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NLR-CR-2024-268 | November 2024

Non-CO_2 mitigation strategies towards climate neutral aviation

Mitigating both CO_2 and non-CO_2 effects of international commercial flights departing the Netherlands

CUSTOMER: Ministry of Infrastructure and Water Management

Royal NLR - Netherlands Aerospace Centre

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REPORT NUMBER
NLR-CR-2024-268

AUTHOR(S)
[redacted]

REPORT CLASSIFICATION
UNCLASSIFIED

DATE
November 2024

KNOWLEDGE AREA(S)
Sustainable Aerospace Operations

DESCRIPTOR(S)
Climate neutral aviation
CO2 and non-CO2 effects
Mitigation strategies

Problem area

In order to reach the goals and ambitions of the Paris Agreement it is important to strive for climate neutrality in all sectors of the economy. Through the Sustainable Aviation Agreement, the Netherlands has set goals to reduce CO_2 emissions from international aviation to net zero. However, non-CO_2 emissions from aviation also have a warming effect on the Earth's temperature. This has incentivised the Ministry of Infrastructure and Water Management to investigate the resulting climate impact if existing scenarios for decarbonisation of aviation are realised, and to explore possibilities for mitigating the warming caused by the most important non-CO_2 effects of aviation, contrails and NO_x.

Description of work

This report provides a first indication of the possible extent of the total (CO_2 and non-CO_2) climate effect of Dutch commercial aviation departing to international destinations based on existing scenarios for decarbonisation. Based on the flight network in 2019 and trends in the traffic volume, fuel consumption and associated emissions for the years 2030, 2040 and 2050 are estimated. Climate impact is determined using climate effect functions based on Thor et. al (2023) for conventional kerosene and tailored to alternative sustainable fuels for hydrogen and SAF. Mitigation strategies targeting non-CO_2 effects are explored. Strategies focused on route-based targeted use of SAF, contrail avoidance and the introduction of more advanced aircraft engine technologies are implemented in the scenario to show the potential resulting reducing effect on climate impact.

Results and conclusions

Results show that the scenarios aimed at decarbonisation only manage to reduce 4% to 48% of the in-sector climate impact of emissions in horizon years excluding cumulative effects, depending on scenario and climate metric. Results of non-CO_2 mitigation strategies show that route-based targeted use of SAF could result in a reduction of up to 1.3% climate reduction depending on scenario, horizon year and climate metric, due to the reducing effect of SAF of contrail climate impact. Avoiding contrails operationally is shown to potentially reduce climate impact by 10-25% climate impact reduction, depending on the climate metric and scenario, at a mere increase in fuel consumption of 1%. The use of advanced aircraft significantly reduces fuel consumption and can also reduce the emission of NO_x and nvPM particles, reducing the climate impact further. The advanced Clean Sky 2 aircraft introduced in these scenarios generally have an expected market introduction between 2030-2035, such that a 14-16% reduction in climate impact may be achieved in 2040 compared to baseline scenarios. In the long-term, largest reductions in climate impact may be yielded from flight specific contrail avoidance manoeuvres and advanced aircraft and engine technology. In the short-term, (route-based) targeted use of SAF may be implemented to reduce climate impact when SAF is not available at a large scale (yet). To increase the likelihood of successful implementation of these strategies in the future, further research is required. In particular, uncertainty in the computation of contrail climate impact should be reduced.

Applicability

The results and conclusions drawn are based on the assessment of international commercial civil aviation departing the Netherlands using climate effect functions. Reducing uncertainties associated with the input weather data and emission models would increase the confidence of the estimates given in this report.

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Bescherming persoonlijke levensfeer

Royal NLR - Netherlands Aerospace Centre

CUSTOMER	**Ministry of Infrastructure and Water Management**
CONTRACT NUMBER	**4500406569**
OWNER	**NLR**
DIVISION NLR	**Aerospace Operations**
DISTRIBUTION	**Limited**
CLASSIFICATION OF TITLE	**UNCLASSIFIED**

APPROVED BY:

Bescherming persoonlijke levenssfeer

Samenvatting

In 2015 committeerde Nederland zich middels het Parijs Akkoord aan de doelstelling om de aardopwarming te limiteren tot maximaal 2°C boven de pre-industriële temperatuur en te streven naar maximale opwarming van 1.5°C. Om dit te bewerkstelligen is het van belang om in alle sectoren klimaatneutraliteit na te streven. Nederland heeft zich middels het Akkoord Duurzame Luchtvaart ten doel gesteld om de CO_2-uitstoot van de internationale luchtvaart terug naar net-zero te brengen. In de rapportages *Klimaatneutrale luchtvaart in 2050* van het PBL (Davydenko, Hilbers, & de Wilde, 2024) en *Destination 2050* (Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) zijn voor de decarbonisatie van de luchtvaart roadmaps gecreëerd waarmee CO_2- neutraliteit bereikt kan worden. Echter, net als CO_2 emissies hebben de niet-CO_2 emissies van de luchtvaart ook een opwarmend effect. Hierdoor is bij het ministerie van Infrastructuur en Waterstaat een behoefte ontstaan om aanvullend aan de bestaande roadmaps voor decarbonisatie ook in kaart te brengen welke mogelijkheden er bestaan om de opwarming door de belangrijkste niet-CO_2 effecten, zijnde contrails en NO_x, van de luchtvaart te mitigeren. Het adresseren van deze niet-CO_2 effecten is een belangrijke stap in de richting van klimaatneutrale luchtvaart.

In dit rapport wordt een eerste indicatie gegeven van de mogelijke omvang van het totale (CO_2 en niet-CO_2) klimaateffect van het Nederlandse groothandelsverkeer vertrekkend naar internationale bestemmingen voor drie scenario's gebaseerd op bestaande decarbonisatietrends. Hierbij wordt op basis van het vluchtnetwerk in 2019 en gestelde trends een inschatting gemaakt van het aantal vluchten, brandstofgebruik en daaraan verbonden emissies voor de jaren 2030, 2040 en 2050. Klimaateffecten voor deze jaren worden berekend door middel van algoritmische klimaatfuncties gebaseerd op Thor et al. (2023) voor conventionele kerosine en aangepast voor alternatieve duurzame brandstoffen. Hieruit blijkt dat de scenario's gericht op decarbonisatie slechts 4 tot 48% van het in-sector klimaateffect weten te reduceren in 2050, afhankelijk van scenario en metriek als gegeven in Figuur 1. Er blijft dus een aanzienlijk deel van het klimaateffect over als de resterende, voornamelijk niet-CO_2, effecten niet ook gemitigeerd worden. Daarnaast moet het effect van cumulatieve emissies in de periode tot deze zichtjaren, in deze studie niet verder onderzocht, niet onderschat worden welke de klimaatimpact van de luchtvaart in de zichtjaren sterk kan vergroten door de doorwerkende klimaateffecten van langdurige emissies zoals CO_2.

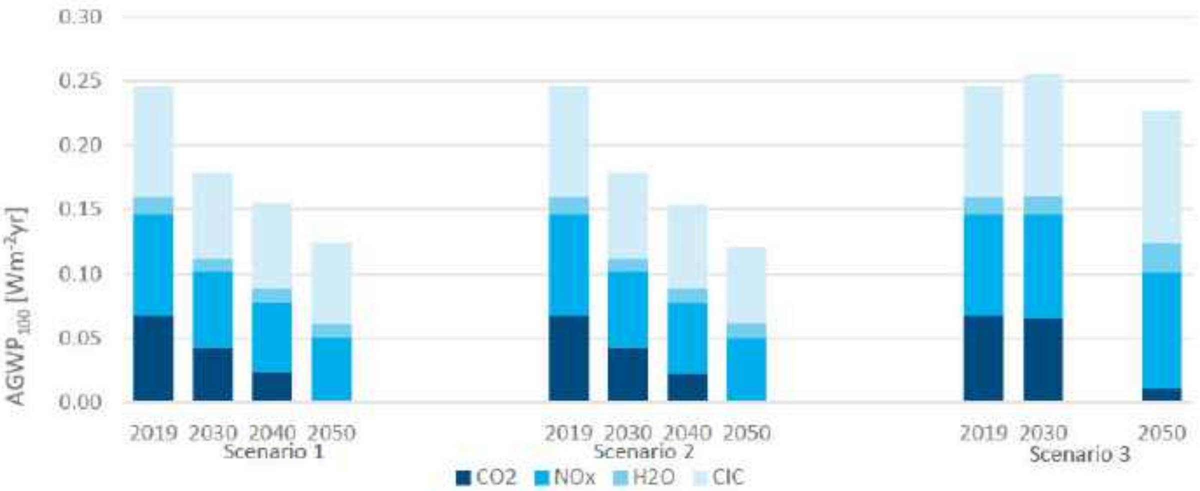

Figure 1: Climate effect in $AGWP_{100}$ for horizon years resulting from the indicated scenarios

Daartoe zijn mitigatiestrategieën gericht op de energiedrager, operationele context en technologische aspecten in kaart gebracht. In dit rapport is voor drie van deze strategieën: klimaatgerichte SAF inzet, het ontwijken van vliegtuigstrepen en introductie van geavanceerde motor-vliegtuigtechnologie, een benadering van de potentiële reductie in klimaateffect gegeven. Hieruit blijkt dat middels klimaatgerichte SAF inzet, gebaseerd op gemiddelde klimaatimpact per vliegroute, de SAF op zo'n manier ingezet kan worden dat tot 1.3% klimaatreductie gewonnen kan worden. Dit wordt voornamelijk gerealiseerd door de lagere klimaatimpact van vliegtuigstrepen die mogelijk met SAF gepaard gaat, zonder additionele SAF in te zetten. Een gerichte inzet van SAF per vlucht, waar ook de lokale weersomstandigheden meegenomen worden zal waarschijnlijk voor hogere klimaatimpactreductie (10%) kunnen zorgen.

Ook het ontwijken van vliegtuigstrepen kan de klimaatimpact sterk verminderen. Hiervoor wordt echter afgeweken van de conventionele vliegroute wat een verhoging van het brandstofgebruik tot gevolg kan hebben. Dit kan echter met relatief beperkte brandstof. Een extra brandstofgebruik van 1% kan mogelijk al 10-25% klimaatimpactreductie teweegbrengen, afhankelijk van metriek en zichtjaar.

De inzet van geavanceerde vliegtuigen reduceert het brandstofgebruik in hoge mate, en kan daarnaast zorgen voor een reductie in NO_x en nvPM deeltjes, waarmee de klimaatimpact gereduceerd kan worden. De in deze scenario's geïmplementeerde geavanceerde Clean Sky 2 vliegtuigen hebben veelal een verwachte marktintroductie tussen 2030-2035 waardoor in 2040 tot 16% reductie in klimaatimpact gerealiseerd kan worden. Op de lange termijn kunnen de grootste reducties in klimaatimpact worden bereikt door vluchtspecifieke vliegtuigstreep-ontwijkingsmanoeuvres en geavanceerde vliegtuig- en motortechnologie. Op korte termijn, wanneer SAF nog niet grootschalig beschikbaar is, kan worden ingezet op klimaatimpactreductie door route-specifieke inzet van SAF.

Om de kans op een succesvolle implementatie van de strategieën in de toekomst te vergroten, is verder onderzoek nodig. Voor de mitigatiestrategie 'klimaatgerichte inzet van SAF' kan een groter reductiepotentieel worden bereikt wanneer vluchten op vluchtniveau kunnen worden geanalyseerd en SAF zodoende specifieker kan worden ingezet, wat ook vereist is voor een succesvolle implementatie van het ontwijken van vliegtuigstrepen. Daartoe kan een meteorologische aanpak worden aangenomen die de mogelijkheid biedt om SAF en vliegtuigstreep-ontwijkingsmanoeuvres in te zetten op individuele vluchten. Hiervoor is het van belang de onzekerheid in meteorologische voorspellingen en in de effecten op de klimaatimpact van het gebruik van SAF, waterstof en geavanceerde lean burn motoren te verminderen, opdat de klimaatimpact van individuele vluchten met een hogere mate van zekerheid kan worden ingeschat. Ook de logistieke uitdagingen, zoals het hebben van separate brandstofsystemen voor SAF en Jet A-1 op luchthavens en aanpassingen aan vluchttrajecten met betrekking tot luchtruimcapaciteit en veiligheid, en implicaties voor directe operationele kosten, vereisen verder onderzoek voor een succesvolle implementatie.

Summary

In 2015, the Netherlands committed through the Paris Agreement to limit global warming to a maximum of 2°C above the pre-industrial temperature and to strive for a maximum warming of 1.5°C. In order to achieve this, it is important to strive for climate neutrality in all sectors. Through the Sustainable Aviation Agreement, the Netherlands has set goals to reduce CO_2 emissions from international aviation to net zero. In the reports of the Dutch Environmental Assessment Agency and Destination 2050, roadmaps have been created for the decarbonisation of aviation through which CO_2 neutrality can be achieved. However, just like CO_2 emissions, non-CO_2 emissions from aviation also have a warming effect on the Earth's temperature. This has incentivised the Ministry of Infrastructure and Water Management to investigate, in addition to the existing roadmaps for decarbonisation, the possibilities for mitigating the warming caused by the most important non-CO_2 effects of aviation, contrails and NO_x. Addressing these non-CO_2 effects is an important step towards climate-neutral aviation.

This report provides a first indication of the possible extent of the total (CO_2 and non-CO_2) climate effect of Dutch commercial aviation departing for international destinations of three traffic scenarios based on existing decarbonisation trends created. Based on the flight network in 2019 and trends in the traffic volume, fuel consumption and associated emissions for the years 2030, 2040 and 2050 are estimated. Climate impact for these years is determined using climate effect functions based on Thor et. al (2023) for conventional kerosene which are tailored for alternative sustainable fuels. This shows that the scenarios aimed at decarbonisation only manage to reduce 4% to 48% of the in-sector climate impact, depending on scenario and climate metric as given in Figure 2. Therefore, a significant part of the climate impact persists if the remaining, mainly non-CO_2, effects are not also mitigated. Moreover, the effect of cumulative emissions in the period up to these target years, not further investigated in this study, should not be underestimated, as the climate impact of aviation in the horizon years could be significantly increased by the continuing climate effects of long-term emissions such as CO_2.

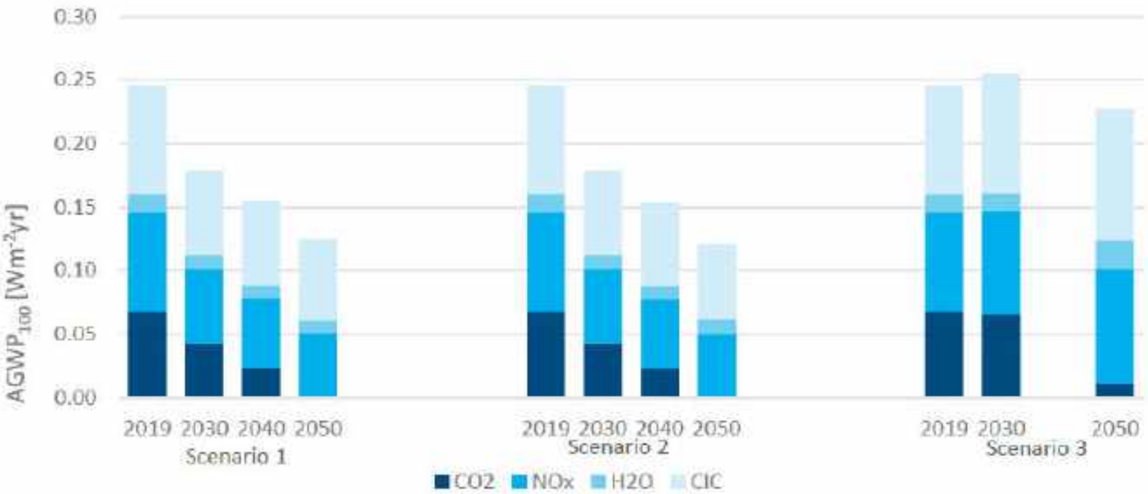

Figure 2: Climate effect in $AGWP_{100}$ for horizon years resulting from the indicated scenarios

To this end, mitigation strategies focused on the use of energy carrier, operational context and technological aspects have been identified. In this report, an approximation of the potential reduction in climate impact is given for three of these strategies: route-based targeted use of SAF (Sustainable Aviation Fuel), contrail avoidance, and introduction of advanced engine-aircraft technology. This shows that through targeted use of SAF, based on the average climate impact per flight route, SAF can be allocated in such a way that up to 1.3% climate reduction can be achieved. This happens mainly through the lower contrail energy forcing that may be associated with SAF, without requiring additional SAF. A targeted SAF approach on individual flight level, taking into account local weather conditions, might yield greater benefits (potentially up to 10%) Moreover, analysis approaches that do not reduce tank-to-wake CO_2 emissions of SAF will higher reduction potential.

