Maximizing the Climate Co-Benefits of Sustainable Aviation Fuel via Targeted Allocation

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CLEAN AIR TASK FORCE

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List of Acronyms

In order of appearance:

SAF	Sustainable Aviation Fuel
Quads	quadrillion British thermal units
EJ	Exajoule
NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides
CO	Carbon Monoxide
vPM	Volatile Particulate Matter
nvPM	Non-Volatile Particulate Matter
CO_2	Carbon Dioxide
LTO	Landing and Take-Off
PM	Particulate Matter
UFP	Ultrafine Particles
ISSR	Ice-Supersaturated Region
GHG	Greenhouse Gas
HEFA	Hydro-processed Esters and Fatty Acids
COCIP	Contrail Cirrus Prediction Tool
CO_2eq	Carbon Dioxide Equivalent
Ton	metric ton
EPA	United States Environmental Protection Agency
COBRA	CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool
U.S.	United States
Europe	All 43 countries in Europe
Jet A-1	conventional fossil jet fuel
IEA	International Energy Agency
Mt	Million Metric Tons
CI	Carbon Intensity
ICAO	International Civil Aviation Organization
VOCs	Volatile Organic Compounds
WHO	World Health Organization
EU	European Union (27 member states)
Bio-SAF	sustainable aviation fuels produced with biogenetic feedstocks
Syn-SAF	Synthetic Sustainable Aviation Fuel
LCA	Life Cycle Assessment
RFNBO	Renewable Fuel of Non-Biological Origin
ASTM	ASTM International (formerly American Society for Testing and Materials)
kg	Kilogram
ppm	parts per million
IATA	International Air Transport Association
FT	Fischer-Tropsch
CDR	Carbon Dioxide Removal
RMI	Rocky Mountain Institute
RFI	Radiative Forcing Index
GWP	Global Warming Potential
GTP	Global Temperature Change Potential
Km	Kilometer
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis v5
ADS-B	Automatic Dependent Surveillance–Broadcast
CARB	California Air Resources Board
CEPS	Central Europe Pipeline System
NEPS	North European Pipeline System
NATO	North Atlantic Treaty Organization
UK	United Kingdom
EASA	European Union Aviation Safety Agency
PPPA	Preparatory Action or Pilot Project

Executive Summary

Mitigating the health and climate impact of the aviation sector will be particularly challenging as success involves transitioning to sustainable aviation fuel (SAF), which at present is more expensive than conventional jet fuel and not produced at a scale that can affect the entire market. In 2024, aviation fuel consumption reached 13.2 quadrillion BTU (quads), or 14 EJ, and some studies project that to grow to 22.7 quads (24 EJ) by 2050. Aircraft cannot be readily electrified at that scale, so the challenges associated with the transition to SAF must be overcome. Conventional jet fuel combustion emits water, sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), non-combusted hydrocarbons, and volatile (vPM) as well as non-volatile particulate matter (nvPM, also known as soot), alongside carbon dioxide (CO_2). Particulate matter (PM) and NO_x worsen local air quality when emitted during landing and take-off operations (LTO), and PM particles can act as nuclei for contrail formation at cruise altitudes. Contrails trap heat in the atmosphere, affecting the climate by contributing significant additional warming beyond what is caused by CO_2 emissions. In large enough quantities, SAF can mitigate a portion of those negative impacts. During this fuel transition period, rather than spreading SAF thinly across the entire aviation network, the cleaner fuel should be allocated to airports where it can deliver the largest combined climate and public health benefits.

Airports are typically located near large population centers, such that aircraft emissions regularly affect the health of millions of people living and working nearby. Epidemiological research on the effect of these emissions has shown that PM, especially fine and ultrafine particulate matter, is associated with cardiovascular harm, inflammation, reduced lung function, and elevated risk of premature death. Furthermore, the area affected by aircraft related PM is strongly influenced by wind direction and can adversely impact communities many kilometers downwind. This behavior was measured in several studies conducted near airports such as LAX, Boston Logan, Amsterdam Schiphol, and Heathrow. Annually, these aircraft emissions during LTO in the U.S. and Europe are estimated to cause thousands of premature deaths and billions of dollars in health damages.

In addition to PM impacts on the ground, contrail cirrus formation is a less well-known climate issue that is caused by PM particles in the exhaust interacting with ice crystals in regions at altitude known as ice-supersaturated regions (ISSR). Particulate matter emitted from the engine while in an ISSR causes the formation of contrails. These cloud-like formations can add about 33% additional warming on top of aviation greenhouse gas (GHG) emissions.

Sustainable aviation fuel is a uniquely important tool among aviation climate impact mitigation options because it reduces both GHG and particulate matter emissions, the latter of which will improve local air quality and reduce contrail-related warming. Depending on how it's produced, neat SAF (that is, SAF unmixed with conventional jet fuel) can reduce lifecycle CO_2 emissions by 26 - 94% relative to fossil jet fuel, and because the fuel has little to no aromatic content, once blended with Jet A-1 it'll also significantly reduce soot formation in engine exhaust. To be clear, SAF is not the complete answer to contrails, as some soot will still be generated during combustion and non-soot exhaust particles also support contrail formation, but even so, blending SAF is a scalable mitigation lever that will improve CO_2 emissions, local air quality, and reduce contrail-related warming.

SAF supply is projected to remain limited in the medium-term, however, which makes targeting the available SAF to high-impact airports a logical optimization strategy. Bio-based feedstocks face sustainability constraints, and synthetic SAF will require a major scale-up in clean hydrogen, carbon capture, production facilities, and enabling infrastructure. Until the global supply of SAF increases significantly and the price of SAF declines, the best near-term approach is to allocate it to airports where the same quantity of fuel can generate non-CO_2 co-benefits along with CO_2 emission reductions.

CATF carried out an analysis of 2024 flight activity at major airports in the United States and Europe (16.6 million flights) using data and modeling from Estuaire to identify where targeted SAF use would have the biggest impact. Contrail impacts were estimated with COCIP using weather data, humidity, and engine characteristics, while LTO PM and NO_x emissions were estimated using ICAO methodologies. This data showed that approximately 2% of flights generate 80% of contrail-related warming, which supports targeting mitigation measures at specific airports. In the U.S., departing flights from JFK (KJFK), LAX (KLAX), SFO (KSFO), and O'Hare (KORD), rank the highest in terms of contrail impact, with JFK standing out because its route map exposes many flights to the ISSR commonly present in the North Atlantic during winter. In Europe, flights departing from Heathrow (EGLL), Istanbul Airport (LTFM), and Paris CDG (LFPG) are responsible for the largest contrail impacts. Heathrow is especially prominent because of its combination of very large traffic volumes, long-haul operations, and a globally distributed route network. The season and time of day are also important parameters. Winter months and overnight departures tend to produce a larger contrail impact, suggesting that time-based targeting may be more efficient than airport-wide blending.

Our air-quality analysis showed that while in most cases LTO PM and NOx emissions are strongly linked to traffic volume, fleet composition matters as well. In the U.S., Hartsfield Airport in Atlanta emerges as the most significant source of LTO emissions because a large share of operations involve older-generation aircraft with much sootier engines (up to 20 times worse than newer engines). On the other hand, NOx emissions are more strongly influenced by the share of widebody aircraft in the fleet. The LTO emissions at LAX, JFK, and O'Hare were also shown to be significant. In Europe, the relationship between LTO emissions and traffic contained fewer outliers as the fleets in that region are generally newer. As such, given the amount of flight activity, Heathrow, Schiphol Airport, Paris CDG, and Istanbul Airport have sizable LTO emissions.

As shown in Figure 1 and 2, a combination of contrail impact and particulate emissions was used to identify candidate airports for targeted SAF allocation. In the U.S., JFK, LAX, and O'Hare were selected because those airports have a good balance of expected contrail impact reductions and air-quality benefits. In Europe Heathrow, Istanbul Airport, and Paris CDG were selected for the same reasons. In this way, SAF targeting would prioritize airports where it can simultaneously reduce

Figure 1: Contrail impact plotted against LTO PM emissions for U.S. airports

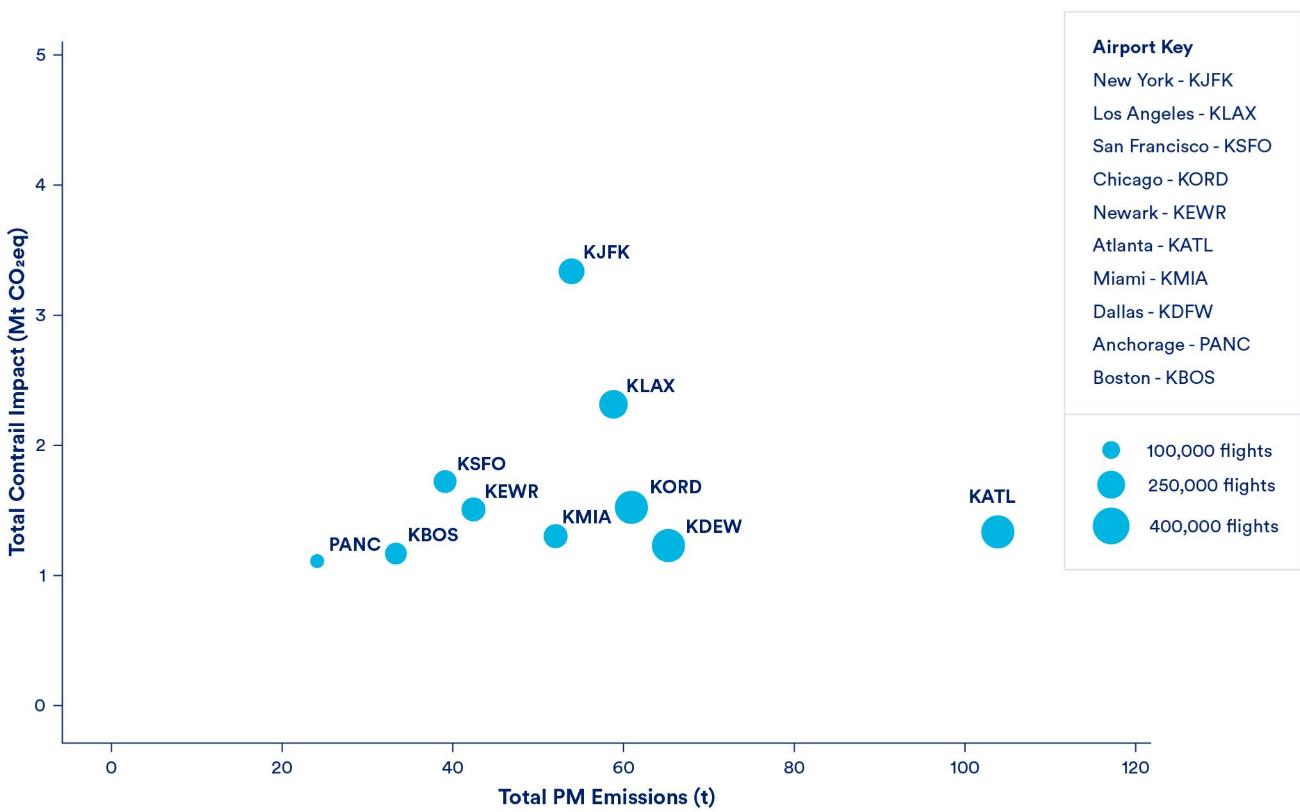
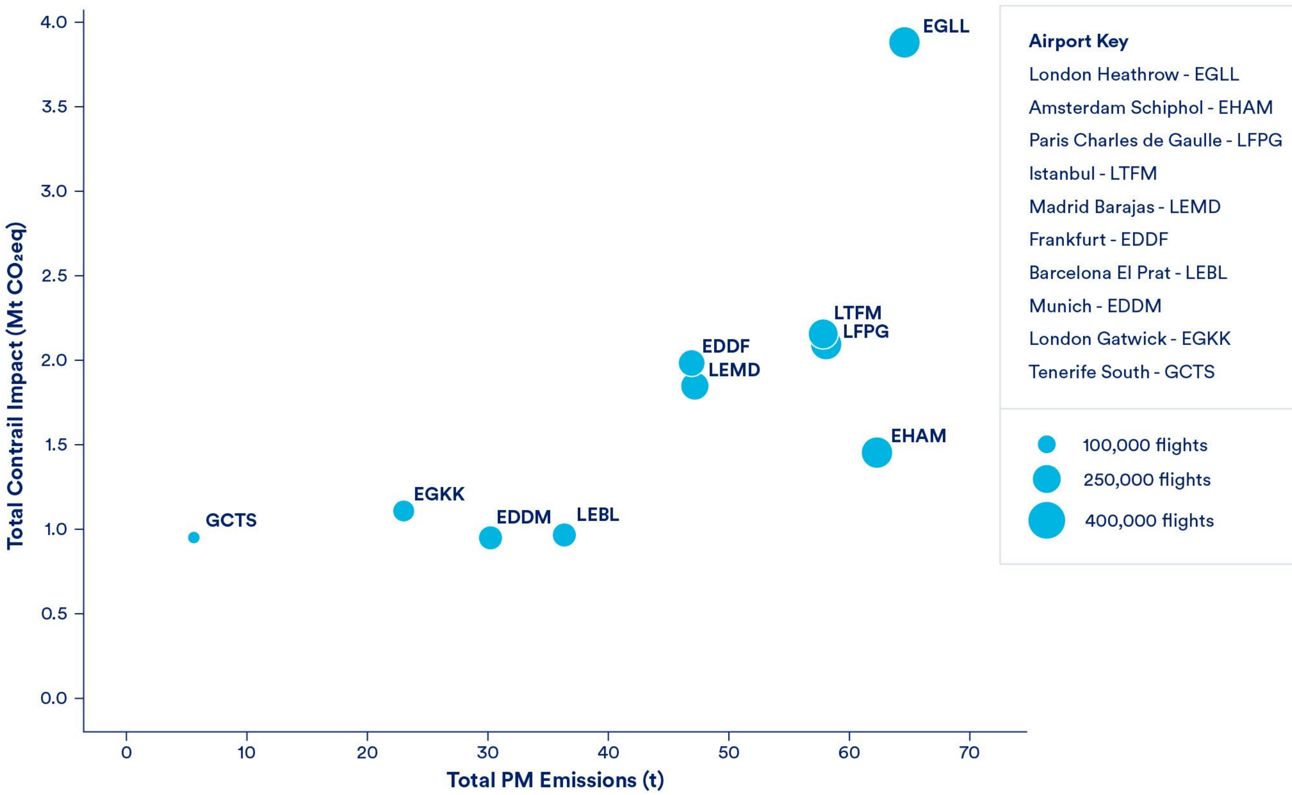


Figure 2: Contrail impact plotted against LTO PM emissions for European airports

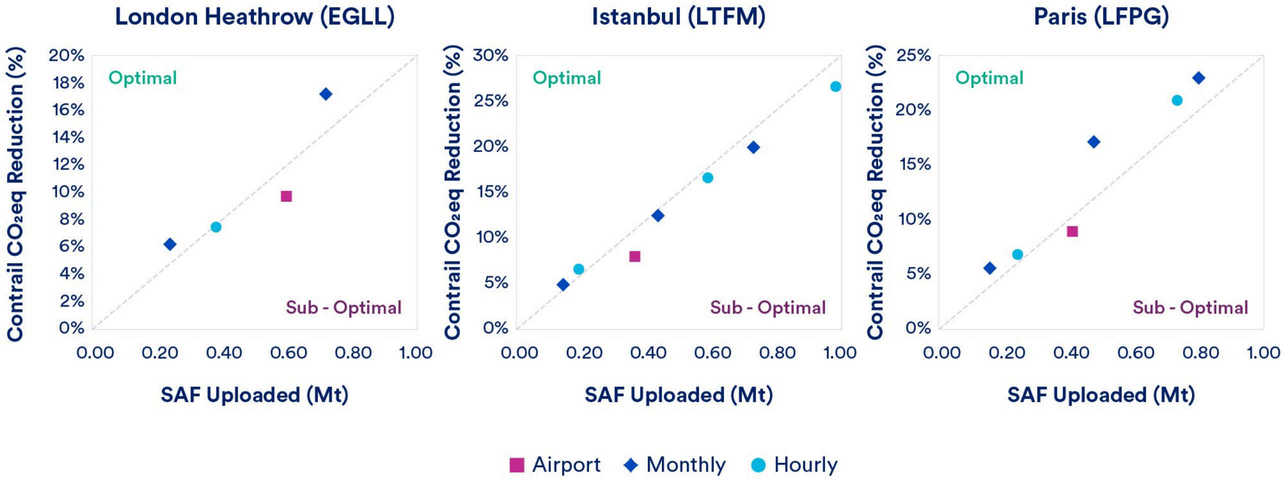


contrail-related warming and harmful local pollution, rather than airports (i.e., Atlanta) where fleet renewal or taxi-efficiency measures may be the more direct solution to ground emissions.

At these six airports, three types of SAF targeting strategies were analyzed: airport-wide targeting, time-based targeting, and flight-based targeting. Airport-wide targeting is the most fuel-intensive, but the simplest from an operational standpoint because the strategy only requires SAF to be blended into the general fuel supply for all departures at a selected airport. Analysis of this approach showed that there are meaningful reductions in both particulate emissions and contrail-related warming if there is enough SAF available to blend at high rates. At a 50% SAF blend, LTO particulate emissions fall by 26 – 28% at all airports, while contrail-related warming was 30 – 34% less at the selected U.S. airports and around 33 – 40% less at the European airports. Time-based targeting allocates SAF to departures during winter months or evening hours. This approach should perform better per ton of available SAF because it focuses on the subset of flights most likely to generate strong warming contrails. The results show this to be true for all airports in the study. Monthly- and hourly-based targeting are compared to airport-wide targeting for the European airports in Figure ES.3.

Targeted SAF allocation can also result in quantifiable health benefits. In the U.S. counties where JFK, LAX, and O'Hare are located, the EPA developed COBRA model was used to estimate the expected avoided premature mortality and monetized health benefits. At a 50% airport-wide SAF blend, the model result showed over $30 million of monetized health benefits at JFK. Larger benefits may be likely in Europe given the broader baseline of air-pollution-related mortality is 2 – 3 times that of the U.S.

Figure 3: Contrail CO_2eq reduction (%) as a function of fuel requirements for airport-wide and two time-based SAF targeting strategies at three European airports



That said, there are logistical challenges that need to be overcome to realize these benefits. As a core policy rationale for SAF adoption (relative to other proposed aviation energy carriers) is that it's a drop-in fuel that can be used in existing aircraft and infrastructure, the following logistical challenges will require careful assessment to determine if this approach makes sense at scale. Targeting SAF to specific airports or specific flights requires blending, storage, and delivery systems that many airports and fuel supply chains are not currently designed to support. Airports served by shared pipeline networks that use onsite hydrant systems to distribute fuel under their tarmacs may face especially high complexity and cost, whereas airports with truck-based fueling or more flexible local infrastructure may be better positioned to pilot targeted SAF allocation. Another potential barrier is transporting SAF to the airports where it would deliver the greatest contrail and particulate matter reductions. Depending on the existing infrastructure, to deliver the SAF blend, the fuel may have to travel a significant distance through sometimes congested pipeline networks, as production facilities are not always near airports.

These logistical challenges, and the options for addressing them, are being actively investigated at Heathrow, where this study has shown there could be major benefits. In 2024, Heathrow uplifted 17% of the globally available SAF and is looking to increase SAF use in 2026. Additionally, the airport may rely on fueling trucks, typically reserved for emergencies or when the fuel demand overwhelms the hydrant system, to deliver SAF to specific flights. Determining if an airport the size of Heathrow can effectively target SAF to flights is a topic of future work. To support this and other SAF targeting efforts, policymakers should explicitly recognize non-CO_2 effects in aviation policy, support further research into targeted allocation strategies, and fund pilot projects at high-impact airports if future research continues to show SAF targeting to be an effective climate impact and air pollution mitigation strategy.

In summary, SAF targeting is an implementable near-term SAF optimization strategy. Every ton of SAF blended with Jet A-1 fuel reduces carbon emissions regardless of where it is uplifted, but by directing limited SAF supplies to the airports where it would have the biggest impact, the industry can realize the largest possible climate and public-health benefits while the supply of SAF is still small. There are logistical and fuel-handling challenges that would need to be addressed, but if those can be overcome, the overall impact of aircraft activity can be meaningfully reduced well before SAF production volumes scale to meet the entirety of aviation fuel demand.

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SECTION 1

Introduction

One of the most difficult challenges we will face on the path to net-zero emissions is the deep decarbonization of the global transportation sector. This is primarily because the optimal decarbonization solution set is highly correlated to the mode of transportation. Many segments of transportation, such as light-duty, on-road vehicles, can be readily electrified. On the other hand, large, heavier vehicles, namely marine vessels and airplanes, are nearly impossible to electrify and must transition from fossil fuel to clean alternatives. We must electrify as much of the transportation sector as is feasible, but for the segments where that is impossible, we need to develop a different set of technologies.

Among the heavier transportation segments, aviation stands out as particularly challenging. In 2024, aviation consumed 13.2 quads (14 EJ) of fuel,[1] nearly all of it kerosene-based Jet A-1, and accounted for 12% of global transportation emissions (1,018 Mt of CO_2). By 2050, according to the IEA Stated Policies scenario,[2] aviation energy consumption is projected to grow to 22.7 quads (24 EJ or approximately 557 Mt of fuel), representing a 71% increase in demand compared to 2024. Due to airframe space and weight constraints, as well as the realities of the existing infrastructure, nearly all of this energy will need to be supplied via drop-in, low carbon intensity aviation fuel. There are other emissions related to the chemical composition of the fuel that must be considered as well. These are typically referred to as non-CO_2 effects.

Combustion of jet fuel results in the emission of various compounds in addition to carbon dioxide; these include water, SO_x, NO_x, CO, non-combusted hydrocarbons, and volatile particulate matter (vPM) as well as non-volatile particulate matter (nvPM). Of particular note are NO_x, which acts as a precursor to ozone, a potent greenhouse gas; and nvPM, or soot. Both nvPM and NO_x are criteria pollutants that adversely affect air quality. Poor air quality has been shown to be strongly correlated with several serious adverse health reactions such as premature mortality and increased risk of lung cancer. According to COBRA modeling data, in 2024, aircraft activity in LA County was responsible for an increase of 196.3 short tons of PM over ambient levels, resulting in approximately $190M of health damages.[3] At high altitudes, these same pollutants, specifically nvPM, can function as condensation nuclei for contrail formation. Contrails trap heat and contribute to additional warming that adds to aircraft CO_2 emissions.

1 IEA (2025), *World Energy Outlook 2025*, Table A.2b, https://iea.blob.core.windows.net/assets/9753df19-0a71-422a-b725-012c555763b3/WorldEnergyOutlook2025.pdf

2 Ibid.

3 EPA, CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA), https://www.epa.gov/cobra

A transition to sustainable aviation fuel (SAF) would reduce greenhouse gas emissions while minimizing non-CO_2 effects. Sustainable aviation fuel is often used as a catch-all term for aviation decarbonization solutions, but is best understood as a complex set of technologies all designed to produce a low carbon intensity (CI), drop-in substitute for Jet A-1. The SAF available today is biofuel, though producing synthetic SAF, where aviation fuel is synthesized from clean hydrogen and captured CO_2, is technologically feasible. Either type of SAF has been shown to be better for the climate, both in terms of greenhouse gas emissions and non-CO_2 effects. Lifecycle analysis models show that depending on the production methodology, SAF achieves anywhere from a 26 – 94% reduction in CO_2 emissions and results in 50 – 70% less soot emissions than 100% Jet A-1. Given this data, a transition from conventional jet fuel to SAF should have profound positive effects on GHG emissions, contrail formation, and local air quality; yet currently, the amount of SAF blended into conventional jet fuel is too small to allow for these benefits to be realized.

Sustainable aviation fuel remains scarce and expensive, commanding just a 0.7% market share in 2025.[4] Biogenic and non-biogenic feedstock availability, SAF refinery capacity, as well as SAF blending and distribution infrastructure all must rapidly scale while costs are brought more in line with conventional jet fuel in order to reduce the sector's climate impact. The size of the challenge to bring this suite of technologies to bear suggests that it will be many years, likely decades, before alternative fuels are ready to fully replace fossil jet fuel.

