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# Sustainable Aviation Fuel Deployment Strategies in Europe: Supply Chain Implications and Climate Benefits

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**Abstract**

Sustainable aviation fuel (SAF) could reduce aviation's $CO_2$ and contrail climate forcing. This study quantifies the contrail mitigation potential and fuel supply chain costs of a uniform SAF distribution scenario, assuming all departing flights use a 10% SAF blend by mass. Building on this, we propose three SAF allocation strategies that optimize the same SAF supply to maximise contrail mitigation, while considering real-world supply chain constraints and additional costs. A seasonal strategy – providing SAF to all flights from October to February at higher blend ratios (28%) – achieves the highest benefit-to-cost ratio (1.7–7.2) and lowest abatement cost (€14–61/t$CO_2$e). It raises annual reductions in contrail energy forcing ($EF_{contrail}$) from 7–8% (uniform vs. no-SAF scenario) to 12–13%, with supply chain costs rising by 0.5% relative to the uniform scenario. Two diurnal strategies – one targeting flights after 16:00 local time, and another adding a constraint of selecting flights with > 250 km of persistent contrails – have lower benefit-to-cost ratios (0.2–2.4) and higher abatement costs (€42–675/t$CO_2$e).

Their 1–2% rise in supply chain costs relative to the uniform scenario, outweighs the additional contrail climate benefits, as annual $EF_{contrail}$ reductions only rise from 7–8% (uniform scenario) to 9–17%.

**Keywords**: Aviation, non-$CO_2$, contrail cirrus, climate forcing, mitigation, sustainable aviation fuel, supply chain

**Synopsis**

Prioritizing sustainable aviation fuel use in winter can deliver contrail mitigation at €14–61/t$CO_2$e, below the 2024 average EU Emissions Trading System carbon price (€65/t$CO_2$e).

# 1 INTRODUCTION

Aircraft gas turbines emit gaseous $CO_2$ and non-$CO_2$ pollutants, including a mixture of volatile and non-volatile particulate matter (nvPM) which can act as condensation nuclei during contrail formation[1–4]. When taken together, the direct and indirect climate effects of these pollutants account for ~3.5% of the global anthropogenic climate forcing in 2018[5], a figure expected to rise as aviation continues to grow and other sectors continue to reduce their climate impact. Among these pollutants, the global annual mean contrail cirrus net effective radiative forcing (ERF) (57.4 [17, 98] mW $m^{-2}$, 95% confidence interval) could be the largest component of aviation's overall net ERF, followed by aviation's cumulative $CO_2$ emissions (34.3 [28, 40] mW $m^{-2}$)[5].

Sustainable aviation fuel (SAF) offers potential co-benefits for reducing aviation's: (i) $CO_2$ lifecycle emissions by 10–125%, depending on the feedstock and production pathway[6–8]; (ii) nvPM number emissions index ($EI_n$) by up to 70%, depending on the SAF properties, blend ratio, and engine thrust settings[9–12]; and (iii) initial contrail ice crystal number[13–15]. While simulations estimate that fleetwide SAF adoption could increase contrail formation by up to 8% due to its higher water vapor emissions index (EI $H_2O$)[16–18], changes in (iii) can result in larger ice crystal sizes, shorter contrail lifetimes, and reduced coverage area and optical depth. Collectively, these changes in contrail properties resulting from SAF could lower the annual mean contrail net radiative forcing (RF) by 15–50% compared to simulations with conventional aviation fuel (CAF)[15,18–20].

Although SAF supply only amounted to ~0.2% of global jet fuel consumption in 2023[21], projections suggest it could replace 2–5% of CAF by 2030[6]. To accelerate uptake, jurisdictions such as the European Union (EU), UK, and Singapore, have introduced SAF mandates requiring fuel suppliers and distributors to blend a minimum share of SAF into fuel for all departing flights: the ReFuelEU Aviation mandate starts at 2% in 2025, rising to 6% in 2030, and 70% in 2050[22]; the UK targets 2% in 2025, 10% in 2030, and 22% in 2040[23]; Singapore mandates 1% in 2026, increasing to 3-5% by 2030, depending on supply availability[24].

While SAF mandates primarily aim to mitigate aviation's $CO_2$ lifecycle emissions, an earlier study proposed to enhance SAF's total climate benefit by considering its potential in reducing the contrail energy forcing ($EF_{contrail}$, i.e., contrail climate forcing cumulated over its lifetime)[18]. This was based on findings that only 12% of all transatlantic flights contribute to 80% of the annual $EF_{contrail}$[25]. By concentrating the limited SAF supply at higher blend ratios to flights with strongly warming contrails, its overall climate benefits, including both $CO_2$ and contrails, could increase ten-fold compared to a scenario where SAF is uniformly distributed to all flights at low blend ratios[18,26]. However, these gains represent an upper limit, as the analysis did not consider contrail forecast uncertainty and potential fuel supply chain constraints.

Building on this, this paper will (i) review existing aviation fuel supply chain in Europe; (ii) quantify the contrail mitigation potential and supply chain costs of uniform SAF distribution scenario, assuming a 10% SAF blend for departing flights from all EU27 and UK airports; (iii) propose alternative SAF allocation strategies to maximize contrail mitigation with the same SAF supply; and (iv) conduct a cost-benefit comparison for these strategies by comparing their incremental climate benefits against their associated supply chain costs, and test key assumptions with a sensitivity analysis. For (iii), we focus on strategies that are feasible within committed policy timeframes and existing supply chain constraints, reflecting practical near-term options available to industry and policymakers.

## 2 AVIATION FUEL SUPPLY CHAIN IN EUROPE

This section summarises the aviation fuel supply chain in Europe, covering both CAF (Section 2.1) and SAF (Section 2.2). The supply chain begins at the refinery, continues through a fuel terminal for storage, and ends at the airport where fuel is loaded onto aircraft (Figure 1). Here, CAF refers to fossil-derived kerosene certified under the American Society for Testing and Materials (ASTM) D1655 standard[27], while SAF refers to a blend of CAF and synthetic blend component (SBC, i.e., synthetic hydrocarbons produced from renewable or waste-derived feedstocks) certified under the ASTM D7566 standard[28]. Broader SAF definitions, such as those from the International Civil Aviation Organization (ICAO)[29] and ReFuelEU Aviation[22], include additional sustainability criteria related to production methods, feedstocks, and lifecycle emissions, but these fall beyond the scope of this study.

