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Decarbonising long-haul flights by 2050:
Is there a pathway through sustainable aviation fuel use, fleet renewal and green energy upscaling?

The European Union's aviation sector faces the significant challenge of achieving net-zero emissions by 2050. Although long-haul flights of more than 3,000 km (1,620 NM) account for less than 10% of all departures, they represent more than half of aviation's carbon emissions, a proportion expected to rise to ~56% by 2050. This disparity in emissions underscores the urgent need to address the problem of emissions from long-haul flights in the EU's decarbonisation strategy.

While electric and hydrogen aircraft solutions are advancing for short-haul aircraft, they are not yet realistic for aircraft flying long-haul, as shown by EUROCONTROL Think Paper #21 on long-haul flight decarbonisation. Indeed, applying electric, hydrogen, methane, ammonia or solar technologies to long-haul flights cannot be envisaged right now due to the immense technical challenges involved. Therefore, alternative solutions are necessary to reduce long-haul flight emissions in the near future.

This Think Paper explores viable strategies for reducing emissions from long-haul flights within existing technological and time constraints, focusing on sustainable aviation fuel (SAF) and fleet modernisation as the most feasible pathways for significant emission reductions, and using the FuellingDecarb module from EUROCONTROL's FlyingGreen platform to produce new estimates that show clearly what needs to be done to advance on aviation sustainability goals.

Regarding SAF, we address the following questions:

- Will there be enough Annex IX-compliant feedstock under the EU Renewable Energy Directive (RED II) between 2025 and 2050 to produce bio-based SAF?
- How much green/clean energy is required to produce the necessary SAF to decarbonise long-haul flights?
- What logistical distribution would maximise the volume of SAF carried on long-haul flights?

We have also analysed by how much fleet renewal could accelerate the decarbonisation of long-haul flights.

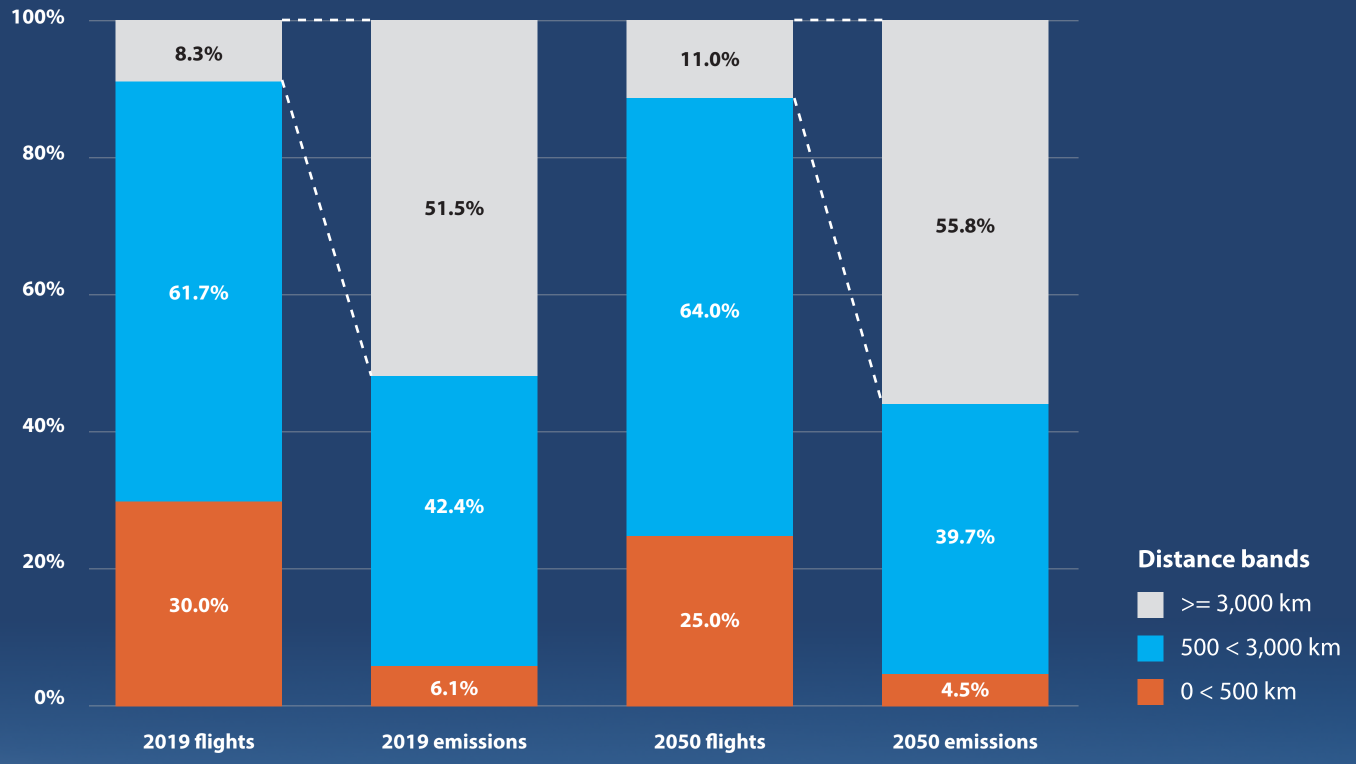
Key findings

- The energy challenge is common to all transportation sectors and synergies with other transport modes could help sectors, and accelerate the production of SAF. The progressive electrification of road transport offers a huge opportunity to reallocate a large part of the EU's existing biofuel production capacity to the production of SAF (2.3 Mt). In turn, aviation decarbonisation, by producing 24 Mt of SAF, will also contribute to maritime decarbonisation by producing 7.5 Mt of biodiesel as a co-product.
- By 2050, we estimate that ECAC aviation will require an estimated 61 Mt of jet fuel a year, with ECAC long-haul flights (>3,000 km) needing 56% or 34 Mt of this. Applying ReFuelEU's 70% SAF blending mandate translates into 24 Mt of SAF, including ~12 Mt of bio-SAF (35%) and ~12 Mt of syn-SAF (35%), supplemented by 10 Mt of conventional aviation fuel. This could be met by collecting and converting 50% of used cooking oil in the ECAC area and 5.5% of the agricultural, forestry residues and municipal waste.
- The challenge of producing SAF and co-products using green/clean energy should not be underestimated. By 2050, SAF and co-products for those ECAC long-haul departing flights over 3,000 km will require various electricity mixes. The amount of electricity needed would be, for example, equivalent to 1.8 times France's total electricity production in 2023 or around 24% of all ECAC electricity production. This is equivalent to 73 nuclear reactors of 1,650 MW, or 8,157 offshore wind turbines, with a capacity ranging from 10 to 30 MW, or a net square edge of 43 km (43 km x 43 km) of photovoltaic solar panels deployed from 2025 to 2050).
- SAF supply could be initially concentrated at a much smaller set of airports to maximise the benefits and ease the transition to deploying SAF at all European airports. Introducing a 20% SAF blend for long-haul flights at five airports (or a 12.5% SAF blend at 20 airports, or 11% at 34) would have the same environmental benefits – assuming sufficient SAF production and supply – as a 10% SAF blend at all 2,165 ECAC airports.
- Accelerating fleet renewal by replacing long-haul (> 3,000 km) aircraft over 10 years old could reduce CO_2 emissions of the long-haul fleet by 10.4%, resulting in a 5.4% reduction in both total aviation emissions as well as SAF needs.

