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The Ascent of SAF

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Publication date: 10 September 2021

Abstract

Multiple stakeholders in the aviation industry have committed to reaching carbon neutrality by 2050. Sustainable aviation fuel (SAF) is emerging as the pivotal way to achieve carbon neutrality for aviation by 2050. It is the only feasible solution for mid to long-haul flights responsible for circa 70% of the aviation CO_2 emissions. Depending on the production pathway and the feedstock used, SAF can produce approximately 80% fewer CO_2 emissions than conventional jet fuel on a lifecycle basis (i.e., across all stages of production, distribution, and usage).

This paper aims to summarise the available pathways of deriving SAF and investigate the cost of using SAF for specific aircraft types. Several simulations included quantify the additional cost of SAF borne by airlines or potentially passed on to passengers or investors. A comparison is made between the newest technology aircraft against the equivalent previous technology types.

For a commodity service industry such as aviation, the cost of SAF compared to fossil fuel is a real challenge. However, this paper concludes that for a small percentage of SAF blend, the cost of SAF may be acceptable for passengers with an ever-growing environmental awareness.

1. *Multiple solutions to reaching sustainability in aviation*

Sustainability in aviation is a topic that concerns all of us, from airlines to OEMs, investors, and passengers. Multiple stakeholders are committed to reaching carbon neutrality by 2050. At present, the aviation industry is exploring several solutions. Key stakeholders, including airlines, government agencies, NGOs, engine and airframe OEMs, oil producers, fuel suppliers, and researchers, have proposed multiple pathways. The pathways comprise improved technology and air traffic management, market-based measures such as EU-ETS (EC, 2021a) and CORSIA (ICAO, 2021) and sustainable aviation fuel (SAF). As governments ramp up efforts to decarbonise aviation and the environmentally conscious public demand action, SAF stands out as the cornerstone technology in bringing about change.

The aviation industry has made several environmental promises — long term ones targeting 2050 and medium-term targets to support the achievement of the 2050 goals. In 2009, IATA adopted three targets aiming to mitigate CO_2 emissions from air transport. IATA committed to i) an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020, ii) carbon-neutral growth from 2020, and iii) the reduction of aviation CO_2 emissions by 2050 to half of their 2005 levels. The first target has been achieved with an annual improvement in fuel efficiency of 2% between 2009 and 2019 (IATA, 2021). IATA is expected to update its position in 2023.

Recently, the EU has set more ambitious targets, committing to reaching climate neutrality by 2050, with an intermediate target of at least a 55% reduction in net emissions by 2030 compared to 1990 levels. The UK government is the first major nation to commit to a net-zero CO_2 emissions target by 2050, with intermediate steps for aviation of a 15% reduction in 2030 compared to 2019 and 40% by 2040.

Total fuel consumption by aviation continues to grow, given the rise in air travel. Since 2005 — a reference year in IATA's targets — fuel consumption grew on average 2.6% annually. Declines were notable only after major events such as the global financial crisis of 2008-2009 and the ongoing COVID-19 pandemic. Notwithstanding this, CO_2 from aviation still grew on average by 2.6% each year during 2005-2019. The CO_2 emissions from aviation during 2019 are estimated at 920 million tonnes (Mt), of which 85% were emitted by passenger flights (ICCT, 2020). As such, the industry requires significant structural change to reach targets such as carbon neutrality in 2050.

A shift towards sustainable fuels will allay this consistent increase in fossil fuels usage. Existing aircraft technology has been developed over the years to reduce the utilisation of fossil fuels. Improved fuel burn attributable to new engine and airframe designs has already helped the industry reduce emissions. Between 2000 and 2019, the energy intensity per available seat kilometer of commercial aviation decreased on average by 2.8% per year, driven by efficiency improvements in operational and technological measures (IEA, 2020). Newly developed sustainable fuels will be implemented with minimal changes to the existing technology. Fuels that are compatible with the existing infrastructure and do not require modifications to the engines' fuel systems are referred to as "drop-in" fuels.

