

ALIGHT

SUSTAINABLE AVIATION

Report on the digital platform for smart use of SAF

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1 Executive summary

The ALIGHT project, part of the EU's Horizon 2020 program, aims to accelerate the deployment and smart utilization of Sustainable Aviation Fuel (SAF) in aviation. This report (Deliverable D3.7) outlines the development and integration of a digital platform and modeling tools designed to optimize the environmental benefits of SAF use at airports and in-flight operations, with a particular focus on reducing non-CO₂ climate impacts, such as contrail formation.

Smart Use of SAF and Platform Development

SAF offers up to an 80% reduction in lifecycle CO₂ emissions compared to conventional aviation fuels and can significantly lower non-CO₂ impacts, particularly by reducing particulate matter (soot) emissions that influence contrail formation. Given the limited supply of SAF in the near term, its deployment must be optimized to maximize climate benefits.

To support this, DLR enhanced its SimFuel platform, originally built for fuel property modeling, to assess SAF across multiple dimensions—including lifecycle properties, engine performance, and environmental impact. SimFuel was extended with:

- A Digital Twin to mirror the SAF lifecycle, enabling predictive modeling and decision-making;
- An expanded data schema using JSON for high flexibility and future integration;
- A dashboard interface for stakeholders to interact with the system without coding skills.
- These tools allow users to assess SAF blends, prioritize their use based on contrail formation potential, and estimate climate benefits dynamically.

Understanding and Mitigating Non-CO₂ Impacts

The report details scientific evidence linking SAF to reduced non-volatile particulate matter (nvPM) emissions, which in turn leads to fewer and shorter-lived contrails. SAF, especially those with low aromatic and sulfur content, produces fewer soot particles. This results in:

- Larger but fewer ice crystals in contrails;
- Reduced radiative forcing from contrail cirrus;
- Improved local air quality.

Results from in-flight campaigns (ECLIF1–3) show that SAF can reduce soot emissions by up to 50–70% and contrail ice crystals by similar amounts. However, newer low-soot engines may enter a “soot-poor regime” where volatile particulate matter (vPM) can become more relevant in contrail formation, warranting further study.



Modeling & Deployment Strategies

DLR's AirClim model was extended to incorporate SAF's impact on nvPM emissions and was applied to 2019 traffic data from Copenhagen Airport to simulate 2030 scenarios under the ReFuelEU SAF mandate. Key findings include:

- Evenly distributing 6% SAF across all flights reduced contrail-related climate effects by ~30 kilotonnes CO₂e.
- Targeted deployment—using higher SAF blends on flights with high contrail-to-fuel-use ratios—achieved up to 90 kilotonnes CO₂e reduction, tripling the benefit.
- Optimal SAF usage varies by region, aircraft type, and meteorological conditions, supporting strategies like “dedicated flights” or “dedicated airports.”

Challenges and Recommendations

Realizing SAF's non-CO₂ benefits faces several challenges:

- **Aircraft Compatibility:** Older aircraft require aromatics for seal swelling; widespread use of 100% SAF needs retrofits or infrastructure segregation.
- **Infrastructure & Logistics:** Segregated storage and delivery systems are required for neat SAF or high-blend use, increasing complexity and cost.
- **Fuel Composition Adjustments:** Reducing aromatics like naphthalene improves emissions but raises refining costs and lifecycle CO₂; feasibility varies by context.
- **Policy & MRV Requirements:** From 2025, operators must report non-CO₂ effects under EU regulation using tools like NEATS, emphasizing the need for accurate, primary data.

Recommendations include advancing in-flight measurement campaigns, refining climate models (especially to account for vPM), enabling targeted SAF deployment, supporting policy incentives, and improving Monitoring, Reporting, and Verification (MRV) processes for non-CO₂ effects.



2 Introduction

The EU Horizon 2020 project ALIGHT is dedicated to tackling environmental challenges in the aviation industry by implementing and demonstrating innovative solutions focused on the integration of Sustainable Aviation Fuel (SAF) and smart energy management at airports. Through demonstrations at its lighthouse airport, Copenhagen, and the development of comprehensive tools, ALIGHT aims to reduce greenhouse gas emissions, align with international environmental targets, and shape a vision for sustainable airports of the future.

A key aspect of the technical work within ALIGHT is the optimal deployment of available SAF quantities. As this requires decision-making within a complex system, the collection of data and information is essential. To support this, digital tools were developed during the project to assess various options for optimal SAF utilization.



3 Background

3.1 Smart use of SAF

Depending on the production pathway and the feedstock used, Sustainable Aviation Fuel (SAF) offers a lifecycle CO₂ reduction potential of up to 80%. Furthermore, recent research indicates that SAF also has the potential to reduce non-CO₂ emissions from aviation. In this context, non-CO₂ emissions refer to water vapor, nitrogen oxides (NO_x) and particulate matter, the latter mainly due to its influence on the formation of contrails. Notably, SAF blends have been shown to reduce the contrail climate effect due to cleaner combustion and consequently lower particle emissions.

Given the limited availability of SAF in the coming decades, these restricted quantities should be utilized in ways that maximize climate benefits, particularly in terms of contrail reduction and associated non-CO₂ effects—referred to as the *smart use of SAF*. For example, available SAF at an airport could be prioritized for flights with a high potential for contrail formation.

However, contrail formation is influenced by a complex set of local parameters, such as flight trajectory, atmospheric conditions, and engine technology. Therefore, determining the optimal use of SAF requires integrating information on the specific SAF blends available with model-based assessments of the climate impact of individual flight missions.

3.2 Digital platform for smart use of SAF

SimFuel is a software platform currently under active development at DLR and has demonstrated its capabilities across numerous research and industrial development projects. Although not originally developed within the scope of the ALIGHT project, SimFuel has been specifically extended to address the particular requirements of downstream SAF applications—namely, utilization at airports and in-flight missions.

The platform serves as a comprehensive tool for the assessment of SAFs across various use cases. One key application is prescreening, which involves the evaluation of SAF candidates with respect to their compliance with specification standards. This process is typically based on small fuel sample quantities and predictive modeling and includes iterative feedback loops with SAF producers.

SimFuel consists of several core components designed to enable a detailed and flexible assessment workflow:

- A **fuel database** containing data from more than 20,000 conventional and 500 synthetic aviation fuels;
- A **flexible fuel data schema** that accommodates a wide range of fuel types and properties;
- **Fuel property models**, which may be physics-based or machine learning-based, and are trained and optimized using the platform's database;



- **Performance models** that predict the influence of specific fuels on engine behavior, aircraft performance, and emissions
- An **optimizer for SAF composition**, supporting targeted fuel design;
- And **visualization tools** to facilitate effective communication and result-sharing among experts from various disciplines.

These integrated components enable SimFuel to support the smart and informed deployment of SAF within real-world aviation contexts. Depending on the use case and the user, different levels of interaction with the platform are possible, from Python code to a dashboard-based GUI for interactive result exploration.

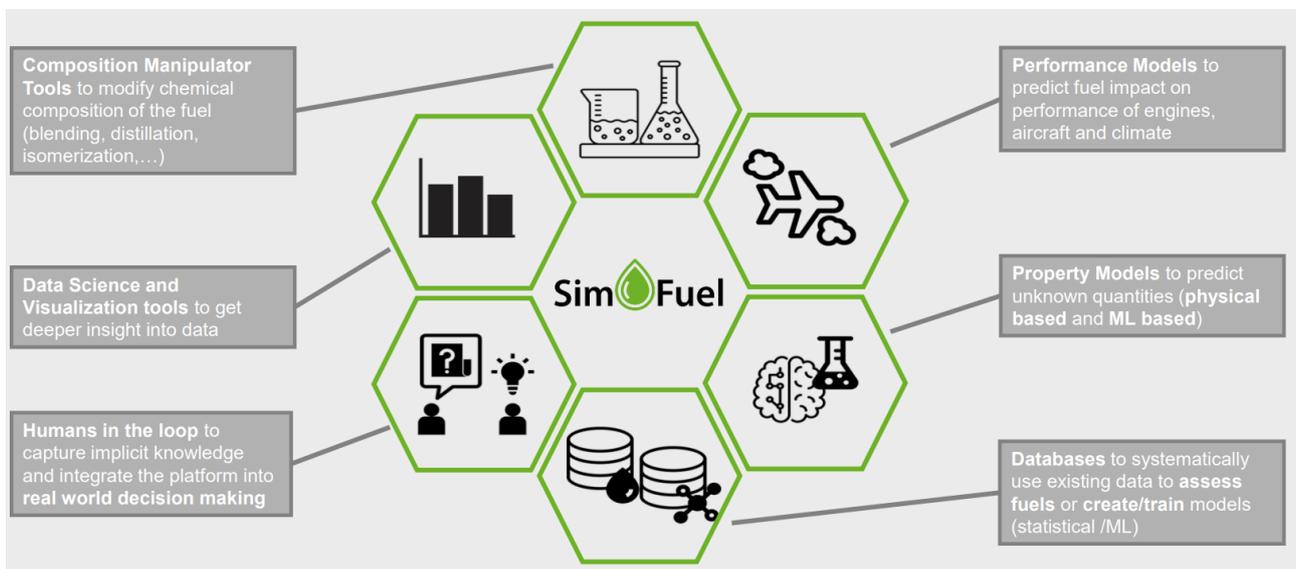


Figure 1 Elements of the SimFuel platform



4 Adaption of the DLR SimFuel platform

4.1 Development of a Digital Twin for SAF

As one of the enabling technologies for the smart use of SAF, a Digital Twin for SAF was developed within the SimFuel platform as part of the ALIGHT project. Results were published at the 2022 AIAA SciTech. For a full overview of the scientific and technical background, the reader is referred to the full publication: B. Enderle et al.: *A proposed Digital Twin concept for the smart utilization of Sustainable Aviation Fuels*. - AIAA SciTech 2022 Forum.

Concept

Smart use of SAF requires the consistent collection and tracking of all relevant data and information across the SAF lifecycle with respect to the scenario under consideration. Only with this knowledge can optimal decisions regarding SAF deployment be made and effective strategies for future climate mitigation through SAF utilization be developed.

Moreover, there is an increasing need for airlines to accurately track the CO₂ footprint of the fuel used in order to benefit from accounting and offsetting schemes such as CORSIA or the EU Emissions Trading System (EU-ETS) when SAF is employed. From a technical standpoint, the quantitative impact of SAF use on Maintenance, Repair, and Operations (MRO) remains unclear. Point measurements suggest the potential for reduced maintenance and repair costs, as well as operational benefits, owing to SAF's lower aromatic content and higher thermal stability. Systematic tracking of fuel-related impacts on MRO could inform future decision-making processes.



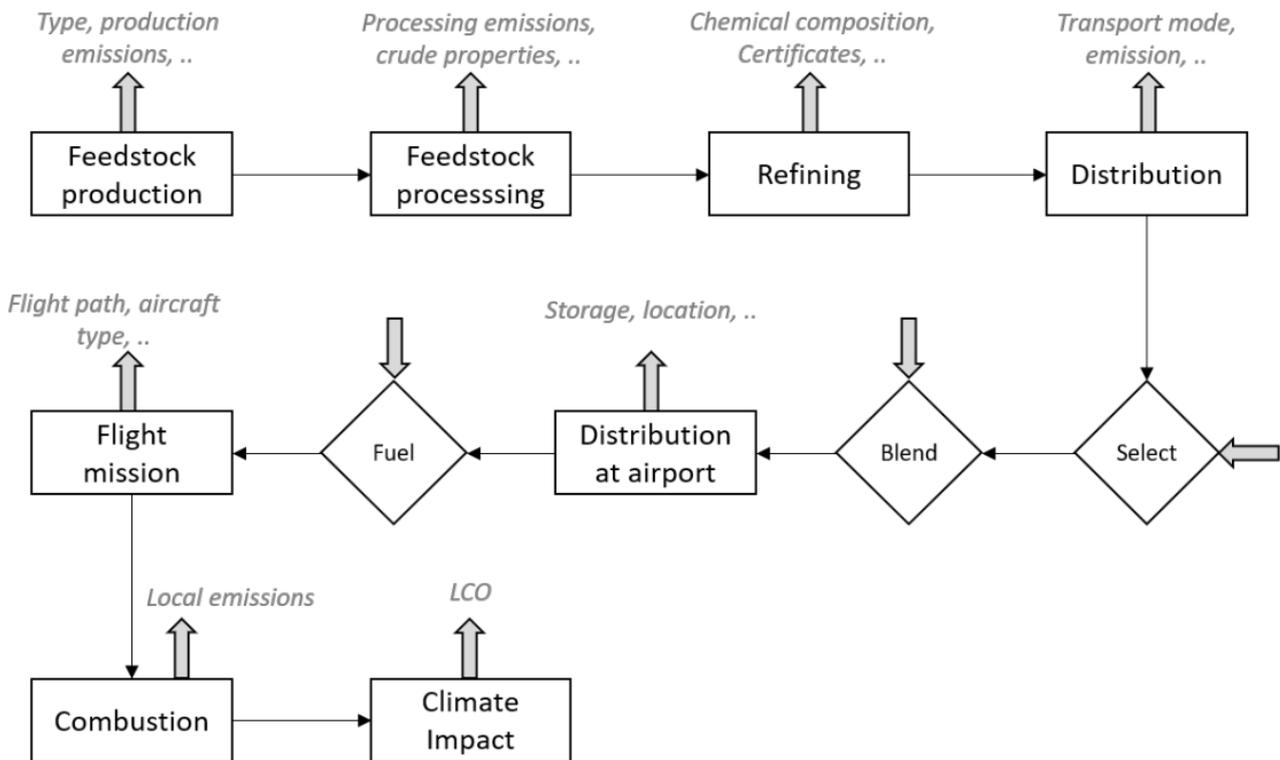


Figure 2 Flowchart of the SAF lifecycle

In addition to collected data, predictive computer models enable lifecycle assessments of SAF usage before actual deployment in aviation operations. These models include, among other capabilities, the prediction of unknown fuel properties [9], analysis of combustion sensitivity to fuel composition [10], and estimation of climate impact—such as expected soot emissions. Linking these models and enhancing them with real-world data results in a holistic virtual representation of the fuel lifecycle and its implications for various stakeholders, a concept commonly referred to as a Digital Thread.

An integral component of the Digital Thread is the Digital Twin (DT)—a digital replica that closely mirrors or emulates the lifecycle of a real-world entity, in this case, the fuel under consideration. A single Digital Thread may incorporate multiple Digital Twins that interact with one another, such as when comparing and selecting among several candidate fuels for a specific scenario. Digital Twins are attracting growing interest for their ability to provide unified virtual representations across sectors such as manufacturing, aerospace, and healthcare. Proposed applications range from smart manufacturing of components to full-scale modeling of physical systems aimed at streamlining certification processes.

Given the high-consequence nature of such decisions, uncertainties in the models and data that constitute a Digital Twin must be carefully addressed. This necessitates an underlying architecture capable of managing uncertain data, often realized through probabilistic approaches. By combining Digital Twin methodologies with uncertainty quantification, risk-informed decision-making becomes possible, based on a comprehensive and consistent information framework.



Due to the diverse sources of data, information, and model predictions feeding into a Digital Twin, maintaining data provenance becomes a critical challenge. Provenance refers to the understanding of data origin and its relationships with other datasets and models. Thus, modeling data provenance forms a foundational backbone of any Digital Thread system. Although a growing body of literature explores Digital Twin concepts current state-of-the-art implementations are largely custom-built, requiring significant deployment resources and deep domain expertise.

Methodology

During the distribution and utilization process, as detailed in the previous section, different stakeholders require access to different types of data related to SAF—such as fuel properties for blending or CO₂ emissions data for reporting and accounting purposes. Ideally, this information is collected, stored, and made accessible through a unified virtual representation of the fuel in question. To support this, a Digital Twin concept for SAF is proposed.

In this approach, the fuel and its physical properties are mirrored in the virtual space using a combination of property models and collected data. A schematic representation of this concept is shown in Fig. 4. In the physical domain, a fuel is characterized by its chemical composition

C and a thermodynamic state $S=\{p,T\}$ where p and T denote the pressure and temperature, respectively, as imposed by the environment. Depending on the composition and the state, measurable physical properties Π of the fuel—such as density ρ , surface tension σ , or kinematic viscosity ν —can be determined.

In the virtual space of the Digital Twin, this system is abstracted through appropriate property models, along with data storage and data fusion methods. As a result, for any state imposed on the fuel in the physical space, the corresponding properties can be retrieved virtually—without requiring additional measurements or experimental input.