Introduction: Sustainable aviation fuels (SAFs) are key to long-haul decarbonisation

Around 8% of flights from the ECAC area cover distances over 3,000 km, but these account for over 50% of aviation's CO_2 emissions. Without significant progress, long-haul flights could contribute to ~56% of emissions by 2050, underscoring the urgent need to decarbonise long-haul aviation.

Figure 1: **Flights departing from ECAC and CO_2 emissions per distance band in 2019 and 2050 (Data from EUROCONTROL STATFOR)**



Almost 90% of these emissions stem from flights operated by heavy aircraft types, such as the Airbus 330, 340, 350 and 380, and the Boeing 747, 767, 777 and 787. Decarbonising these flights is a major challenge due to the high energy density required, and the technical limitations of the current alternatives such as electricity, hydrogen, ammonia, methane, or solar-powered aircraft, all of which are not expected to become viable for several decades, as *EUROCONTROL Think Paper #21 - Long-haul flight decarbonisation* has shown. In the meantime, SAF has emerged as a promising solution: SAF is a drop-in fuel that can be blended with conventional aviation fuel (CAF) using current infrastructure and equipment.

SAF, while releasing the same amount of CO_2 as CAF when combusted, can reduce by over 90% fossil CO_2 emissions over their entire life cycle. This makes SAF the most valuable existing means of achieving sustainability in long-haul aviation.

Additionally, SAF's lower aromatic content reduces soot and therefore contrail formation [1,2], with future potential pathways to eliminate aromatic compounds entirely. Contrails can form persistent cirrus clouds at cruising altitude, reflecting sunlight by day (cooling) but trapping heat at night (warming) [2]. This warming effect outweighs the cooling effect, contributing to global warming [3].

SAF comprises several different types of aviation fuel [4], as follows:

Bio-SAF:

- Advanced biofuels produced from feedstocks listed in Part A of Annex IX of RED II (e.g. algae, municipal waste, animal manure, agricultural and forestry residues)
- Biofuels produced from feedstocks listed in Part B of Annex IX of RED II (e.g. used cooking oils, category 1 and 2 fats).
- Other biofuels capped at 3% (e.g. produced from category 3 animal fats).

Recycled carbon aviation fuels:

- Recycled carbon fuel (e.g. fossil wastes that cannot be prevented, reused or recycled).

Synthetic SAF:

- Synthetic-based fuel – also known as electrofuel (e-fuel) or power-to-liquid fuel (PtL) – is a renewable fuel of biological origin obtained using renewable electricity to produce hydrogen and capture CO_2.

Other eligible aviation fuels:

- Synthetic low-carbon aviation fuel derived from non-fossil low-carbon hydrogen (produced from nuclear electricity)
- Low-carbon hydrogen for fuel cells, or direct combustion-powered aircraft.

In this paper, we use "bio-SAF" to refer to SAF produced from bio feedstock and recycled carbon, and "syn-SAF" for synthetic-based fuel or low-carbon aviation fuel.

To minimise the use of biomass necessary for bio-SAF production, hydrogen is added, which increases the electricity consumption needed to produce comparable quantities of SAF [5]. Additionally, SAF output has been maximised relative to other co-products such as diesel, naphta, gas and others using this feature in the EUROCONTROL FuellingDecarb tool [60]. The deployment of infrastructure for SAF production has been assumed to occur gradually from 2030 to 2050, considering improvements in conversion processes, electrolysers, as well as advancements in solar panels, wind turbines, and nuclear technologies. This gradual approach is crucial, especially compared to studies that assume a static scenario and do not consider technological variation improvements.

Would there be enough feedstock to produce the required bio-SAF between 2030 and 2050, and what percentage of CO_2-eq emissions could be saved?

After years of preparation, on 9 October 2023 Europe adopted the ReFuelEU Aviation Regulation [4,7], making it the first continent in the world to adopt a set of ambitious ramp-up targets for greener aviation fuel. It sets the following SAF mandates:

Years	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Advanced bio SAF	2%	4.8%	15%	24%	27%	35%
Minimum synthetic SAF		1.2%	5%	10%	15%	35%
Total mandate	2%	6%	20%	34%	42%	70%

Figure 2: **ReFuelEU Aviation mandates**

At present, SAF constitutes only 0.05% of total aviation fuel consumption in Europe [8], highlighting the challenge of reaching 2% by 2025, 6% by 2030, and 70% by 2050. Europe's potential SAF production capacity is currently estimated at 2.3 million tonnes per year [8], sufficient to meet 7% of long-haul flight needs in 2050 – but only if all production were dedicated entirely to aviation. However, most current production is used to produce bio-based fuel for the road transport sector.

Various technological pathways can be used to convert feedstock into SAF, each differing in efficiency [10,11,12,59,60], CO_2 savings [13-16], and costs [17,44-48]. The high cost of bio-SAF production is often due to considerable operational expenditure (OPEX), notably high electricity and/or feedstock prices [18].

Figure 3 estimates the SAF (in Mt) that could be produced from ECAC feedstock according to Annex IX of RED II between 2030-2050. These estimates include various sectors, but exclude non-energy uses such as pharmaceuticals, plastics, and straw for animal feed and bedding. Additionally, biofuel imports are not considered; only biomass such as agricultural residues, wood pellets and used cooking oil. The estimates also consider sustainable removal levels at the place of cultivation. To remain conservative, the feedstock estimates are based on the lowest values from CONCAWE and Imperial College [13] for the EU27, suplemented by data from [49-58] for European Civil Aviation Conference (ECAC) area non-EU27 countries.

Figure 3: **Estimated volume of ECAC feedstock (in Mt), as per Annex IX of RED II (EUROCONTROL)**

2030-2050 Feedstock	**Detailed feedstock**	**2030 Minimum estimation feedstock dry Mt ECAC**	**2050 Minimum estimation feedstock dry Mt ECAC**	**2030 % CO_2eq reduction**	**2050 % CO_2eq reduction**	**2030 SAF cost € per tonne**	**2050 SAF cost € per tonne**
Waste oils and fat	Used cooking oil	7	13	79%	83%	1,000 to 1,834	1,020 to 1,500
	Waste fat						
Agriculture residues Cover crops	Straw-like	360	396	75%	80%	2,100 to 3,500	1,750 to 2,500
	Lignocellulosic crops (grassy)						
	Manure						
	High moisture, sugarbeet, leaves						
Forestry residues	Agriculture (woody) and forest residues	154	163	35%	85%	2,100 to 3,500	1,750 to 2,500
	Lignocellulosic crops (woody)						
Municipal and industrial waste	Biowaste	218	215	80%	84%	2,100 to 3,500	1,750 to 2,500
	Sewage sludge						
	Solid industrial waste (secondary)						
Synthetic SAF	Hydrogen and CO_2 captured	na	na	70%	70%	1,750 to 5,000	1,500 to 2,700
Total		**739**	**787**	**74%**	**82%**	**1,541 to 3,060**	**1,531 to 2,471**

The ECAC feedstock breakdown (see Figure 4) shows two primary sources: agricultural lignocellulosic and residues 49% (360 Mt), and municipal-industrial waste 29% (218 Mt). Waste oils and fat represent less than 1% (7 Mt) while forestry residues make up 21% (154 Mt) of the total 739 Mt.