This paper presents an idea on how to optimize SAF use during this decades-long scale up of SAF technologies. Rather than indiscriminately blending SAF into jet fuel at a small percentage over a large number of airports, SAF should be targeted at airports with comparatively large non-CO_2 effects to maximize co-benefits. Each ton of SAF uplifted will have the same impact on CO_2 emissions regardless of location, but targeting that ton to specific airports can also minimize contrail and adverse health impacts. We utilized information from Estuaire, a data company specialized in the climate impact of aviation and non-CO_2, to determine which airports have flight activity that contributes most to contrail formation and poor local air quality, then analyzed the benefits of targeting SAF to those locations.

4 IATA (2025), *Global Feedstock Assessment for SAF Production Outlook to 2050*, https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf

SECTION 2

Impact of Airport Emissions on Local Air Quality

In many ways, air travel is one of the most convenient forms of modern transportation. Airports are often located near major population centers to allow the largest number of people access to thousands of locations around the world. The downside of such convenience is that millions of people, estimated at 40 million in the U.S.[5] and 51 million in Europe,[6] live in areas affected by health-damaging aircraft-related pollution.

Studies have attempted to quantify the adverse health impact of these emissions on surrounding populations. Modeling from Yim et al. estimated that emissions from global civil aviation was responsible for 16,000 premature deaths per year, with 87% attributable to PM2.5 or smaller ultrafine particulate matter (UFP).[7] Another study found that significant impacts are likely to go beyond airport workers, finding that over 65,000 California students spend 1 – 6 hours a day during the school year near enough to an airport to be affected by aircraft emissions.[8] As illustrated in Figure 4, the mass of non-CO_2 emissions in aircraft engine exhaust is significant. Compared to on-road heavy vehicles, this is the same amount of NO_x and twice as much PM as 150 diesel trucks driving for an hour.[9]

5 UW, *Clearing the air,* https://www.ce.washington.edu/news/article/2021-06-15/clearing-air

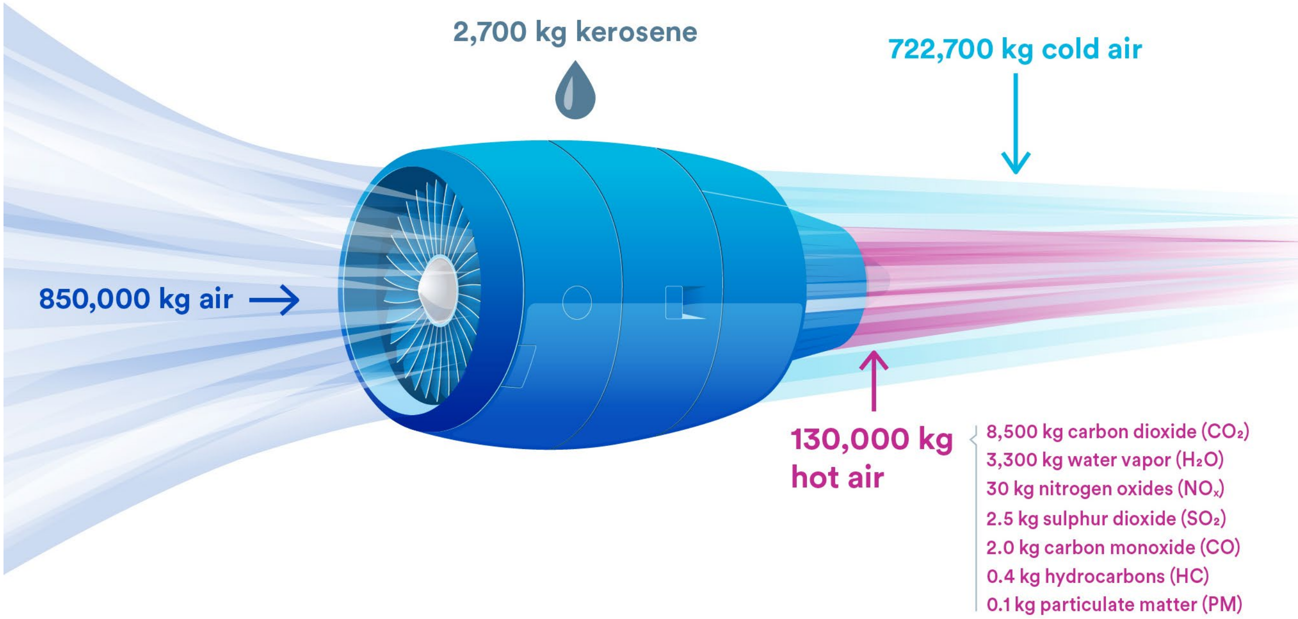
6 Simple Flying, *Can Living Next To An Airport Impact Your Health?,* https://simpleflying.com/airport-proximity-health/

7 S. H. L. Yim, et al. (2015), *Global, regional and local health impacts of civil aviation emissions*, https://iopscience.iop.org/article/10.1088/1748-9326/10/3/034001/pdf

8 R. C. Henry, et al. (2019), *Estimating potential air quality impact of airports on children attending the surrounding schools*, https://www.sciencedirect.com/science/article/abs/pii/S1352231019303516

9 California Energy Commission (2023), *In-Use Emissions Testing and Activity Profiles for On-Road Heavy-Duty Vehicles*, See Figure 43 and Figure 45 for emissions per mile driven for goods movement on diesel trucks (assuming 50 miles/hour), https://www.energy.ca.gov/sites/default/files/2023-03/CEC-500-2023-002.pdf

Figure 4: Exhaust emissions from a representative two-engine airplane per hour of flight[10]



Of the non-CO_2 emissions, particulate matter (PM), whether emitted directly or formed as a result of other emissions, is the primary cause of adverse health impacts from aviation emissions. The size of particulate matter varies based on the makeup of the exhaust and the type of engine, but generally PM is classified as PM10 (≤10μm in diameter), PM2.5 (≤2.5μm), and UFP (≤0.1μm). Aircraft engines typically emit PM2.5 and UFP; however, UFPs can coalesce into larger diameter PM2.5, muddling the picture. PM can harm nearly every organ, but it most commonly affects the respiratory and cardiovascular systems. UFPs are considered particularly dangerous since their small size allows them to bypass the body's natural defenses. The danger of PM, even in small quantities, is a topic discussed in several epidemiological studies.

Schraufnage[11] states in a study that exposure to particulate matter causes inflammation that arises in response to noxious material on the surface of particles interacting with the cells in the lung. This can cause coughing and reduced airflow, sometimes resulting in hospital admissions, especially for those with asthma. UFP typically does more harm and has been shown in some studies to cause emphysema.[12] He et al. reported[13] similar findings after studying the effect of aircraft emissions near Los Angeles International Airport (LAX). By analyzing the chemical composition of urban air samples and comparing that to emissions from an aircraft engine test stand, the study was able to isolate the ambient PM in the urban environment from those associated with aircraft emissions. Laboratory testing of a culture of lung tissue exposed to aircraft exhaust PM showed a non-trivial increase in inflammation.

10 European Environment Agency (2019), *European Aviation Environmental Report 2019*, https://www.easa.europa.eu/sites/default/files/eaer-downloads/219473_EASA_EAER_2019_WEB_HI-RES_190311.pdf

11 D.E. Schraufnagel (2020), *The health effects of ultrafine particles*, https://www.nature.com/articles/s12276-020-0403-3.pdf

12 J. Yang (2017), *Importance of indoor dust biological ultrafine particles in the pathogenesis of chronic inflammatory lung diseases*, https://pmc.ncbi.nlm.nih.gov/articles/PMC5735549/pdf/eht-32-e2017021.pdf

13 R-W He, et al. (2018), *Pro-inflammatory responses to PM0.25 from airport and urban traffic emissions*, Figure 4, https://www.sciencedirect.com/science/article/abs/pii/S0048969718320394

Adverse cardiovascular effects are also of concern. Another study[14] from Schraufnagel points out PM can cause systemic inflammation and coagulation changes, predisposing diseases such as endothelial dysfunction, vascular inflammation, and atherosclerosis. Lammers et al.[15] carried out a study on health subjects near Amsterdam's Schiphol Airport in order to determine if there was a demonstrable effect on people that were otherwise healthy. In this study 21 healthy, non-smoking volunteers between 18 and 35 were repeatedly exposed for 5 hours to air near Schiphol. The study concluded that the exposure to airport UFP was correlated with a drop in the test group's lung and cardiac function.

Other engine exhaust emissions are not direct contributors to adverse health impacts but often help create an environment conducive to PM formation. A study from the International Civil Aviation Organization (ICAO) notes that NO_x generates long-lived ozone which descends to the surface where it promotes the formation of particulate matter.[16] SO_x is also an important component of ambient PM formation while being an irritant to the human respiratory system. A report from Transport & Environment also calls out VOCs and CO emissions in exhaust as substances that can cause premature mortality in sufficient concentration.[17]

Science clearly shows that the interaction between these particles and the body can be severe. However, as the general public only spends a few hours near an airport a handful of times a year, another key area of research is the extent these particles disperse into nearby communities. Looking at the California South Coast Air Quality Management District, for example, aviation was responsible for 193 short tons of PM2.5 emissions in 2022 according to the California Air Resources Board.[18] The biggest source of aviation activity in that area was from commercial flights in and out of LAX. Hudda et al. tracked the dispersion of emissions from LAX to determine the extent the PM propagated to surrounding communities.

The results, a subset of which are shown in Figure 5, showed that when winds blew from the west a two-fold increase in particle number concentration over baseline concentrations was measured 16 kilometers away from the airport.[19] This 2014 report shows that airport emissions have a major impact on air quality, sometimes increasing freeway particle concentrations by more than 75,000 particles/cm^3, where the wind direction largely determined the extent communities are affected. Westerly wind is common for that area, making the communities east of the airport hotspots for PM-related pollution.

14 D.E. Schraufnagel, et al. (2019), *Air Pollution and Noncommunicable Diseases*, https://journal.chestnet.org/article/S0012-3692(18)32723-5/fulltext

15 A. Lammers, et al. (2020), *Effects of short-term exposures to ultrafine particles near an airport in healthy subjects*, https://www.sciencedirect.com/science/article/pii/S016041201934797X

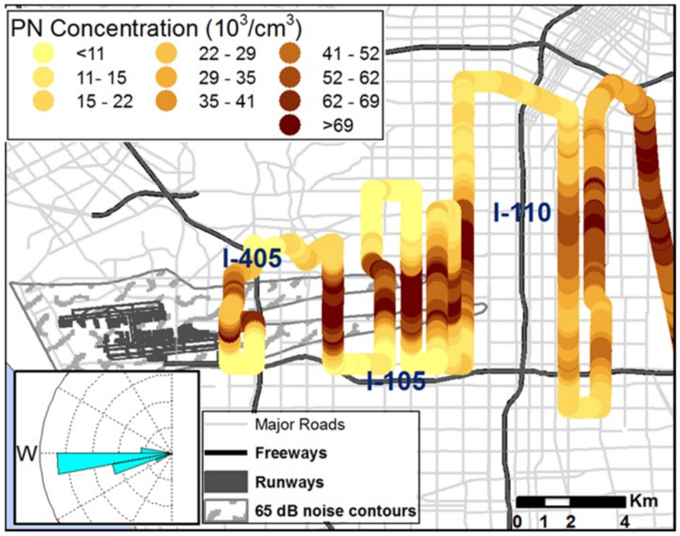
16 ICAO (2024), *Assessment of the impact of airport emissions on local levels of NO_x and human health; impacts of cruise emissions of NO_x on human health; impacts of cruise NO_x on climate*, Section 3, https://www.icao.int/sites/default/files/sp-files/environmental-protection/Documents/ScientificUnderstanding/ICAO-CAEP12-Assessment-Report-on-impacts-of-aviation-NOx-emissions-on-air-quality-human-health-and-climate.pdf

17 CE Delft (2024), *Health Impacts of Aviation UFP Emissions in Europe*, https://cedelft.eu/wp-content/uploads/sites/2/2024/06/CE_Delft_220396_Health_Impacts_of_Aviation_def.pdf

18 CARB (2024), *California Aircraft Emissions Inventory (CAI2024) Technical Documentation*, https://ww2.arb.ca.gov/sites/default/files/2024-10/CAI2024%20-%20Main%20Document_Final1021_ada.pdf

19 N. Hudda, et al. (2014), *Emissions from an International Airport Increase Particle Number Concentrations 4-fold at 10 km Downwind*, https://pmc.ncbi.nlm.nih.gov/articles/PMC4215878/pdf/es5001566.pdf

Figure 5: Particle number concentration near LAX[20]



On the other U.S. coast, Hudda et al. conducted a similar study at Boston Logan International Airport. These results were even more wind dependent, as the wind direction often changes in the Boston area. When the wind was blowing from the direction of the airport, this study found a 50% increase in particle number in the neighboring city of Chelsea relative to other wind directions.[21] The situation near London Heathrow Airport is similar. A study from Stacey et al. shows that UFP particle count increased by a factor of nearly 7 during a southerly wind, the direction originating from the airport.[22] Overall, the data clearly shows that airport emissions can adversely affect communities near major airports, but the local wind patterns play heavily into which communities bear the brunt of the impact.

Given the number of variables at play quantifying adverse health impacts due to ambient air quality is challenging and often contains a level of uncertainty, even if the science on the impact of PM on the human body and the extent that these particles can move downwind is clear. That said, there have been efforts in the U.S. and EU to estimate these health damages. A MIT led study by Yim et al. modeled air quality with GEOS-Chem and CMAQ, then used those results with a published WHO concentration–response function to compute premature deaths from lung cancer and cardiopulmonary disease due to PM. Their results showed an average of 650 (range: 290 – 1,300) premature deaths from landing and take-off operations (LTO) in the U.S. and 1,800 premature deaths (range: 1,100 – 2,600) in Europe.[23] The health damages from these premature deaths are estimated in the study to cost $3.07B and $4.09B[24] respectively.

20 Ibid.

21 N. Hudda, et al. (2014), *Aviation Emissions Impact Ambient Ultrafine Particle Concentrations in the Greater Boston Area*, https://pmc.ncbi.nlm.nih.gov/articles/PMC5650728/pdf/nihms875009.pdf

22 B. Stacey, et al. (2023), *Emissions of ultrafine particles from civil aircraft: dependence upon aircraft type and passenger load*, Table 1, https://www.nature.com/articles/s41612-023-00477-1.pdf

23 S. H. L. Yim, et al. (2015), *Global, regional and local health impacts of civil aviation emissions*, Table 2, https://iopscience.iop.org/article/10.1088/1748-9326/10/3/034001/pdf

24 Monetary value in 2006 U.S. dollars

SECTION 3

Mitigating Emissions from the Aviation Sector

Aviation emissions can largely be separated into two categories: greenhouse gas emissions (primarily CO_2) and non-CO_2 effects, most notable of which are NO_x and PM. Both categories must be addressed if emissions from the sector are to be effectively mitigated.

Greenhouse gas emissions are the biggest contributor to aviation-related warming and will be primarily mitigated by transitioning to SAF, with a small contribution from aircraft and engine efficiency improvements. The term SAF is used to describe a wide range of fuels but can be broadly separated into biogenic SAF (bio-SAF) and synthetic SAF (syn-SAF), both of which are drop-in substitutes for conventional jet fuel and require no major modifications to aircraft engine design or fuel delivery infrastructure. Fossil kerosene-based Jet A-1 emits 88.7 grams CO_2eq per megajoule on average[25] and lifecycle analysis models indicate that SAF generally achieves anywhere from a 26 – 94% reduction in CO_2 emissions,[26] depending on the production method. In the EU, for a fuel to qualify as SAF, the LCA must show at least a 50 – 70% CI reduction.[27]

Currently commercialized bio-SAF production makes use of waste biogenic feedstocks such as used cooking oils, animal fats, or vegetable oils through a conversion process known as hydro-processed esters and fatty acids (HEFA). The alcohol-to-jet process, where ethanol is the primary feedstock, as well as Fischer-Tropsch synthesis of gasified biomass (municipal solid waste, forest residues, energy crops) are other emerging bio-SAF production methods.

Bio-SAF production is expected to grow as demand for low-CI fuel increases, but the growth of the global aviation industry is expected to far outpace that supply. Biofuels are inherently limited by feedstock constraints and sustainability concerns related to the indirect effect of biofuel production on agriculture and land use, whereas rapid aviation growth is expected, especially in developing countries. Given this, the IEA expects aviation energy demand to reach 22.7 quads (24 EJ) by 2050 while modern liquid bioenergy supplies are only projected to reach 11.3 quads (12 EJ) in their ambitious Net Zero Emissions scenario.[28] Even if all of that liquid bioenergy is used in the form of SAF, it would not be enough to meet the aviation sector's projected energy demand, and the gap between supply and demand would be even larger if some of that liquid bioenergy goes to on-road, marine, and non-transportation sectors. A previous report from CATF (2022)[29] detailed how exclusive reliance on biofuels to decarbonize aviation is unlikely to succeed.

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25 L. Jing, et al. (2022), *Understanding variability in petroleum jet fuel lifecycle greenhouse gas emissions to inform aviation decarbonization*, https://www.nature.com/articles/s41467-022-35392-1

26 K. Moriarty, et al. (2021), *Port Authority of New York and New Jersey Sustainable Aviation Fuel Logistics and Production Study*, https://docs.nlr.gov/docs/fy22osti/80716.pdf

27 Under the Directive (EU) 2023/2413 Renewable Energy Directive (RED III), SAF must meet EU sustainability and greenhouse gas criteria. Renewable Fuels of Non Biological Origin (RFBOs) must achieve at least 70% GHG emissions savings compared to the fossil fuel comparator of 94 gCO_2e/MJ, while biofuels must achieve 50–65% savings depending on the production installation date. Commission Delegated Regulation (EU) 2023/1184 defines the methodology for RFNBOs.

28 IEA (2025), *World Energy Outlook 2025*, Table A.2c, https://iea.blob.core.windows.net/assets/9753df19-0a71-422a-b725-012c555763b3/WorldEnergyOutlook2025.pdf

29 Merchant, et al. (2022), *Decarbonizing Aviation: Challenges and Opportunities for Emerging Fuels*, Section 3, https://www.catf.us/resource/decarbonizing-aviation-challenges-and-opportunities-for-emerging-fuels/

Decarbonizing the rest of the aviation sector will need synthetic SAF produced with clean hydrogen and captured CO_2, direct hydrogen combustion, and potentially, in some niche cases, electricity. A 2024 report from CATF[30] finds that while there are significant challenges with these alternative fuels, these technologies could fill the gap and alongside bio-SAF deeply decarbonize the sector.

In addition to greenhouse gas emissions, non-CO_2 effects must also be addressed. Non-CO_2 emissions in engine exhaust, particularly PM, worsen local air quality and damage the health of those living near airports. Separately, in certain locations at cruise altitudes known as ice-supersaturated regions (ISSR), PM emitted from the engine allows for the formation of cirrus clouds made of ice crystals. Known as contrails, these clouds trap a significant share of Earth's outbound infrared radiation, according to some studies adding about 33% additional warming on top of aviation GHG emissions.[31]

There are two ways to mitigate particulate matter emissions. The first method is to use newer aircraft engines. New engines that use low soot combustors as well as optimized engine geometry are less polluting. An example of such an engine is the CFM Leap-1B engines on the 737MAX. These engines emit orders of magnitude less PM than older engines like the CFM56 on the 757. Regardless, engines can be in service for up to 50,000 flight cycles or 35 years,[32] making it slow and difficult to solve air quality issues by relying exclusively on these types of advancements.

The second method is to transition to a cleaner burning fuel, such as low-aromatic kerosene and SAF. Aromatic content, which is strongly correlated with nvPM emissions, varies due to the characteristics of the crude oil input. Current ASTM standards set a maximum limit of 25% by volume for aromatic content, with an actual average content of 15 – 20% in jet fuel sold in Europe. U.S. average aromatic content in jet fuel is about 12%. A minimum aromatic content of 8% has also been established by ASTM to achieve certain fuel properties and to protect engine seals. Hydrotreating conventional jet fuel or blending it with SAF will lower aromatic content and reduce soot in the exhaust. This paper focuses on SAF, rather than low aromatic jet fuel, as SAF has both CO_2 and non-CO_2 benefits.

Although it is a drop-in fuel, the underlying chemical composition of SAF is slightly different than Jet A-1. SAF contains 1 – 2%[33] more hydrogen by mass that acts to saturate aromatic compounds in conventional jet fuel. The formation of nvPM, or soot, is primarily associated with aromatic content since these compounds promote soot nucleation in fuel-rich zones within the combustion chamber. As such, combustion of 100% SAF should emit little nvPM. This was shown by Durand et al. who conducted measurements of nvPM emissions for jet fuel with various hydrogen concentrations. That study found that increasing hydrogen content by mass from 13.8% (conventional jet fuel) to 15.2% (100% HEFA SAF) reduced the mass of nvPM in the exhaust from approximately 300 mg/kg_{fuel} to nearly zero during standard main engine start operations.[34] Moore et al. showed that SAF blends also substantially reduce soot formation. That testing resulted in 50 – 70% lower soot emissions when combusting a 50% blend of Jet A-1 and SAF compared to 100% Jet A-1.[35]

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30 T. Walker, et al. (2024), *Decarbonizing Aviation: Enabling Technologies for a Net-Zero Future*, Sections 4, 5, 6, https://www.catf.us/resource/decarbonizing-aviation-enabling-technologies-net-zero-future/

31 Aviation Impact Accelerator (2024), *Five Years to Chart a New Future for Aviation*, Page 12 https://report.aiazero.org/report/2030%20Sustainable%20Aviation%20Goals%20Full%20Report.pdf

32 Simple Flying (2023), *How Many Engines Do Airliners Go Through In A Typical Lifespan?*, https://simpleflying.com/how-many-engines-do-airliners-go-through/

33 R. Teoh, et al. (2022), *Supporting Information for Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits*, Page S11 in Table S6, https://pubs.acs.org/doi/suppl/10.1021/acs.est.2c05781/suppl_file/es2c05781_si_001.pdf

34 E. Durand, et al. (2021), *Impact of fuel hydrogen content on non-volatile particulate matter emitted from an aircraft auxiliary power unit measured with standardized reference systems*, Figure 2(b), https://www.sciencedirect.com/science/article/abs/pii/S0016236120326338

35 R. H. Moore, et al. (2017), *Biofuel blending reduces particle emissions from aircraft engines at cruise conditions*, https://www.nature.com/articles/nature21420

For air quality, any method that reduces PM will have a positive effect. Arter et al. found that using a 50% SAF blend would result in a 19% decrease in PM2.5 health damages per ton of fuel burned at U.S. airports.[36] But for contrails, the situation is more complex. . Lower nvPM emissions (or soot) will reduce, but not eliminate, contrails. Additionally, other particles, such as organic vPM, are relatively unaffected by aromatic content and can serve as nuclei for contrail formation in a soot-lean environment. On the other hand, blending SAF will have a positive effect on sulfur-related vPM emissions, as SAF contains little sulfur in comparison to Jet A-1. In the 2024 ECLIF3 test campaign, the data showed HEFA-SAF contained 700ppm of sulfur while Jet A-1 contained 21,100 ppm.[37] This can vary based on the SAF production method and the type of crude refined into jet fuel.

These complicating factors are the reason why a recent study showed that combusting a jet fuel blend that is 34% SAF reduces soot by approximately 40%, while the change in total emitted particle number falls short of that, only dropping about 20%.[38] As discussed in a recent CATF report (2025) on contrails,[39] a fuel transition to cleaner fuels like SAF will have to occur alongside engine improvements and flight deviation schemes aimed at avoiding ISSR to completely eliminate contrail-related warming. Flight deviation has seen recent success as illustrated in Sankar et al.,[40] which found that 69.3% of contrail-related warming was eliminated with ISSR avoidance operations.

Of all the solutions to mitigate aviation climate impacts, SAF is the only one that has a positive impact on all types of emissions. Combusting SAF greatly reduces GHG and PM emissions, the result of which reduces CO_2-related warming, contrail related warming, and improves local air quality.