SAF is emerging as the most realistic way to achieve carbon neutrality for aviation by 2050. It is seen as the only feasible solution for mid to long-haul flights responsible for nearly 70% of the aviation CO_2 emissions. Other solutions, such as electric and hydrogen-powered aircraft, are feasible for short-haul and regional flights only. Further, SAF is ready to use and compatible with the existing aircraft technology. The main impediment to immediate use is price, yet in short order, it could be scaling the production sufficiently.

SAF produce on average 80% fewer CO_2 emissions than conventional fuels. The CO_2 emissions reduction depends on the production pathway and the feedstock used. Over time, SAF such as the e-fuels, detailed in section 2.2, can produce up to 100% less CO_2 emissions. Besides CO_2 emissions, other pollutants such as nitrogen oxides (NO_X), sulphur oxides (SO_X), soot particles, and water vapours pose environmental challenges. SAF has been shown to burn cleaner than fossil fuels, thus contributing to reducing non-CO_2 emissions (Voigt et al., 2021).

2. SAF pathways

SAF has been researched, produced, and utilised for many years. New initiatives to derive SAF are being proposed and developed in many parts of the world. Two main SAF categories have emerged. Both can be used as "drop-in", mixed with A-1 jet fuel without the need to modify the aircraft design or the supply infrastructure: biofuels and e-fuels.

2.1 Biofuels

ASTM International (previously known as the American Society for Testing and Materials) is the standards organisation responsible for defining the requirements for aviation fuels. It is a non-government entity based in the US, and its fuel specifications are recognised internationally. ASTM D1655 is the specification for conventional fuels, and ASTM D7566 is the standard specification for synthetic blending components mixed with conventional fuels (ASTM, 2020). The synthetic fuels standard, D7566, is built and updated on an annex structure. With the certification of new synthetic fuel, a new annex is added to the D7566 standard. To date, there are seven annexes, summarised in Table 1. Each annex provides the production pathway for the new jet fuel. A description of each pathway is included in the Appendix section.

Table 1: the list of ASTM D7566 annexes, the year of approval, the name of the new fuels introduced, the maximum percentage blend of the new fuel approved for mixing with conventional jet fuel. Only fuels in Annex A1, A2 and A5, are commercially available. All fuels listed are "drop-in" fuels

Annex	Approval year	Fuel Name	Max blend rate
A1	2009	FT-SPK	50%
A2	2011	HEFA-SPK	50%
A3	2014	HFS-SIP or DSHP	10%
A4	2015	FT-SPK/A	50%
A5	2016	ATJ-SPK	50%
A6	2020	CHJ	50%
A7	2020	HC-HEFA SPK	10%

The new fuels do not have the same chemical complexity as fossil fuels, and it is recommended that their usage is limited to blends of up to 50% with traditional fuels. Fossil fuels contain more than 2,000 compounds (Roth, 2020), while synthetic fuels consist of a much more constrained chemical compound combination. For example, one of the synthesised fuels consists of a single compound, known as farnesane ($C_{15}H_{32}$). However, due to its single-molecule structure and, in particular, lack of aromatics, farnesane can be used as a drop-in fuel of a maximum 10% blend with Jet A-1. Aromatics are molecules whose presence in fuels contributes to up to 90% of the soot produced during fuel burn. Their contribution to sooting makes these compounds undesirable per se, but they are essential to fuel system seals swelling (Fu, 2019). The seals compress more in the absence of aromatics (Anuar et al., 2021), which can lead to fuel leakage or reduction in the useful life of the seals. The final blended fuel must comply with a minimum of 8% aromatic content; therefore, synthetic fuels have so far been approved as blendstock and not as 100% substitutes for conventional jet fuel. For the moment, out of caution, blends can contain a maximum of 50% synthetic fuel, although several test flights have already taken place replacing kerosene by 100% SAF (Airbus, 2021a).