The HEFA (Hydrotreated Esters and Fatty Acids) conversion process remains the most commercially mature method for producing SAF in line with the Renewable Energy Directive [13,19]. However, limited feedstock availability, currently just 1% of the total, poses a challenge. Despite this, HEFA remains the cheapest option, with prices ranging from EUR 1,000 to 1,834 per tonne [16,45-48].

Increasing the feedstock collection rate could significantly enhance SAF availability. Raising the collection rate of waste oils and fat from 14% in 2025 to 50% of the 13 Mt by 2050 (6.5 Mt) could, after conversion into SAF (3.52 Mt), supply 10% of the total jet fuel needed for long-haul flights over 3,000 km, or 5.7% of all ECAC flights [22].

The ongoing progressive transition to electric vehicles in Europe could further boost SAF availability [23,24,25]. Increased adoption of electric vehicles is expected to free up by 2050 about 17.8 Mt of low-carbon biofuels currently used in road transport. This would potentially enable, for those listed in Parts A and B of Annex IX, their conversion into SAF to support aviation decarbonisation [25,26].

Forestry residues, agricultural residues and municipal waste biomass, which together make up the majority of total feedstock, hold considerable promise for aviation decarbonisation [27]. However, using 100% of forestry or agricultural residues for energy purposes should be avoided, to preserve biodiversity and prevent carbon displacement [27].

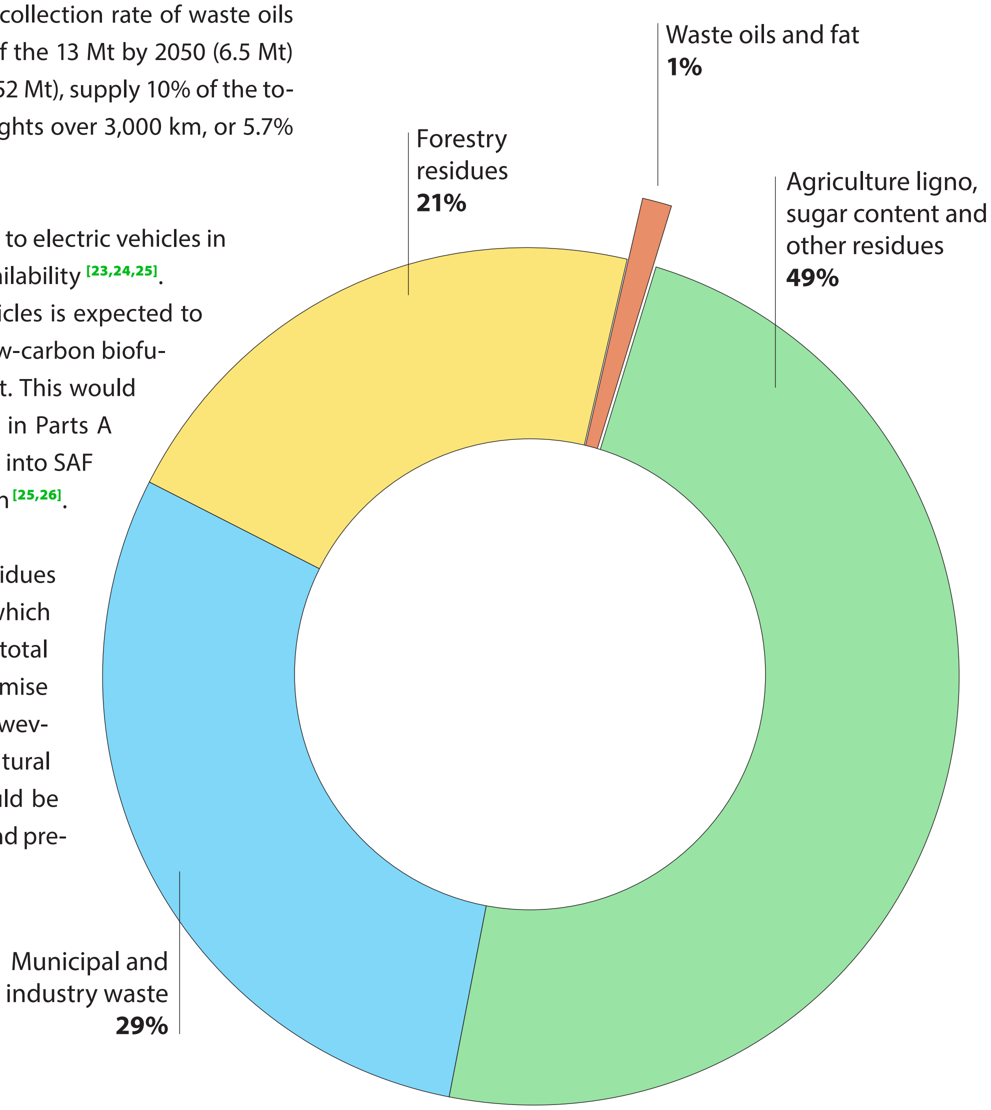


Figure 4: **Breakdown of feedstock by type in 2030**

How much biomass would be needed to meet the SAF needs of long-haul flights (>3,000 km) between 2025 and 2050?

The available biomass potential in 2030 (739 Mt) is expected to rise slightly by 2050 (787 Mt) [12] due to:

- Policies regulating land and water resource use, including a 30% reduction in agricultural land by 2050 [13]
- Increased awareness of waste reduction
- Nature restoration efforts following the European Parliament's decision on 27 February 2024 to adopt a law to restore 20% of the EU's land and sea.

SAF production is expected to increase due to:

- Improved conversion pathways for more efficient bio-SAF production
- Better feedstock mobilisation and forest management, although progress may be slow due to long forest growth cycles [13]
- Stricter recycling regulations, e.g. an estimated 50% oil and fat collection rate
- Increasing maximum certified SAF blends for aircraft from 50% today, to 100% by 2050
- Reduced SAF costs due to improved production efficiency, increased supply, and growing demand.

SAF will also improve greenhouse gas reductions by using more sustainable, low-carbon electricity in power generation.

By 2050, we estimate that 6.5 Mt (50%) of the 13 Mt of available waste cooking oil and fat in the ECAC area could be collected and converted into 3.5 Mt of SAF [60]. To meet the needs of long-haul (>3,000 km) flights, this would need to be supplemented by 42.5 Mt (5.5%) of biomass from agricultural and forestry residues or municipal waste to produce 8.4 Mt of bio-SAF[60]. The total (6.5 Mt + 42.5 Mt) would represent about 6.2% of the 787 Mt of waste cooking oil and fat, agricultural and forestry residues, and municipal waste potentially available in the ECAC area, fulfilling 35% of the bio-SAF requirement as per the ReFuelEU mandate for long-haul flights.

Various processing options exist for converting biomass into SAF, depending on factors such as the type of biomass, the transformation pathway, and the mass fraction of SAF in the output.