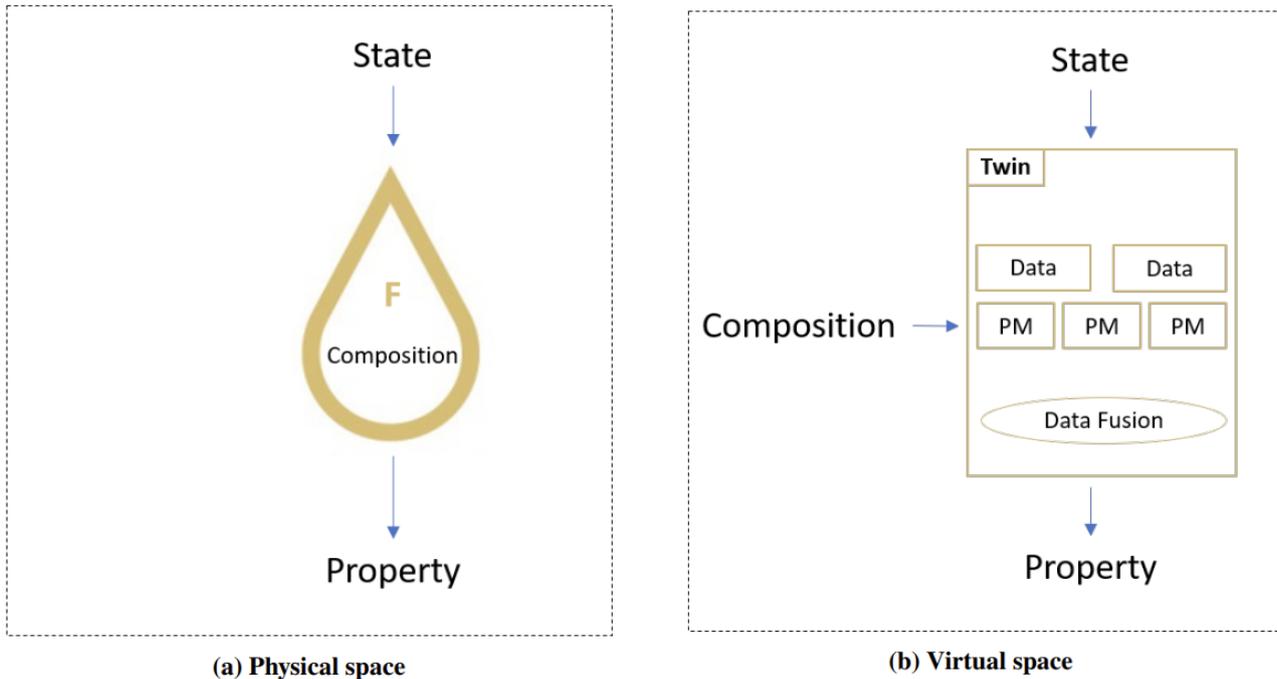


Figure 3 Abstraction of a fuel through a Digital Twin (PM=Property Model)

Implementation

The described concept was implemented and demonstrated as a proof of concept in the Sim-Fuel software platform. Tested use cases include blending studies for different SAF and the unified collection of data on fuels from the fuel monitoring measurement campaign from Task 3.5.



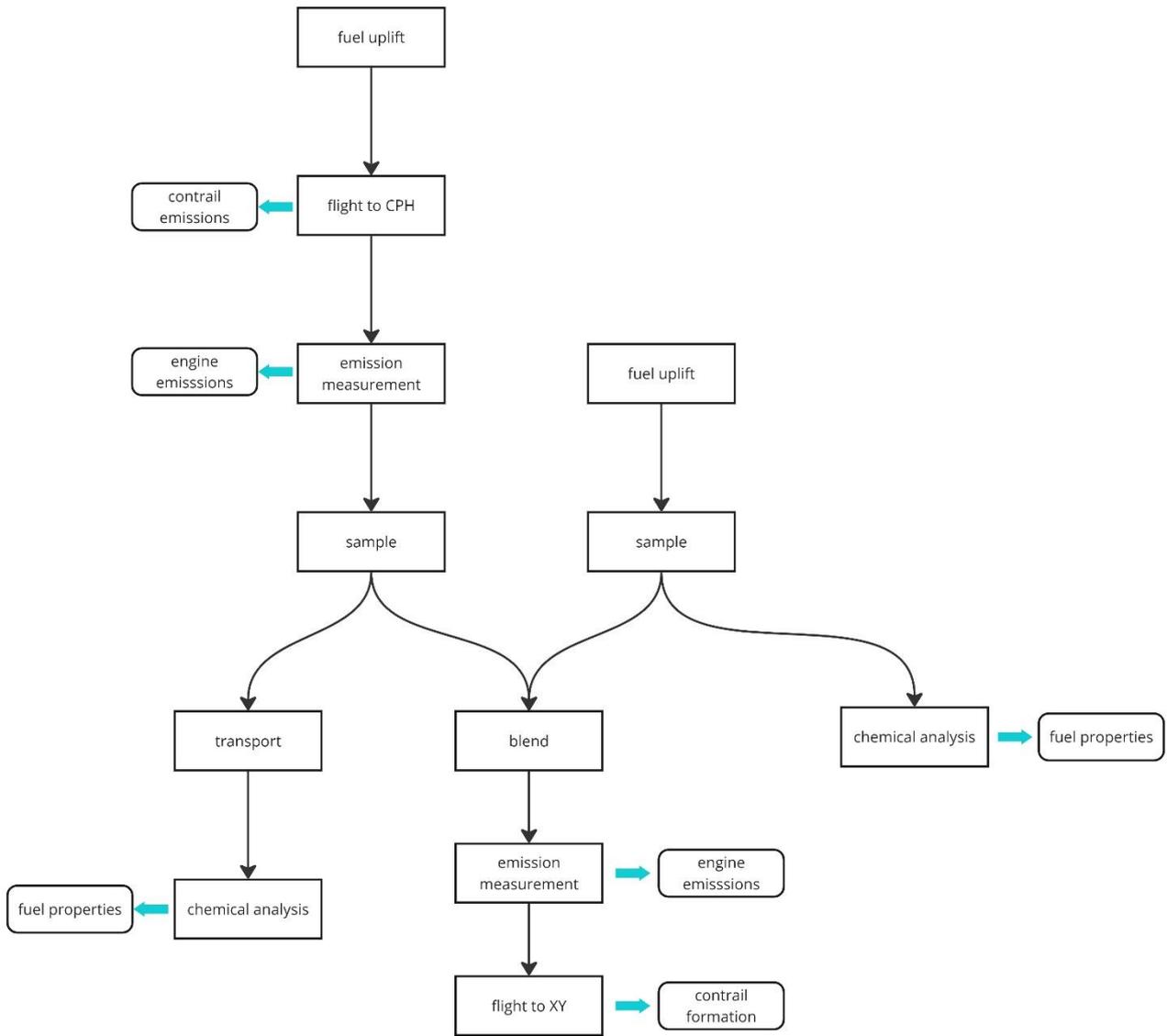


Figure 4 Digital Twin flowchart for a flight and fuel from the fuel measurement campaign from Task T3.3

4.2 Extension of the SimFuel data schema

In the SimFuel database, parameters and data related to aviation fuels are stored using a structured data schema originally developed within the EU project JETSCREEN. Naming conventions and detailed specifications are documented in the respective project deliverables. Special attention was given to ensuring the readability and extensibility of the resulting data structures, allowing for straightforward use and future expansion.

Due to its flexibility, compactness, and ease of implementation, JSON was selected as the underlying data format. While the schema was initially designed for the storage of fuel property data, it has been extended and adapted within the ALIGHT project to accommodate additional requirements, particularly those related to downstream SAF utilization.



```

"vapor_pressure":
[
  {
    "test_method": "D6378",
    "temperature_unit": "C",
    "temperature_value": 20.0,
    "unit": "psi",
    "value": 0.07,
    "information": "Absolute"
  },
  {
    "test_method": "D6378",
    "temperature_unit": "C",
    "temperature_value": 40.0,
    "unit": "psi",
    "value": 26.5,
    "information": "absolute",
  }
]

```

Figure 5 Example for the fuel data schema

4.3 Example application of the SimFuel platform within ALIGHT

The fuel property models and the fuel database integrated into the SimFuel platform were utilized for various tasks throughout the ALIGHT project. One example is briefly described below, drawn from a fuel measurement campaign.

Figure 6 presents results from the short-term SAF measurement campaign conducted in February 2023 (refer to Deliverable D3.5 for further details). The analysis compares key fuel properties—such as aromatic content and hydrogen content—based on Certificates of Analysis (CoA) from jet fuels at the Copenhagen and Arlanda fuel farms, as well as the SAF blend used in the campaign. These properties were evaluated against representative data from the SimFuel database (shown as a boxplot).

As hydrogen content is not included in the standard CoA, it was estimated using a machine learning model developed within the SimFuel platform. This model infers hydrogen content from fuel density and aromatic content.



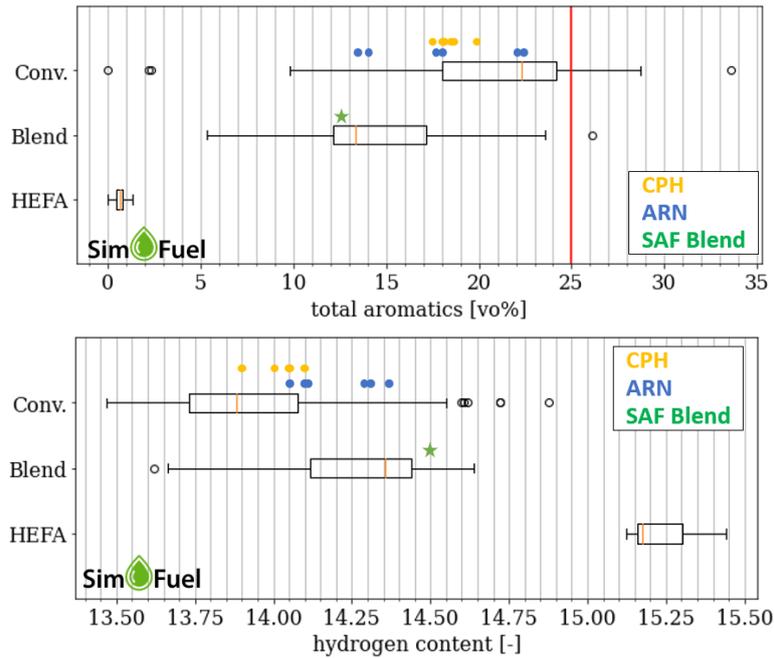


Figure 6 Evaluation of fuels from the SAF measurement campaign 2023 utilizing the SimFuel platform

Prior to the measurement campaign, SAF blending studies were carried out using the SimFuel platform and its integrated performance models. These studies aimed to assess the theoretical impact of the SAF blend on particulate matter emissions and to determine the minimum required blend ratio for the measurement campaign.

Key results from these simulations are presented in Figure 7. Additional details can be found in Deliverable D3.1.



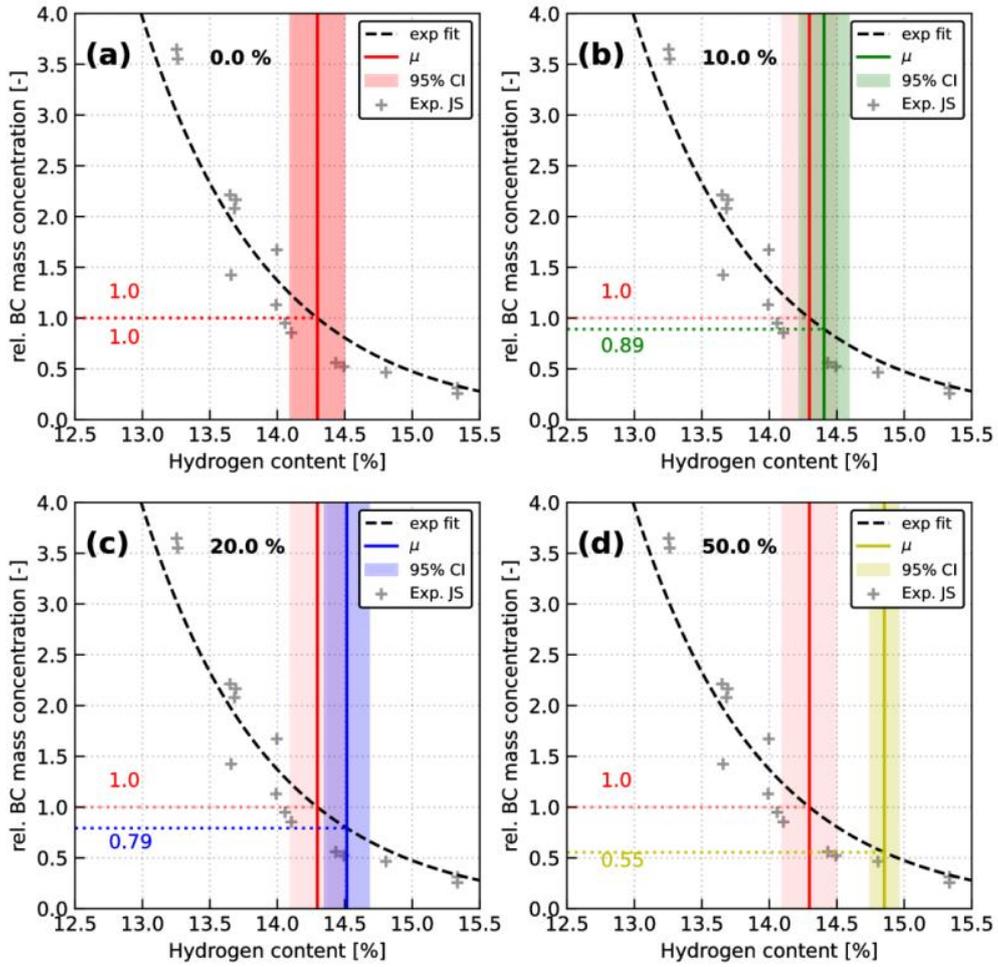


Figure 7 Assessment of soot emission reduction potentials for the SAF measurement campaign in 2023



4.4 Online dashboard for SimFuel results

For developers and technical experts, interaction with the SimFuel platform typically occurs at the code level using Python. This includes integrating individual components into other code-based tools or using interactive coding notebooks to perform analyses.

However, given the multidisciplinary nature of jet fuel-related topics and the implementation- and demonstration-focused scope of the ALIGHT project, it became essential to develop a no-code graphical user interface for the SimFuel platform. This interface was designed to present, explore, and discuss analysis results with project partners—many of whom are domain experts but not necessarily proficient in programming.

To address this need, tailor-made online dashboards were developed using Dash Enterprise. These dashboards offer several key advantages:

- **Data visualization:** Present complex results in an accessible and interpretable format
- **High-level access:** Provide stakeholders with simplified access to data science outcomes
- **Interactive exploration:** Allow users to explore options and scenarios dynamically
- **Data privacy:** Separate sensitive data from public results to maintain confidentiality
- **Collaborative discussion:** Facilitate informed discussions around data and insights
- **Partner engagement:** Demonstrate the added value of data contributions



As part of the ALIGHT project, Dash Enterprise was installed and hosted on DLR server infrastructure, ensuring compliance with IT security requirements and maintaining a reliable connection to the SimFuel platform.

Figure 8 shows an example of a draft dashboard developed to analyze ReFuelEU quotas for European airports. The final version of this dashboard will be made available through ALIGHT's online replication toolbox, developed under Work Package 8.



D3.7
Report on the Digital Platform for SAF

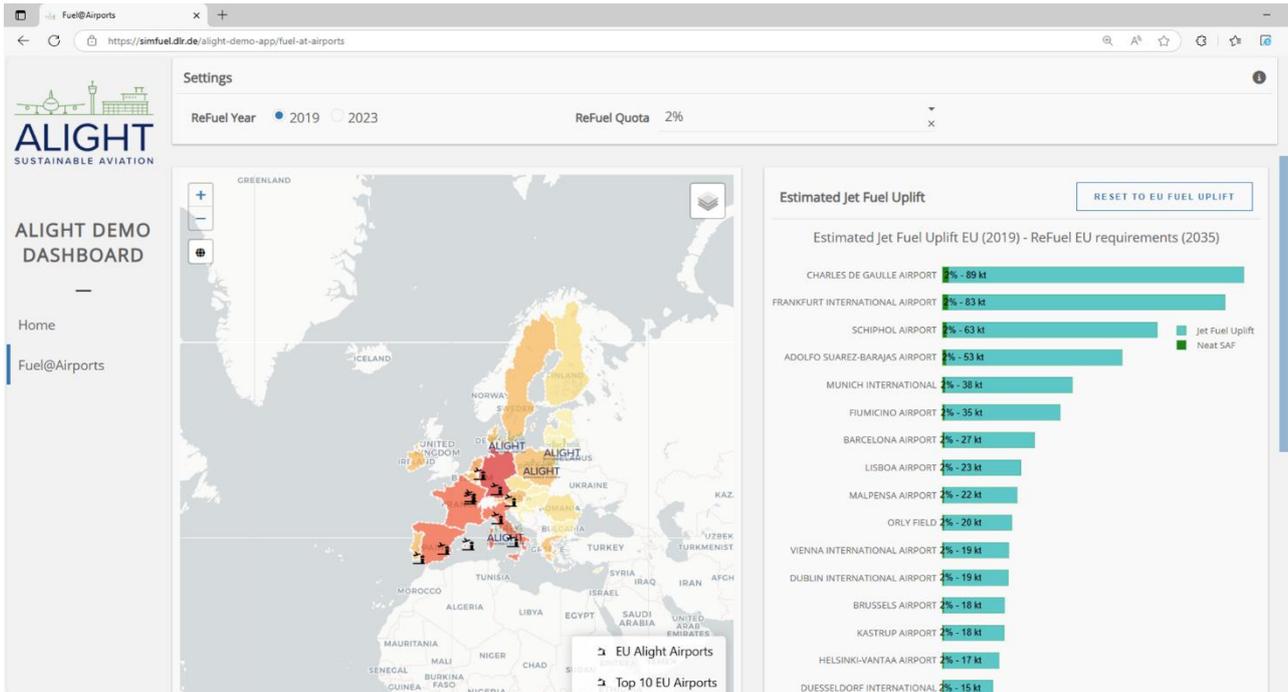


Figure 8 Example of an online dashboard for interactive visualization of data from the digital platform



5 SAF non-CO₂ co-benefits: Current scientific knowledge, uncertainties, and challenges

5.1 Introduction

The use of sustainable aviation fuels (SAF) can significantly lower the amount of carbon dioxide (CO₂) emissions produced by the aviation industry compared to traditional jet fuel, known as conventional aviation fuel (CAF). SAF refers to fuel made from renewable sources like plant-based materials or waste products. For it to be used in aircraft, SAF must meet strict quality and sustainability standards, considering both carbon impact and environmental effects. However, SAF cannot be used on its own—it must be blended with CAF to work properly in existing aircraft.