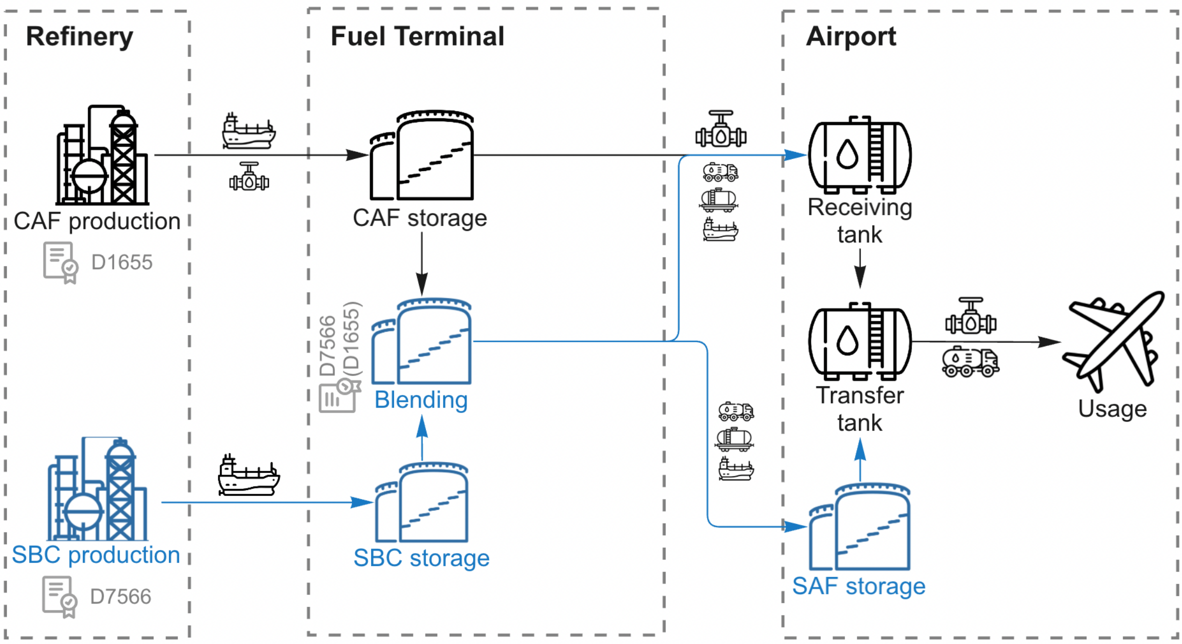

**Figure 1: Overview of the downstream supply chain for conventional aviation fuel (CAF) in Europe. The additional steps required for synthetic blend component (SBC) and sustainable aviation fuel (SAF) are coloured in blue.**

## 2.1 Conventional Aviation Fuel

Fuel is transported from refineries to fuel terminals via waterways or pipelines. These terminals, typically located near major ports, refineries, or major airports, serve as intermediate storage facilities. Here, fuel is stored in large tanks for several days, depending on fuel demand and import rates, before being transferred to airports by pipeline, barge, rail, or road tanker[30]. This provides additional storage capacity beyond the limited airport storage depots.

When transported in tanks or pipelines dedicated to a single fuel type, fuel can be transferred directly to local airport storage tanks (i.e., transfer tanks) that feed the fuel distribution system. However, if transported via multi-product pipelines or tanks that have not been cleaned according to the EI/JIG Standard 1530[31], fuel must first be transferred to segregated intermediate tanks upon reaching the airport to avoid contamination. After settling for several hours, samples are sent for re-certification before the fuel can be moved to the transfer tanks.

Airport storage capacity depends on fuel demand and supply mode[32]. Pipeline-supplied airports typically maintain storage capacity for at least three days of demand, with an additional buffer – typically around 20% - to cover future growth, supply disruption risks (notably from road tanker deliveries), tank maintenance, and seasonal fluctuations[33]. Large airports typically utilise a hydrant system to transfer fuel from airport storage to hydrant pits located at aircraft parking areas[30,34]. Hydrant dispenser trucks (i.e., vehicles connecting the hydrant pit to aircraft fuel receptacles) reduce reliance for transporting fuel via refueler trucks, thereby enhancing safety by reducing vehicle movements on the airport apron (i.e., area where aircraft are parked, refueled, and serviced during turnarounds) while also lowering both operational costs and emissions[35]. However, hydrant systems require significant capital expenditures (CAPEX) and regular maintenance to prevent system degradation, fuel contamination, and leakage. The fuel farm (i.e., area of the airport where aviation fuel is stored) is typically managed and operated either by a specialised company or a consortium of fuel suppliers, with the airport itself not owning the fuel.

## 2.2 Sustainable Aviation Fuel

SAF offers a key advantage with its drop-in capability compared to other alternative energy carriers, thereby enabling seamless integration into existing aircraft, airport fuel systems, and transport and storage infrastructure.[28] After blending with CAF, the resulting SAF must meet the full ASTM D7566 specifications. Once certified, SAF is re-designated as Jet A-1 under the ASTM D1655 specification[27], allowing it to be transported and stored using the same infrastructure. However, until certification, SBC must be transported and stored separately from CAF. Compliance is verified by the issuance of the Certificate of Quality.