Figure 5: **ECAC Biomass and bio-SAF production (in Mt) in 2030-2050 (EUROCONTROL)**

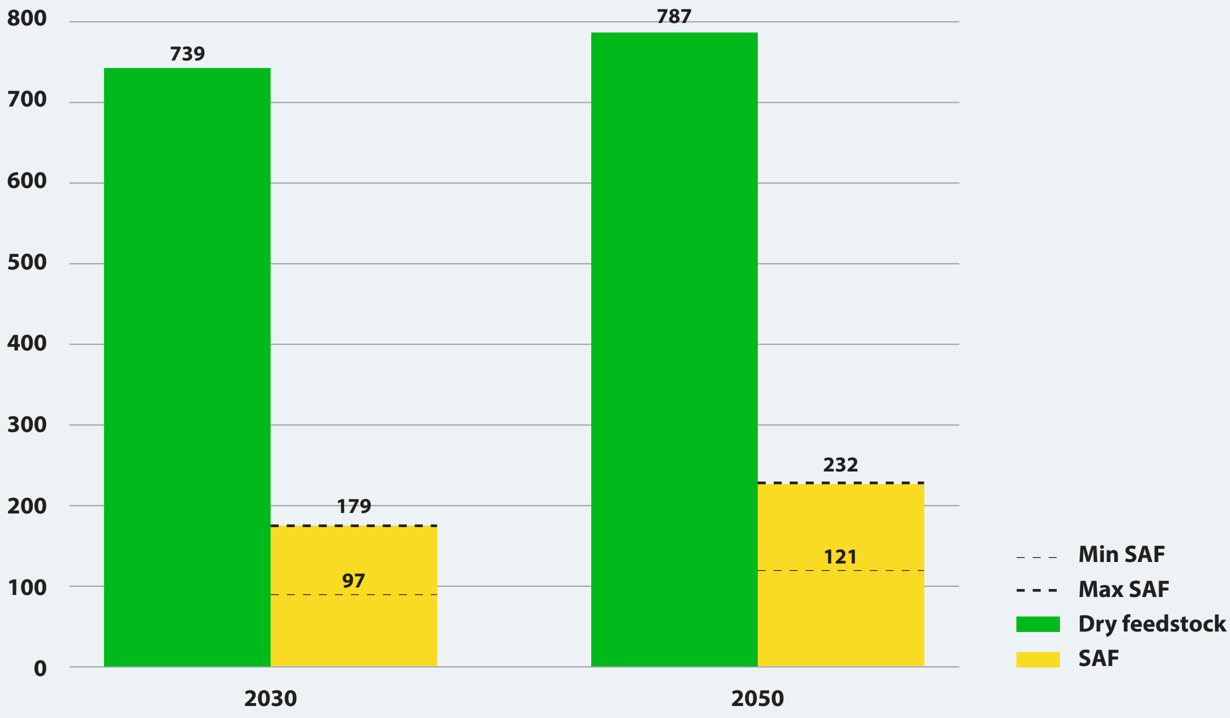
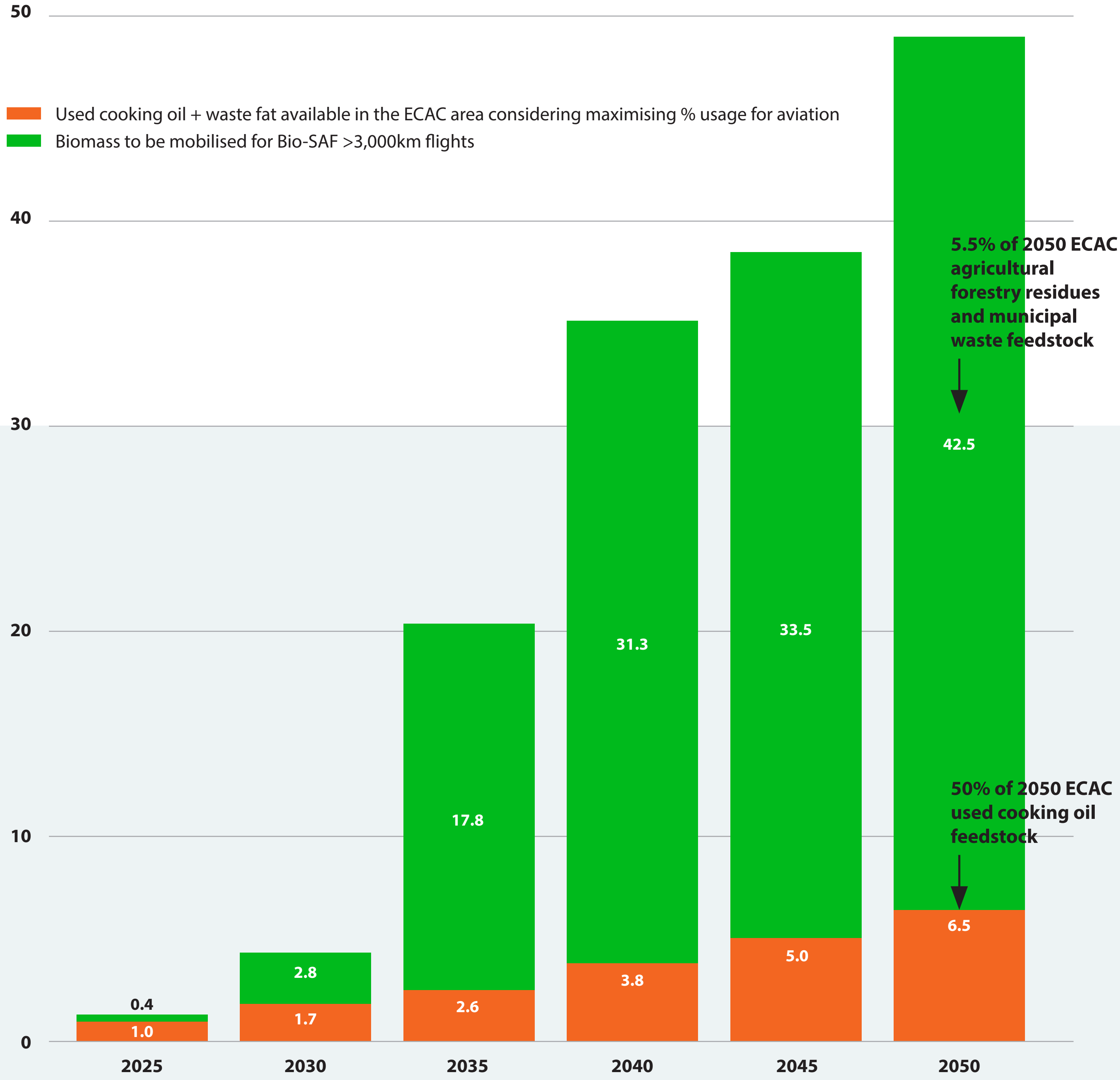


Figure 6 illustrates the volume of waste oil, agricultural, forestry and municipal waste that could be mobilised for bio-SAF production (in Mt) between 2025 and 2050.

Figure 6: **Feedstock mobilised for SAF production for use by long-haul (>3,000 km) flights from 2025 to 2050 (EUROCONTROL)**



How much electricity would be required to produce this SAF?