36 C. A. Arter, et al. (2021), *Air quality and health-related impacts of traditional and alternate jet fuels from airport aircraft operations in the U.S.*, https://www.sciencedirect.com/science/article/pii/S0160412021005833

37 IATA (2025), *The non-CO_2 climate co-benefit of SAF and other fuels with low aromatic and sulfur content*, Table 2, https://www.iata.org/globalassets/iata/publications/sustainability/saf-non-co2-benefits.pdf

38 S. Schmitt, et al. (2026), *Emission Impacts from Sustainable Aviation Fuel Blends via Engine Plume Measurements and Predictive Modeling at the Airport Scale*, Figure 6, https://pubs.acs.org/doi/10.1021/acs.energyfuels.5c05413

39 R. Sanchez and T. Walker (2025), *Aviation Non-CO_2 Effects: Strategies for Minimizing Contrail Climate Impact*, https://www.catf.us/resource/aviation-non-co2-effects-strategies-for-minimizing-contrail-climate-impact/

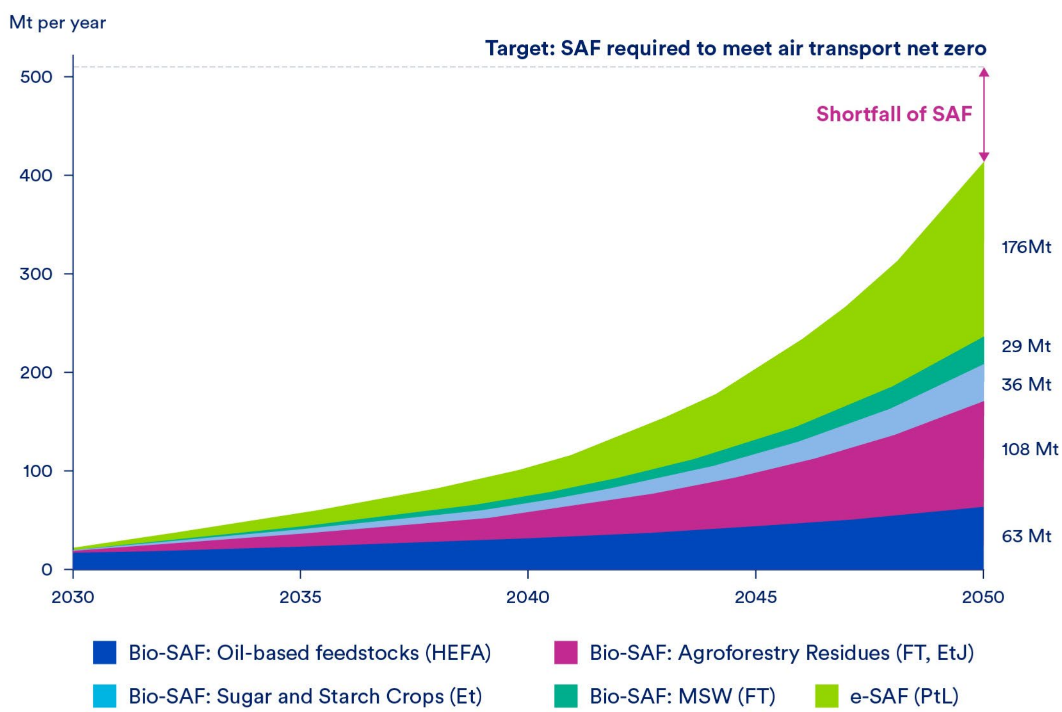
40 T. Sankar, et al. (2026), *Efficacy of Scalable Airline-led Contrail Avoidance*, https://arxiv.org/abs/2603.06909

SECTION 4

Current State of the Sustainable Aviation Fuel Market

Growing global SAF supply to meet aviation demand is an enormous challenge that the fuel market must tackle in order to decarbonize aviation. According to the estimate of SAF production potential by the International Air Transport Association (IATA) shown in Figure 6, SAF production volumes could grow by approximately 20 times between 2030 and 2050, while several new SAF production technologies come online.[41]

Figure 6: Estimated global SAF supply 2030 – 2050[42]



[41] IATA (2025), *Global Feedstock Assessment for SAF Production Outlook to 2050*, Chart 11, https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf

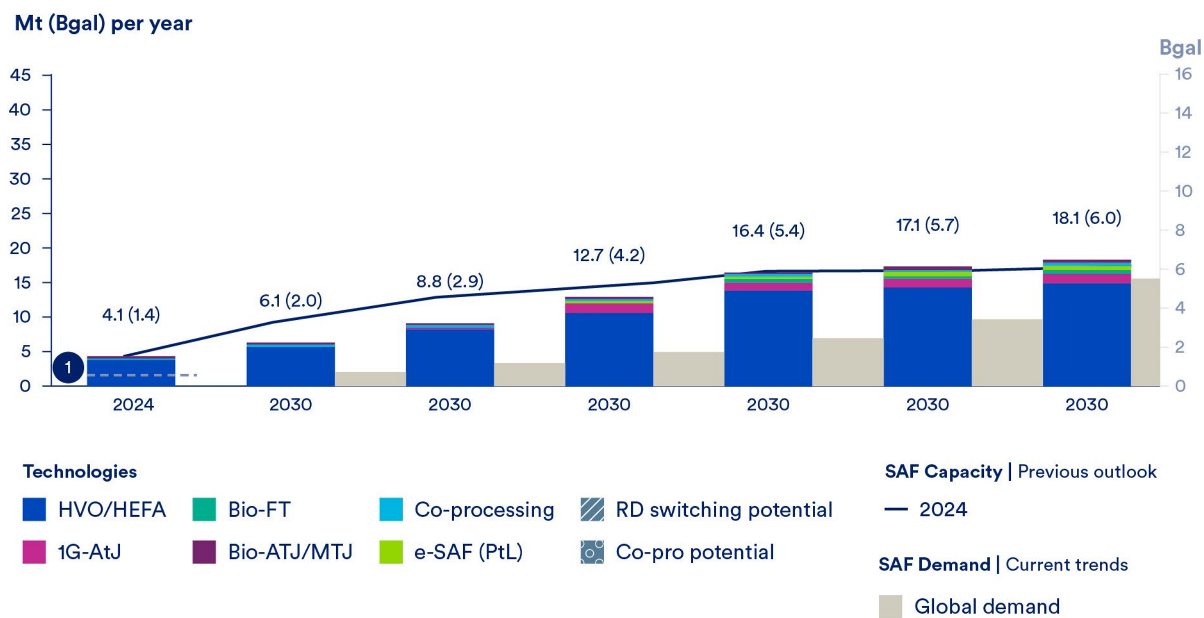
[42] Ibid.

Before 2030, SAF volumes should continue to be dominated by HEFA-based bio-SAF; whereas, in 2050, IATA projects forest residue FT and alcohol-to-jet to make up the majority of bio-SAF supply, with HEFA just making up 15% of the total. The total amount of bio-SAF in the IATA 2050 projection, 236 Mt (9.6 quads/10.1 EJ) is similar to the IEA projection for total transportation biofuel supply (8.5 quads/9 EJ),[43] lending credence to these projections. Notably, IATA is projecting syn-SAF to scale rapidly as well, expecting it to make up 42% of the total SAF supply in 2050. The shortfall noted in the figure will need to be made up by an even more rapid syn-SAF scale up, direct combustion of hydrogen, or continued use of fossil jet fuel combined with carbon removal technologies (CDR) to reduce net emissions to near zero.

Over the next few years, the industry must lay the groundwork, in terms of refining capacity, blending infrastructure, and technology development, so that this market can quickly scale after 2030 as forecasted by IATA.

A report from SkyNRG that looks at the next few years projects moderate bio-SAF growth from 6.1 Mt (0.23 quads/ 0.24 EJ) in 2025 to 18.1 Mt (0.67 quads/ 0.7 EJ) in 2030, the vast majority of it produced with HEFA.[44] The SkyNRG 2030 projected quantities nicely line up with the starting point in the IATA forecast. Figure 7 also notes that currently the global demand for SAF, from mandates and other climate regulations (shown in grey), is still small enough that SAF is being over supplied. That said, post-2030 these demands are expected to rapidly increase to satisfy stated decarbonization goals. The report highlights that co-processing of renewable feedstocks and renewable diesel production switching to SAF could be technologies that jump-start the necessary post-2030 scale up.

Figure 7: Current global SAF supply through 2030[45]



[43] IEA (2025), *World Energy Outlook 2025*, Table A.2c, https://iea.blob.core.windows.net/assets/9753df19-0a71-422a-b725-012c555763b3/WorldEnergyOutlook2025.pdf

[44] Sky NRG (2025), *SAF Market Outlook*, https://skynrg.com/safmo25/

[45] Sky NRG (2025), *SAF Market Outlook*, Figure 3 cut off at 2030, https://skynrg.com/safmo25/

A SAF outlook report led by RMI also came to similar conclusions. That report projects 6 – 8.2 billion gallons (18.1 – 24.7 Mt) of SAF per year by 2030, stating that the lower end of that projection is more realistic.[46] Of note, both of these projections show significant HEFA dominance in 2030, something that will need to change, due to limited supply of waste vegetable oil feedstocks, if SAF is to scale. Of the 344 Mt (14 quads/14.7 EJ)[47] of jet fuel consumed in 2025, just 0.23 quads (0.24 EJ), or 1.4%, of that demand could be met by SAF, given current production capacity. In reality, only 0.7% of jet fuel demand is being produced and uplifted as SAF[48] due to cost[49] and other constraints.

This data makes it very clear that for the foreseeable future, SAF will be in limited supply and expensive, only capable of replacing a small amount of fossil fuel use. The question thus becomes: how can we maximize the benefit that can be derived from the limited amount of SAF that will be available?

The GHG benefits of SAF will occur no matter where the SAF is uplifted; however, contrail benefits depend on uplifting SAF at an airport with a preponderance of flights through ISSR. For example, in the North Atlantic, a region prone to ISSR formation (especially in the winter), Teoh et al. showed that targeting the approximately 2% of flights likely to generate warming contrails with a 50% SAF blend would result in a 9-15 times greater climate benefit when compared to blending that same volume of SAF across all flights in the region.[50] Furthermore, location also matters to air quality as SAF uplifted at airports near major population centers will more strongly affect health outcomes. All of this suggests that optimizing SAF use by targeting high impact U.S. and European airports could allow the industry to maximize SAF co-benefits while reducing greenhouse gas emissions.

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46 RMI (2024), *Market Outlook October 2024 Sustainable Aviation Fuel*, https://saf.rmi.org/assets/pdf/market-outlook-oct-2024.pdf

47 IATA (2025), *Global Outlook for Air Transport Trade, AI, and the energy transition*, Table 7, https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport-december-2025/

48 IATA (2025), *Global Feedstock Assessment for SAF Production Outlook to 2050*, https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf

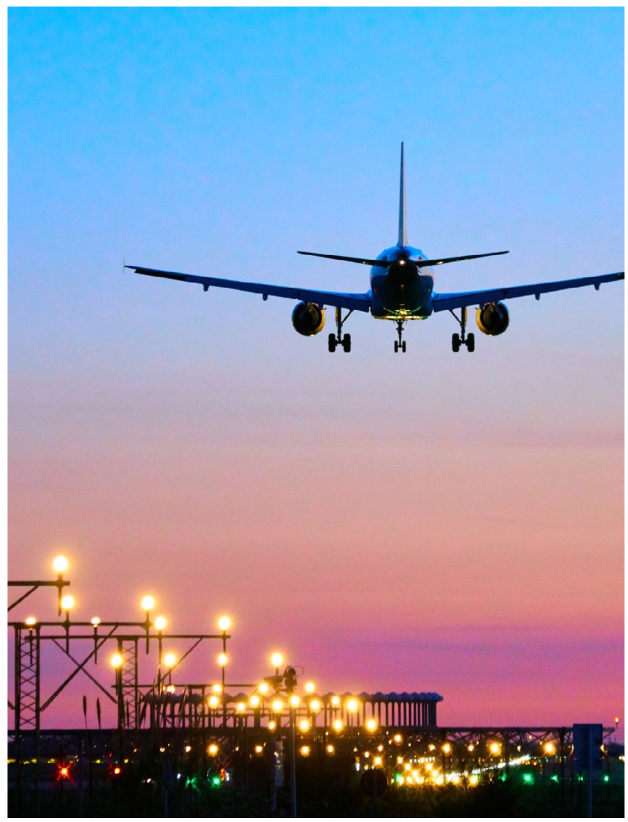
49 According to the EASA, in 2025 the reference price of conventional jet fuel was around €640/ton, approximately a third of the €1,925/ton for aviation biofuels. Advanced biofuels and synthetic SAF pathways were significantly higher, reaching €2,760/ton and up to €7,520/ton respectively. EASA (2025), *2025 Aviation Fuels Reference Prices for ReFuelEU Aviation*, https://www.easa.europa.eu/en/downloads/143282/en

50 Teoh, et al. (2022), *Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits*, https://pubs.acs.org/doi/pdf/10.1021/acs.est.2c05781

SECTION 5

Quantifying Aircraft Non-CO_2 Effects Associated with Major Airports

Maximizing climate benefits, specifically reducing contrail-related warming and improving air quality, during the transition from conventional jet fuel to SAF requires a comprehensive, quantitative assessment of global flight activity to determine which airports should be allocated large amounts of the cleaner fuel. This assessment focuses on U.S. and European airports, a total of 16.6 million flights, which together accounted for approximately 45% of global flight activity and 42% of CO_2 emissions in 2024. This data as well as the information in Sections 5 and 6 of this report are from Estuaire, a data company specialized in the climate impact of aviation and non-CO_2, that worked with CATF on this analysis.[51]



Contrail impact as well as PM and NOx emissions during landing and take-off operations (LTO) were computed for the flights in this study by considering weather (ECMWF ERA5), humidity, aircraft engine types, and engine emission indices. Contrail impact was computed using the latest industry model, COCIP[52],where the climate metric was GWP100 with an assumed contrail warming efficacy factor, in literature set between 0.38[53] – 0.42[54]. LTO emissions were computed using an established ICAO methodology.[55] A simplified flowchart illustrating the different parts of the analysis is shown in Figure 8.

51 Estuaire, https://estuaire.aero/

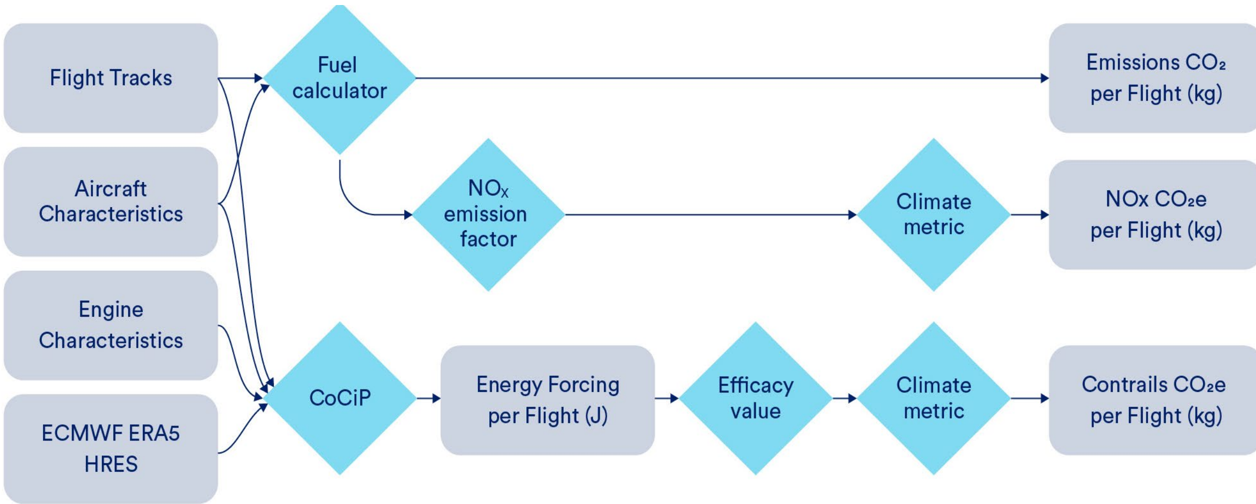
52 Deutsches Zentrum für Luft- und Raumfahrt (DLR) (2009), *A Contrail Cirrus Prediction Tool*, https://elib.dlr.de/68002/1/Schumann_CoCiP_TAC2_DLR_FB_2010_10_p_69_74.pdf

53 M. Bickel (2023), *Climate Impact of Contrail Cirrus*, https://elib.dlr.de/197602/1/Climate_Impact_of_Contrail_Cirrus-Marius_Bickel.pdf

54 D. S. Lee, et al. (2021), *The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018*, Figure 3, https://www.sciencedirect.com/science/article/pii/S1352231020305689

55 ICAO (2020), *Doc 9889 Airport Air Quality Manual*, https://www.icao.int/sites/default/files/2025-04/9889_cons_en.pdf

Figure 8: Methodology for computing aircraft emissions[56]



Some of the limitations of the modeling include handling of lean-burn engines, as COCIP can underestimate the PM emissions (in particular, the vPM emissions) from these engines, resulting in lower contrail and air quality impacts than reality. Incomplete ADS-B flight tracking, requiring the use of average emissions and contrail impact values, was a minor issue, as well as general uncertainty associated with contrail-related warming calculations. Contrail modeling uncertainty comes from the difficulty of predicting relative humidity at high altitudes, the evolution of contrail plumes being computed with simplified assumptions, the difficulty of calculating nvPM emissions at cruise altitudes, and the necessity of short- and medium-term atmospheric weather adjustments (i.e., correcting for the occurrence of fewer natural cirrus clouds).[57] Reducing uncertainty associated with quantifying the climate impact of contrails is an active field of study.

Contrail Impact

Surface warming due to contrail formation adds to the greenhouse effect caused by CO_2 emissions from the aviation sector. Contrail cirrus has a similar impact on our climate as natural cirrus clouds that form at high altitudes and reflect a portion of incoming solar radiation back to space while trapping a significant share of Earth's outbound infrared radiation. The net effect is additional warming. Energy forcing or radiative forcing is a measure of the difference between incoming and outgoing radiation of the Earth and is commonly used to quantify the greenhouse effect. Computing cumulative radiative forcing is a useful way to compare the effects of various changes to the atmosphere, such as those caused by phenomena like contrails. The radiative forcing index (RFI) is the ratio of total aviation climate impact, including contrails, to CO_2 emissions.

56 NO_x CO_2eq was not a focus of this study, but tons of NO_x and PM as determined by the fuel calculator were the primary emissions of concern with regards to air quality.

57 In recent studies, modeling uncertainty regarding the impact of contrails on surface warming is approximately ±70%.

Contrail radiative forcing varies year-to-year, and quantification of the resulting warming is highly dependent on the timeframe and the climate metric: under longer timeframes, the climate impact appears less. For example, Toeh et al.[58] used GWP100 to compute the contrail impact relative to CO_2 emissions (RFI minus 1) for the years 2019, 2020, and 2021 to be 0.32, 0.27, and 0.28, respectively. The same study from Toeh et al. re-computed contrail impact for 2021 using GWP20 and found that it was 1.02. In other words, when Toeh et al. assessed the global warming impact of contrails over a 100-year period, they found that contrails accounted for 28% additional aviation-related warming in 2021; when the contrail global warming potential was assessed over a 20-year period instead, contrails accounted for 102% additional aviation-related warming in 2021. With contrails, GWP20 will always be larger because contrail cirrus are short-lived phenomena. Other studies may use different climate metrics, some preferring a different timescale or a different metric altogether, such as global temperature change potential (GTP). This paper uses GWP100 for all calculations.

Figure 9 shows the total RFI for the U.S. and European regions for all flights in the Estuaire database. While an impact (RFI minus 1) of 0.16 in the U.S. is lower than is seen in some contrail studies, the overall impact for both regions is considered to be similar to what is generally seen in literature, especially considering the inherent uncertainties with contrail calculations as discussed above. In any case, 16 – 24% additional surface warming added to the significant GHG impact from aviation is something that must be addressed in order to achieve our climate goals.

Figure 9: U.S. and European contrail impact

Scope	Flight Count	Distance Flown (Mkm)	CO_2 Impact ($MtCO_2eq$)	Contrail Impact ($MtCO_2eq$)	RFI
United States	9,234,406 (25%)*	15,114 (25%)*	222 (23%)*	37 (26%)*	1.16
Europe	7,400,112 (20%)*	11,624 (19%)*	185 (19%)*	45 (31%)*	1.24

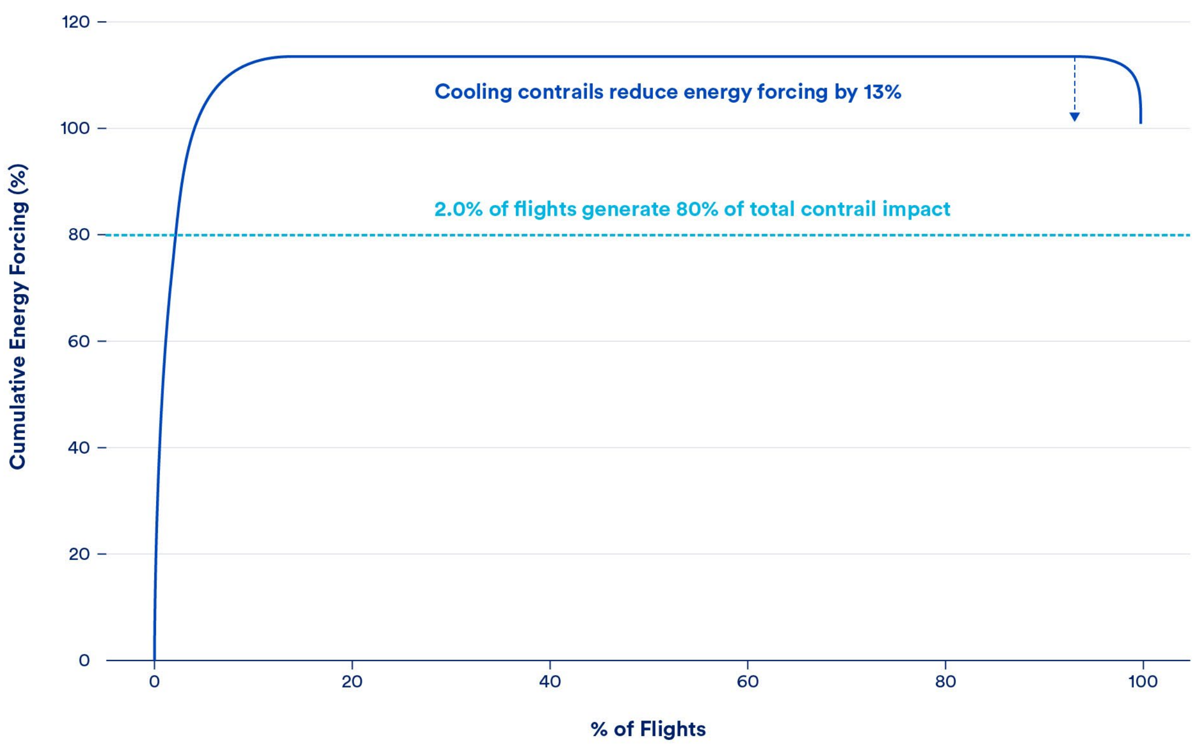
* Percent of world

58 R. Teoh, et al. (2023), *Global aviation contrail climate effects from 2019 to 2021*, Table 1, https://acp.copernicus.org/articles/24/6071/2024/acp-24-6071-2024.pdf

Despite the sizeable climate impact, only a small number of flights generate contrails. This is illustrated in Figure 10. In 2024, just 2% of flights generated 80% of total contrail radiative forcing. Cooling contrails – that is, contrails that reflect solar radiation out of the atmosphere into space – are rare in comparison to warming contrails, only reducing the overall warming impact of contrails by 13%.

This data, denoted as the 80% pareto impact, fundamentally supports strategies that focus on the most impactful routes, particularly ISSR avoidance and SAF targeting. Identifying the airports from which these flights originate and allocating large amounts of SAF to those locations could help eliminate much of this additional warming. Optimizing SAF distribution in such a way would maximize the co-benefits of SAF use, reducing non-CO_2 effects like contrails while decarbonizing the sector.

Figure 10: Contrail impact as a function of percentage of flights



U.S. Airports

By total flights, the U.S. accounts for about 25% of global aviation activity. That said, only a small portion of those flights will contribute to contrail-related warming. Contrail formation is dependent on flying through ISSR at cruise altitudes, making when and where a flight departs, as well as its route, a key factor. Using the information in the Estuaire database and the calculation methodology laid out in Figure 8, we identified the ten U.S. airports where departing flights had the largest contrail impact. These results are listed in Table 1.