The aviation industry has committed to reducing its net CO₂ emissions by 2050 to zero, and SAF is expected to play the most significant role in reaching this goal. In 2021, the International Air Transport Association (IATA), supported by airlines, made history by becoming the first industry group to voluntarily pledge such a large-scale decarbonization plan.

To meet this ambitious target, the industry must take a multi-faceted approach that includes more fuel-efficient aircraft, with future planes having improved designs and engines. Operational improvements, such as better air traffic management, taxiing, and ground handling, will also help reduce emissions. Additionally, investing in verified carbon offset and removal projects will counteract remaining emissions.

However, the most substantial reduction—an estimated 62%—will come from increasing the production and use of SAF, the lever within the different measures that will contribute the most in terms of CO₂ lifecycle emission reductions¹. The following figure illustrates these different levers and their potential contribution to lower CO₂ emissions from aviation according to the

¹ <https://www.iata.org/en/pressroom/2024-releases/2024-04-17-01/>



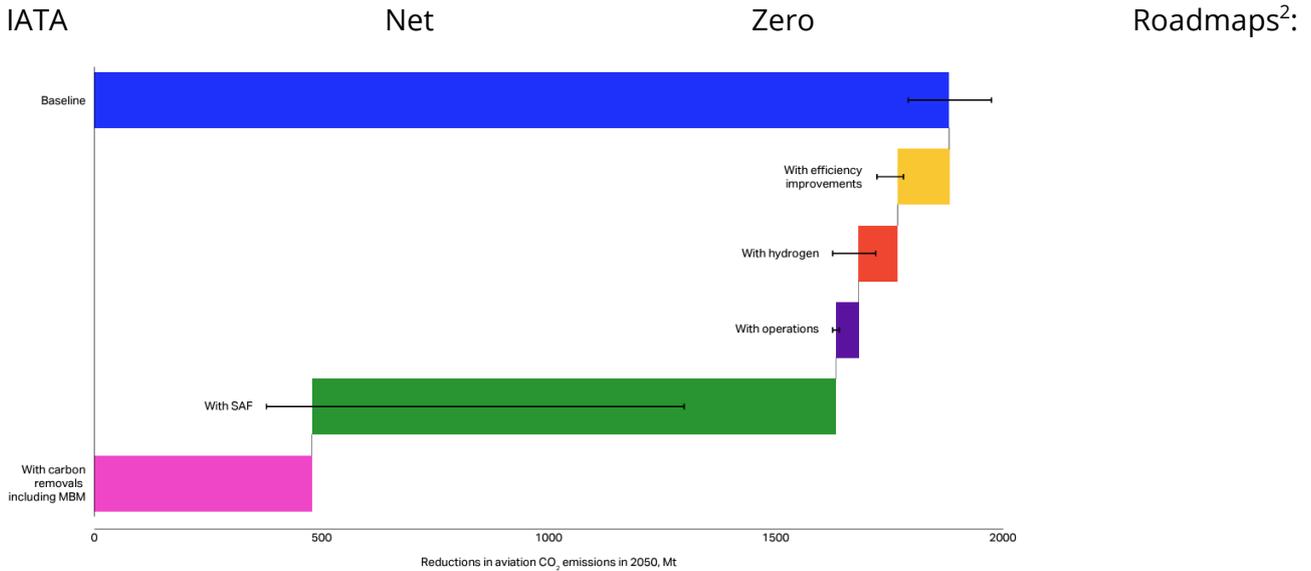


Figure 9 Levers of action for aviation CO₂ emissions reductions by 2050

Source: IATA Sustainability and Economics, ICAO LTAG SAF availability scenarios³.

While CO₂ is a major concern, aircraft also release non-CO₂ emissions, which contribute to global warming. These emissions are harder to measure accurately but may have up to three times the impact of CO₂¹¹. SAF can help reduce non-CO₂ emissions, improving both climate impact and local air quality (LAQ). Compared to CAF, SAF contains little to no sulphur or aromatics, leading to fewer soot (particulate matter) emissions and cleaner air⁴⁵⁶. This reduction in particulate emissions can also influence contrail formation, making them less persistent and reducing their overall climate impact⁷. Additionally, lowering particulate emissions during takeoff and landing can improve air quality around airports, benefiting local communities.

Despite its benefits, SAF is still not widely available, and its use will increase gradually. Expanding SAF production and adoption requires careful planning and overcoming challenges such as ensuring aircraft engines are fully compatible with SAF, developing a supply chain that can produce and distribute SAF efficiently, and updating fuel infrastructure to support the transition. Although other technologies, like advanced engine designs, can also help reduce emissions, SAF is the most immediate and impactful measure for cutting aviation’s environmental impact.

This section summarizes the current scientific understanding of how SAF can help reduce aviation’s climate impact. The role of airports and aircraft operators in advancing research on aviation’s non-CO₂ climate effects is also discussed as well as guidance for aircraft operators on collection of data for Monitoring, Reporting, and Verification (MRV). Key takeaways are provided and challenges and barriers to fully realizing SAF’s benefits are highlighted.

² [IATA Executive Summary Net Zero Roadmaps, 2023](#)

³ The solid bar indicates the central case and the black lines indicate maximum and minimum reductions based on the scenarios modelled.



There is significant positive impact on air quality and human health that reductions in aircraft particle emissions can have near the vicinity of airports. However, this topic is not further discussed here because the subject is complex and warrants a separate document.

This document has been developed with extensive use of IATA's recent publication: [The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulphur content](#), (May 2025).

5.2 Non-CO2 climate impact from aviation (SAF impact on contrail cirrus)

Aviation contrails affect the climate by interacting with both sunlight and heat emitted from the Earth. The ice crystals in contrails reflect some of the Sun's incoming shortwave radiation, which has a cooling effect (similar to how white clouds reflect sunlight). At the same time, these ice crystals absorb and reemit the Earth's outgoing longwave radiation, contributing to a warming effect (like how greenhouse gases trap heat). The overall climate impact of a contrail depends on its microphysical properties, such as the number, shape, size, and mass of its ice crystals, as well as how long it lasts in the atmosphere. These factors influence the contrail's optical depth, or how much light and heat it scatters or absorbs. Scientists calculate the total impact of a contrail by comparing the difference in radiation levels in the atmosphere with and without the contrail. This impact varies based on contrail properties and environmental conditions such as the brightness of the Earth's surface, the presence of other clouds, and the position of the Sun.

Contrail cirrus clouds, the spread-out, wispy clouds formed from contrails, are a major part of aviation's non-CO₂ climate effects¹¹. Even with large uncertainties in calculations, their warming effect is still significant, at least half the impact of CO₂ emissions from aviation, which makes them important to address. Reducing contrail formation and their impact could be a way to lessen aviation's climate footprint in the short term. One approach is to modify the microphysical and optical properties of contrails by using SAF with low or no aromatic content. This change is expected to make contrails thinner and less heat-absorbing, reducing both their warming and cooling effects.

Additionally, SAF-based contrails are expected to contain fewer but larger ice crystals than those from CAF. This happens because the available water vapor in the air condenses onto a smaller number of soot particles when SAF is used. As a result, the larger ice crystals fall out of the sky faster, causing the contrail to disappear sooner. Due to these two effects—lower optical depth and shorter lifespan—contrails produced from SAF are expected to have a smaller overall climate impact than those from kerosene-based fuels.

The following first explains the connection between the number of emitted soot particles and the number of ice crystals in contrails. It then reviews recent studies that have modeled or measured these effects.

Key points

- Contrail cirrus clouds caused by aviation have a significant warming effect on the climate, estimated to be between one-half to three times the impact of aviation's CO₂ emissions.



- Using aviation fuel with little or no sulphur and aromatic content—or new engine technologies that emit fewer soot particles—can reduce the climate impact of contrail cirrus by forming contrails with fewer but larger ice crystals that disappear more quickly.

5.3 Theory on the relationship between aircraft particulate matter emissions and ice crystal concentrations

The theoretical relationship between the number of soot particles emitted by an aircraft engine and the number of ice crystals formed in contrails can be explained in a few key steps. The soot emission index (EI_{soot}), which refers to the amount of soot particles produced by an engine, depends on the type of fuel used and how the fuel burns in the engine. Most modern aircraft using conventional kerosene emit a large number of soot particles ($> 10^{14}$ per kg of burnt fuel), which act as the main sites for water vapor to condense on and form ice crystals in contrails. In this situation, called the “soot-rich” regime, the number of ice crystals is almost directly related to the number of soot particles¹³. When the air is very cold, well below the temperature at which contrails start to form, nearly all the soot particles will lead to the formation of ice crystals.

The following figure illustrates this dependency of nucleated contrail ice crystal numbers as a function of EI_{soot} , ambient temperature (T), diameters of primary soot particles (d_p), fuel sulphur, and concentrations of condensable organics (sulphur/organics) based on a process model. In soot-rich regime, ice crystal and soot particle numbers decrease nearly in proportion. In soot-poor regime, at temperatures well below the contrail formation threshold (upper curve), ice crystal numbers increase due to water activation and subsequent freezing of vPM¹³:

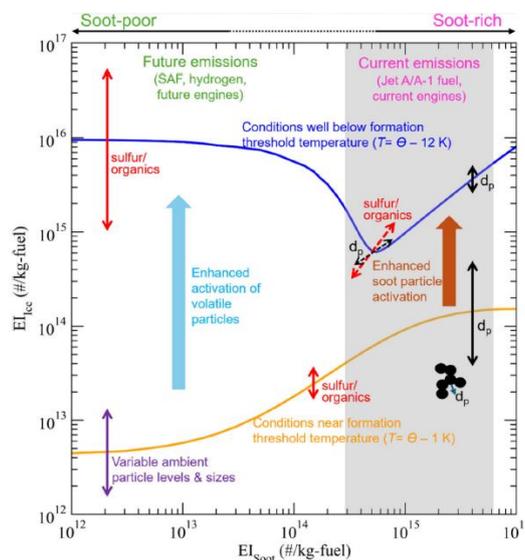


Figure 10 Dependency of nucleated contrail ice crystal numbers as a function of various parameters

Source: Yu F., Bernd Kärcher and Anderson, B.E. (2024)

The yellow line on the above figure shows conditions near the temperature threshold, and the blue line represents conditions when the temperature is much lower (about 12°C colder). When



the temperature is near the threshold, the number of ice crystals formed in a contrail decreases with EI_{soot} , levelling off near the amount of ambient aerosol particles ($\sim 10^{13}$ soot particles per kilogram of fuel). At temperatures below the threshold, the relationship is more linear, and when EI_{soot} drop below a certain level (around 10^{14} to 10^{15} kg^{-1}) the number of ice crystals may actually increase. This happens because vPM, like sulfuric acid or oil compounds, can start forming ice crystals, especially in colder conditions.

This has important implications for the use of SAF and newer engine technologies that produce fewer soot particles. For example, lean burn combustors found in newer engines work in the soot-poor regime and may, under some conditions, create more ice crystals than traditional engines, which operate in the soot-rich regime. If emissions of vPM (such as from vaporized fuels in the exhaust) cannot be reduced, the number of ice crystals may be lowest when soot emissions are between 10^{14} and 10^{15} particles per kilogram of fuel. This complexity highlights the importance of having well-planned strategies to minimize ice crystal formation from soot particles.

The interaction between exhaust plume and ambient air is also of consideration to understand relationship between aircraft particulate matter emissions and ice crystal concentrations. As the exhaust plume mixes with the much colder air, it rapidly cools, becoming saturated with water vapor. This vapor then condenses onto aerosol in the exhaust, forming water droplets. These particles mostly consist of soot and volatile particulate matter (vPM), which can include sulfuric acid, lubrication oil, and organic compounds, along with ambient particles. The vPM emitted by engines are very small, often just a few nanometers in size. These particles generally need a higher level of supersaturation (the air must hold more water vapor than usual) to form water droplets. Soot particles, in contrast, have larger sizes (on the order of tens of nanometers) and need lower levels of supersaturation to trigger the condensation of water vapor onto their surfaces. In the “soot-poor” regime, where there are fewer soot particles, the air can reach higher supersaturation levels, allowing vPM to activate and form ice crystals. However, in the soot-rich regime, water droplets form on the soot particles first, preventing the supersaturation levels from becoming high enough to activate the vPM. This principle is illustrated in the following figure:

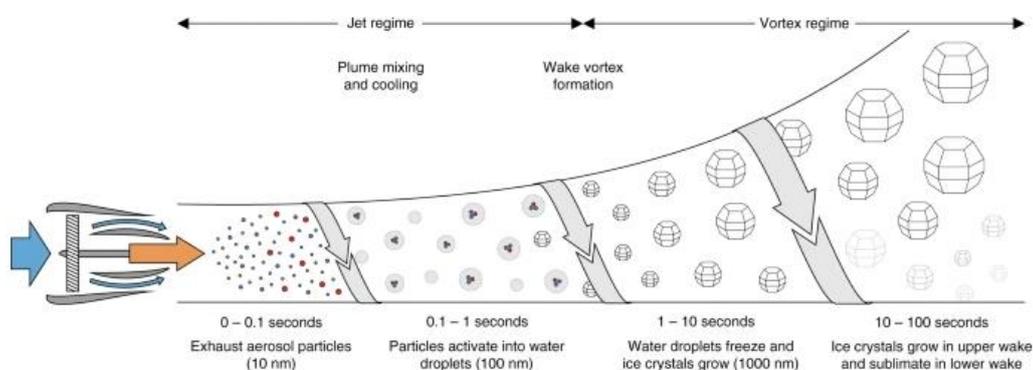


Figure 11 Interaction Between Exhaust Plume and Ambient Air: Formation of Water Droplets from Soot and Volatile Particulate Matter (vPM) in Different Supersaturation Regimes - Source: Kärcher et al. (2018).



The temperature threshold at which contrails begin to form depends on several factors, including the water vapor emission index (EI_{H_2O}) of the fuel and the engine's efficiency. When the ambient temperature is near this threshold, there is limited supersaturation in the exhaust plume (~ 100% relative humidity), and only a few ice crystals form. However, when the temperature is lower than the threshold, there is a higher level of supersaturation, and more ice crystals form. The nucleation efficiency, or the fraction of soot particles that can become active and form ice crystals, depends on the difference between the ambient temperature and the contrail formation temperature threshold. As the ambient temperature drops further from this threshold, the number of ice crystals formed increases, but this increase is not linear. This is illustrated on the following figure taken from a 2019 study by Bier and Burkhardt that used a global climate model to investigate the dependency of the apparent emission index of ice (AEI_i) on the ambient temperature for three different EI_{soot} scenarios¹⁴. "As the ambient temperature decreases further from the contrail formation temperature threshold (~225.5 K), the number of nucleated ice crystals increases non-linearly for all three cases. Note that at maximum plume saturation (RH = 120%), 50% of the soot particles have activated in the soot-rich regime compared to 65% in the soot-poor regime. This suggests that methods that reduce soot particle emissions for contrail climate impact mitigation are more effective in colder regions where ambient temperatures are well below the contrail formation saturation threshold⁴."

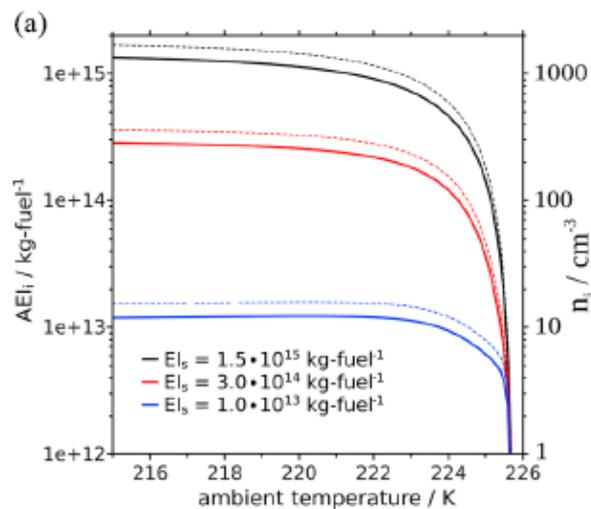


Figure 12 Dependency of the AEI on the ambient temperature for three different EI_{soot} scenarios - Source: Bier and Burkhardt (2019)

Key points

- In the "soot-rich" regime ($EI_{soot} > \sim 10^{15}$ particles per kg of fuel), most ice crystals form on larger nvPM particles, and as the number of soot particles decreases, the concentration of ice crystals in the contrail also decreases. This can reduce the climate impact of the contrail.