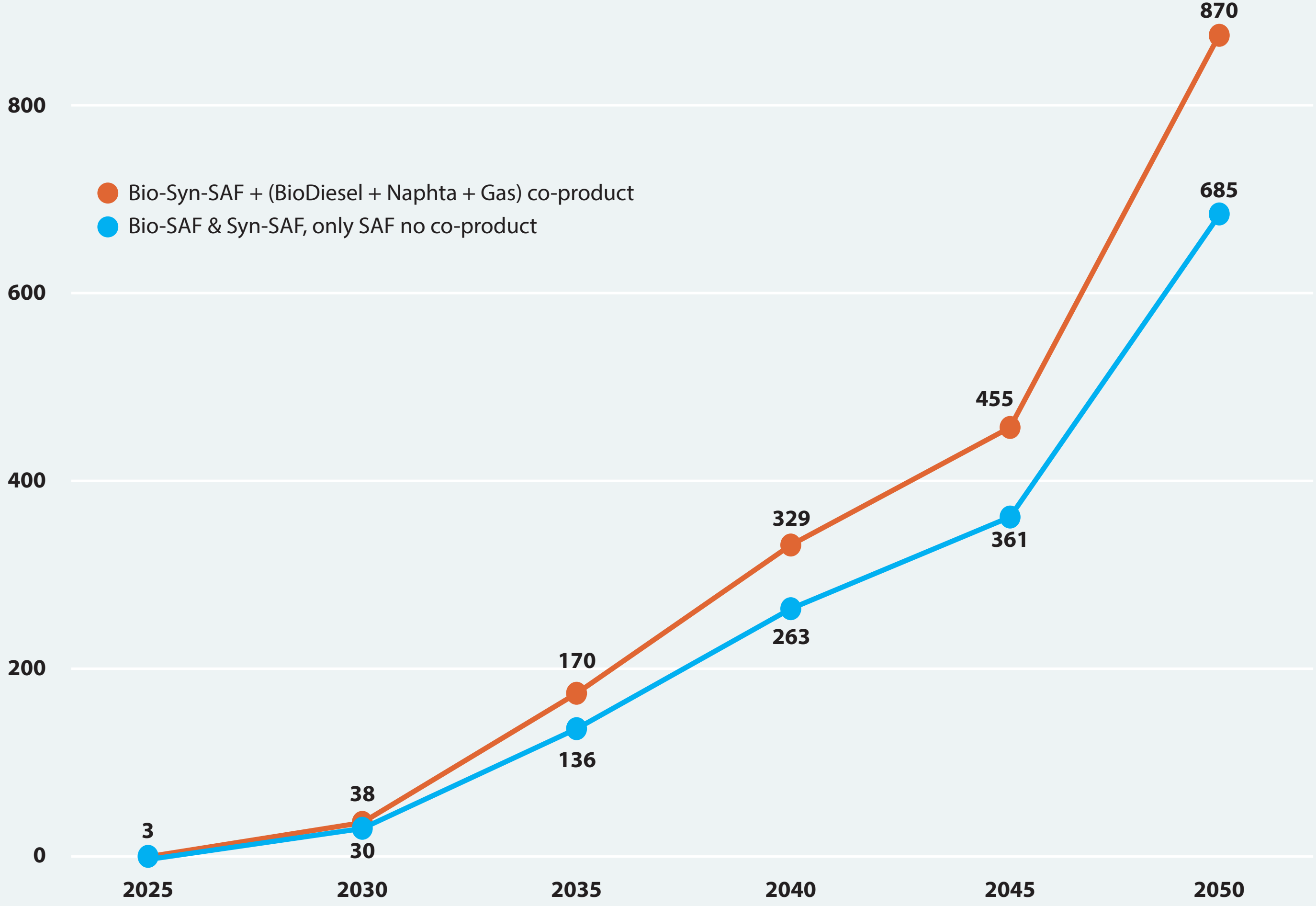
Producing bio and syn-SAF for long-haul flights would require in total ~870 TWh/yr of electricity. This includes the production of co-products such as diesel, naphtha and light gas. Of this total, and applying energy mass balancing, 685 TWh/yr would be used for bio and syn-SAF production, while the remaining 185 TWh/yr would go towards co-product production.

Various certified production processes, such as Fischer-Tropsch, Alcohol-to-Jet (ATJ), Hydrotreated Esters and Fatty Acids (HEFA), Power-To-Liquid (PtL), etc., use high or low-temperature electrolysis for hydrogen production, fermentation, CO_2 capture from the air, or industrial flue gases, all impacting energy production efficiency [5, 12, 19, 29-33]. Our estimates consider improvements in efficiency pathways from 2030 to 2050 based on the EUROCONTROL FuellingDecarb tool [60].

Co-products generated during bio-SAF or synthetic SAF production, such as bio-diesel (7.5 Mt), would contribute to help decarbonise other transportation modes, such as road and shipping. This creates an opportunity to curtail emissions in the maritime sector by seamlessly integrating co-products like biodiesel. A synergistic approach could accelerate decarbonisation of both aviation and shipping by leveraging shared infrastructural investments in production, distribution, and end-use facilities [28].

In 2050, considering reductions in fuel needs due to improvements in aircraft fuel efficiency, ATM operational measures and the adoption of liquid hydrogen, electric and hybrid aircraft, aviation in the ECAC area will require an estimated 61 Mt of jet fuel, with ECAC long-haul flights (>3,000 km) needing ~56% of this (34 Mt). Bearing in mind the 70% SAF blending mandate by ReFuelEU, this translates into 24 Mt of SAF, including ~12 Mt of bio-SAF (35%) and ~12 Mt of syn-SAF (35%), supplemented by 10 Mt of CAF.

Figure 7: **Electricity required for the production of SAF (in TWh/yr), with and without co-products, for use by ECAC long-haul (>3,000 km) flights (EUROCONTROL)**