Avoiding contrails can also significantly reduce the climate impact. However, this requires a deviation from the planned flight path, which may result in an increase in fuel consumption. However, this can be done with relatively limited additional fuel use. An additional fuel consumption of 1% is projected to already achieve a 10-25% climate impact reduction, depending on the climate metric and scenario.

The use of advanced aircraft significantly reduces fuel consumption and can also reduce the emission of NO_x and nvPM particles, reducing the climate impact further. The advanced Clean Sky 2 aircraft introduced in these scenarios generally have an expected market introduction between 2030-2035, such that a 16% reduction in climate impact may be achieved in 2040. In the long-term, largest reductions in climate impact may be yielded from flight specific contrail avoidance manoeuvres and advanced aircraft and engine technology. In the short-term, (route-based) targeted use of SAF might be worth to implement when SAF is not available at a large scale (yet).

To increase the likelihood of successful implementation of these strategies in the future, further research is needed. For the mitigation strategy route-based deployment of SAF, a higher reduction potential can be achieved if flights can be analysed at flight level, which is also required for successful implementation of contrail avoidance. To this end, a meteorologically driven approach can be adopted that allows for flight specific targeted use of SAF and aircraft contrail avoidance manoeuvres on individual flights. However, this requires reduction in uncertainty in meteorological forecasts. Additionally, uncertainty in the effects of the use of SAF, hydrogen and advanced lean burn engines on climate impact must be reduced, such that the impact of individual flights can be estimated with a higher degree of certainty. Also logistical challenges, such as having dual fuel systems for SAF and Jet A-1 at airports and adjustments to flight paths with respect to airspace capacity and safety, and implications for direct operational costs, need to be investigated further before implementation at scale.

Contents

Abbreviations and acronyms

ABBREVIATION/ACRONYM	DESCRIPTION
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ATR	Average Temperature Response
BADA	Base of Aircraft Data
BFFM2	Boeing Fuel Flow Method II
CIC	Contrail induced cloudiness
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CROR	Contra-rotating open rotors
DAC	Double annular combustor
EF	Energy Forcing
EFTA	European Free Trade Association
EI	Emission index
ERF	Effective Radiative Forcing
EU ETS	European Union Emission Trade Scheme
GWP	Global Warming Potential
ICAO	International Civil Aviation Organisation
IATA	International Aviation Transport Association
KEV	Klimaat- en Energieverkenning
LR	Long range
MEEM	Mission Emissions Estimation Methodology
MRV	Monitoring, Reporting and Verification
NLR	Royal NLR – Netherlands Aerospace Centre
nvPM	non-volatile Particulate Matter
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
RED II	Renewable Energy Directive II
SAF	Sustainable Aviation Fuel
SMR	Short and Mid-Range
TAPS	Twin annular premixing swirler
TP	Turboprop
UHPE	Ultra-High Propulsion Efficiency

CHEMICALS	DESCRIPTION
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O (g)	Water vapour
NO_x	Nitrogen oxides

1 Introduction

To achieve the climate goals of the 2015 Paris Agreement, aviation emissions have to reduce drastically. Specific targets for aviation have been set to reach carbon neutrality by the year 2050, including those by the International Civil Aviation Organisation (ICAO, 2022), the European Union (2021) and national governments, which are supported by in-sector organisations such as the International Aviation Transport Association (IATA, 2021), and the Advisory Council for Aviation Research and Innovation in Europe (ACARE, 2022). Through the Civil Aviation Policy Memorandum (Ministerie van Infrastructuur en Waterstaat, 2020) targets have been set to reduce future CO_2 aviation emissions from the Netherlands and as such align Dutch aviation with global decarbonisation goals. To reach net zero carbon emission targets by 2050, roadmaps have been developed by governing bodies and the aviation sector itself. In 2021 the European aviation sector, for example, published a roadmap to net zero CO_2 emissions (Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), and in 2024 the Netherlands Environmental Assessment Agency published scenarios towards CO_2 free aviation in 2050 (Davydenko, Hilbers, & de Wilde, 2024).

However, aviation has emissions besides CO_2, so-called non-CO_2 emissions, which are estimated to may have accounted for about 2/3 of aviation's total climate effect up to 2018 – with large contributions from NO_x emissions and contrail cirrus formation (Lee, et al., 2021). Therefore, reaching carbon neutrality in 2050 does not mean that future aviation will also be climate neutral. To address remaining non-CO_2 effects additional mitigation measures may be necessary. The climate impact of non-CO_2 emissions depends on the geographical and temporal location of aircraft emissions (e.g. (Frömming, et al., 2021; Grewe, et al., 2014)), such that mitigation of these is less straight forward than for CO_2.

In this report, the CO_2 and non-CO_2 climate effect of international commercial aviation departing from major Dutch airports is evaluated in three scenarios when current European and Dutch decarbonisation trends are followed. Furthermore, to reduce remaining non-CO_2 climate effects mitigation opportunities are identified, of which promising mitigation strategies are incorporated in the scenarios and evaluated.

Computation of CO_2 and non-CO_2 emissions and effects is elaborated upon in Chapter 2. The resulting emissions and climate impact of Dutch international aviation following current scenarios is described in Chapter 3. A selection of possible mitigation opportunities and resulting climate impact reduction are described in Chapter 4. Overall conclusions and recommendations for further research are given in Chapter 5.

2 Climate effects of CO_2 and non-CO_2 emissions

This chapter describes the climate effects of Dutch international commercial aviation. First, the emissions of aviation and their climate effects are introduced in Section 2.1. The derivation of the emissions of Dutch international commercial aviation is described in Section 2.2. The translation of those emissions to impact on the climate is described in Section 2.3.

2.1 Climate effects of aviation

Aviation emissions can change Earth's radiative balance by directly or indirectly changing the atmospheric concentration of greenhouse gases or aerosols, by inducing the formation of clouds, or by affecting cloud composition. The long lived greenhouse gas emission of CO_2 by aviation is well understood, and proportional to (kerosene) fuel burn. Aviation's CO_2 emissions can be linked directly to global warming following a near linear temperature response (Allen, et al., 2009; Collins, et al., 2013; Friedlingstein, et al., 2014; Gillet, Arora, Matthews, & Allen, 2013; MacDougall, 2015; Matthews, Gillet, & Zickfeld, 2009), such that limiting these will aid in the reduction of further climate warming. However, aviation emissions of kerosene powered aircraft also include NO_x, H_2O, and both volatile and non-volatile particulate matter. These non-CO_2 emissions and associated effects depend on fuel, engine, aircraft, operations, and local atmospheric and solar conditions such as incoming radiative forcing.

Aviation NO_x emissions in the troposphere, for example, increase ozone production on the short term (warming) and increase oxidation of methane on the long term, which leads to long term reduction of tropospheric ozone (cooling). Moreover, in the stratosphere, NO_x emissions can reduce stratospheric water vapour, leading to an additional cooling effect on the climate. In the upper troposphere, at commercial aircraft cruise altitude, the warming effect of ozone production dominates such that net warming is expected (Terrenoire, et al., 2022; Fuglestvedt, et al., 1999; Szopa, et al., 2021; Lee, et al., 2023). Furthermore, emissions of water vapour have a warming climate effect, especially when emitted into the stratosphere. Soot and sulphur oxides are found to interact with clouds resulting, respectively, in warming and cooling effects on the climate. Moreover, aviation emissions of water vapour and soot at high altitudes may cause the formation of persistent linear contrails that develop into contrail induced cloudiness which may have a large warming effect on the climate. In Figure 3, an estimate of the magnitude of the effect of various aviation emissions is given, showing the large contributions of contrails, CO_2 and NO_x (Lee, et al., 2021; EASA, 2020), on which this study is focused.

The majority of CO_2 and non-CO_2 effects on the climate is caused by long-range flights at high altitude (Thor, et al., 2023; EUROCONTROL, 2023). The scope of this study has therefore been limited to international commercial[1] aviation departing from major airports in the Netherlands, i.e. Amsterdam Airport Schiphol, Eindhoven Airport, Rotterdam The Hague Airport, Groningen Airport Eelde and Maastricht Aachen Airport.

[1] Following the definitions in Annex 6 to the Convention on International Civil Aviation report Operation of Aircraft part I International Commercial Air Transport – aeroplanes, and part ii – international general aviation.

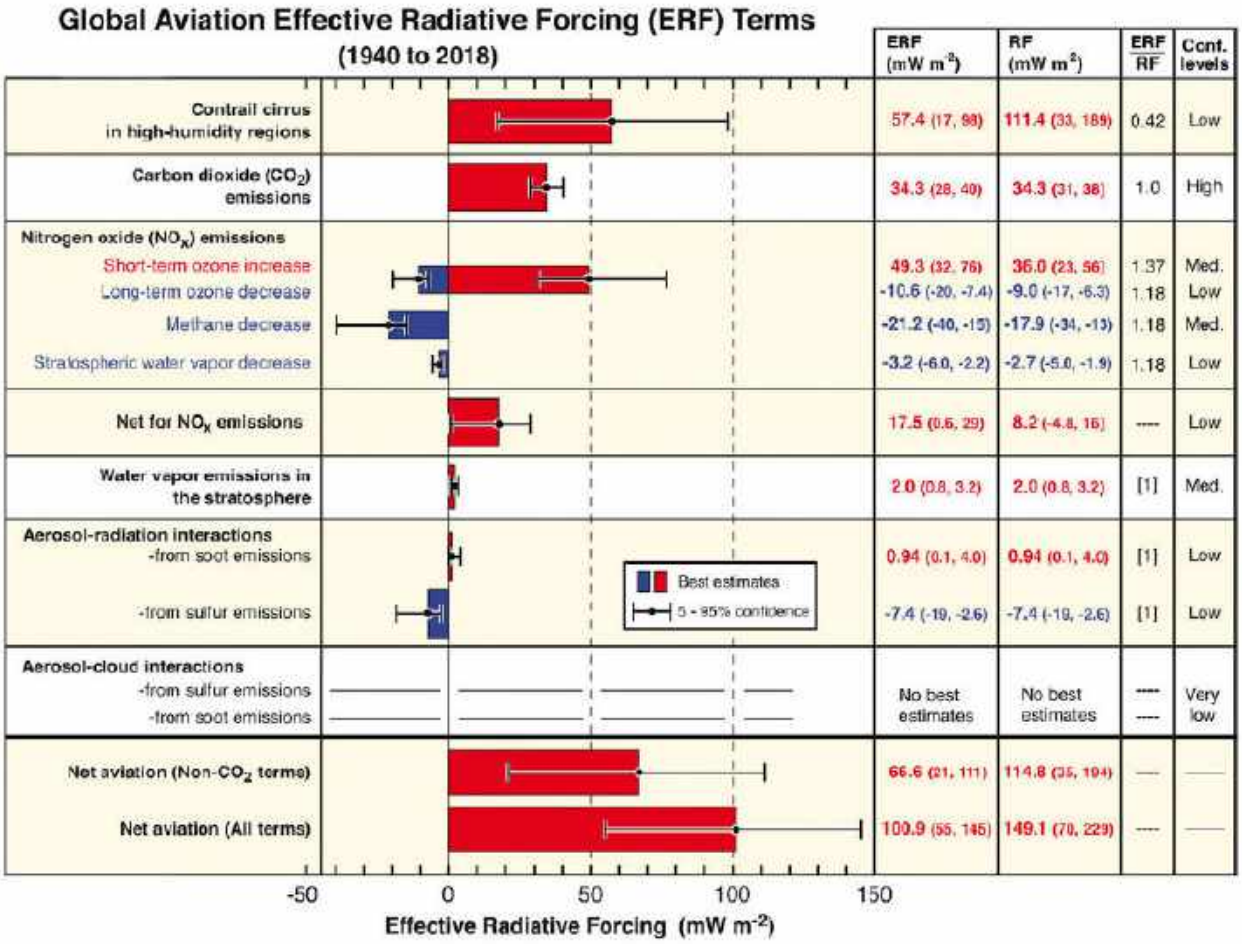

Figure 3: Best-estimates for effective radiative forcing (ERF) terms from global aviation from 1940 to 2018. Red bars indicate warming terms and blue bars indicate cooling terms. From Lee et al. (2021)

2.2 Modelling of CO_2, H_2O and NO_x emissions

The reference scenarios towards carbon neutral aviation are created for different scopes than international commercial flights departing from the major airports in the Netherlands and are not provided on origin-destination pair level. As the climate effects of non-CO_2 emissions depend on the location where they are emitted, this information is required to evaluate the effects. The network of flights departing from the Netherlands in 2019 has been used as a baseline and effects on demand have been assumed to be valid over the entire European and intercontinental networks. Emissions from future flights are modelled using scaling factors in line with trends specified in the scenarios for fuel burn of different aircraft categories, and trends derived for NO_x and nvPM (non-volatile Particulate Matter) emissions of ICAO (2022). The CO_2 and non-CO_2 emissions of H_2O and NO_x in the reference scenarios are computed as baselines, not including additional mitigation through selected strategies.

Kerosene and SAF flights

To derive an estimate of the CO_2, NO_x and H_2O emissions of the international commercial flights departing from major airports in the Netherlands using on kerosene and/or SAF, the NLR BeyondCO_2 gross emissions model (Peerlings, Wijn, Engler Faleiros, & Söffing, 2024) is used. The tool uses Base of Aircraft Data performance data (BADA) and idealised trajectories between origin and destination airport to estimate fuel consumption. CO_2 and H_2O emissions can be directly computed through fuel consumption and their respective emission indices, which are constant and, thus, independent of engine settings. NO_x emissions are computed in the BeyondCO_2 tool based on the Boeing Fuel Flow

Method II (BFFM2, (DuBois & Paynter, 2006)) and nvPM emissions based on the Mission Emissions Estimation Methodology (MEEM, Ahrens, et al. (2023)).

Flights using SAF are firstly modelled as conventional kerosene flights after which correction factors are applied for changes in energy content and emissions[2]. Due to in general higher hydrogen content in SAF, the water vapour emission index is expected to be higher (Teoh R. , Engberg, Shapiro, Dray, & Stettler, 2024):

$$EI_{H_2O,SAF} = EI_{H_2O,REF}\frac{H_{SAF}}{H_{REF}}.$$

Where the hydrogen content (H_{REF}) and water vapour emission index ($EI_{H_2O,REF}$) of typical aviation fuel (Jet A1) are 13.8% and 1.237 kg/kg (Teoh R. , Engberg, Shapiro, Dray, & Stettler, 2024), respectively.

NO_x emissions are not only influenced by the consumed fuel but also by the engine design, operation and ambient atmospheric conditions. Due to the limited dependence on the fuel, the effects of SAF on NO_x emissions are found to be approximately the same as that of Jet A-1 (Schripp T. , et al., 2018; Schripp T. , et al., 2022; Schripp, et al., 2019; Hamilton, et al., 2018; Riebl, Braun-Unkhoff, & Riedel, 2017).

Hydrogen flights

Hydrogen flights are modelled to replace some of the flights that are now powered by fossil kerosene. The amount of hydrogen fuel required to replace the kerosene flights is computed based on similar energy requirements. Water vapour emissions of hydrogen fuel depend on fuel usage and are computed using emission indices. The combustion of hydrogen,

$$2H_2 + O_2 \rightarrow 2H_2O,$$

leads to $EI_{H_2O,Hydrogen}$ = 8.94 kg/kg fuel.

In addition, with future combustion technologies that minimise flames and enhance mixing of hydrogen and oxygen, the emission index of NO_x for hydrogen combustion flights is expected to reduce by 24-80% compared to conventional kerosene combustion (Funke, 2019; Clean Sky, 2020; Carter R. , 2021). In the 2030 scenarios a 24% decrease in NO_x emission index is projected for the first generation of hydrogen planes, while in 2040 and 2050 scenarios a 52% (average of 24% and 80%) reduction in NO_x emission index is projected.

2.3 Modelling of CO_2, H_2O, NO_x and contrail climate effects

Physical climate metrics are used to quantify the climate effects of emissions. Equivalent metrics can be used to compare and aggregate the effect of different emissions on the climate on the same scale. Physical climate metrics can, for example, be expressed in radiative forcing, temperature changes or sea level rise. A widely used metric in international climate policy, such as the Kyoto Protocol, is the Global Warming Potential with a time horizon of 100 years (GWP_{100}). The GWP is defined as the time-integrated radiative forcing (RF) due to a pulse emission of a certain gas, relative to a pulse emission of an equal mass of CO_2 (Shine, 2009). However, due to its dependence on time horizon, there has been criticism on the use of the global warming potential for the transport, and especially aviation, sector where the contribution of short lived climate forcers is large. Alternative metrics have been designed of which

[2] Correction factors are in line with NLR-CR-2024-211 – Influence of the composition of SAF and H_2 on non-CO_2 climate effects – in which they are elaborated upon in detail.

the Average Temperature Response (ATR, (Dallara, 2012)) is becoming increasingly used in aviation research. The ATR is also an integrated metric but instead of cumulative radiative forcing, the average change in temperature is used as a measure of climate impact, for which a climate model is required in the evaluation of effects adding additional uncertainty. In this report, aviation climate effects are expressed in both the absolute GWP_{100} ($AGWP_{100}$) and ATR_{100}.

