Flying with e-kerosene and without worry?

E-kerosene, contrails, route optimization and energy transition: A stocktaking

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Flying with e-kerosene and without worry?

Summary

Sustainable e-kerosene has the great advantage of burning CO_2-neutral: Only so much CO_2 comes out of the engine as was previously extracted from the atmosphere for the production of e-kerosene, if produced according to the atmosfair fairfuel standard with CO_2 originating from non-fossil residues or direct air capture.

Does this mean that we can already fly climate-neutral with green e-kerosene? Unfortunately not, because the use of e-kerosene in jet turbines also leads to a number of other climate effects similar to fossil kerosene. These include in particular the formation of contrails and ozone at high altitudes, collectively known as "non-CO_2 effects". These actually warm the climate twice as much as the pure CO_2 from the kerosene.

This paper presents how e-kerosene performs in terms of non-CO_2 effects. We will see that e-kerosene has significantly lower non-CO_2 emissions and thus causes significantly less non-CO_2 effects. Although scientific research does not yet provide a final answer, it can be roughly estimated that the use of 100% sustainable e-kerosene could roughly halve the total climate impact of aviation (CO_2 and non-CO_2).

The remaining contrails and ozone formation, and consequently the overall climate impact of air traffic, could ultimately fall to almost zero if flight routes and altitudes are also optimised. However, since this would increase fuel consumption, and e-kerosene requires significantly more energy to produce than it contains, it will be necessary to balance it from a climate policy perspective: How much e-kerosene production with the needed high energy input is appropriate in relation to the total renewable energy production, as long as the energy transition is not yet complete?

Sustainable e-kerosene is therefore an important first step towards climate compatible flying and, if applied correctly, can also lead to climate-neutral flying in the long term. Until then the following applies: Flying less is better for the climate.

Climate impact and non-CO_2 effects of aviation

We first provide a brief overview of the state of the scientific research on non-CO_2 effects and discuss the use of sustainable e-kerosene.

We consider the following non-CO_2 effects caused by aviation that influence the atmospheric radiation budget. They occur in addition to the pure CO_2 emissions, which are the same for e-kerosene and fossil kerosene (3.16 kg CO_2/ kg kerosene).

- Contrails: The hot, particle-rich exhaust from aircraft can lead to contrail formation under certain atmospheric conditions. The atmospheric conditions for contrail formation depend on the humidity and temperature of the surrounding air, and thus on the time of year (Yin, et al., 2018) .
  When contrails form, their optical properties (including reflectivity) and lifetime are largely determined by the surrounding air and the number of initial ice particles (Burkhardt, 2018) . In the relevant region, this behaves approximately linear to the number of particles in the exhaust gas.

In addition to the lifespan and the optical properties of the contrails, the reflectivity of the ground (depending on the properties and colour of the ground, technical term: albedo) and the time of day also determine their effect on the climate. If the climate impact of contrails is averaged over a longer period of time and the whole world, it is about as strong as that of CO_2 emissions from air traffic.

- NO_X: Nitrogen oxides have an effect on the local ozone concentration (analogous to the former ozone smog formation in cities), and in a further step on the methane concentration of the atmosphere (methane depletion). Both effects have opposite climate impacts (warming and cooling), with the warming effect being the clearly predominant one. As in the contrails case, the rule of thumb calculation shows that the net warming effect of nitrogen oxides from a flight is about as strong as that of CO_2 alone.
- Other components: Water vapor leads to only minor warming due to its short lifetime in the atmosphere. Black carbon leads to warming independently of the above-mentioned influence on contrail formation, while sulphate compounds have a cooling effect. Roughly speaking, the warming potential of these effects roughly cancel each other out.

To simplify the complex dynamic processes of the different effects, scientists have introduced so-called metrics that compare the climate impact of the effects listed above with the climate impact of pure CO_2 emissions.

The metrics differ, for example, in the consideration of historical climate impacts or the feedbacks in the climate system. Among other things, a time horizon is chosen over which the climate impact is considered. Which metric and time horizon is chosen also depends on the climate policy. According to international climate policy and the Kyoto Protocol Convention, a time horizon of 100 years is usually assumed in order to adequately take into account the long-lived effects of gases such as CO_2 or nitrous oxide.

The German Federal Environment Agency (UBA) recommends the *average temperature response (ATR100)* metric for aviation over a 100-year period. (Niklaß, et al., 2020) . Another generally established metric (not specifically for emissions from aviation) is the *global warming potential (GWP)*, which is specified by the *Intergovernmental Panel on Climate Change (IPCC)* over time horizons of 20, 50 and 100 years, depending on whether short- or long-term climate impacts are to be considered. In 2020, Lee et al. also developed the GWP*, which no longer compares the absolute effects of different pollutants, but their change over time. The question GWP* asks is: How much CO_2 would air traffic have to emit worldwide in order to achieve the same increase in global warming as that caused by the increase in, for example, contrails between 2000 and 2018?