⁴ [IATA The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulphur content, May 2025](#)



- When EI_{soot} become sufficiently low (i.e., $< 10^{14}$ to 10^{15}) and ambient temperatures are significantly lower than the contrail formation temperature threshold, smaller vPM (such as sulfuric acid, lubrication oil, and organic compounds) can begin to form ice crystals, causing the concentration of ice crystals in the contrail to increase as EI_{soot} decreases. This can increase the climate impact of the contrail.
- In the case of conventional rich-burn engines, SAF-related reductions in EI_{soot} still remain within the soot-rich regime ($\sim 10^{14}$ to 10^{15} kg^{-1}), while newer aircraft with lean burn combustors emit soot particles in the “soot-poor” regime.
- To minimize the number of contrail ice crystals with the use of SAF and CAF with low or no sulfur and aromatic content, it is necessary to reduce both nvPM and vPM emissions simultaneously.
- Additional measurement campaigns of EI_{soot} in the soot-poor regime are required to better understand the relationship between vPM emissions and ice crystal formation, improving the accuracy of model predictions.

5.4 Potential non-CO₂ climate benefits from SAF usage

Tests conducted on the ground and in-flight have shown that using SAF can lower soot emissions, which in turn leads to fewer ice crystals forming in contrails when operating in conditions with high soot emissions. In these cases, where EI_{soot} exceeds approximately 10^{14} to 10^{15} particles per kilogram of fuel, reducing soot results in fewer but larger ice crystals in contrails^{5 8 15}. This change is expected to decrease the ice crystals’ ability to trap heat and shorten their presence in the atmosphere. When humidity levels remain the same, these larger but less numerous ice crystals reduce the contrail’s density and longevity, which could lessen its overall warming effect. Although SAF produces about 10% more water vapor emissions ($EI_{\text{H}_2\text{O}}$), potentially increasing contrail formation, research suggests that this additional effect on warming is minimal, though further investigation is warranted^{16 24}.

Ongoing research is continuously gathering valuable data to fully understand how SAF influences contrail formation and its impact on the atmosphere. These measurements help improve scientific knowledge on how emissions from SAF affect the way ice crystals form. This information is crucial for refining models that simulate contrail development and their effects on climate. Some global studies indicate that reducing the number of ice crystals in contrails, whether through alternative fuels or cleaner engines, can lower their contribution to atmospheric warming^{9 10}. However, current models do not yet factor in the activation of vPM, making further research necessary to refine climate impact assessments and reduce uncertainties.

5.4.1 Impact of SAF on engine emissions

Over the past decade, numerous ground-based studies have provided strong evidence that lowering the aromatic and sulfur content in aviation fuel helps reduce particulate emissions^{4 5 8}. One comprehensive analysis reviewed data from multiple test campaigns (APEX, AAFEX-I, AAFEX-II, and ACCESS-I), examining how the properties of 15 different aviation fuels affected emissions from CFM56-2-C1 engines¹⁴. Findings show that the amount of naphthalene in the



fuel plays a key role in determining nvPM emissions. Reducing both sulfur and naphthalene levels to nearly zero could lead to a roughly tenfold decrease in the number of aerosol particles released per kilogram of fuel burned. Another study observed a significant 60% increase in EI_{soot} when the aromatic content was raised from 17.8% to 23.6%. It also found that even when total aromatic content remained constant, increasing the naphthalene concentration (from 0.78% to 1.18%) led to higher soot emissions. Laboratory experiments support these findings, identifying naphthalene as the main aromatic compound in CAF responsible for soot formation.

In-flight studies have also investigated the impact of SAF blends on particulate emissions and reported similar results. One study found that using a "HEFA-SPK" blend reduced nvPM emissions from CFM56-2-C1 engines by 50-70%, while another observed up to a 50% decrease with SAF blends¹⁴. Additionally, most research confirms a strong link between nvPM emissions and the hydrogen content of the fuel, which increases as the aromatic content decreases.

5.4.2 Impact of SAF on contrail formation

While previous studies have linked lower aromatic (specifically naphthalene) and sulfur content in fuel to reduced particle emissions, the "Emission and Climate Impact of Alternative Fuel" (ECLIF) in-flight campaigns explored how these reductions affect contrail microphysics. A key objective of the ECLIF campaigns was to examine how the naphthalene content in SAF blends influences both soot emissions and the formation of ice particles in contrails. Multiple flight tests conducted over several years provide strong experimental evidence that SAF can lead to both lower soot emissions and a reduced number of ice crystals in contrails⁸.

The ECLIF1 (2015) and ECLIF2 (2018) campaigns assessed the effects of four different types of 100% Jet-A1 fuel, as well as Jet-A1 blended with "Fischer-Tropsch" (FT) based SAF (SSF1) and two variations of HEFA-SPK based SAF. These studies accounted for differences in fuel properties, as shown in the following table:

ECLIF fuels	Ref1	Ref2	Ref3	Ref4	SSF1	SAF1	SAF2
Fuel composition	100% Jet A1	100% JetA-1	100% Jet A1	100% Jet A1	59% Ref1+ 41% FT-SPK	51% Ref3+ 49% HEFA-SPK	70% Ref4 +30% HEFA-SPK
Aromatics (vol%) (ASTM D6379) SASOL/ Petrolab	18.8 (±2.5)	17.2 (±2.5)	18.6 (±2.5)	16.5 (±2.5)	11.4 (±2.5)	8.5 (±1.5)	9.5 (±1.5)
Naphthalenes (vol%) (ASTM D1840)	1.51 (±0.07)	1.83 (±0.08)	1.17 (±0.06)	0.13 (±0.02)	0.82 (±0.05)	0.61 (±0.04)	0.045 (±0.01)
Hydrogen content (mass%) (NMR ASTM D7171)	13.67 (±0.14)	13.73 (±0.08)	13.65 (±0.05)	14.08 (±0.18)	14.36 (±0.02)	14.40 (±0.07)	14.51 (±0.04)
H:C ratio (NMR ASTM D7171)	1.89 (±0.02)	1.90 (±0.01)	1.88 (±0.01)	1.95 (±0.02)	2.00 (±0.01)	2.00 (±0.01)	2.02 (±0.01)
Specific Energy (MJ/kg) (ASTM D3338)	42.80 (±0.02)	43.20 (±0.02)	43.14 (±0.01)	43.34 (±0.01)	43.50 (±0.02)	43.63 (±0.01)	43.63 (±0.01)
Sulfur Total (mass%) (ASTM D2622) SASOL/ Petrolab	0.117 (±0.003)	0.135 (±0.003)	0.012 (±0.001)	<0.001 (±0.001)	0.057 (±0.002)	0.007 (±0.001)	<0.001 (±0.001)

Fuel properties (± uncertainties according to certification standards) for fuels used for the contrail observations during ECLIF1 and ECLIF2/ND-MAX. Four reference fuels (Ref1 to Ref4), the semisynthetic jet fuel blend SSF1 and the sustainable aviation fuel blends SAF1 and SAF2 were probed in flight and/or in ground tests. Ref1 and Ref4 fuels were only included in the ground tests and were used for creating the alternative fuel blends. At similar atmospheric conditions, contrails were only observed on Ref2 fuel and on the alternative fuel blends SSF1, SAF1 and SAF2. Aromatics were determined by gas chromatography according to certification standard⁵⁶ ASTM D7566 by SASOL and Petrolab, the sulfur content was determined by SASOL for ECLIF1 and by Petrolab for ECLIF2/ND-MAX according to standard⁵⁷ ASTM D2622. Other components were measured by DLR, bi-cyclic naphthalenes according to certification standard method⁵⁸ ASTM D1840. The hydrogen content and the H:C ratio were measured using nuclear magnetic resonance relaxometry according to the standard⁵⁵ ASTM D7171 standard. Fuel properties were measured in the laboratory after the flight tests.

Figure 13 Properties of fuels burned during the ECLIF1 and ECLIF2/ND-MAX experiments - Source: Voigt et al. (2021)



Using SAF blends appeared to lead to significantly lower soot emissions and a decrease in the number of ice particles¹⁷. The EI_{soot} for HEFA-based SAF blends was found to be 45–53% lower than that of Ref2 Jet A1 fuel, which aligns with earlier studies. Similarly, the FT-based blend showed an approximately 50% reduction in EI_{soot} ⁵. The decrease in soot emissions across all SAF blends resulted in 45–74% fewer ice crystals forming compared to Ref2 Jet A1 fuel. The study further revealed that SAF2, which contained the highest hydrogen levels and the lowest naphthalene content, produced the least soot and ice emissions. These results suggest that bi-cyclic naphthalenes contribute more significantly to soot formation than mono-cyclic aromatic or aliphatic hydrocarbons.

Research also indicates that when ice crystals in contrails are larger, they settle and dissipate more quickly, reducing their atmospheric lifespan and overall impact on climate¹⁸. Data from the ECLIF2 campaign support this, showing that the Fischer-Tropsch fuel blend (SSF1) led to a decrease in the number of ice crystals while increasing their average size compared to contrails formed by Jet-A1 fuel, as illustrated in the following figure:

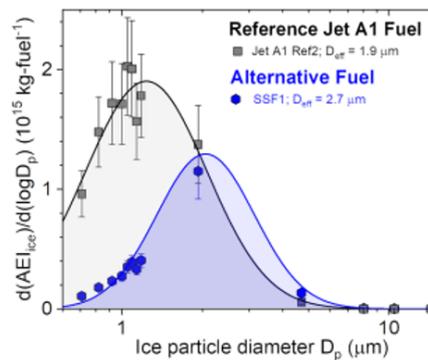


Figure 14 ECLIF2 campaign - FT fuel blend and ice crystal formation - Source: Voigt et al. (2021)

The ECLIF1 and ECLIF2 campaigns focused on studying how SAF blends affect soot emissions and the number of ice crystals in contrails. In 2021, the ECLIF3 campaign expanded on this by examining the effects of using 100% HEFA-SPK fuel compared to 100% Jet A-1 fuel in an Airbus 350 equipped with Rolls-Royce Trent XWB-84 engines. These engines are more advanced and generate fewer soot particles than the older engine models tested in the previous ECLIF campaigns. Additionally, the Jet A-1 fuel used as a reference in this campaign contained an aromatic content of about 13%, which is lower than the global average. The following table shows corresponding fuel specifications:



	Jet A-1	HEFA-SPK
Fuel composition	100 %	100 %
Aromatics (vol %) (ASTM D6379) ^a	13.4	0.41 ^a
Naphthalene (vol %) (ASTM D1840) ^a	0.35	0.002 ^a
Hydrogen content (mass %) (ASTM D3701)	14.08	15.11
Carbon content (mass %) ^b	85.90	84.89
H : C mole fraction ratio	1.95	2.12
El _{CO₂} (g kg ⁻¹)	3149	3111
Sulfur total (mass %) (ASTM D5453)	0.0211	0.0007

Figure 15 HEFA-SPK and Jet A-1 fuel properties used in ECLIF3 - Source: Märkl et al. (2024)

During the ECLIF3 campaign, tests showed that using 100% HEFA-SPK fuel resulted in 35% fewer soot particles and 56% fewer ice crystals compared to relatively clean Jet A-1 fuel with low aromatic content, as previously shown in **Fehler! Verweisquelle konnte nicht gefunden werden..** The greater reduction in ice crystals is likely due to the significantly lower sulfur content in SAF, which is 97% lower than in Jet A-1. When sulfur dioxide (SO₂) is released in engine exhaust, it can form sulfates that coat soot particles, making them more likely to attract moisture and form ice crystals. Further analysis suggests that the size of the individual soot particles, rather than the overall size of soot clusters, plays a key role in determining how they interact with water¹². Since SAF combustion produces smaller soot particles than conventional aviation fuel, a higher level of moisture saturation is needed for them to take up water. This increases the chances of smaller vPM becoming water-activated and contributing to ice crystal formation¹²; the following figure illustrates this principle:



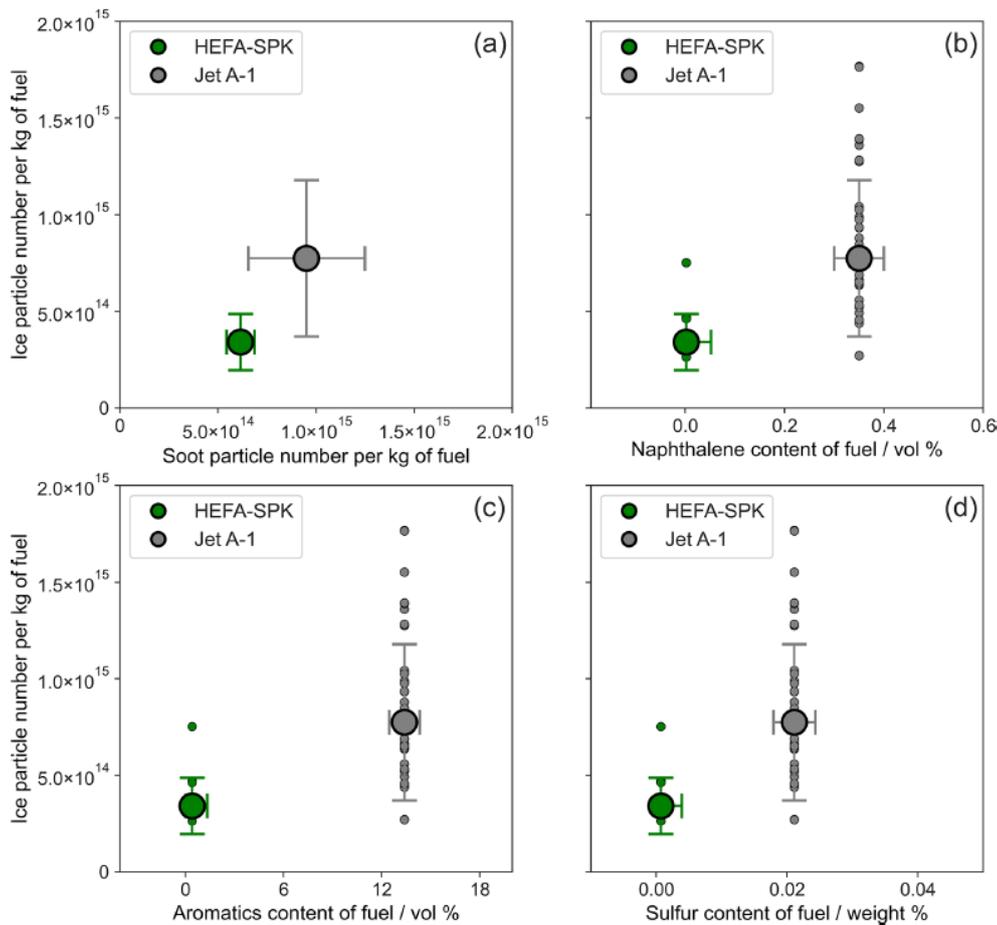


Figure 16 Contrail measurements of Jet A-1 and HEFA-SPK fuels versus (a) nvPM emission indices and versus the respective fuel parameters (b) naphthalene content, (c) aromatic content, and (d) sulfur content. - Source: Märkl et al. (2024)

The findings from the ECLIF3 campaign were compared with earlier ECLIF studies to better understand how engine type and fuel properties influence emissions (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Although previous campaigns only used SAF blends rather than pure SAF, the reduction in soot emissions and ice crystals in those contrails was greater than in ECLIF3. This suggests that the potential for emission reductions may be higher in older engines that naturally produce more soot. Interestingly, the Jet A-1 fuel used in ECLIF3 contained more aromatics and sulfur than the SAF blends from earlier campaigns, yet the number of ice crystals in its contrail was lower. This is likely due to the advanced Rolls-Royce engine, which generates far less soot than the older IAE V2527 engine tested in previous studies. The results indicate that using fuels with higher hydrogen content, along with modern, cleaner engines that emit fewer particles, could help reduce the climate impact of contrails, provided that soot emissions remain within the soot-rich range. The following figure illustrates such findings:



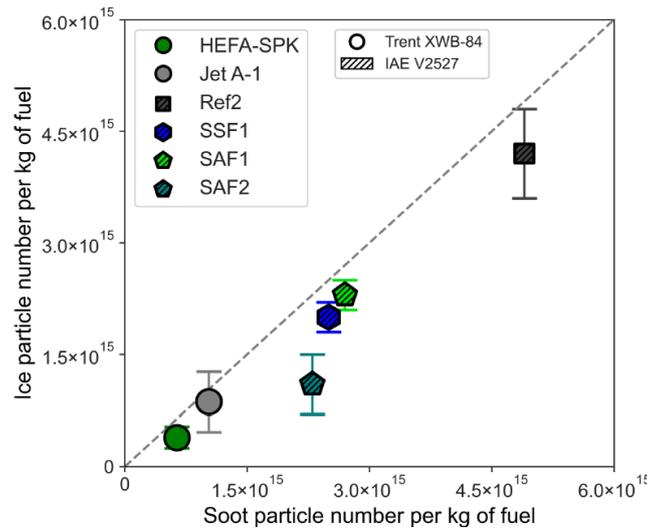


Figure 17 Ice emission indices versus nvPM emission indices for Jet A-1 and HEFA-SPK - ECLIF3 - Source: Märkl et al. (2024) - see Table 1 for legend description

The characteristics of contrails, such as the size, density, and number of ice crystals, play a major role in determining their impact on climate and how long they last in the atmosphere. As shown by several measurement campaigns, these features are mostly influenced by the amount and type of particulate matter emitted from aircraft engines, which depends on the fuel type and how the engine it burns. Because SAF leads to fewer soot particles being released, it can potentially reduce the radiative and climate effects of contrails.