Strategic partners to the SAF producers are service suppliers like Shell or Air BP for their global distribution capabilities and technology companies for the license agreements (e.g., Fischer-Tropsch technology). Other essential partners are the airlines that sign long-term supply contracts for large biofuel quantities. Many airlines already signed offtake agreements with SAF producers, and some airlines are also equity investors in these refineries. Several refineries are being planned by both current and new industry players. Over ten bio-refineries are expected to open between 2021-2025, primarily located in Europe and the US.

Currently, the pathways approved by ASTM describe the only feasible alternative to fossil aviation fuels for powering commercial aircraft. These pathways will reduce CO_2 emissions[1]; however, some of them could be temporary solutions due to limitations related to feedstock. Most of the raw materials used to derive biofuels require land and water for growth and may compete with food crops. The first generation of biofuels used edible biomass, which competed with food crops for humans and animals. The second generation of biofuels (advanced biofuels) was developed to use non-food crops that do not need rich soils or irrigation. The third and fourth generations — still in the early stages of development — are to use algal biomass and genetically modified algae, respectively (Alalwan, 2019). Not all biofuels are sustainable. Biofuels contribute to reducing CO_2 emissions, but only conditional on considerate use of land, low emissions during biomass cultivation at all stages of fuel production, distribution, and usage. In the absence of these requirements and robust policies to enforce them, biofuels would be no better than the fossil fuels they are replacing.

Additionally, the biofuels' ability to meet the global demand for jet fuel over time is debatable due to feedstock availability. Some pathways that use inorganic substances instead of biomass are not limited by feedstock availability (e.g., LanzaTech recycles steel mill emissions to produce ethanol). In the long term, there are non-biogenic pathways that may offer a better solution. Such alternatives are fuels obtained via Power-to-X and Sun-to-Liquid technologies.

2.2. E-fuels

One path towards using renewable energy is via Power-to-X technologies, also referenced as PtX. Power-to-X is the broad term that encompasses a wide range of technologies focused on extracting renewable energy, storage and conversion to hydrogen or heat. Power-to-Liquid is the sub-field of Power-to-X, which can help aviation get closer to climate neutrality by transforming renewable power into synthetic fuels for flying. The resulting aviation fuel is referred to as e-fuel, PtL fuel, power-based kerosene, electrofuel or powerfuel.

E-fuels are similar to and can be used as a drop-in with their fossil fuel equivalents. Like biofuels, the e-fuels are clean-burning jet fuels, with the added benefit of using renewable energy (solar, wind) and no biomass. The Power-to-Liquid method for obtaining jet fuels requires energy, water and carbon dioxide (CO_2); the electricity and the CO_2 need to be from renewable sources. The CO_2 can be captured from concentrated industrial sources or recycled from the atmosphere.

One way is to obtain e-fuels via a high-temperature electrolysis technology that uses renewable energy to split water into hydrogen and oxygen. Together with carbon dioxide, the resulting hydrogen is converted via the Fischer–Tropsch (FT) synthesis process into jet fuel. This process can help overcome the fluctuations that generally characterise sustainable energy resources (Loewert & Pfeifer, 2020). The other way to obtain e-fuels is via methanol synthesis. Hydrogen from the electrolysis and the carbon dioxide are converted to methanol, further refined into jet fuel. E-fuels derived via methanol synthesis are not ASTM approved, but the FT synthesis is certified as part of Annex 1 of the ASTM D7566 standards. Like biofuels, the FT-based e-fuels lack

[1] CO_2 emissions reductions from biofuel use come from feedstock production and fuel conversion, not from fuel combustion. Biofuel is designed to have very similar properties to fossil fuel, burns the same way, and emits a similar amount of CO_2 (3.16 kg of CO_2 per kg of jet fuel). Recent research suggests SAF produces less contrail cloudiness (Voigt et al., 2021).

aromatic hydrocarbons and are only certified for a maximum of 50% blend with conventional jet fuels.