The top airports in the results are John F. Kennedy International Airport (KJFK or JFK) in New York City, Los Angeles International Airport (KLAX or LAX), and San Francisco International Airport (KSFO or SFO).

Generally, busy airports that originate lots of long-distance flights are good locations to target SAF to reduce the incidence of contrail formation enroute. There is another factor as well: aircraft route distribution. For example, JFK, which leads the list in Table 1, is only 5th in terms of total departures, but it is 2nd in terms of average flight distance. Comparing JFK to LAX, the average flight distances are similar and LAX has around 50,000 more departures, yet because 44.9% of flights from JFK are international, flights from JFK tend to cover a larger global extent and thus are more likely to encounter ISSR. Another note is that the 80% pareto impact for JFK is much higher than the global average of 2%. More flights leaving the airport are generating contrails, another reason why it should be a good location for SAF targeting.

Table 1: Top 10 U.S. airports where departing flights had the largest contrail impact (2024)

"Dom" and "Int" refer to domestic or international destinations, respectively.

Airport		Number Departing Flights	Climate Impact				Route Info		
			CO_2 ($MtCO_2eq$)	Contrail ($MtCO_2eq$)	RFI	80% Pareto Impact (%)	Average Distance Flown (km)	Dom (%)	Int (%)
KJFK	New York	226,063	15.2	**3.4**	1.23	6.2	3,049	55.1	44.9
KLAX	Los Angeles	276,087	17.2	**2.4**	1.14	3.6	2,977	75.7	24.3
KSFO	San Francisco	179,111	10.9	**1.8**	1.16	3.9	2,906	77.8	22.2
KORD	Chicago	377,615	11.1	**1.6**	1.14	2.0	1,705	86.6	13.4
KEWR	Newark	199,729	7.1	**1.6**	1.22	3.2	2,230	72.6	27.4
KATL	Atlanta	390,310	9.1	**1.4**	1.15	1.9	1,505	88.5	11.5
KMIA	Miami	224,893	8.6	**1.4**	1.16	3.1	2,281	50.8	49.2
KDFW	Dallas	362,609	8.4	**1.3**	1.16	1.7	1,641	88.5	11.5
PANC	Anchorage	81,829	8.9	**1.2**	1.14	6.2	3,532	79.8	20.2
KBOS	Boston	175,091	5.2	**1.2**	1.23	2.8	2,086	83.2	16.8

Figure 11 shows more clearly that JFK is an outlier in terms of contrail impact. Most of the airports are clustered near the red line, which is a visual representation of the RFI. The average RFI for U.S. airports is 1.16, meaning that contrails are adding 16% of additional warming to CO_2 emissions. The dashed line, which has a slope of 0.16, shows that compared to the other airports, flights that depart from JFK generate significantly more contrails than expected.

The reason can be seen on a map of the most common routes departing JFK, shown in Figure 12. Of the 44.9% of flights that are international, a large percentage fly over the North Atlantic Ocean enroute to Europe. The North Atlantic is an area known for ISSR formation, especially during the winter months. On the other hand, flights from LAX, of which only 24.3% are international, will travel through this region far less frequently.

Figure 11: Relative impact of contrails vs. CO_2 for the U.S. (2024)

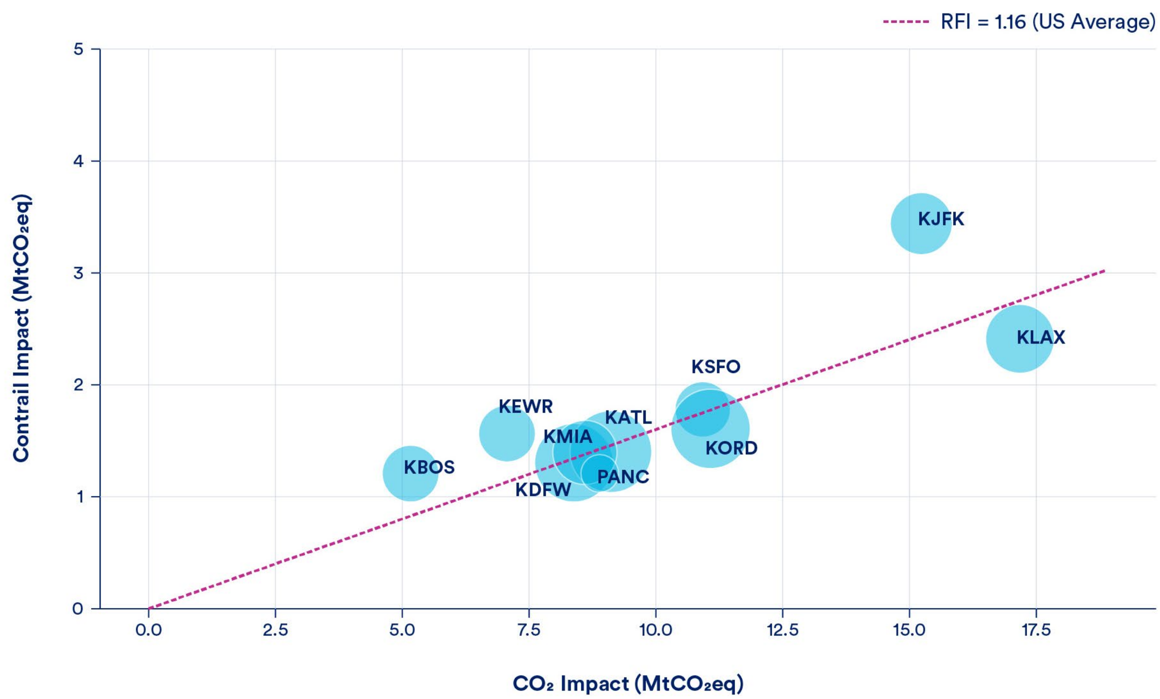
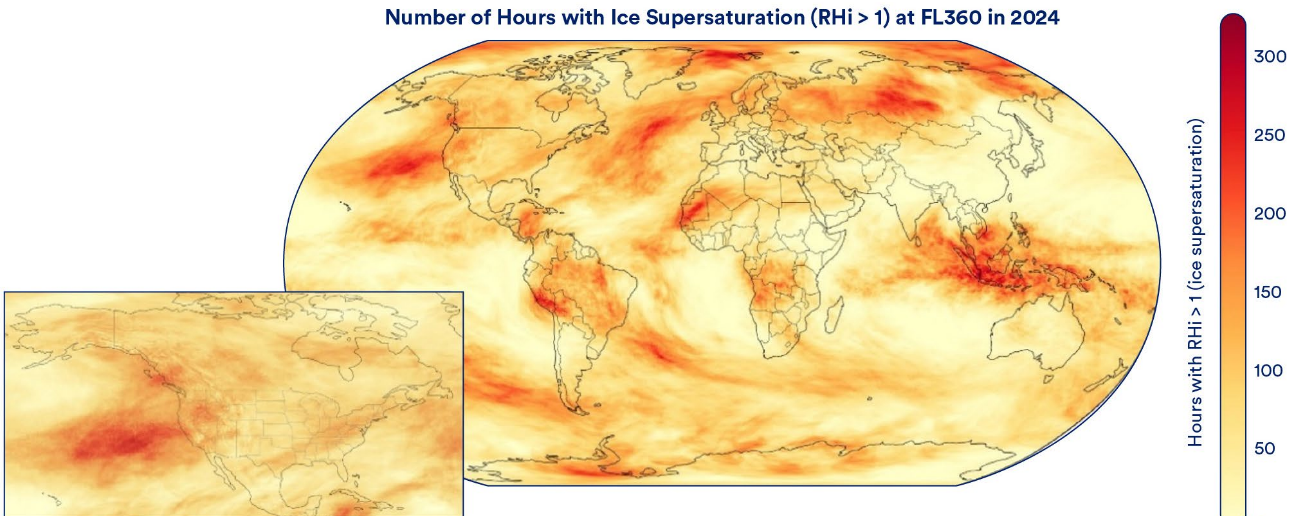


Figure 12: Route map for JFK. Many of the international flights are to Europe

The importance of the North Atlantic region is depicted in Figure 13, which shows the number of hours when the air was supersaturated with ice at 36,000 feet during December 2024. It's important to note that this ISSR map is for a single flight level during a single month; however, it still is useful as a qualitative illustration of the distribution of ISSR during winter for a very common cruise altitude. There is a clear ISSR hotspot in the North Atlantic which will strongly affect a significant number of international flights from JFK. There are other hotspot regions as well, including: just off the California coast, the north-western part of Africa, and a large area in south-east Asia. Flights that leave LAX heading to Asia could be affected by two of these hotspots, but with 75.7% of LAX flights departing to U.S. locations, the impact is limited enough to put total contrail-related warming behind JFK.

Figure 13: Tropospheric weather map depicting the number of hours with ice supersaturation at 36,000 ft in December 2024



Time of departure is another factor that affects the contrail impact of different U.S. airports. Contrail CO_2eq is higher at night because contrails only have cooling impacts during daytime when sunlight might be reflected. If an aircraft creates a contrail during an overnight flight, it will result in additional surface warming.

For most airports, the majority of flights leave in the morning through afternoon, but the flights that do leave during the late afternoon or evening are responsible for the vast majority of contrail impact. Figure 14 illustrates this behavior for three airports selected from the list of ten. A SAF targeting strategy that prioritizes uplifting SAF at night may have some merit.

Figure 14: Contrail impact and flight count by departure hour for select U.S. airports

The red line is the number of departures and the blue bars the contrail CO_2eq during a given hour.

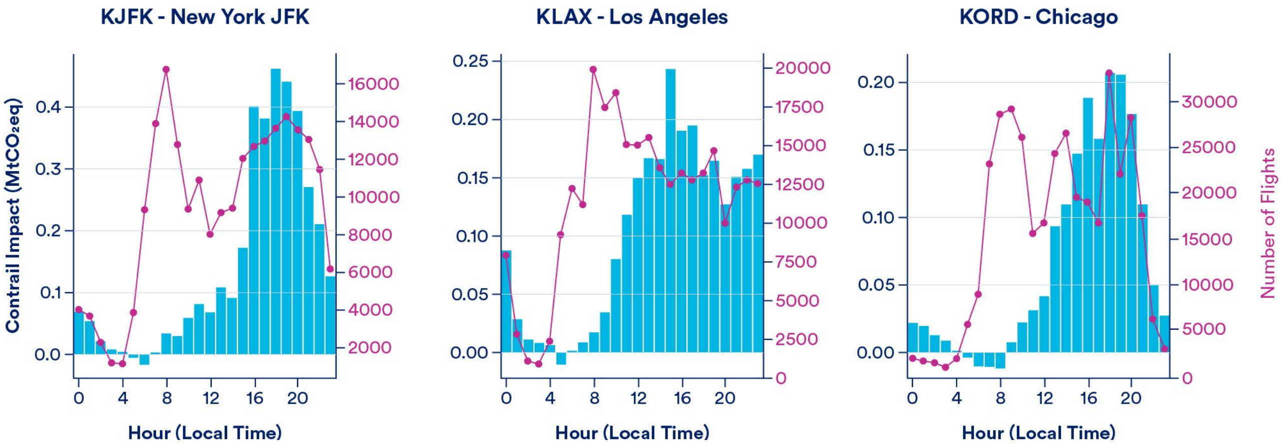


Figure 15: Contrail impact and flight count by departure month for select U.S. airports

The red line is the number of flights and the blue bars the contrail CO_2eq during a given month.

One last consideration is the time of year. As stated above, ice-supersaturated regions form more commonly in the winter months. For many U.S. airports, departures peak in the summer, drop before rising again during the year-end holidays, then drop off sharply during January and February. That said, as shown in Figure 15, ISSR are so prevalent during the northern hemisphere's winter months that the biggest contrail impact is during that time period despite the lack of flights as compared to summer. For JFK and LAX, for example, the contrail CO_2eq in December is over triple that of July even though there are several thousand less departures.

Finally, there is Miami International Airport (KMIA or Miami Airport), which given its southern location was a surprising inclusion in the list. The reason is due to the number of flights from Miami Airport that occur during the winter months, so much so that the shape of the flight activity data is opposite that of JFK and LAX. This unique distribution leads to flights from Miami Airport being surprisingly prone to contrail formation. A SAF targeting strategy that focuses on uplifting SAF during the winter months may also have some merit.

European Airports

A similar analysis was carried out for airports in Europe and the United Kingdom. The metrics analyzed were the same as U.S. airports, with the only exception being international vs. domestic substituted for intra-Europe vs. extra-Europe, as this provides a more direct comparison of activity inside versus outside of each region. Overall, in 2024 the contrail impact in Europe was significant, especially on a per flight basis. The RFI in the region was 1.24, or 33% larger than it was for the U.S., even though there were 25% fewer departures.

The airports with departing flights that had the biggest contrail impact in the results shown in Table 2 are London Heathrow (EGLL or Heathrow), Istanbul (LTFM or Istanbul Airport), and Paris Charles de Gaulle (LFPG or Paris CDG). Contrail impact related to flight activity at these ten airports is strongly linked to average flight length, the one exception being Tenerife South Airport in the Canary Islands (GCTS or Tenerife). In that case, while flights leaving that airport have the biggest RFI, there are not enough departures for Tenerife to place higher on the list.

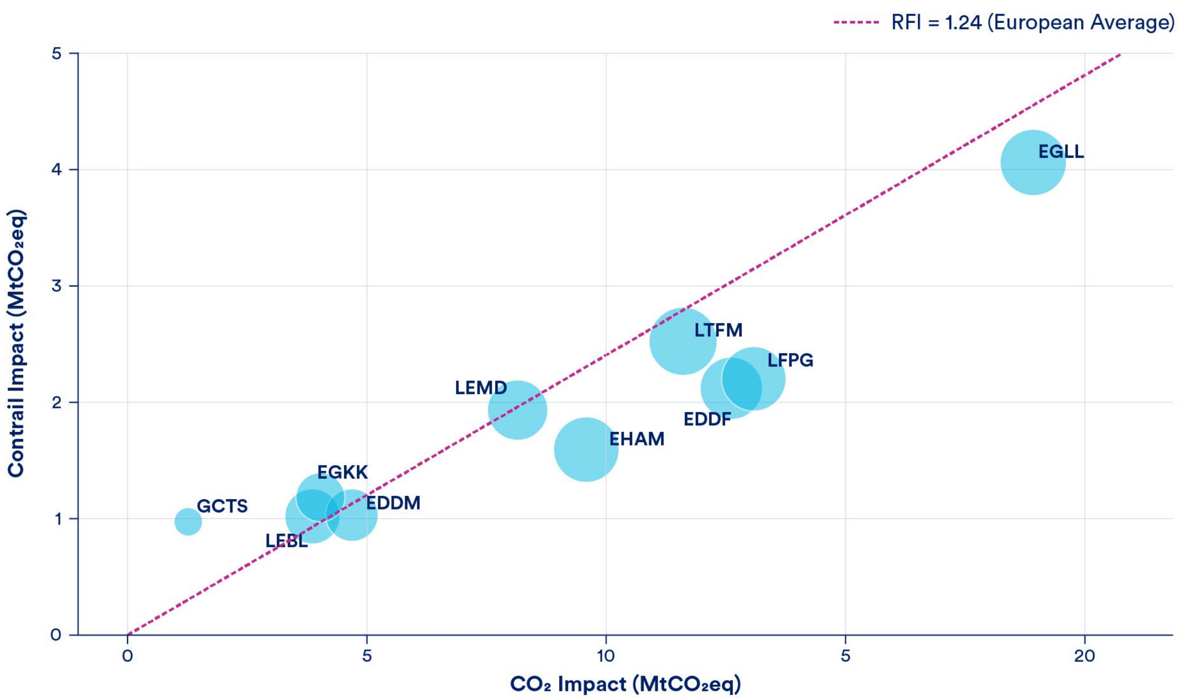
Table 2: Top 10 European airports where departing flights had the largest contrail impact (2024)

Airport		Number Departing Flights	Climate Impact				Route Info		
			CO_2 ($MtCO_2eq$)	Contrail ($MtCO_2eq$)	RFI	80% Pareto Impact (%)	Average Distance Flown (km)	Intra-EU (%)	Extra-EU (%)
EGLL	London Heathrow	238,310	18.9	**4.10**	1.21	7.1	2,945	59.0	41.0
LTFM	Istanbul	256,650	11.6	**2.50**	1.22	5.0	2,300	56.2	43.8
LFPG	Paris Charles de Gaulle	227,687	13.1	**2.20**	1.17	4.5	2,266	66.1	33.9
EDDF	Frankfurt	213,587	12.6	**2.10**	1.17	4.3	2,269	72.6	27.4
LEMD	Madrid Barajas	202,004	8.2	**1.93**	1.24	4.0	2,131	79.0	21.0
EHAM	Amsterdam Schiphol	235,018	9.6	**1.60**	1.17	3.2	1,911	81.5	18.5
EGKK	London Gatwick	132,077	4.0	**1.20**	1.29	4.0	1,846	82.2	17.8
EDDM	Munich	154,935	4.69	**1.03**	1.22	2.9	1,607	86.9	13.1
LEBL	Barcelona El Prat	167,641	3.87	**1.02**	1.26	2.5	1,487	89.7	10.3
GCTS	Tenerife South	42,421	1.27	**0.97**	1.76	9.5	2,919	99.0	1.00

Also of note is that airports with flights destined to locations predominantly within Europe are near the bottom of the list. This may be because the formation of ISSR hotspots directly over Europe is not always the case. Figure 13 shows nearby hot spots to be in the North Atlantic, north-west Africa, and in Russia for December 2024, but outside of a few locations in Scandinavia or the Baltics, generally ISSR were not concentrated over significant portions of Europe. Lastly, the 80% pareto impact was above the global average for all airports, including some like Heathrow which were several times the average of 2%. By all measures, the Europe region was a contrail hotspot in 2024.

While the overall impact was considerable, no single airport in Europe had an extremely outsized contrail impact like was seen with JFK. In Figure 16 the biggest outlier as compared to the dashed red line, which is a visual representation of the RFI, was Tenerife. Similar to Miami Airport, this airport is a unique case as it is in the Spanish Canary Islands,[59] which is located near the December 2024 north-western Africa ISSR, and has many more departures during the winter months. As the location of an ISSR is weather dependent, this may not be the case in a different year. Although Heathrow is near the dashed-red line, flights departing from Heathrow generate a lot of contrail-related warming, in fact, more than any other airport in the world. The reason can be explained by the route pattern for Heathrow shown in Figure 17.

Figure 16: Relative impact of contrails vs. CO_2 for Europe



[59] While interesting from a contrail perspective, the Canary Islands are exempt from the SAF mandate and bunkering obligations in RefuelEU given their condition of "European Outermost Region".

Figure 17: Routes from Heathrow

The routes are very evenly globally distributed.

The flights leaving Heathrow are numerous, fly long distances, and are extremely well globally distributed. This implies that a large number of these flights will fly through many of the ISSR hotspots shown in Figure 13. As such, while the Heathrow contrail impact is not outsized as compared to aircraft CO_2 emissions, both impacts are extremely large. For flights departing Heathrow, the combination of CO_2 emissions and the impact of contrails together, are the biggest single contributor to aviation-related warming, a fact likely to continue into the future considering the planned expansion.[60]

Shown in Figure 18 and 19, time of departure and season matter with European airports as well. Due to the number of departures leaving for the U.S., the time period with a large contrail impact extends to earlier in the day as compared to U.S. airports. The seasonality effect is stronger as well, especially at Heathrow where there are four months with a contrail impact over 0.5 Mt CO_2eq. Once again, the strong contrail impact during the winter months as well as during the evening is a reason to explore SAF targeting. Targeting may even be more effective in Europe given that the contrail impact is larger while showing a similar distribution with respect to departure time.

60 Heathrow, *Our Proposal for Expanding Heathrow*, https://www.heathrow.com/content/dam/heathrow/web/common/documents/expansion/expanding-heathrow-proposal-summary.pdf

Figure 18: Contrail impact and flight count by departure hour for select European airports

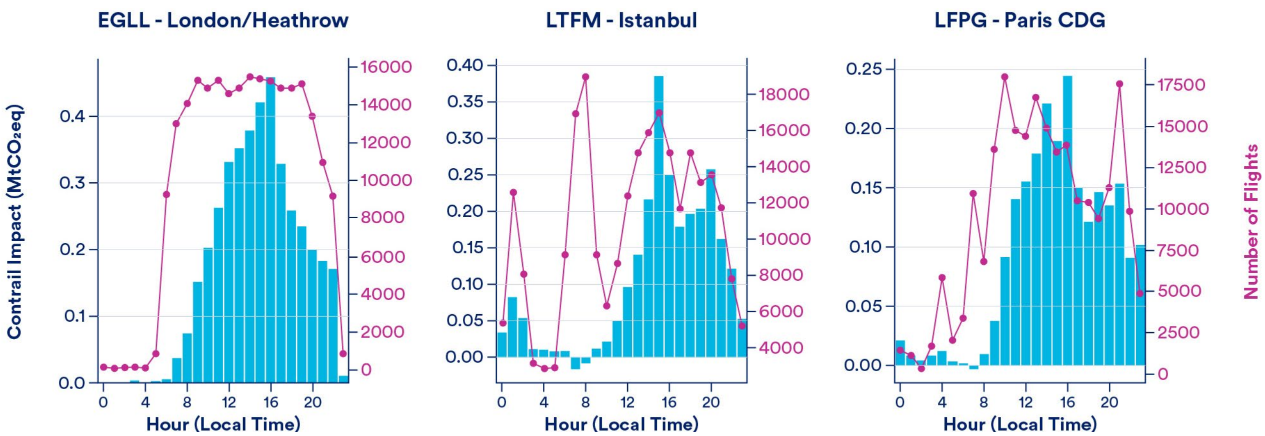
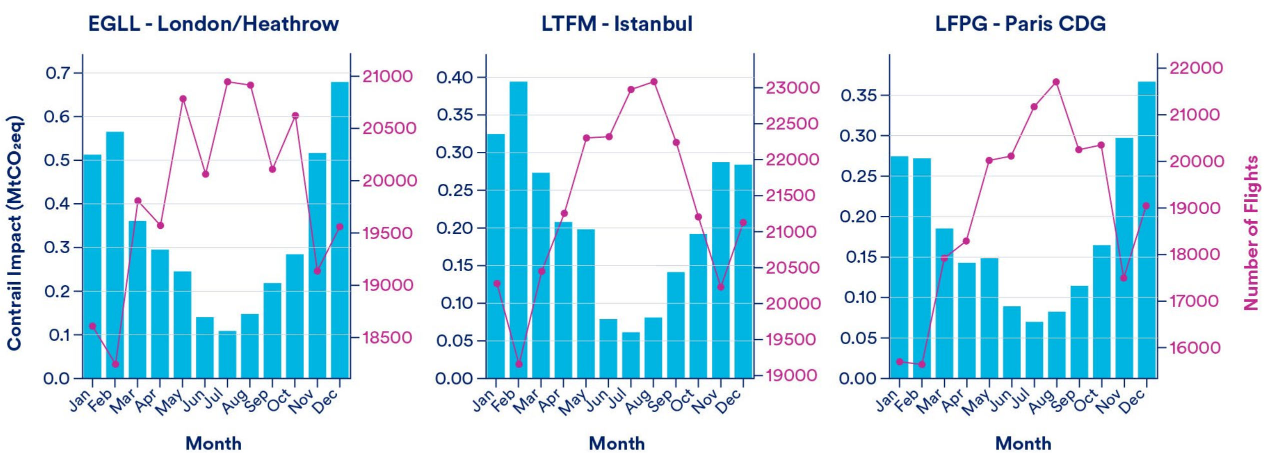


Figure 19: Contrail impact and flight count by departure month for select European airports

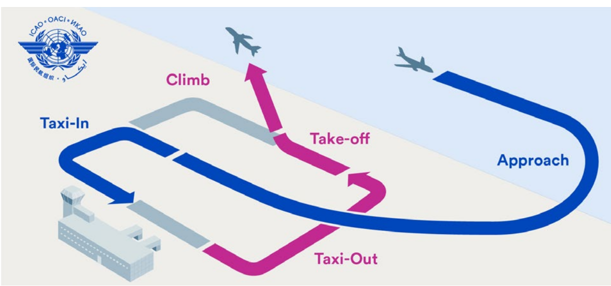


Air Quality Impact

Aircraft emissions adversely affect the ambient air quality for people who live and work near airports, especially those in communities that are downstream of prevailing winds. Poor air quality, specifically airborne particulate matter, can contribute to respiratory and cardiovascular issues that in severe cases may lead to serious illness or premature death. This is discussed in detail in Section 2. Particulate matter in the engine exhaust can function as the nuclei for ice crystals that grow into contrails at cruise altitudes while negatively impacting air quality when emitted during landing and take-off operations. NO_x emissions are a factor as well, as NO_x generates long-lived ozone which, on top of being a GHG, promotes the formation of PM near the surface. The data on the amount of PM and NO_x emitted near airports during LTO will be critical to understanding how much airport flight activity contributes to poor air quality in surrounding communities.