Two types of blending processes have been approved for mixing SBC with CAF[31]: (i) inline blending, where the SBC and CAF are introduced simultaneously into a tank with adequate mechanical energy to ensure thorough mixing; and (ii) sequential blending, where the denser CAF is added to the tank first, followed by the lighter SBC, with the inlet located at the bottom of the tank and the blending process relying on the difference in fuel densities[36]. To achieve the required homogeneity, additional equipment such as side-entry mixers and recirculation systems is typically required. The product usually has a blend ratio of around 30% to ensure economic viability of the blending itself while reducing the probability of non-compliance of the blend with the required fuel specifications[37]. Among the eight SBC production pathways approved under ASTM D7566, five allow for a maximum SAF blend ratio of 50%, while the remaining pathways are limited to a 5–10% blend ratio. Although ASTM D7566 annexes recognize co-processed fuels, where bio-based feedstocks are refined alongside petroleum, our paper focuses exclusively on SAF produced from blending SBC and CAF. The most common type of SBC produced today is hydroprocessed esters and fatty acid synthetic paraffinic kerosene (SPK), which allows a maximum blend ratio of 50%. Other commonly used pathways include the Fisher-Tropsch and Alcohol-to-Jet SPK.

Currently, two approaches are used for distributing the SAF blends: (i) direct injection into a network system pipeline, which results in a loss of control over the final airport destination; or (ii) transportation to a specific airport, where SAF must be stored in separate tanks at the fuel terminal and transported in a traceable manner until reaching its destination. For (ii), the SAF blend is typically further mixed with CAF in the local storage tanks at the airport. From there, SAF is uniformly distributed to departing flights utilising the fuel batch, but the $CO_2$ lifecycle emission reductions can only be claimed by the airline purchasing the SAF.

# 3 MATERIALS AND METHODS

Section 3.1 outlines the contrail simulation workflow. Section 3.2 introduces the SAF allocation strategies and benchmark scenarios, while Section 3.3 discusses their supply chain implications. Section 3.4 describes the sensitivity analysis, which tests key assumptions affecting contrail mitigation estimates and supply chain costs. Additional methodological details are provided in the Supporting Information (SI). Figure S1 provides a visual overview of the methodological framework used in this study.

## 3.1 Contrail simulation

The contrail simulation utilises the: (i) global aviation emissions inventory based on ADS-B (GAIA)[38]; (ii) ERA5 high-resolution realisation (HRES) reanalysis meteorology from the European Centre for Medium Range Weather Forecast (ECMWF)[39]; and (iii) contrail cirrus prediction model (CoCiP)[40]. Four distinct contrail simulation runs were performed, where all flights are assumed to be powered by CAF, and SAF with blend ratios of 10%, 30%, and 50% respectively. We assume that the available SBC supply amounts to 10% of the 2019 annual fuel consumption from all flights departing EU27 and UK airports, totaling $5.3 \times 10^9$ kg (Table

S1). While the ReFuelEU SAF target is a 6% blend by 2030, our 10% assumption is justified by broader industry ambitions[41].

### 3.1.1 Global aviation emissions inventory

GAIA provides the following data for 40.2 million flights globally in 2019: (i) flight metadata, which records the origin-destination airports; (ii) historical flight trajectory flown, provided as a sequence of flight waypoints with temporal resolution of 40–60 s; and (iii) the fuel mass flow rate ($\dot{m}_{\mathrm{f}}$), overall efficiency, and nvPM $\mathrm{EI_n}$ at each waypoint[38]. Here, GAIA is filtered to only include the 6.8 million flights that departed from EU27 and UK airports in 2019 (Figure S2), reflecting the operational scope of the ReFuelEU and UK SAF mandates.

The nvPM $\mathrm{EI_n}$ is influenced by different fuel properties (i.e., aromatics and hydrogen content)[11,12]. Since the nvPM $\mathrm{EI_n}$ estimates from GAIA assumes fleetwide CAF usage, we estimate the reduction in nvPM $\mathrm{EI_n}$ resulting from SAF with different blend ratios ($p_{\mathrm{blend}}$ in %) as follows[18],

$$\Delta \mathrm{nvPM\ EI_n}[\%] = \begin{cases} \left(-114.21 + 1.06\hat{F}\right) \times \Delta H & \text{, when } \Delta H \leq 0.5\% \\ \left(-114.21 + 1.06\hat{F}\right) \times \Delta H \times e^{0.5\times(0.5-\Delta H)} & \text{, when } \Delta H > 0.5\% \end{cases} \quad (1)$$

where the engine thrust settings ($\hat{F}$ in %) is estimated as the ratio of the equivalent $\dot{m}_{\mathrm{f}}$ at mean sea level conditions ($\dot{m}_{\mathrm{f}}^{\mathrm{MSL}}$, calculated using Eq. 2 of Teoh et al.[18]) to the engine-specific maximum $\dot{m}_{\mathrm{f}}^{\mathrm{MSL}}$ given by the ICAO Aircraft Emissions Databank[42], and $\Delta H$ is the difference in hydrogen mass content between the CAF ($H_{\mathrm{ref}} = 13.8\%$) and SAF ($H_{\mathrm{SAF}}$),

$$H_{\mathrm{SAF}}[\%] = H_{\mathrm{ref}} + 0.015 \times p_{\mathrm{blend}}\ [\%]. \quad (2)$$

### 3.1.2 Meteorology

Meteorological and radiation fields are provided by the ECMWF ERA5 HRES reanalysis at a spatiotemporal resolution of 0.25° longitude × 0.25° latitude over 37 pressure levels and at hourly intervals[43]. To address the limitations of the ERA5 HRES humidity fields[25,44,45], we apply a global humidity correction[46] to adjust the probability density function of the ERA5-derived RHi so it is consistent with those obtained from in-situ measurements[47,48].

### 3.1.3 Contrail cirrus prediction model

CoCiP simulates the contrail lifecycle, its microphysical properties and climate forcing along flight trajectories[40,49]. Contrail segments are initialised when the ambient temperature at two consecutive flight waypoints is below the Schmidt-Appleman Criterion threshold temperature ($T_{SAC}$)[1]. It then simulates the wake vortex downwash[50] and evolution of persistent contrail segments with model time step of 300 s until its end-of-life[40]. Persistent contrail segments are defined when their post-wake vortex ice water content is above $10^{-12}$ kg kg$^{-1}$. The contrail segment lifetime ends when ice crystal number concentrations fall below ambient levels (< $10^3$ m$^{-3}$), optical depth drops below $10^{-6}$, or when its lifetime exceeds the prescribed limit of 12 h[46].