Emissions to equivalent effects

The non-CO_2 effects are calculated using climate equivalent factors as developed by Thor et al. (2023) which have also been used in the ANCO tool (Raphaël & Grebe, 2024). The method results in climate effect functions, developed from evaluation of a global set of detailed flight trajectories, flight emissions and climate responses. The climate effect functions are latitude, distance and emission dependent, with separate correlations for short-haul (<462.5km), tropical (mean-latitude within ±29.7°), and mid-latitude flights (all others) and various seat categories.

The existing kerosene-based factors are extended with corrections for SAF and hydrogen usage (as developed in NLR-CR-2024-211 – Influence of the composition of SAF and H_2 on non-CO_2 climate effects) to reflect upon the changes in ice crystal formation and contrail lifetime. Due to the higher hydrogen content in SAF and the in general lower bicyclic aromatic content, also cleaner combustion is reached and less soot is formed. To account for the change in contrails due to change in fuel properties, correlations[2] have been developed to account for change in nvPM emissions based on ground-based (Durdina, et al., 2021; Brem, et al., 2015) and in-flight measurements (Moore, et al., 2017; Voigt, et al., 2021) and change in the number density of ice crystals (Voigt, et al., 2021; Märkl, et al., 2024). The change in radiative forcing follows then from the simulations performed by Burckhardt et al. (2018). During hydrogen combustion no nvPM emissions are expected but more water vapour is emitted hence also changing contrail lifetime and properties.

Limitations and uncertainties

Limitations and uncertainties involved in the computations should be taken into account when interpreting the results. These include limitations on computations of fuel flow, which rely on simplifications of aircraft performance (BADA 3.16), emissions and, especially, the simplified methodology of computing climate impact estimates based on correlations. The correlations depend only on flight distance, mid-latitude of origin and destination airports and on the flight emissions (Thor, et al., 2023), and represent the results of climate response model AirClim (Grewe & Stenke, 2008; Dahlmann, Grewe, Frömming, & Burkhardt, 2016) at mean absolute relative error of 9-16%, depending on flight cluster. In addition, the conversion factors for flights fuelled with SAF and hydrogen increase the uncertainties of the results.

For instance, the MEEM method used for computations of nvPM mass and number show for most cases an agreement within 20-30% with the full proprietary T3P3 method (Ahrens, et al., (2023), while the BFFM2 method shows an agreement within 10% for rich-burn engines and 20% for staged combustor systems. The MEEM method is also applied when using SAF, but the emission indices at ground level (ICAO emission databank) are first corrected for the change in fuel properties, which relies on measurement data and adds uncertainty to the calculation.

In addition, estimating the number of ice crystals formed in a contrail is another source of uncertainty, also relying on limited measurement data. For Jet A-1 and SAF it is assumed to be a fraction of the initial nvPM number, which is computed using a correlation that considers the naphthalene content of the fuel. For hydrogen aircraft, it is assumed that no nvPM is emitted and only background particles can serve as nuclei for the formation of ice crystals. Due to limited information available on the role of volatile particles in ice crystal formation, only nvPM is considered, which is another limitation of this study. Volatile particles, such as ultrafine (<100 nm) jet lubrication oil droplets, could play a relevant role on the formation of ice crystals in the soot-poor regime (Ponsonby, King, Murray, & Stettler, 2024), e.g. in contrails formed in wake of hydrogen aircraft, lean-burn engines or possibly when using 100% SAF. Accurate estimates for the size distribution and emission indices of both lubrication oil droplets and ambient aerosol would help reduce the uncertainty in the estimation of apparent ice crystal emission indices in the soot-poor regime.

3 Climate impact of commercial international aviation departing from the Netherlands

In this chapter we introduce three scenarios for the CO2 and non-CO2 emissions and climate impact of international commercial aviation from the Netherlands. These scenarios follow decarbonisation, SAF and movement trends of existing decarbonisation scenarios. Two scenarios follow the decarbonisation, SAF and movement trends as specified for Dutch aviation by the Planbureau voor de Leefomgeving (PBL, Netherlands Environmental Assessment Agency) (Davydenko, Hilbers, & de Wilde, 2024). A further scenario is modelled that does include the decarbonisation trends of the Destination 2050 roadmap for European aviation (Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) towards carbon neutrality in 2050. We assess what following a decarbonisation pathway in line with these scenarios would mean for Dutch aviation in terms of CO_2 as well as the modelled non-CO_2 emissions and the associated climate impact in horizon years 2030, 2040 and 2050. As the network of commercial flights departing from the major Dutch airports in 2019 is used as a base year in this study, in this chapter the climate impact of the base year is elaborated upon first in Section 3.1. Then, Section 3.2 describes the first two scenarios based on the decarbonisation trends in the PBL study and Section 3.3 explains the scenario based on decarbonisation trends in Destination 2050.

3.1 2019 emissions and climate impact

Using the BeyondCO_2-tool (Peerlings et al. 2024), CO_2 emissions for international commercial flights departing from the five major Dutch airports are calculated. The network consists of about 280k departing commercial flights departing from the major Dutch airports in 2019, most operated using aircraft with capacities up to 200 seats within the intra-European, UK and EFTA area. The flights departing to destinations outside of this area are, however, in general responsible for the largest climate impact due to their large fuel requirements. In total these flights are modelled to be responsible for at least 10 Mt CO_2[3], 50 kt of NO_x and 4 Mt of water vapour emissions. This would imply an ATR_{100} of 1.12 mK and an $AGWP_{100}$ of 0.25 $Wm^{-2}yr$.

The CO_2 emissions of aviation are found to be responsible for about a quarter of the modelled climate impact in ATR_{100} and $AGWP_{100}$ as shown in Table 1. The contribution to the climate impact of NO_x, although having a small contribution in emission mass, is larger and may be responsible for 30 to 50% of the climate impact, depending on the climate metric used. Contrail cirrus also are found to be responsible for a large part of the climate impact, further stressing the need to strive for full climate neutrality instead of mere carbon neutrality.

Table 1: Shares of contribution to climate impact of different aviation emission species and effects

Climate metric	H_2O	NO_x	Contrail cirrus	CO_2
ATR_{100}	6%	50%	21%	23%
$AGWP_{100}$	6%	32%	35%	28%

3.2 Scenarios 1 and 2

In *Klimaatneutrale luchtvaart in 2050* (Davydenko, Hilbers, & de Wilde, 2024), two scenarios are presented towards carbon neutral Dutch aviation. Both scenarios rely heavily on the usage of alternative sustainable aviation fuels (SAF),

[3] As estimated using the BeyondCO_2-model, excluding tankering, wind and high-speed flying

either fully reliant on SAF or with an emphasis on the use of e-fuels and hydrogen. The scenarios are based on a reference scenario (KEV2022, (Hammingh, vanSoest, Daniels, Koutstaal, & Menkveld, 2022)) modelled using the AEOLUS aviation model. To allow for non-CO_2 emission and climate impact evaluation, flight trajectories are of importance. Therefore, the network of commercial flights departing from the major Dutch airports in 2019 is used and altered in line with traffic movement and fuel usage prognoses in the PBL scenarios to determine emissions and climate effects for horizon years 2030, 2040 and 2050.

3.2.1 Traffic volume expectations

PBL and KEV2022 expect Dutch aviation to recover and steadily grow (ca. 2% p.a.) afterwards, outpacing energy efficiency trends. However, as the scenarios rely on renewable energy which comes at higher cost, demand reduction effects are forecasted. In the PBL study the demand effect was partly incorporated through AEOLUS modelling in KEV2022 and partly adapted to reflect the additional usage of SAF and hydrogen on the demand. Combining the KEV2022 and additional demand effects, Table 2 shows the reduction in traffic volume expected for the full Dutch aviation network. In this study the 2019 commercial international network at major Dutch airports is used as a base year, consisting of about 280k flight departures, and the network for future horizon years is scaled according to the combined demand effects for the PBL scenarios.

Table 2: Demand effects as estimated by KEV2022 and PBL

	Number of flights KEV2022	**Additional demand effect w.r.t. KEV2022** in PBL	**Total reduction w.r.t. 2019** used in scenarios 1 & 2
2019	565k		-
2030	487k [4]	-4%	-17%
2040	561k	-10%	-11%
2050	612k	-15%	-8%

Therefore the estimated network for the five major airports comprises 233k departing flights in 2030, 250k departing flights in 2040, and 258k departing flights in 2050.

3.2.2 CO_2 emissions for horizon years

For horizon years 2030, 2040 and 2050, advances in aircraft technology and operations as well as increased use of sustainable fuels is expected, which have a reducing effect on the aviation CO_2 emissions.

Fuel requirement effects due to operational and technical development

To account for efficiency improvements in engine and aircraft technologies, as well as operational improvements, and changes in aircraft utilisation, an 1.0% p.a. improvement in fuel burn is introduced in the PBL scenarios. Therefore, the reduction in fuel burn that can be obtained due to efficiency improvements in future horizon years equals 10%, 19% and 27%, respectively, compared to the 2019 base year.

Uptake of alternative fuels in horizon years

Following the PBL scenario with an emphasis on biofuels and those with an emphasis on e-fuel and hydrogen an above-mandated SAF uptake (compared to the ReFuelEU Aviation mandate (EC, 2023)) is modelled equally over the network per horizon year. Hydrogen uptake is also modelled equally over flights with a maximum range of 2000km. The modelled uptake percentages are given in Table 3.

[4] Note that the recently published KEV2024 (Hammingh, et al., 2024) shows quicker traffic recovery from Covid19 and larger growth until 2030

Table 3: Modelled SAF (total of biofuel and synthetic fuel) and hydrogen uptake following scenarios 1 and 2; the values show the percentage of kerosene replaced with the alternative energy carrier

	emphasis on biofuels		emphasis on e-fuels and hydrogen		
	Bio-SAF uptake [%]	Syn-SAF uptake [%]	Bio-SAF uptake [%]	Syn-SAF uptake [%]	H_2 uptake [%]
2019	0	0	0	0	0
2030	13	1	13	1	0
2040	42	10	22	30	2.5
2050	65	35	30	60	10

Resulting CO_2 emissions for horizon years

Based on the RED II directive, tank-to-wake CO_2 emissions of the biofuels are counted as a 100% reduction such that CO_2 emissions of scenarios 1 and 2 result in carbon neutrality in 2050 as shown in Table 4.

Table 4: Estimated CO_2 emissions for horizon years following scenarios 1 and 2, based on PBL

	Scenario 1 (emphasis on biofuels)		Scenario 2 (emphasis on e-fuels and hydrogen)	
	CO_2 [Mt]		CO_2 [Mt]	
2019	10.1	-	10.1	-
2030	6.4[5]	-36%	6.4	-36%
2040	3.5	-66%	3.4	-67%
2050	0	-100%	0	-100%

3.2.3 Non-CO_2 emissions of H_2O and NO_x

Even if carbon neutrality can be reached for Dutch international aviation in 2050, non-CO_2 species are still emitted. Based on the fuel composition and use, H_2O and NO_x emissions of Dutch international aviation are computed for horizon years 2019, 2030, 2040 and 2050. Due to the increased use of hydrogen in the scenario with emphasis on e-fuels and H_2 (scenario 2), an increase in water vapour emissions is obtained. The generally higher hydrogen content in SAF also results in higher water vapour emissions than from fossil kerosene such that reductions in water vapour emissions are less than reductions in fuel usage. The effects of SAF usage on NO_x are found to be negligible.

Table 5: Estimated non-CO_2 emissions of NO_x and H_2O of scenarios 1 and 2

	Scenario 1 (emphasis on biofuels)		Scenario 2 (emphasis on e-fuels and hydrogen)	
	NO_x [kt]	H_2O [Mt]	NO_x [kt]	H_2O [Mt]
2019	50	4	50	4
2030	37[5]	3	37	3
2040	35	3	35	3
2050	33	3	32	3

3.2.4 Climate-impact

The estimated climate impact of both CO_2 and non-CO_2 emissions of the horizon years are shown in Table 6. In both scenarios it can be seen that even when the CO_2 climate impact would be completely disregarded, i.e. when reducing

[5] Note that the recently published KEV2024 (Hammingh, et al., 2024) shows quicker traffic recovery from Covid19 as well as larger growth such that numbers shown are likely an underestimation

lifecycle emissions to zero, climate impact is not fully mitigated. Given the expected value of non-CO_2 emissions' climate impact, approximately 50% of the total climate impact of the 2019 network remains, when following the PBL scenarios towards carbon neutrality. For non-CO_2 effects a larger share of about 67% of the climate impact of 2019 remains as SAF does still have a non-CO_2 impact even if the CO_2 effects are neglected. If CO_2 climate impact of SAF is still attributed to aviation some 48-55% of the 2019 climate impact would remain, depending on the chosen metric.

Table 6: Estimated total and non-CO_2 climate impact of emissions in horizon years of scenarios 1 and 2

	Scenario 1 (emphasis on biofuels)				Scenario 2 (emphasis on e-fuels and hydrogen)			
	ATR_{100} [mK]		$AGWP_{100}$		ATR_{100} [mK]		$AGWP_{100}$	
	Total	non-CO_2	Total	non-CO_2	Total	non-CO_2	Total	non-CO_2
2019	1.11	0.86	0.25	0.18	1.11	0.86	0.25	0.18
2030	0.81[5]	0.65	0.18	0.14	0.81	0.65	0.18	0.14
2040	0.71	0.62	0.15	0.13	0.71	0.62	0.15	0.13
2050	0.58	0.58	0.12	0.12	0.57	0.57	0.12	0.12

3.3 Scenario 3

Scenario 3 is based on the decarbonisation trends of *Destination 2050* (Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), in which a roadmap is presented towards net carbon neutral European[6] aviation. The pathway relies heavily on improvements in aircraft and engine technology including hydrogen-powered aircraft. Other large CO_2-reducing contributions are expected from the usage of sustainable aviation fuels, and operational and economic measures. The roadmap is based on a reference scenario in which scheduled flight data is expected to increase by 55% in terms of flights and 67% in terms of CO_2 emissions. To allow for non-CO_2 emission and climate impact evaluation of Dutch aviation, the network of flights departing from the major Dutch airports in 2019 is used and altered in line with prognoses in the Destination 2050 roadmap for fuel efficiency improvements, and the uptake of alternative fuels to determine CO_2 emissions for horizon years 2030 and 2050[7], again non-CO_2 emissions and effects are modelled additionally to give indication of the climate impact of the horizon years.

3.3.1 Traffic volume expectations

Destination 2050 expects aviation to recover from covid-19 in 2024 and steadily grow afterwards. In the reference scenario forecast growth is differentiated per destination region, showing slower growth rates for flights within the European[6] region and larger growth rates to destinations outside the European area. In this study, traffic expectations for the European[6] region are applied to Dutch international aviation.

Table 7: Traffic volume growth expectations excluding demand impacts due to economic measures and uptake of sustainable aviation fuel

	Intra-European flights	Extra-European flights	Total flights
2030	+11%	+21%	+13%
2050	+46%	+89%	+45%

[6] The geographical scope of the Destination 2050 roadmap includes, the European Union, the United Kingdom and the European Free Trade Association EFTA.
[7] The Destination 2050 roadmap does not specify 2040 emissions nor traffic.

3.3.2 CO_2 emissions

Fuel requirement effects due to operational and technical development

The Destination 2050 roadmap assumes large CO_2 reductions due to technological improvements of conventional kerosene-powered aircraft as well as those of hydrogen-powered aircraft which are modelled to enter into service from 2035 onwards. The contributions of these technological improvements and further reductions due to operational developments with respect to the estimated emissions from the traffic volume forecast are given in Table 6.

Table 8: Reductions in CO_2 due to technological and operational improvements compared to Destination 2050 reference scenario emissions

	Intra-European flights	Extra-European flights	Total flights
2030	-13%	-11%	-11%
2050	-14%	-30%	-27%

Uptake of alternative fuels in horizon years

In the Destination 2050 roadmap, hydrogen-powered aircraft are modelled to enter into service from 2035 onwards. They are assumed to be operated on the intra-European network only and with a maximum flight range of 2000km. SAF is modelled at average lifecycle emissions reduction factor of 72% in 2030 and 98% in 2050. In 2030 6% of the network is estimated to be operated using SAF. In 2050 this percentage rises up to 66% with an additional 21% of the flights being operated by hydrogen, a smaller share of 13% of flights is still expected to be fuelled by conventional kerosene as summarised in Table 9.

Table 9: Fuel uptake in the Destination 2050 scenario; the values show the percentage of kerosene replaced with the alternative energy carrier

	Conventional kerosene	SAF	H_2
2030	94%	6%	-
2050	13%	66%	21%

Demand impacts

The reliance on sustainable aviation fuels as well as economic measures, such as EU ETS, is also expected to have an impact on the demand, up to 3% in 2030 increasing to up to 15% in 2050 in terms of CO_2 when compared to the Destination 2050 reference scenario.