This analysis relies on established ICAO methodologies to compute LTO emissions. To that end, ICAO breaks LTO into 5 modes: taxi-in, taxi-out, take-off, climb, and approach. Each of these modes has a standard thrust setting and an average time spent in that mode. This information is summarized in Figure 20. Of these modes, taxiing is responsible for most of the emissions. Accounting for the difference in taxi-in versus taxi-out times at LAX, a California Air Resources Board (CARB) report found that for every additional minute of total taxi time, 4.7% more PM and 1.6% more NO_x is emitted on average.[61] As this is the longest part of LTO, reducing taxi time is one of the ways a portion of emissions at the airport can be mitigated without fuel switching.

Figure 20: ICAO landing and take-off operation definitions[62]



Operational Phase	Engine Mode	Thrust Setting	ICAO Average Time in Mode
Taxi Out	Idle	7%	26 min
Taxi In			
Take-off	Take-off	100%	0.7 min
Climb-Out	Climate-Out	85%	2.2 min
Approach	Approach	30%	4 min

Particulate matter emissions were computed by taking the fuel flow rates for the engines on a given flight in the Estuaire database, multiplying that by the thrust setting and amount of time in each mode, the latter based on the ICAO reference data, then finally multiplying that result by an emissions factor found in ICAO reference materials. If the engine type is unknown, ICAO documentation suggests a simplified approach for achieving a reasonable approximation of particulate matter emissions, in which aircraft type, rather than engine type, is mapped to PM.

The last variable is that emission indices vary depending on the type of particle. The nvPM and NOx indices come from the public ICAO Engine Emission Databank, while the volatile PM (vPM) emission indices were computed based on available documentation.[63] Additionally, vPM emissions were broken down into $vPM_{sulphate}$ and $vPM_{organic}$, where the molecular weight of the sulfur content was included in the calculation for maximum accuracy. The result of this calculation was the PM (nvPM + total vPM) and NO_x emissions during LTO in 2024 at each of the 20 airports in the study.

The goal of this analysis is to identify airports that have significant air quality impacts and originate a large number of flights likely to generate contrails at altitude, in order to assess the efficacy of targeting those locations with an increased SAF allocation. Uplifting SAF at these types of airports would significantly increase non-CO_2 climate co-benefits; as such, determining if the same airports from the contrail impact analysis are also sites of significant PM and NO_x emissions during LTO has merit.

61 CARB (2024), *California Aircraft Emissions Inventory (CAI2024) Technical Documentation*, Table 6 and 7, https://ww2.arb.ca.gov/sites/default/files/2024-10/CAI2024%20-%20Main%20Document_Final1021_ada.pdf

62 ICAO (2020), *Doc 9889 Airport Air Quality Manual,* Table 3-A1-1, https://www.icao.int/sites/default/files/2025-04/9889_cons_en.pdf

63 ICAO (2020), *Doc 9889 Airport Air Quality Manual*, https://www.icao.int/sites/default/files/2025-04/9889_cons_en.pdf

U.S. Airports

Emissions during landing and take-off operations for the same ten U.S. airports were computed using the aforementioned methodology. While these airports were originally selected due to the amount of contrail CO_2eq generated by departing flights, significant LTO emissions are expected at these airports as well. This is because many of these airports are among the busiest in the U.S.,[64] and LTO emissions are strongly correlated with flight activity.

The results of the LTO emissions calculation are shown in Table 3. First, regarding definitions, narrowbody and widebody refer to one-and two-aisle aircraft, respectively. The labels, old, medium, and new refer to a categorization of engines on a given aircraft. This categorization was developed for this study and looked to group the engines by the vintage of the technologies included in the design, as newer engines are often designed with emission reductions in mind. Examples of aircraft with old generation engines are the B753, CRJ7, B735, A310, and the B772; whereas the B738 and A320 are considered medium generation, and the B789 and A21N are examples of aircraft equipped with new generation engines.

The results in Table 3 show that flight activity at Hartsfield-Jackson Atlanta International Airport (KATL or Hartsfield) is responsible for the most LTO PM emissions by a wide margin. This is followed by Dallas-Fort Worth International Airport (KDFW or DFW) and O'Hare International Airport in Chicago (KORD or O'Hare). For NO_x emissions during LTO, flight activity at LAX, Hartsfield, and JFK top the list, but generally, NO_x emissions are more clustered than PM, and activity at many of the airports are in the range of 3,500 – 5,000 tons per year.

Table 3: LTO PM and NOx emissions computed for U.S. airports in study (2024)

Airport		Number Total Flights	Aircraft Body Type			Aircraft Generation			Emissions	
			Regional (%)	Narrow Body (%)	Wide Body (%)	Old (%)	Medium (%)	New (%)	PM (tons)	NO_x (tons)
KATL	Atlanta	779,700	12	82	7	39	51	10	**103.9**	4,750
KDFW	Dallas	724,216	31	63	6	13	77	10	**65.3**	3,890
KORD	Chicago	754,396	41	49	10	24	62	13	**60.9**	4,070
KLAX	Los Angeles	551,727	15	63	21	12	59	29	**58.8**	4,890
KJFK	New York	451,127	21	49	30	21	55	23	**53.8**	4,340
KMIA	Miami	449,202	10	69	21	17	55	29	**52.0**	3,480
KEWR	Newark	399,380	26	59	15	28	47	25	**42.4**	2,720
KSFO	San Francisco	357,984	20	61	19	14	60	26	**39.1**	3,180
KBOS	Boston	349,783	32	59	9	7	74	20	**33.3**	2,050
PANC	Anchorage	162,504	20	29	50	41	40	19	**24.1**	2,330

64 Airports Council International (2025), *Airports Council Releases 2024 North American Airport Traffic Rankings*, https://airportscouncil.org/press_release/airports-council-releases-2024-north-american-airport-traffic-rankings/

Figure 21: PM emissions plotted as a function of total flight activity for U.S. airports

Looking at Figure 21, PM emissions are well correlated with total flight activity. This result was expected as overall aviation activity should dictate emissions near the ground. However, Hartsfield is an extreme outlier in this figure. Both DFW and O'Hare have a similar amount of annual flight activity, but LTO at Hartsfield is responsible for roughly 65% more particulate matter. This is due to the number of old-generation aircraft operating out of Hartsfield. Flight activity out of Hartsfield leads the U.S. airports in the study at 39% old-generation aircraft. The next closest is Newark Liberty International Airport (KEWR or Newark Airport) at 28%. As shown below in Figure 22, aircraft PM emissions can vary extensively depending on the aircraft body type and engine generation.

Firstly, on average, the data shows that widebody aircraft emit more PM than narrowbody aircraft or regional jets. This is due to the size of the engines. The additional fuel needed for the larger engines on widebody aircraft will increase LTO PM emissions. Secondly, older generation engines like those on the B753 emit significantly more PM, in some cases an order of magnitude more than newer generation aircraft. For example, even though they are both narrowbody, single-aisle aircraft, the older generation B753 emits 400kg of PM per flight while the new generation A21N emits about 20kg, a 20 times difference. The preponderance of older generation aircraft operating at Hartsfield is the reason for the outsized PM emissions, the result of which negatively impacts air quality near that airport. This data shows that, unrelated to transitioning to SAF, fleet upgrades are another way that air quality can be improved.

Figure 22: PM emissions organized by aircraft body type for U.S. airports

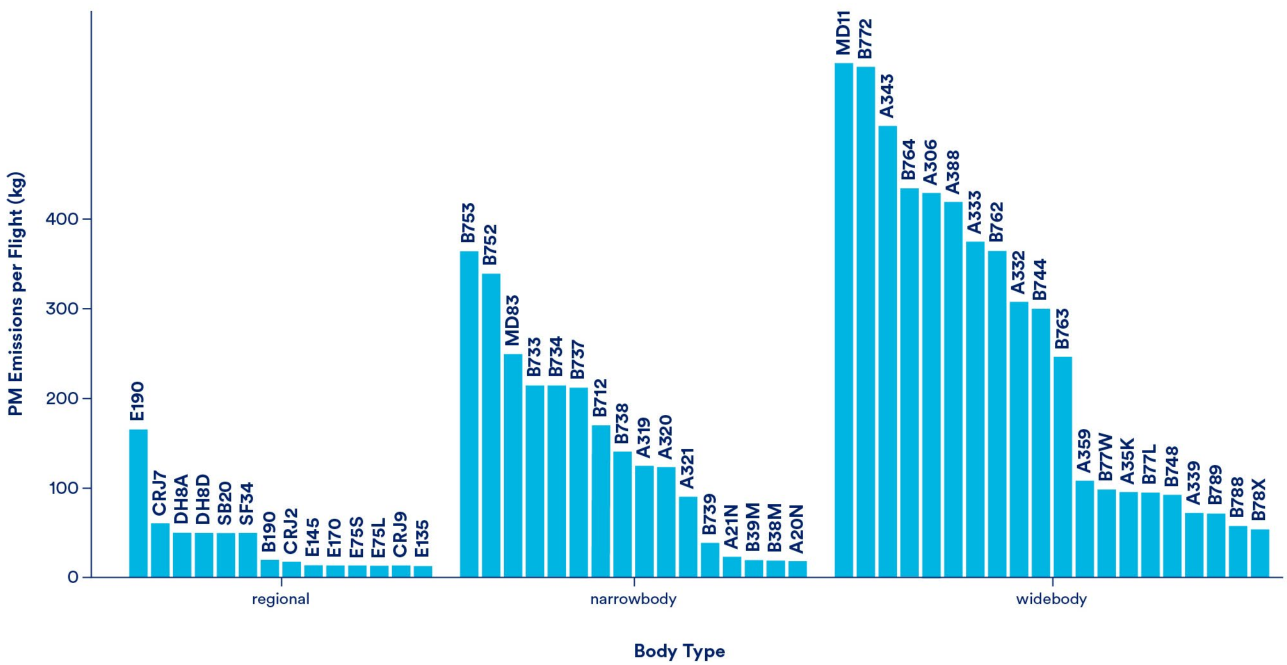


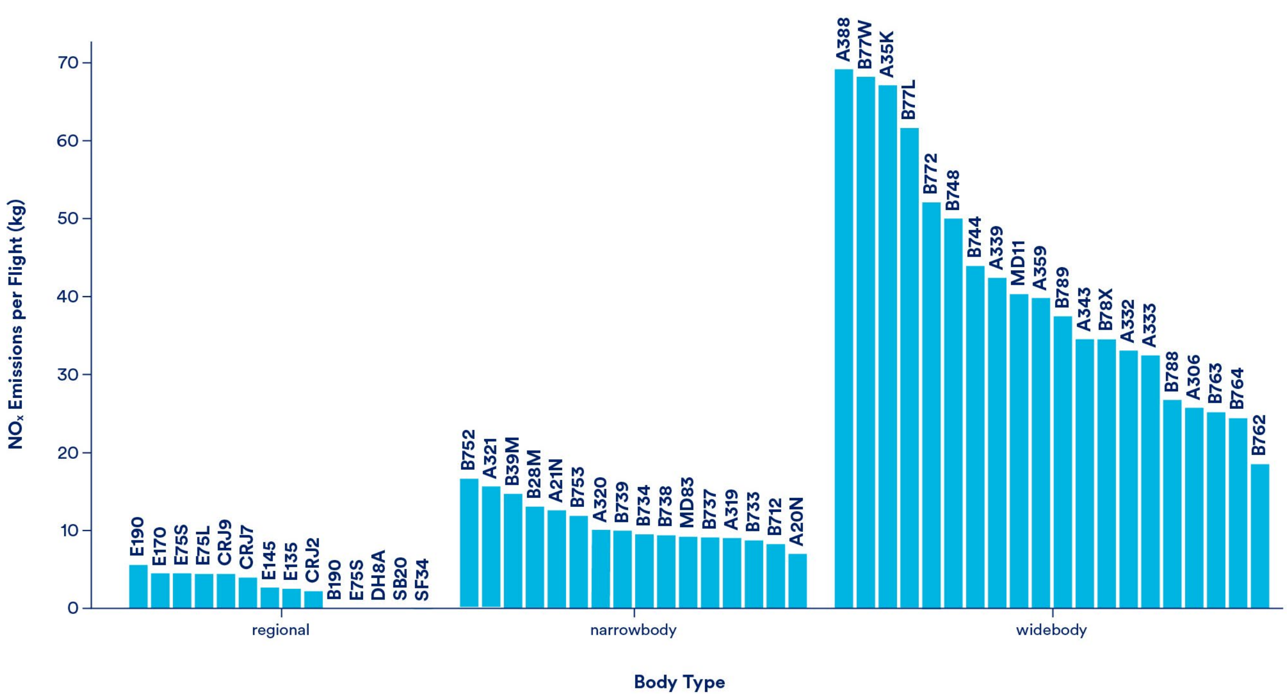
Figure 23 shows NO_x emissions plotted against flight activity. Like PM, NO_x emissions data is also correlated with total flight activity, albeit with more scatter. For NO_x emissions, LTO at LAX is responsible for the most.

Aircraft at Hartsfield, O'Hare, and DFW emit less NO_x during LTO than expected given the amount of flight activity. The reason for this is related to the body type of the aircraft that make up the bulk of said activity. Similar to PM emissions, new engines also emit less NO_x. However, this trend, which is shown in Figure 24, is much less pronounced. NO_x emissions from a B753 are only about 50% worse than those from an A21N (compared to the 20 times difference in PM emissions). Rather, it's wide body aircraft that drive up NO_x emissions.

Due to thrust requirements, two-aisle, widebody planes need large, powerful engines. Thermodynamically, NOx emissions are tied to the fuel combustion temperature, as that heat decomposes air into free nitrogen radicals that can later form NO_x. As aircraft engines on large planes are pushed to do more work to increase thrust, combustion will occur at a higher temperature, which in turn leads to more NO_x formation. Given this, LTO NO_x emissions at Hartsfield, O'Hare, and DFW airports are less than expected due to widebody aircraft only accounting for 7%, 10%, and 6% of total flight activity at those three airports, respectively.

Figure 23: NO_x emissions plotted as a function of total flight activity for U.S. airports

Figure 24: NO_x emissions organized by aircraft body type for U.S. airports



European Airports

The same analysis of PM and NOx emissions during landing and take-off operations was also carried out for the ten European airports identified as part of the contrail analysis. As with the U.S., these ten airports are some of the busiest in the region[65] so the expectation is that LTO emissions will also be considerable.

The results of the LTO emissions calculation are listed in Table 4. Of note is that none of the flight activity at any of the European airports on this list included more than 15% old-generation aircraft. Given this, it is unsurprising that the top airport in terms of PM emissions during LTO, Heathrow, saw 39% less emissions during LTO compared to Hartsfield. On the other hand, a larger percentage of flight activity in Europe is made up of widebody aircraft, especially at Heathrow. For that reason, the 6,150 tons of NO_x emitted in 2024 during LTO at Heathrow is more than any other airport in either region.

Table 4: LTO PM and NOx emissions computed for European airports in study (2024)

Airport		Number Total Flights	Aircraft Body Type			Aircraft Generation			Emissions	
			Regional (%)	Narrow Body (%)	Wide Body (%)	Old (%)	Medium (%)	New (%)	PM (tons)	NO_x (tons)
EGLL	London Heathrow	476,167	1	58	41	9	47	44	64.3	6,150
EHAM	Amsterdam Schiphol	472,781	28	52	20	5	77	18	62.1	3,450
LFPG	Paris Charles de Gaulle	460,043	14	55	31	9	73	18	57.9	4,570
LTFM	Istanbul	503,425	1	70	29	3	73	25	57.2	5,230
LEMD	Madrid Barajas	403,906	13	67	20	5	61	34	47	3,100
EDDF	Frankfurt	429,935	17	58	25	9	69	22	46.7	3,990
LEBL	Barcelona El Prat	335,045	2	91	7	2	77	21	36.2	2,120
EDDM	Munich	310,247	22	66	11	14	64	22	30.1	1,940
EGKK	London Gatwick	264,118	3	88	9	6	68	26	22.9	1,670
GCTS	Tenerife South	84,762	9	90	1	10	54	36	5.6	438

65 OAG (2026), Top 10: *Europe's Busiest Airports*, https://www.oag.com/blog/europes-busiest-airports

Figure 25, which plots PM as a function of total flight activity, shows a much more linear trend without obvious outliers. This is due to only a small number of older planes remaining in the fleet being used at European airports. Munich International Airport (EDDM or Munich Airport) is the only airport with more than 10% of flight activity on older aircraft. Istanbul Airport was at a tiny 3%. Regardless of fuel composition, utilizing a newer fleet will be beneficial to local air quality.

Older generation aircraft emitting substantially more PM remains a trend at European airports. Of note is that PM emissions for the A346 are an extreme outlier. This 4-engine aircraft, comparable to a B747, was never adopted by the U.S., explaining why it makes its first appearance in Figure 26. Ideally, fleet turnover will soon push older aircraft with PM emissions this far above the average out of operation.

Figure 25: PM emissions plotted as a function of total flight activity for European airports

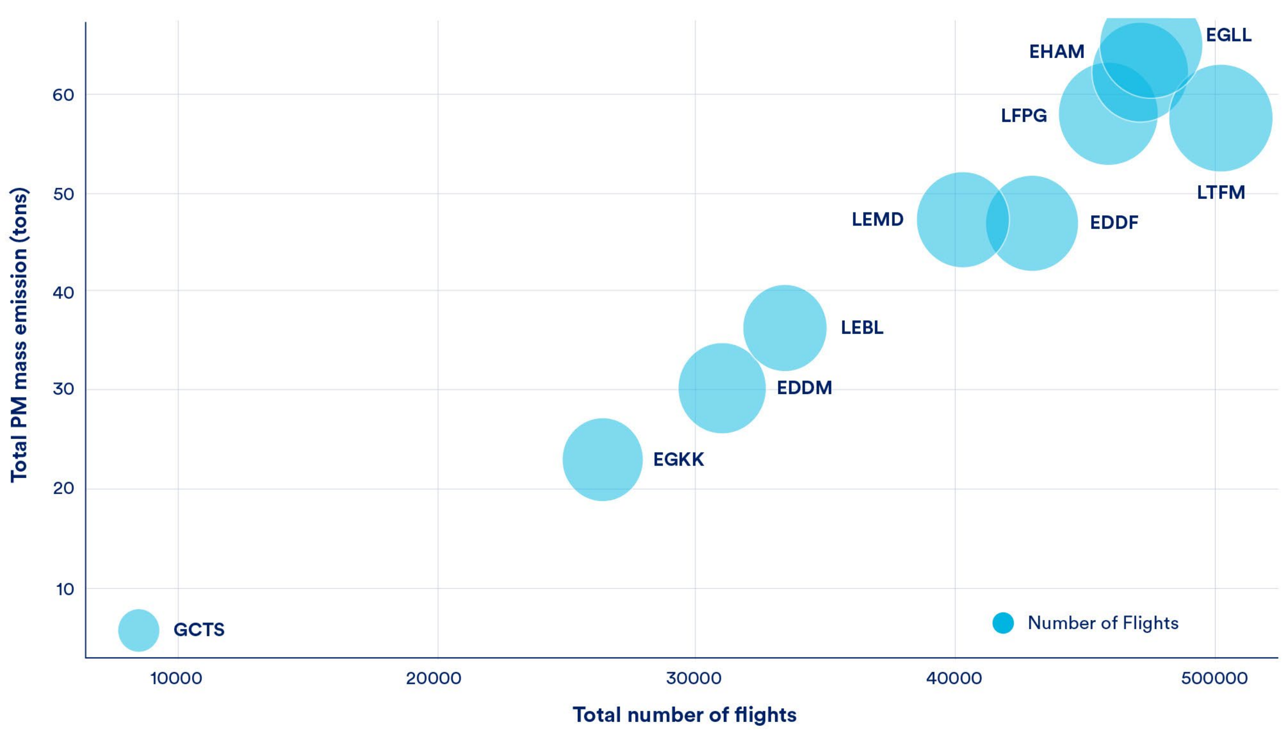
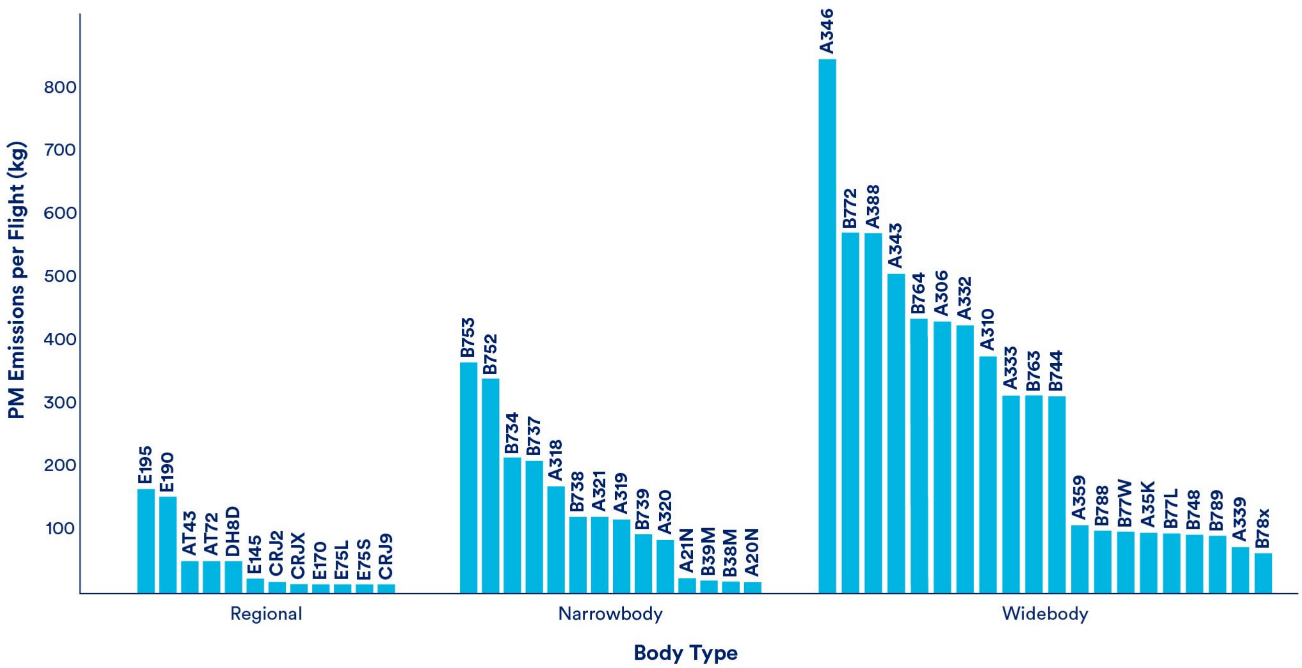


Figure 26: PM emissions organized by aircraft body type for European airports



The NO_x emissions as a function of flight activity (Figure 27) are also roughly linear. As this is largely a function of the utilization of widebody aircraft (Figure 28), it follows that excluding Heathrow, the top 6 EU airports by flight activity all saw similar widebody usage, between 20 – 30%. Similarity in fleet makeup in European airports is the main reason for the clear trend in the plots of NO_x and PM emissions. Essentially, in Europe, PM and NO_x emissions during LTO are tied to overall flight activity, with few other variables entering into the equation.