For SAF simulations, the fuel lower calorific value ($Q$) and EI $H_2O$, both of which influences $T_{SAC}$, is assumed to increase linearly with $p_{blend}$[18],

$$Q_{\mathrm{SAF}} = Q_{\mathrm{ref}} + 10700 \times p_{\mathrm{blend}}\ [\%], \text{ and} \tag{3}$$

$$\mathrm{EI}_{\mathrm{H_2O,SAF}} = \mathrm{EI}_{\mathrm{H_2O,ref}} \times \left(\frac{H_{\mathrm{SAF}}}{H_{\mathrm{ref}}}\right), \tag{4}$$

where $Q_{ref}$ = 43.1 MJ kg$^{-1}$ and $\mathrm{EI}_{\mathrm{H_2O,ref}}$ = 1.23 kg kg$^{-1}$. SAF also lowers the nvPM $EI_n$, see Eq. (1), thereby lowering the initial number of contrail ice crystals, which can increase the ice crystal sizes and lower the contrail lifetime and $EF_{contrail}$[18].

### 3.1.4 Climate metrics and monetization

We use the $EF_{contrail}$ metric to evaluate the effectiveness of different SAF allocation strategies[51],

$$\mathrm{EF}_{\mathrm{contrail}}[\mathrm{J}] = \int_0^T \mathrm{RF}'_{\mathrm{net}}(t) \times L(t) \times W(t)\, \mathrm{d}t, \quad (5)$$

where $\mathrm{RF}'_{\mathrm{net}}$, $L$, $W$, and $T$ are the contrail local net RF, contrail segment length, width, and lifetime respectively. Unlike the RF metric, which estimates the contrail forcing at a defined spatial region and at one point in time, the $EF_{contrail}$ can attribute the contrail RF to individual flights and compare the contrail mitigation potential between different SAF allocation strategies.

The $EF_{contrail}$ can be monetized by converting it to a $CO_2$ mass-equivalent ($m_{\mathrm{CO_2,eq}}$) and then multiplying it with the traded price of carbon ($\mathrm{TP}_{\mathrm{CO_2}}$),

$$m_{\mathrm{CO_2,eq}} \times \mathrm{TP}_{\mathrm{CO_2}}, \text{ where} \quad (6)$$

$$m_{\mathrm{CO_2,eq}} = \frac{\mathrm{EF}_{\mathrm{contrail}} \times (\frac{\mathrm{ERF}}{\mathrm{RF}})}{\mathrm{AGWP}_{\mathrm{CO_2,TH}} \times S_{\mathrm{Earth}}} \quad (7)$$

We make the following assumptions: (i) $\mathrm{TP}_{\mathrm{CO_2}}$ = €100 per metric tonne of $CO_2$ ($tCO_2$) reflects the projected price for the EU emissions trading scheme (ETS) in 2026–2030[52]; (ii) ERF/RF ratio of 0.42 converts the contrail net RF to an ERF estimate[5]; (iii) $CO_2$ absolute global warming potential over a 100-year time horizon ($\mathrm{AGWP}_{\mathrm{CO_2,100}}$ = 2.78 $\times 10^{-6}$ J $m^{-2}$ per kg-$CO_2$)[53]; and (iv) the Earth's surface area ($S_{Earth}$) is 5.101 $\times 10^{14}$ $m^2$. Assumptions (ii) and (iii) are adopted to be conservative with the contrail climate forcing estimates.

## 3.2 SAF allocation

Table 1 summarises the three proposed SAF allocation strategies alongside three reference scenarios that serve as benchmarks for evaluating their effectiveness. Across all scenarios and strategies, the SBC supply is assumed to be 10% of the 2019 annual fuel consumption from departing flights in the EU27 and UK. We devise the three SAF allocation strategies based on known diurnal and seasonal factors that influence the contrail warming effects[25]. Additionally, various supply chain requirements are considered to assess the storage, transport, and distribution options for the three SAF allocation strategies.

**Table 1: Summary of the three SAF allocation strategies (seasonal, diurnal, and diurnal-plus-contrail forecast strategies) and three reference scenarios (no-SAF, uniform, and hypothetical scenarios) evaluated in this study. For each scenario and SAF allocation strategy, we also evaluate the change in contrail mitigation potential and supply chain costs, where applicable, as part of a sensitivity analysis to test key assumptions (see Section 3.4).**

| | Description | Supply chain requirements |
|---|---|---|
| | **Reference scenarios⁺** | |
| **No-SAF scenario** | Business as usual, where all flights are powered by CAF. | n/a |
| **Uniform scenario** | • SBC is assumed to be uniformly distributed to all flights with a 10% SAF blend ratio*.<br>• Expected implementation of the ReFuelEU and UK SAF mandates. | • Requires blending facilities at the fuel terminal. |
| **Hypothetical scenario** | • SBC is blended with CAF to produce SAF with a 30% blend ratio*, where it is targeted to flights with the largest absolute reduction in $EF_{contrail}$ until supply runs out.<br>• Provides an idealised upper bound for the contrail mitigation potential achievable with the available SAF supply. | • Requires SAF storage facility and additional refueler trucks at the airport, and,<br>• Assumes perfect contrail forecast without accounting for uncertainties. |
| | **Proposed SAF allocation strategies** | |
| **Seasonal strategy** | • SBC is blended with CAF to produce SAF with a mean blend ratio of 28%, where it is provided to all flights from October to February.<br>• During these months, persistent contrail formation and its warming effects are expected to be at a seasonal peak. | • Requires additional fuel storage and blending facilities at the fuel terminal. |
| **Diurnal strategy** | • SBC is blended with CAF to produce SAF with a 30% blend ratio*, where it is targeted to flights departing after 16:00 local time until supply runs out.<br>• Contrails formed at dusk/night are expected to be warming (i.e., positive $EF_{contrail}$). | • Requires SAF storage facility at the airport,<br>• Assumes a daily re-supply of SAF at 16:00 local time. |
| **Diurnal-plus-contrail forecast strategy** | • SBC is blended with CAF to produce SAF with a 30% blend ratio*, where it is targeted to flights: (i) departing after 16:00 local time; and (ii) and were simulated to form at least 250 km of persistent contrails until supply runs out.<br>• Contrails formed at dusk/night are expected to be warming (i.e., positive $EF_{contrail}$). | • Requires SAF storage facility and additional refueler trucks at the airport, and a contrail forecasting tool,<br>• Assumes a daily re-supply of SAF at 16:00 local time. |

$^{+}$: The three reference scenarios are used as benchmarks to evaluate the effectiveness of the proposed SAF allocation strategies in mitigating the contrail climate forcing.