The technology used in producing e-fuels is ready and already implemented. The capacity is low, but the number of pilot plants is growing (Roth, 2020). Several plants are currently operated or under planning by cleantech companies or research centres who have all pioneered different approaches to creating e-fuels:

- Germany (Sunfire plant in Dresden founded in 2010, opening PtL demonstration plant in 2014; first fully working integration of FT synthesis)
- Finland (Soletair proof of concept plant)
- Norway (Nordic Blue Crude and Norsk e-fuel plants under planning in Herøya; both using FT synthesis with Sunfire patented technology)

Besides the e-fuels, the other non-biogenic pathway to derive alternative jet fuels is the Sun-to-Liquid approach (Roth, 2020). Solar heat from concentrated solar radiation can be used to split water and carbon dioxide into H_2 and CO, separated into syngas and further liquified via FT synthesis. The resulting jet fuel is certified, in line with Annex 1 of ASTM D7566, like FT-SPK and e-fuels. The first implementations of fuel deriving solar-thermochemical technologies were demonstrated by the European Union-funded projects SUN-to-LIQUID and SOLAR-JET. While this pathway is only in its early stages, it is another promising step towards cleaner jet fuel.

Another relevant development is the possibility of removing CO_2 from the atmosphere using direct air capture (DAC). CO_2 captured with DAC technology may be sequestered or used to enhance oil production in older fuel reservoirs (Meckling & Biber, 2021). It can also be used in the production of SAF, particularly in the emergent e-fuels market. Unlike CO_2 captured from point sources which are typically large-scale facilities (steels mills, cement factories, power plants), the DAC facilities are geographically flexible. They have modular designs and do not require productive land. Depending on the DAC technology used, the energy and water requirements can be high, making the price of SAF using DAC more expensive than other SAF.

3. Support for SAF production

SAF is an emerging market. Despite being researched and developed for many years, the SAF market has not grown as fast as was initially anticipated. In the early 2010s, when the first SAF pathways were being certified, it was thought that by 2020, the SAF usage might grow to 15% of the jet fuel market. However, in 2020, only 190,000 tonnes of SAF were produced, representing less than 0.1% of annual jet fuel consumption in commercial aviation (Airbus, 2021b). SAF needs support to grow production, given its price premium to Jet A-1.

Support for SAF comes from airlines who signed forward purchase agreements with SAF producers. Seven billion liters of SAF were signed in offtake agreements spanning 2021-2030. Airlines have also set up ambitious self-imposed mandates to increase SAF usage by 2030, e.g., Delta (10%), IAG (10%), and Ryanair (12.5%).

Governments are also doing their share in supporting the growth of the SAF market. For example, the SAF market is growing in the US, supported by tax credits from the federal legislature and state policies. There is a biodiesel tax credit of 1 USD/gallon at the federal level extended to producers/blenders of SAF. The Pacific coast states adopted low carbon fuel standard credit (LCFS) trading programmes at the state level. Similar proposals are under assessment by other states. Californian LCFS credits trade close to 1 USD/gallon. One US gallon is equivalent to 3.78541 liters.

In its quest to reach climate neutrality by 2050, the EU has proposed an intermediate step to cut emissions by at least 55% by 2030 compared to 1990. As part of the “Fit for 55” package, the ReFuelEU aviation initiative proposes new legislation to incentivise SAF use in Europe. SAF (advanced biofuels and e-fuels) should account for at least 5% of aviation fuels by 2030 and 63% by 2050 (EC, 2021b). The new proposal includes a mandate on jet fuel suppliers to blend more SAF with the fuel provided at European airports. Obligations apply to all airlines uniformly, and all internal European or internationally departing flights, including long-haul ones, are required to uplift fuel from European airports to avoid fuel tankering. An essential aspect of the initiative is that it contains sub-mandates for renewable fuels of non-biological origin (e-fuels). The mandate starts in 2025 with a 2% SAF target. It gradually increases the use of e-fuels from 0.7% of the total 5% SAF mandated in 2030 to 28% of the 63% SAF mandated in 2050.

4. Cost of using SAF

Current SAF prices are between 2x and 5x that of Jet A-1 fuel (World Economic Forum, 2021). These are projected to drop with increased production volumes, market competition, and supportive policies. It is expected that SAF prices will drop to less than 2x the unsubsidised price of Jet A-1 fuel by 2030. Moreover, SAF prices are expected to be less volatile than standard jet fuel.