Figure 27: NO_x emissions plotted as a function of total flight activity for European airports

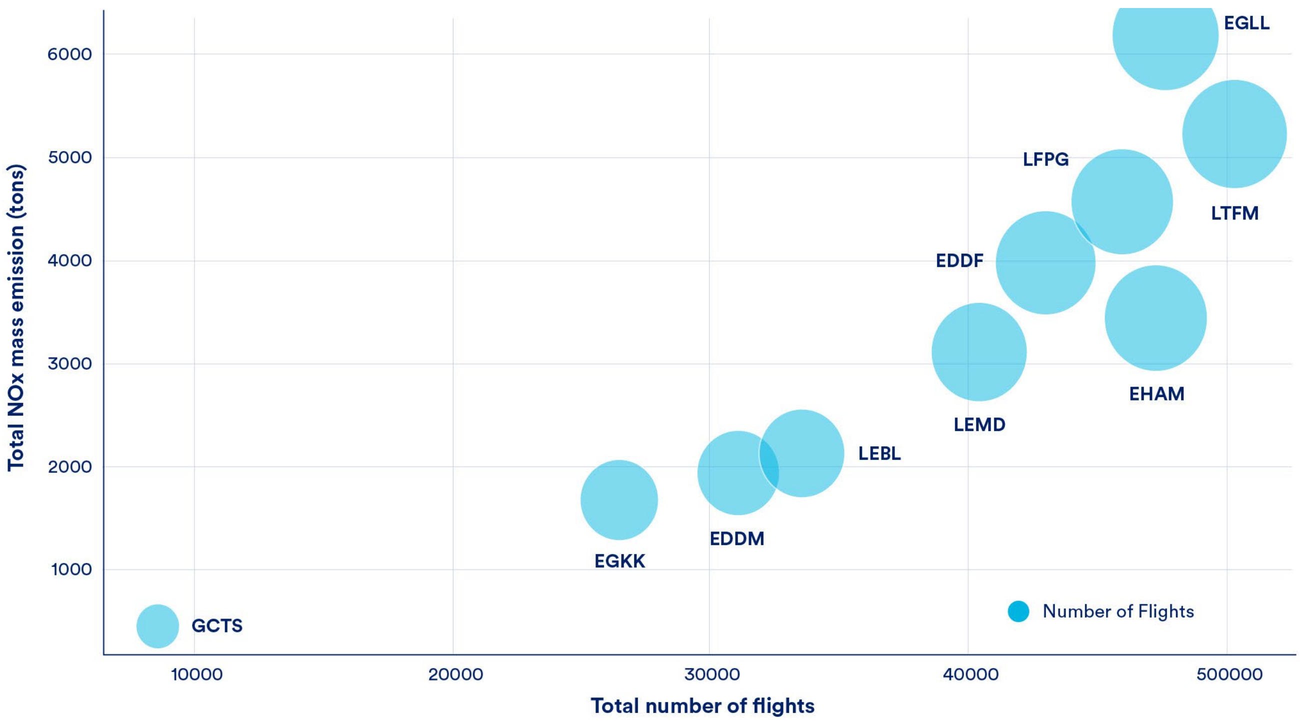
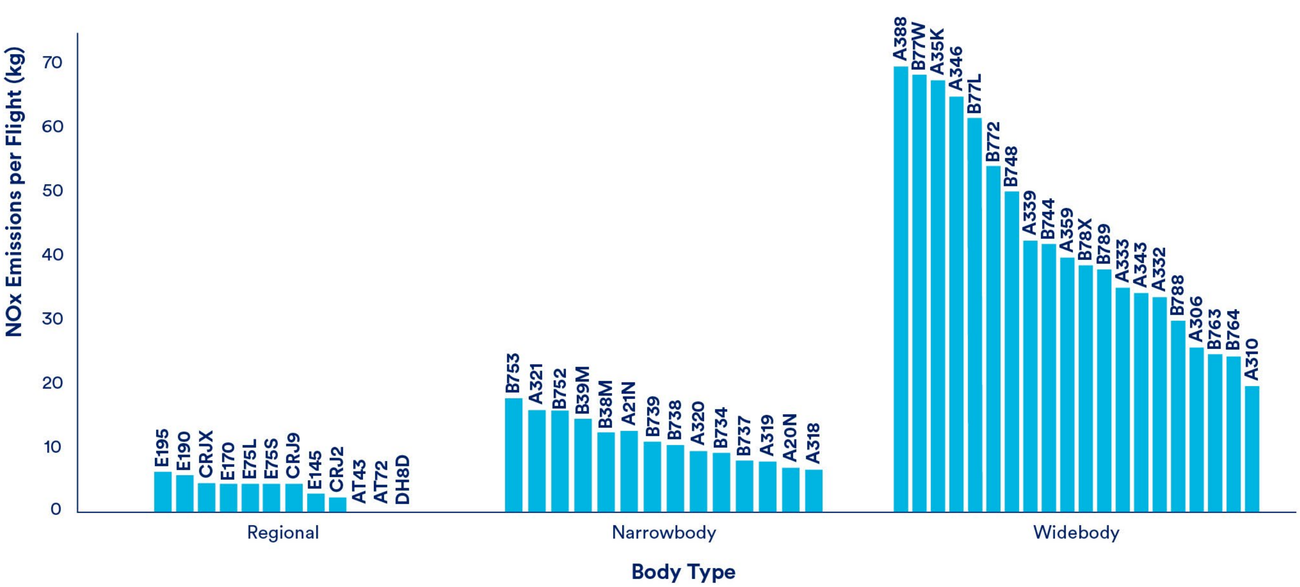


Figure 28: NO_x emissions organized by aircraft body type for European airports



SECTION 6

SAF Targeting Strategies for the U.S. and Europe

Widespread adoption of sustainable aviation fuel is one of the most promising aviation decarbonization strategies. Uplifting SAF blended with Jet A-1 will always benefit the climate due to SAF's lower carbon intensity. Using SAF also reduces harmful particle emissions, which will improve local air quality and, depending on the location of ISSR at altitude, will also reduce contrail-related warming. Yet it will be decades before there is enough SAF supply to realize these benefits across the full sector. Optimization via SAF targeting could bring about these benefits sooner.

Every ton of SAF blended with Jet A-1 reduces carbon emissions regardless of where it is uplifted; however, that is not the case with non-CO_2 effects. Certain characteristics such as location, flight activity, and route distribution mean that some airports offer better opportunities to maximize the co-benefits of SAF. If a ton of SAF is uplifted at airports with a disproportionally large impact on local air quality and a large number of flights with a high propensity for contrail formation, the impact of that ton of SAF could be maximized. The overall result would be reduced warming and lower levels of health-damaging pollution while SAF is still costly and scarce, as opposed to the current approach of distributing SAF without a plan for maximizing its co-benefits.

The first step is a determination of the airports that would benefit the most from targeting. Figure 29 takes the results of the analysis of U.S. contrail impacts and LTO PM emissions discussed in Section 5 and plots them against each other. An airport with flight activity that maximizes the co-benefits of SAF would be represented by a point on the upper right-hand side of this graph. Given this, JFK, LAX, and O'Hare were selected for the SAF targeting analysis. None of the flight activity at U.S. airports had both a large contrail impact and significant LTO PM emissions, so the airports where departing flights had the largest contrail impact were selected. This decision was made because solutions unrelated to SAF adoption are available to airports with outsized PM emissions. For example, Hartsfield, which doesn't have an outsized contrail impact, would benefit greatly from airlines upgrading their fleets. Data suggests that PM emissions at Hartsfield would fall more in line with the other U.S. airports if older generation aircraft were replaced. Additionally, LTO emissions can also be reduced by optimizing ground operations to reduce total taxi time. Lastly, flights from O'Hare and SFO have a very similar contrail impact, so in this case, O'Hare was selected for targeting due to there being more PM emissions during LTO.

For European airports, Heathrow appears at the top right corner of Figure 27 and is a clear choice for SAF targeting. Due to airlines using newer aircraft, none of the airports in Europe stand out as having larger than average PM emissions. As such the second and third ranked airports by departing flights with a significant contrail impact, Istanbul Airport and Paris CDG, were chosen as the other two airports for deeper study.

Figure 29: Contrail impact plotted against PM emissions for U.S. airports

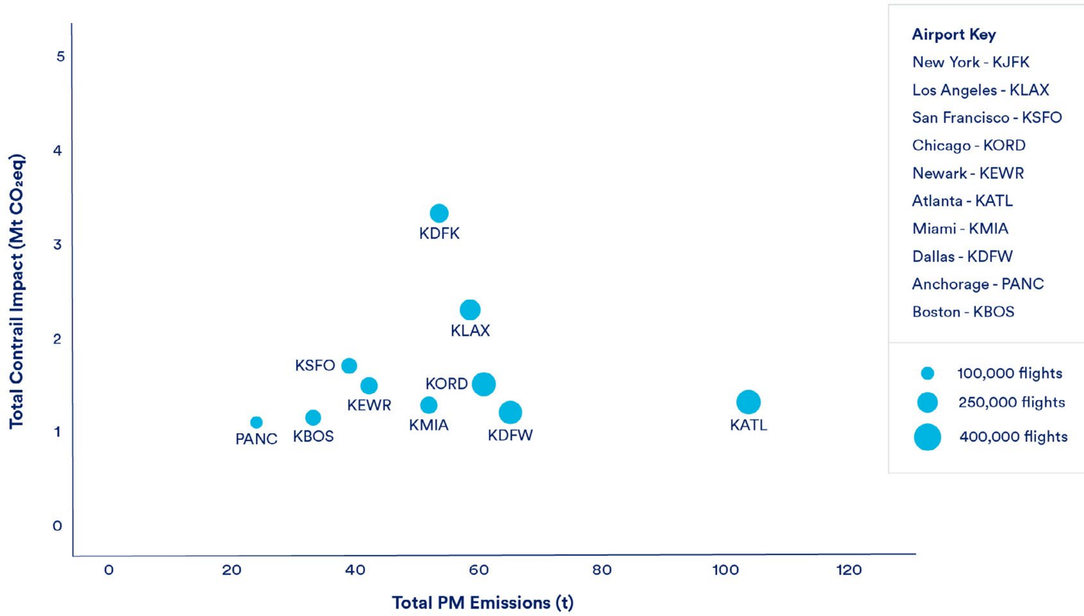
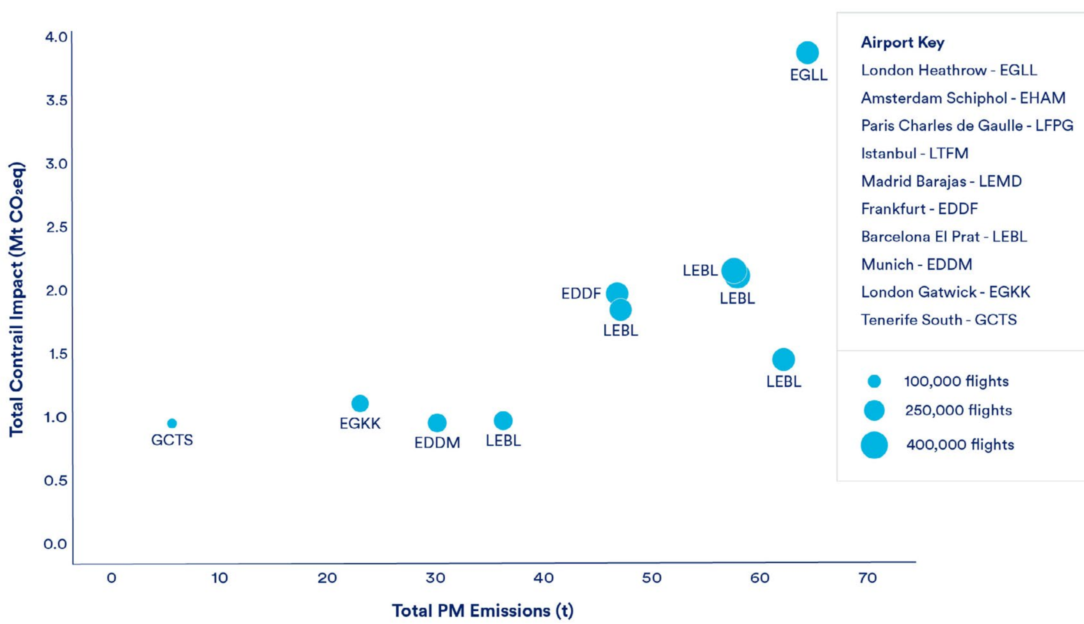


Figure 30: Contrail impact plotted against PM emissions for European airports



The following analysis seeks to quantify the benefit of SAF targeting strategies for contrail reduction and air quality improvements for the airports selected above: JFK, LAX, O'Hare, Heathrow, Istanbul Airport, and Paris CDG. For each flight departing from these airports, changes in contrail impact alongside changes in PM emissions during LTO were computed using the Estuaire database for 10%, 30%, 50%, 75% and 100% SAF blends. The higher blend rates of 75% and 100% are theoretical, as current ASTM regulations cap the SAF percentage at 50%.[66]

Finally, the focus will be on three types of targeting strategies: airport-wide targeting, time-based targeting, and flight-based targeting. All types of SAF targeting should be more effective at reducing contrails and improving air quality than spreading the current SAF supply, 2 million tons, or 0.7% of the jet fuel demand[67] across the aviation landscape based on a willingness to purchase or regulatory compliance-driven decisions. That said, it also must be determined if these benefits will outweigh the additional cost and operational complexity associated with this strategy.

SAF Targeting Impacts on Local Air Quality

As the modeling in Section 5 showed, over 50 tons of particulate matter are emitted during landing and take-off operations annually at airports around the world. These emissions affect the air quality in communities located near airports and, as epidemiological studies have shown, poor air quality caused by PM emissions has severe negative health impacts. Part of the solution to this issue is switching to SAF, a drop-in fuel that can replace conventional jet fuel without changes to aircraft engines or fueling infrastructure.

The methodology laid out in Annex 16 to the Convention on International Civil Aviation links the level of nvPM in the exhaust to the hydrogen content of the SAF blend via a correction factor to Jet A-1 emissions.[68] This factor was applied to the Jet A-1 nvPM emission indices in the Estuaire database to compute how varying SAF blends affect particulate emissions. The nvPM calculation was done on a flight-by-flight basis as it was with the previous calculations for Jet A-1. For the $vPM_{sulphate}$ calculation in this targeting analysis, it was assumed that 100% SAF contains no sulfur. The change to $vPM_{sulphate}$ emissions for different SAF blends was then assumed to be linear, ranging from zero for 100% SAF to the same as Jet A-1 emissions for 0% SAF. This was also computed on a flight-by-flight basis. Additionally, SAF has not been shown in literature to affect organic compounds in the engine exhaust. As such, $vPM_{organic}$ emissions are assumed to be the same as conventional jet fuel.

Lastly, there are a few aircraft PM emissions that blending SAF at targeted airports will not change. For one, emissions during approach and taxi-in after landing will remain unchanged, as the impact of SAF is only considered at the airport where it is uplifted, rather than the airport where the aircraft landed. As more SAF is available this will change, but as it pertains to targeting SAF to a small number of airports, arriving flights are assumed to be burning 100% Jet A-1.

Beginning with the U.S., the change in PM emissions during LTO at each of the 3 airports in the study is shown in Figure 31. The trend is linear, such that uplifting increasing amounts of SAF reduces PM emissions during LTO proportionally. The maximum reduction in PM for 100% SAF is around 50% for all airports. The benefit is limited by targeting not affecting emissions on arriving flights and $vPM_{organic}$ emissions being unaffected by SAF usage. For 2024, total LTO PM emissions at U.S. airports in the study ranged between 50 – 60 tons. If a 50% SAF blend is applied, LTO PM emissions drop to around 40 – 45 tons a year, a 28% decrease. That is a big enough change in emissions to positively affect air quality.

Figure 32 contains the results for European airports. Overall, the LTO PM emissions at these airports are very similar to the airports selected in the U.S. Furthermore, the percentage decrease in PM at various SAF blends is also similar. This owes to the fact that there is little difference in the type of aircraft utilized in each region (other than at Hartsfield as discussed in Section 5) so it follows that emission benefits when switching to SAF blends are similar. LTO PM emissions at European airports improve about 27% for a 50% SAF blend, from 55 – 65 tons per year down to 40 – 50 tons per year. As with the U.S., this is a significant reduction.

66 Alternative Fuel Data Center (AFDC), https://afdc.energy.gov/fuels/sustainable-aviation-fuel

67 IATA (2025), *Global Feedstock Assessment for SAF Production Outlook to 2050*, https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf

68 ICAO (2023), *Annex 16 to the Convention on International Civil Aviation Environmental Projection*, 6.2.2, https://www.bazl.admin.ch/dam/en/sd-web/2zooNDDnJSFa/icao_annex_16_environmentalprotectionvolumeii-aircraftengineemis.pdf

Figure 31: Change in LTO PM emissions due to SAF targeting at three U.S. airports

Percentage reduction relative to Jet A-1 noted on chart.

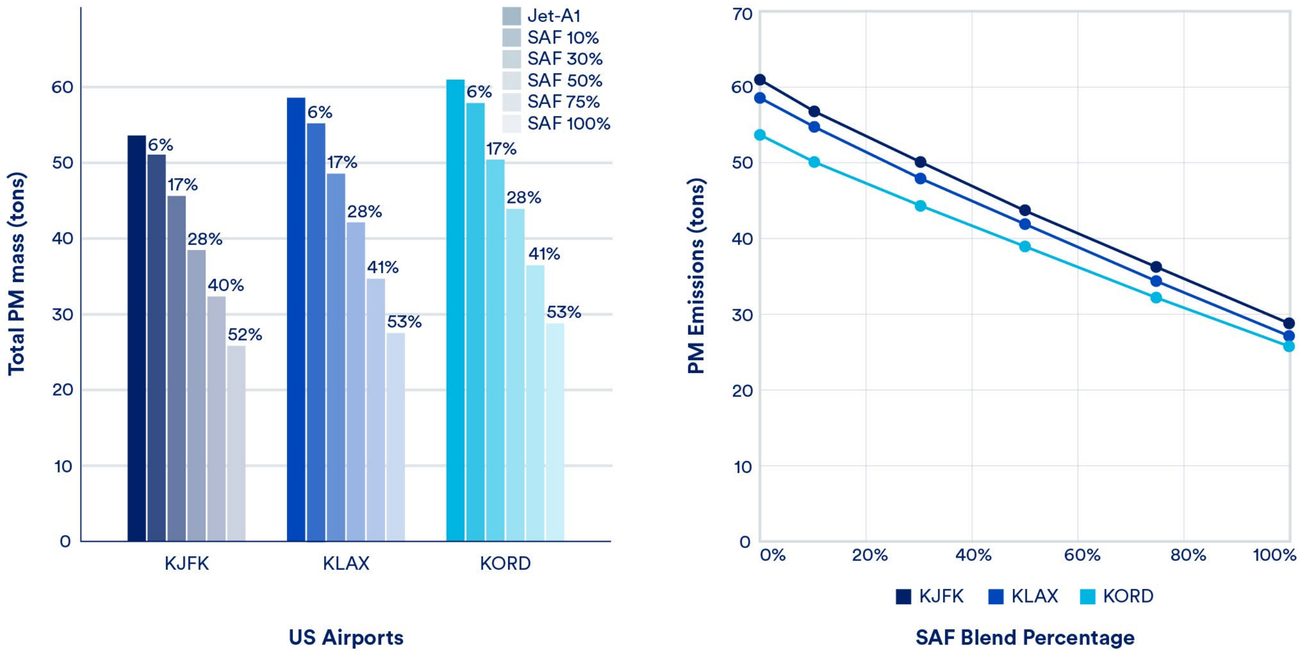
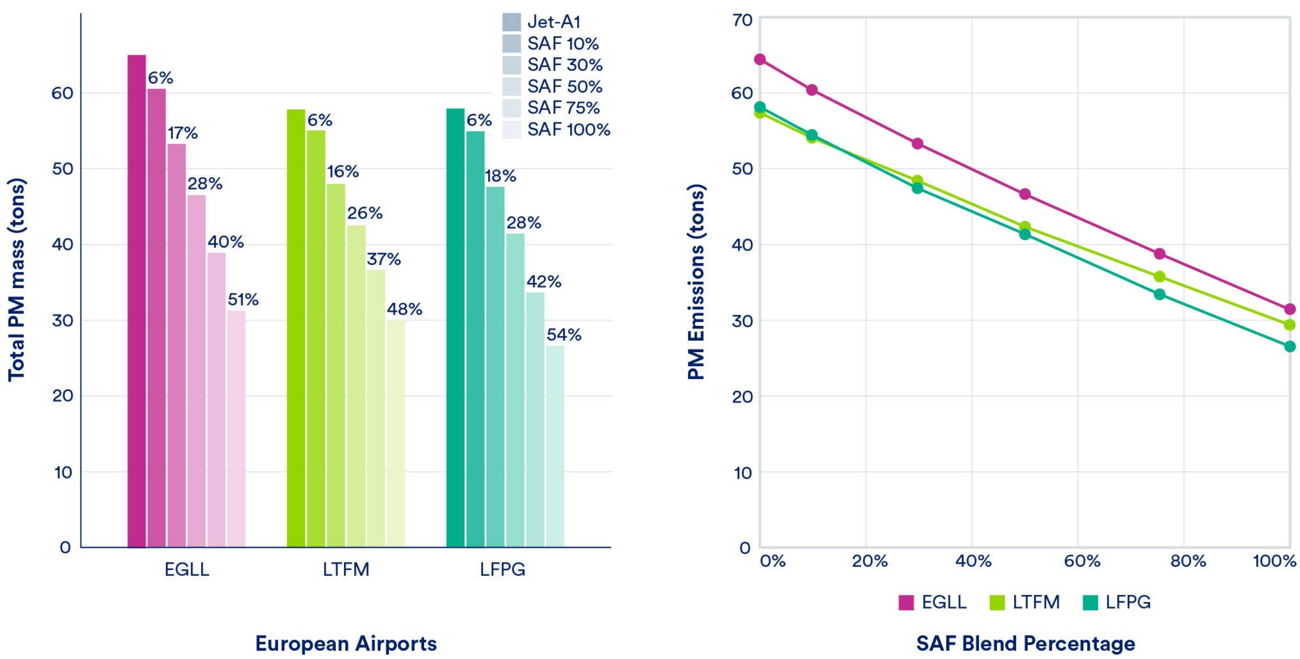


Figure 32: Change in PM emissions due to SAF targeting at three European airports

Percentage reduction relative to Jet A-1 noted on chart.



With airport-wide SAF targeting the LTO emission benefits are capped around 50%; and other SAF targeting strategies, based on time of day or targeting specific flights, will not make a difference. Essentially, more SAF uplifted at an airport will bring proportional benefits to air quality, regardless of which flights are allocated the cleaner fuel. Further LTO PM emission reductions will come from widespread SAF adoption (such that arriving flights are also burning SAF blends), fleet turnover, optimizations that reduce taxi time, and additional engine improvements. However, the reductions in LTO PM emissions due to SAF targeting shown here should still improve air quality and the health of those who live near airports.

Linking particulate matter emissions to health impacts is not infallible. There is a level of uncertainty, and modeling does require simplifying assumptions. That said, there are generally accepted models that produce reasonable results. One such model, which was developed by the U.S. Environmental Protection Agency (EPA), is COBRA.[69] COBRA generates health impact assessments by modeling changes in ambient air pollution levels due to a pollution source (such as an airport), calculating the associated change in adverse health effects (such as premature mortality), and then assigning an economic value to these effects.

Using the EPA database, aircraft emissions were separated from other emission sources at an airport, such as ground equipment, and modeled separately to isolate the impact of LTO PM emissions on health. COBRA estimated the adverse health impacts from these emissions, alongside the monetized economic damages, both of which were based on health impact functions taken from established epidemiological studies. Also included in the COBRA calculation was the baseline incidence rate for the health impact in a given location, the nature of the affected population, and the estimated change in the concentration of the pollutant as compared to the ambient levels.

COBRA is designed to operate on a county-by-county basis in the U.S. To determine the health impacts of LTO PM emissions at U.S. airports, COBRA was first used to compute the health impacts due to all aircraft in LA County, Queens County, as well as Cook and Dupage County. These are the counties where JFK, LAX, and O'Hare are located. Those airports are the major source of aviation activity in those counties, but they are not the only active airfields. LA county, for example, is home to 4 other major airports beside LAX, in addition to several small private airfields. To isolate the three airports from other aviation activity in a county, for the 100% Jet A-1 reference case the health impacts were proportionally scaled down using the ratio of LTO PM emissions at each airport of interest to the total aviation emissions in a county.