*: An X% SAF blend ratio refers to a mixture of X% SBC and (100 – X)% CAF by mass.

### 3.2.1 Uniform scenario

Airports handling over 1 million passengers or 100,000 metric tonnes of freight annually are subject to the ReFuelEU mandate[22]. Applying this to EU27 and UK airports yields a total of 150 airports, which collectively account for 98.2% of the annual jet fuel demand. We assume that SAF is uniformly distributed across these airports, i.e., “all airports” scenario, with allocations based on each airport’s share of their 2019 annual fuel consumption. No additional supply chain infrastructure nor operation is needed.

### 3.2.2 Seasonal strategy

SBC is blended at a higher ratio (mean of 28%) and distributed exclusively to all flights from October to February, when persistent contrail formation and its warming effects are at a seasonal peak[25,46]. We assume that SBC is produced consistently throughout the year. Therefore, additional storage tanks are necessary for storing the SBC reserves between March and September (SI §S2.2.1). These extra storage capacities are assumed to be installed at fuel terminals rather than airports, where larger tank capacity and land are more readily available at lower costs. During these months, SBC is blended on a just-in-time basis and mixed into the fuel supply as it leaves the terminal. There are no other additional requirements at the airport.

### 3.2.3 Diurnal strategy

Following current blending practice, we assume that a 30% SAF blend is re-supplied to airports daily at 16:00 local time and utilized on a first-come-first-serve basis until depletion. This strategy focuses on targeting contrails formed during dusk and nighttime, when their warming is at a diurnal maximum. It requires separate SAF storage facilities at the airport, but aircraft re-fueling can still be done through the hydrant system.

#### 3.2.4 Diurnal-plus-contrail forecasting strategy

SAF is blended at a 30% ratio and targeted to flights departing after 16:00 local time and with over 250 km of persistent contrails, as identified using theERA5 HRES reanalysis meteorology (Section 3.1.2). SAF is re-supplied daily at 16:00 local time and allocated on a first-come-first-serve basis until depletion. To target SAF to specific flights, it must be stored in separate tanks at the airport and supplied to aircraft using refueler trucks instead of the hydrant system to avoid mixing it with non-SAF fuel[26]. Moreover, this strategy also requires a contrail forecasting tool which entails coordination with additional stakeholders (i.e., airlines and flight planners) and the establishment of new operational workflows. As a recent study demonstrated that a contrail forecasting tool can be readily integrated into a commercial flight planning system[54,55], we assume that associated computing and labour costs are negligible and exclude them from the supply chain modelling.

#### 3.2.5 Hypothetical scenario

This scenario assumes that a 30% SAF blend is allocated to flights in order of their highest absolute reduction in $EF_{contrail}$ until supplies are depleted[18]. It represents an idealized upper bound for the potential climate benefits and serves as a benchmark to evaluate how much of this benefit is captured by the three allocation strategies. In practice, achieving these benefits is challenging due to the requirement of a perfect contrail forecast without uncertainties, and incompatibility with real-world supply chain logistics. Therefore, we do not model the supply chain costs for this scenario.

### 3.3 Supply chain costs

We model the aviation fuel supply chain costs starting from the refinery until it is loaded onto aircraft. These costs consist of transportation costs from the refinery to the fuel terminal, and from the fuel terminal to airports (Section 3.3.1), fuel terminal costs, encompassing both storage and blending costs (Section 3.3.2), and airport-related costs, which includes the storage and handling of fuel (Section 3.3.3). The unit costs for CAF and SBC are assumed to be €0.64/kg and €2.46/kg respectively.

### 3.3.1 Transportation costs

Specific fuel transportation costs depend on the share of transport modes used, but detailed cost information is generally not publicly available. Based on industry estimates that incorporate representative transport distances for each mode, we assume average fuel transportation costs of €10/m$^3$ for pipeline, €15/m$^3$ for barge, €30/m$^3$ for sea vessel, €50/m$^3$ for rail, and €100/m$^3$ for road transport respectively. In 2019, the EU imported 23% of its CAF from international markets[56], with our assumption being that it was transported via sea vessel to EU fuel terminals. The remaining 77% is assumed to be transported via pipeline from EU refineries to fuel terminals. Additionally, we assume all SBC is sourced locally and transported by barge to fuel terminals, as around 80% of European SBC production capacity is located near ports[57]. Based on these assumptions, the annual CAF and SAF transportation costs from the refinery to fuel terminals across all strategies are estimated at €997 million (Table S1). However, if SBC is instead imported via international markets, these transportation costs will rise by 11% to €1.1 billion as SBC must be transported via sea vessels instead of barges. The transportation modes for CAF from fuel terminals to the top 20 EU27 and UK airports are estimated from publicly available data and interviews with subject matter experts (Table S5): (i) 62% of the fuel reaches these airports via multi-product pipelines, thereby requiring additional certification at the airport; and the remaining (ii) 19% by dedicated pipelines; (iii) 9% by road tankers; (iv) 7% by rail; and (v) 3% by barges. For smaller airports, we assume that their fuel is delivered by road tankers. For the uniform scenario, the fuel transportation costs from fuel terminals to all airports are estimated at €3.06 billion (Table S6). The same costs apply to the seasonal SAF strategy, as it relies on existing transportation infrastructure.

Strategies that target SAF to specific flights can pose challenges to existing pipeline operations, such as the Central Europe Pipeline System, where fuel flows through a shared network accessible to all connected airports. To facilitate targeted supply of specific fuel batches, we assume that all SAF transportation in these strategies are shifted from pipelines (€10/$m^3$) to road tankers (€100/$m^3$). This reflects a worst-case scenario, as cheaper rail alternatives (€50/$m^3$) could also be used for some airports. Consequently, the modal share of road tankers increases from 36% (uniform scenario) to 43%, while pipeline use decreases from 56% to 50%. This leads to a 14% increase in transportation costs, from €3,061 million (Table S6) to €3,478 million (Table S7).