Table 10: Reductions in CO_2 due to demand impact compared to Destination 2050 reference scenario emissions

	Intra-European flights	Extra-European flights	Total flights
2030	-4%	-4%	-4%
2050	-8%	-19%	-7%

Resulting CO_2 emissions for horizon years

The resulting CO_2 emissions for the horizon years based on the trends in the Destination 2050 studies are thus as given in Table 11. As growth with respect to 2019 is expected in the reference scenario, absolute emissions of CO_2 decrease comparatively slowly. Moreover, Destination 2050 scenario does depend on carbon removal and offsetting to reach net-zero in 2050, such that in-sector CO_2 emissions remain.

Table 11: Resulting estimated CO_2 emissions of horizon years in scenario 3, following the Destination 2050 decarbonisation trends, and relative to 2019 emissions

	CO_2 [Mt]	
2019	10.1	-
2030	9.8	-3%
2050	1.7	-83%

3.3.3 H_2O and NO_x emissions

Based on the fuel composition and use, H_2O and NO_x emissions of Dutch international aviation are computed for horizon years following scenario 3. In 2030, no breakthrough technologies are yet expected such that emissions decrease with fuel, although lesser so for fuels replaced by SAF due to the higher hydrogen content in the sustainable aviation fuels. Due to growth, total emissions still increase. In the following years, water vapour emissions are expected to increase due to the extensive use of hydrogen powered planes within the intra-European flight network. Implications of usage of new engine designs such as ultrafan engines (elaborated upon in Section 4.4) on e.g. NO_x emissions are here not yet incorporated. Therefore, the NO_x emissions may be overestimated in Table 12 should these new technologies find their way to the market and are widely taken up.

Table 12: Estimated H_2O and NO_x emissions of horizon years for scenario 3

	NO_x [kt]	H_2O [Mt]
2019	50	4
2030	52	4
2050	56	7

3.3.4 Climate-impact

Due to the expected growth, total climate impact in scenario 3 also increases towards 2030. However, in 2050 a larger share of the CO_2 climate impact can be reduced due to higher uptake of alternative fuels and higher lifecycle reductions achieved for these fuels. In 2050 this, however, does not imply climate neutrality, even if non-CO_2 effects are overestimated. Rather, climate impact may be still comparable with 2019 levels although a larger share, increasing to ca. 96% in 2050, is caused by non-CO_2 effects, as shown in Table 13.

Table 13: Estimated climate impact of total and non-CO_2 climate effects of emissions in horizon years of scenario 3

	ATR_{100} [mK]		$AGWP_{100}$	
	Total	non- CO_2	Total	non-CO_2
2019	1.11	0.86	0.25	0.18
2030	1.16	0.90	0.26	0.19
2050	1.07	1.03	0.23	0.22

3.4 Comparison of scenarios towards carbon neutrality

The above described scenarios towards carbon neutrality result in different CO_2 and non-CO_2 emissions. The differences in CO_2 emissions can be explained by the differences in the system bounds[8] of neutrality. Whereas the scenarios 1 and 2, based on decarbonisation trends by PBL, require the aviation sector to reduce its CO_2 emissions completely in the year 2050, the Destination 2050 roadmap allows for some of aviation's carbon emissions to be compensated through CO_2 removals in other sectors. Therefore, scenario 3 – following Destination 2050 decarbonisation – a 83% reduction in CO_2 emissions can be achieved, instead of the 100% reduction in scenarios 1 and 2. If the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation, (ICAO, n.d.)) methodology was also applied to scenarios 1 and 2 some CO_2 emissions would remain and a reduction of about 98% could be achieved in 2050, assuming similar lifecycle reductions as in Destination 2050.

In terms of climate impact the differences are larger, mostly due to differences in expected flight numbers (-8% in scenarios 1 and 2 versus +42% flights in scenario 3 in 2050 with respect to 2019). Whereas the scenarios 1 and 2 result in 45-48% reduction of climate impact in 2050 compared to 2019 levels, scenario 3 results in 4-8% reduction of climate impact as seen in Figure 4 and Figure 5. Differences between scenarios 1 & 2 are small and caused only by the additional hydrogen uptake in the scenario with focus on e-fuels. This has a small decreasing effect on the climate impact of NO_x and contrail induced cirrus (CIC) and a small increasing effect on water vapour effects, totalling a 2% additional reduction in ATR_{100} compared to the scenario with emphasis on biofuels. The effect of increased hydrogen usage is also visible in scenario 3 in which the water vapour climate contribution outpaces growth in flight numbers.

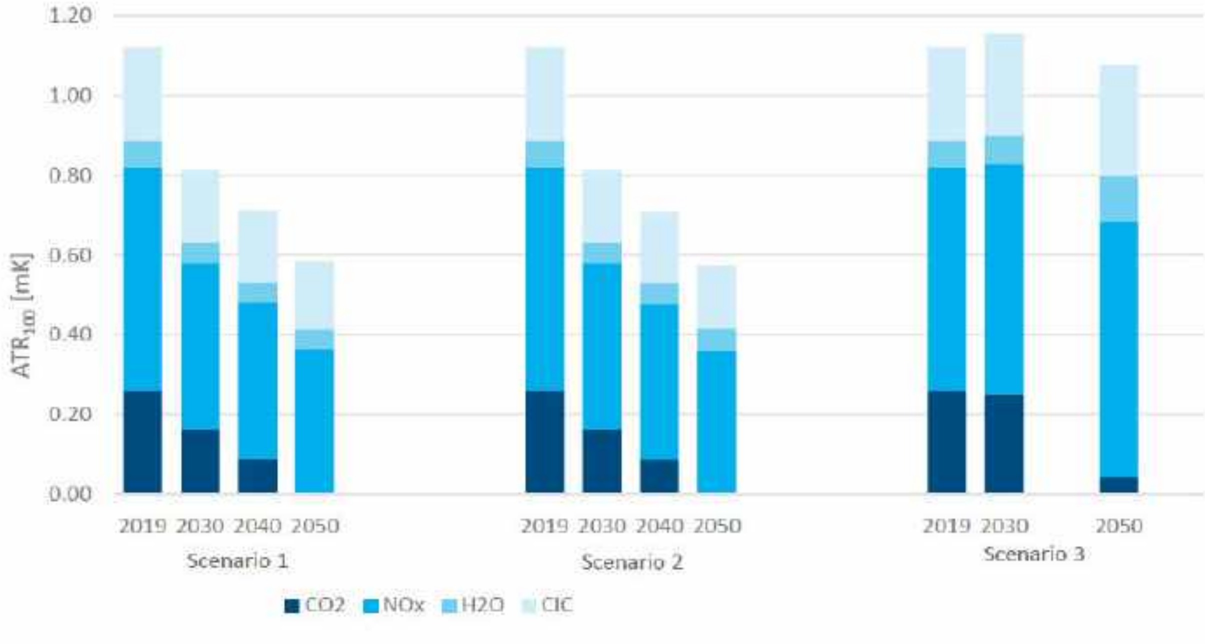

Figure 4: Climate effect in ATR_{100} for horizon years resulting from the indicated scenarios

[8]Necessitating to achieve net-zero CO_2 emission targets fully within the aviation sector or allowing for out-of-sector compensation.

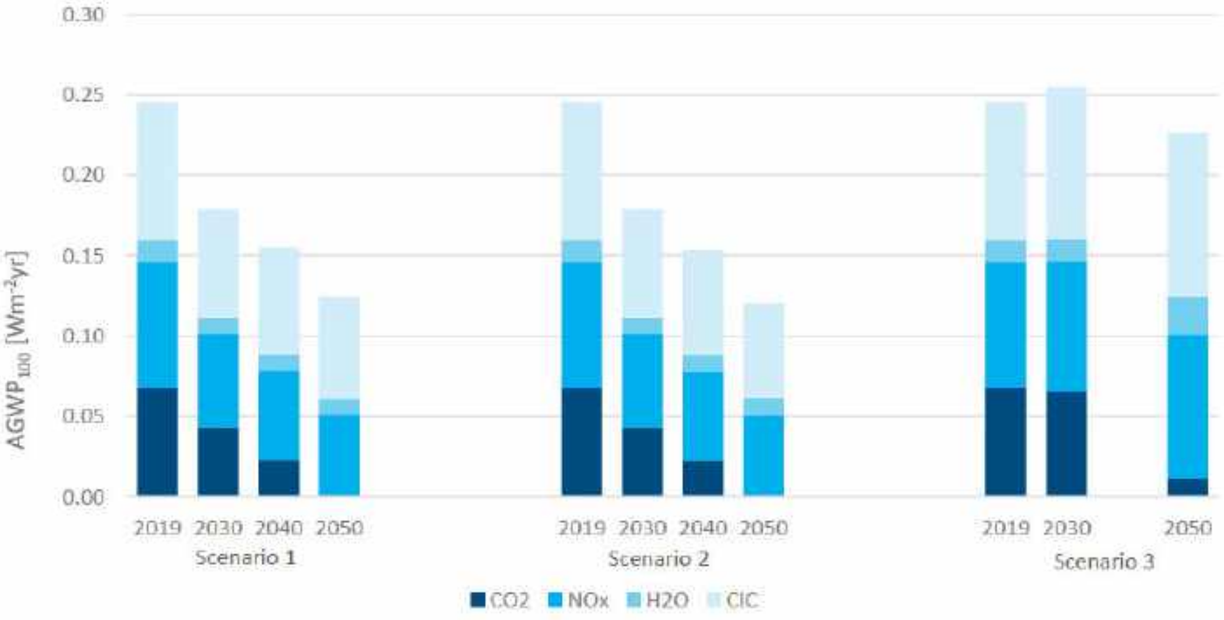

Figure 5: Climate effect in $AGWP_{100}$ for horizon years resulting from the indicated scenarios

4 Non-CO_2 mitigation strategies

To reduce the non-CO_2 climate effects of the remaining emissions in the scenarios for carbon neutrality, mitigation strategies can be devised. In section 4.1 an overview of the different measures is given. Three of the measures, (climatological based) targeted use of SAF, contrail avoidance and improved aircraft engine technology are further detailed in sections 4.2, 4.3 and 4.4., including the potential climate impact reduction that can be achieved when introducing these strategies in the baseline scenarios.

4.1 Overview of non-CO_2 mitigation strategies

The non-CO_2 mitigation strategies can be categorised into (prioritised) usage of alternative sustainable energy carriers (abbreviated to "Fuel" in Figure 6), improved operations (abbreviated to "Operations" in Figure 6) and improved aircraft and engine technology (abbreviated to "Technology" in Figure 6). Three mitigation strategies are further investigated in this study, covering all three categories. Contrail avoidance and advanced aircraft with lean burn engines are expected to have high benefit for the reduction of non-CO_2 effects, with contrail avoidance specifically targeting contrail effects and advanced aircraft with lean burn engines also targeting NO_x. As the reduction of the aromatic content in the fuels and hydrogen flights are already covered to some extent by the uptake of bio-, syn-SAF and H_2 in the scenarios, the mitigation strategy targeted use of SAF is selected for further investigation. The remaining mitigation strategies are presented in Appendix A but not modelled in detail.

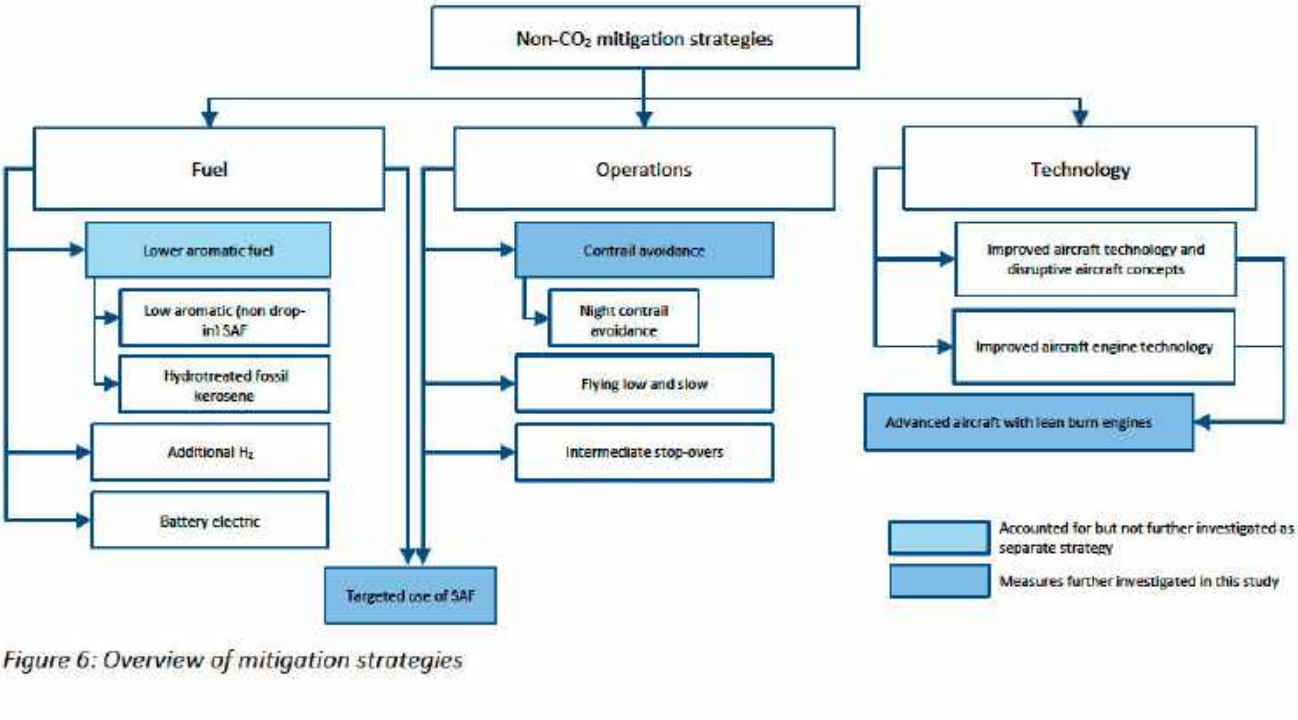

Figure 6: Overview of mitigation strategies

4.2 Route-based targeted use of SAF

While SAF supply is still scarce, a preferential allocation to certain flights which are responsible for a strong warming effect due to contrails could drastically increase the climate benefit. A study on North-Atlantic flights by Teoh et al. (2022) showed that "intelligently allocating the limited SAF supply could multiply its overall climate benefit [in terms of energy forcing, related to $AGWP_{100}$] by factors of 9-15". Figure 7 illustrates the principle. When 1% SAF is blended equally in all flights (1:99 ratio SAF/Jet A-1), a reduction of 0.6% in terms of energy forcing of the climate impact of contrails is observed. When the SAF is used on 1.9% of the flights with a 50:50 ratio SAF/Jet A-1, the energy forcing from contrails for the total considered flight set could be reduced by 10.2%, resulting in a climate benefit of 6% as shown in Figure 7.

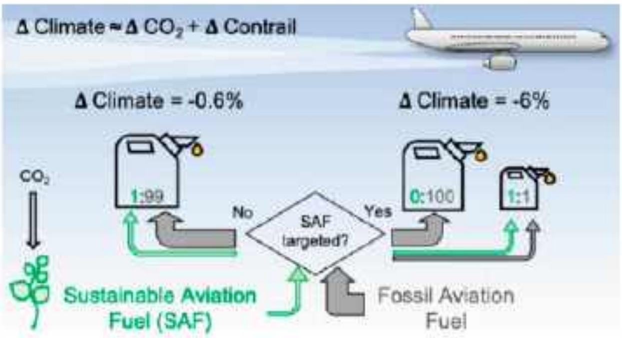

Figure 7: Targeted use of SAF (Teoh, et al., 2022)

More values for allocation options are given in Table 14. In this case study, the benefit is reducing for SAF blending ratios above 50% because with a fixed amount of available SAF less flights that produce warming contrails can be targeted.

Table 14: Benefits for different allocation of SAF

Flights with SAF	Ratio SAF to Jet A-1	Change in Energy Forcing of contrails
100%	1:99	-0.6%
9.4%	10:90	-5.2%
3.1%	30:70	-9.2%
1.9%	50:50	-10.2%
1.3%	70:30	-10.1%
0.9%	100:0	-9.3%

For the Dutch scope, especially flights crossing areas which are prone to contrail formation could be targeted, e.g. flights above the North Atlantic Ocean. Currently SAF is delivered to the Netherlands only at Amsterdam Airport Schiphol and made available to other airports on a book and claim[9] basis. On Amsterdam Airport Schiphol, SAF is distributed to flights by mass balance and therefore does not allow for targeting specific flight pairs for SAF. However, in the future SAF may become more widely available (especially with the ReFuelEU Aviation mandate) and setting up a dual fuel infrastructure for SAF and conventional kerosene may be more feasible. That way targeting the use of SAF to flights that are likely to fly through contrail prone areas may be easier. Another, rather more challenging, means to ensure SAF is used when flying through contrail prone areas would be to use SAF only specifically on certain flight segments by having multiple fuel tanks on board. This could potentially reduce contrail energy forcing by 55% compared to a base case of less than 5%, as shown by full year simulations of Quante et al. (2024) for the years 2017, 2018 and 2019, shown in Figure 8.