Table 1 lists these metrics for the non-CO_2 effects described above. The reference parameter is always CO_2, which is given here as the "lead gas" and for normalization with a warming effect of 1. Depending on the metric, contrails and nitrogen oxides have a contribution to climate impact comparable to that of CO_2 emissions (see the "rule of thumb" above). Water vapour, black carbon and sulphate compounds have a comparatively small and partly opposite effect.

	CO_2	Condensation trails	NO_X	H_2O	Carbon black	SO_2	∑	Source
Simple ATR100	1.00	1.00	1.2	0.2	N/A	N/A	3.4	(Niklaß, 2020)
GWP*100	1.00	1.77	0.33	0.04	0.02	-0.15	3.0	(Lee, 2020)
GWP50	1.00	1.09	0.28	0.04	0.02	-0.14	2.3	(Lee, 2020)
GWP20	1.00	2.32	0.86	0.08	0.04	-0.30	4.0	(Lee, 2020)

Table 1: Comparison of metrics for the climate impact of air traffic

Result: A climate factor of 3 relative to pure CO_2 emissions

Overall, this leads to the conclusion that air traffic in total (CO_2 and non-CO_2) warms the climate three times more (in the table 3.0 or 3.4) than the CO_2 emissions alone. Therefore, atmosfair applies this "factor 3" to all CO_2 emissions at high altitudes to the pure CO_2 emissions in order to capture the climate impact of the non-CO_2 emissions.

How does e-kerosene affect the non-CO_2 effects?

The use of synthetic kerosene in aviation affects the non-CO_2 effects directly through a change in the composition of exhaust gases and indirectly through the option of rerouting with a reduced climate impact. In this section, we discuss hypothetical scenarios for the use of 100% e-kerosene.

1. Direct reduction of emissions

A complete fuelling with e-kerosene affects the emissions as follows:

- With sustainable e-kerosene, CO_2 emissions are reduced to about 1% (only residual emissions from the upstream chain, e.g. plant construction), because the production of e-kerosene has previously removed this CO_2 from the atmosphere. (Schmidt, et al., 2016) .
- Depending on the estimate, particulate emissions are reduced by around 45% to (Lobo, et al., 2011) to 98% (Blakey, et al., 2010) (Corporan, et al., 2007) . Various studies with different methodologies (experiments on the ground or in the air) arrive at a wide range of results here. Further studies are necessary for a more precise quantification. (Gierens, et al., 2016) .
  Since the number of ice seeds depends sublinearly on particle emissions, an assumed 45% reduction in particle emissions leads to about a 20% reduction in the climate impact of *radiative forcing of* contrails; a 98% reduction in particle emissions leads to about a 90% reduction in *radiative forcing of* contrails (see Figure 1). (Burkhardt, et al., 2018) .

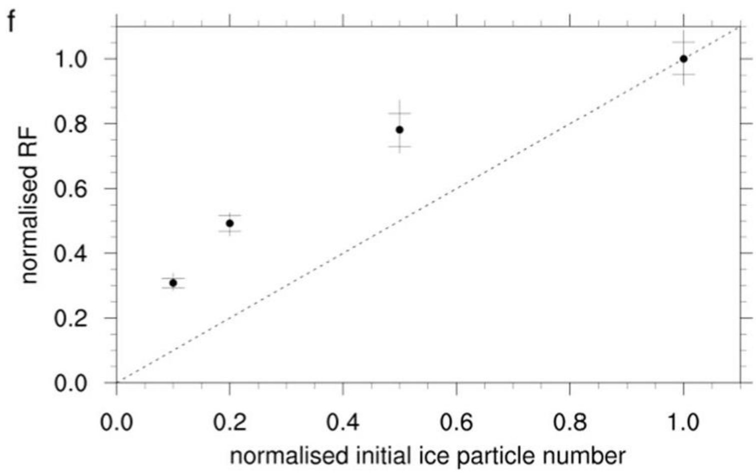

Figure 1: Climate impact (radiative forcing, RF) as a function of normalized number of ice particles (Burkhardt, et al. 2018).

- Nitrogen oxide emissions are reduced by up to 12 %. (Blakey, et al., 2010) and thus also the warming effect via ozone formation.
- Due to the lack of Sulphur, synthetically produced e-kerosene is assumed to reduce aerosols by a factor of 10 (Braun-Unkhoff et al., 2017)

Conclusion direct emission reduction

The non-CO_2 effects of aviation are therefore significantly reduced by the use of synthetic kerosene. This is due to the reduced particulate and nitrogen oxide emissions. Under the simplifying assumptions that the e-kerosene is also completely CO_2-free in the upstream chain and that the reduction in emission quantities has a linear effect on the climate impact of the non-CO_2 effects, we obtain the following rough estimate for the climate impact for the use of 100% e-kerosene (Table 2).

