

# INSIDER'S PERSPECTIVE

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## AVIATION'S NET ZERO CHALLENGE

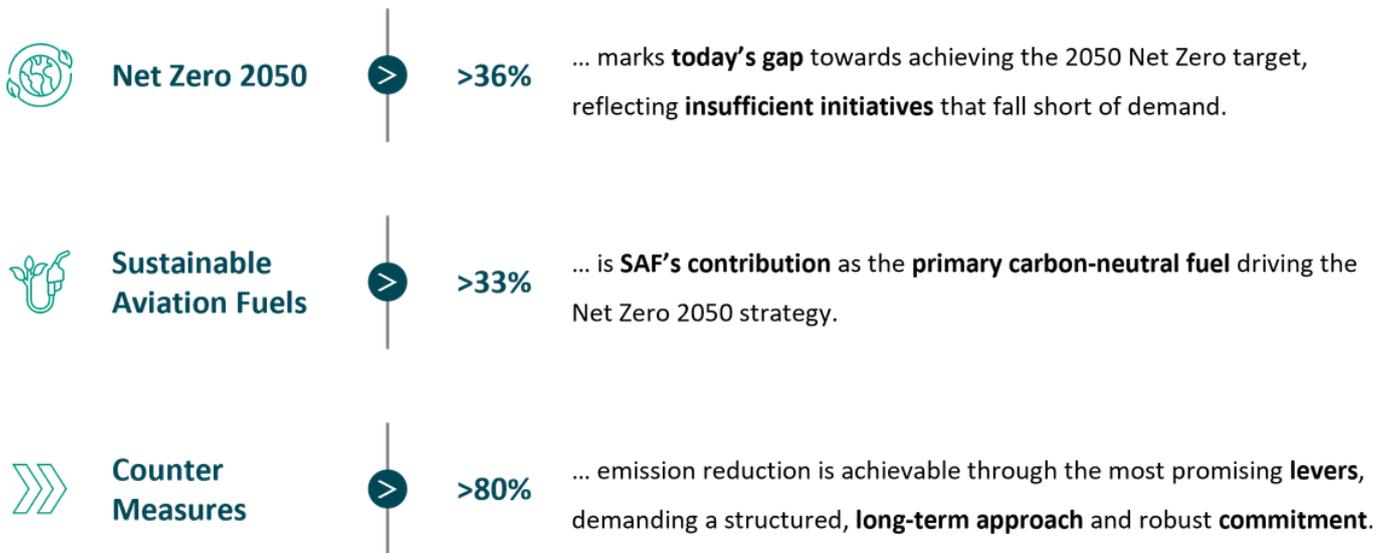
**Today's perspective on carbon-free aviation**

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## Abstract

Achieving Net Zero, defined as balanced greenhouse gas emissions causing no further impact on the climate, seems no longer realistic for the aviation sector by 2050; current trajectories reveal a substantial gap of over 36% between ambition and actual progress. This analysis highlights three core dimensions: the magnitude of emissions reduction shortfall, the primary role of Sustainable Aviation Fuels (SAF) and the necessity for a robust portfolio of countermeasures.



This insight quantifies the critical levers and adoption challenges, providing strategic overview for aviation and aerospace into the urgent and coordinated actions required to close the gap towards Net Zero Emissions 2050 objectives.

## Introduction

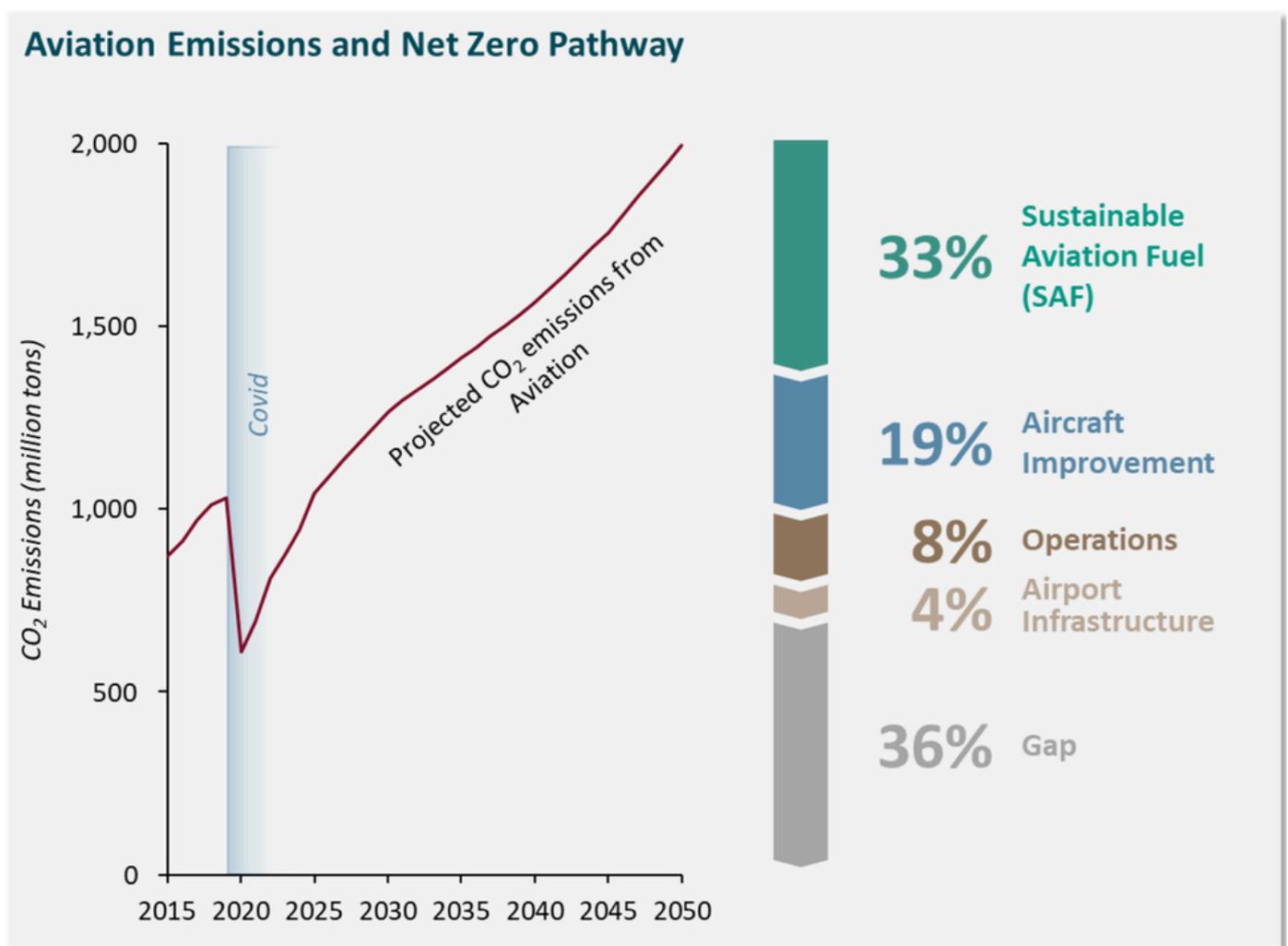
The aviation industry, despite officially committing to achieving Net Zero emissions by 2050, is currently expected to miss this target by 36%. This shortfall is significant given its alignment with the Paris Agreement, which mandates a 45% emission reduction by 2030 and Net Zero by 2050.

