Climate Impacts of Aviation and the Potential of Aviation Powerfuels Toward Their Mitigation

Gunnar Quante, Christiane Voigt, and Martin Kaltschmitt

Abstract The UN Conference of the Parties, representing nearly all UN member states, agreed in the Paris Agreement to "hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". The International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have set a "Net-Zero Carbon Emissions" target by 2050. While the Paris Agreement focuses on limiting global temperature increase, the aviation industry targets primarily address CO_2 emissions. However, aviation's climate impact extends beyond CO_2 to contrails and indirect effects of nitrogen oxide (NO_x) emissions. Research shows that only one-third of aviation's climate impact (in terms of effective radiative forcing, ERF) is due to CO_2, with the remaining two-thirds from the other non-CO_2-related cliamte impacts. The largest climate impacts of aviation, by magnitude, are contrails, CO_2 emissions, and NO_x effects. Addressing only CO_2 emissions would overlook a significant portion of aviation's climate impact, making it essential to consider all related climate factors to align aviation industry targets with the Paris Agreement. This chapter first describes aviation's climate effects and then explores how increased use of powerfuels as example for renewably sourced kerosene might influence its overall climate impact.

Keywords Aviation Climate Impact · Non-CO_2 Effects · Contrails · Nitrogen Oxide · Aerosol Effects

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1   Introduction

Manifold human activities affect the earth's weather system in the short term and the climate system in the longer term. The primary cause of these substantial changes is the combustion of fossil fuel-based energy carriers, resulting mainly in carbon dioxide (CO_2) emissions. In addition, emissions of other climate-effective gases such as methane (CH_4), nitrous oxide and halogenated gases, aerosols and their direct and indirect effects on clouds (e.g., aviation contrails) contribute to anthropogenic climate change (Fig. 1).

The influence of human activities on weather and climate results not only in an increase of globally averaged surface temperature levels. Furthermore, global mean sea levels increase, glaciers retreat, extreme weather events such as concurrent heat-waves and heavy precipitation occur more frequently and climate zones are shifting poleward [1, 2]. These developments are more and more visible; e.g., basically all glaciers within the European Alps are rapidly disappearing since a couple of years.

Hence, the UN Conference of the Parties (COP), representing almost all United Nations (UN) member states, agreed within the so-called Paris Agreement to "hold the increase in the global average temperature to well below 2 °C above pre-industrial
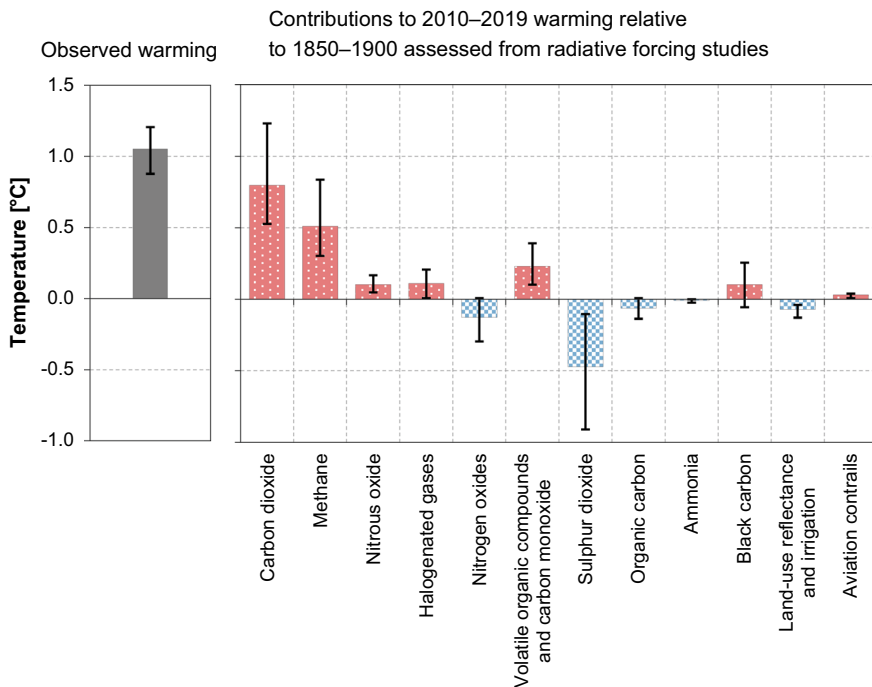

Fig. 1 Observed global warming (left) and associated drivers (right), adopted from [1]

levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" [3].

A central element of this Paris Agreement is the definition of nationally determined contributions, which require each party of the agreement to lay out mitigation measures to constrain anthropogenic climate change to the abovementioned global average temperature increase [3].

The national framework of the nationally determined contributions is difficult to apply to international transport modes, such as aviation and the maritime sector; e.g., the greenhouse gas (GHG) emissions for a flight/ship journey carrying passengers/freight of various nationalities from one country to another, potentially even with an intermediate stop in a third country, can be allocated in manifold ways.

The two international aviation organizations, the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) both defined a "Net-Zero Carbon Emissions" target by 2050 [4, 5]. Both targets focus on the abatement of CO_2 emissions, while the Paris Agreement defines a maximum in globally averaged temperature change. This difference is important because the climate impact of aviation does not only result from "classical" greenhouse gases like CO_2, but also from contrails and indirect effects of nitrogen oxide (NO_x) emissions (among others). The current state of research attributes around one-third of aviation's climate impact (in terms of effective radiative forcing (ERF)) to CO_2 emissions and the remaining two thirds to other, so-called non-CO_2 climate terms [6]. The largest climate effects of aviation are (by decreasing order of magnitude) contrails, CO_2 emissions and indirect effects from NO_x emissions. Mitigating only the climate impact of aviation's CO_2 emissions would omit a significant share of aviation's climate impact. Therefore, a consideration of all aviation-related climate terms is indispensable to align the aviation industries mitigation targets with the Paris Agreement.

The aim of this paper is to describe and characterize the climate effects of aviation and then to discuss the effects of a potentially increased use of powerfuels[1] onto aviation's overall climate impact. The paper is structured accordingly, while the discussion of the individual climate terms is sorted by their magnitude in terms of effective radiative forcing (ERF).

2   Climate Impacts of Aviation

The aviation sector consumed around 300 Mt of fuel (mainly fossil fuel-based kerosene) in the year 2018 resulting in CO_2 emissions of about 1 Gt (2018) [6, 7]. This corresponds to approximately 2.4% of the worldwide anthropogenic CO_2

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[1] In the context of this chapter , the term "powerfuels" refers to fuels produced based on electrical power. "Aviation powerfuels" more specifically denotes powerfuels suitable for the use in aviation turbine engines.

emissions and ~0.9% of the anthropogenic effective radiative forcing due to emissions of greenhouse gases (GHG) [6, 8]. Contrails and indirect effects from NO_x emissions (among others) increase the overall climate impact beyond gaseous emissions. Keeping this in mind, an assessment of aviation's impact on climate available to date estimates a climate impact for the time period between 1940 and 2018 to 101 mW/m^2 in terms of effective radiative forcing (ERF) [6]. This corresponds to 3.5% of the overall anthropogenic climate forcing of 2,840 mW/m^2 (time span 1750 until 2019) [8].

