]) would lead to considerable short-term warming, offsetting some of the benefits from reduced CO_2 emissions.

The Aviation Impact Accelerator (AIA) RECCE tool

The AIA uses simple, evidence-based models to support and inform decisions, policies and plans related to alternative aviation fuels, aircraft design and flying patterns. This includes looking at the overall climate impact of flights, including the in-flight non-CO_2 climate impact.

At present, only the RECCE: Resource to Climate Comparison Evaluator tool[9] is publicly available. RECCE evaluates the climate impact from contrails and in-flight emissions of CO_2, NOx, water vapour, hydrogen and soot in terms of their global warming potential (GWP) for the year 2035. These are given as ranges in CO_2e. We find that the estimates used by the AIA for fossil jet fuel generally agree well with those of Lee et al. (2021).

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[6] https://www.sciencedirect.com/science/article/pii/S1352231020305689
[7] https://iopscience.iop.org/article/10.1088/1748-9326/ab4942
[8] https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-022-014854/MediaObjects/41558_2022_1485_MOESM1_ESM.pdf
[9] https://recce.aiatools.org/

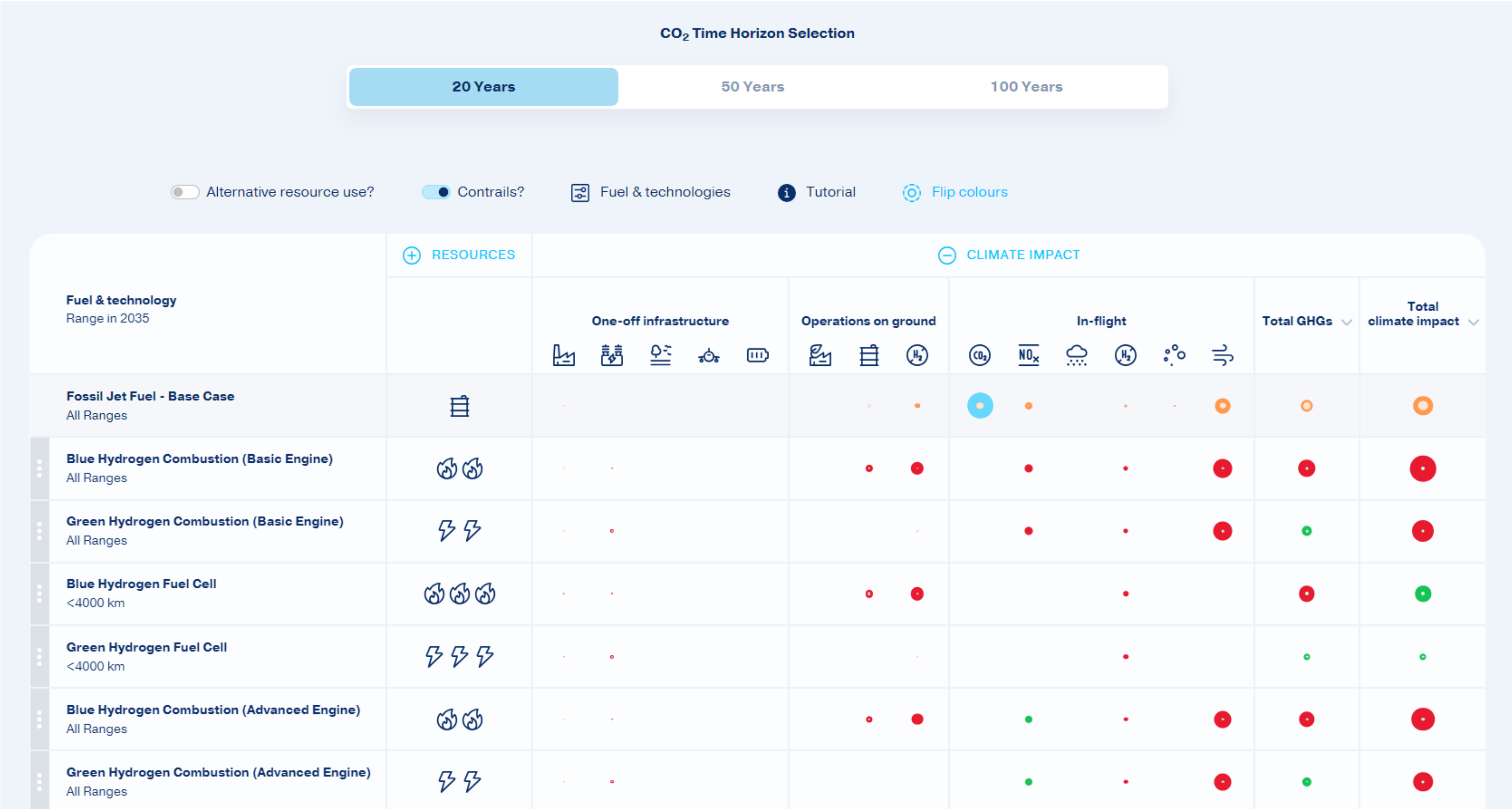

Figure 1: Screenshot of first AIA public product (RECCE), designed for comparing the climate impact of future fuels. https://recce.aiatools.org/ (accessed 26 September 2023). Fossil jet fuel baseline is compared against future fuels in terms of the various resources required, source of emissions (various aspects of infrastructure, operations and in-flight), total GHG emissions, and total climate impact. Circle area is proportional to climate impacts (and includes uncertainty range as outer circle). Red = higher than base case; orange = same as base case; green = lower than base case. Additional information including numbers can be found within the tool.