Analysis of current strategies and initiatives shows that Sustainable Aviation Fuels (SAF) are the single largest lever, with the potential to deliver roughly one third of the achievable reductions. In contrast, technological aircraft improvements, together with better flight operations and upgraded airport infrastructure, offer substantial long-term potential but are expected to deliver only 19% of the reductions. Even when combined, these initiatives will not be sufficient to fully achieve the Net Zero target.

Moreover, the SAF contribution is facing a variety of challenges such as limited production capacities and lower price competitiveness towards kerosene. Also, development is slow for particularly propulsion technologies and uncertain in terms of the feasibility and scalability of new aircraft designs. In addition, adaptation in flight operations and infrastructure investments, vital for system-wide efficiency gains, have lagged necessary momentum.

This situation shows an urgent need for coordinated and pragmatic approaches addressing not only technology and fuel-based solutions but also systemic and infrastructural challenges.

Forecast of aviation emissions and seen reductions until 2050 towards Net Zero (CYLAD Analysis).



### What is net-zero emissions?

Net zero indicates that an organization absorbs as much greenhouse gases as it releases. The total emissions are therefore zero.

## Background

The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 parties in 2015, with a goal to limit global temperature rise below 2 °C. Additionally countries are pursuing efforts to restrain temperature increase below 1.5 °C as a stretched target.

To limit temperature rise to 2 °C, the Paris Agreement aims to reduce emissions by 45% by 2030 and reach net zero emissions by 2050. Through their Nationally Determined Contributions (NDCs), countries communicate actions they will take to reduce their greenhouse gas emissions. The NDCs are submitted to the UN Framework Convention on Climate Change (UNFCCC) which provides guidelines and frameworks to ensure comparability and recording. The UNFCCC does not set or approve the NDC targets hence, there are no direct financial or

legal penalties for failing to meet national targets.

At the 77th IATA Annual General Meeting in Boston, USA in 2021 a resolution was passed by IATA member airlines committing to achieve net-zero CO<sub>2</sub> emissions by 2050, in line with the Paris agreement. In 2022, the long-term net-zero ambitions were further adopted by ICAO (International Civil Aviation Organization) which includes 184 member states and 57 organizations. ICAO represents a broader range of aviation stakeholders, encompassing countries, commercial airlines, air cargo airlines, general aviation, airports and air navigation service providers.

The Net Zero Target has become an industry-wide goal requiring coordinated efforts by airlines, airports, OEMs, regulators and fuel suppliers.

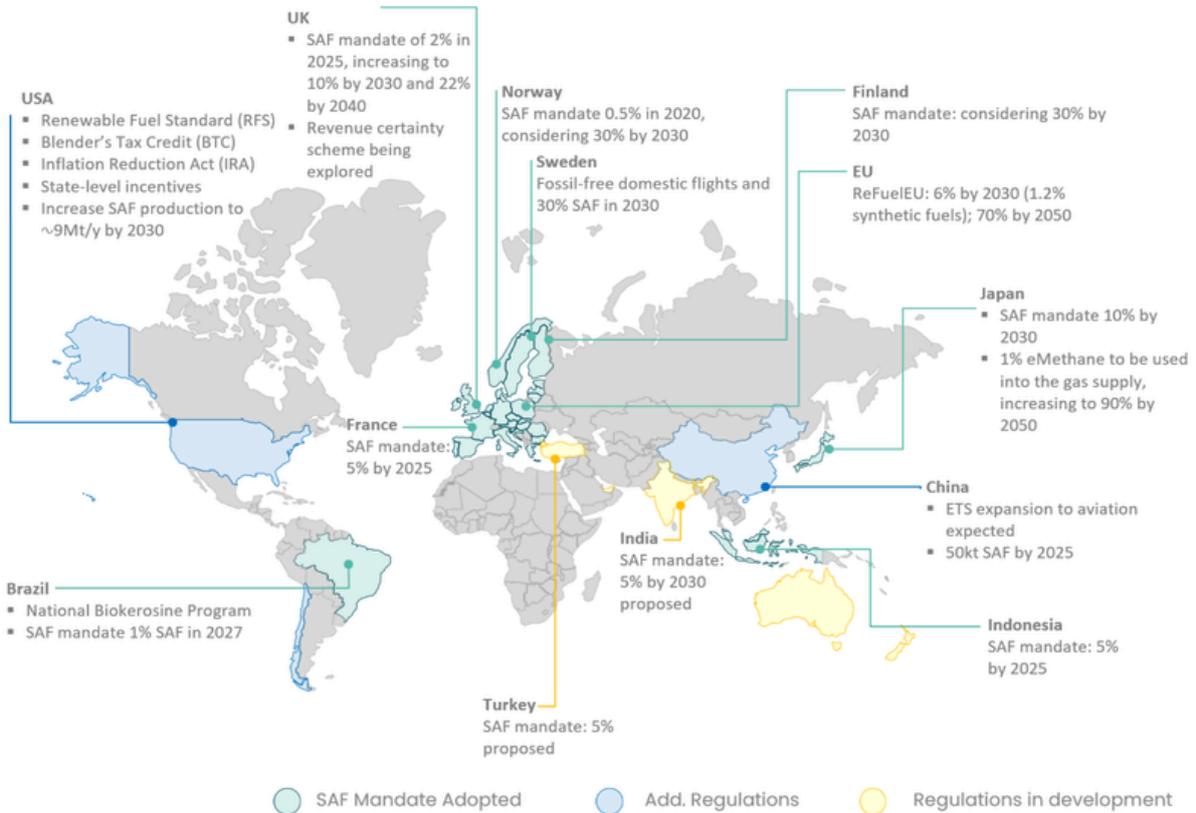
## Today's Regulatory Landscape

To accelerate the large-scale adoption of SAF, it is essential to establish regulatory frameworks that incentivize both its production and use. In pursuit of net-zero objectives, many countries have already implemented or are developing such regulations. As of today, regulations referring primarily on SAF typically comprising the following key measures:

- **Blending Mandates:** require airline to increase the proportion of SAF used in flights. Current and planned regulations encompass approximately 75% of global commercial aviation, with SAF blendings ranging from 1% to 30%.
- **Production incentives:** aim to scale global SAF production capacity and achieve cost parity with kerosine through economies of scale. Programs such as the U.S. Inflation Reduction Act, Brazil's National BioKeroSine Program, and emerging European initiatives are expected to boost output to ~9 million tons annually in 2030 and following years, supporting blending mandates.