The measurements discussed above focus on emissions in the soot-rich regime, where vPM had little impact on contrail formation. Recent campaigns, like VOLCAN and NASA's ecoDemonstrator, have explored how SAF, paired with newer engine technology such as lean-burn combustors, affects particle emissions and the formation and properties of contrails. While the full results are not yet available, on-going work support predictions made by models, which suggest that vPM becomes more significant as cloud condensation nuclei when EI_{soot} values fall below a certain level ($\sim 10^{14}$ to 10^{15})^{12 13}. These findings are helping to refine models that explain how the properties of contrail ice crystals depend on both vPM and nvPM in soot-poor regime, further empirical evidence is warranted to arrive to conclusions.



Key points

- Naphthalene, an aromatic compound, has been shown to be a key precursor to soot emissions from jet engines.
- In-flight measurement campaigns have shown that aircraft engines burning SAF blends of up to 50% with low naphthalene and sulfur content can significantly reduce soot emissions and produce contrails with fewer, larger ice crystals compared to CAF.
- A limited number of in-flight measurements taken in the soot-poor regime ($< \sim 10^{14}$ particles per kg fuel) confirm theoretical model predictions that emitted ultrafine volatile particulates (e.g., sulfuric acid, lubrication oil, and organic compounds) can serve as cloud condensation nuclei, resulting in an increase in contrail ice crystal number concentrations.

5.4.3 Modelling studies assessing the contrail climate benefits of SAF

Understanding the effects of SAF on contrails and their impact on the climate is complicated and cannot be measured directly. To estimate these impacts, scientists rely on computer models that simulate contrails and their effects on the climate. These models vary in how detailed and computationally demanding they are, and all of them carry some level of uncertainty. This uncertainty comes from two main factors: a lack of complete scientific understanding of some processes such as how vPM form contrail ice crystals, and the simplifications made to represent these processes in the models.

Even though they have their flaws, these numerical models are essential tools for analysing climate effects and exploring how interconnected and sometimes unpredictable processes influence climate forces. For example, several research studies use these models to examine how reducing soot emissions, by using SAF or cleaner fuels with fewer aromatic compounds, might change contrail-related climate effects. However, the models referenced in these studies don't include the potential role of "vPM water activation in forming contrail ice crystals." In some cases, like when EI_{soot} levels are in the poor-soot regime, might lead to overestimating the climate benefits of SAF and cleaner-burning engines. While scientists are working on improving the models to include such factors, more data from direct measurements in real-world conditions is needed to make these representations accurate.

5.4.3.1 *Contrail formation, evolution and persistence*

The ECHAM-CCmod global climate model (GCM) has been widely used to analyse how contrail cirrus affects climate and radiative forcing (RF). A study exploring the impact of soot emission reductions and the resulting decrease in initial ice crystal numbers, found that these changes have a nonlinear effect on RF, due to the complex, nonlinear nature of the related processes²⁰. Using an updated version of the model, which includes adjustments for ice crystal losses during the vortex phase and how ice nucleation depends on the difference between ambient temperature and the contrail formation threshold, identified a nonlinear connection between global



RF and reductions in soot emissions (**Fehler! Verweisquelle konnte nicht gefunden werden.**)⁹.

A reduction of current soot emissions (10^{15} particles per kilogram of fuel) by 50%, 80%, and 90%, would lead to approximately 41%, 72%, and 84% fewer ice crystals after the vortex phase (see Box 1). As a result, global RF would decrease by roughly 15%, 41%, and 59%, respectively. These results are slightly less impactful than earlier estimates using an older version of the model because of the improved simulation of processes mentioned above. Specifically, the updated model accounts for "reduced ice crystal loss during the vortex phase," which partially offsets the decrease in nucleated ice crystals, as fewer larger ice crystals sublime⁵.

Once ice crystals form, the aircraft exhaust mixes with wake vortices, circulating air currents behind the plane during the vortex phase. At this stage, a significant portion of the ice crystals (over 80%) can sublime due to adiabatic heating when the contrail is pulled downward in the wake. This ice crystal loss depends on various factors, including the ambient temperature, relative humidity, initial ice crystal numbers, atmospheric stability (measured by Brunt-Vaisala frequency), the aircraft's weight and wingspan, and its water vapor emissions¹⁹. However, SAF-induced contrails are expected to lose fewer ice crystals during this phase because the larger crystal sizes counteract the reduced number of ice crystals formed, compared to those formed by CAF. Therefore, when assessing the climate benefit of alternative fuels, it is essential to consider not just the reduction of the E_{soot} or initial ice crystal concentrations but also ice sublimation during the vortex phase.

The black circles on the following figure show relationship between normalized soot number emission indices and the global mean normalized net radiative forcing by contrail cirrus. Bars indicate the full range of single year mean radiative forcings, and on the normalized globally summed total ice crystal number after the vortex phase (blue circles). Illustrated via the red circles is the mean net radiative forcing depending on the normalized initial contrail ice crystal number as calculated by Burkhardt et al. (2018).

BOX 1: Vortex Phase

"Within a few seconds after ice crystals are formed, the aircraft exhaust plume mixes with the wake vortices (circulatory airflow patterns) formed behind the aircraft during the so-called contrail "vortex phase". During this phase, many ice crystals can sublime due to adiabatic heating as the contrail is forced downward in the wake. This partial loss of ice crystals due to sublimation can be significant (>80%) and is dependent on ambient temperature, relative humidity over ice, the number of nucleated ice crystals, Brunt-Vaisala frequency (a measure of atmospheric stability), the weight and wing span of the aircraft, and the water vapor emission (Unterstrasser, 2016). Ice crystal loss during the vortex phase is expected to be reduced SAF-induced contrails due to the larger ice crystal sizes. Therefore, the climate benefit of alternative fuels cannot be inferred solely from the reduction of the E_{soot} or the initial crystal concentration, ice sublimation during the vortex phase must also be considered. ([IATA The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulphur content, May 2025](#))

⁵ [IATA The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulphur content, May 2025](#)



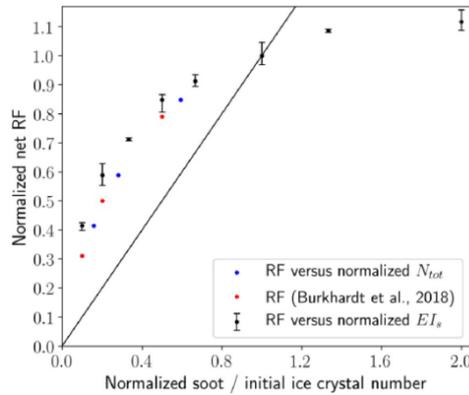


Figure 18 Global mean normalized net radiative forcing by contrail cirrus depending on normalized soot number emission index - Source: Bier and Burkhardt (2022)

Significant regional differences in the impact of soot emissions reductions on the RF are highlighted in Bier and Burkhardt (2022). Regions exhibiting the highest impact potential such as the eastern U.S., North Atlantic, and eastern Europe could be targeted for increased SAF use while supplies are limited (Figure 6).

There are notable regional differences in how reducing soot emissions impacts RF⁹. Areas with the highest potential for impact, such as the eastern U.S., the North Atlantic, and eastern Europe, could be prioritized for increased use of SAF while supplies remain limited⁶. The following figure identifies the global distribution of absolute differences (80% reduced soot minus present-day soot) in contrail cirrus coverage with optical thickness of at least 0.05 in % (left) and net radiative forcing by contrail cirrus in mWm⁻². Hatched patterns are not statistically significant at the 99% level⁹:

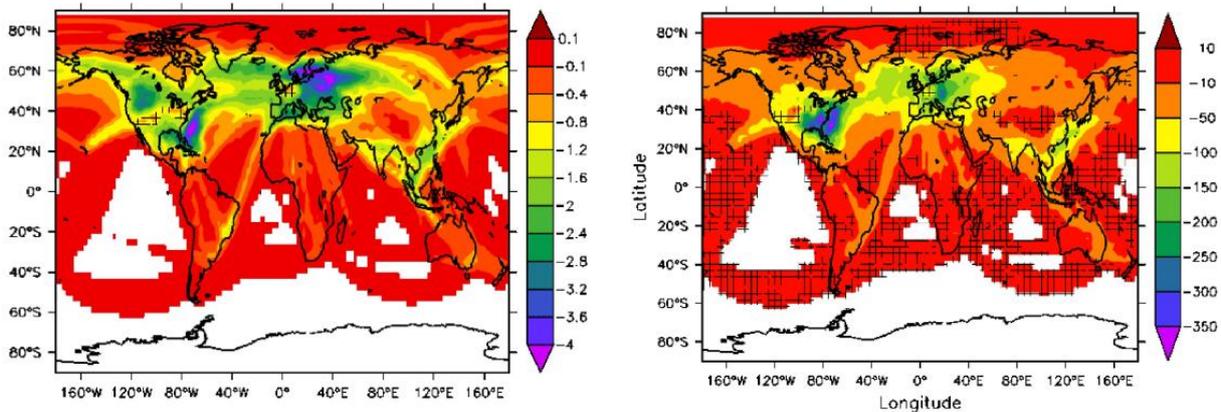


Figure 19 Global mean normalized net radiative forcing by contrail cirrus depending on normalized soot number emission index - Source: Bier and Burkhardt (2022)

For instance, colder, high-latitude regions have greater potential for reductions in ice nucleation because their temperatures are often far below the threshold for contrail formation, and the number of ice crystals formed is closely tied to the number of soot particles emitted.

⁶ [IATA The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulphur content, May 2025](#)



Additionally, the duration of contrails largely depends on the prevailing weather patterns, or synoptic conditions. In specific scenarios, "the larger ice crystals produced by SAF-contrails" can shorten contrail lifetimes more effectively than in other conditions where smaller ice crystals may undergo adiabatic heating and sublimation¹⁹.

The climate advantages of SAF-contrails are greatest when the weather conditions enable the ice crystals to grow large enough to fall at their terminal velocity into areas of low moisture (sub-saturated layers). However, if these conditions instead push the air masses downward into sub-saturated layers, the ice crystals will sublimate, regardless of their size, diminishing the climate benefit of SAF on contrails. By analysing meteorological data, it becomes possible to optimize SAF deployment on specific flights to increase its non-CO₂ climate benefits^{9 10 19}.

While reducing soot emissions and the initial count of ice crystals has a relatively clear effect on contrail RF in today's soot-heavy scenario, determining how these influence surface temperatures is more complex. This is because factors such as the lifespan of contrails and the relationship between RF and surface temperature must be accounted for. Additionally, the climate efficacy of contrail cirrus, which measures how global surface temperatures change per unit of contrail RF, remains poorly defined and quantified. This lack of clarity makes it challenging to calculate the precise climate benefit of using SAF²³.

Furthermore, while cutting soot emissions can limit the persistence and overall radiative effects of long-lasting contrails, ambient weather conditions, which vary widely, may have an even greater influence. For instance, a SAF-contrail and a kerosene-contrail in identical weather conditions might show less difference compared to the variations seen between contrails formed by the same fuel type but under distinct meteorological settings.

5.4.3.2 Large-scale climate impact

The Contrail Cirrus Prediction Tool, or "CoCiP," is a trajectory-based model frequently used to study the radiative effects of contrail cirrus and how SAF could provide additional environmental benefits^{10 15 20}. CoCiP works by tracking the development of contrail clouds for individual flights or fleets of airplanes. It uses basic calculations based on things like aircraft type and fuel characteristics to predict ice formation in contrails. Then, it estimates how these contrails influence atmospheric energy. However, CoCiP doesn't consider how weather or other cloud systems interact with contrails, which is something more advanced models can do like the General Circulation Models (GCMs).

One big advantage of CoCiP is its speed and simplicity. It can analyse contrails for specific flights, making it easy to compare the environmental effects of different aircraft designs, engines, or fuels. That said, predictions for single flights aren't as reliable; the uncertainty for individual flight estimations is quite high compared to data averaged over time (annually) or space (regionally or globally). This is because the radiative impact of individual contrails varies significantly (+/- 100 W/m²) depending on weather conditions, which strongly affect a contrail's lifetime and microphysical properties^{23 19}. Over longer periods lasting several years, these fluctuations tend to average out, giving a clearer picture of how contrails affect the climate.



The CoCiP model was used to explore how contrail properties and climate impacts change in the North Atlantic, a region prone to contrails, when different blends of SAF are used. The study used a relationship based on fuel hydrogen content to model soot emissions and showed that using 100% SAF could reduce El_{soot} by 51% and lower ice crystal amounts by 55%¹⁰. However, the formation of persistent contrails increased slightly by around 1% due to higher water vapor emissions (El_{H_2O}). It's worth noting that these findings likely represent the upper limit of potential climate benefits, as certain factors, like the activation of vPM, were not included in this analysis. The following figure illustrates such results:

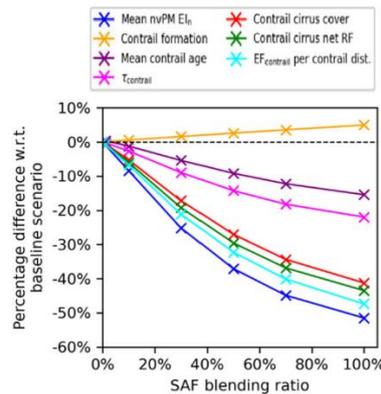


Figure 20 Relative difference in the fleet-aggregated Elsoot, contrail properties, and climate forcing in the North Atlantic for different SAF blending ratios relative to the baseline scenario using CAF - Source: Teoh et al. (2022a)

The increase in persistent contrails is balanced out by a reduction in their average lifetime (~15%). This happens because the larger ice crystals form due to higher water vapor emissions, or El_{H_2O} , and fewer non-volatile particulate matter emissions (nvPM El_n). To illustrate, larger ice crystals tend to fall out of the atmosphere faster, reducing the overall duration of the contrails. Regarding their radiative effects, the annual average contrail cirrus net RF is estimated to decrease by 44%, and the RF per kilometre of contrail ($E_{Fcontrail}$) is reduced by 47%. These reductions are slightly smaller compared to the findings of Bier and Burkhardt (2022).

While the supply of SAF remains limited, blending SAF at higher ratios and prioritizing its use for flights that produce the most warming contrails could significantly enhance its environmental benefits, potentially by a factor of 9–15¹⁰. Previous studies also support the idea that only a small percentage of flights are responsible for the majority of contrail cirrus RF. However, results from particular studies reveal that lower SAF blending ratios may actually be more effective at reducing contrail cirrus RF, compared to higher blending ratios, within the North Atlantic region¹⁰. This is because concentrating SAF usage on a select few flights becomes less efficient after a certain point.

Conversely, using lower SAF blend ratios allows the limited supply to be distributed across more flights easing on the inefficiencies and higher handling costs of fuel segregation. Additionally, this broader distribution minimizes the risk of forecast errors in identifying which flights generate the most warming contrails and ultimately achieves better overall RF reduction^{25 19}. Under this premise, SAF should be allocated to flights based on their potential to reduce energy forcing ($\Delta E_{Fcontrail}$), rather than the absolute energy forcing ($E_{Fcontrail}$) value of a flight. For example, older



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aircraft with engines that emit higher amounts of soot show greater potential for RF reduction ($\Delta EF_{\text{contrail}}$) and would benefit more from SAF use.