In this section, several simulations are included to demonstrate the additional cost of SAF incurred by airlines or equivalently if transferred to passengers or investors. A comparison is made between new technology aircraft such as the NEO against the CEO equivalent types. Current fuel prices of SAF ~ 4.00 USD/gallon and Jet A-1 ~ 1.75 USD/gallon are assumed for all simulations. Also, we assume an average utilisation rate of 9 flight hours per day for all narrowbody types, or equivalently an average of 4.5 flight cycles per day, each cycle consisting of a two-hour flight. This utilisation rate amounts to 1,650 flight cycles at two-hour flights or 3,300 flight hours annually. All aircraft are assumed to operate at 80% load factors.

SIMULATION 1: Actual cost of using SAF for operators (A320 NEO)

In this example, we estimate the additional cost of using SAF for A320 NEO aircraft. We consider three different scenarios for a 2018 built A320 NEO aircraft depending on the SAF blending rates of 1%, 5%, and 10%. The resulting additional annual costs for the airline based upon the listed assumptions are:

- 61,000 USD (1% blend), 305,000 USD (5% blend) and 610,000 USD (10% blend) per aircraft per year
- 0.25 USD (1% blend), 1.23 USD (5% blend) and 2.46 USD (10% blend) per passenger per flight
- For comparison, the average passenger ticket fare in Europe for low-cost carriers is ~ 60 USD.

Conclusion: Simulation 1 indicates that for low SAF blend rates, even at today's prices, the overall cost of SAF may be considered affordable for specific passenger segments.

SIMULATION 2: Cost differential between A320 CEO and A320 NEO (if A320 CEO was to reduce CO_2 emissions to match those of the A320 NEO)

The results from Simulation 1 focused on new technology. A new technology aircraft such as A320 NEO consumes less fuel and produces fewer emissions than the previous technology it was developed to replace. To make previous technology as green as the new technology requires additional SAF use to compensate for the CO_2 emissions resulting from the differential in fuel consumption. If an A320 NEO uses SAF, an A320 CEO trying to match the NEO's emissions would have to use the SAF quantity the A320 NEO uses and, further, an additional and significant amount of SAF to offset the emissions from the extra fuel consumption of the A320 CEO compared to NEO.

A 2018 built A320 NEO consumes 11% less fuel than a 2018 built A320 CEO (Hensey & Magdalina, 2018), resulting in a similar CO_2 emissions reduction. To level up for this differential in CO_2 emissions, an A320 CEO would need to reduce the emissions from the additional ~350k gallons of jet A-1 fuel per year. Therefore, SAF blend rates of 0%, 1%, 5%, and 10% for the A320 NEO translate into matching blend rates of 14.4%, 15.3%, 18.8%, and 23.2% for the A320 CEO. Previous technology aircraft must uplift an extra quantity of SAF, which incurs an additional cost to match the new aircraft technology emission. The resulting additional annual costs for the airline based upon the previous assumptions are:

- 1 million USD per A320 CEO aircraft per year to level up with the NEO vs CEO emissions differential or equivalently, 4.00 USD per passenger per flight assuming 80% load factors (14.4% blend for CEO and <u>0% blend for NEO</u>)
- 1.05 million USD per A320 CEO per year (15.3% blend for CEO or equivalently <u>1% blend for NEO</u>), 1.30 million USD (18.8% blend for CEO or equivalently <u>5% blend for NEO</u>) and 1.60 million USD (23.2% for CEO or equivalently <u>10% blend for NEO</u>)
- 4.25 USD per passenger per flight on an A320 CEO aircraft (15.3% blend for CEO or equivalently <u>1% blend for NEO),</u> 5.23 USD (18.8% blend for CEO or equivalently <u>5% blend for NEO</u>) and 6.46 USD (23.2% for CEO or equivalently <u>10% blend for NEO</u>)

Conclusion: The cost of bringing the previous technology to the same level of emission reductions as the new technology is significantly high. From the start, it would cost an A320 CEO an additional 1 million USD per year to offset the additional fuel consumption compared to an A320 NEO. The comparison, in this case, is performed between aircraft of the same vintage. In reality, airlines introduce new technology aircraft in their fleets to replace 10-15 years older aircraft. In this case, the gap between the new and previous technologies increases beyond the 1 million USD estimated above.