Table 5: Average annual avoided premature deaths and monetized health benefits from SAF targeting at three U.S. airports relative to the 100% Jet A-1 reference case

SAF %	JFK		LAX		O'Hare	
	Avoided Premature Mortality	Monetized Health Benefits	Avoided Premature Mortality	Monetized Health Benefits	Avoided Premature Mortality	Monetized Health Benefits
SAF 10%	0.5	$7,136,118	0.2	$3,513,237	0.4	$5,785,123
SAF 30%	1.4	$20,388,910	0.7	$9,963,929	1.1	$16,448,512
SAF 50%	2.2	$32,910,360	1.1	$16,112,093	1.8	$26,564,659
SAF 75%	3.2	$47,758,805	1.6	$23,480,131	2.6	$38,572,698
SAF 100%	4.2	$61,964,556	2.0	$30,565,158	3.4	$50,080,402

69 EPA, *CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)*, https://www.epa.gov/cobra

The health benefits for each of the SAF blends were computed using the same methodology. The health benefits due to reduced LTO PM emissions were computed by proportionally scaling down the results by the PM reductions seen in each of the SAF blend cases. Table 5 lists those benefits relative to the 100% Jet A-1 reference case. For a 50% SAF blend, the biggest benefits are realized at JFK, with an average of 2.2 avoided premature deaths per year and $32 million of monetized health benefits from avoided negative health impacts. The data confirms that benefits grow with increasing SAF blend percentages and that targeting SAF to specific airports could result in tangible health co-benefits while reducing CO_2 emissions.

While COBRA cannot be used for assessing health impacts in Europe, we are able to provide an estimate based on our data and past epidemiological studies. Baseline health impacts due to air pollution in the U.S. and Europe have been studied over a period of time. In 2010, the total premature deaths from air pollution in the U.S. was estimated to be 160,000, whereas in Europe the estimate was significantly larger, 414,000.[70] This nearly 2.5 times difference has remained the same during the past decade. By 2020, premature deaths from air pollution in the U.S. had dropped into the 120,000 – 130,000 range,[71] while 2019 data in the EU showed a similar improvement having dropped to 332,000 deaths.[72] Given that the computed LTO PM emissions at U.S. and European airports are similar and this underlying health data, estimated avoided mortality and monetized health benefits from SAF targeting could be 2-3 times larger in Europe than the results shown in Table 5 for the U.S. This data clearly shows that in both regions there are significant human health related benefits from pursuing SAF targeting.

Airport-wide SAF Targeting Impacts on Contrail-related Warming

The targeting strategy with the least complexity is uplifting a SAF blend in equal quantities on all flights departing an airport. In other words, a relatively large amount of SAF would be blended into the airport's general fuel supply. This approach should be effective if a large-enough quantity of SAF is available to be allocated to airports where departing flights generate significant contrail CO_2eq. Using the Estuaire database, the impact of uplifting SAF was computed for each of the five blend rates for all 2024 flights at the six airports in the study. The fuel composition changes due to SAF blending and the resulting decrease in PM is the same as discussed. The following analysis focuses on how those changes in PM emissions impact contrail formation at altitude.

The result of the contrail analysis for SAF blends uplifted at the three U.S. airports is shown in Figure 33. At a high level, there was a similar benefit at each airport in terms of the percentage decrease in contrail CO_2eq as a function of blend rate. For a 50% SAF blend, the reduction of contrail-related warming was 30 – 34%. In absolute terms, JFK contrail CO_2eq for a 50% SAF blend rate was 1.1 Mt less than Jet A-1. Over a million tons of CO_2eq is a significant reduction; however, this case requires 2.4 Mt of SAF, which is more than was produced globally in 2025. O'Hare on the other hand only saw a reduction of 0.5 Mt CO_2eq for the same blend rate and would require 1.8 Mt of SAF to be uplifted at the airport.

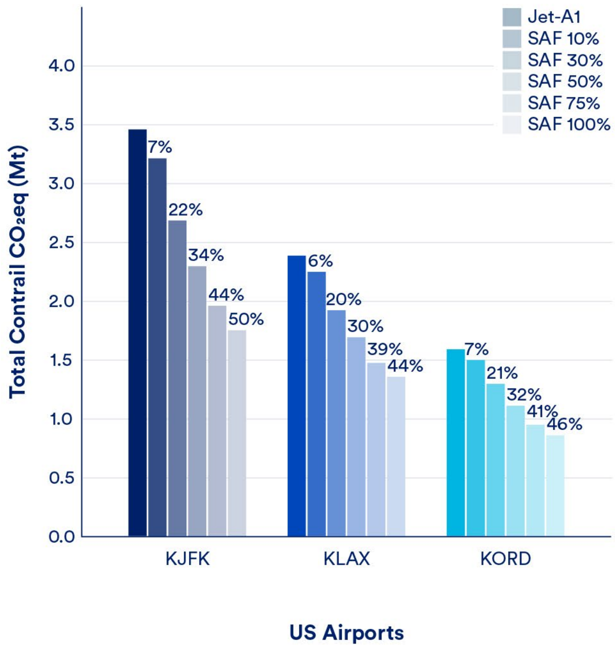
70 U. Im, et al. (2018), *Assessment and economic valuation of air pollution impacts on human health over Europe and the United States as calculated by a multi-model ensemble in the framework of AQMEII3*, https://acp.copernicus.org/articles/18/5967/2018/acp-18-5967-2018.pdf

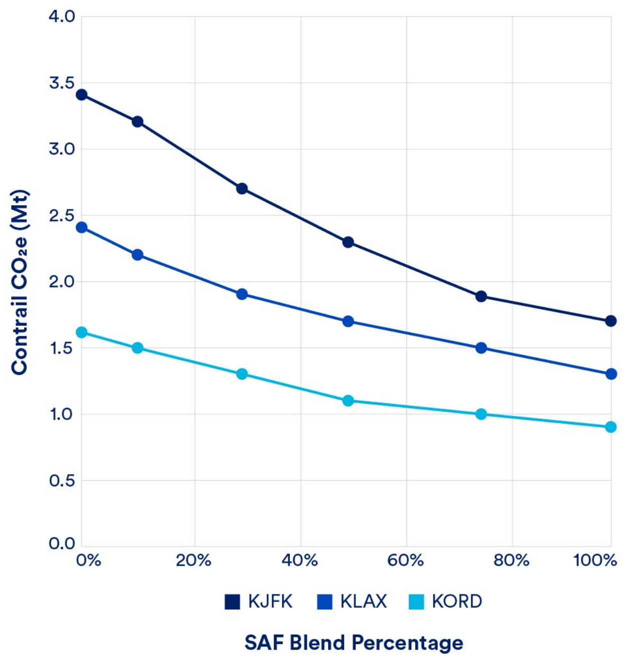
71 J. Wei, et al. (2023), *Long-term mortality burden trends attributed to black carbon and PM2·5 from wildfire emissions across the continental USA from 2000 to 2020: a deep learning modelling study*, Figure 3 (I), https://www.thelancet.com/action/showPdf?pii=S2542-5196%2823%2900235-8

72 A. Juginović, et al. (2021), Health impacts of air pollution exposure from 1990 to 2019 in 43 European countries, Table 1, https://www.nature.com/articles/s41598-021-01802-5.pdf

Figure 33: Change in contrail CO_2eq due to airport-wide SAF targeting at three U.S. airports

Percentage reduction relative to Jet A-1 noted on the chart.





This shows the limitation of airport-wide SAF targeting as bigger benefits require large amounts of SAF that may not be obtainable. Targeting at a 10% SAF blend rate results in an average reduction of 0.13 Mt of CO_2eq at each of the three airports, but that would still require 23% of the 2025 global SAF supply to be delivered to each location. SAF supply needs to scale in order to make full use of airport-wide targeting at blend percentages close to the current 50% blend limit. This should be more realistic as we move into the next decade. That said, there are diminishing returns for the higher SAF blends. Contrails will still form in soot-lean conditions, as SAF does not completely eliminate soot formation. Additionally, other types of particles can function as the nuclei for ice crystals. At 100% SAF, no U.S. airport saw more than a 50% reduction in contrail-related warming.

Nonetheless, there is still a significant climate benefit to airport-wide SAF targeting in comparison to the alternative, which is uplifting SAF wherever it happens to be available. This will result in SAF being fairly evenly distributed to a number of airports, bringing blend rates closely in line with the 0.7% global SAF market share. If the SAF blend rate is near one percent, this data makes it clear that there will be very little change in contrail CO_2eq. For example, a 1% SAF blend rate uplifted at JFK would mean a 0.02 Mt reduction in contrail CO_2eq, assuming linear scaling which is implied by the right-side of Figure 33 for small blend rates. This makes it clear that targeting 24% of the SAF available in 2025 to JFK to achieve a 10% blend rate would be 10 – 12 times more effective in terms of contrail reductions.

The results for European airports shown in Figure 34 are more pronounced, suggesting that targeting would be an even more effective strategy in that region. By percentage, at both Heathrow and Paris CDG, the maximum CO_2eq reduction at a 50% SAF blend rate is approximately 40%. Put differently, at that same blend rate, targeting all three airports would result in an additional reduction in total CO_2eq of 14.6%, on top of halving the CO_2 emissions. This highlights the impact of SAF targeting if the flights departing an airport are prone to contrail formation.

Figure 34: Change in contrail CO_2eq due to airport-wide SAF targeting at three European airports

Percentage reduction relative to Jet A-1 noted on chart.

For flights departing Heathrow, there is still a notable reduction in contrail-related warming for blend rates less than 50%. This is due to flights from Heathrow contributing more to contrail CO_2eq than any other airport. Heathrow is a prime location for SAF targeting. Interestingly, Heathrow has already started to aggressively target SAF supply to uplift at the airport. In 2024, 17% of the global SAF supply was uplifted at Heathrow.[73] (According to IATA, 1 million tons of SAF was produced in 2024,[74] 170,000 tons of which were burned on flights departing from Heathrow.) Interpolating these results, in 2024 Heathrow was operating at approximately a 2.8% SAF blend, which in addition to the CO_2 benefits, reduced contrail-related warming by 2.7% or 0.11 MtCO_2eq. According to Green Air,[75] in 2026 Heathrow is looking to double the amount of SAF uplifted at the airport to 350,000 tons.

Although less pronounced, this analysis also shows that there would be an advantage to allocating SAF to Istanbul Airport and Paris CDG that would significantly outpace blending at the global average of 0.7%. That said, airport-wide targeting may not be the most effective way to utilize a ton of SAF. Time-based and flight-based SAF targeting may also have merit.

Time-based SAF Targeting Impacts on Contrail-related Warming

Contrails can occur at any time, but the phenomenon is more common during the winter, when cold conditions promote ice-supersaturated regions, and at night when radiation from the sun cannot be reflected out of the atmosphere. This implies that a SAF targeting strategy based on departure month or time of day could be a more efficient use of a ton of SAF than treating all flights equally. However, the fuel handling logistics will be more complex with these time-based targeting strategies than with airport-wide targeting.

73 Green Air (2026), *UK SAF projects progress as Heathrow increases SAF incentive for airlines*, https://www.greenairnews.com/?p=8597

74 IATA (2024), *Disappointingly Slow Growth in SAF Production*, https://www.iata.org/en/pressroom/2024-releases/2024-12-10-03/

75 Green Air (2026), *UK SAF projects progress as Heathrow increases SAF incentive for airlines*, https://www.greenairnews.com/?p=8597

Two time-based SAF targeting strategies were evaluated as part of this analysis. The first is a month-based strategy where a SAF blend is purchased year-round but stored in special tanks in the airport fuel farm to be uplifted to all flights starting November through the end of March. For the six airports in the study that resulted in uplifting SAF on 35 – 40% of flights. The second strategy is hourly, where a SAF blend is uplifted daily to all flights that depart between 12pm – 10pm. More flights are included in this second time-based strategy, in the range of 50 – 60% depending on the airport.

As with airport-wide targeting, these time-based strategies are possible to implement in the next few years if sufficient incentive is provided. Given that, the two time-based strategies are compared to airport-wide targeting for up to one million tons of SAF delivered in jet fuel blends per year. This would have been 50% of the global supply in 2025, though SAF production is expected to continue to grow. A single airport uplifting one million tons of SAF is considered aspirational, but not impossible during the next few years. As discussed above, the goal at Heathrow is to uplift 350,000 tons of SAF in 2026.

Optimal SAF targeting strategies use the least amount of fuel while achieving the largest reduction in contrail CO_2eq. Looking at Figure 35, this is represented by points that are in the upper left-hand corner of the plot, labeled as “optimal”. In the U.S., airport-wide targeting was located towards the “sub-optimal” corner of the plot for all three airports. Moreover, out of the five blend rates in the study (10%, 30%, 50%, 75%, 100%) the only one that requires less than 1 Mt of SAF for airport-wide targeting is a 10% blend rate. Higher blend rates that require more SAF for airport-wide targeting are unlikely to be achievable in the near term. In comparison, while time-based strategies add complex fuel management logistics, they require less SAF for a given blend rate, something that should help with costs.

For JFK and LAX, hourly-based targeting is optimal if approximately 1 Mt of SAF is available; otherwise, for smaller amounts of fuel, monthly-based targeting would be preferable. For O’Hare, either time-based strategy utilizes SAF more efficiently than airport-wide targeting. The situation for European airports is similar in many respects, most notably that time-based targeting is always preferred to treating all flights equally. This is shown in Figure 36. For Heathrow and Paris CDG, monthly targeting is the clear winner. At Heathrow, for example, with monthly SAF targeting there is a 6% reduction in contrail CO_2eq for uplifting a 10% SAF blend (0.24 Mt SAF) onto flights departing from November to March (40% of annual flights). Whereas for airport-wide targeting, the same blend percentage requires nearly 3 times more fuel for an additional 4% reduction of contrail CO_2eq. Generally, more SAF utilization is better for the climate, but for the near term while the fuel remains expensive and scarce, optimizing SAF allocation via a time-based targeting strategy offers real benefits while keeping SAF purchase costs down.

Figure 35: Contrail CO_2eq reduction (%) as a function of fuel requirements for airport-wide and two time-based SAF targeting strategies at three U.S. airports

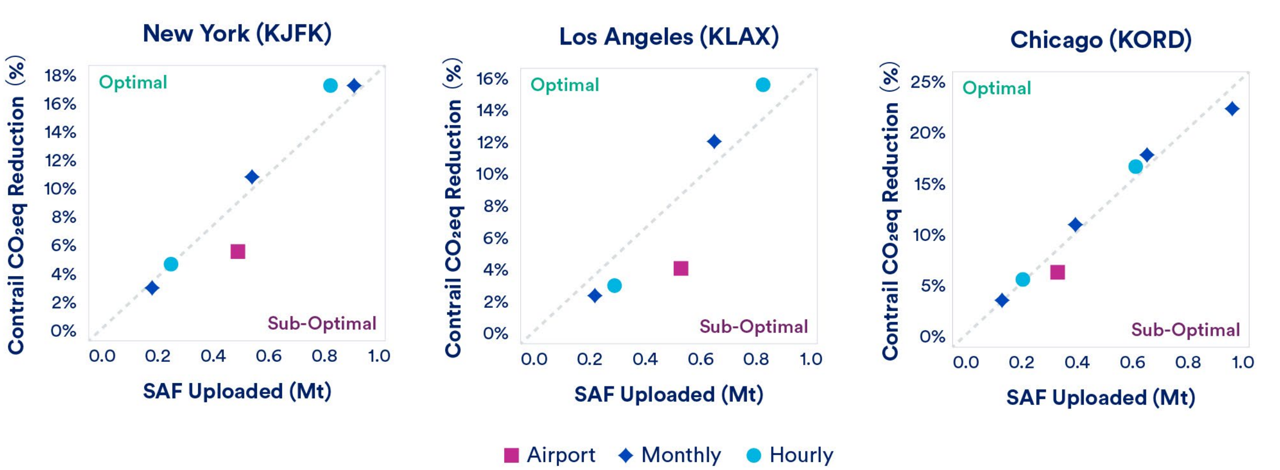
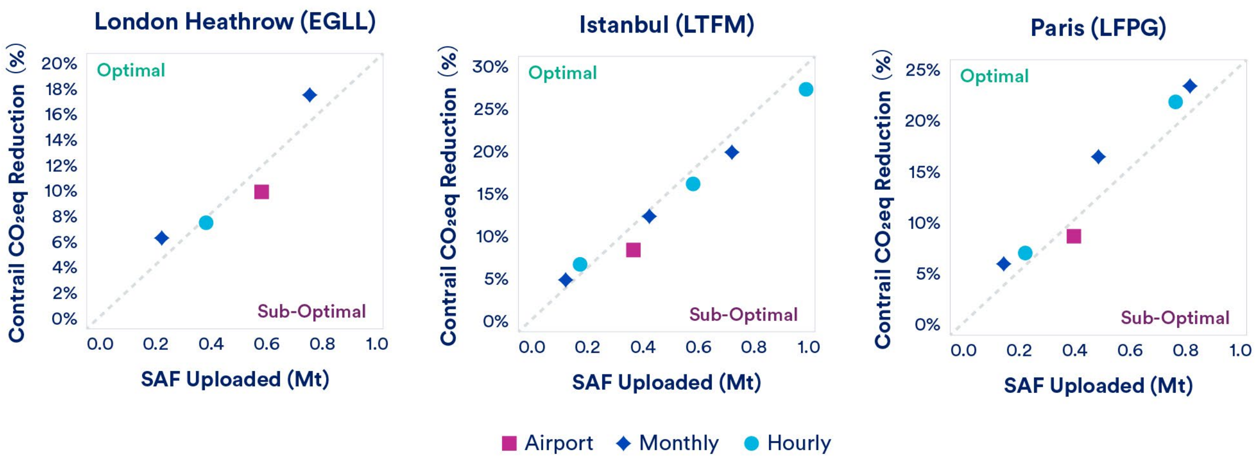


Figure 36: Contrail CO_2eq reduction (%) as a function of fuel requirements for airport-wide and two time-based SAF targeting strategies at three European airports



Looking at Istanbul Airport, there is little difference between the time-based methods. Both are better than airport-wide targeting, but there is little advantage for one over the other. Likely, the option with the least complex logistics would be preferred. In summary, while there are airport-to-airport variations, time-based SAF targeting offers additional optimization in terms of realized climate benefits for an available ton of SAF.

Flight-based SAF Targeting Impacts on Contrail-related Warming

The most optimized form of SAF targeting is to uplift SAF onto select flights deemed likely to generate contrails on-route. Restricting SAF utilization to these flights will reduce the fuel required while maintaining the amount of avoided CO_2eq, as approximately 2% of flights generate 80% of contrail-related warming. Theoretically, selecting contrail prone flights in this manner is possible if SAF targeting strategies are paired with ISSR forecasting software. Currently, this type of forecasting software is being developed, tested, and deployed for contrail avoidance.

Contrail avoidance, whether pre-tactical or tactical, on flights likely to encounter ISSR is the best way to reduce contrail-related warming. However, re-routing may not always be possible; weather, turbulence, congestion, and pilot preference are some of the reasons why an aircraft may not change altitude to avoid a forecasted ice-supersaturated region. Re-routing is still early in the demonstration phase, but during the recent American Airlines trial only 9% of eligible flights performed contrail avoidance maneuvers.[76] If all 1,232 flights eligible for avoidance maneuvers were also loaded with SAF blends as part of a flight-based SAF targeting strategy, then the aircraft that could not avoid passing through ISSR would generate less warming.

While flight-based targeting strategies are likely to be effective, they would be difficult to employ today. In addition to needing accurate ISSR prediction software, fuel logistics to support such a targeting scheme would be highly complex. Beginning with one of the simpler targeting strategies in the short-term before pivoting to something more complex like flight-based targeting in the future would make sense.

[76] T. Sankar, et al. (2026), *Efficacy of Scalable Airline-led Contrail Avoidance*, https://arxiv.org/abs/2603.06909

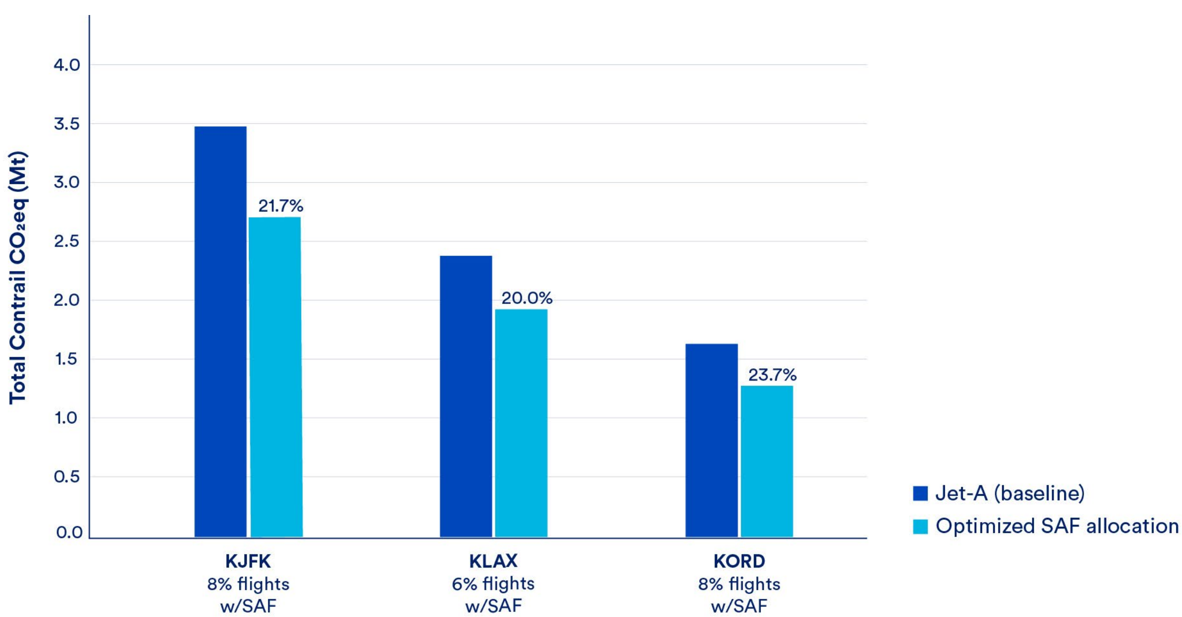
Along these lines, rather than a one million ton cap of SAF to model near-term strategies, the following analysis for flight-based targeting uses the 2030 6% SAF target in ReFuelEU as a reasonable cap on future SAF volumes. Assuming that enough SAF is available to fuel 6% of global aviation means approximately a 30% SAF blend could be targeted to select airports. Furthermore, this analysis was for 2024 flights, where the flights that generated the most contrail CO_2eq is already known. The following is not meant to show the typical benefits to expect from SAF targeting; rather, this analysis represents the theoretical upper-bound for realizable climate benefits from a flight-based SAF targeting strategy (i.e., if ISSR forecasting software was 100% accurate).

Targeting a 30% SAF blend to specific flights departing JFK, LAX, and O'Hare could reduce contrail-related warming up to 21.7%, 20%, and 23.7%, respectively (Figure 37).[77] A key result is that SAF only needs to be uplifted to 6 – 8% of flights to realize these gains, significantly less than other targeting strategies, while having little effect on the decrease in CO_2eq. By comparison airport-wide targeting of the same blend led to a 20 – 22% reduction.

The results in Figure 38 for European airports reveal similar theoretical reductions in contrail-related warming of 26%, 23.7%, and 25.2% for Heathrow, Istanbul Airport, and Paris CDG, respectively. The percentage of flights targeted was slightly higher at 7 – 13%, though this would still require significantly less SAF than other strategies. A theoretical maximum reduction of 1Mt CO_2eq at Heathrow from flight-based SAF targeting shows the potential of this strategy. These findings are directionally similar to the results reported in Teoh et al. (see fn. 50), which showed approximately a 20% reduction in contrail cirrus radiative forcing if a 30% SAF blend was allocated to the subset of air traffic that traversed the North Atlantic in 2019 (1.2% of global departures). This serves as an additional example of the effectiveness of SAF targeting if contrail-likely flights – in this case, flights through the North Atlantic – play a central role in the mitigation strategy. While flight-based SAF targeting would be difficult from a logistics standpoint and would require software to accurately forecast the flights likely to generate contrails, the potential SAF co-benefits are substantial if flight-based targeting can be effectively implemented.