### 3.3.2 Fuel terminal costs

Fuel terminal costs are comprised of: (i) storage costs, based on storage duration and fuel volume; and (ii) blending costs, which encompass both CAPEX for new blending infrastructure and their associated operational costs (OPEX). CAPEX is derived from tank capacity and fuel volume considerations[58], while the OPEX is estimated as a function of labour, utilities, and fuel certification (SI §S2.2).

CAF is assumed to be stored for 72 h, while SAF blending takes another 90 h (Table S3). Fuel storage is estimated at €10/$m^3$/month. In line with current production practice, we assume that CAF and SBC are both produced and imported all year long. Specifically, for the seasonal strategy, SBC is stored in reserves between March and September (Section 3.2.2), which increases its annual storage costs by €222 million relative to the uniform scenario (SI §S2.1).

### 3.3.3 Airport fuel storage and distributing costs

Fuel storage costs at airports include both: (i) CAPEX (e.g., floating roof tanks, Table S9); and (ii) OPEX, including labour, utility, and fuel certification (Table S10). The diurnal and diurnal-plus-contrail forecast strategies both require additional low-volume tanks to segregate SAF (Table S11), thereby increasing annual airport fuel storage costs by €457 million (Table S12).

The top 20 airports are modelled to distribute fuel to individual aircraft via hydrant systems, except at Helsinki-Vantaa airport, while remaining airports are assumed to rely on refueling trucks. For the uniform scenario, and the seasonal and diurnal strategies, annual fuel distribution costs are estimated at €53 million (SI §S2.5 and Table S14). For the diurnal-plus-contrail forecast strategy, these costs rise by €4 million, as SAF must be delivered to specific flights using refueler trucks instead of the hydrant system (Table S14).

### 3.4 Sensitivity analysis

We conduct three sensitivity analyses to quantify the changes in contrail mitigation potential and supply chain costs resulting from: (i) lowering the time horizon used to monetize the contrail climate forcing from 100 years to 20-years ($AGWP_{CO_2,20}$ = 7.54 $\times 10^{-7}$ J $m^{-2}$ $kg^{-1}$)[53], which places a higher weight on short-lived forcers such as contrails; (ii) increasing the SAF blend ratio from the current practice of 30% to 50% , which lowers the volume of SAF handled and reduces supply chain costs; and (iii) limiting SAF availability to the top 20 EU27 and UK airports, instead of all airports. Allocating SAF to the top 20 airports, which collectively represent 70% of the annual jet fuel demand (Figure S3), could streamline the supply chain requirements by focusing resources on fewer and high-demand airports.

## 4 RESULTS & DISCUSSION

### 4.1 Contrail mitigation potential

Table 2 summarizes the reduction in annual $EF_{contrail}$ for the three strategies, and reference scenarios. These are compared to a no-SAF scenario, where the annual $EF_{contrail}$ is estimated at 2.81 $\times 10^{20}$ J. The reduction in annual $EF_{contrail}$ ranges from 7.7% (uniform scenario) to 25.3% (hypothetical scenario).

The diurnal-plus-contrail forecast strategy has the highest contrail mitigation potential (-14.5% reduction in annual $EF_{contrail}$ relative to the no-SAF scenario). It achieves this despite utilizing only 95% of the available SAF supply, as smaller airports lacked enough flights simulated with >250 km of contrails. The seasonal strategy has a higher contrail mitigation potential than the diurnal strategy (-12.9% vs. -11.8% reduction in annual $EF_{contrail}$) which can be attributed to the: (i) shorter daylight hours in wintertime, which increases the probability of forming net warming contrails; (ii) larger coverage of ice supersaturated regions in winter, which increases the (iii) persistent contrail formation by around two-fold; and (iv) mean contrail lifetimes by around 0.5 h relative to the summer[25,46,59]. Despite operating within supply chain and forecast constraints, the SAF allocation strategies still achieve 47–57% of the contrail climate benefits as estimated for the hypothetical scenario.

**Table 2: Percentage change in annual $EF_{contrail}$ for the reference scenarios and SAF allocation strategies compared to a no-SAF scenario (annual $EF_{contrail}$ = 2.81 $\times 10^{20}$ J). The default analysis assumes that SAF is distributed to all airports, and SAF is blended at a 30% ratio for the diurnal and diurnal-plus-contrail-forecast strategies. Additionally, as part of the sensitivity analysis in Section 4.4, two alternative scenarios are included, where: (i) SAF is distributed only to the top 20 EU27 and UK airports; or (ii) SAF is blended at a 50% ratio for the diurnal and diurnal-plus-contrail forecast strategies. The values in brackets indicate the multiplier of additional contrail climate benefits relative to the uniform scenario.**

| Scenarios | | Change in annual $EF_{contrail}$ vs. no-SAF scenario (Multiplier relative to uniform scenario) | | | | |
|---|---|---|---|---|---|---|
| SAF distribution | SAF blend ratio for diurnal strategies | Uniform | Seasonal | Diurnal | Diurnal-plus-contrail forecasts | Hypothetical |
| All airports | 30% | -7.7% | -12.9% (1.68) | -11.8% (1.53) | -14.5% (1.88)[a] | -25.3% (3.29) |
| Sensitivity analysis: Section 4.4 | | | | | | |
| Top 20 airports only | 30% | -7.2% | -11.6% (1.61) | -8.6% (1.19) | -10.7% (1.49) | -16.5% (2.29) |
| All airports | 50% | -7.7% | -12.9% (1.68) | -12.6% (1.64) | -16.6% (2.16)[b] | -34.2% (4.44) |

[a]: Only 94.8% of the available SAF supply was utilized due to the lack of flights departing from smaller airports that were simulated to form persistent contrails over 250 km.

[b]: Only 97.8% of the available SAF supply was utilized due to the lack of flights departing from smaller airports that were simulated to form persistent contrails over 250 km.