Following Fig. 2, the most prominent effect of aviation on climate are contrails, in particular contrail cirrus cluster at night. Compared to that, CO_2 emissions and indirect effects of NO_x emissions contribute less to the effective radiative forcing (ERF). Beside this, water vapor emissions in the stratosphere, aerosol-radiation effects and aerosol-cloud interaction have a still relevant but smaller climate impact than the aforementioned climate terms [6]. Below, those climate terms and their cause-and-effect relationships are described in detail.
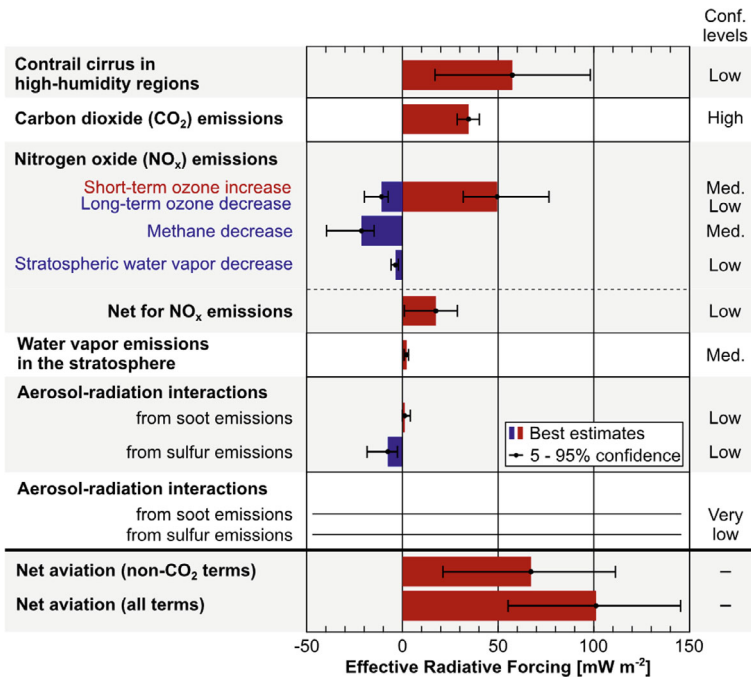

Fig. 2 Global Aviation Effective Radiative Forcing (ERF) Terms for the time 1940 to 2018, adopted from [6]

2.1 Contrails

The climate impact of contrails has been estimated as 57.4 (17 to 98) mW/m^2 in terms of effective radiative forcing (ERF). This corresponds to ~56% of the overall aviation-related effective radiative forcing (ERF) until 2018 [6].

The formation of contrails is triggered by particles (soot and aerosols) emitted from aircraft engines. These particles serve as condensation nuclei initiating the condensation of water. When during a flight at the typical cruising altitude of a commercial airplane, the hot engine exhaust mixes with the cool ambient air, rapidly cools down and can reach values above the saturation vapor pressure. In those cases, the water vapor will condense on the nuclei, freeze instantaneously and form a line-shaped condensation trail ("contrail") behind the respective aircraft engine/turbine [9]. These contrails affect the earth's radiative balance by scattering incoming solar radiation (cooling effect) and absorb outgoing terrestrial heat radiation (warming effect). Hence, the climate effect of an individual contrail strongly depends on the time of the day or more precisely the solar zenith angle. In general, around noon contrails tend to have a cooling climate impact, while they have a clearly warming impact at night, as they do not scatter any solar irradiation, but absorb the outgoing terrestrial heat radiation and reemit it at a colder temperature compared to the ground.

Figure 3 shows the cumulative density function for annual energy forcing (EF) by share of contrail forming flights for a global fleet dataset between 2019 and 2021 [10]. Thus, only ~20% of the flights produce contrails. Most of them are short and medium range flights during the day and are therefore characterized by a slightly cooling effect. Nevertheless, the impact of warming contrails clearly outweighs cooling contrails. As a result, the net impact of aviation contrails on global climate is warming. Simultaneously, the majority of the warming contrail climate impact is caused by less than 5% of all flights.

The contrail climate impact over the time of the day is shown for flights in the North Atlantic flight corridor for each day in the year 2019 in Fig. 4 [11]. The distinction between a mainly warming impact at night (red colors) and a predominantly cooling impact during day (green colors) can be seen by the horizontal change in contrail cirrus net radiative forcing (RF). As all investigated flights take place on the Northern hemisphere, a seasonal trend becomes visible by the vertical change in Fig. 4. On the Northern hemisphere, days are shorter in winter and accordingly, times with a warming contrail climate impact increase for winter days.

Contrail formation is initiated when the mixture of aircraft engine exhaust and ambient air becomes supersaturated with regard to water under the presence of condensation nuclei. The thermodynamic conditions (temperature, humidity) under which a supersaturation and thus contrail formation occurs, can be determined by the Schmidt–Appleman criterion (SAC) [12, 13]. They depend on the local meteorological situation (pressure and humidity of the surrounding air) and selected aircraft properties (e.g., propulsive efficiency, released combustion heat and water vapor emissions due to fuel combustion) [12, 14, 15].
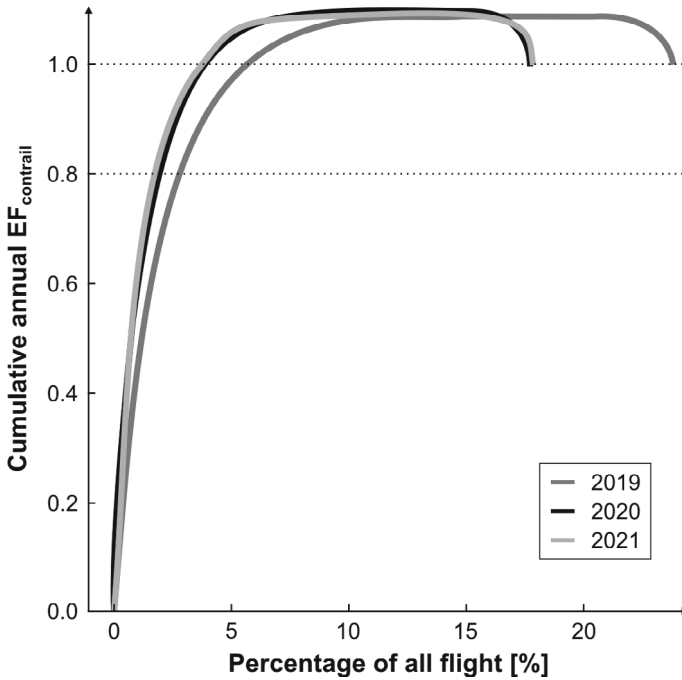
Fig. 3 Cumulative density function of the annual energy forcing (EF) of the percentage of contrail forming flights (for simplicity, warming contrails are described by EF values > 1 and cooling contrails by EF values < 1) adopted from [10]

Different particles can serve as condensation nuclei for aviation contrails. Aircraft engines emit soot and ultrafine aqueous particles. Additionally, the ambient air contains typically high numbers of aerosols. The amount of soot emissions for a given engine are strongly affected by fuel composition on the fuel side and design aspects as well as the maintenance situation on engine/turbine side. Aviation kerosene typically consists of different hydrocarbon species, such as straight chain alkanes, cycloalkanes and aromatics. Especially aromatics act as an initial soot precursor, due to their molecular structure, specifically the strong molecular bonds in the aromatic ring. Among different hydrocarbon components contained in jet fuel/kerosene, the soot formation tendency roughly decreases from poly- to monocyclic aromatics via cycloalkanes toward alkanes [16].