# Aviation's Net Zero Challenge: Today's perspective on carbon-free aviation

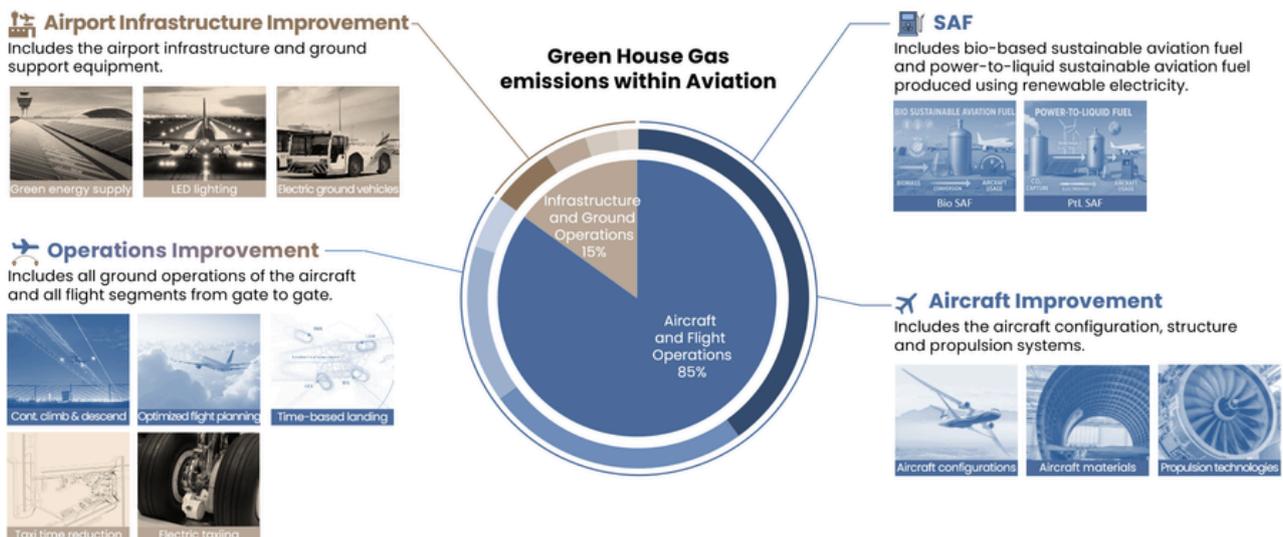
Overview of key global regulations to increase SAF usage and production.



## Overview of Emissions in Aviation

Greenhouse gas emissions in aviation can be broadly divided into Aircraft and Flight Operations, as well as into Infrastructure and Ground Operations. The biggest share are aircraft and flight operations accounting for 85%. The remaining 15% originate from airport infrastructure and ground operations.

Emissions breakdown key levers for emissions reduction.



This highlights the importance of targeting in-flight and aircraft-specific measures towards a Net Zero in Aviation industry. The figure below illustrates the emission shares and introduces four major decarbonization levers within aviation. In the following sections, each of these four levers is discussed in detail, with a focus on their impact potential and feasibility – starting with the largest opportunity, Sustainable Aviation Fuels.



### Sustainable Aviation Fuel

Utilizes bio-based and power-to-liquid synthetic fuels made using renewable energy.



### Aircraft Improvement

Focuses on configuration, materials, and propulsion systems to enhance fuel efficiency.



### Operations Improvement

Covers gate-to-gate flight optimization, including climb/descent profiles, landing, taxiing, and electric towing.



### Airport Infrastructure Improvement

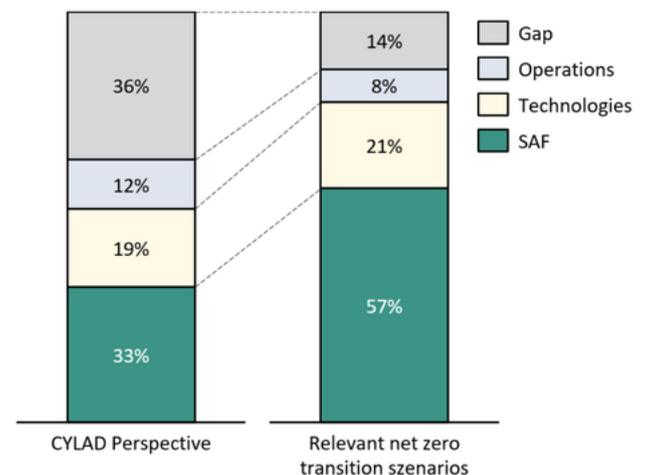
Encompasses ground support equipment, lighting, and renewable airport energy systems.

## Sustainable Aviation Fuels

### The Cornerstone of Decarbonization

SAF refers to jet fuel produced from sustainable sources or synthesized using renewable energy. In contrast to fossil-based kerosene, SAF enables a lifecycle CO<sub>2</sub> emission reduction of up to 80%. This characteristic and its wide compatibility with current aircrafts and corresponding infrastructure makes SAF a crucial pillar in the aviation industry's pathway towards net-zero. According to major aviation roadmaps, SAF is **projected to contribute on average 57% of the total CO<sub>2</sub> reduction**. This makes it the most impactful lever for achieving net-zero; however, **recent analysis perceive the projected contribution may be overly optimistic**.

CYLAD Perspective opposed to mean of Net Zero contributions from widely cited Net Zero scenarios (CYLAD Analysis, Airport Improvements included in Operations).



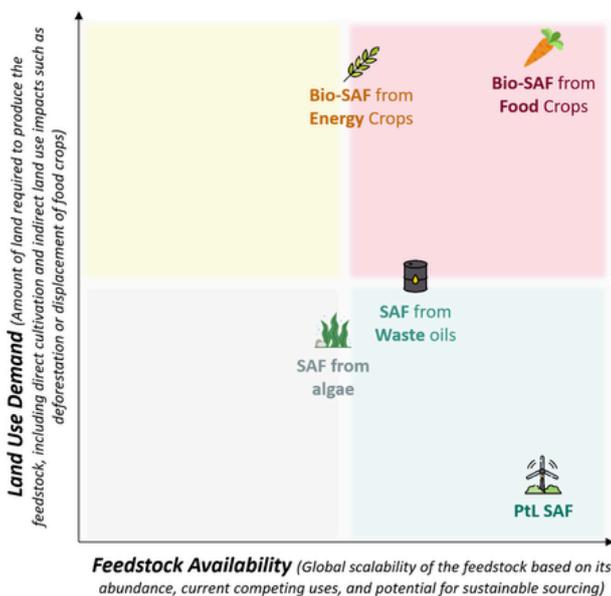
### Constraints on SAF Scalability

While SAF is pivotal to aviation decarbonization, its large-scale adoption is constrained by several factors. Limited sustainable feedstock availability, high production costs, and inadequate production infrastructure hinder scalability. Regulatory uncertainty further slows investment while the industry's price sensitivity challenges market uptake. Among these, securing sufficient feedstock is a central bottleneck to SAF scalability. Current SAF production relies largely on biomass-based inputs, categorized into **three generations: 1st gen** feedstocks such as edible crops, **2nd gen** in-edible and waste-derived materials like used cooking oils (UCO) or organic waste and **3rd gen** non-food sources including microalgae.

### Feedstock-specific Constraints to SAF Scalability

SAF scalability is tightly linked to the characteristics of its feedstocks, each with distinct benefits and limitations. **1st generation** sources like food crops are readily available but compete with agriculture and require large amounts of land. **2nd generation** sources, as for example energy crops, reduce food system pressure but remain land- and water-intensive. Waste oils, however, are highly sustainable with minimal land impact, yet globally scarce and fluctuant in quality. **3rd generation** options such as microalgae often offer strong theoretical yields with low land use but face major technical and economic hurdles.

Feedstock-specific classification based on required land use and global availability.



# 33%

### Total Net Zero Savings through SAF

Scenarios estimate that SAF will provide well over 50% of the sector's needed emission reductions by 2050. Considering the limited availability of raw materials for SAF production, its limited production capacities, and the high cost of SAF compared to kerosene, SAF's contribution to net-zero may fall well below the most widely cited forecasts.