The following figure shows the “change in the annual contrail energy forcing in the North Atlantic as a function of (a) SAF blending ratio that is provided to flights with the largest energy forcing (blue line) and change in energy forcing (i.e., reduction potential) (orange line) and (b) the percentage of flights that is targeted with SAF from the different blending ratios¹⁰”:

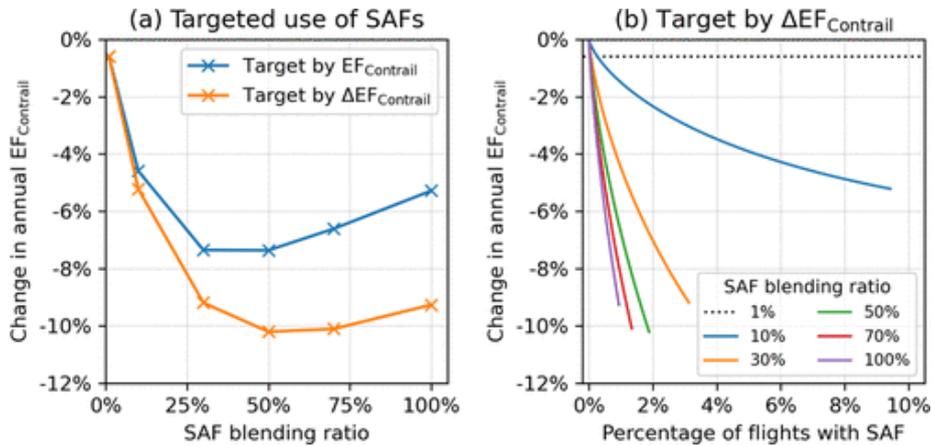


Figure 21 Targeted use of SAF – EF_{contrail} vs. $\Delta EF_{\text{contrail}}$ - Source: from Teoh et al. (2022a)

If the option is to segregate SAF supply to the flights that form these contrails, mainly at night and during the winter, it would also contribute towards minimizing contrail climate impacts from aviation; the following figure illustrates this premise showing the effectiveness of SAF in reducing the contrail cirrus net RF in the North Atlantic by time of day (x-axis) and day of year (y-axis), where the color bar denotes the difference in contrail cirrus net RF between SAF100 vs the baseline simulation with CAF:

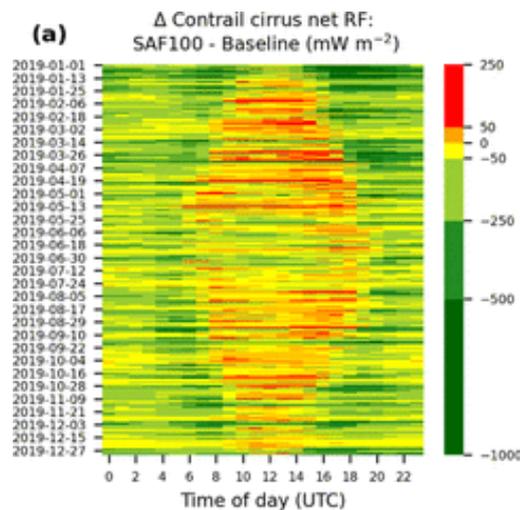


Figure 22 SAF impact on contrail by time of day - Source: from Teoh et al. (2022a)

In contradiction to findings that the increase in contrail formation caused by SAF’s higher water vapor emissions (E_{H_2O}) had a minor effect¹⁰, an earlier study by MIT in 2017 suggested that this increase could have a more significant impact, potentially raising contrail cirrus RF by up to 18%.



This discrepancy depended heavily on the assumed shape of ice crystals, which strongly influences how much short-wave radiation is reflected. Based on their findings, the MIT researchers proposed limiting SAF use to nighttime flights, as nighttime contrails have a more significant warming effect. However, this strategy's practicality was not addressed and would require further evaluation on the impact to fuel handling and logistics practices.

In contrast, other studies indicate that the rise in El_{H_2O} linked to SAF has little to no effect on the overall reduction in contrail cirrus RF achieved through lower El_{soot} ^{9 10 23}. For example, Narciso et al. (2021) used the CoCiP model to show that different types of SAF caused less than a 1% increase in contrail formation frequency due to higher El_{H_2O} . This increase resulted in slightly longer contrails but did not lead to new or additional contrails, illustrated in the following figure:

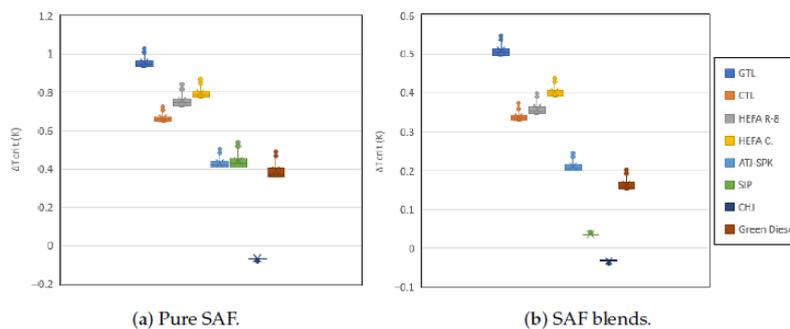


Figure 23 Absolute differences in contrail formation threshold temperature between pure SAF and blends to conventional fuel - Source: Narciso et al. (2021)

With a few exceptions³⁰, most studies align with estimations concluding that a 10% increase in El_{H_2O} from alternative fuels would only slightly raise the contrail formation threshold temperature (by less than 1 K)²⁵. This minor change translates to a lower altitude for contrail formation by approximately 100 to 150 meters. Moreover, the effect of higher El_{H_2O} is partially offset by a decrease in the fuel's heating value.

The inconsistency between the MIT study and other findings highlights the need for further research, particularly on the influence of ice crystal shapes on short-wave RF. It also underscores the importance of comparing different modelling approaches and reducing uncertainties through sensitivity analyses. For example, a study assessing contrails' radiative properties showed that RF estimates could vary significantly, by a factor of 3 to 5, depending on variations in ice water content (IWC) and ice crystal number concentrations (N_{ice})¹⁹. Despite this variability, the study suggested that an 85% reduction in N_{ice} could result in a 35% reduction in RF, findings similar to those of Burkhardt et al. (2018). However, they emphasized the need for more accurate measurements of N_{ice} and IWC to refine models and better predict SAF's impact on contrail RF.

Additional uncertainties exist, such as the challenges of estimating engine soot formation¹⁵. Assumptions about soot particle size, engine power, and how these factors differ with various fuel types can lead to inaccuracies. For instance, SAF blends with fewer aromatics than standard Jet A-1 fuel are known to produce smaller soot particles^{6 19}. However, most models do not yet account for these effects, which might only be significant at temperatures above the contrail



formation threshold. Insights from the ECLIF campaigns have been valuable¹², but more data are needed to fully understand the link between a fuel's composition, engine power, and the resulting particle sizes.

Although comparing results across studies is challenging due to differences in input data, time frames, and regions, most findings point to SAF's positive climate benefits. The significant reduction in soot particle emissions, and therefore in ice crystal formation, suggests that SAF could reduce the radiative impact of contrails. However, uncertainties remain in quantifying this effect. It is also important to note that none of the models used considered the role of vPM in contrail formation¹³, which could alter outcomes for cleaner engines using high SAF blends. Additionally, a reduction in soot particles does not always equate to a lower overall climate impact, as this depends on other variables like surface albedo and weather conditions.

Key points

- Global modeling studies show that reductions in soot emissions associated with SAF usage can lead to significant decreases in the net contrail-cirrus RF (~44% to 59%).
- Small increases in water vapor emissions (E_{H_2O}) associated with SAF usage may lead to a slight increase in persistent contrails or their path length. Most modeling studies suggest that this has a negligible effect on the contrail climate impact, though it remains an open question.
- Modeling studies suggest that targeting a few, limited flights that have the highest contrail warming potential based on geographic region (e.g., Europe, US and the North Atlantic region), time of year (i.e., winter), and time of day (e.g., late afternoon) for higher SAF blend usage could be an effective way to optimize the climate co-benefits of SAF. These

5.5 Challenges and Barriers

Extensive research has demonstrated the environmental and air-quality benefits of using SAF or CAF with reduced aromatic and sulfur content. In addition to the uncertainties already discussed, there are also challenges that exist in either the deployment and usage of SAF at higher blends or in producing cleaner CAF which would maximize the non-CO₂ co-benefits. In addition, while blended and certified SAF is a drop-in solution, using it neat, or unblended (100%) requires further work to make it fully compatible with existing distribution systems, storage infrastructure and aircraft. An overview of the logistical, technical, infrastructural, and economic challenges is presented in this section.

5.5.1 Using neat SAF or higher blends

Neat SAF does not contain aromatics, and therefore it is not compatible with all aircraft nor with the current aviation fuel infrastructure. To make SAF compatible and usable as a drop-in fuel, it must be blended (up to 50% as per current regulation) with CAF to a level that meets international standards regarding composition and performance. The ASTM international and others



(e.g., UK Defence) set the technical aviation fuels standards. Any SAF blend must comply with the ASTM D7566 standard which specifies, among other criteria, that the aromatic content must be within the range of 8% - 25%. In this section, a high-level overview of the challenges associated with using SAF at higher blends is presented.

5.5.2 Aircraft compatibility

Aromatics in jet fuel ensure its safety and compatibility with all aircraft engines. SAF with low/no aromatic content is not compatible with most aircraft today. One of the main issues concerns the ability of the fuel to swell seals in the system. Aircraft fuel systems contain O-ring (elastomer) seals, and the high aromatic content of CAF encourages these seals to swell, providing more protection from leakage. In the case of fuel without aromatics, the seals tend to extract and shrink. Newer aircraft use seals that are compatible with 100% paraffinic fuel (fuels with near zero sulfur and aromatics). However, there are still issues with older aircraft that use nitrile seals.

Another issue is related to the lower lubricity associated with low/no aromatic content of the fuel which can deteriorate the fuel pump more quickly over time. While the lubricity of the fuel can be improved with additives, this could lead to other problems that are not yet known or fully understood and require more experimental research. The lower density of SAF also affects fuel gauging, but this is not a major issue since adjustments to the gauging system can be made relatively easily. Finally, there are concerns regarding the poor electrical conductivity of the fuel which may lead to static charge build-up.

The problems associated with neat SAF usage can be overcome by adding aromatics to the fuel. In this case, however, the non-CO₂ co-benefits are lost, unless effort is made to keep the content near the minimum standard (i.e., 8%). There is ongoing work in the fuels community to investigate how and what aromatic species could be added back (i.e., excluding naphthalenes) into SAF while keeping particle emissions to a minimum to conserve the non-CO₂ benefits⁷. In the meantime, newer aircraft are being made compatible with neat SAF through different materials for the seals or calibrated gauging. However, fleet turnover is long with an average aircraft lifespan of 25-30 years, and older aircraft which are not certified for 100% SAF would need to be retrofitted and made SAF-compatible. Alternatively, airports would need to ensure the availability of both SAF and CAF. This would require separate storage and handling of both fuel types and careful management of aircraft refueling to prevent uploading the wrong fuel. Due to the high costs, and the complex logistical challenges, it remains more practical for airports to only stock blended fuel compatible with all aircraft.

⁷ Anuar, A., Undavalli, V.K., Khandelwal, B. and Blakey, S. (2021). "Effect of fuels, aromatics and preparation methods on seal swell." *The Aeronautical Journal*, [online] 125(1291), pp.1542–1565, <https://doi.org/10.1017/aer.2021.25>.



5.5.3 Supply chain and airport infrastructure

Jet fuels are transported in bulk quantities to airports. They often use shared systems between fuel suppliers and other fuel grades. Although there are requirements to separate CAF from other fuels, the same storage sites (different tanks) can be used, and vessels and pipelines can transport multiple kinds of fuels, with appropriate quality control measures. If a SAF blend is compliant with ASTM D1655, it can be treated in the same way as conventional kerosene. However, the scaling up of SAF and strategies designed to maximize the non-CO co-benefits (e.g., designated flights or airports), would require separate storage and fuel supply infrastructure. This would also have implications for the book and claim system, because SAF would need to be physically transported to specific airports and flights.

CAF is transported to airports in bulk, often using shared systems between suppliers and fuel grades. Although CAF storage is separated from other types of fuels, shared facilities such as storage sites, tanks, and transport systems (e.g., pipelines and vessels) can accommodate multiple fuel types with strict quality control protocols. SAF blends meeting the ASTM D1655 Standard Specification for Aviation Turbine Fuels can be treated like conventional kerosene for storage and transport. However, scaling up SAF supply and optimizing its climate benefits may require dedicated storage infrastructure and separate supply chains, particularly for strategies focusing on specific flights or airports.

In the current airport design system, the shared use of tanks and supply lines prevents a segregated supply of particular fuel batches to be uplifted to individual aircraft.⁸ From the airport storage tanks (i.e., fuel farm), aircraft are supplied either via underground hydrant systems or fuel trucks. Strategies aimed at maximizing the non-CO₂ co-benefits of SAF usage such as targeting specific flights or airports might require some restructuring of existing infrastructure. For example, an existing storage tank could be used for only SAF blends to avoid dilution with CAF and to ensure that the highest blended SAF possible are uplifted to aircraft serving the routes with the largest climate impact. Alternatively, blended SAF could be prioritized to selected airports qualified to optimize non-CO₂ co-benefits. For a supply of non-drop in 100% SAF, a fully segregated system along the supply chain and at the airport would be needed. These different scenarios are being explored within the EU 2020 horizon ALIGHT project.⁹

Under current airport designs, shared storage tanks and supply lines make it difficult to segregate fuel batches for individual aircraft¹⁹. Aircraft are supplied with fuel either via underground hydrant systems or fuel trucks. Strategies to maximize SAF's non-CO₂ benefits, such as targeting specific routes or airports, might require significant infrastructure adjustments. For instance, certain storage tanks could be designated exclusively for SAF blends to prevent dilution with CAF, ensuring the highest SAF ratios are used for flights identified to potentially achieve the greatest climate impact, simply, dedicated flights. Alternatively, SAF blends could be prioritized for specific airports characterized to provide the greatest benefits in LAQ improvements, or dedicated airports. To enable the use of non-drop-in 100% SAF, a fully separate supply chain

⁸ <https://www.ati.org.uk/wp-content/uploads/2022/06/saf-integration.pdf>

⁹ <https://alight-aviation.eu>



and airport system would be necessary, this requires segregated and separated fuel handling practices.

As the aviation sector is predicted grow in the coming years, additional fuel production capability as well as infrastructure will be required to increase the capacity of pipelines, tank storage, and airport distribution systems regardless of the fuel used. In these early planning and design stages, it would be wise to consider non-CO₂ co-benefit factors as well.

Such scenarios are actively being researched; of much importance is the “Best practice handbook and tools for fuel logistics, quality monitoring, and accounting” authored by IATA with the ample collaboration of consortium partners published in the same page as this document, within the the knowledge center of [Project ALIGHT](#). Given the expected growth of the aviation sector, expanding fuel production capacity and upgrading pipeline, storage, and distribution infrastructure will be essential regardless of the grade and type of fuel used. It seems wise for current and planned airports to incorporate fuel handling and airport infrastructure considerations to accommodate services that provide options to minimize non-CO₂ climate impacts from aviation.

5.5.4 Altering fuel composition – feasibility, policy, and incentives.

Adjusting the composition of CAF by reducing or removing aromatic and sulfur content is a promising method for addressing non-CO₂ climate impacts. Crude oil composition, which depends largely on geographic origin, determines the properties of derived products like CAF. Crude oil consists of thousands of different hydrocarbon compounds, along with small quantities of impurities such as sulfur, nitrogen, oxygen, and certain metals. Certification standards for jet fuel, such as ASTM D1655, ensure consistency and safety, specifying acceptable ranges for aromatics and sulfur content. While refining processes for reducing aromatics are commonly used in products like gasoline and diesel to meet emissions regulations, these methods can also be adapted to manage the aromatic and naphthalene content of CAF.

5.5.4.1 Aromatics

CAF contains four primary classes of hydrocarbons: normal paraffins, iso-paraffins, naphthenes, and aromatics. As previously mentioned, aromatic compounds are beneficial because they enhance lubricity, reduce freeze points, and interact with polymer seals in engines and fuel systems to prevent leaks. Among the aromatics, naphthalenes have been identified to produce soot particles, making them a key target for removal to help reduce the environmental impact of aviation¹⁸.

Currently, two main refining methods can manage the naphthalene content in CAF: hydrotreating and extractive distillation. Hydrotreating is widely used in refineries and works by converting naphthalenes into other hydrocarbons, which helps maintain the final fuel volume. Extractive distillation, on the other hand, uses solvents to completely remove naphthalenes, a least preferred process as it results in a loss of fuel volume^{21,22}.

Reducing or removing naphthalenes requires additional refinery processes, which involve the use of fuel, steam, electricity, and hydrogen. These activities increase operational costs and add greenhouse gas emissions to CAF’s life cycle. Studies have analyzed the feasibility and cost-



effectiveness of naphthalene removal. For example, the FAA ASCENT Project 039 evaluated the societal costs and benefits of reducing CAF naphthalene content in the U.S. by 95%. Using hydrotreatment or extractive distillation, they examined 116 refineries with capacities exceeding 1,000 barrels per day. The findings revealed that the climate impacts of increased refinery CO₂ emissions outweigh the air quality and climate benefits of soot reduction. For extractive distillation, the median air quality and climate advantages roughly balanced out the societal costs of added CO₂ emissions. These results indicate that naphthalene removal on a national scale is unlikely to be cost-effective unless outweighed by the climate benefits from reducing the impact of contrails. Nevertheless, naphthalene removal could be beneficial in specific scenarios, such as at airports with localized air quality concerns or in regions and times where contrail formation is most impactful³⁶.

In alignment with the above findings, the International Council on Clean Transportation (ICCT) conducted a separate study to evaluate the technological and economic feasibility of controlling naphthalene levels in CAF. The study concluded that extractive distillation is considerably more expensive than hydrotreating due to significant fuel volume losses. Additionally, hydro-skimming refineries faced higher average costs for naphthalene removal than conversion refineries, largely because of differences in refinery sizes and associated capital costs³⁵.