The variation of the molecular structure of the hydrocarbon species also affects the mass fraction of hydrogen contained. For example, the alkane Tridecan ($C_{13}H_{28}$) shows a hydrogen content of ~15.2 m-%, cycloalkanes have a hydrogen content of ~14.3 m-%, the mono-aromatic benzene is characterized by a hydrogen content of ~7.7 m-%, and the bicyclic naphthalene ($C_{10}H_8$) shows even a hydrogen content of ~6.3 m-%. Therefore, for currently used engines/turbines in commercial airplanes,
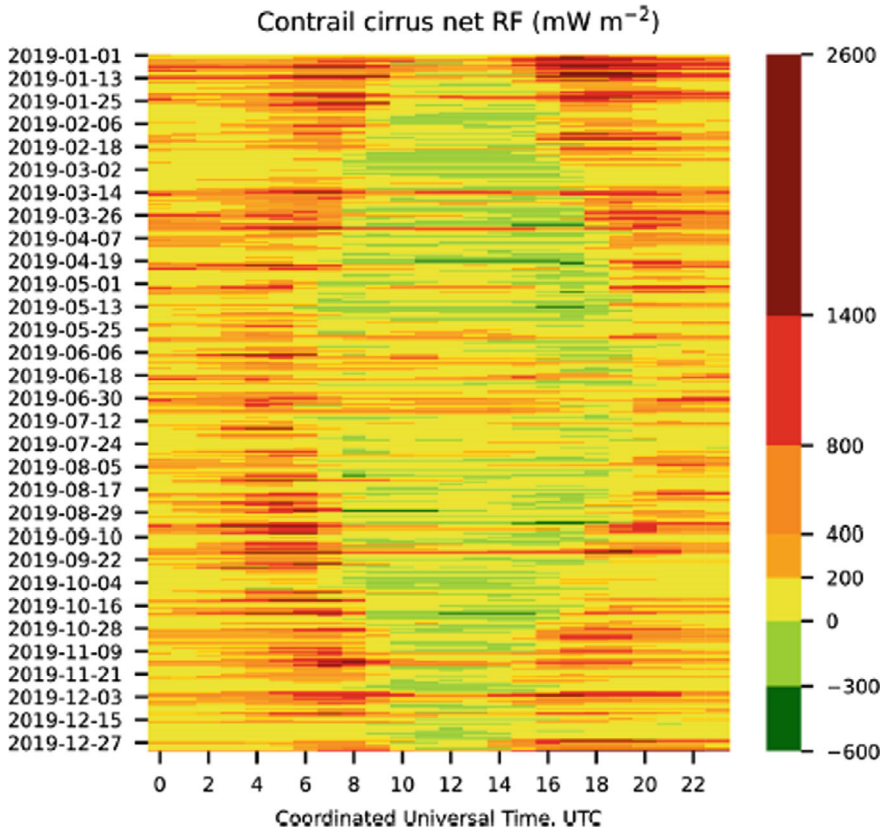
Fig. 4 Contrail cirrus net radiative forcing (RF) by time of day (*x*-axis) and calendar day (*y*-axis), adopted from [11]

the hydrogen content of a particular kerosene can serve as simplified estimate for its sooting tendency [16–20].

Particulate matter emissions of most modern aircraft engines/turbines range from 10^{14} to 10^{16} particles/kg—fuel (soot-rich regime, Fig. 5). For these engines/turbines, soot particles are the predominant condensation nuclei. Here, the number of ice crystals formed under the respective weather conditions within the cruising altitude is roughly proportionate to the number of soot particles emitted [18, 21–24].

Ambitions to further increase engine/turbine efficiency and to improve local air quality around airports have facilitated the development of engines/turbines with substantially reduced soot emissions. Assuming that modern or future engines/turbines can reduce soot emissions substantially below 10^{14} particles/kg of fuel burned, another process would become important for ice nucleation. In this range (soot-poor regime), ice nucleation is primarily initiated by ultrafine aqueous particles and aerosols from ambient air.
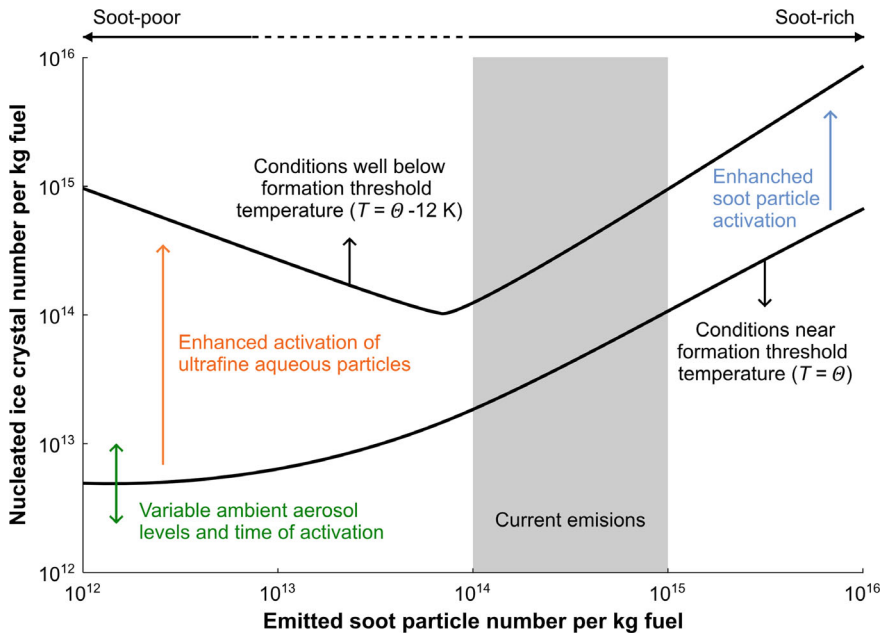
Fig. 5 Effect of soot particle emissions on nucleated ice crystal numbers, adopted from [9]

The lifetime of a contrail is mainly determined by processes taking place after ice nucleation. If further mixing and cooling of engine/turbine exhaust and ambient air results in sub-saturation, the contrail diminishes relatively fast and its climate impact is small. In some atmospheric regions, however, the relative humidity with respect to ice is greater than 100% (ice-super-saturated regions). If a contrail is formed under these circumstances, it grows by uptake of water vapor from the ambient air and can reach a contrail lifetime up to a few hours (so-called persistent contrail). Such persistent contrails typically exist for several hours but usually not longer than one day [25–27]. Thus, this type of contrails can cause a large climate impact, depending on the solar zenith angle and vertical wind shear [11, 28, 29]. Under the influence of vertical wind shear, persistent contrails can lose their linear shape, reach large horizontal extents and form so-called contrail cirrus or merge into contrail cirrus cluster. In these cases, the large surface area further increases the contrail's climate impact.

Concluding, the climate impact of contrails is severely influenced by atmospheric and aircraft parameters. The first group is comprised of the ice saturation of the ambient air, potential wind gradients and the solar zenith angle. The latter group depends on the aircraft's propulsive efficiency (a parameter of the Schmidt–Appleman criterion), soot and ultrafine aqueous particle emissions. Atmospheric parameters are externally defined by the prevailing weather situation, hence their impact can only be mitigated by avoiding regions with high contrail formation probability [30, 31]. High propulsive efficiencies are generally preferred for high fuel

efficiencies and thus lower CO_2 emissions and operating cost. Another option in the high soot regime of current engine technologies would be to lower soot emissions, either by developing new engine/turbine technology [32] or by using fuels with a lower aromatics content/increased hydrogen content [9, 11, 18, 21]. Further studies are required to investigate the ice nucleation processes in the low soot regime, when the reduced abundance of soot might lead to the activation of volatile aerosol or background aerosol.