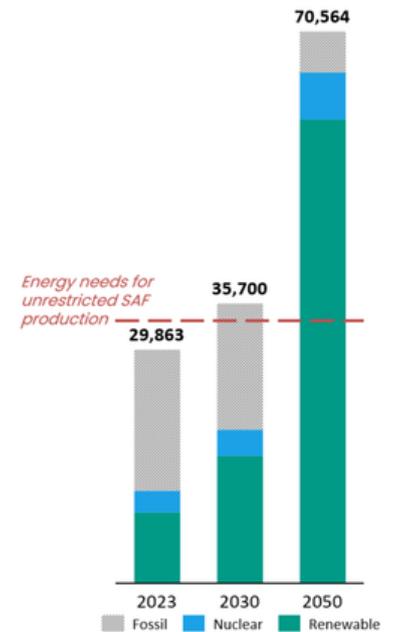
On the other hand, **Power-to-Liquid (PtL)** fuels, synthesized from renewable electricity and captured CO<sub>2</sub>, are land-independent and highly scalable in theory, but dependent on renewable energy access and supporting infrastructure. These constraints highlight the need for a strategic, **multi-pathway approach** – one that balances Bio-SAF options, despite land and food competition, with the co-utilization of waste- and/or algae-based routes and scalable, land-neutral PtL fuels to meet long-term net-zero targets.

## Worldwide Green Energy Capacity and Impact on PtL Production

Green energy sources such as hydropower, solar and wind serve as the fundamental inputs for producing electricity based PtL fuels. Using renewable electricity for hydrogen production and fuel synthesis substantially reduces the overall carbon footprint of PtL fuels.

To meet the anticipated PtL demand, projected to reach around 600,000 kt by 2050, it is essential to consider long-term forecasts for renewable electricity generation. In an unconstrained scenario (see graph), meeting this demand would require approx. 50% of the available renewable energy capacity by 2050. However, as many industries pursue decarbonization, renewable resources will be increasingly shared across sectors. Consequently, it is unlikely that such a high share of renewable electricity could be allocated exclusively to PtL production, highlighting the need for diversified and realistic energy-supply strategies. As shown in the graph, the projected total energy generation capacity of approximately 70,500 TWh in 2050 represents an optimistic outlook; beyond 2030, these forecasts may be influenced by evolving regulations and geopolitical factors.

Projection of green and nuclear energy generation capacities up to 2050 (in TWh, CYLAD Analysis).



## SAF and Kerosene Prices

In 2022, PtL SAF was priced at roughly 4 times the cost of fossil kerosene, reflecting its significant cost disadvantage. While production scale up and cheaper renewable energy are expected to narrow this gap, PtL fuels will likely remain structurally more expensive than fossil kerosene even by 2050.

### CYLAD Example

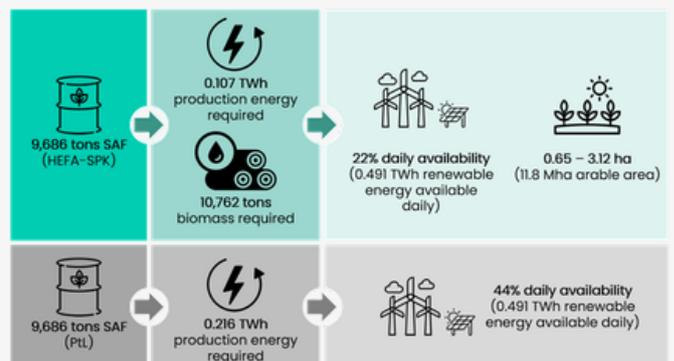
Resources required for FRAPORT flight operation within a day

Airport kerosene consumption per day ...



9,686 tons/day kerosene (Frankfurt Airport, 2022)

... and SAF required incl. therefore needed resources in production



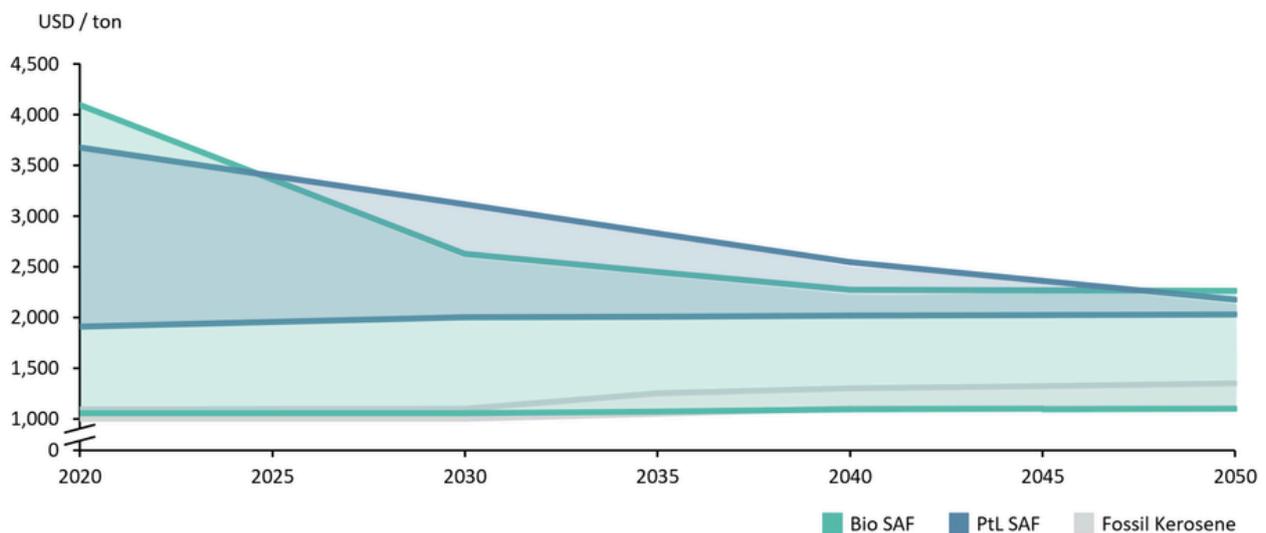
Bio-SAF, although cheaper to produce in the near term, faces growth limitations from feedstock scarcity, particularly as sustainable biomass sources compete with food production, land use, and other bioenergy applications. By 2050, prices for Bio SAF types are expected to converge toward USD 1,100/ton, yet Bio-SAF's share in total SAF fuel supply will stay capped due to feedstock scarcity. This positions PtL SAF as the main long-term solution despite its higher costs.

### Structural and Economic Price Drivers

The main challenge for Bio-SAF is not price but production capacity. Even with declining production costs, the finite supply of sustainable feedstock (wastes, residues, used oils) and growing

competition from other sectors limit expansion potential. This structural cap makes Bio-SAF a transitional contributor rather than a dominant long-term option. PtL SAF offers virtually unlimited potential but at a high price. Its economics are dominated by renewable electricity (60–70% of total costs) and electrolyzer efficiency, which determine hydrogen production costs. Because plants need a continuous power supply, renewable intermittency leads to either underutilization or costly storage and grid integration. Added to this, CO<sub>2</sub> capture, from air or industrial sources, further increases capital and operating costs. As a result, PtL SAF remains highly sensitive to energy prices, financing conditions, and policy support.

Evolution of SAF and kerosene prices up to 2050 (CYLAD Analysis).