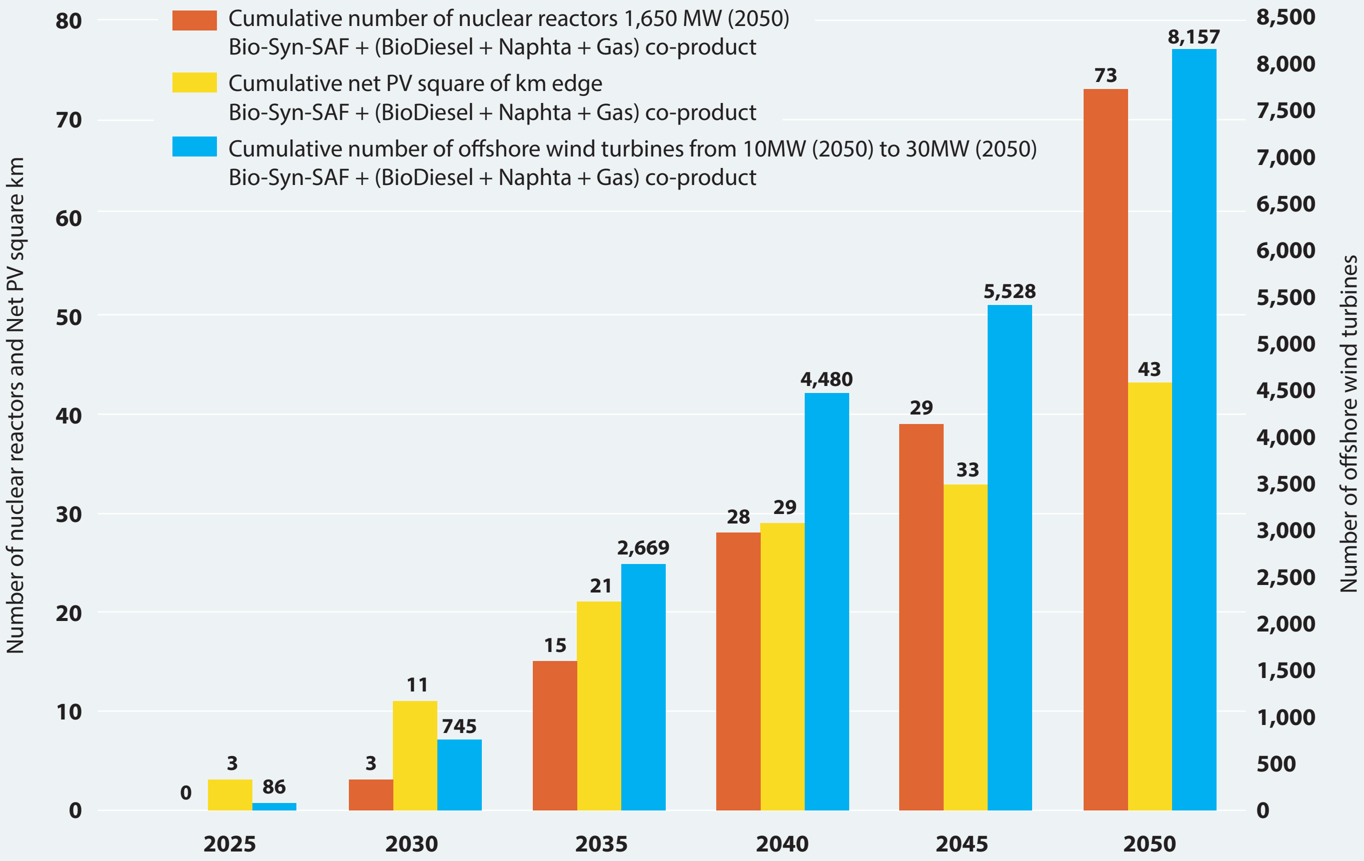


How many nuclear reactors, offshore wind turbines or solar panels would be needed to produce bio and synthetic SAF for long-haul flights between 2025 and 2050?

Figure 8 illustrates the magnitude of green/clean electricity needed to produce SAF from a unique source of electricity; however, this could allow multiple scenarios to be created with various electricity mixes. For example, by 2050, the electricity needed could be supplied by 8,157 offshore wind turbines, assuming an increase in power and efficiency from 10 MW (load factor of 40%) in 2025 to 30 MW (load factor of 60%) by 2050. Alternatively, photovoltaic solar panels with an efficiency increase from 20% in 2025 to 23% in 2030, and to 37% by 2050, covering a 43 km x 43 km area, could generate the necessary electricity. Finally, this amount of electricity would be equivalent to 73 nuclear reactors with a capacity of 1,650 MW at a load factor of 77% in 2025, rising to 84% in 2050.

Synthetic SAF, with costs ranging from as little as EUR 1,750 to EUR 5,000/tonne [33,45-47], is more expensive than current CAF. Depending on the biomass and production process used (cooking oil being the cheapest, costing EUR 1,000 to EUR 1,834/tonne [17, 45-47]. The high cost of syn-SAF is driven by its high OPEX cost, with electricity accounting for almost two-thirds of the total cost [34, EUROCONTROL].

Figure 8: **Order of magnitude illustrating the total required number of nuclear reactors OR offshore wind turbines OR solar panels to generate the electricity needed to produce bio-SAF and synthetic SAF and co-products for use by long-haul (>3,000 km) flights (EUROCONTROL)**



How can airport SAF delivery logistics boost the benefits of SAF for long-haul flights?

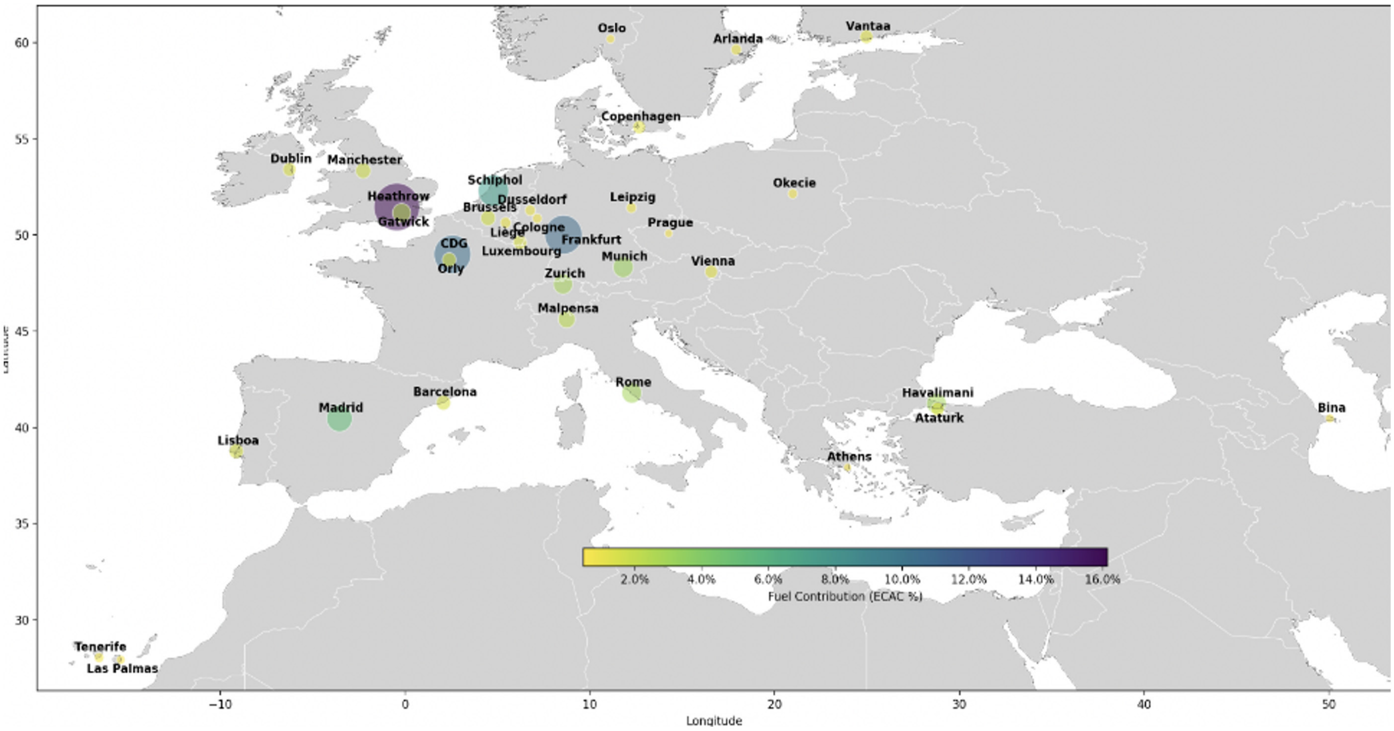
The logistics of supplying SAF to refuel aircraft pose a challenge, but this depends on how many airports require the necessary infrastructure. There are 2,165 airports in the ECAC area – making it a much simpler solution to make SAF available at just a few major airports as a priority, as it is from these that most long-haul flights depart, and thus from these that the greatest impact could be achieved by SAF usage on long-haul flights.

Regulation (EU) 2023/2405 (ReFuelEU Aviation) proposes a flexibility mechanism for the supply of SAF until 2035, potentially allowing for an increased share of SAF in jet fuel supplied at airports.