[9] https://skynrg.com/book-claim-explained-what-is-book-and-claim

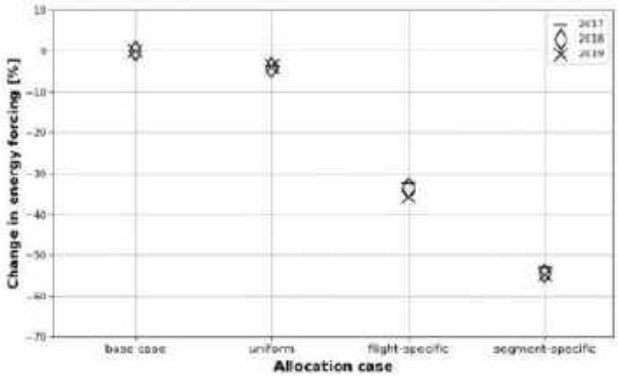

Figure 8: Reductions in energy forcing of contrails when applying no SAF, uniformly, flight specific or segment-specific. From (Quante, Voigt, & Kaltschmitt, 2024)

4.2.1 Implementation

In this study, a climate-based approach of targeting certain routes with extra SAF is investigated. In contrast, the study by Teoh et al. (2022) uses the weather-based approach where the contrail energy forcing is calculated for individual flights. In the present study, the flights are aggregated by route, and also the climate impact is calculated per route, without calculating the formation of contrails along each trajectory with the use of weather data. It is therefore expected that the climate-based approach, which is based on averages, will yield lower benefits than a weather-based approach would bring.

In the baseline cases a uniform SAF blending on all flights is assumed. Higher blending ratios of SAF are modelled to influence the radiative forcing of the contrails and therefore decrease the climate impact of contrails measured with a climate metric such as ATR100 or AGWP100. Implementing the mitigation strategy of SAF first requires the determination of the total amount of SAF that is available for a certain year in a certain scenario. Then, a chosen blending percentage, higher than the uniform blending percentage, is assigned to the routes with the highest $ATR_{100,contrails}$ per flight divided by the fuel burn per flight. This indicator highlights the routes, where a kilogram of SAF would lead to the biggest climate impact reduction. The remaining flights are assumed to fly with Jet A-1 only, thus SAF blending ratio of 0%.

The mitigation strategy of route-based targeted use of SAF is only reasonable for scenarios where the SAF supply is limited. Therefore, scenario 3 – based on the decarbonisation trends of Destination 2050 – is investigated for the modelled years 2030 and 2050. For scenarios 1 and 2 – based on decarbonisation trends of PBL –, the years 2030 and 2040 are analysed. As in these scenarios in 2050 100% renewable fuel is used, this mitigation strategy cannot be applied in the year 2050.

4.2.2 Results

The routes with the highest $ATR_{100,contrails}$ divided by the fuel burn per flight are found to be flights to airports with a high latitude e.g. Northern Europe, where according to the used climate impact functions by Thor, et al. (2023) contrails occur more often on average. Other routes that have a high contrail climate impact per kilogramme burnt fuel are, for example, found to be routes to South Africa and Argentina, with mid-latitudes of the flown routes in the tropics. The improvements compared to the baseline case are shown in Figure 9, for the contrail climate contribution only. The contrail climate impact reduction is up to 2.9%.

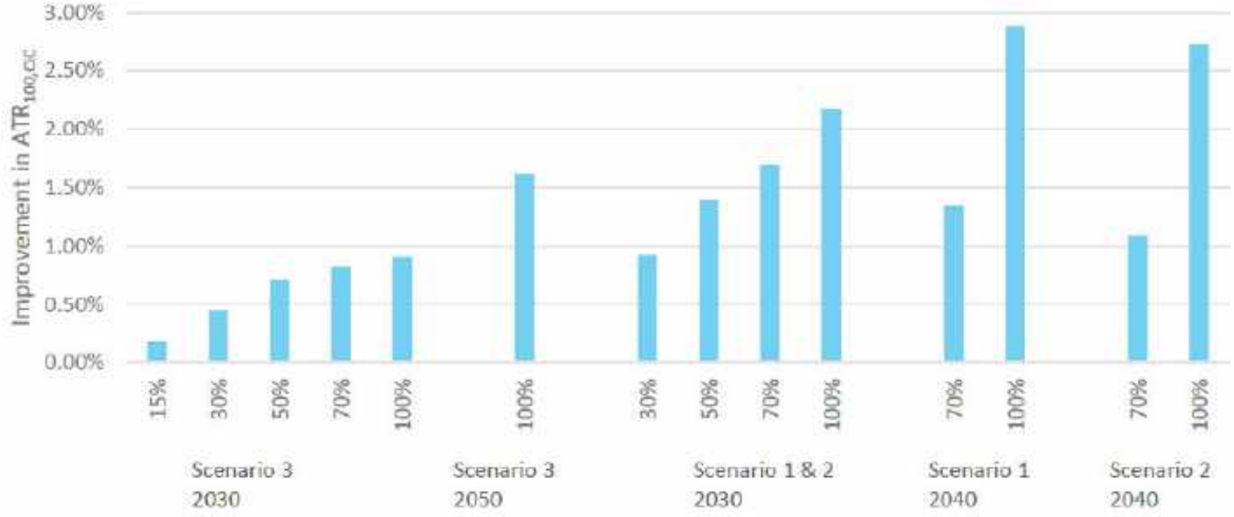

Figure 9: Reduction of the estimated climate impact in terms of ATR_{100} of contrail cirrus clouds for different scenarios with the mitigation strategy targeted use of SAF. Percentages denote the blending level flights selected for SAF

When not only looking at contrail induced cloudiness, but at the whole climate impact measured in total ATR_{100} or $AGWP_{100}$, the improvement is lower because the targeted use of SAF strategy just has an impact on the contrail contribution. The other components of the total $AGWP_{100}$ metric, such as the climate impact of H_2O and CO_2, are not altered by the mitigation strategy as still the same amount of SAF is used. Therefore the improvements are lower and reach maximal 0.8% to 1.3%, see Figure 10 and Figure 11.

Figure 10: Reduction of the estimated climate impact in terms of ATR_{100} for different scenarios with the mitigation strategy route-based targeted use of SAF. Percentages denote the blending level flights selected for SAF

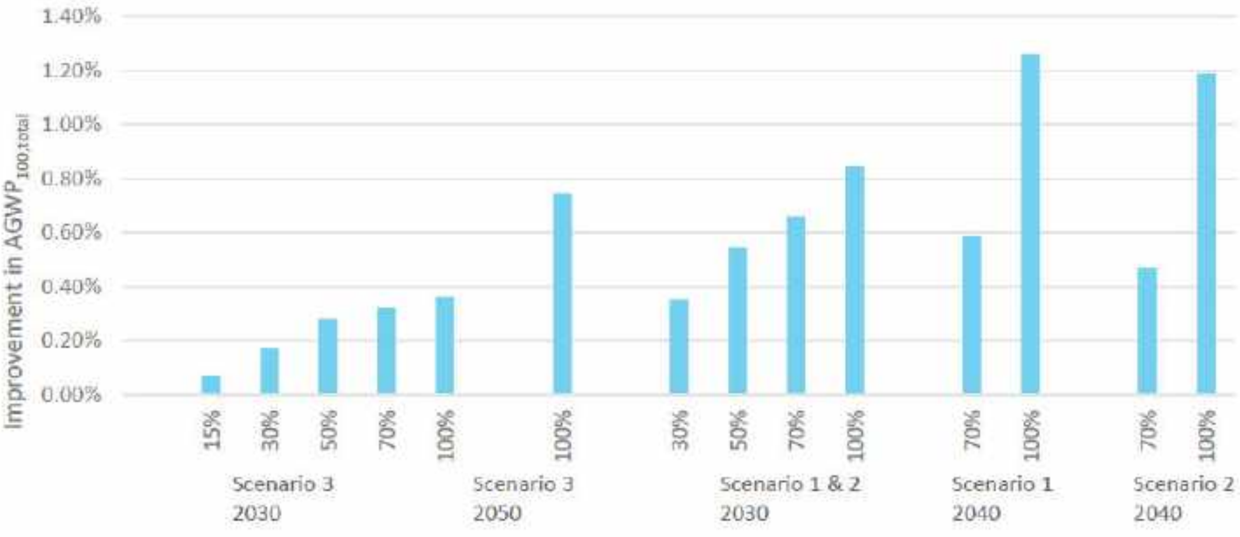

Figure 11: Reduction of the estimated climate impact in terms of $AGWP_{100}$ for different scenarios with the mitigation strategy targeted use of SAF. Percentages denote the blending level flights selected for SAF

The relatively low numbers of climate impact improvement are due to the climate-based approach of redistributing the available SAF. The advantage from a logistical planning point of view is that flights selected to be allocated higher SAF blends are known far in advance, easing refuelling procedures. However, the logistical and legal challenges, such as having dual refuelling systems and the minimum requirement in uplift of SAF at airport level (EC, 2023), need further investigation. In this study, no actual nor predicted weather data was used to devise a more refined targeted use of SAF strategy (e.g. targeting SAF on individual flights). As there is indication that with a weather-based approach the benefits could be up to 10% (Teoh, et al., 2022)[10], it is recommended to further investigate that option both in terms of climate impact reduction potential and operational challenges.

4.3 Contrail avoidance

Contrail avoidance through lateral or vertical flight deviations of regions where warming and persistent contrails are likely to form is a promising solution to reduce non-CO_2 climate effects of aviation. Although flight reroutings lead to more fuel consumption (hence costs and CO_2 emissions) and additional workload to air traffic controllers (ATC), a large share of the contrail climate impact (80% of the energy forcing, EF) can be mitigated by rerouting a small share of flights (2% in Japan; Teoh et al. 2020); 12% in the North Atlantic Flight Corridor (NAFC) (Teoh, et al., 2022); 2% globally, Teoh et al. (2024). Furthermore, Teoh et al. (2020) has shown that contrail avoidance of 1.7% of the flights within the Japanese airspace could lead to a contrail EF reduction of 59.3% with only an increase of 0.014% in fuel consumption. Martin Frias et al. (2024) did a similar study for American Airlines (USA domestic and international flights) and showed that by rerouting 2.66% of the flights, the contrail energy forcing was reduced by 65.68%. while fuel consumption increased only by 0.05%.

The fraction of intra-European flights responsible for most contrail warming seems to fall in between the global and NAFC estimates – at least, if long-lived contrails is used as a proxy for highly warming contrails (Figure 12). The fraction of intra-European flights producing contrails with lifetime longer than 4 hours is about 7%. This means that, for a

[10] The NLR-CR-2024-211 report on 'Influence of the composition of SAF and H_2 on non-CO_2 climate effects' – describes similar results for total reductions in ATR_{20} due to targeted use of SAF using a weather-based approach.

similar outcome, probably more flights would have to be rerouted in Europe than, for instance, within North America (3% of flights) or Asia (2% of flights), while the European airspace has one of the highest air traffic density (Figure 13).

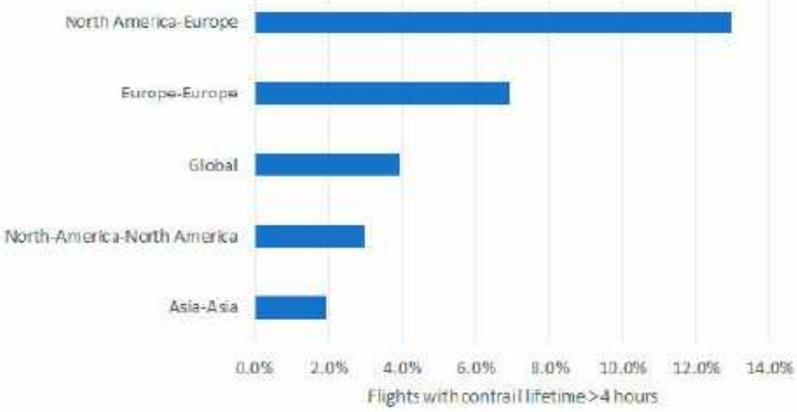

Figure 12: Percentage of flights with contrail lifetime larger than 4 hours. Figure reproduced from Ghosh et al. (2024)

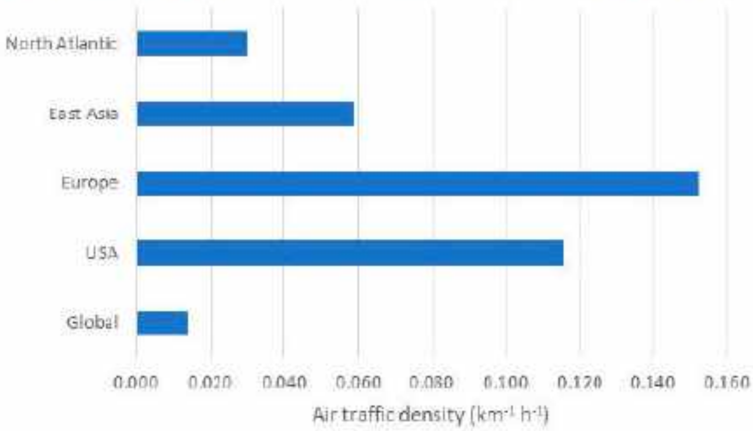

Figure 13: Air traffic density per region. Figure reproduced from Teoh et al. (2024)

In spite of the challenges in rerouting intra-European flights, persistent contrails formed within Europe have a high average energy forcing per contrail length (Figure 14), which indicates a better trade-off with CO_2 than most regions, with the highest energy forcing per contrail length in the NAFC. Lührs et al. (2021) have shown that by re-optimising two thousand intra-European flight routes, the climate impact could be reduced by 50% (mainly due to contrail) with an increase in fuel consumption of 0.75%. Their work, however, only comprised one day with strong contrail formation conditions and although two thousand routes were optimised, a climate reduction of 50% was already achieved with about 750 reroutings.

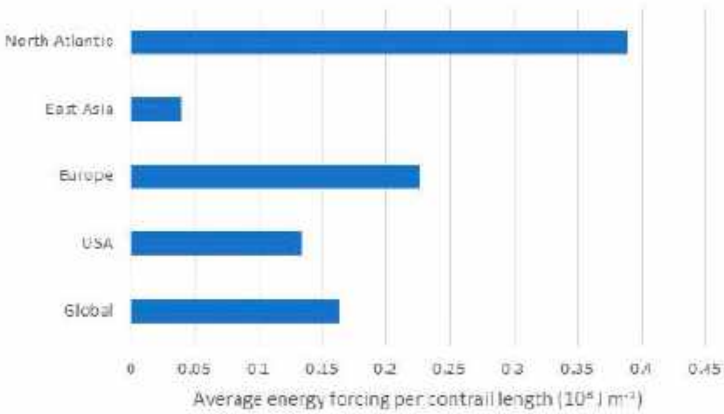

Figure 14: Average energy forcing per contrail length. Figure reproduced from Teoh et al. (2024)

4.3.1 Implementation

In this study, the potential of contrail avoidance is analysed by verifying changes in total climate impact, evaluated as ATR_{100} and $AGWP_{100}$. Trajectories are not optimised for this purpose, which would require non-CO_2 effects computations at flight level, which have not been performed. Instead, it is verified how the total climate impact changes by assuming three possible changes in contrail EF ($\Delta EF_{contrail}$) of Jet A-1 and SAF-fuelled flights:

1. -20%
2. -50%
3. -80%

Considering that the reviewed studies have shown mitigation potential of contrail energy forcing between 60-70%, the assumption of $\Delta EF_{contrail}$ = -50% is considered to be conservative, while -80% optimistic and -20% pessimistic.

The change in total climate impact depends also on the increased fuel consumption and associated CO_2, NO_X and H_2O emissions. The reduction in $\Delta EF_{contrail}$ is analysed for different assumptions of fuel consumption increase up to 1%, with the higher limit being a very conservative estimate (e.g. for 20% of reroutings with 5% fuel consumption increase per flight). In contrast, the studies reviewed considered reroutings of a small fraction of flights (2-10%), leading to small increases in fuel consumption (0.02-0.05%). Even when the optimisation was applied to all flights, the fuel consumption was increased by only 0.75%.