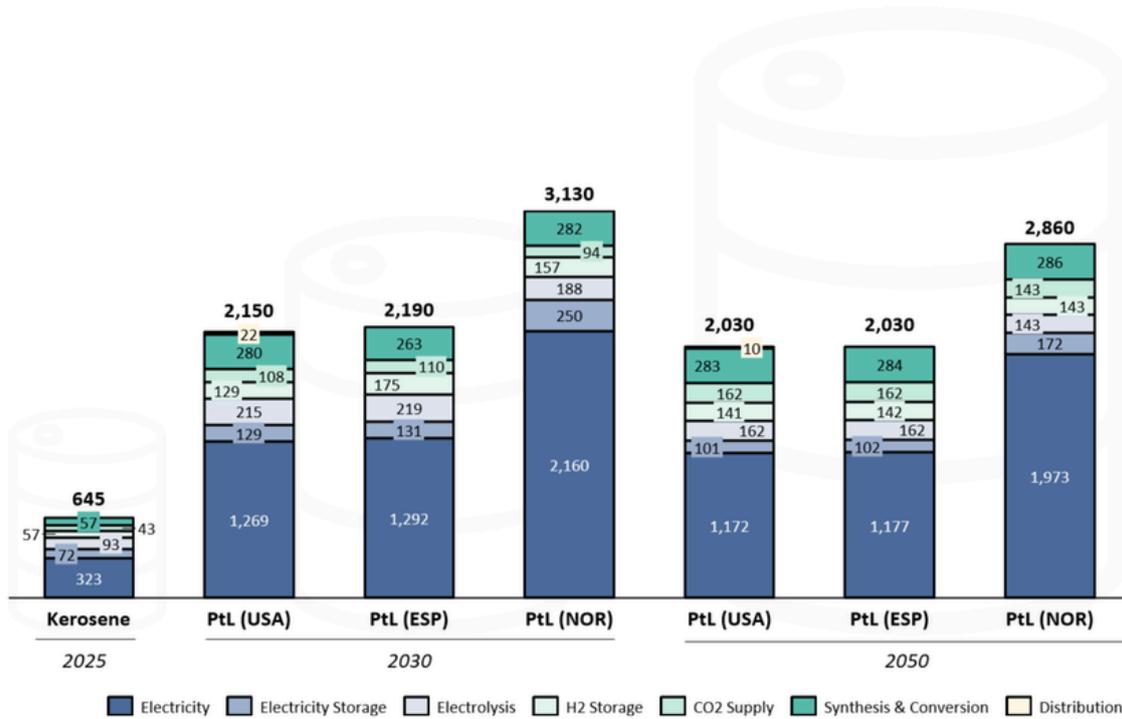


### Market Competitiveness depending on Cost Reductions

The future of aviation fuels is dominated by a non-competitive price of SAF, especially valid for PtL SAF. Even though higher blending mandates have already been established, for example through the EU ReFuel Regulation.

Especially the cost of renewable electricity is driving PtL SAF costs compared to kerosene, next to the supply costs of green hydrogen and CO<sub>2</sub>. Based on the availability of renewable energy capacity, major price differences are expected with higher production costs in the EU (compared to e.g. the US).

Costs of kerosene and PtL SAF in 2025, 2030 and 2050 for USA and EU in USD/ton (assumption based on full production capacity and commercial potential, IATA/LBST & CYLAD Analysis).



Nonetheless, EU sunbelt countries are expected to have competitive prices as the examples of Spain and Norway show. A major risk for extended infrastructure investments are uncertain government policies and regulations leading to volatile market. Those investments would enable additional production facilities,

power grids and renewable capacities towards a market maturity of PtL SAF. A boost for a full PtL SAF market maturity would be a further industrialization of the production process. Besides the technology development, cross-industry usages of renewable fuel would allow to reach a competitive market position.

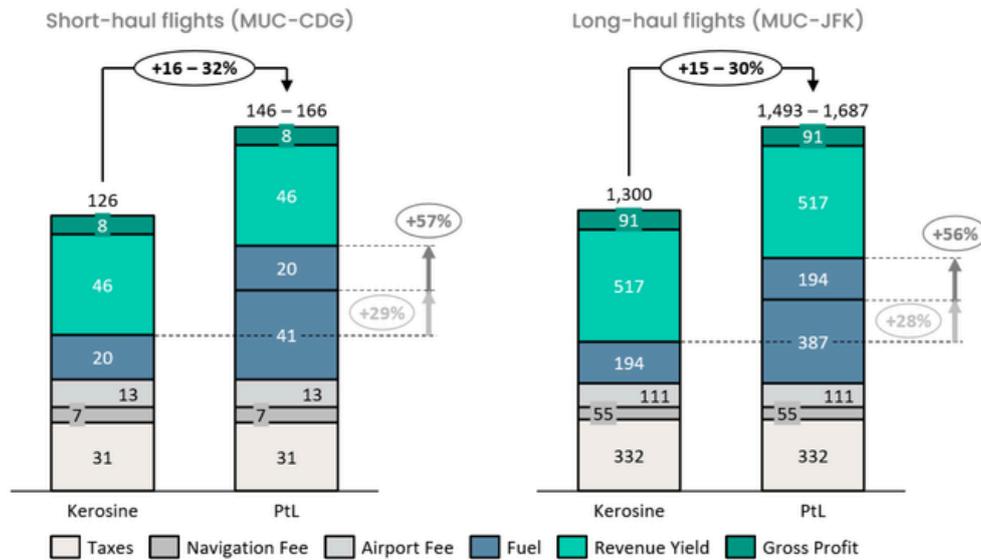
### Impact of PtL SAF on Ticket Prices

PtL SAF represents a crucial pathway to decarbonize aviation, however its higher production costs pose significant implications for airlines and passengers. An entire switch from kerosene to PtL SAF would increase fuel costs substantially, with most of this premium likely passed on to ticket prices. For instance, a Munich - Paris flight could see fares rise by approximately 16% to 32% , while a Munich - New York route might experience a 15%-

30% increase (based on ticket and SAF prices in November 2025). Although the absolute difference is greater on long-haul flights, the relative impact remains similar across distances, reflecting the major role of fuel in total operating costs. The extent and pace of PtL adoption, as well as cost shares passed to passengers, will ultimately depend on policy mandates, subsidy frameworks and market dynamics shaping SAF pricing.

## Aviation's Net Zero Challenge: Today's perspective on carbon-free aviation

Development of short and long-haul ticket prices utilizing SAF as fuel (in EUR, CYLAD Analysis).