Supplying SAF to just five major airports could cover 50% of the total ECAC jet fuel used by long-haul (>3,000 km) flights. To cover 80% of the jet fuel, SAF would need to be supplied to 20 major EU airports, and to cover 90%, it would need to be supplied to 34 major airports.

This strategy would simplify the logistics to achieve a 20% SAF blend for long-haul flights at 5 airports, or a 12.5% SAF blend at 20 airports, or an 11% SAF blend at 34 airports, all of which would be much more achievable than aiming to achieve a 10% SAF blend at all 2,165 ECAC airports [39, 40].

Figure 9: **Top 28 European network airports refuelling 90% of total jet fuel for long-haul flights of over 3,000 km (EUROCONTROL)**



Fleet renewal: Progressive decarbonisation through greater efficiency

Long-haul aircraft typically remain in service for about 23 years.

Faster fleet renewal contributes to reducing aviation's CO_2 emissions.

However, the benefits of renewing an aircraft depend on its age, the total distance flown, its jet fuel consumption, and how frequently it is operated.

Of the 22,105 registered aircraft operating in the European aviation network in 2019, 14,266 flew more than 3,000 km at least once, while 90% of the CO_2 emitted came from aircraft built between 1998 and 2019.

Figure 10: **Widebody survival curve (EUROCONTROL STATFOR)**

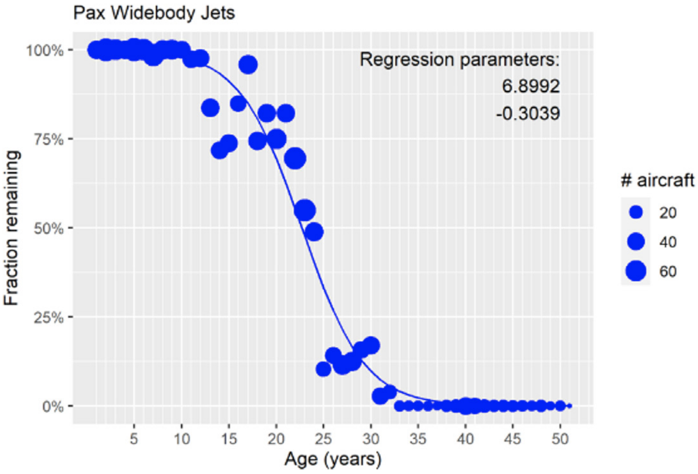
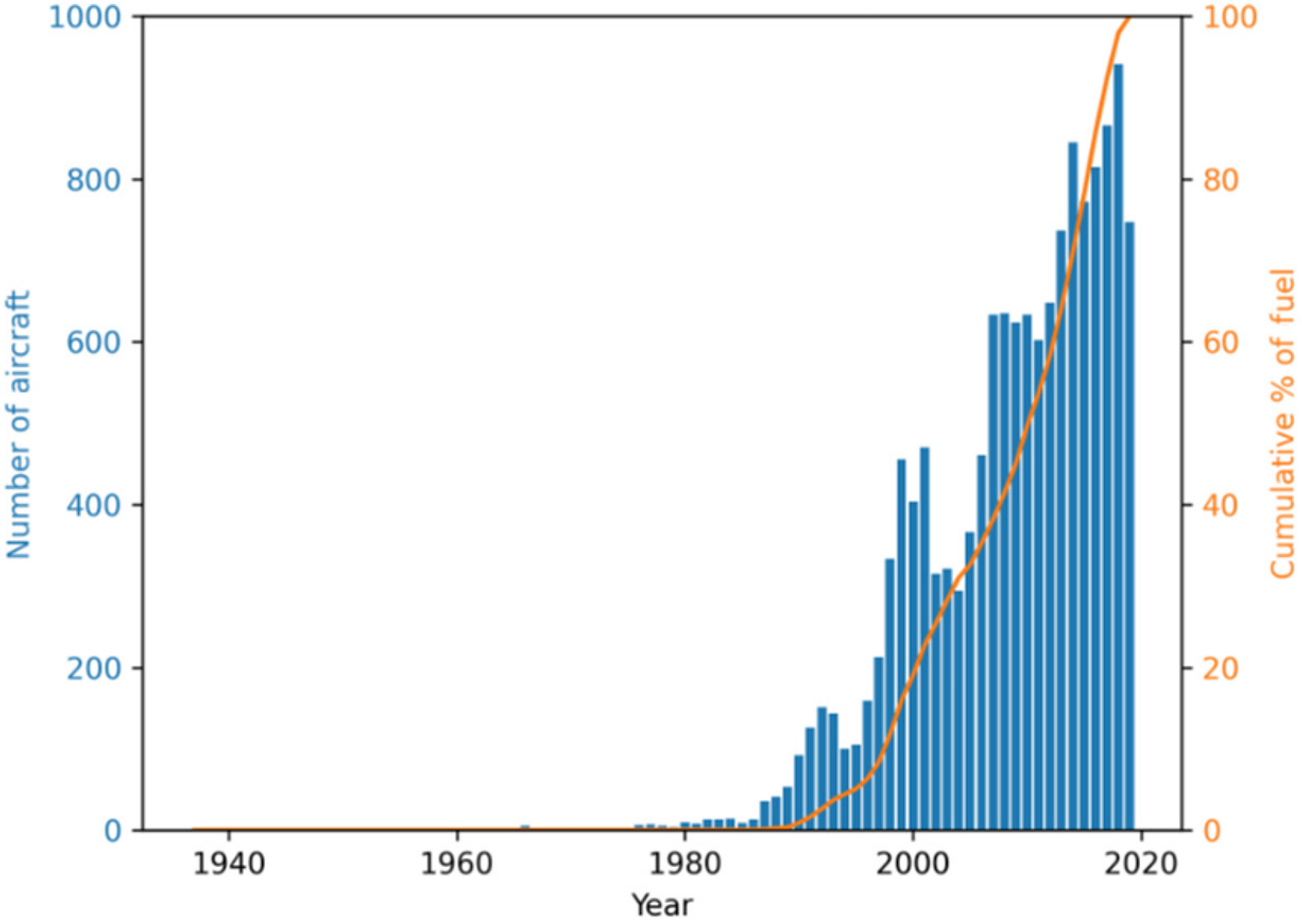


Figure 11: **Manufacturing years and number of aircraft contributing to >3,000 km CO_2 emissions in 2019 EUROCONTROL)**