	CO_2	Contrails	NO_X	∑
Simple ATR100	1.00	1.00	1.2	3.4
Simple ATR100, E-Kerosene	0.0	0.10 - 0.80	1.0	1.1 - 1.8
GWP*100	1.00	1.77	0.33	3.0
GWP*100, E-kerosene	0.0	0.4 - 1.4	0.3	0.7 - 1.7

Table 2: Highly simplified rough estimate of the climate impact of sustainable e-kerosene

The effects of water vapour, sulphates and black carbon were neglected in this estimation.

It can be seen that the use of 100% e-kerosene would significantly reduce the overall climate impact of aviation through the reduced emissions and subsequently reduced non-CO2 effects. It is estimated that the climate impact could be reduced by about 50% to 75% in this case. This shows that e-kerosene can have a significant climate change impact for aviation even beyond the pure CO_2 emissions. In the next section, we show that this potential can be significantly increased by changing routing of aircrafts.

2. Reduction potential through modified routing

In addition to the direct reduction of emissions, the use of e-kerosene opens up further possibilities for reducing non-CO_2 effects through flight route optimisation.

The formation of contrails can be minimized by flying around areas where contrails can form. Typically, the air layers where the air is cold and humid enough for the formation of permanent contrails are only several hundred meters thick. Flying over or under them means for the aircraft to deviate from the optimized flight altitude, which increases fuel consumption and thus CO_2 emissions. In addition, these routes deviate from the cost and time optimisation.

Yin et al. found that flight path optimisation can reduce the routes where the atmospheric conditions for formation of long-lived contrails are met by 40% on average, for an additional flight time of less than 2%. (Yin, et al., 2018) . This shows that route optimisation can provide significant relief to the climate even without the use of e-kerosene.

Yamashita et al. found through simulation that the optimisation of 100 transatlantic flights on a typical winter day reduced ATR20 by about two-thirds (Yamashita, et al., 2019) . This corresponds to an almost complete reduction in non-CO2 effects, since about one third of the climate impact is caused by CO_2. At the same time, flight time in this scenario increased by 6% due to the detours, but more importantly fuel consumption increased by about 20%. With fossil kerosene, this would be a significant disadvantage of this scenario from a climate protection perspective. With CO_2-neutral e-kerosene, on the other hand, this environmental disadvantage does not apply.

Now, the North Atlantic is generally an area where contrails are more likely to occur, compared to the equatorial region. Therefore, a lot of contrails can also be avoided over the North Atlantic by changing flight paths. In addition, studies on flight path optimisation have so far been based on numerical simulations and still require experimental validation. In addition, optimisation of a real flight route requires knowledge of precise weather situation, which is currently not measured with high enough precision. (Grewe, et al., 2017). .

Generally speaking, it will not be possible to fly around all contrail areas in the future, as these layers will have to be penetrated at times during the climb and descent to and from the airport alone. However, these unavoidable residual effects should remain small compared to the potential savings on longer flights mentioned before.

Prerequisite: Advanced energy transition

The production of e-kerosene with today's current processes requires several times the amount of energy that is later contained in the e-kerosene. As long as the energy turnaround has not yet brought the CO_2 emissions of the entire economy to zero through the expansion of renewable energies, the question arises whether the use of the still scarce renewable energies can be justified for this inefficient use when they can reduce CO_2 several times over elsewhere.

There is a risk that the use of e-kerosene will result in a shortage of renewable electricity elsewhere. For this reason, it cannot simply be said that the best solution for climate protection is a switch to 100% e-kerosene and optimised routing as quickly as possible. Instead, it will be necessary to see and manage the development of e-kerosene in the context of the development of the energy transition.

Conclusion changed routing, climate neutrality in 2050?

It has been shown that the remaining non-CO_2 effects of e-kerosene can be significantly, almost completely, reduced by optimised routing. However, this finding is only based on model-based scenario calculations. From an environmental point of view, the resulting additional kerosene consumption would be acceptable if 100% green e-kerosene were used. However, this presupposes that the energy transition has progressed so far that there is no shortage of renewable energies needed elsewhere, where they can be used more efficiently from a climate protection perspective.

All in all, this "climate-neutral air traffic" scenario is likely to have the following assumptions

- flight routes are optimised (which also requires significant changes in national and international flight control and safety systems),
- e-kerosene is produced on a large industrial scale,
- the energy transition is successfully implemented at a level without significant shortages of renewable energy,

which are not expected to be realised in the next two decades. Only then, however, would it be justified to speak of "climate-neutral flying".

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