2.2 Carbon Dioxide (CO_2)

The climate impact of CO_2 has been estimated as 34.3 (28 to 40) mW/m^2 in terms of effective radiative forcing (ERF). This corresponds to ~34% of the overall aviation-related effective radiative forcing (ERF) until the year 2018 [6].

Virtually all aviation kerosene used today consists of hydrocarbons. For the short- and medium-range fleets, electric propulsion concepts, fuels cells and hydrogen combustion are currently investigated and tested, in order to advance their introduction into the global commercial airplane fleet. Still, especially for long-haul aircraft, due to the long development and use times for such airplanes and engines/turbines as well as their high development cost and associated risks it appears unlikely that a carbon-free fuel or battery-electric solutions can be introduced fleet-wide clearly before 2050 [33].

Despite differences in the exact composition of the various groups of hydrocarbons within aviation kerosene, for a hypothetical ideal combustion the products are always water (H_2O) and carbon dioxide (CO_2). An ideal combustion of fossil-based kerosene would yield ca. 74 g_{CO2}/MJ_{fuel} [34]. In reality, the formation of soot and other products of non-ideal combustion lowers this value slightly; nevertheless, due the fact that the unburned and partly burned fuel components oxidize over time within the atmosphere, it is advisable to stick to the value mentioned above.

Emissions from combustion are commonly referred to as "Tank-to-Wake (TtW)" emissions. Additionally, the provision of kerosene also requires energy and this causes necessarily further CO_{2e} emissions,[2] which have to be added to the emission budget calculations in terms of "Well-to-Wake (WtW)" emissions. But in basically all cases, the largest fraction of the "Well-to-Wake (WtW)" emissions are the "Tank-to-Wake (TtW)" emissions.

Crude oil extraction and processing in "classical" refineries and transportation contribute the majority of the so-called "Well-to-Tank (WtT)" GHG emissions. Figure 6 shows sources of CO_{2e} emissions from fossil-based kerosene provision and use in absolute and relative terms.

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[2] In particular, the provision of fuels may cause the emissions of other greenhouse gases (e.g., CH_4). In the following, overall emissions of greenhouse gases are referred to as CO_{2e} emissions and emissions of CO_2 specifically are referred to as CO_2 emissions.
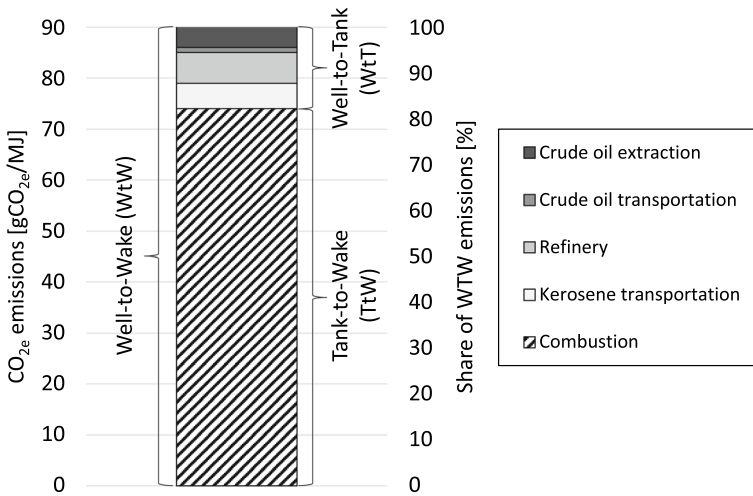
Fig. 6 CO_{2e} emissions of different steps in the kerosene value chain; based on [34–36] (values are indicative and will change for different crude oil types and supply chains)

The largest fraction of the "Well-to-Tank (WtT)" emissions is caused by crude oil refining (Fig. 6). The upgrading of crude oil toward specification compliant aviation fuels (kerosene type Jet A/A-1) requires hydrogen and heat. In present-day refineries, hydrogen is usually supplied by steam methane reforming (SMR) or petrol coke gasification [37]. Both processes incur GHG emissions, approximately 10 kg_{CO2}/kg_{H2} for steam methane reforming and about 20 kg_{CO2}/kg_{H2} for petrol coke gasification [38–41]. The provision of heat for the various upgrading processes and the catalyst regeneration incurs further CO_{2e} emissions release by conventional refineries to be allocated to kerosene [37]. As fossil resources become increasingly depleted, crude oils tend to become "heavier" (i.e., the density of the crude oil increases) and usually contains higher amounts of sulfur. As a result, upgrading toward specification compliant fuels requires larger amounts of hydrogen as well as thermal energy [42]. If this trend persists, emissions from refining of fossil-based kerosene can be expected to increase in the future [37].

Various modes of transport are available for the transportation of crude oil and aviation kerosene. In general, shorter transport distances and scale effects from larger transport volumes can reduce transport emissions; e.g., specific emissions of maritime transport are typically lower than for rail transport, which in most cases still shows lower specific GHG emissions than road transport.

The increasing depletion of fossil resources does not only affect emissions from refinery operations, but also from crude oil extraction. Enhanced oil recovery technologies require additional (thermal) energy usually resulting in increased CO_{2e} emissions. The second major influence on emissions from crude oil extraction are gas flaring practices [43]. If gas from a specific oil field is not economically saleable, it is either flared, vented or reinjected. Flaring refers to the burning of the crude oil gas

released from the crude oil due to pressure relief during production (causing mainly CO_2 emissions), while venting refers to directly releasing the gas into the atmosphere. Gas from oil fields typically contains methane, which has a clearly higher mass-specific impact on global climate compared to CO_2. Thus, in most cases the climate impact of flaring is lower than the climate impact of venting. Once released, naturally occurring local and global atmospheric circulations distribute the emitted CO_2 virtually uniformly across the globe.

The atmospheric lifetime of a CO_2 pulse emission is regulated by the fast and the slow carbon cycle.

- The fast carbon cycle encloses land uptake of CO_2 by biomass growth and ocean uptake. It removes about a third up to half of the CO_2 pulse emission.
- The slow carbon cycle encloses the reaction of CO_2 with calcium carbonate and silicate weathering.

The land and ocean uptake of the CO_2 (fast cycle) takes place at timescales up to 100 years, and reactions with calcium carbonate have typical timescales of 1,000–10,000 years while silicate weathering rather takes place between 10,000 and millions of years (slow cycle) [44, 45]. The large durations of both cycles yield a thorough mixing of CO_2 across the entire atmosphere and a very slow removal of CO_2 from the atmosphere by natural processes.

In conclusion, CO_2 emissions from aviation are primarily caused by fossil-based kerosene combustion in the engines/turbines and additional emissions arise from the production/provision from crude oil. The removal of CO_2 from the atmosphere by natural processes takes decades to centuries and partly even longer. Thus, a pulse emission of CO_2—in contrast to an individual contrail—is characterized by a long-lasting climate impact. This is the reason CO_2 emissions partially accumulate in the atmosphere over time, provided that the emissions rate is greater than the removal rate, which is clearly the case for present-day CO_2 emission levels.

2.3   Nitrogen Oxide (NO_x)

The net climate impact of indirect effects from emissions of NO_x has been estimated at ~17.5 (0.6 to 29) mW/m^2 in terms of effective radiative forcing (ERF), corresponding to 18% of the overall aviation-related ERF until the year 2018 [6]. The term NO_x commonly refers to nitric oxide (NO) and nitrogen dioxide (NO_2), since most of the nitric oxide (NO) from combustion oxidizes to nitrogen dioxide (NO_2).