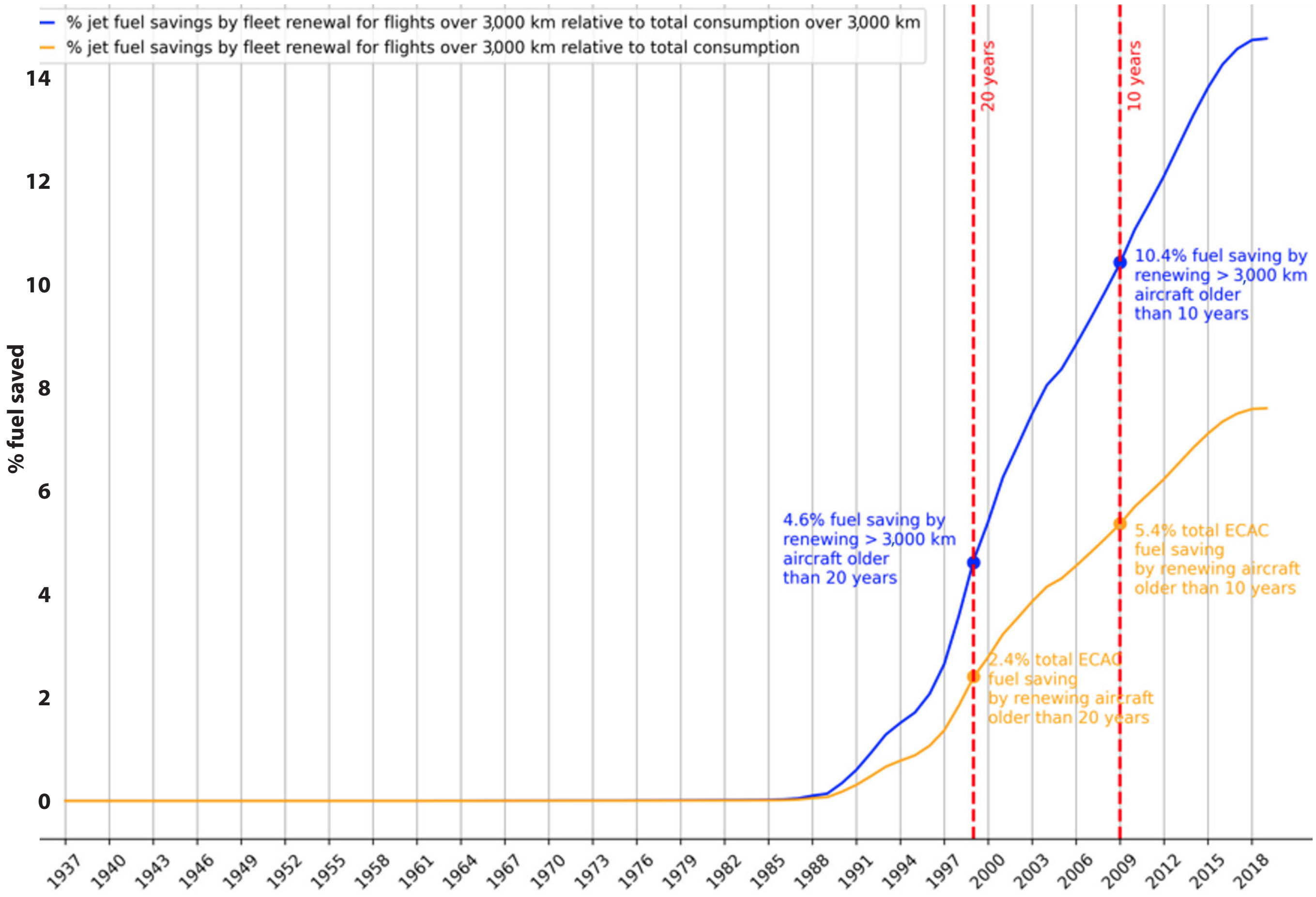


What if they were replaced by newer aircraft?

Replacing the oldest widebody aircraft, which typically fly infrequently and contribute minimally to total emissions in this segment, would not significantly reduce CO_2 emissions at iso-distance flown. However, replacing aircraft manufactured more than 20 years ago, a category which contributes to 16% of total emissions in the long-haul (> 3,000 km) segment, would decrease long-haul emissions by 4.6% and total ECAC aviation emissions by 2.4%. And accelerating fleet renewal by replacing long-haul aircraft older than 10 years could reduce long-haul emissions by 10.4% and total ECAC aviation emissions by 5.4%.

Fleet renewal will not only temporarily compensate for the shortage of SAF, but also preserve its use. This is beneficial for both emission reduction and economic reasons.

Figure 12: **% jet fuel savings achieved by renewing the fleet operating ECAC departure flights over 3,000 km with newer aircraft (EUROCONTROL)**



Conclusions

Decarbonising activities reliant on fossil fuels is urgent but highly challenging, especially in aviation. Long-haul flights (>3,000 km) represent about 8% of all departures, but contribute over 50% of aviation emissions. SAF is a promising interim solution to help decarbonise these type of flights. As a drop-in fuel, it can be blended with CAF. Currently, aircraft can operate with up to 50% SAF, with this percentage potentially increasing to 100% by 2030.

The potential of SAF is considerable for the decarbonisation of aviation, but the carbon intensity, electricity cost and feedstock price all significantly impact the final cost of SAF. Prioritising increased low-carbon and renewable electricity production and enhancing SAF supply and distribution are imperative.

By 2050, meeting SAF needs for long-haul flights will require ~870 TWh/yr of electricity, with 685 TWh/yr for bio and synthetic SAF and 185 TWh/yr for SAF co-products. This is equivalent to 73 nuclear reactors, or a 43 km by 43 km area of photovoltaic solar panels, or 8,157 offshore wind turbines. The necessary electricity (870 TWh) for producing all ECAC SAF and co-products would represent 24% of today's ECAC area electricity generation[61-63].

The aviation and maritime sectors can clearly synergise: 24 Mt of SAF production also yields a number of co-products, including 7.5 Mt of diesel, that would be useful for maritime. Optimising shared infrastructure investments can accelerate decarbonisation for both sectors.

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Excerpt: This means that the biofuel production infrastructure currently installed in the EU could produce up to 2.3 million tonnes of SAF on a yearly basis. However, this is currently not the case because this available capacity is used to produce other outputs. Using the 2.3 million tonne capacity to produce SAF would mean reducing the output of other types of fuel or chemicals. Source: European Aviation Environmental Report 2019 – EASA, EUROCONTROL, EEA

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Excerpt: Currently, around 80% of the EU biofuels market is made up of biodiesel, mainly produced from vegetable oils, and 20% consists of bioethanol. In addition, EU drivers are the top consumers of palm oil – more than half of all EU imports of palm oil end up in EU’s cars and trucks.

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Abbreviations

CAF	conventional aviation fuel
ECAC	European Civil Aviation Conference
H2	hydrogen
HEFA	Hydrotreated Esters and Fatty Acids
IEA	International Energy Agency
km	kilometre
MW	megawatt
MWh	megawatt-hour
OPEX	operational expenditure
RED	Renewable Energy Directive
SAF	sustainable aviation fuel
TWh/yr	terawatt-hours per year

Assumptions

Total France 2023 electricity 494 TWh [61-63]

Total ECAC electricity 3,626 TWh (country data 2021 or 2023) [61-63]

Years	2025	2030	2035	2040	2045	2050
Nuclear reactor power MWc	1,650	1,650	1,650	1,650	1,650	1,650
Nuclear reactor load factor	77%	77%	80%	82%	83%	84%
Offshore wind turbine power MWc	10	15	17	20	25	30
Offshore wind turbine load factor	40%	40%	45%	50%	55%	60%
PV efficiency	20%	23%	27%	30%	34%	37%
Average daily ECAC solar irradiance	3.98	3.98	3.98	3.98	3.98	3.98

years	2025	2030	2035	2040	2045	2050
Cooking oil & waste fat collection rate (max % collected for aviation)	14%	21%	28%	36%	43%	50%
Mt used cooking oil + waste fat available (UCO+ waste fat), in ECAC	7.0	8.2	9.4	10.6	11.8	13.0

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