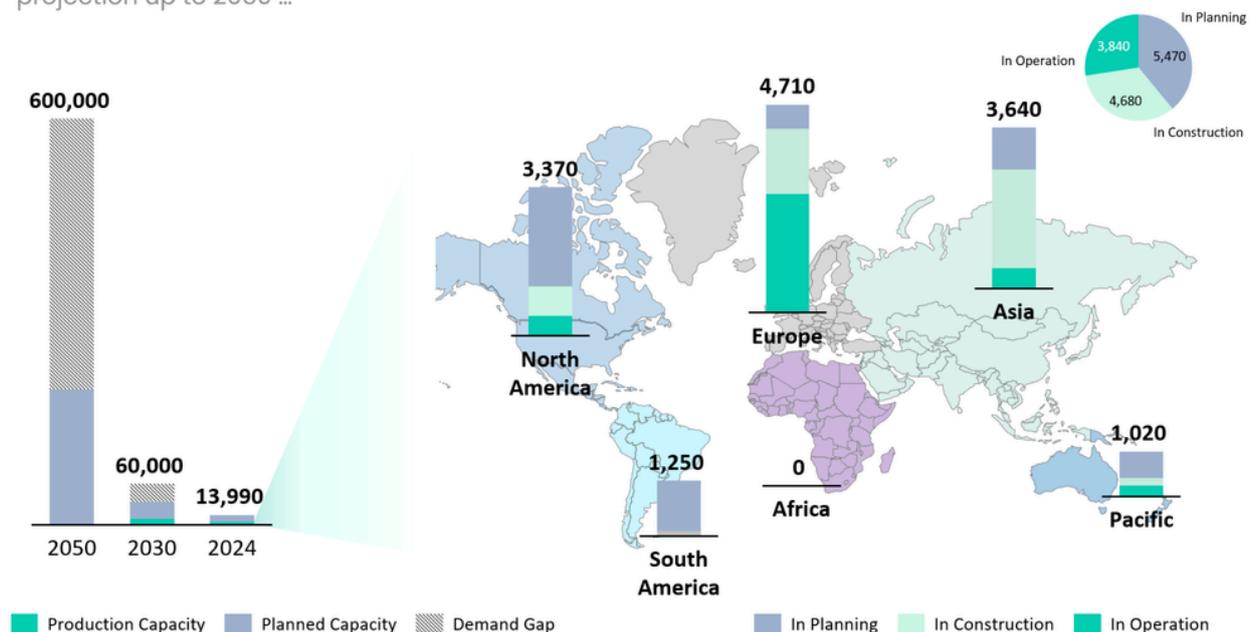
### Worldwide SAF Production Capacities

Current operational capacity for SAF production is approximately 3,840 kton, which is significantly below what is needed to decarbonize aviation. By 2030, projections indicate that demand for SAF would be around 60,000 kton, resulting in a demand gap of about 26,660 kton even under optimistic scenarios. Looking ahead to 2050, an estimated 600,000 kton of SAF will be required to achieve net-zero emissions. However, current projections suggest production of only up to 200,000 kton, leaving a substantial demand gap of 400,000 kton.

Global Bio & PtL SAF capacity and demand projection by 2050 with today's breakdown (in kton, ICAO & CYLAD Analysis).

Worldwide SAF capacity as of today and demand projection up to 2050 ...

... with breakdown of planned and available production capacities by today



In addition to the supply-demand gap, there are significant regional disparities in the development of production capacities. North America and South America benefit from large agricultural industries, providing a steady feedstock base for Bio-SAF. In contrast, Africa's relatively weak industrial base has limited planned investments. Meanwhile, strong renewable energy capacity in North America, Europe, and Asia supports the potential for PtL SAF production. Furthermore, the policy landscape in Europe and North America actively encourages higher levels of investment and capacity expansion.

### Minor challenges in SAF Supply Chain from Production to Propulsion

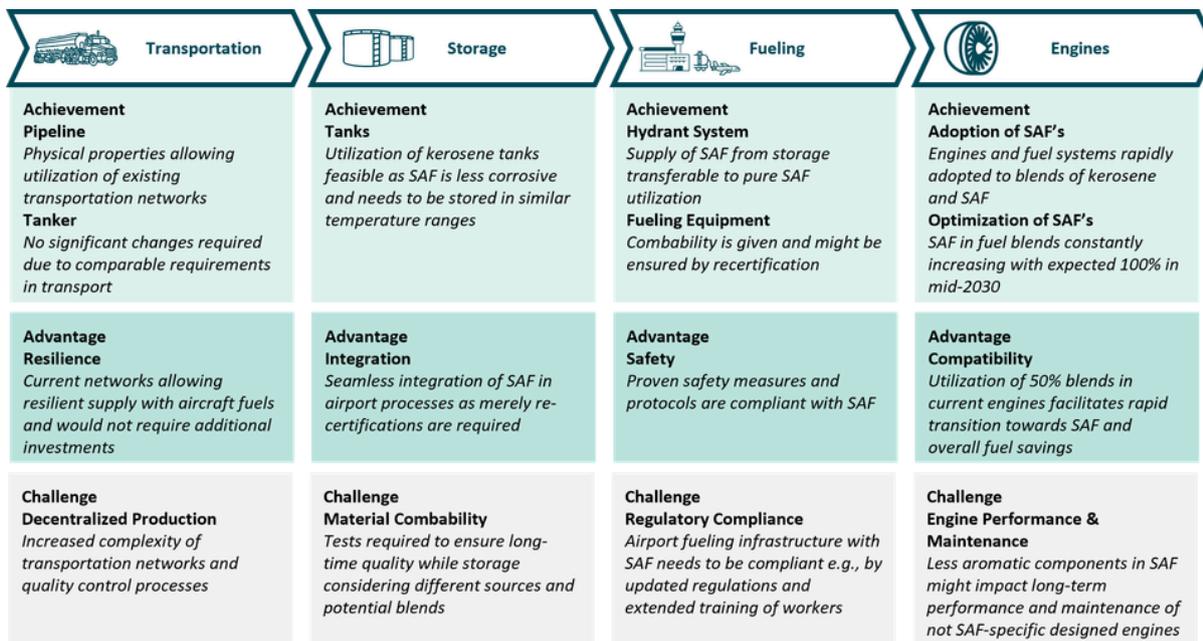
The transition from fossil kerosene to Bio and PtL SAF comes with smaller challenges along the aviation supply chain, from production towards the fueling of airplanes. As the physical and chemical properties of SAF are identical to kerosene, only minor adjustments are required.

In transportation and storage, the aviation industry benefits from existing, robust and resilient network that can be utilized. Even though the decentralized production and related quality standards are challenging, distribution is far from requiring heavy investments. Assuming consistent, high quality SAF despite varying feedstocks, storage is also no issue.

For the fueling step, aviation industry is already SAF-ready. Airport systems and equipment can handle SAF with only certification updates and slight technical adjustments supported by updated safety protocols.

Modern engines can handle 50% blends as of today, enabling immediate utilization and emission reduction. Full SAF utilization for next generation engines were already successful in full scale tests.

Aspects throughout the Bio and PtL SAF delivery chain from production towards propulsion.



## Aircraft Improvement

Advancements in aerodynamics, lightweight materials, and next-generation engine technologies can significantly enhance aircraft efficiency. These innovations enable lower fuel consumption and, as a result, reduced CO<sub>2</sub> emissions during flight.

Based on current developments and trends, there are three main categories of aircraft improvements that are expected to contribute a total of 19% reduction in CO<sub>2</sub> emissions by 2050:

- New propulsion technologies e.g., geared turbofans and open-rotor concepts (11%),
- Aircraft materials like thermoset, thermoplastics and natural fibers (6%),
- Aircraft configurations such as blended wing and truss-braced wing (2%).

Potential CO<sub>2</sub> emission saving contribution per aircraft improvement category until 2050.



### Propulsion Technologies

New propulsion technologies represent the largest technological contributor to achieve the aviation sector's 2050 Net Zero target. This contribution will primarily result from the adoption of advanced engine designs that improve fuel efficiency and reduce emissions. The following three propulsion solutions are the most promising under development:

#### 1. High-bypass and Geared Turbofans (GTF)

High efficiency turbofans (bypass ratio of 10 or higher), as well as geared turbofans, which use a reduction gearbox between the fan and the engine core, offer significant fuel efficiency gains. These technologies are already deployed in the latest generation of narrow-body aircraft (e.g., A320neo). **Their application is expected to extend to wide-body aircraft in the 2030s.** Hence, a high adoption rate for passenger aircrafts of up to 90% until 2050 is expected.

#### 2. Open-rotor Concept

Open-rotor engines, using single- or double-stage propellers coupled with a conventional engine core, have been tested in relevant environment.

# 19%

### Total Net Zero Savings through aircraft improvements

The most significant impact will come from next-gen engines, which are set to dominate the passenger aircraft market and deliver an 11% reduction in CO<sub>2</sub> emissions. Adoption of advanced materials is projected to increase steadily through 2050, accounting for a 6% contribution. New aircraft configurations are expected to enter service in the 2030s, but with limited impact on emissions, contributing only 2% toward the Net Zero target.