As the atmospheric lifetime of NO_x emissions is very short, its direct climate impact is negligibly small. However, NO_x emissions affect the climate by a short-term formation of ozone and a longer term reduction in atmospheric methane [46, 47]. The increase in atmospheric ozone (O_3) has a warming effect (~38 mW/m^2), while the methane reduction has a cooling effect (~- 21 mW/m^2). Accordingly, the resulting net effect of NO_x emissions from aviation is warming. The ozone production rate and lifetime depend on ambient NO_x and OH concentrations. For global NO_x emissions,

the methane lifetime reduction is more pronounced and the ozone production rate is lower compared to the rather specific case of aviation NO_x emissions at aircraft cruise altitudes. Therefore, the net climate impact of global NO_x emissions is most likely cooling, while the net effect of aviation NO_x emissions is clearly warming (Fig. 1) [48].

NO_x are formed during fuel combustion, when molecular oxygen (O_2) is disso-ciated with atomic oxygen (O•) and reacts with molecular (N_2) or atomic (N•) nitrogen inside the hottest parts of the combustor of the turbine [49]. The forma-tion of NO_x can be attributed to four different processes: Thermal NO formation, the N_2O mechanism, prompt NO formation and fuel nitric oxide formation 50. The first three processes describe different reactions for the oxidation of atmospheric N_2 into NO and N_2O, while the latter refers to the formation of NO_x from fuel-bound nitrogen. Aviation kerosene typically contains less than 2 m-% of nitrogen while the atmosphere contains ~75 m-% of nitrogen. Thus, the reaction of fuel-bound nitrogen is of lower importance for the overall NO_x formation [50]. Nevertheless, the contri-bution of each formation process largely depends on combustion temperature and equivalence ratio (actual vs. stoichiometric fuel/air ratio) [32, 50, 51].

In general, an equivalence ratio close to one yields the highest combustion temper-ature and pressure. This in turn results in increased NO_x emissions (Fig. 7). For high thrust settings and high fuel efficiency, however, higher combustion chamber temperatures would be desirable [32]. This causes a trade-off between engine/turbine efficiency and NO_x formation. To counteract this trade-off, the design of combus-tors has become increasingly advanced with the goal to facilitate both, low nitrogen oxide NO_x emissions as well as a high fuel efficiency (e.g., the "Rich-Quench-Lean" (RQL) combustor) [32, 50].
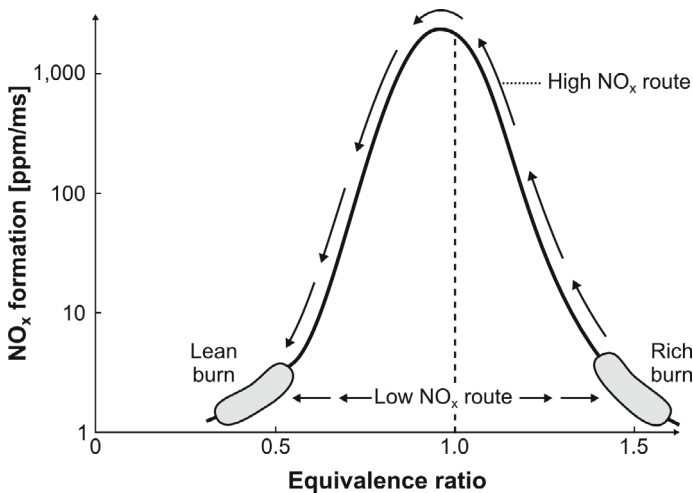

Fig. 7 Nitrogen oxide (NO_x) formation as function of fuel/air ratio ("equivalence ratio"), adopted from [50]

Once NO_x emissions are emitted from the engine/turbine exhaust, a combination of photochemical and catalytical processes alter the atmospheric composition and thus indirectly its radiative balance. Photochemical reactions with OH yield in an increase in atmospheric O_3 at the expense of NO_x and atmospheric CH_4. Catalytical reactions result in an O_3 decrease. These reactions strongly depend on the background concentration ratio of NO, OH and O_3. For low ratios the O_3 depletion is dominant, while higher ratios favor an O_3 increase [47]. As the NO/O_3 ratio changes geographically, also the effect of nitrogen oxide NO_x emissions on atmospheric ozone (O_3) varies regionally [52]. The CH_4 decrease is less regionally dependent, due to methane's CH_4 comparatively long average atmospheric lifetime of 8 to 9 a, allowing for thorough atmospheric mixing [53].

In conclusion, the climate impact of indirect NO_x effects is to a large extend determined by the engines/turbines thrust setting and combustor design, as well as the flight route. Aviation kerosene properties do not substantially influence overall NO_x emissions, since the amount of NO_x formed from fuel-bound nitrogen contribute only to a (very) small share to the overall NO_x emissions.

2.4 Water Vapor (H_2O) in the Stratosphere

The climate impact of water vapor within the stratosphere has been estimated as 2.0 (0.8 to 3.2) mW/m^2 in terms of effective radiative forcing (ERF). This corresponds to ~2% of the overall aviation-related effective radiative forcing (ERF) until 2018 [6].

Weather phenomena (e.g., wind, clouds and rain) occur in the troposphere, the lowest atmospheric layer. Within this layer, atmospheric circulations cause horizontal and vertical movements of air masses and thus wash out additional water emissions comparatively fast. The boundary between the troposphere and stratosphere (atmospheric layer above the troposphere) is called tropopause. Its height changes with latitude, reaching higher elevations above ground in equatorial (~16 km) than in polar regions (~8 km). Cruise altitudes of present-day aircraft vary between 9 and 13 km height and thus tend to take place in the stratosphere more frequently with increasing latitude [54]. Due to the atmospheric stability of the troposphere, the vertical exchange of air masses between troposphere and stratosphere is quite limited. Once injected into the stratosphere, the lifetime of water vapor increases as it follows the general circulation patterns. For this reason, the lifetime of water vapor emissions is substantially higher in the stratosphere compared to the troposphere. Hence, the climate impact of water vapor emissions becomes significant in the stratosphere. This is particularly relevant for potential supersonic flights, which would usually take place at even higher altitudes than most commercial flights today [55].

2.5 Aerosol Effects

Aerosol effects can be distinguished as direct influence of aerosols on radiation and indirect effects from aerosols altering the optical properties of clouds and thereby affecting the earth's radiative balance. The climate impact of aerosol-radiation effects has been estimated as 0.9 (0.1 to 4.0) mW/m^2 in terms of effective radiative forcing (ERF) for soot emissions and -7.4 (-19 to -2.6) mW/m^2 for sulfur aerosols. Estimates of aerosol–cloud interaction effects exhibit large uncertainties presently preventing the formulation of best estimate values [6].

2.5.1 Aerosol-Radiation Effects

Emissions of soot and sulfate aerosols have a direct forcing impact by scattering and absorbing radiation. Soot primarily absorbs incoming short-wave radiation and hence has a warming impact. Sulfate aerosols in turn mainly scatter incoming short-wave radiation, less solar radiation reaches the ground and thus they have a cooling impact [6, 56] (for the formation mechanism of soot see Sect. 2.1).

Sulfate aerosols are formed by the full oxidation of sulfur components contained within aviation kerosene. Lower levels of sulfur contained in aviation kerosene would directly reduce the emissions of sulfate aerosols as well as the activation of co-emitted soot particles and their associated climate impacts.