5.5.4.2 Sulphur

Sulphur occurs naturally in crude oil, but its concentration varies depending on the source. At high levels, sulphur can interfere with chemical reactions during the refining process or cause corrosion to refinery equipment. As stated previously, CAF contains sulphur and it emits SO_x during combustion, which then oxidize into sulfates in the engine exhaust. These sulfates may contribute to climate warming by acting as cloud condensation nuclei in the formation of contrails. Near the surface, they also pose risks to human health.

For CAF, the maximum allowable sulphur content is 3,000 ppm, though the average concentration is estimated to be around 600 ppm. The higher the sulphur content in the crude oil, the more extensive the removal process required increasing production costs. Despite the lack of any functional benefits of sulphur in CAF, refineries often limit sulphur removal to the minimum necessary to meet regulatory standards in order to manage expenses.



Key points

- Global modeling studies show that reductions in soot emissions associated with SAF usage can lead to significant decreases in the net contrail-cirrus RF (~44% to 59%).
- Despite the climate and air quality benefits, fuel suppliers do not have any incentives to minimize the aromatic content of SAF blends, and often use CAF with high amounts to ensure that the blended product meets international standards.
- Strategies targeting SAF usage on selected flight routes with the highest contrail warming potential would require separate fuel storage and handling at airports. The associated restructuring of existing infrastructure can be cost-prohibitive.
- Removing the naphthalenes and sulfur from CAF can be an effective strategy in reducing the non-CO₂ impacts of air transportation. The two main refining technologies currently available to remove or reduce naphthalenes from CAF are hydrotreating and extractive distillation. From an economic perspective, hydrotreating may be more feasible at refineries with existing infrastructure because of the significant loss in volume associated with extractive distillation.
- Refineries have the capability to remove sulfur from crude oil and keep the maximum level below the 3000 ppm standard for CAF, but have no incentive to completely remove it due to the associated added costs.



5.6 Initial Guidance for Aircraft Operators on Monitoring, Reporting, and Verification (MRV) of Non-CO₂ Aviation Effects

This section provides guidance for aircraft operators on how to collect, report, and verify data for the Monitoring, Reporting, and Verification (MRV) of non-CO₂ aviation effects. It outlines the data requirements, collection methods, and the role of the European Commission's IT tool 'Non-CO₂ Aviation Effects Tracking System' or NEATS.

The MRV obligations began on January 1, 2025, and operators must monitor and report non-CO₂ effects annually. Although NEATS is not yet available, operators must collect and store data in compliance with regulations. Once NEATS is fully operational, it will streamline the process and reduce administrative burdens.

The content of this section is based on the document published by the European Commission on February 2025¹⁰.

5.6.1 Overview of the MRV Cycle

The MRV process follows the same cycle as the EU Emissions Trading System (EU ETS) for CO₂. Throughout the year, operators shall collect data, which must be reported by March 31 of the following year. The data is then verified, and compliance checks are performed. NEATS, once available, will assist in automating calculations and reporting.

5.6.1.1 Scope of the MRV

Operators are required to report non-CO₂ effects for jet-engine aircraft. Initially, reporting is only mandatory for flights within the European Economic Area (EEA), including Switzerland and the UK. Over time, this may expand to more routes.

Operators can choose between three levels of geographical coverage:

- **Reduced Scope:** Covers intra-EEA flights, including Switzerland and the UK.
- **Intermediate Scope:** Covers the reduced scope plus selected extra-EEA routes.
- **Full Scope:** Covers all flights departing from and arriving in the EEA.

NEATS will be the primary tool for MRV, but in the future, operators may use Commission-approved alternatives.

5.6.2 NEATS Primary Data Requirements

The MRV process uses two categories of data:

- **Primary Data:** Information directly collected by the operator, such as flight trajectory, fuel flow, and aircraft mass.
- **Secondary Data:** Data automatically provided by NEATS from external sources, including EUROCONTROL and weather data providers.

Using Primary Data is encouraged, as relying solely on NEATS' default Secondary Data may lead to overestimation of emissions.

¹⁰ European Commission, Energy, Climate Change, Environment. 'MRV non-CO₂ Guidance document for Aircraft Operators,' Version 1.4 Feb. 2025: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://climate.ec.europa.eu/document/download/6aec6267-74ff-435a-87c7-92062db7ccb8_en%3Ffilename%3Dpolicy_ets_aviation_gd_non_co2_mrv_pre-neats_en.pdf&ved=2ahUKewjW3uOsvpuMAxWZ_7siHY-JmN0kQFnoECBYQAQ&usq=A0vVaw3PQiiPI2PRCKRieMg56Znl



5.6.2.1 Calculation Methods

Operators must use one of two methods to calculate non-CO₂ effects:

- **Method C (Weather-Based Approach):** This method is mandatory for large operators and uses detailed flight, aircraft, and weather data to estimate emissions.
- **Method D (Simplified Approach):** This method is available to small emitters and relies on basic flight trajectory and limited weather data.

Method C – Detailed Guidance

Under Method C, operators should collect:

- **Flight Information:** Flight number, departure and arrival times, airport codes.
- **Flight Trajectory Data:** 4D flight paths, including latitude, longitude, altitude, and timestamps.
- **Weather Data:** Provided by NEATS, including temperature, humidity, and wind conditions.
- **Aircraft Properties:** Aircraft type, engine identifier, and mass.
- **Fuel Properties:** Hydrogen-to-carbon ratio, sulfur content, and burn rate.
- **Aircraft Performance:** Fuel flow rate and engine efficiency.

NEATS uses this data to estimate emissions with models such as:

- **Boeing Fuel Flow Method 2 (BFFM2):** Calculates emissions of NO_x, CO, and HC.
- **CoCiP (Contrail Prediction Model):** Evaluates contrail formation.
- **aCCF (Algorithmic Climate Change Functions):** Assesses climate impact.

Once processed, NEATS generates an XML report for submission.

Method D – Simplified Approach

Small emitters using Method D need to collect similar data but with fewer requirements:

- **Flight Information & Trajectory Data:** Follows the same structure as Method C.
- **Weather Data:** Includes only air temperature, specific humidity, and pressure altitude.
- **Fuel Properties:** Not required.
- **Aircraft Performance:** Optional.

This method uses:

- **BFFM2 Model** for emissions.
- **openAirClim Model** for climate impact calculations.

At the end of the reporting period, NEATS generates a report detailing flight emissions and CO₂-equivalent values for different time horizons (20, 50, and 100 years). This simplifies compliance and verification.

NEATS will also process additional data requirements from the following sources:

- **Appendix 1:** Input descriptions for flight, aircraft, and fuel data.
- **Appendix 2:** Examples of collected Primary Data files.
- **Appendix 3:** Weather data parameters used in emissions calculations.



To conclude, aircraft operators must begin collecting MRV data now using the methods described above, even before NEATS is fully operational. This early adoption is meant to ensure compliance and a smooth transition. While NEATS provides default secondary data, using primary data improves accuracy and reduces the likelihood of overestimations. Proper monitoring and reporting will help ensure compliance with environmental regulations and contribute to a better understanding of aviation's non-CO₂ climate impacts.

More details may be found in the European Commission's publication '[MRV non-CO2 data collection Guidance for Aircraft Operators.](#)'

5.7 Conclusions and recommendations

The use of sustainable aviation fuels (SAF) offers substantial potential for reducing the non-CO₂ climate impacts of aviation, in addition to its well-documented CO₂ reduction benefits. Scientific research has shown that SAF can lower emissions of soot and sulfur-containing particles, leading to fewer and less persistent contrails. This, in turn, reduces the radiative forcing impact of aviation-induced cirrus clouds, which can contribute to global warming. The reduction in particulate matter emissions from SAF also improves local air quality, particularly around airports.

Despite these advantages, uncertainties remain regarding the full extent of SAF's non-CO₂ benefits, particularly in the formation and behavior of contrail cirrus. While studies indicate that SAF can produce contrails with fewer but larger ice crystals that dissipate more quickly, further research is required to refine climate models and validate these findings under various atmospheric conditions. Additionally, the impact of volatile particulate matter (vPM) in low-soot conditions is not yet fully understood, and recent studies suggest that vPM could play a role in ice crystal formation in certain scenarios.

A robust monitoring, reporting, and verification (MRV) framework for non-CO₂ aviation effects is needed for accurately assessing and mitigating aviation's total climate impact. With MRV obligations taking effect in 2025, aircraft operators must collect and report data on non-CO₂ emissions, including contrail formation, using standardized methodologies. The Non-CO₂ Aviation Effects Tracking System (NEATS) will support this process by automating calculations and integrating external data sources. However, challenges remain in ensuring data accuracy, particularly as reliance on default NEATS values may lead to overestimations, making primary data collection essential. Furthermore, the models used to estimate the effects are associated with a high degree of uncertainty and even omit important processes such as the role of vPM in contrail formation.

This the document highlights the pivotal role of SAF in achieving aviation's sustainability goals while acknowledging the logistical, technical, and policy challenges that must be addressed. The complexity of non-CO₂ emissions modeling, especially in relation to contrail formation and radiative forcing, highlights the need for continued research. Strategic SAF deployment, targeting high-impact flights, regions, or airports, offers a path to maximize environmental benefits. Advancing measurement capabilities, refining models, and fostering international collaboration will be key to fully realizing the climate and air quality advantages SAF provides while addressing associated complexities and uncertainties.



5.7.1 Recommendations

To maximize the non-CO₂ climate benefits of SAF, a combination of scientific research, strategic deployment, infrastructure investment, and policy support is essential. Addressing current uncertainties, optimizing SAF implementation, and fostering industry collaboration will enhance its effectiveness in reducing aviation's overall climate impact. The following recommendations outline key actions to advance SAF's role in mitigating non-CO₂ emissions:

- **Advance SAF Research and Climate Modeling:** Expand in-flight studies, laboratory experiments, and numerical modeling to refine understanding of SAF's impact on contrail formation, microphysics, radiative forcing, and the role of vPM.
- **Optimize SAF Deployment and Aircraft Compatibility:** Prioritize SAF use on flights with high contrail warming potential while researching aircraft and fuel system modifications to enable higher SAF blending ratios and eventual 100% SAF adoption.
- **Ensure Accurate and Reliable Data Collection:** Encourage operators to prioritize primary data collection over default NEATS values to improve accuracy in tracking non-CO₂ effects while providing industry support for smooth MRV implementation.
- **Continuously Improve MRV Methodologies:** Regularly refine contrail impact assessments and reporting processes by integrating the latest scientific research, operator feedback, and technological advancements to enhance precision and practicality.
- **Support Operator Compliance and Adaptation:** Provide industry guidance, training, and technological support to help operators efficiently integrate MRV requirements into their existing reporting systems.
- **Support Policy and Regulatory Incentives:** Develop policies, funding mechanisms, and regulatory measures to encourage SAF adoption, contrail mitigation strategies, and advancements in alternative fuel technologies.
- **Enhance Industry Collaboration and Knowledge Sharing:** Foster partnerships between fuel producers, airlines, regulators, and research institutions to accelerate SAF innovation and ensure effective implementation of non-CO₂ climate benefits.



6 Extension of the DLR AirClim simulation tool

6.1 Modeling approach and AirClim description

Several approaches are applicable for making use of limited amounts of SAF. In general, the climate benefit from these approaches increases with the logistical effort to be made in preparation and operation. A conceptual overview for these solutions is provided in Figure 24. Even distribution of a fixed SAF ratio to all flights implies little logistical effort, but due to the above explained physical behavior of the contrail climate effect, the total climate benefit is limited this way. On the other extreme, a system could be implemented that includes actual weather forecasting to the refueling process, meaning that flights receive large SAF blend ratios explicitly when they are predicted to be flying through an ice-supersaturated region. This could potentially maximize the climate benefit of targeted SAF use, but adds another level of complexity to refueling operations that is connected with huge logistical efforts. This tradeoff makes clear that intermediate solutions are to be sought that promise high climate benefit with reasonable effort. These intermediate solutions include for example choosing night time or winter time flights for high SAF blend ratios, or generally long-haul flights or those flights with the largest contrail climate effect in a climatological sense. Effectiveness of these solutions may depend on various variables and would have to be assessed for each case separately. A more climate benefit-effective solution (but still less than including weather forecasting) is selecting those flights with the climatologically highest contrail to fuel use ratio. In the present study, we chose this solution as prime focus as it promises high climate benefit while keeping logistical effort at a reasonable level.

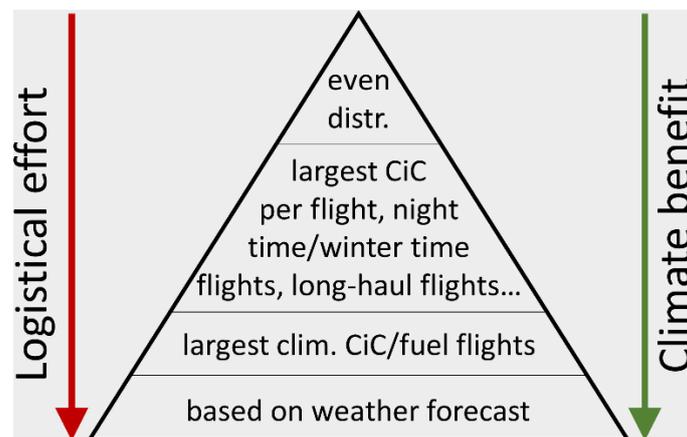


Figure 24: Conceptual logistical effort and climate benefit estimate of various SAF distribution solutions. CiC stands for contrail-induced cloudiness.

For this approach and also as we are particularly focusing on the year 2030 in our study, it is reasonable to make a number of assumptions for the climate effect calculations. As mentioned above, we do not include the current meteorological situation, which to date is unknown for the year 2030, instead we use a climatological approach. Moreover, our modeling approach focuses on the high-soot regime, hence does not include lean-burn engines or other



technologies such as hydrogen and electric propulsion systems. If we consider the general fleet roll-over of aircraft, we consider this to be reasonable for the year 2030 for the bulk of the fleet. As currently only SAF blending up to 50% is certified, it is also reasonable to assume enough nvPM to remain in the aircraft exhausts such that the regime where vPMs become relevant for contrail formation is not reached.

In consequence of the assumptions made above and the design of the analysis, we chose to use the AirClim model for the study. AirClim is a climate response model for estimating the climate effects of air traffic CO₂ and non- CO₂ emissions in a computationally fast way (Grewe and Stenke, 2008). AirClim includes precalculated atmospheric impact data to calculate for example the aviation climate impact for a multitude of emission inventories or the climate effect of basic aircraft/engine configurations and general operational strategies. For the precalculated data, idealized emission regions with normalised emission strength were defined on 84 grid boxes (7 latitudes & 12 altitudes). For each of the idealized emission regions, a climate-chemistry simulation using E39/CA (Stenke et al., 2008) was employed with normalized emissions to obtain the chemical perturbations and radiative forcing of ozone (O₃), methane (CH₄), water vapor (H₂O) and contrails. For contrail cirrus, simulations with ECHAM4-CCMod Burkhardt et al. (2009) are used. AirClim combines these computing time expensive precalculated data with air traffic emission data to calculate composition changes, radiative forcing (RF) and near surface temperature changes. Further, it computes the temporal evolution of aviation-induced RF as well as the resulting near surface temperature change for a given temporal development and spatial distribution of aviation emissions for CO₂, H₂O, NO_x, O₃, Primary Mode Ozone (PMO), CH₄ and contrails. AirClim estimates the aviation climate impact in a climatological sense, meaning that it captures the average of the impacts of all weather situations that occur during a year. It can account for different propulsion types by including the probability of fulfilling the Schmidt-Appleman criterion (SAC) in dependency of the overall propulsion efficiency, lower heat value of the fuel and emission index of water vapour. AirClim includes a parametrization for SAF which has specifically been extended for the ALIGHT project, it is described in more detail below.

6.2 Parameterization of SAF-blend impact on particulate matter emissions

Non-volatile particulate matter (nvPM) emitted by aircraft engines enhance ice crystal nucleation thereby fostering contrail formation. In AirClim, an nvPM reduction therefore leads to a reduction of contrail RF. For this, the relation that was developed by Burkhardt et al. (2018) is used, assuming a linear relation between ice crystal and nvPM number concentrations, which is appropriate in the soot-rich regime.

Since SAF blends have demonstrated a reduction in nvPM emissions, a suitable correlation was required to estimate changes in nvPM emission indices (EI_n) as a function of SAF blend ratios. In the AirClim model, this is represented through a scaling factor on the nvPM depending on the SAF ratio. For this extension of the SAF parametrization, the correlation developed by Teoh et al. (2022) was implemented in AirClim for ALIGHT. This correlation estimates the relative



reduction in nvPM EI_n based on two primary factors: the difference in hydrogen content ΔH between conventional jet fuel and the SAF blend, and the current engine thrust setting \hat{F} . The correlation, calibrated against experimental data, is extrapolated for hydrogen content differences.