## 4.2 Supply chain costs

Table 3 presents the estimated supply chain costs for the uniform scenario and three SAF allocation strategies. In the uniform scenario, SAF is blended at the fuel terminal and distributed to airports similarly to CAF, resulting in the lowest annual cost (€49.6 billion). This cost can be broken down into CAF (63.0%) and SBC supply costs (26.4%), transportation from refineries to fuel terminals (2.0%), blending and storage at terminals (0.3%), transportation from terminals to airports (6.2%), storage at airports (2.0%), and distribution to aircraft (0.1%).

For the three SAF allocation strategies, the increase in overall supply chain costs relative to the uniform scenario range between €222 million (+0.45%) and €879 million (+1.8%). The seasonal strategy exhibits the smallest increase in overall costs (€222 million) because it only requires additional fuel storage capacity at fuel terminals to accommodate the SBC reserves between March and September (Figure S4). Meanwhile, SAF can be distributed to airports using existing infrastructure and processes. The additional costs incurred from the two diurnal allocation strategies (€874–879 million) can be attributed to: (i) higher transportation cost from fuel terminals to airports (€417 million, +14%, Table S6 vs. Table S7) because SAF can only be transported via road tankers; (ii) additional storage tank requirements to segregate SAF at airports (€457 million, +46%, Table S12); and (iii) higher fuel distribution costs for the diurnal-plus-contrail forecast strategy (€4.0 million, +7.5%, Table S14) because targeted flights must be refueled using refueler truckers instead of the hydrant system.

**Table 3: Total supply chain costs for the uniform scenario, along with the additional supply chain costs incurred by the proposed SAF allocation strategies (i.e., seasonal, diurnal, and diurnal-plus-contrail forecasts) relative to the uniform scenario. These estimates assume that SAF is distributed to all airports in the EU27 and UK, and SAF is blended at a 30% ratio in the diurnal and diurnal-plus-contrail-forecast strategies. Detailed calculations of these cost estimates are provided in the SI §S2.**

| Supply chain costs (€ million) | Total costs | Additional costs relative to the uniform scenario (SAF distribution to all EU27 and UK airports) | | |
|---|---|---|---|---|
| | Uniform | Seasonal | Diurnal (30% blend) | Diurnal-plus-contrail forecasts (30% blend) |
| CAF supply costs[a] | 31,226 | 0 | 0 | 0 |
| SBC supply costs[b] | 13,070 | 0 | 0 | 0 |
| Transportation costs (Refinery to terminal) | 997 | 0 | 0 | 0 |
| Storage and blending costs at terminal | 169 | +222 (+131%) | 0 | 0 |
| Transportation costs (Terminal to airport) | 3,061 | 0 | +417 (+14%) | +417 (+14%) |

| | | | | |
|---|---|---|---|---|
| **Storage costs at airport** | 1,005 | 0 | +457 (+46%) | +457 (+46%) |
| **Fuel distribution at airport** | 53 | 0 | 0 | +4.0 (+7.5%) |
| **TOTAL** | 49,581 | +222 (+0.45%) | +874 (+1.7%) | +879 (+1.8%) |

[a]: The annual CAF supply costs are calculated by multiplying the total annual CAF consumption (48.79 $\times 10^9$ kg, see Table S1) by the assumed unit cost (€0.64/kg).

[b]: The annual SBC supply costs are calculated by multiplying the total annual SBC consumption (5.313 $\times 10^9$ kg, see Table S1) by the assumed unit cost (€2.46/kg).

## 4.3 Cost-benefit comparison

We evaluate the cost-effectiveness of our SAF allocation strategies by estimating their: (i) specific abatement cost, a commonly used metric for assessing climate mitigation strategies in aviation[54,60], which measures the incremental supply chain cost for reducing $m_{\mathrm{CO_2,eq}}$ above the uniform scenario (Eq. (7) and Table 2); and (ii) benefit-to-cost ratio, where the incremental reduction in $m_{\mathrm{CO_2,eq}}$ is monetized using Eq. (6) and divided by the additional supply chain costs (Table 3). Both metrics assume a 100-year $CO_2$ AGWP.

**Table 4: Cost-benefit comparison for the three targeted SAF allocation strategies (i.e., seasonal, diurnal, and diurnal-plus-contrail forecasts) relative to the uniform scenario. The default analysis assumes a $CO_2$ AGWP time horizon of 100 years ($AGWP_{CO_2,100}$), see Eq. (6) and (7), and SAF is distributed to all airports and blended at a 30% ratio for the diurnal and diurnal-plus-contrail forecast strategies. Additionally, as part of the sensitivity analysis in Section 4.4, three alternative scenarios are included, where: (i) a 20-year $CO_2$ AGWP time horizon is assumed; (ii) SAF is distributed only to the top 20 EU27 and UK airports; or (iii) SAF is blended at a 50% ratio for the diurnal and diurnal-plus-contrail forecast strategies.**

| **Scenarios** | | | **Specific abatement costs, in € per metric tonne of $CO_2$e** | | | **Benefit-to-cost ratio** | | |
|---|---|---|---|---|---|---|---|---|
| **SAF distribution** | **$AGWP_{CO_2}$ time horizon** | **SAF blend ratio for diurnal strategies** | **Seasonal** | **Diurnal** | **Diurnal-plus-contrail forecasts** | **Seasonal** | **Diurnal** | **Diurnal-plus-contrail forecasts** |
| **All airports** | 100 years | 30% | €51.30 | €256 | €155 | 1.95 | 0.39 | 0.64 |
| Sensitivity analysis: Section 4.4 | | | | | | | | |
| **All airports** | 20 years | 30% | €13.91 | €69.47 | €42.13 | 7.19 | 1.44 | 2.37 |
| **All airports** | 100 years | 50% | €51.30 | €134 | €73.98 | 1.95 | 0.75 | 1.35 |
| **Top 20 airports only** | 100 years | 30% | €60.62 | €675 | €272 | 1.65 | 0.15 | 0.37 |

Table 4 shows that the seasonal strategy is the only approach with a benefit-to-cost ratio above one (1.95) while also achieving the lowest specific abatement cost (€51.30/t$CO_2$e). In contrast, both diurnal allocation strategies have benefit-to-cost ratios below 1, meaning that the increase in supply chain costs exceeds the incremental contrail climate benefits. Consequently, their abatement costs (€155–256/t$CO_2$e) are 3 to 5 times larger than that of the seasonal strategy. Notably, the benefit-to-cost ratio of the diurnal-plus-contrail forecast strategy (0.64) is around 1.7 times larger than that of the pure diurnal strategy (0.39), suggesting that the additional climate benefits of targeting SAF to specific flights outweigh the extra costs of re-fueling aircraft via refueler trucks.