SIMULATION 3: The cost of SAF for A320 CEO and A320 NEO, assuming the additional cost is carried into an operating lease

In this example, we compare the cost of SAF for 2018 built A320 CEO and A320 NEO aircraft, assuming an average utilisation rate of 9 flight hours per day and SAF blending rates of 1%, 5%, and 10% for both aircraft types, relative to own fuel consumptions. Unlike the previous examples, which assume the extra cost of SAF is carried by the airlines or distributed to passengers, this simulation assumes the cost of SAF is carried into operating lease contracts by monthly payments.

Currently, for an A320 CEO, the monthly market lease rates[2] are approximately 190,000 USD, trading significantly below the base lease rates[3] of 280,000 USD. Similarly, for an A320 NEO, the monthly market lease rates are approximately 280,000 USD, trading significantly below the base lease rates (330,000 USD). These are generic quotes; actual rentals vary significantly, subject to airline credit risk, interest rates, jurisdictional risk, contracted redelivery conditions, maintenance reserve or end-of-lease compensation terms and other deal-specific factors.

The additional monthly costs for the lessors/investors are estimated at:

- 1.54% of the base lease rate or, equivalently, 5,079 USD per A320 NEO per month for 1% SAF blend
- 2.05% of the base lease rate or, equivalently, 5,741 USD per A320 CEO per month for 1% SAF blend

Conclusion: The additional monthly cost amounts to 2.05% of base lease rates for every percentage point of SAF in the fuel blend for the A320 CEO and even more, 3.02% if calculated relative to current market lease rates. Likewise, for the A320 NEO, the monthly cost amounts to 1.54% relative to the base lease rate and 1.81% relative to the market lease rate for every percentage point of SAF. Considering margins in the competitive aircraft leasing market, the aircraft owners could not easily absorb these costs. On the other hand, they give a sense of the impact if an element of cost burden was allocated to the owner.

SIMULATION 4: Cost of using SAF on long-haul routes using widebody aircraft (A330 CEO)

While the previous three simulations focused on the cost impact of SAF on narrowbody aircraft, Simulation 4 estimates the additional cost of using SAF for an A330 CEO aircraft. For a 2018 built A330 CEO aircraft, we assume SAF blending rates of 1%, 5%, and 10% and an average utilisation rate of 14 flight hours per day. The utilisation rate is equivalent to flying every day of the year return flights between Dublin and New York. Although the maximum seating capacity for A330-300 is 440, we assume a two-class layout of 287 standard economy seats and 30 business class seats. As in the previous simulations, the load factor is assumed to be 80%. The resulting additional annual cost to use SAF for the airline are estimated at:

- 195,501 USD (1% blend), 972,506 USD (5% blend) and 1,945,013 USD (10% blend) per aircraft per year
- 1.05 USD (1% blend), 5.25 USD (5% blend) and 10.51 USD (10% blend) per passenger per flight
- For comparison, the one-way economy ticket price from Dublin (DUB) to New York (JFK) during September 2021 starts from 549.55 EUR (~645 USD) (Aerlingus, 2021).

Conclusion: Simulation 4 indicates that for low SAF blend rates, the additional cost of SAF may be considered affordable even for long-haul flights for specific customer segments.