They are scheduled to enter service on narrow-body aircraft during the 2030s and offer a 25% efficiency gain. However, due to its diameter of up to 4.5 m, they will not fit under the wings, and thus must be installed in the back, leading to design, structure and integration challenges. Given this, an estimated adoption rate of 5% by 2050 is assumed.

### 3. Water-enhanced Turbofans (WET)

WET are in **early stages of development**. These turbines use heat exchangers to enable wet combustion, with market introduction planned for 2035 and further improvements expected by 2050. As of now, their fuel efficiency and emissions reduction potential have not been quantified.

## Aircraft Materials

By replacing traditional components like aluminum with lighter and more sustainable alternatives, manufacturers aim to improve aircraft efficiency and reduce carbon emissions. Among these innovations, thermoplastic and thermoset fuselages as well as sustainable fibers and resins will play a major role.

### 1. Thermoplastic and Thermoset Fuselages

Thermoset fuselages are projected to provide a 15% efficiency improvement compared to current aircraft designs and are already integrated in today's Boeing B787 and Airbus A350 wide-body aircrafts. In contrast, the latest narrow body models, A320neo and B737MAX, still use aluminum fuselages. Looking forward, thermoplastic fuselages are anticipated to be introduced in narrow-body aircraft in the 2030s, particularly in clean-sheet, single-aisle models that will replace older aircraft generations.

### 2. Natural Fibers and Resins

Application opportunities of natural fibers, such as flax, bamboo, sugar cane, and natural resins sourced from conifer plants or chemically converted are continuously investigated. These materials are currently implemented for interior and non-critical parts, and while they are promising, their contribution to Net Zero is perceived minor.

# 11%

## Net Zero Savings through propulsion technologies

High-bypass ratio engines are already introduced (e.g., B737MAX, A320neo, B787, A350), gradually replacing older models. Current estimated high adoption rates expect a high contribution of 10% toward the Net Zero emissions target.

Open-rotor engines face significant aircraft design and integration challenges. They are projected to remain a niche solution with a 1% contribution to Net Zero until 2050.

# 6%

Net Zero Savings through aircraft materials

As next-gen narrow-body aircrafts with thermoplastic fuselages are not anticipated before the mid-2030s, a low estimated adoption rate of around 20% is expected. This corresponds to a contribution of ~6% toward Net Zero 2050.

## Aircraft Configurations

Three major aircraft configurations and aerodynamic improvements are under consideration for emission-improved aircraft configurations but highly unexpected to enter service until 2050:

### 1. Truss-braced Wing

The truss-braced wing design features extra-long, slender wings that generate less drag and are supported by diagonal struts. Studies show a potential 30% efficiency improvement compared to state-of-the-art narrow-body aircrafts. An adoption rate of 5% is assumed as latest developments have been shelved due to high costs and complexity.

### 2. Blended Wing

The blended wing design, a hybrid between the traditional "tube and wing" and flying wing configurations, expect more than 20% in efficiency improvements. Small-scale demonstrators have been built; however a market introduction is not expected within the next decade due to integration issues to the existing infrastructure and flight physics concerns. The expected adoption rate is <1%.

### 3. Morphing Wing

The morphing wing concept involves optimizing the wing shape dynamically during flight using actuators. It offers a 10–20% efficiency gain following tests on isolated demonstrators on business jets. Nonetheless, the assumed adoption rate is <1% due to remaining constrains in technical complexity by broader applications.

DGLR (German Society for Aeronautics and Astronautics) estimates that next-generation aircrafts could achieve 40–50% lower fuel burn compared to an A350 by leveraging additional advancements in gust and maneuver load reduction, and reduced stability combined with thrust vectoring. However, widespread adoption of all these technologies before 2050 is considered unlikely, meaning their practical contribution to achieve Net Zero will remain limited within this timeframe.

2%

### Net Zero Savings through aircraft configurations

Due to remaining technical and economic challenges, the classic tube and wing design will dominate and the adoption of new aircraft designs remain unlikely.

## Propulsion Technologies across Flight Segments

Decarbonizing aviation requires solutions that work across a wide range of flight segments that can be distinguished by distance and passenger numbers. Urban Air Mobility covers very short trips of 50 to 100 nautical miles (nm) with around four passengers. Regional flights span between 100 to 500 nm with around 100 seats, while short-haul flights run between 500 to 1500 nm and carry 100–200 passengers. Long-haul flights exceed 1,500 nm and typically accommodate more than 200 passengers.

To meet the decarbonization needs across these diverse flight segments, multiple propulsion technologies are being developed, each suited to specific ranges and aircraft types.

**Sustainable Aviation Fuels** are the only drop-in fuel capable of powering all flight distances and aircraft sizes. Certified since 2011, it can be blended with conventional jet fuel without redesigning aircraft or infrastructure, making it the **sole viable option for long-haul operations today**.

**Hydrogen propulsion** enables both **hydrogen fuel-cell** and **hydrogen combustion-based aircrafts**, offering potential across different flight ranges. Fuel cells are best suited for regional operations due to their lower power output, while hydrogen combustion can power larger aircraft over distances up to 1,500 nm. Both technologies require major advances in production, storage, and infrastructure, with fuel-cell aircrafts expected to enter service between 2025 and 2030, while hydrogen combustion aircrafts service entry is expected beyond 2035.

**Battery-electric propulsion** is constrained by the weight and low energy density of current lithium-ion batteries. As a result, it is **feasible only for very short trips and small passenger loads, such as urban air mobility**, with prototypes targeting service entry in the 2030s.

In summary, Sustainable Aviation Fuels stand out as the only technology ready for immediate, large scale use, particularly for long-haul aviation, while hydrogen and battery-electric systems will play increasingly important roles in regional and short-haul operations. Together, these propulsion pathways represent the foundation for aviation's transition toward net-zero emissions by 2050.

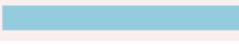
## Hydrogen Aviation Infrastructure

Hydrogen as an alternative aviation fuel faces a series of **technical, economical and operational challenges** across the entire supply chain. Focusing on the delivery from production to propulsion, **higher efforts are required in comparison to SAF**.

Transportation of Hydrogen is challenged by the physical properties, either requiring

lowest temperatures or high pressures. Hydrogen-derivates enabling easier transportation then require a chemical transformation on the other side. Together with the need of new distribution systems, transportation is connected to **high infrastructure investments**. Identically, the storage at the airport comes with high investments in containments and safety measures.

Propulsion technologies across flight segments and expected service entry.

	Urban Air Mobility	Regional Travel	Short-Haul	Long-Haul	Expected Service Entry
Range (NM <sup>3</sup> )	50 - 100	100 - 500	500 - 1,500	> 1,500	
Passengers	4	100	100 - 200	> 200	
 Sustainable Aviation Fuel					2011
 Hydrogen Combustion					2035 - 2040
 Hydrogen Fuel Cell					2025 - 2030
 Battery Powered					2025 - 2030

First fueling concepts were successfully tested and proved a relatively short process compared to electric alternatives. Dual-fueled or modified engines were successfully tested with Hydrogen in full scale tests, leveraging the higher energy density compared to fossil kerosene. Nonetheless, Hydrogen lacks globally harmonized systems and requires major aircraft redesigns to cope with the unique storage and combustion needs while ensuring safety and reliability.

Aspects throughout the Hydrogen delivery chain as alternative aviation fuel from production towards propulsion.