Using RECCE to compare hydrogen and kerosene, hydrogen has a larger possible range of contrail climate impact than kerosene (although advanced hydrogen engine technologies have less contrail impact, presumably from more efficient engines). There is also a small direct climate warming from fugitive hydrogen.

NOx impacts from hydrogen could meanwhile be substantially lower (and soot emissions are assumed to be zero). There is a small stratospheric water vapour impact, which would be expected to increase in line with the increased hydrogen content of the fuel.

As above, the conclusions from RECCE generally match the scientific literature: the non-CO_2 impacts of hydrogen are likely to be slightly lower than those of kerosene, principally as a result of reduced NOx and contrail cirrus forcings.

The exception is fuel cell hydrogen: RECCE assumes zero contrail forcing for fuel cell hydrogen, but this is actually likely to be similar to the forcing from liquid hydrogen combustion contrails[10]. The approaches behind the tool and alternative fuel choices are summarised in Appendix 1.

Scientific knowledge gaps regarding hydrogen as an alternative aviation fuel and recommendations for future work

Reducing atmospheric science-related uncertainties associated with contrails will be particularly important in quantifying the climate impact of using hydrogen as an alternative aviation fuel. Priorities for research include:

- Developing improved flight path emission inventories
- Studies of background cloud climatology properties
- Studies of the radiative properties of cirrus clouds
- Process studies of persistent contrails
- Considering expected climate conditions and flight paths up to 2050 for all of the above

The largest (and most overlooked) uncertainty however involves aviation particulate emissions and their role in modifying clouds. There is therefore a need for more research into quantifying the climate impacts of aerosol-cloud interactions from aviation aerosol emissions.

Low-level clouds cool the climate, an effect currently enhanced by pollution from industry, transport and agriculture. As sulphur pollution from shipping and coal combustion falls, particulate emissions from aviation could become more important as cloud condensation nuclei, increasing low-level cloud reflectance, leading to considerable cooling. The strength of this cooling effect has important implications for whether hydrogen and other particulate-free fuels provide a non-CO_2 net climate benefit compared to kerosene. Modelling the climate impact of hydrogen emissions in the upper troposphere will also be important in understanding its non-CO_2 impacts.

If engine design for hydrogen aircraft can consider non-CO_2 climate benefits in an interdisciplinary and open way, reducing small non-CO_2 radiative forcings could be designed in. Examples include investigating water release from fuel cells, and flight altitude optimisation for contrail avoidance. Overall, the more engine and aircraft design engineers and atmospheric scientists work together, the greater potential for designing climate neutral aircraft. There are exciting opportunities for an open research environment where ideas can be explored, and the Whittle approach to rapid technology development[11] could be a useful way forward.

[10] Report for FlyZero by the University of Leeds
[11] https://whittle.eng.cam.ac.uk/new-whittle-laboratory/

Appendix 1

Hydrogen contrails and other non-CO2 impacts within the RECCE tool

RECCE looks at the climate impact of a given fuel and technology in 2035 relative to the in-flight CO_2 impacts of jet aircraft, based on 'global' impact figures. The metric used on the live version of RECCE is Global Warming Potential (GWP) over a 20, 50, or 100 year time horizon.

At present, the GWP for jet aircraft are taken from Lee et al. (2021), but a coming update to the tool will allow users to choose between those in Lee et al. (2021) and Grobler et al. (2019). There is only a small variation in most non-CO_2 impacts between these sources, with the exception of NOx.

These figures are then corrected in a couple of ways: RECCE assumes that contrails scale with km flown, so the GWP of contrails relative to in-flight CO_2 is scaled with the expected efficiency improvements of 2035 new aircraft vs the 2018 fleet-average from Lee et al. (2021). This is a significant assumption, including uncertainty around the fuel burn per km in 2035 (the AIA team is currently investigating potential improvements to engine efficiency).

There is also conflicting evidence on what the NOx trajectory will be for newer engines. Historically, there has been a year-on-year increase of ~0.5% per unit of fuel burnt. The AIA team is also looking at this to better understand the likelihood of reduced NOx emissions in future.

No adjustments have been made to soot or water emissions. For hydrogen, the soot impact is set to zero and fuel stoichiometry is used to scale water vapour impact.

Regarding hydrogen leakage, recent studies estimate the GWP of hydrogen to be around 11+/-5 kg CO_2/kg H_2. On-board leakage is expected to be small, but on-ground leakage could be significant (estimated by comparison of hydrogen flow behaviour in pipelines, tanks and other equipment to natural gas leakages).

RECCE also excludes the cooling impact of sulphur emissions from jet aircraft.

As no reliable contrail models have been found for hydrogen, the tool relies on expert judgement to assess the impact of hydrogen (the live version of RECCE uses adjustment factors from Dray et al., 2022). There is however still a substantial uncertainty range.

NOx production per megajoule of fuel for hydrogen and jet fuel has been found to be similar. However, ongoing industrial and academic work suggests that emissions from hydrogen-fuelled aircraft could be reduced by 25-50%. This has not been accounted for in RECCE yet (although it would not make a large difference to the current figures).

There are future ambitions to add an accompanying information page within RECCE detailing the assumption in its calculations.