2.5.2 Aerosol–Cloud Interaction

In addition to contrail formation, both, supercooled aqueous solutions (e.g., sulfate aerosol particles) and insoluble ice nuclei particles (e.g., dust particles and soot) can trigger the formation of ice in cirrus clouds and they can modify existing cirrus and low level clouds [57]. They occur in the background atmosphere, and their concentration is affected by aircraft emitting soot and sulfate aerosols. As the processes governing the formation and the modification of clouds from those particles are not yet scientifically well understood, the magnitude and sign of the resulting impact on climate is still unclear. Some studies suggest that their absolute value may be even larger than contrail-related climate effects (warming or cooling) [58–64].

2.6 CO$_2$ and Non-CO$_2$ Effects

The comparison of aviation CO$_2$ and Non-CO$_2$ effects requires careful consideration of their spatiotemporal characteristics. This can be illustrated by an exemplary comparison of CO$_2$ emissions and contrails.
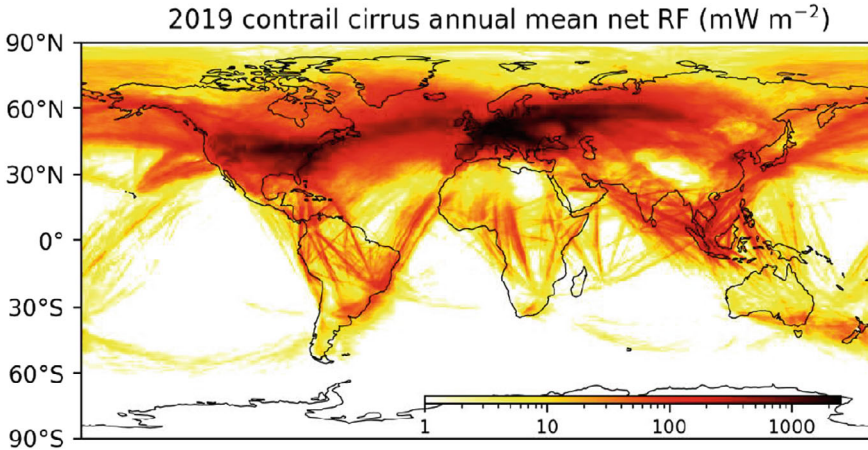
Fig. 8 Contrail cirrus annual mean net radiative forcing for 2019, adopted from [10]

In temporal terms, contrails exist not longer than one day, but a portion of a CO_2 pulse emission remains in the atmosphere for more than hundred years. For a given point in time, the climate impact of contrails is determined by all contrails existing in this particular moment. But for CO_2, not only current, but also historic emissions need to be considered, even for centuries. In other words, while the climate impact of contrails is primarily determined by the present situation, the climate impact of CO_2 (partially) accumulates over time.

In spatial terms, contrails affect mostly their coverage area resulting in a regionally constrained strong climate impact. Due to the large global variations in air traffic density, the contrail climate impact is regionally very inhomogeneous and concentrated within the flight corridors and in heavily flown areas, where they contribute significantly the anthropogenic radiative forcing (Fig. 8) (i.e., contrails have a large climate impact regionally). CO_2, however, mixes very well in the atmosphere and thus its regional differences are negligibly small.

Different climate metrics can be distinguished following the driver-response-impact chain (Fig. 9). Uncertainties increase from emissions/radiative forcing via temperature change estimates which require climate modeling toward socio-economic impacts. However, measures such as welfare loss or other indicators would be desirable from a socio-economic perspective, as these are common targets for political measures instead of physical state variables such as the earth's radiative balance.

These aspects complicate a generally valid comparison between different aviation climate terms. At first, the choice of a metric needs to find a balance between low uncertainty and relevance for policy. Secondly, the choice of time horizon has a strong influence on, e.g., global warming potentials (GWP) or absolute temperature change potential (ATP) used to compare different climate terms. The time horizon is decisive for the relative weight placed on effects taking place on different time scales.
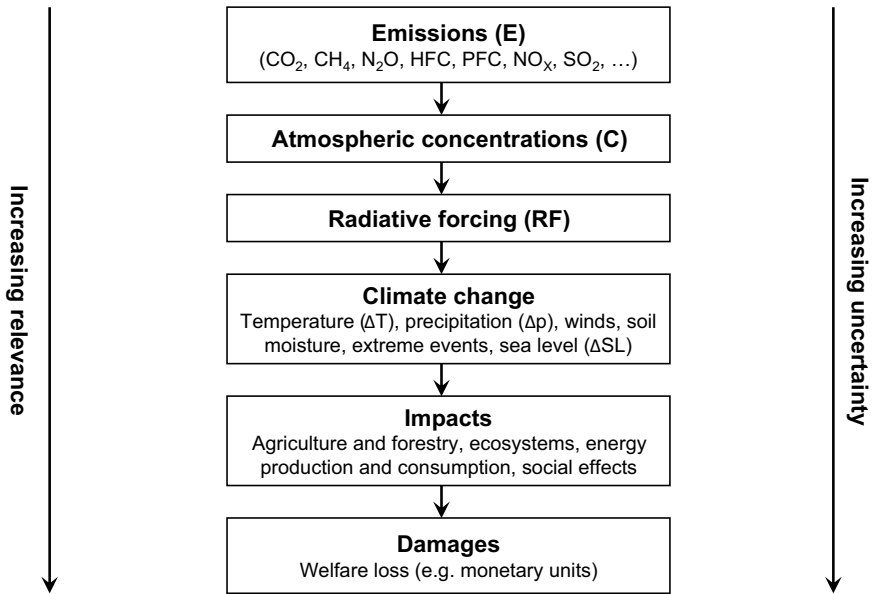
Fig. 9 Driver-response-impact chain of climate effects from greenhouse gas (GHG) emissions, adopted from [65]

Hence, their choice is rather a value judgment than a physically based selection [66]. Instead, the weighting of short- and long-term effects is rather a political than a scientific decision about how much emphasis should be placed on the situation today versus the mid- to long-term future.

3   Climate Impact Mitigation Potentials of Aviation Powerfuels

The average service duration for commercial aircraft is around 20 to 30 years. This results in long delays for the adoption of new technologies. In order to facilitate their timely introduction, renewably sourced kerosene is often required to be "drop-in capable". This means that they are approved for in-service aircraft and infrastructure without any modifications. To meet this requirement, renewably sourced kerosene and thus also aviation powerfuels have to fulfill the same specification as fossil-based kerosene plus some additional requirements. But in reality, some characteristic differences between aviation powerfuels and fossil-based kerosene remain.

There are virtually no aromatics in neat aviation powerfuels[3] yielding in a ~1 to 2 m-% higher hydrogen content, resulting in a slightly (<5%) increased gravimetric energy content and marginally increased water emissions from combustion. Another difference is that the carbon contained in aviation powerfuels is sourced from recent carbon sources (e.g., the atmosphere, biomass) instead of fossil resources. Aviation powerfuels also contain hardly any molecules contaminated with heteroatoms, such as sulfur or nitrogen.

Against this background, climate relevant properties of aviation powerfuels and their effect on aviation's climate impact are qualitatively discussed below. As there is hardly any effect of aviation kerosene type on aviation NO_x emissions [16, 68], a discussion of the impact of aviation powerfuels on this climate term is omitted. The following aspects are discussed in depth.

- The lack of aromatics in aviation powerfuels can reduce the contrail climate impact (Sect. 3.1).
- The use of carbon from renewable sources allows for large reductions in lifecycle CO_2 emissions (Sect. 3.2).
- Water vapor in the atmosphere, aerosol-radiation effects and aerosol–cloud interactions could be affected to some extent. Since their magnitude is most likely far smaller and some of their effects on weather and climate are not yet scientifically well understood, potential effects from using aviation powerfuels on these climate terms are briefly summarized (Sect. 3.3).