Transportation	Storage	Fueling	Engine
<b>Achievement</b> <b>Tanker &amp; Trucks</b> <i>Systems to transport Hydrogen in liquid or chemically bound state</i>	<b>Achievement</b> <b>Tanks</b> <i>Long-term experience in space, early aviation and automotive applications</i>	<b>Achievement</b> <b>Commercialization</b> <i>First successes in commercial and light aviation applications</i>	<b>Achievement</b> <b>Feasibility</b> <i>Utilization demonstrated with modified engines, also in dual fuel concepts</i>
<b>Advantage</b> <b>Pipeline</b> <i>Development of pipeline networks for long-distance transportation e.g., in EU and utilization of natural gas grid by transformation or blending with hydrogen</i>	<b>Advantage</b> <b>Scalability</b> <i>Storage solutions are widely scalable e.g., in salt caverns and synergies with other industries feasible</i>	<b>Advantage</b> <b>Refueling Process</b> <i>Shorter refueling process in comparison to electric charging process</i>	<b>Advantage</b> <b>High Energy Density</b> <i>Increased specific energy content compared to conventional kerosene enabling potential for greater engine efficiency in next generation designs</i>
<b>Challenge</b> <b>Physical properties</b> <i>High costs through required pressures up to 700 bar or liquification at -253 °C</i> <b>Material Durability</b> <i>Long-term stability and safety endangered by brittle steel and coatings</i>	<b>Challenge</b> <b>Costs</b> <i>Costly storage by required space, material requirement and safety measures</i> <b>Safety</b> <i>Highly flammable and explosive substance requiring special handling and storage</i>	<b>Challenge</b> <b>Refueling Stations</b> <i>Lack of installed stations available for a more complex and dangerous fueling process</i> <b>Standardization</b> <i>Missing global standard for expansion of hydrogen fuel stations leading to incompatibilities</i>	<b>Challenge</b> <b>Engine Design</b> <i>Handling of Hydrogen properties requiring significant redesign (e.g., flame temperature)</i> <b>Cryogenic Storage</b> <i>Integration challenges in managing storage and delivery of liquid hydrogen ensuring safety</i>

## Operation Improvements

By implementing efficient routing both in the air and on the ground, as well as optimizing climb and descent profiles, aircrafts can improve performance, reduce fuel consumption, and lower CO<sub>2</sub> emissions.

Current innovations offer an 8% reduction potential in CO<sub>2</sub> emissions which can be grouped into three main categories:

- Flight operation, from initial climb, over cruise to approach and landing (5%),
- Ground operations from gate to take-off and from landing to gate (3%).

Potential CO<sub>2</sub> emission saving contribution per operation improvement category until 2050.



## Flight Operations

Improving flight operations holds a meaningful potential in reducing aviation emissions toward the 2050 Net Zero target. Three measures are considered:

### 1. Continuous Climb and Descent Operations

Continuous Climb Operations (CCO) and Continuous Descent Operations (CDO) are flight procedures that let aircrafts climb and descend smoothly instead of in steps. This minimizes thrust changes, saving fuel and reducing emissions. By 2018 about 74% of flights in Europe used CCO, but only 24% used CDO – although CDO can achieve up to ten times more fuel savings. Assuming moderate adoption rates, a low one-digit percentage is achieved towards Net Zero.

### 2. Optimized Flight Planning

Often enabled by AI, weather conditions, air traffic control constraints, and historical routing data are considered to determine an optimal flight route. First adoptions show an average 3% efficiency gain assuming a widespread application by 2050 with a 2% total Net Zero saving.

### 3. Time-based Separation

This system improves the runway throughput and reduces delays by applying time-based rather than distance-based separation between arriving aircraft, e.g., during strong headwinds. This lowers holding patterns and loitering time in the air, contributing to Net Zero similar as CCO & CDO.

## Ground Operations

Aside from flight operations, ground operations present a second lever to reduce Aviation's emissions:

### 1. Taxi Time Reduction

Leveraging intelligent gate allocation, e.g., through AI, to minimize the time aircraft spend taxiing. These systems aim to reduce unnecessary gate changes and prevent aircrafts from having to taxi across the entire airport. Such technologies are already operational at major airports like Dallas Fort Worth, with further implementations expected even though savings are in the lower one digit range.

### 2. Electric Taxiing

This technology has the potential to reduce ground-related aircraft emissions by 61–85% during operation compared to typical dual-engine taxiing. Although electric taxiing has already been successfully demonstrated on narrowbody aircrafts, it has not yet seen widespread adoption across commercial fleets.

# 8%

## Total Net Zero Savings through Operations

Improved flight operations will contribute 5% whereof the majority will come from optimized climb and descend. Ground operations optimization will contribute 3% through the adoption of shorter and electrified taxing.

## Infrastructure Improvements

Investments in airport infrastructure, such as renewable energy systems and energy-efficient lighting, can substantially reduce emissions from airport operations. These measures lower overall energy consumption and reduce aviation-related CO<sub>2</sub> output. Based on current projections, improvements in airport infrastructure are expected to contribute 4% toward CO<sub>2</sub> emissions reduction by 2050.

# 4%

### Net Zero Savings through infrastructure improvements

Assuming major hubs achieving 90% Net Zero emissions as well as being accountable for half of the airport-related emissions.

Potential CO<sub>2</sub> emission saving contribution from airport infrastructure improvements until 2050.



### Airport Infrastructure

Improving airport infrastructure represents a powerful lever to reduce aviation-related emissions. Three focus areas are investigated:

#### 1. Green Energy Supply

75% of an airport's energy consumption is electricity, used to power terminals and aircrafts to avoid the usage of APUs. So far, major airports, such as Adelaide, Munich, and Vienna are installing solar panels and wind turbines on-site, covering 15–40% of their annual electricity needs. Targets were set to source **90% of their energy from renewable sources by 2050**.

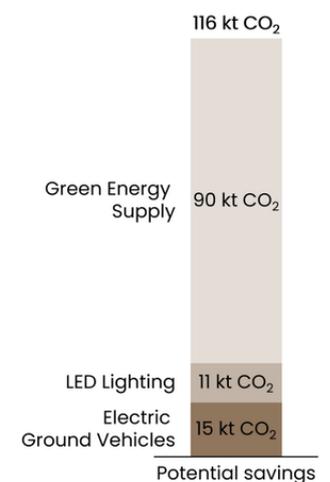
#### 2. LED Lightning

Lighting for terminals, runways, taxiways, and aprons makes up about 15% of an airport's total energy consumption. Airports are **increasingly replacing conventional halogen systems with smart LED lighting** which can improve energy efficiency by 60–80%.

#### 3. Electric Ground Vehicles

Ground vehicles contribute approx. 15% of total airport-related CO<sub>2</sub> emissions. Electrified ground support vehicles are already in place at major hubs with regulatory emissions targets likely to accelerate deployment. If powered by renewable electricity, a full transition would save around 15% for major hubs such as for Munich airport.

Munich airport insights (CYLAD Analysis).



## KEY RESULTS

>36%

... marks **today's gap** towards achieving the 2050 Net Zero target, reflecting **insufficient initiatives** that fall short of demand.

>33%

... is **SAF's contribution** as the **primary carbon-neutral fuel** driving the Net Zero 2050 strategy.

>80%

... emission reduction is achievable through the most promising **levers**, demanding a structured, **long-term approach** and robust **commitment**.



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## About CYLAD

Independent consulting firm, CYLAD advises executives from industries and associated services to overcome performance, transformation and growth challenges. The firm combines Consulting Methodology with Senior Experts' experience for sustainable results for its clients of all sizes, offering a comprehensive range of services. CYLAD supports companies, especially in the Aerospace & Defence, Pharmaceutical/Health, Energy, Electronics and Transportation sectors.

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