4.3.2 Results

The changes in total ATR_{100} and $AGWP_{100}$ for the assumed contrail EF reductions (-20%, -50% and -80%) and associated increase in fuel consumption (up to 1%) are shown in Figure 15 (Scenario 1, with an emphasis on bio-SAF), Figure 16 (Scenario 2, with an emphasis on e-fuels, including SAF and H_2) and Figure 17 (Scenario 3). Notice that each line in these figures represent a constant reduction in contrail EF, while checking for the sensitivity of the total climate impact with respect to the increase fuel consumption, which is not known. First, it is clear that the increase in fuel consumption and associated emissions (represented by the slope of the curves) has only a small influence on the total climate impact change, which is dominated by the contrail reduction (different line colours). For example, Figure 15 shows that if a 50% contrail reduction could be achieved by a 1% increase in fuel usage for scenario 1 in 2030, potentially 10.4% reduction in climate impact (ATR_{100}) could be achieved. If, instead, the same contrail reduction could be achieved more efficiently with a 0.5% fuel consumption increase, the total climate impact benefit only increases to 10.8%. On the other hand, if for the same scenario, a contrail energy forcing reduction of 80% is achieved by a 1% increase in fuel, the total ATR_{100} is reduced by 17.1%. Second, the comparison between metrics shows that the contrail climate impact has a higher weight in the computation of $AGWP_{100}$ relative to ATR_{100}, yielding, therefore, a higher measure of climate impact mitigation when computed with $AGWP_{100}$. Third, the reduction in climate impact due to contrail avoidance becomes relatively higher with time, with the highest mitigation potential obtained for the 2050 scenarios. This is because the increasing SAF and H_2 adoption reduces the relative importance of CO_2 to the total climate impact, increasing as a consequence the importance of contrails to the total climate impact. Finally, the relative mitigation through contrail avoidance is slightly better for scenarios 1 and 2 than for scenario 3, while the scenarios 1 and 2 – with or without H_2-aircraft are fairly similar. It is worth noting, however, that although the relative differences among the scenarios are similar, their absolute value depends on the total climate impact estimated for each scenario (Figure 4 and Figure 5).

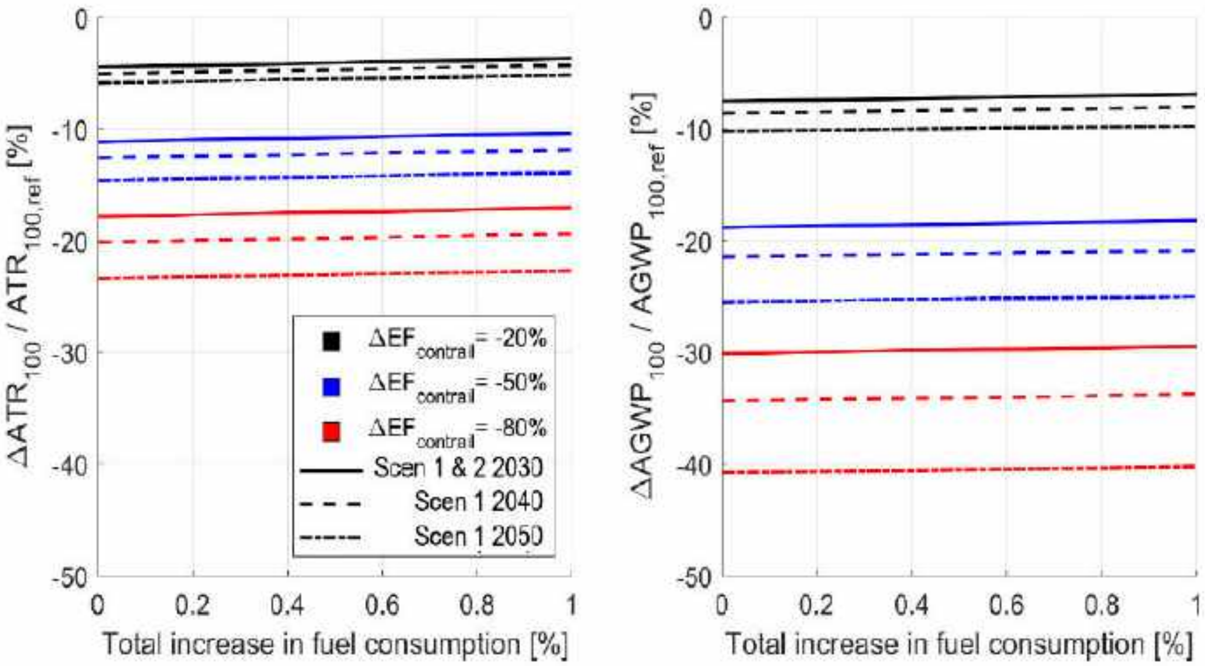

Figure 15: Contrail avoidance for scenario 1 with an emphasis on bio-SAF (homogeneously distributed). Lines show the difference in total climate impact with respect to the baseline scenarios for horizon years 2030 (solid), 2040 (dashed) and 2050 (dash-dotted) when a reduction in contrail energy forcing of 20% (black), 50% (blue) or 80% (red) can be achieved by fuel increases of 0% to 1%

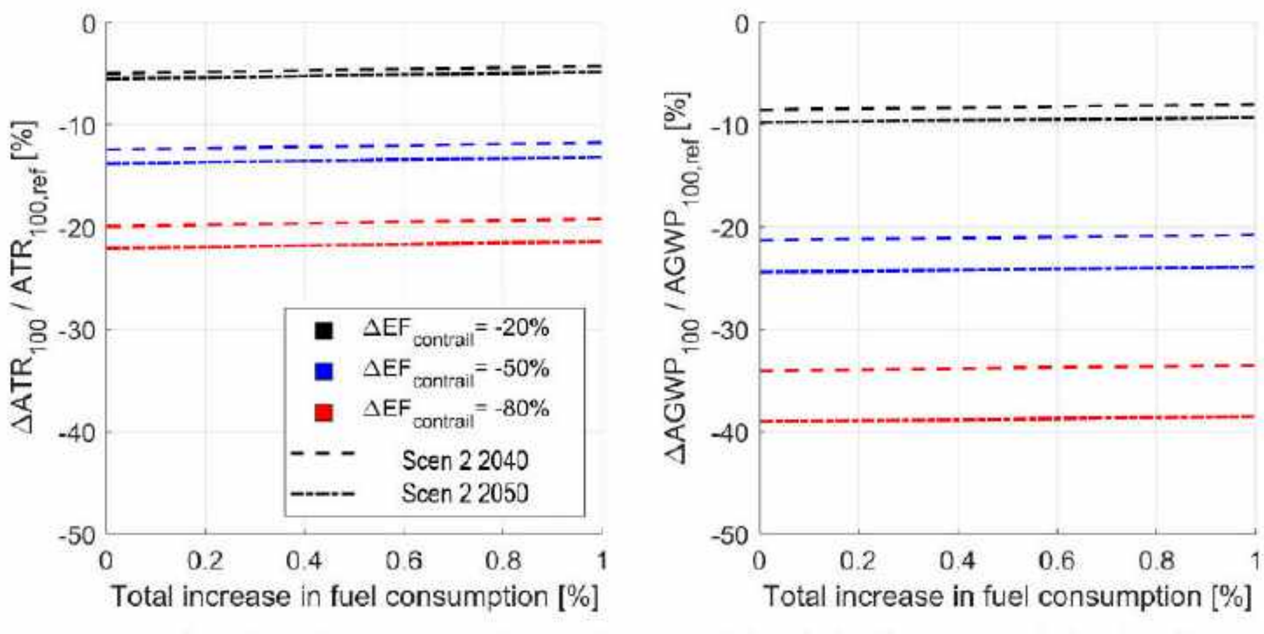

Figure 16: Contrail avoidance for scenario 2 with an emphasis on e-fuels including (homogeneously distributed) SAF and H_2. Lines show the difference in total climate impact with respect to the baseline scenarios for horizon years 2040 (dashed) and 2050 (dash-dotted) when a reduction in contrail energy forcing of 20% (black), 50% (blue) or 80% (red) can be achieved by fuel increases of 0% to 1%

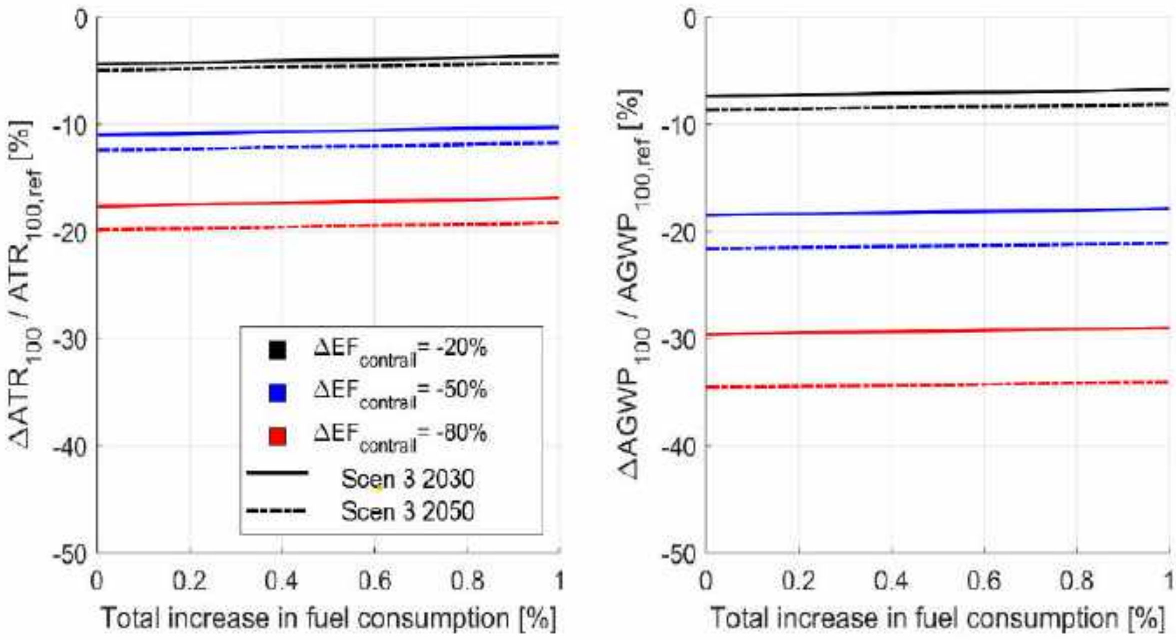

Figure 17: Contrail avoidance for scenario 3 including SAF (homogeneously distributed) and H_2. Lines show the difference in total climate impact with respect to the baseline scenarios for horizon years 2030 (solid) and 2050 (dashed) when a reduction in contrail energy forcing of 20% (black), 50% (blue) or 80% (red) can be achieved by fuel increases of 0% to 1%

Based on this analysis, and focusing on the conservative assumption of $\Delta EF_{contrail}$ = -50%, contrail avoidance could lead to total ATR_{100} reductions of 10-15% (or 18-25% for $AGWP_{100}$) in the period from 2030 to 2050, with the relative reduction potential increasing with time as the CO_2 fraction of total climate impact reduces. Analysis of the feasibility of implementing such strategy, including an increase of operational costs and the airspace capability constraints, is beyond the scope of this study but should be considered for policy making.

4.4 Improved aircraft engine technology

The potential of technology improvement of mitigating aircraft emissions (CO_2, H_2O and NO_X) of aircraft categories in scope of this study is estimated based on the Clean Sky 2 aircraft concepts (Clean Sky 2 Technology Evaluator, 2021), summarised in Figure 18 and Table 15. The emission reductions summarised in Table 15 are due to aerodynamic, structure, system and engine improvements. For instance, the advanced TP is equipped with a very large propeller (4.87 m diameter), the Advanced SMR is propelled by SAFRAN's Ultra-High Propulsion Efficiency (UHPE) turbofan (Figure 19, left), the Ultra-Advanced SMR comes with SAFRAN's contra-rotating open rotors (CROR) installed next to the aircraft tail (Figure 19, middle), and the Advanced LR is equipped with Rolls Royce's Ultrafan (Figure 19, right). Important to point out that the emission reductions are per flight and that the NO_X emission reductions are in some cases only due to fuel consumption improvements.

Figure 18: Aircraft concepts from Clean Sky 2 Technology Evaluator (2021)

Table 15: CO_2, H_2O and NO_X emissions reductions estimated for the Clean Sky 2 aircraft concepts (Clean Sky 2 Technology Evaluator, 2021)

AC cat.	Seats	Range (nm)	EIS	Ref. AC	$\Delta CO_2/\Delta H_2O$	ΔNOx
Multi-mission TP	70	1000	2025	C295 (50 seats)	-7%	-49%
Innovative TP	90	1600	2025+	ATR72-500 upscaled	-34%	-67%
Advanced TP	130	1200	2035+	A220-300	-26%	-56%
Advanced SMR	200	2000	2030	A321neo	-17%	-39%
Ultra-Advanced SMR	200	2000	2035+	A321neo	-26%	-8%
Advanced LR	315	6700	2030	A350-900	-13%	-38%
Ultra-Advanced LR	315	6700	2035+	A350-900	-21%	-45%

Figure 19: Clean Sky 2 engine technologies (Clean Sky 2 Technology Evaluator, 2021). From left to right: SAFRAN's Ultra-High Propulsion Efficiency (UHPE), SAFRAN's contra-rotating open rotors (CROR); Rolls Royce's Ultrafan (Rolls Royce, 2024)

In addition to the CO_2, H_2O and NO_X emission reductions from SAF and the considered improvements in conventional engine efficiency, improvements in nvPM emissions through lean combustion is also important to consider. Lean combustors reduce both negative air quality impacts as well as the climate impact of NO_X and contrails. Staged combustors such as the double annular combustor (DAC) and the twin annular premixing swirler (TAPS) engine (Boies et al. (2015); (Stickles & Barrett, 2013)) have a sharp decrease in nvPM emissions when transitioning from pilot combustion (rich-burn) to lean operation, which occurs at about 30% thrust setting.

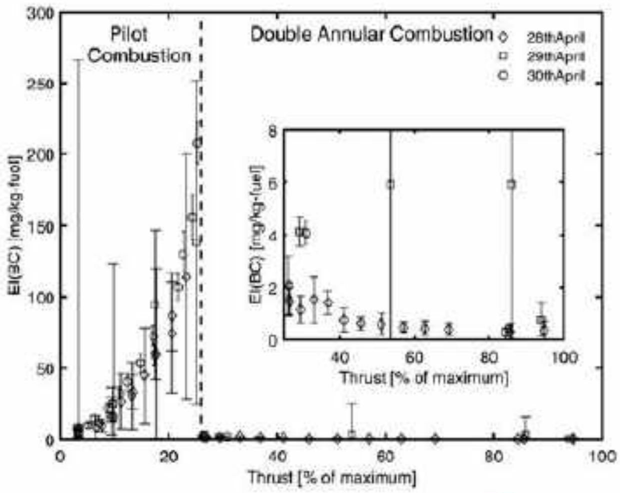

Figure 20: Black carbon (soot) mass emission index, EI(BC), for CFM56-5B4-2P (From Boies et al. (2015))

As given in Figure 21, the lean burn engines can reduce the non-CO_2 effects of NO_x and especially contrail cirrus compared to rich burn engines, when consuming the same amount of Jet A1. This may, depending on operating rate, decrease climate impact in ATR_{100} by 52-58%.

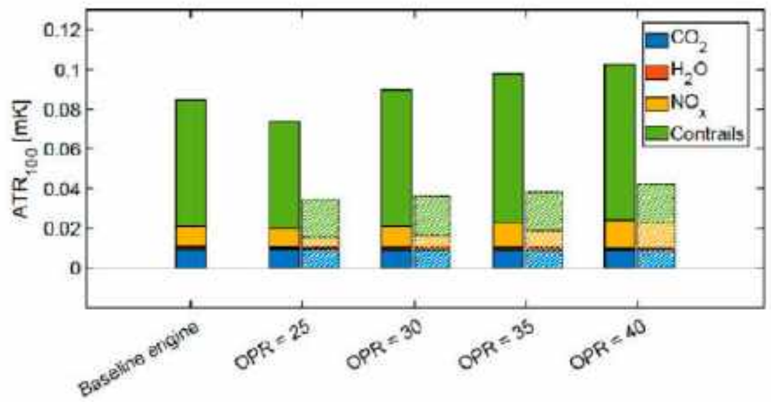

Figure 21: Comparison of lean and rich burn engines in terms of climate impact, measured in ATR_{100}, with changing OPR. Rich burn combustor results are shown in solid and lean burn in hatched. (From Singh Saluja et al., (2023))

4.4.1 Implementation

Within the scenarios the advanced aircraft from Clean Sky 2 and their lean combustion engines are implemented in a technology optimistic manner, such that all aircraft that are not yet equipped with lean combustion engines are eventually replaced by lean burn combustors. Once available, i.e. after the EIS as given in Table 15, all suitable aircraft on basis of range and seats are assumed to be replaced over a period of 10 years[11]. The aircraft are assumed to be fleet-wise operated for a minimum of 10 years after which they are phased out over a period of 10 years again if more advanced aircraft types enter the market. Figure 22 shows the aircraft within the 2019 network and their replacement aircraft based on range and seating capacity.

[11] Based on airline aircraft acquisition periods. KLM, for example, purchased their A330 fleet over a period of 9 years, and their first generation of B737s over a period of 13 years.