3.1 Contrails

Figure 10 shows the relationship between increasing the aviation kerosene hydrogen content by higher blend ratios of renewably sourced kerosene and the relative change in contrail climate impact relevant parameters. The lower amount of aromatic components in renewably sourced kerosene (including aviation powerfuels) results in a reduction of soot formation and their higher hydrogen content leads to a slight increase in water emissions from combustion.

Various in-flight measurement campaigns studied engines/turbines emitting in the soot-rich regime and several of them investigated the effect of a reduced content in aromatics and an increased content in hydrogen on the soot particle emission numbers and ice nucleation [15, 18, 23, 49, 69]. Evidently, ice crystal numbers decrease proportionally with soot particle emissions. Therefore, the optical thickness of the contrail is reduced compared to contrails from fossil-based kerosene. As the water available for ice particle formation remains roughly constant, it condenses on fewer ice particles growing under these circumstances to larger sizes [18, 21]. These heavier ice particles tend to sediment faster into warmer air masses/warmer parts of the atmosphere,

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[3] Currently, alternative kerosene are only certified to be used as blend with fossil-based kerosene as per ASTM D7566. But, ASTM is currently developing a standard for unblended alternative aviation fuels (status 2023) [67].
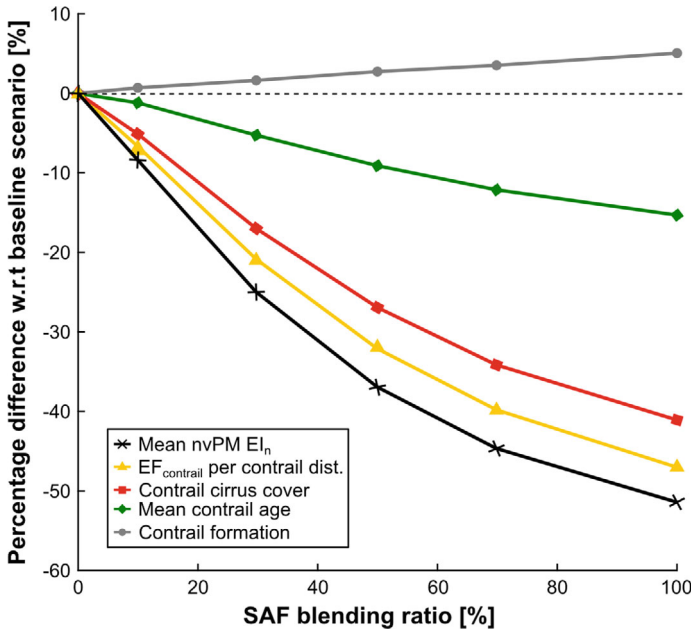
Fig. 10 Changes in non-volatile soot particle emissions, contrail formation potential, contrail lifetime, contrail cover, and contrail climate impact in terms of radiative forcing and energy forcing per contrail distance when increasing the hydrogen content of aviation kerosene (left), adopted from [11]

where they sublimate by reducing the lifetime of the contrails. Both effects—i.e., the faster sedimentation causing a reduced contrail lifetime and the reduced optical depth reducing the contrail cover—help to reduce the contrail climate impact [29]. For engines/turbines emitting in the soot-poor regime it is not yet clear to which extent this effect diminishes and how ice nucleation on ultrafine volatile particles and low levels of background aerosols affects the climate impact of contrails formed from those engines/turbines [23]. Aviation powerfuels, which typically contain hardly any sulfur, might reduce the ice nucleation on sulfate aerosols.

The increase in water emissions slightly enhances the occurrence of contrails (Fig. 10) [11]. The exhaust air contains more water from combustion, which increases the likelihood that its mixing with ambient air results (at least temporarily) in supersaturation and subsequent condensation. Also, the higher energy content of the fuel changes the range of atmospheric conditions under which the contrails can form. Even though the use of aviation powerfuels can slightly increase contrail occurrence, modeling studies suggest that this effect is not as pronounced as the reduction in contrail lifetime. Hence, a net reduction in contrail climate impact can be expected from using aviation powerfuels, especially for high blend shares or especially neat aviation powerfuels.

So far, only few studies on the effect of renewably sourced kerosene on the contrail climate impact exist. One uses a global model and finds that a 50% reduction in ice crystals lowers the contrail climate impact in terms of radiative forcing (RF) by almost 25% [29]. Another study of the North Atlantic flight corridor finds for a 50% reduction in soot emissions and ice crystals in contrails a related reduction in radiative forcing from contrails of ~ 42% [11].

Current market shares of renewably sourced aviation kerosene are below 1%, aviation powerfuels are not even produced at commercial scale yet [33]. As only a small fraction of all flights causes climate-relevant contrails, the targeted supply of renewably sourced aviation fuels could enable a faster contrail-climate impact reduction [11]. As of now, the implications of infrastructural changes and associated cost are unclear for a targeted use of renewably sourced kerosene. Hence, aviation powerfuels can substantially reduce the contrail-climate impact of aviation, but the exact extent of this reduction remains uncertain.

3.2 Carbon Dioxide (CO_2)

As shown by Fig. 6, the majority of CO_{2e} emissions from aviation kerosene stems from their combustion in aircraft engines/turbines. A smaller, but still relevant share of CO_{2e} emissions is created during fuel refining, transport and crude oil extraction.

The fundamental approach of renewably sourced kerosene (including aviation powerfuels) is to replace the carbon of fossil origin contained in fossil-based kerosene by carbon of renewable sources. The carbon of these sources stems more or less directly from atmospheric CO_2 and is bound by various biological and/or thermo-chemical processes within the powerfuel. In such a way, a closed carbon cycle is established preventing the net increase of atmospheric CO_2 levels. Since the "Tank-to-Wake (TtW)" emissions from combustion remain unaffected and only the net emissions of the fuel's entire lifecycle are reduced, the net effect is often referred to as "lifecycle CO_2 emissions".

However, the closed carbon cycle is a simplification, the fuel need to be produced and transported also resulting in so-called secondary emissions. These are caused by, e.g., energy provision or logistics. Literature indicates that the residual emissions of aviation powerfuels range from 1 to 27 gCO_{2e}/MJ [70–73]. This amounts to less than a third of the ICAO standard emissions value for fossil-based kerosene [34]. Additionally, it is most likely that over time these secondary emissions are more and more reduced because the overall energy system needs to be increasingly defossilized to fulfill the goals of the Paris Agreement and thus, e.g., fuel logistics should show less and less GHG emissions.

As Fig. 11 illustrates, hydrogen production and direct-air-capture (DAC) of CO_2 are the main contributors toward the residual CO_{2e} emissions of aviation powerfuels. This can be traced back to the provision of renewably sourced electricity in both cases. Hence, the key determinant for the CO_{2e} emissions of aviation powerfuels is the emission factor of the electricity source used. For both conversion routes, the

Fischer–Tropsch and the Methanol-to-Jet route, heat integration can cover most of the heat demands [74]. Hence, energy demands (and associated emissions) for the provision of heat can be neglected.

Another factor comes into play when comparing fossil-based kerosene and aviation powerfuels. Aviation powerfuels primarily consist of alkanes (Sect. 2.1), while fossil-based kerosene also contains various cyclic hydrocarbon components. This results in a slightly higher energy and hydrogen content of aviation powerfuels. In comparison with fossil-based kerosene, the increased hydrogen content yields slightly higher water and slightly lower CO_2 emissions assuming a fully stoichiometric combustion.