Figure 37: Decrease in contrail CO_2eq due to flight-based SAF targeting at three U.S. airports (30% blend rate)

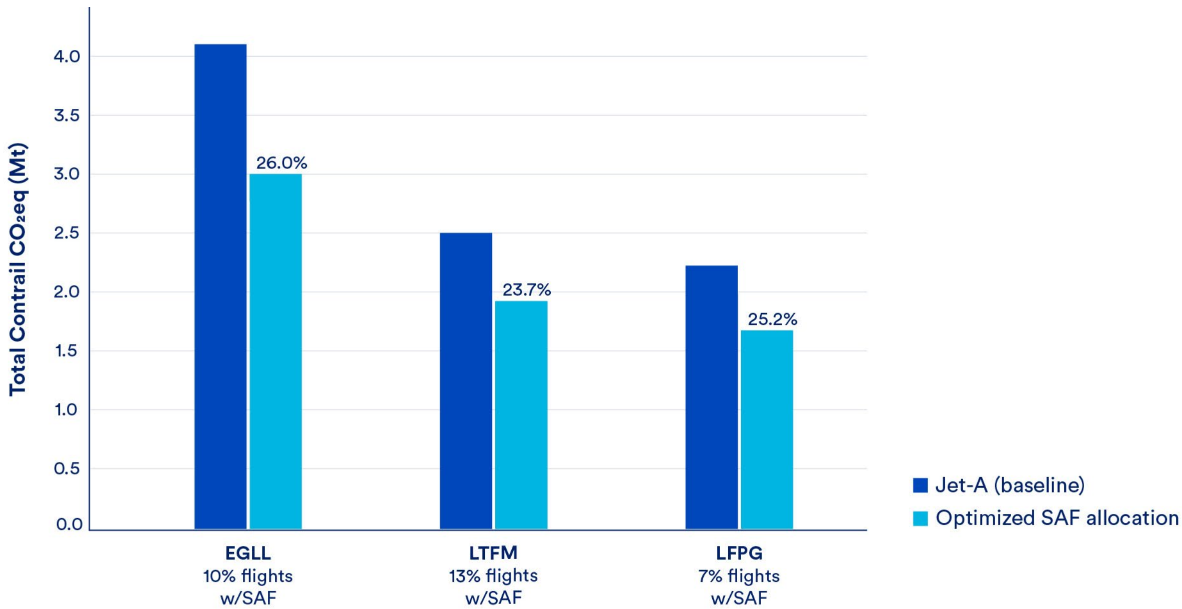
Percentage reduction relative to Jet A-1 noted on chart.



77 These numbers represent the theoretical maximum impact of flight-based SAF targeting assuming that contrail avoidance strategies are not being implemented. This could be due to congestion, weather, turbulence, air traffic controller-related challenges, or pilot/airline preference.

Figure 38: Decrease in contrail CO_2eq due to flight-based SAF targeting at three European airports (30% blend rate)

Percentage reduction relative to Jet A-1 noted on chart.



SAF Targeting Challenges: Fuel Handling Logistics

Logistics and operations at a large commercial airport are immensely complex. Airline flight activity, airport ground staff, fuel handling, aircraft maintenance, and air traffic management are only some of the items that affect logistics, much of which isn't handled by airport staff. An airport's primary function is to serve as a location where a large number of businesses come together to transport passengers around the world. At Heathrow in 2024, over 83.8 million passengers[78] either arrived or departed on 476,167 flights. Without a highly optimized, cost-effective operation, managing that much activity would be impossible.

Introducing SAF into the general Jet A-1 fueling system is a fairly straightforward process so long as airlines are willing to purchase the more expensive fuel and the fuel providers have access to a pipeline with blended SAF or the ability to receive neat SAF and blend. Targeting specific airports or specific flights, on the other hand, introduces real complexity into the highly optimized airport operations. The following draws on available literature along with discussions with those in the airport ecosystem to explore how airport fueling logistics might mesh with a SAF targeting strategy in the U.S. and Europe.

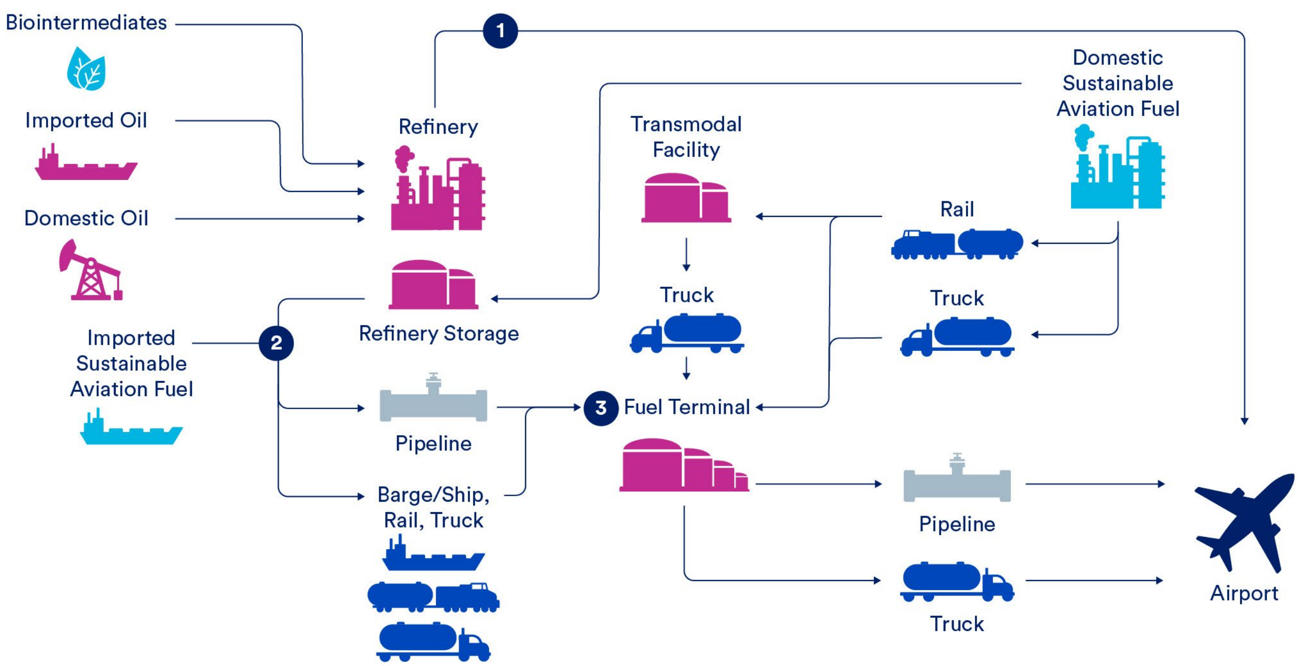
78 Heathrow Traffic Statistics, https://www.heathrow.com/company/investor-centre/reports/traffic-statistics

Two of the most common ways airports in the U.S. receive jet fuel are illustrated in Figure 39. The first approach is to build a direct connection between a refinery and an airport. The second approach involves refining the fuel, storing it, sending it to an intermediate fuel terminal, before eventually delivering it to an airport.

SAF, depending on the existing infrastructure as well as where and how it is produced, can be blended at one of the intermediate terminals or at the refinery. Of note is that current regulations (ASTM D1655) prohibit 100% neat SAF from being moved via pipeline.[79]

Figure 39: Conventional jet fuel and SAF supply chain diagram[80]

① depicts an airport receiving fuel directly from a refinery.
② and ③ depict the fuel first being stored, then piped to a fuel terminal that eventually supplies the airport.



[79] R. Calderon, et al. (2024), *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process*, https://docs.nlr.gov/docs/fy24osti/87802.pdf.

[80] Ibid.

For JFK and Newark Airport (both of which are in the top 10 airports in the U.S. by departing flights that generate contrail-related warming) and LaGuardia International Airport (KLGA or LaGuardia), the existing infrastructure is most similar to the second delivery method, where the fuel passes through several terminals before being delivered to the airport. Specifically, at Buckeye Linden in New Jersey, jet fuel received from several smaller terminals is pooled then piped to those three airports.[81] In theory, if the SAF percentage in the fuel from Linden could be increased, the cleaner fuel could be targeted to these airports.

This, however, presents several challenges. To start, neither Buckeye Linden nor the airports are currently incentivized to make significant capital investments in the near-term to install blending equipment and SAF blend storage capability. Additionally, JFK and Newark Airport use a hydrant fuel system[82] and LaGuardia, which currently trucks fuel to aircraft, will soon complete a switchover.[83] Today, SAF uplifted at these airports is added far upstream at the head of the Colonial pipeline in Texas. The SAF Jet A-1 blend produced in Texas is shared with all the airports that pull from the pipe as it runs up the U.S. east coast.

Targeting these three airports with SAF would require several of the smaller terminals upstream of Linden to receive, store, then blend SAF with Jet A-1 to raise the SAF percentage of the fuel received from Texas. That higher blend could then be sent to Linden before being delivered to the airports. To accomplish this, neat SAF would have to be either barged or trucked into these smaller terminals, a process which is about 60% more expensive per gallon than relying on a pipeline.[84]

Despite the difficulty, currently, this is feasible. The terminals upstream of Linden are equipped to receive SAF by barge and have storage tank space that can be leased to store SAF prior to blending.[85] However, the relevant blending infrastructure would have to be built, and all the additional costs added along the supply chain, on top of the cost difference between SAF and Jet A-1, would need to be paid for by the airlines. In short, it is possible to target JFK, along with the other major New York airports with SAF, and by doing so there would be a demonstrable improvement in contrail CO_2eq and air quality. But in the near-term it is unlikely that airlines and fuel providers would commit to the additional costs without a policy to incentivize this behavior.

The situation in Europe is more varied. Many of the largest airports get jet fuel directly from two large NATO pipelines, CEPS and NEPS.[86] There are dozens of airports, both commercial and military, which pull from these pipelines, so any available SAF will be split up at very small blend rates. For that reason, tracking the amount of SAF delivered to a specific airport would be difficult and therefore SAF percentages are not guaranteed.[87] Typically, airports that pull from one of these pipelines store the fuel in their local fuel farm before using a hydrant system to distribute that fuel to the aircraft. In theory, external fuel trucks could carry a SAF blend from a different location to the airport to be used for SAF targeting, but there is little incentive for the fuel producers to adopt more complex logistics. Moreover, trucking in fuel from outside the airport will be difficult to scale.

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81 K. Moriarty, et al. (2021), *Port Authority of New York and New Jersey Sustainable Aviation Fuel Logistics and Production Study*, https://docs.nlr.gov/docs/fy22osti/80716.pdf

82 Ibid., Table 14

83 Skanska (2024), *Skanska awarded $113M contract to construct LaGuardia Airport's Jet Fuel Transmission Systems*, https://metroairportnews.com/skanska-awarded-113m-contract-to-construct-laguardia-airports-jet-fuel-transmission-systems/

84 K. Moriarty, et al. (2021), *Port Authority of New York and New Jersey Sustainable Aviation Fuel Logistics and Production Study*, Section 3, 8.44 cents/gal for barge vs 5.18 cents/gal for pipeline (U.S. dollars), https://docs.nlr.gov/docs/fy22osti/80716.pdf.

85 Ibid., Section 3.1

86 Set up during the Cold War to supply NATO forces with fuel, the NATO pipeline system is approximately 10,000 kilometers long and runs through 12 NATO countries. It links storage depots, military air bases, civil airports, pumping stations, and refineries. Fuel distribution is carried out using facilities part of the common-funded NATO Security Investment Program. https://www.nato.int/en/what-we-do/deterrence-and-defence/nato-pipeline-system

87 After 2034, RefuelEU compliance with SAF blending mandates will be assessed, ideally strengthening the link between SAF supply and uplifted airport. However, as the system will continue to rely on mass balance accounting and airport fuel supplier-level reporting, the exact SAF share physically delivered to a given airport may remain difficult to trace.

Another option could be to barge SAF to an offshoot of the CEPS (or NEPS) pipeline that heads directly into an airport and inject neat SAF at that location to increase the blend percentage. This may be cheaper than employing a fleet of external fuel trucks, but whether this is possible depends heavily on the existing layout of near-airport pipeline infrastructure. Regardless, without a large public and private investment in SAF targeting – in pursuit of say, better air quality – European airports without a dedicated pipe with ports for neat SAF injection or compatible upstream fuel terminals will likely only see increases in SAF percentage as mandated by EU-wide regulations.

That said, not all European airports get jet fuel from these pipelines. Airports like Heathrow are supplied with fuel via a different pipeline system. Even in western Europe, the airport infrastructure is quite varied and there are many airports that are fueled entirely by trucks. These airports, such as the ones in southern France, have more options. Airports that are entirely truck-served can uplift SAF blends at higher percentages if airlines are willing to purchase the more expensive fuel. Much depends on the specific fuel provider, but blending near these airports, trucking the blend to airport fuel tanks, some of which can be reserved for SAF blends, and then targeting flights with those SAF blends is possible. Along those lines, SAF targeting strategies aimed at non-CO_2 benefits were recently explored at Bordeaux airport.[88] There would be some additional costs, especially as it relates to software development and training of personnel, but SAF targeting at airports where the fuel handling logistics are currently based around trucks, is quite feasible.

Targeting SAF to specific airports has a number of logistical challenges that in many cases will need significant investment to overcome. Smaller airports that already use trucks to move fuel would incur the least amount of additional cost when adopting a SAF targeting strategy, though the impact of allocating SAF to these airports may be muted. For larger airports, the costs will depend on whether there is a suitable upstream fuel terminal location that could receive neat SAF and build blending infrastructure or a dedicated pipeline near the airport where SAF could be injected. For larger airports where neither of those things are true, SAF targeting strategies will be difficult to adopt in the near-term.

There are some large airports that are forging ahead despite the aforementioned complexity and cost. Rolls-Royce, British Airways, and Heathrow are part of the Quantifying Reduction in Thermal Contrails by Optimizing SAF (QRITOS) project, which aims to reduce contrails by targeting SAF to Heathrow.[89] To accomplish this, the airport may rely on fueling trucks, typically reserved for emergencies or when the fuel demand overwhelms the hydrant system, to deliver SAF to specific flights. Moreover, there are a number of SAF production projects beginning in the UK, one of which is headed up by LanzaJet and plans to make a £600 million investment to produce SAF at scale, targeting around 80,000 tons of SAF or 1% of UK jet fuel requirements. Projects like this lend credence to the aggressive sustainability goals at Heathrow. Despite the operational challenges, it is encouraging that some major airports are looking at SAF targeting as a viable climate strategy.

88 Bordeaux Airport (2025), *Reducing aviation's non-CO_2 effects: Bordeaux Airport, Estuaire and Elyse Energy bet on a targeted SAF distribution strategy*, https://www.bordeaux.aeroport.fr/en/laeroport/press/press-releases/reducing-aviations-non-co2-effects-bordeaux-airport-estuaire-elyse

89 Rolls-Royce (2025), *Rolls-Royce leads UK project to demonstrate smarter use of Sustainable Aviation Fuel*, https://www.rolls-royce.com/media/press-releases/2025/04-11-2025-rr-leads-uk-project-to-demonstrate-smarter-use-of-sustainable-aviation-fuel.aspx

SECTION 7

Policy Recommendations

Our findings show that targeted deployment of SAF can significantly increase climate and public health benefits. By directing SAF toward high-impact airports, warming can be reduced beyond what is possible by eliminating CO_2 emissions while also improving air quality and protecting communities near airports.

SAF targeting should not be viewed as a standalone mitigation strategy but rather as an optimization tool that can complement other non-CO_2 mitigation measures, including fleet renewal and contrail routing avoidance. While large-scale deployment of high SAF blends across all airports may be difficult in the near term due to supply constraints and logistical challenges, targeted implementation at specific locations, times, or for certain flights could begin much sooner. As SAF availability improves post-2030, this approach could become increasingly relevant. Therefore, policymakers should start creating the conditions for a more targeted and impact-driven deployment of SAF during this time.

Policymakers Should Explicitly Recognize Non-CO_2 Fuel Effects in Aviation Policy

Current regulatory frameworks are first and foremost designed around GHG emissions with little consideration of contrail-related warming and local air quality impacts. SAF will deliver CO2 reductions regardless of where it is used, but additional climate and health co-benefits are achievable with SAF targeting.

Incorporating non-CO_2 effects into policy frameworks would help ensure that SAF is not only used to reduce carbon intensity but also deployed in ways that maximize total benefits. Regulatory frameworks should therefore move beyond treating all SAF use as equivalent and introduce mechanisms that recognize and reward deployment in high impact times and locations where the same unit of fuel delivers greater overall climate and health benefits.

Policymakers should support research and analysis on targeted SAF deployment strategies.

Future work should assess how the benefit of targeted deployment compares against the additional infrastructure and logistical costs associated with concentrating SAF use to different airports, time periods, or flights. Governments should support public-private research efforts to evaluate different SAF targeting strategies and delivery models including desk research, operational modelling, and engagement with fuel infrastructure operators, airports, airlines, and pipeline companies. The aim is to assess the different delivery strategies that could be used to concentrate SAF at the best locations by comparing the associated costs to the CO_2eq benefits of projected contrail reductions and monetized avoided health damages. If those analyses confirm that the benefits are greater than the costs, it may make sense to pursue pilot programs.

In the U.S., such work could be convened through institutions such as the National Academies of Sciences. In Europe, a similar effort could be coordinated through the European Union Aviation Safety Agency (EASA), the European Commission's Joint Research Center, or initiatives supported by Horizon Europe, bringing together research centers, airlines, fuel suppliers and infrastructure operators.

Governments Should Support Pilot Programs to Test Targeted SAF Deployment at High-impact Airports

If further research confirms that the climate and public health benefits of targeted SAF allocation outweigh the additional operational and infrastructure costs associated with the strategy, governments should support pilot projects in order to show the benefits of targeted high-SAF blend rates under real operating conditions.

These pilot projects could focus on a small number of high impact airports, potentially creating targeted SAF corridors, where SAF co-benefits are likely to be the greatest, noting that benefits remain highly dependent on weather conditions that promote ISSR formation. These pilot projects should help assess the logistical, operational, cost, and distribution related implications of concentrating SAF use and generate real world evidence of the effectiveness of this approach.

In the EU, the European Commission could potentially launch a pilot project on targeted SAF deployment. The effort could be financed as a Preparatory Action or Pilot Project (PPPA) under the EU budget. The initiative should focus on a high-impact airport, target specific flights or time windows using contrail prediction tools such as ISSR forecasting models, and help develop close coordination between airlines, fuel suppliers, airports, and air traffic management on contrail-related matters.

The project should complement existing research and policy efforts on SAF, contrail science, and air quality, as well as operational measures such as flight trajectory optimization.[90] Its main purpose would be to generate real-world evidence on the scale of non-CO_2 benefits, infrastructure needs, fuel logistic constraints, and cost impact across stakeholders. This evidence could help inform future revisions of the ReFuelEU Aviation regulation and support a more efficient use of SAF over time.

Governments should invest in enabling infrastructure for targeted allocation of SAF

The SAF targeting approach outlined above requires investment in fuel infrastructure to enable a more flexible distribution system, allowing each ton of uplifted SAF to deliver the greatest overall climate and air quality benefits. This implies a shift from today's largely uniform supply model to one that can allow for differentiated blending as a function of location.

In practice this means segregated storage and delivery mechanisms both along the fuel supply chain and at airports that do not create disproportionate added costs for airlines and airports. Furthermore, the infrastructure must be designed in a way that does not undermine the lifecycle emissions from SAF, including by minimizing indirect emissions from supporting operations related to employing fuel trucks or additional fuel handling. The infrastructure also must be able to expand and evolve as SAF delivery requirements change. Given the scale of investment required, efforts should prioritize a limited number of high impact airports, such as those identified in earlier sections where targeted SAF allocation can deliver the biggest results. In the EU context, these investments could be supported through existing funding instruments, including the Innovation Fund and Connecting Europe Facility.

[90] The PPPA could build upon EU funded projects such as PACIFIC, that analyzes how SAF could help reduce soot and ice crystal formation. https://cordis.europa.eu/project/id/101192334

SECTION 8

Conclusion

While much of the transportation sector is expected to electrify as we approach mid-century, aircraft size and weight constraints will require different strategies for aviation decarbonization. Today, combustion of conventional jet fuel results in CO_2, alongside NO_x and PM emissions, the latter two of which adversely affect local air quality. A 2015 estimate attributes 16,000 premature deaths to global aviation activity annually. Additionally, at cruise altitudes PM particles can function as condensation nuclei for contrail formation, a phenomenon that traps heat, further warming the Earth's surface. As the sector cannot rely on electrification, a transition to sustainable aviation fuel is one of the primary ways to reduce CO_2 emissions, limit contrail formation, and improve air quality.

Currently SAF is scarce, commanding just a 0.7% jet fuel market share in 2025 due to high costs and limited production capability. However, as just 2% of flights generate 80% of contrail impact and any SAF uplifted will improve near-airport air quality, our analysis shows that by identifying the airports with flights that generate a large amount of contrail CO_2eq and strongly affect air quality, a small amount of SAF can make a big difference. Allocating SAF to these airports would derive the maximum benefit from a ton of fuel while the market is still small.

In the U.S., our results show that flights departing from New York JFK contribute the most to contrail-related warming. Ground emissions, specifically PM, during landing and take-off operations (LTO) at JFK are substantial as well. Looking at both contrail and LTO emissions together, JFK, LAX and O'Hare are the best locations for SAF targeting, noting fleet turnover would solve much of the LTO emissions issue at Hartsfield (newer engines emit up to 20 times less PM). The data for European airports was more straightforward. Flights from the busiest airport, London Heathrow, were responsible for the most contrail-related warming and the most emissions during LTO. The targeting analysis in Europe also includes Istanbul Airport and Paris CDG, as there are sizable impacts at those airports as well.

The results from the analysis at those six airports support the conclusion that targeting SAF to high-impact locations is always more beneficial than uniformly spreading the fuel globally. The specifics of the targeting strategy matter as well. Airport-wide targeting is comparatively simple from a logistics standpoint but would require significantly more fuel. To the extent there is SAF available for airport-wide targeting, our analysis shows there will be notable health benefits. At JFK, for example, a 30% airport-wide SAF blend results in $20.3 million in monetized health benefits.

Allocating SAF during specific months or at specific times of day is more complex but would be more fuel efficient. For example, targeting the winter months at Heathrow with a 30% SAF blend resulted in a 17.2% reduction in contrail CO_2eq and only requires SAF uplifted onto 40% of annual flights. Flight-based targeting is the most efficient use of SAF but requires accurate ISSR prediction software to determine which flights should get the fuel. This is something we see as a longer-term possibility.

Regardless of the specific strategy, airport fuel handling logistics will play a major role. Larger airports using a hydrant fuel system where fuel is distributed to aircraft through a large, sub-tarmac pipe network would face the most challenges. Still, Heathrow, which has a hydrant fuel system, used truck-based fueling in support of its effort to uplift 17% of the globally available SAF in 2024, and the airport is looking to increase its SAF use in 2026. Heathrow's experience suggests that SAF targeting is possible at major airports.

Policy to provide proper incentives is needed to help SAF targeting play a role in aviation decarbonization. We recommend policymakers explicitly recognize non-CO_2 effects and create policies that include support for further research and analysis on SAF targeting strategies. Furthermore, if that research shows benefits, governments should be ready to support pilot programs to ground test targeted SAF allocation at high-impact airports.

In summary, SAF targeting is a strategy that optimizes the effectiveness of each available ton of the cleaner fuel by uplifting it at airports where it will have the most tangible impact on local air quality and contrail-related warming. There are challenges related to fuel logistics as well as a need to incentivize this behavior via policy; however, the climate and air quality benefits can be substantial and do not require a massive SAF scaleup before they can be realized. Aviation emissions have a wide-ranging negative impact on public health and the environment. By targeting the available supplies of SAF to specific airports, we can maximize the extent to which high SAF blends can reduce both health-damaging pollution and planet-warming contrail formation.