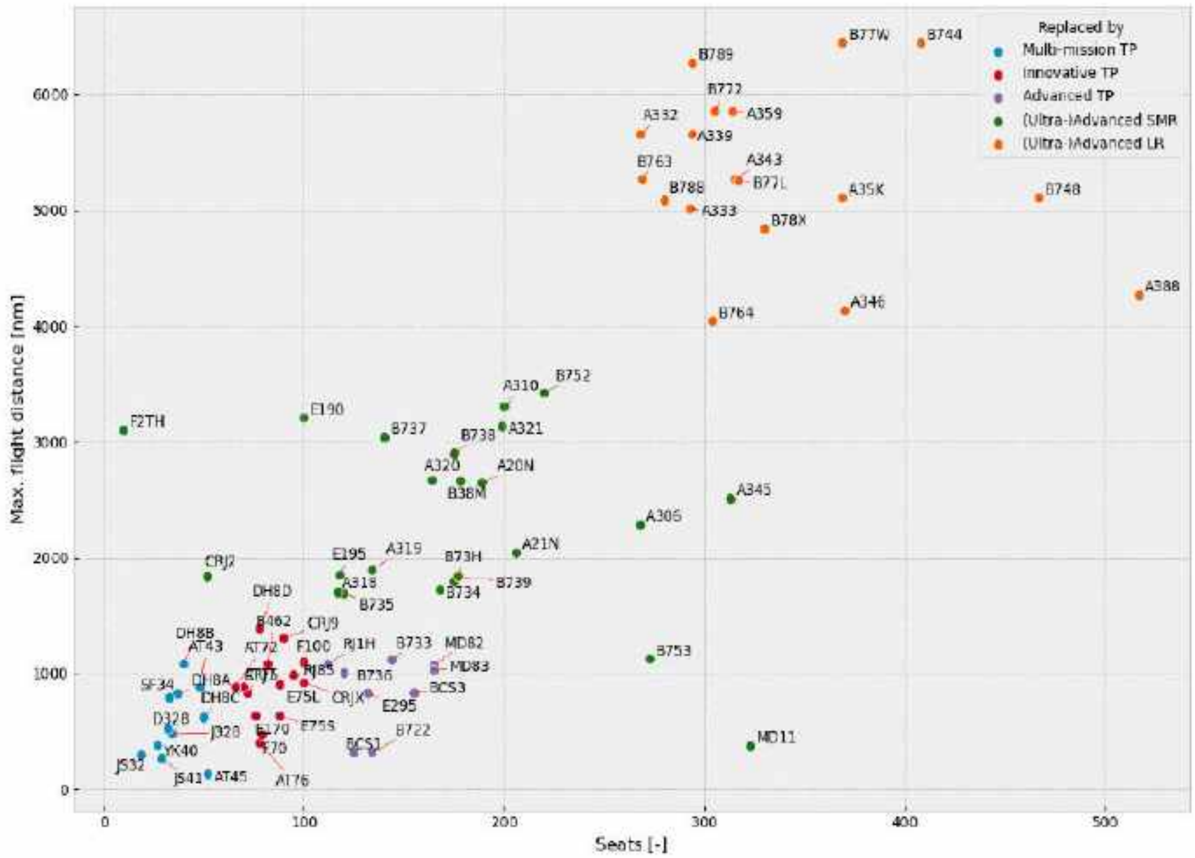

Figure 22: Modelled aircraft replacements based on 2019 aircraft range and seating capacity

Using the specified Clean Sky 2 reductions the CO_2 and NO_X emissions have been calculated for the replaced aircraft. Furthermore, reductions in nvPM mass emissions are modelled both due to reductions in fuel consumption and emission indices due to the replacement of rich burn by lean burn engines. A selection has been made on the engine types with other combustor types than DAC or TAPS (assumed in the reference scenario), to which the flight distance-based reductions in nvPM mass emissions have been applied (Figure 23). These reductions are obtained by comparing A320 flights powered with the CFM56-5B4 engine with DAC combustor against the same flights powered with CFM56-5B4 engine with other combustor types. As shown in Figure 20, most emission reductions with DAC engines are achieved above ca. 30% thrust setting. Therefore the relative reduction in nvPM emissions due to DAC is generally higher with greater flight distances, where the time spent in idle is relatively smaller.

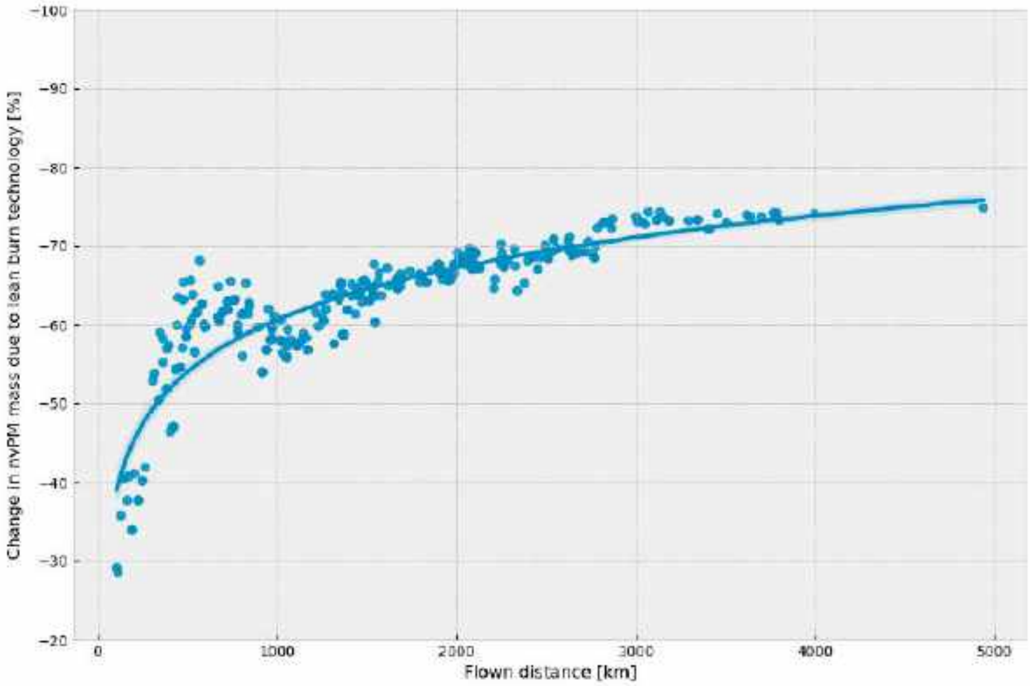

Figure 23: Modelled change in nvPM mass per flight due to the implementation of lean burn engine technology, as a function of flight distance

Then, nvPM number emissions are estimated by correlating mass and number emissions of existing DAC or TAPS engines (Figure 24). The nvPM number emissions strongly correlates with the number of ice crystals formed within contrails, which influences the radiative forcing and climate impact of induced cirrus clouds.

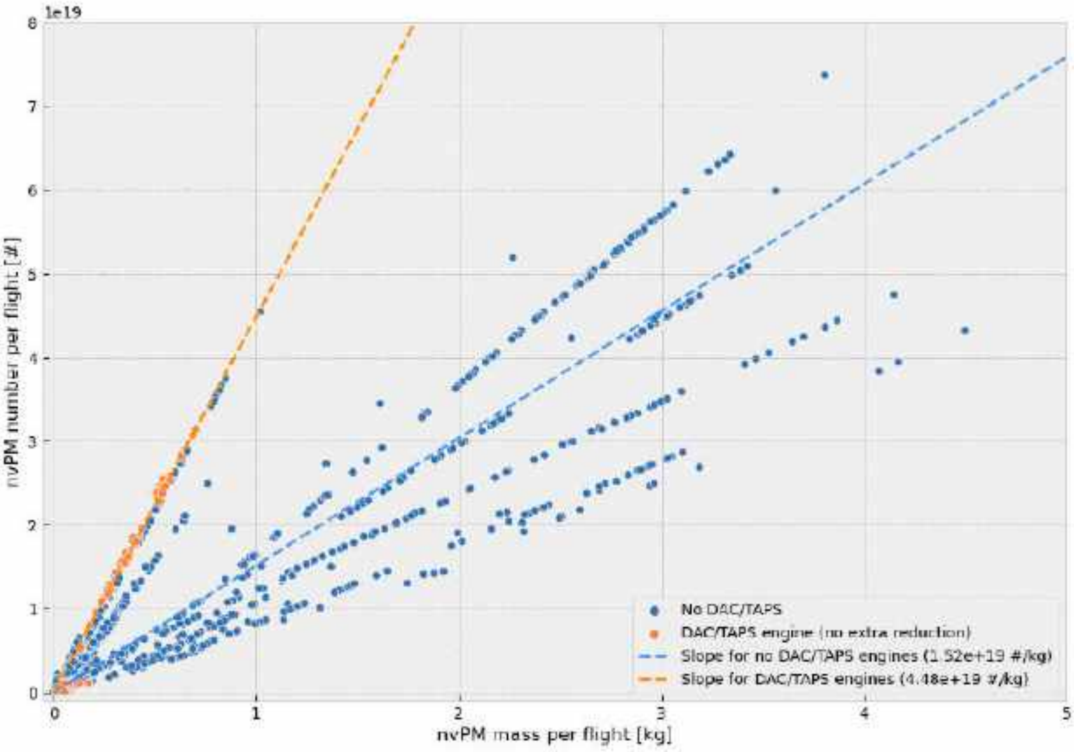

Figure 24: nvPM mass plotted versus nvPM number, for DAC/TAPS engines (orange) and for all other engines (blue). Linear trendlines with an intercept of zero are also shown. Note that some outlying data is not shown for visualisation purposes

4.4.2 Results

Total emissions for CO_2, NO_x, and nvPM resulting from aforementioned implementation reduce on single flight level. However, the growth in traffic volume following from Destination 2050 as well as the changes in demand from PBL data have been incorporated in the scenarios. Therefore, it is possible that novel aircraft types and technologies with concomitant emission reductions are being offset by traffic volume growth. When fully implemented, the resulting climate impact could reduce by 14-16% depending on scenario and horizon year as is given in Figure 25 and Figure 26. As most advanced aircraft types are expected to enter the market between 2030 and 2035, largest reductions in climate impact are foreseen for the horizon year 2040. Thereafter, the specified use of advanced aircraft result in similar, slightly lower, climate impact to that of the general anticipated trends of the scenarios. However, in the future even more advanced aircraft may enter the market such that 2050 values may decrease even further. If reductions in line with Singh Saluja et al., (2023) – reductions of contrail cirrus and NO_x effects by 70% and 27% – may be obtained, which could lead to even larger reductions in climate impact.

Figure 25: Estimated climate impact with introduction of CleanSky (ultra-)advanced aircraft as measured in ATR_{100}. Percentages denote change with respect to baseline scenario values

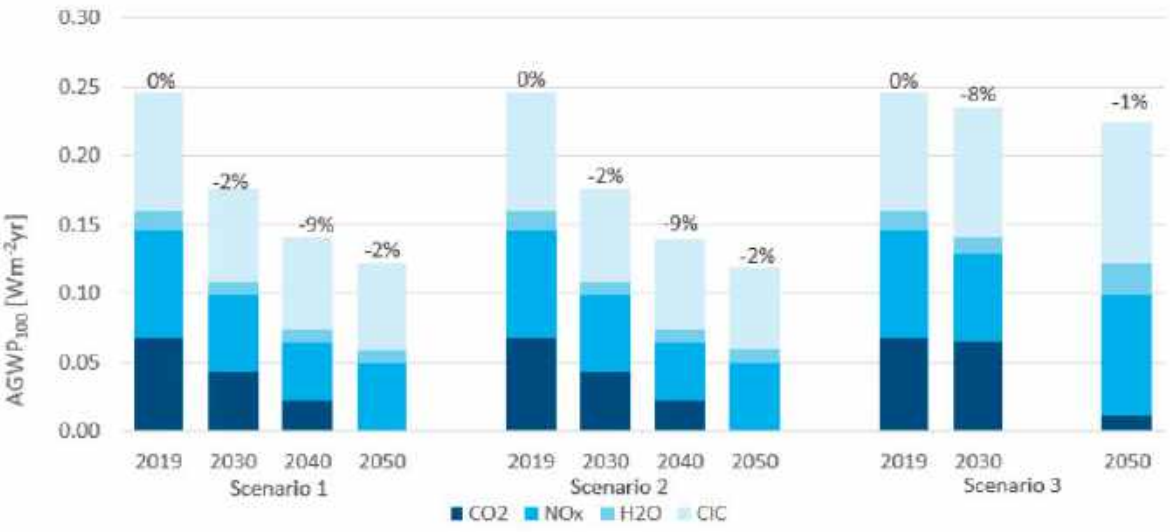

Figure 26: Estimated climate impact with introduction of CleanSky (ultra-)advanced aircraft as measured in $AGWP_{100}$. Percentages denote change with respect to baseline scenario values

5 Conclusions and recommendations

In this report, a high level outlook is given to what extent non-CO_2 effects can be reduced in three different aviation decarbonisation scenarios for commercial international aviation departing the Netherlands. Two scenarios are based on decarbonisation trends presented in *Klimaatneutrale luchtvaart in 2050* (Davydenko, Hilbers, & de Wilde, 2024), with one depending heavily on biofuels and another including the use of hydrogen. Moreover, a scenario in line with decarbonisation trends of Destination 2050 (Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) is presented, which to some extent still relies on fossil fuels.

Using the NLR BeyondCO_2 model, the CO_2 and non-CO_2 emissions of commercial international aviation departing the Netherlands are derived for 2019 and estimated for horizon years 2030, 2040 and 2050. This analysis is based on a combination of aircraft movements, fuel efficiency and usage trends specified in the scenarios and complemented with ICAO trends for improvements in NO_x and nvPM emissions. Existing relations for climate impact based on climate equivalent factors as developed by Thor et al. (2023) are extended with literature derived relations to describe the effects of replacement of kerosene powered flights by SAF (Sustainable Aviation Fuel) and hydrogen. While the tank-to-wake climate impact of CO_2 can be reduced to large (83-100%) extents, non-CO_2 climate impact does not decrease proportionally. Total climate impact reduction of horizon year emissions ranges therefore between 45-48% compared to the 2019 levels for scenarios 1 and 2. Scenario 3, which contains stronger growth and a dependency on kerosene, results in a reduction of 4-8% of the climate impact only, depending on utilised climate metric. Therefore, to mitigate the remaining climate effect, additional measures to address non-CO_2 climate effects would be necessary besides strategies to reduce the climate impact of accumulated long lived emissions.

In this report various mitigation strategies have been explored. A more detailed analysis was performed for route-based targeted use of SAF, contrail avoidance and the introduction of advanced aircraft with cleaner engines. A route-based targeted use of SAF was introduced to allocate a fixed amount of SAF (dependent on the scenario) to the flights where on a climatological average, the highest climate impact occurs. Flights with high levels of cirrus warming per kg fuel burnt were allocated SAF at blending levels higher than the scenario reference and less warming flights where allocated Jet-A1. This resulted in a potential contrail induced cloudiness impact reduction of up to 3% and total climate impact reductions of up to 1.5% depending on metric and scenario. The potential climate impact reduction of contrail avoidance was studied by analysing potential contrail energy forcing reductions (-20%, -50% and -80%) and a bandwidth of the related increase in fuel consumption (up to 1%, enabling contrail avoiding detours). When implemented in the scenarios, a potential reduction of climate impact of 10-25% could be achieved, depending on metric and scenario. To explore the potential of new aircraft and engine technologies, Clean Sky 2's (ultra-) advanced aircraft were introduced in the scenarios, based on entry-into-service year, range and seating capabilities. As most aircraft have expected introduction years between 2030-2035, the largest reduction potential (up to 16%) was observed for the scenarios in the 2040 horizon years, with lesser reduction potential for early years where few (ultra-)advanced aircraft were available and later years in which scenario trends already indicated large technology improvements, however, new disruptive aircraft designs may reduce climate impact on the long term even further.

In the long-term, largest reductions in climate impact may be yielded from flight specific contrail avoidance manoeuvres and advanced aircraft and engine technology. In the short-term, (route-based) targeted use of SAF may be implemented to reduce climate impact, when SAF is not available at a large scale (yet). Combinations of the various strategies are not analysed in detail. Combining contrail avoidance and targeted use of SAF may, however, would be inefficient as both strategies specifically target contrail induced cirrus clouds. Nevertheless, when SAF supply is still limited, contrail avoidance and targeted use of SAF can complement each other. Combinations of targeted use of SAF or contrail avoidance with the introduction of Clean Sky 2's (ultra-)advanced aircraft likely result in an increased benefit as targeted use of SAF and contrail avoidance target contrail induced cloudiness and the advanced aircraft technologies yield largest climate impact reductions in NO_x.

To ensure the strategies can be implemented successfully in the future, further research is required. In particular, uncertainty in the computation of contrail climate impact should be reduced. For this purpose, different methodologies, assumptions and datasets used to compute contrail climate impact should be compared. For instance the use of climate change functions enable simple and fast computation of contrail climate impact, but at the cost of lower accuracy. Other methods such as CoCiP (Schumann, 2012) model the contrail development and radiative forcing in more detail at the cost of higher computational time and increased difficulty of implementation. Assessing the trade-offs in accuracy of the models and uncertainties associated with the input weather data and emission models would increase the confidence of the estimates given by this report. This could better inform policymakers of the mitigation potential of the strategies analysed in this report.