In terms of "Well-to-Tank (WtT)" emissions, aviation powerfuels provide a further mitigation potential. The provision of such synthetic fuels is realized by the Fischer–Tropsch or Methanol-to-Jet route and thus in theory powered fully by renewably sourced electricity; thus, the respective GHG emissions on the fossil fuel side can be avoided. The pendant to crude oil refining for aviation powerfuels is the upgrading to specification compliant aviation kerosene. If this step is also powered by renewably sourced electricity and renewably sourced hydrogen is used, CO_{2e} emissions of this step can also be mitigated to a large extent or even fully avoided. Due to the "drop-in" requirement, logistics for aviation powerfuels will most likely be similar to those of fossil-based kerosene. Emissions in this area might decrease, provided that the overall defossilation of the transport sector progresses and "green" fuels are used during the various transport processes.

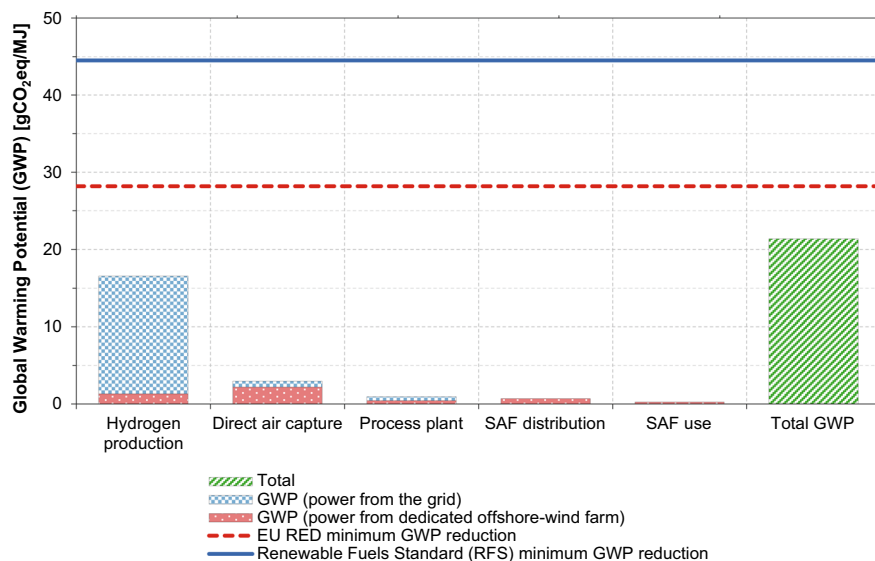
Fig. 11 Exemplary lifecycle emissions of an aviation powerfuel (FT-SPK using electricity from wind power plants; **DAC**—Direct-Air-Capture, **GWP**—Global Warming Potential, **SAF**—Sustainable Aviation Fuel,), adopted from [73]

The emissions factor of the electricity used to produce aviation powerfuels largely determines their lifecycle CO_{2e} emissions. If the power would be supplied from a coal-fired power plant, the powerfuels' life-cycle CO_{2e} emissions would be higher than those of fossil-based kerosene. If power from renewable sources (e.g., wind mills, photovoltaic systems) is used instead, far lower life-cycle CO_{2e} emission values can be achieved. However, it seems questionable to achieve net-zero emissions without additional CO_2 sequestration (e.g., to mitigate residual emissions from the construction of wind or photovoltaic power plants) [70–73] on the short term; on the long term this seems to be possible if defossilation of our overall economy progresses.

3.3 Water Vapor and Aerosol Climate Impacts

The increased hydrogen content of aviation powerfuels slightly shifts the stoichiometric ratio between the final oxidation products CO_2 and H_2O toward H_2O. While CO_2 emissions marginally decrease, H_2O emissions increase slightly. For flights within the stratosphere, this would also slightly increase the climate impact of water vapor emission.

The reduction in soot emissions does not only affect contrail formation, but also reduces aerosol-related climate impacts from soot. Aviation powerfuels are virtually free of sulfur, hence also effects of sulfate emissions are reduced or even avoided. In which direction (more warming/more cooling) this changes the net climate impact of direct and indirect aerosol effects still needs to be investigated [55].

4 Conclusion

In 2015, a global consensus was reached to limit global warming below 2 °C in order to prevent detrimental effects of anthropogenic climate change. International aviation climate mitigation goals currently focus on the abatement of CO_2 emissions. Aviation powerfuels are considered a key measure to achieve these mitigation goals. However, the climate impact of aviation does not only result from CO_{2e} emissions, but—beside other effects of minor importance—also contrails and indirect NO_x effects contribute substantially to the total climate impact from aviation. Against this background, this chapter quantifies and describes aviation climate terms first. Then, the current knowledge on the effect of aviation powerfuels on the overall climate impact from aviation is summarized.

By decreasing order of magnitude, the individual contributions to the total effective radiative forcing (ERF) from aviation are contrails, emissions of CO_{2e}, indirect effects of NO_x and—to a substantially smaller extent—water vapor in the stratosphere as well as direct and indirect aerosol effects.

- The climate impact of contrails is determined by atmospheric and aircraft-related parameters. While the first group includes ice saturation of the ambient air, potential wind gradients and the solar zenith angle, the latter primarily depends on the aircraft's propulsive efficiency, fuel and engine/turbine parameters (soot and ultrafine aqueous particle emissions).
- CO_2 emissions from aviation are primarily caused by fuel combustion in the engines/turbines and emissions from crude extraction and refining.
- Indirect NO_x climate effects are to a large extend determined by the engine's/turbines thrust setting and combustor design, as well as the flight route; fuel properties do not substantially influence overall NO_x emissions.
- Emissions of water vapor become climate-relevant for flights in the stratosphere due to the increased atmospheric residence time in this atmospheric layer.
- Direct and indirect aerosol climate effects are caused by soot and sulfate aerosol emissions. They cause warming and cooling climate effects; however, especially in the case of indirect aerosol effects the magnitude of the climate impact is highly uncertain.

The use of aviation powerfuels has significant effects on contrail formation and lifecycle CO_{2e} emissions. For the contrail-related climate impact, aviation powerfuels reduce the emissions of soot particles (at least in the soot emission regimes of most present-day aircraft engines/turbines) and in the end shorten the contrail lifetime and reduce the associated net climate impact of contrails. A quantification of the contrail climate mitigation potential of renewably sourced kerosene is still ongoing, existing studies range between 30% and 60%. However, those studies would require market shares of alternative aviation fuels of around 50% or more, and current market shares are below 1%. As just a small fraction of all flights causes contrail formation, targeting those flights specifically with renewably sourced kerosene might allow for a faster reduction in aviation's climate impact while their market matures.

In principle, aviation powerfuels can reduce the CO_{2e} emissions of aviation by more than 80% and in theory on a longer perspective by 100%. However, this is only realistic if the electricity used for fuel production originates from renewable sources of energy, such as wind power or solar radiation used by wind mills and photovoltaic power plants. Electricity provision with higher CO_{2e} emissions can even result in lifecycle CO_{2e} emissions clearly above the values for fossil-based kerosene.

Other aviation climate terms remain largely unaffected by the use of aviation powerfuels (indirect NO_x effects) or are substantially smaller than the aforementioned climate terms. As contrails and CO_{2e} emissions account for a large share of aviation's climate impact, aviation powerfuels allow for a substantial reduction of aviation's overall climate impact and are not limited to CO_{2e} emissions.

In the future, targeting flight routes with a particularly high contrail-climate impact might enable faster reductions in aviation's climate impact. Further studies and flight experiments are required to improve the understanding of the necessary requirements of a targeted fuel use.

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