The complete correlation is given by:

$$\Delta npPM EI [\%] = \begin{cases} (\alpha_0 + \alpha_1 \hat{F}) \times \Delta H, & \text{when } \Delta H \leq 0.5\% \\ (\alpha_0 + \alpha_1 \hat{F}) \times \Delta H \times e^{(0.5 - \Delta H) \times 0.5}, & \text{when } \Delta H > 0.5\% \end{cases}$$

with parameters $\alpha_0 = -114.21$ and $\alpha_1 = 1.06$. The resulting reductions in EI_n across thrust settings from 10% to 100% are illustrated in Figure 25.

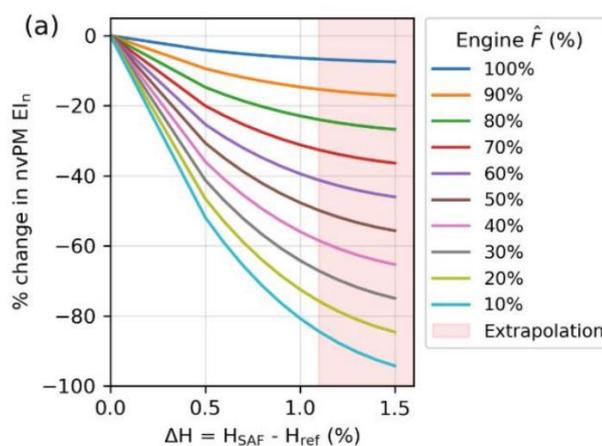


Figure 25 Correlation between fuel hydrogen content H and change in emission index for nvPM

Estimation of mean SAF blend properties in 2030

As AirClim was employed to calculate the contrail-related climate impact of various SAF deployment scenarios for the year 2030 under Task 3.6, it was necessary to estimate the expected properties of SAF blends available by that time—specifically, the hydrogen content—in order to apply the previously mentioned emission reduction correlation.

According to the ReFuelEU Aviation blending mandate, 25% of the SAF supplied in 2030 must consist of renewable fuels of non-biological origin (RFNBO), such as Power-to-Liquid (PtL) products. Given current technological maturity, it is assumed that the remaining 75% will primarily consist of bio-based SAF produced via the HEFA pathway. Among PtL technologies, the Fischer-Tropsch (FT) process is considered the most mature and therefore most likely to dominate PtL supply in this time frame.

Based on this assumption, data for the hydrogen content H of currently available HEFA and FT fuels was extracted from the SimFuel database, as introduced in Section XY. This resulted in a total of 17 data points for hydrogen content. These values were then weighted according to the ReFuelEU blending quota and further adjusted by the respective fuel densities to yield a virtual mean neat SAF for 2030. The resulting average hydrogen content and density were:



$$H_{SAF,2030} = 15.33 \text{ kg/kg}$$

and

$$\rho_{SAF,2030} = 755 \text{ kg/m}^3$$

Using the corresponding average values for conventional Jet A fuel as reported by Teoh et al. (2022) ($\rho_{JetA-1} = 798 \text{ kg/m}^3$, $H_{JetA-1} = 13.8 \text{ kg/kg}$), SAF blend properties for 2030 were calculated for a range of blending ratios. These values were then inserted into the original Teoh et al. (2022) correlation and reformulated as a function of SAF blend ratio, yielding a derived expression for nvPM EI_n reduction specific to expected SAF blends in 2030.

Figure XY illustrates the resulting correlation at a representative engine thrust setting of $\hat{F} = 30\%$. Within the context of the available data, this correlation is considered valid for blend ratios up to 73%.

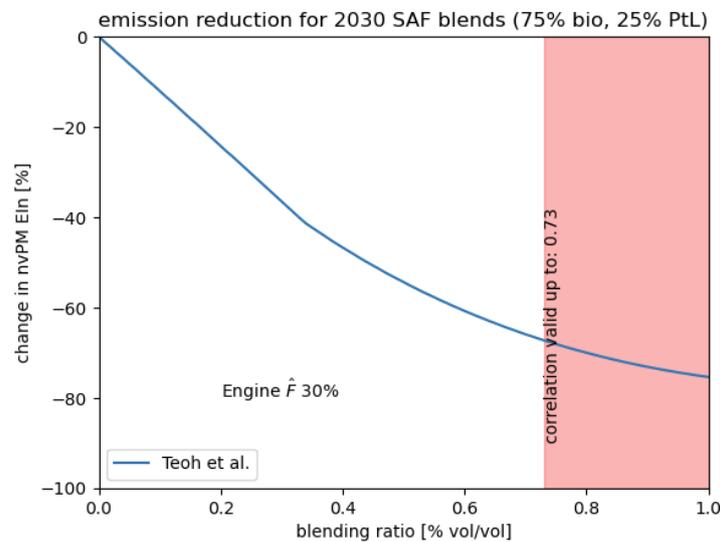


Figure 26 Final correlation between SAF blending ratio for the assumed neat SAF and change in emission index for nvPM

6.3 Calculation method

We use the 2019 base year traffic, the year before the COVID-19 pandemic strongly reduced air traffic. The annual route network of CPH airport consists of a flight schedule with 129,631 instrument flight rules departing from CPH. We refrained from including other elements in the analysis that could distort the clear identification of the non-CO₂ effects by involving additional uncertainty, such as traffic growth or replacements in the aircraft fleet over time. The emission inventory contains 3-dimensional distributions of annual CO₂, NO_x, H₂O emissions as NO₂ mass-equivalent and the flown distance per grid cell. The trajectories are stored in a database of Reduced Emission Profiles (RedEmP) for all available aircraft types and various discrete flight distances in 100 NM steps, seat load factors and cruise altitudes. For the baseline scenario with 100% Jet A-1, constant emission indices of 3.159 kg CO₂/kg fuel and 1.237 kg H₂O/kg fuel are applied. NO_x emissions depend on both the engine combustor and flight phase and are non-linear with fuel burn.

For each air connection, the DLR Global Air Traffic Emission Distribution Laboratory (GRIDLAB) is used to pick the best-fitting RedEmP with regard to the mission-specific seat load factor,



cruise flight level and the air distance of an appropriate randomly selected routing profile from the database. The cruise phase of the RedEmP with constant speed and fuel flow is truncated to the actual wind-corrected air distance and the restricted climb and descent phases are adjusted to fit to the local airport elevation, as given in the applied airport database. Finally, the adjusted RedEmP is georeferenced along either the selected routing profile or otherwise great circle route on the assigned constant cruise altitude and projected on a 3-dimensional numerical grid with a resolution of $0.25^\circ \times 0.25^\circ \times 1000$ ft. To consider air traffic management (ATM) effects and inefficiencies implicitly, the RedEmPs are projected on up to five different flight paths per mission and their emission amounts are weighted and summed up over all modeled routes of each air connection.

In AirClim, this 2019 base year traffic emission inventory is applied as pulse emissions in the year 2030. We use the SSP245 climate scenario (medium pathway of future greenhouse gas emissions) to determine the background climate conditions, in particular the CO_2 , N_2O and CH_4 mixing ratios. The ReFuelEU SAF mandate of 6% in 2030 implies that the total available SAF at the airport is 6% of the total fuel use of all flights departing from CPH. The RF or rather the temperature perturbation of the pulse emissions of the aggregate of all flights departing from CPH in 2030 with varying fuel specifics is assessed. We use the climate metric EAGWP, which is the efficacy-weighted (E) absolute (A) GWP (global warming potential). This integrated climate metric has been chosen by the EU Commission as the standard for the monitoring, reporting and verification (MRV) system that is currently being implemented to track EU-wide aviation non- CO_2 emissions and the analysis by Megill et al. (2024) showed that this metric fulfills the criteria necessary to represent aviation climate effects well. The primary time horizon in this study is 100 years, as in integrated climate metrics, longer time horizons represent better the impacts of both short-lived climate forcers, such as contrails and ozone and long-lived climate forcers such as CO_2 (Megill et al., 2024). To assess the robustness of the results, we additionally use the climate metrics ATR and AGWP and the additional time horizons 20 and 50 years. The output of the climate metric computations is then translated to CO_2 -equivalents (CO_2e) to obtain a common ground for comparisons and to allow direct monetization of the results. A CO_2e is the climate impact of a climate species relative to the climate impact of a certain CO_2 unit.

To achieve the largest climate effect with 6% SAF of total available fuel we sort the flights by their contrail effect to fuel use ratio (see Figure 27 for concept). Selecting the topmost flights in this list for higher (than 6%) SAF blend ratios will yield a larger climate benefit with the available SAF. This means that in comparison to equipping all flights with 6% SAF, here not all flights receive SAF, but those that do receive more than 6%. The number of flights that receives SAF depends on the chosen blending ratio. Here we perform the calculations for 30, 40, 50, 60, 70 and 100% SAF. Note that as currently only 50% SAF blends are licensed the 70 and 100% examples are to be understood as theoretical considerations. Additionally, a sensitivity experiment was conducted sorting the flights simply according to their total contrail climate effect. This reduces the achievable climate benefit, but also reduces the logistical effort, as much less flights need to be fueled with SAF.



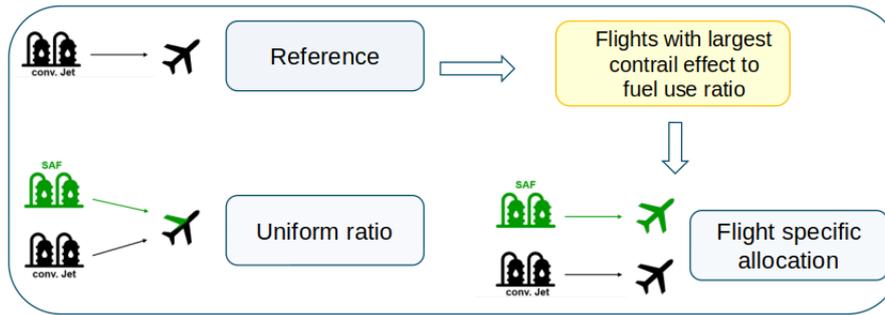


Figure 27 Concept for flight selection for targeted SAF use.

6.4 AirClim Results

For the scenarios with selected flights equipped with SAF, Figure 28 displays the CO₂e reduction for CO₂, contrail effect and total both in absolute and in relative terms. Note that we assumed SAF to be CO₂-neutral in these calculations, which means that the CO₂ reduction here is over-estimated. This has to be considered when interpreting the relative reduction (left y-axis) and the CO₂ and total reduction lines. However, we here focus on the absolute contrail effect reduction, which is not affected by this assumption. All other non-CO₂ climate effects are unchanged through SAF but contribute to the total CO₂e.

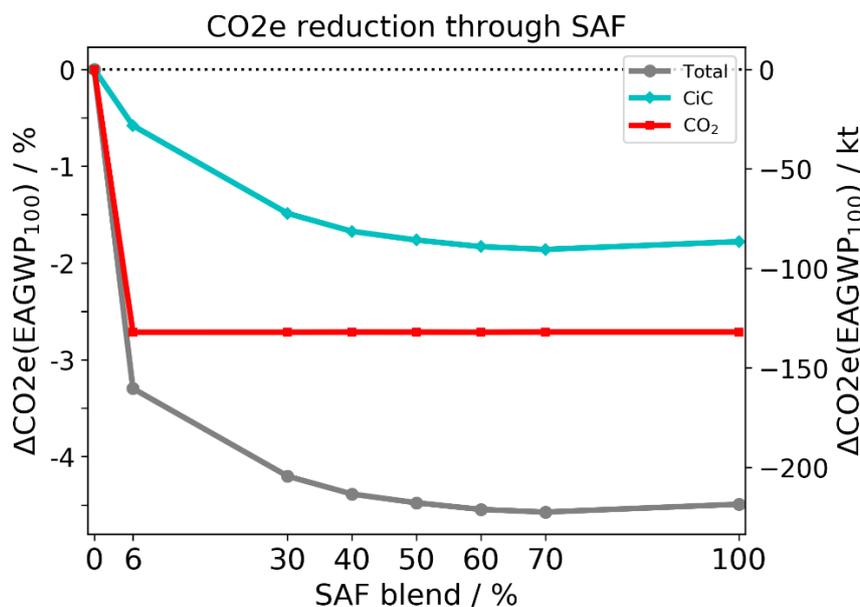


Figure 28 EAGWP100-based CO₂e reduction through 6% of SAF at CPH in 2030 uniformly distributed to all flights and with targeted SAF allocation to specific flights with blending ratios of 30%, 40%, 50%, 60%, 70% and 100%. The left vertical axis shows the relative

For CO₂, the CO₂e reduction logically is the same in all the here analyzed SAF scenarios. When the 6% SAF are equally distributed among all flights, the contrail effect reduces by about 30 kt. Targeted SAF use with less flights equipped with SAF but higher blending ratios increases the climate benefit through contrails. Here, the climate benefit increases with higher SAF blending ratios until 70% and it diminishes slightly again for 100%. At 50% SAF blending ratio, the total CO₂e reduction is about 90 kt yielding a 60 kt increase of the benefit in comparison to the 30



kt of the even distribution approach. Within the range of licensed scenarios, this constitutes the 50% SAF blend is the scenario with the largest climate benefit. Note that the uncertainties (not shown) are rather large for these climate effect reductions.

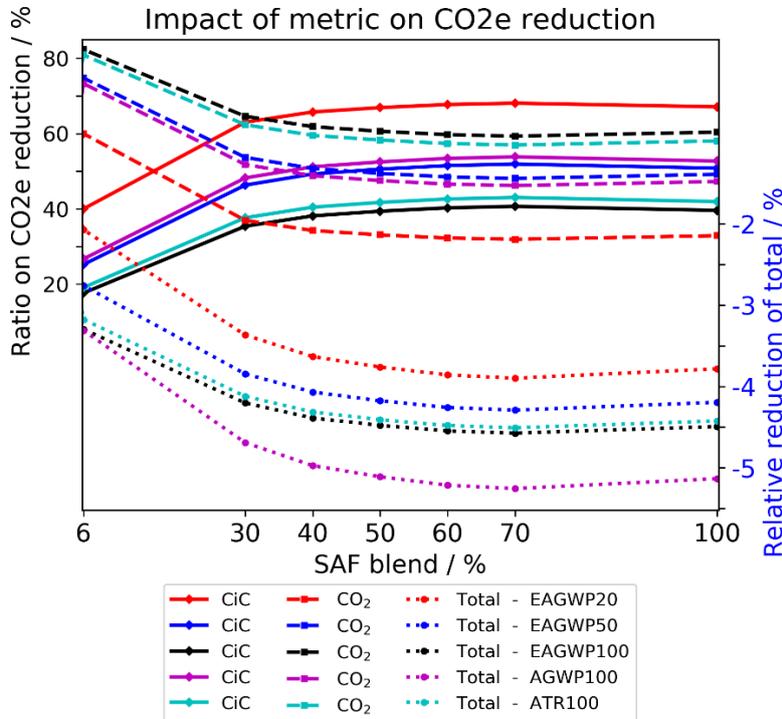


Figure 29 Relative reduction of total climate effect and ratio on CO₂ as well as contrail CO₂e reduction

Figure 29 shows the relative reduction of the total climate effect and the ratio of the CO₂ and the contrail effect on the total reduction for the additional climate metrics AGWP and ATR (each with 100 year time horizon) and for EAGWP with the three time horizons 20, 50 and 100 years. It shows that the total climate benefit strongly depends on applied climate metric and time horizon. The relative total reduction varies between -3.5% and -5.5% depending on the metric and time horizon chosen. This is not only due to the amount of reduction, but also due to the different absolute baseline values that emerge through the different time horizons and metrics. The relative importance of the contrail effect for CO₂e reduction increases with the SAF blending ratio and is larger for GWP and for shorter time horizons.

This analysis provides the baseline non-CO₂ climate effect results that has been taken into account in the cost benefit analysis considering all monetary aspects of the targeted SAF use including logistics at the airport. For this, the EAGWP100 with 50% SAF blend results have been taken in a quantitative manner. This means, the monetized value of the ~60 kt CO₂e difference is charged up against the additional costs for realizing the targeted SAF use in operation at CPH airport. As mentioned above, we also tested using in a sensitivity analysis the effect of equipping the most contrail-intense flights with SAF instead of those with the largest contrail to fuel use ratio. This approach leads to less flights and less different flight routes being eligible for SAF use, hence reducing the logistical effort at the airport, but also reduces the additional climate benefit to ~30 kt CO₂e. A description of these calculations can be found in the cost benefit analysis.



7 Conclusions

This report presents a comprehensive approach to maximizing the climate benefits of Sustainable Aviation Fuel (SAF) through digital innovation, scientific modeling, and strategic deployment. The enhancements made to DLR's SimFuel and AirClim platforms enable a data-driven, lifecycle-aware assessment of SAF, supporting smarter decisions around its use in airport and flight operations. Scientific evidence strongly supports SAF's potential to reduce both CO₂ and non-CO₂ impacts—particularly contrail formation—through reduced soot and sulfur emissions. However, realizing these benefits requires addressing technical barriers such as fuel infrastructure, aircraft compatibility, and limited SAF availability. The report underscores the need for continued investment in modeling capabilities, in-flight measurements, and policy frameworks, including Monitoring, Reporting, and Verification (MRV) systems. By combining targeted SAF use with robust digital tools and stakeholder collaboration, the aviation industry can significantly reduce its climate footprint and accelerate its transition to a more sustainable future.



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