Furthermore, a larger reduction potential may be achieved for the mitigation strategy of targeted use of SAF when flights are analysed on flight level, which is also required for a successful implementation of contrail avoidance. Therefore, a weather-based approach gives the possibility to target SAF for individual flights and refined diversion possibilities for contrail avoidance. However, to effectively implement this strategy, greater certainty is needed in meteorological predictions and the climate impact effects of using SAF, hydrogen and lean burn engines. This would allow for more accurate estimation of climate impact of individual flights. Additionally, logistical challenges, such as having separate fuelling systems for SAF and Jet A-1 at airport piers, adjustments to flight trajectories in relation with air traffic management and implications to direct operating cost require further investigation.

Finally, it must be noted that in the present study, climate impact has been analysed for emissions of horizon years only and that to reach full aviation climate neutrality, also climate effects of accumulated emissions in the years leading to the horizon years must be addressed.

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Appendix A Alternative mitigation strategies

Non-CO_2 climate emissions and climate effects can be mitigated through various manners. In the study, the potential of targeted use of SAF, contrail avoidance and improved aircraft engine technology have been analysed, however, more strategies can be conceived. Alternative strategies may, for example, focus on the extended use of fuels with lower climatic impact, and operational improvements targeted to reduce climate impact of specific flights. The strategies do in some cases yield promising results but require larger changes to the flight schedules, and are harder to scale up, e.g. due to for example the limited range of battery electric flights.

Appendix A.1 Additional hydrogen

The previously discussed PBL and Destination 2050 scenarios that lead to carbon neutrality in 2050 readily include the uptake of hydrogen in aircraft fleet. Within the time horizon till 2050 the use of hydrogen energy within all departing flights from the major Dutch airports reaches 10% of in 2050. In the Destination 2050, the use of hydrogen is much larger (21%) in 2050 which may be unlikely to materialise. The limited projected use of hydrogen compared to e.g. SAF in the PBL scenarios is due to the practical limitations that hydrogen-powered aircraft face. These are summarised below:

- The four times lower volumetric energy density of hydrogen compared to conventional jet fuel means much larger tanks are needed to carry the same amount of energy. This puts a strain on the flight range of hydrogen-powered aircraft but also requires radical changes in the overall aircraft design (with associated costs and investment risk).
- Currently, the production of (sustainable) hydrogen available for aviation is insufficient to provide the entire aviation industry;
- The airport infrastructure is not yet adapted for large-scale use of hydrogen as aviation fuel.

The factors mentioned lead various studies to conclude that commercial deployment of hydrogen-powered aircraft may still take a while. E.g. Lammen, Peerlings, Van der Sman, & Kos (2022) for an entry-into-service (EIS) of 2035 for regional and single aisle short and mid range (SMR) hydrogen aircraft, and 2040 for twin aisle SMR. The earlier mentioned PBL scenarios integrate hydrogen aircraft in the overall fleet from 2040 onwards.

In Lammen, Peerlings, Van der Sman, & Kos (2022), the seat class of novel hydrogen-powered aircraft extend up to 300 seats and a design range of about 3,700 km. For even larger aircraft, hydrogen propulsion seems yet infeasible. The study shows that compared to future (2035) kerosene aircraft with associated efficiency improvements, a small increase in NO_x emissions may be expected for SMR aircraft using hydrogen combustion, as a consequence of the higher energy consumption of these hydrogen aircraft due to required changes in the overall aircraft design. With respect to future kerosene aircraft, increases in H_2O emissions per flight are expected in between roughly 70% (Regional) and 180% (single and twin-aisle SMR), depending on the aircraft configuration. It shows that besides practical and operational limits, the implementation of additional hydrogen in aircraft fleet does not lead to a trivial reduction of aviation's climatological impact. Yet technological improvements and optimisation of the combustion process can lead to significant reductions of up to 80% in NO_x emissions due to hydrogen combustion in the future (Carter R. , 2021; Funke, 2019; Clean Sky, 2020). Apart from reductions in NO_x emissions, a significant reduction in contrail climate effect can be achieved. Due to the absence of nvPM, the ice crystal numbers of hydrogen combustion induced contrails could be as low as 90% than those of conventional kerosene combustion. Moreover, the optical thickness of the contrails will reduce and contrail lifetime will decrease (Bier, et al., 2024). However, contrails will also be able to form at lower altitudes where conventional contrails will not form due to an increase of the formation threshold temperature of about 10K (Gierens, 2021). In general, contrail climate impact of hydrogen is estimated to be reduced when using additional hydrogen fuels.

Appendix A.2 Low aromatic SAF

Sustainable aviation fuel (SAF) has the potential to reduce radiative forcing from contrails (Burkhardt, Bock, & Bier, 2018; Bier & Burkhardt, 2022). The reason is that SAF generally contains less aromatic compounds that are (largely) responsible for non-volatile particle emissions (nvPM), which at cold and humid air - i.e. when the Schmidt-Appleman criterion is satisfied (Schumman, 1996) – act as nuclei on which water vapour condense and subsequently freeze, forming ice crystals, which continue to grow in ice supersaturated regions (Kärcher, 2018). Fewer nvPM lead to less ice crystals, which grow larger compared to those with conventional nvPM emissions. Larger ice crystals are heavier and reach lower and warmer altitudes faster, causing them to sublimate and, therefore, reducing the contrail lifetime. In addition, a reduction of aromatic content also reduces the optical depth contrails resulting in a lower radiative forcing (Voigt, et al., 2021). The radiative forcing reduces non-linearly with reduction in ice crystal number as shown in Figure 27.

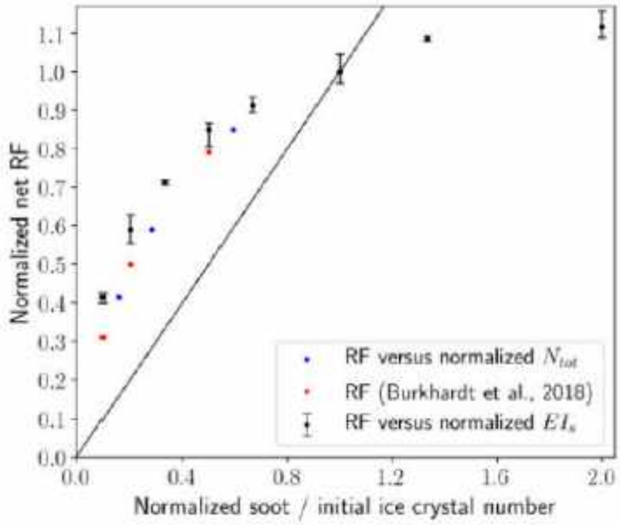

Figure 27: Changes in global mean radiative forcing by contrail cirrus depending on the emission index of soot (black), and on the globally summed total ice crystal number after the vortex phase (blue). The dependence of the radiative forcing on the initial ice crystal number is shown in red. From (Bier & Burkhardt, 2022)

The expected benefit is linked to the blending ratio of SAF with fossil kerosene. In the European context, the ReFuelEU Aviation mandate prescribes the blending percentages (Council of the European Union, 2023). An important factor to consider still, however, is that in order to fulfil the ASTM 7566 standard (ASTM), the blend of SAF and Jet A-1 needs to have a minimum aromatic content of 8%. This requires for certain SAF types (e.g. Alcohol to Jet based SAFs) a blending of aromatics. Decreasing this minimum requirement (to possibly even aromatic free SAF, for which aircraft can be designed) would likely lead to even more non-CO_2 benefits.

A related mitigation strategy is an additional hydrotreatment step to fossil-based aviation fuels to reduce aromatics and sulphur (Faber, Király, Lee, Owen, & O'Leary, 2022). The maximum limit for aromatics in Jet A-1 adhering to the ASTM1655 standard is 25% by volume (ASTM). Most Jet A-1 in Europe has an aromatic content in the range of 15-20% by volume. For naphthalene (an aromatic compound with two fused benzene rings) it is 3% per volume and for sulphur 0.3% by mass. The reduction of aromatics will lead to less soot, while a reduction of sulphur could lead to less soot particles becoming activated and acting as condensation nuclei. The combined effect is expected to reduce the contrail climate impact, similarly as explained above for SAF. Aerosol-radiation interactions, with soot emissions having a warming and sulphur emissions having a cooling effect (larger than the aerosol-radiation effect of soot) (Lee, et al., 2021) would also be reduced or disappear. The net effect of reducing sulphur is uncertain.

Appendix A.3 Battery electric flight

Battery electric flight would be a highly efficient means to reduce the climate impact of both CO_2 and non-CO_2 as there are no emissions during flight. However, the scope of battery electric aircraft is very limited. Currently, battery-electric aircraft (e.g. Heart ES-19[12]) are only considered feasible for short ranges (< 400 km) and small payloads(< 19 passengers), such that only 10% of flights in the 2019 commercial international network would be replaceable, reducing the 2019 CO_2 and non-CO_2 footprint only by 1%. However, recently larger promising aircraft have been conceptualised by Elysian (Wolleswinkel, deVries, Hoogreef, & Vos, 2024; deVries, Wolleswinkel, Hoogreef, & Vos, 2024) which with a range of 800km and up to 90 seats may serve a larger share of the flight network (37% of flights) which in 2019 resulted in 6% of H_2O and CO_2 emissions and 4% of NO_x emissions. Elysian expects their introduction in the mid-2030s.

Appendix A.4 Intermediate stop-overs

Adding an additional stop-over to flights could reduce the emissions associated with long-haul flights. The strategy most effectively targets fuel consumption and CO_2 emissions. If aircraft are not redesigned for shorter ranges, fuel consumption could be reduced up to 25% (Hartjes & Bos, 2015), the majority being between 5 and 10% (Linke, Grewe, & Gollnick, 2017; Martinez-Val, Perez, Cuerno, & Palacin, 2012). However, when analysing all Airbus A330 and Boeing 777 flights as operated in 2007, Langhans et al. (2013) showed that this is heavily depended on ideal locations of intermediate airports and found only a 2.8% reduction. At shorter ranges an increase in CO_2 and non-CO_2 emissions may even be encountered due to larger proportions of flight being in fuel-intensive flight phases (Martinez-Val, Perez, Cuerno, & Palacin, 2012). Moreover, when optimising aircraft for intermediate stop-operations aircraft are likely to become lighter, such that cruise levels may shift higher and CO_2 and non-CO_2 emissions are released in higher more climate sensitive areas causing increased climate effects. (Linke, Grewe, & Gollnick, 2017). However, at cost of additional fuel burn, climate optimised intermediate stop-operations could also be sought. In (ClimOp, 2022), for example, routes have been modelled with stop-overs optimised for climate impact showing (Figure 28) that with increased fuel burn still a smaller impact on the climate could be obtained. The implementation of stop-overs also would impact flight schedules, and flight times will increase. In the ClimOp study, restrictions of additional flight time to 10% and additional fuel to 0% lead to a possible reduction in ATR100 of 6%.

[12] Heart Aerospace partners with Aernnova to design and develop the structure for the ES-19 Electric Airplane | Heart Aerospace

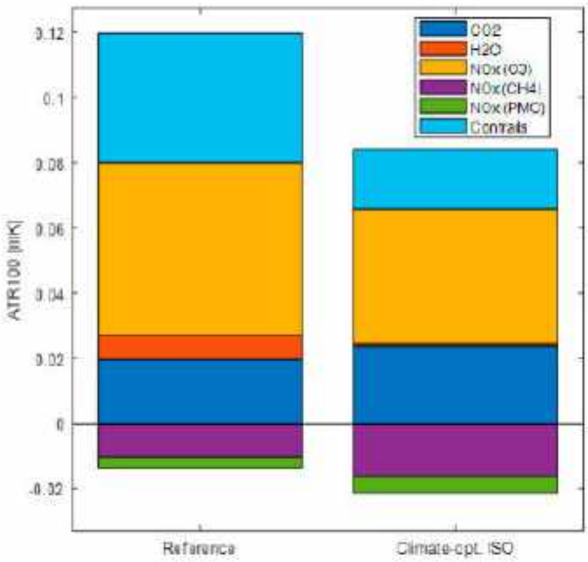

Figure 28: Climate impact of reference and climate optimised stop-overs, from (ClimOp, 2022)

Appendix A.5 Flying low and slow

To reduce direct operating cost and increase fuel efficiency aircraft typically fly at design altitudes. This enables a reduction of CO_2 emissions and CO_2 climate effects. However, the emissions of other species does have an increased effect on the climate at high altitude. By flying lower climate sensitive areas could be avoided. However, this increases fuel burn, by flying slower this increase can partly be mitigated, such that 'flying lower and slower' is seen as a potential mitigation strategy. In (ClimOp, 2022) long range flights over the North Atlantic were rerouted to fly lower and slower resulting in climate impact reductions of 13% on a summer day. Analysing the North Atlantic Flight Corridor and intra-European area within limits to additional time and fuel significant reductions could be achieved as shown in Table 16Table 16: Reductions in ATR20 when applying flying low and slow to different flight sets.

Table 16: Reductions in ATR20 when applying flying low and slow to different flight sets, from (ClimOp, 2022)

Flight set	Maximum of fuel and time penalty	Climate mitigation potential [ATR20]
Long-range flights, summer	1 %	-2.5%
	5 %	-6.3%
	10 %	-6.9%
Intra-European flights, summer	1 %	-2.7%
	5 %	-12.5%
	10 %	-14.6%

As non-CO_2 emissions also depend on the ambient meteorological conditions, results differ per flight mission. In an assessment of all flights over the North Atlantic on four days in 2018, Zengerling et al. (2023) found reductions in terms of ATR20 are in general largest during winter days and lower in summer, as shown in Figure 29. Largest reductions in climate effect were found to be caused by reductions in contrail impact, with NO_x climate impact increasing in some cases.

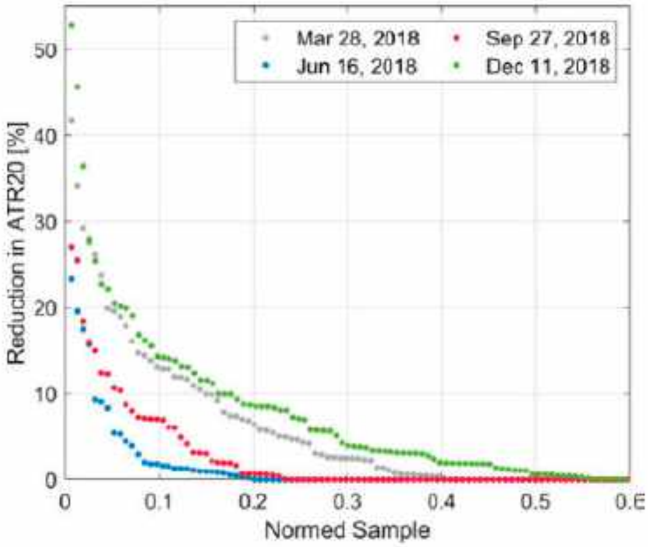

Figure 29: Relative reduction in ATR20 per flight mission over relative sample size for different season-representative days. Adapted from Zengerling et al. (2023)

Appendix A.6 Night contrail reduction

The radiative forcing exerted by contrails is a combination of the blocking of incoming solar radiation and outgoing longwave radiation from the Earth's surface. At night no incoming solar radiation is blocked such that contrails persisting through the night are in general warming. Avoidance of these could therefore reduce the contrail climate impact. As the lifetime of contrails can be up to several hours, not only night flights, but also late afternoon or evening flights could also lead to contrails that persist until night time. Banning night flights would be one straight-forward, although legally and operationally difficult, approach of trying to limit night contrails. Under the assumption that networks are transposed to daytime flights no changes would be expected in emissions, however, formed contrails may have a lower impact on the climate. Following the results of (Newinger & Burkhardt, 2012) and (Stuber, Forster, Rädel, & Shine, 2007) as presented in Table 17, night time flights contribute 55% to 75% of the total contrail radiative forcing. However, adapting flight schedules to not have night time flights may be difficult to implement.

Table 17: Contribution of night time air traffic to contrail cirrus RF per region, from (Newinger & Burkhardt, 2012) and (Stuber, Forster, Rädel, & Shine, 2007)

	Percentage of night time flights	Contribution of night time flights to young contrail RF	Contribution of night time flights to contrail cirrus RF	Approximate contribution of night time flights to contrail RF
GLOBAL MEAN	31%	64% ± 1%	49% ± 1%	60%
USA	25%	54% ± 2%	45% ± 2%	55%
WESTERN EUROPE	28%	63% ± 5%	50% ± 3%	60%
NORTH ATLANTIC	61%	103% ± 7%	65% ± 5%	75%
SOUTHEAST ASIA	35%	65% ± 3%	52% ± 4%	75%

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