### 4.4 Sensitivity analysis

The cost-benefit metrics for our SAF allocation strategies are most sensitive to the $CO_2$ AGWP time horizon used to calculate $m_{\mathrm{CO_{2,},eq}}$ in Eq. (7). When the time horizon is reduced from 100 to 20 years, the benefit-to-cost ratio for all three strategies increases by a factor of 3.7 and exceed one, while the specific abatement costs reduce by 73% (Table 4). This change places a higher emphasis on short-lived forcers, thereby amplifying the perceived contrail mitigation benefits of SAF.

For the two diurnal strategies, raising the SAF blend ratio from 30% to 50% approximately doubles the benefit-to-cost ratio and halves the abatement costs. This is because SAF's contrail mitigation potential is increased by 7–15%, while total supply chain costs are reduced by around 5% (Table S16 vs. Table 3). The increased SAF mitigation potential comes from a higher proportion of SAF being concentrated to flights departing at dusk, when contrail warming effects are more likely to be larger than those formed after midnight[25]. Additionally, higher blend ratios result in smaller SAF volumes, lowering the total supply chain costs across all stages (Section S3).

Finally, limiting SAF availability to the top 20 airports lowers the benefit-to-cost ratio of each allocation strategy by 15–62% (Table 4). This is primarily due to a 6–26% reduction in SAF's contrail mitigation potential (Table 2), likely driven by the higher share of long-haul, widebody flights (> 6 h) departing the top 20 airports compared to all airports (13.9% vs. 7.1% of all flights), which consume 2.3 times more fuel per kilometer than short- and medium-haul flights (7.8 vs. 3.4 kg $km^{-1}$). Consequently, their higher fuel consumption rate likely causes the mean $\Delta EF_{contrail}$ per kilogram of SAF to be 18% lower at the top 20 airports compared to smaller airports (-3.7 vs. -4.5 $\times 10^8$ J $kg^{-1}$).

While restricting SAF to the top 20 airports reduces SAF's contrail mitigation potential, it also cuts airport SAF storage costs by 57% compared to the all-airports scenario (Table S12) because fewer SAF storage tanks are required (Table S11). However, these savings are partially offset by a 41% increase in SAF transportation costs from fuel terminals to the top 20 airports (Tables 3 and S15), because pipeline delivery must be replaced with road transport (Sections 2.2 and 3.3.1), whereas smaller airports already rely on road tankers.

# 5 IMPLICATIONS

SAF can reduce aviation's $CO_2$ lifecycle emissions, engine particle number emissions, and contrail climate forcing[12,13,15]. An earlier study found that prioritizing the limited SAF supply towards flights with strongly warming contrails can increase its overall climate benefits by 9–15 times, though without accounting for supply chain implications[18]. Here, we propose three SAF allocation strategies and compare their additional contrail climate benefits and supply chain costs against those of a uniform scenario.

While targeted SAF allocation strategies can increase the overall climate benefits by up to two-fold compared to the uniform scenario (Table 2), it also introduces supply chain complexity. Given these trade-offs, we recommend a seasonal allocation strategy which blends SBC at higher ratios and supplied to all departing flights between October and February. This strategy offers the highest benefit-to-cost ratio (1.7–7.2), consistently above one across different $CO_2$ AGWP time horizons (100 vs. 20 years) and airport SAF availability (top 20 vs. all airports). Its effectiveness stems from: (i) SAF's greater contrail mitigation potential in winter[25]; (ii) lower storage costs at terminals relative to airports; and (iii) operational simplicity, as SAF is distributed to airports using existing infrastructure. Its specific abatement costs (€14–61/t$CO_2$e, Table 4) also fall between those of contrail mitigation via flight trajectory optimization (< €1–3/t$CO_2$e)[54] and the 2024 average EU ETS carbon prices (€65/t$CO_2$e)[61]. In contrast, the two diurnal strategies have higher abatement costs (€42–675/t$CO_2$e) and only exhibit benefit-to-cost ratios above one under a 20-year $CO_2$ AGWP time horizon.

While our strategies assume fixed time-based thresholds, more flexible approaches, such as variable monthly SBC allocations and/or seasonally adapted start times, may further improve outcomes. Our proposed strategies may also apply to hydrotreated CAF, which has lower unit costs than SAF and can similarly reduce engine particle number emissions and contrail climate forcing[62,63]. We acknowledge limitations in our study, including: the need to adapt the book and claim system[64] to allow SAF delivery to specific airports; exclusion of second-order environmental impacts from changes in supply chain operations (e.g., $CO_2$ emissions from SBC imports and additional road tankers); and the unmodeled potential activation of volatile particulate matter in forming contrail ice crystals, which may reduce SAF's contrail mitigation under specific conditions[3,65,66], Finally, our findings may not be directly applicable to other regions outside Europe due to spatial variabilities in contrail formation and its warming effect[46].

## Author contributions

EW, RT, MEJS and RM conceptualised the study and developed the methodology. EW and RT undertook the investigation, created the figures, and wrote the original manuscript. MEJS and RM acquired funding. All authors have read, edited, and reviewed the manuscript, and they agreed upon the published version of the paper.

## Supporting Information

The Supporting Information is available at <assigned URL>: and provides additional methodological details on the: (i) contrail simulation workflow; (ii) supply chain costs, including transportation, fuel terminal, airport fuel storage, and fuel distribution costs; and (iii) sensitivity analysis for each SAF allocation strategy across different scenarios.

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