5. Overall conclusions

- There are multiple pathways to decarbonise aviation.
- SAF offers the most promising solution to the decarbonisation of aviation through 2050.
- There are two types of SAF: biofuels (advanced stage development; available today) and e-fuels (early-stage development; long-term solution by 2030s).
- Calculations indicate that for smaller SAF blend quantities, even at today's prices, the overall cost of SAF may be considered affordable when assessed on a cost per passengers basis.
- For new technology aircraft, on short-haul flights, the cost per passenger per flight is 2.5 USD for a 10% blend of SAF, under specific assumptions.
- Single-aisle previous technology aircraft will incur a higher additional cost of 1 million USD per year to match the new aircraft technology emissions due to increased SAF requirement.
- For twin-aisle aircraft used on long-haul flights, the cost per passenger per flight is 10.5 USD for a 10% blend of SAF.
- The increased commitment from airlines and governments will lead to an increased demand for SAF and hence a price reduction in SAF to make it comparable to fossil fuel prices in the long term.

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[2] Market lease rate is an estimate of the monthly lease rate as impacted by market conditions.

[3] Base lease rate is an estimate of the monthly lease rate in an "open, unrestricted, stable market environment with a reasonable balance of supply and demand" (AVITAS, 2021).

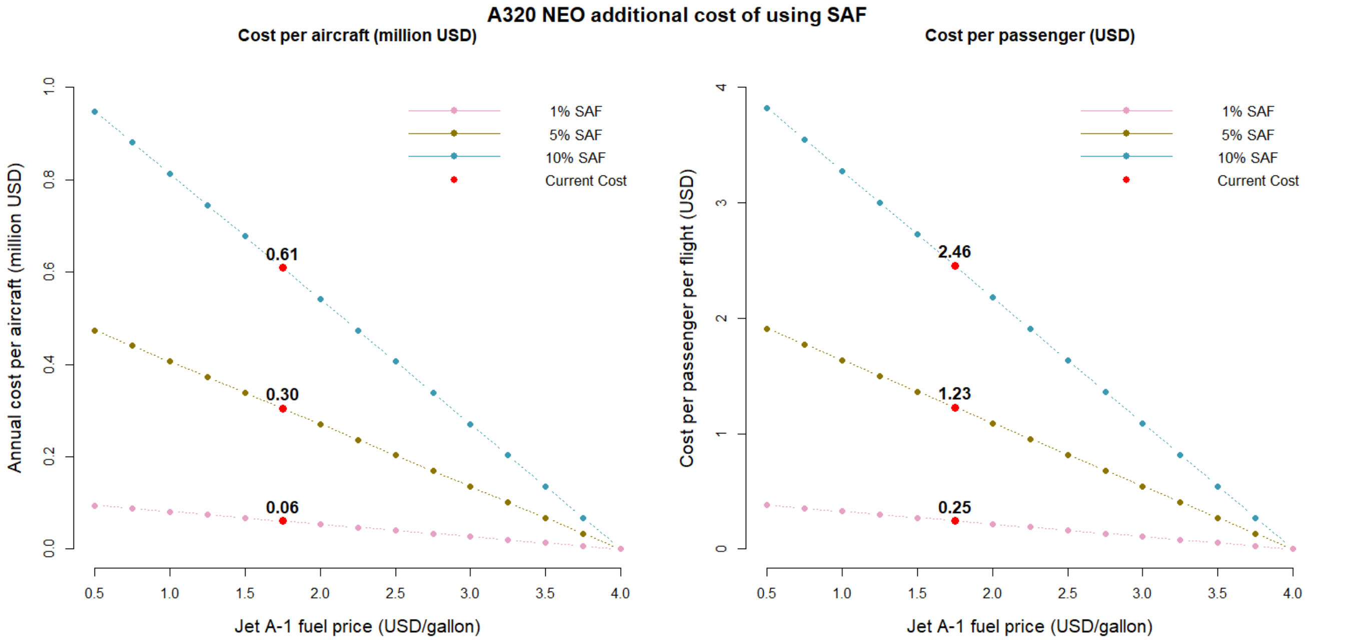

Figure 1. Simulation results: the additional cost for an A320 NEO when using SAF blended with Jet A-1 fuel. SAF blending rates of 1%, 5%, and 10%. Each 1% SAF leads to a cost increase of 60,000 USD per aircraft per year, or equivalently 0.25 USD per passenger per flight at 80% load factors.

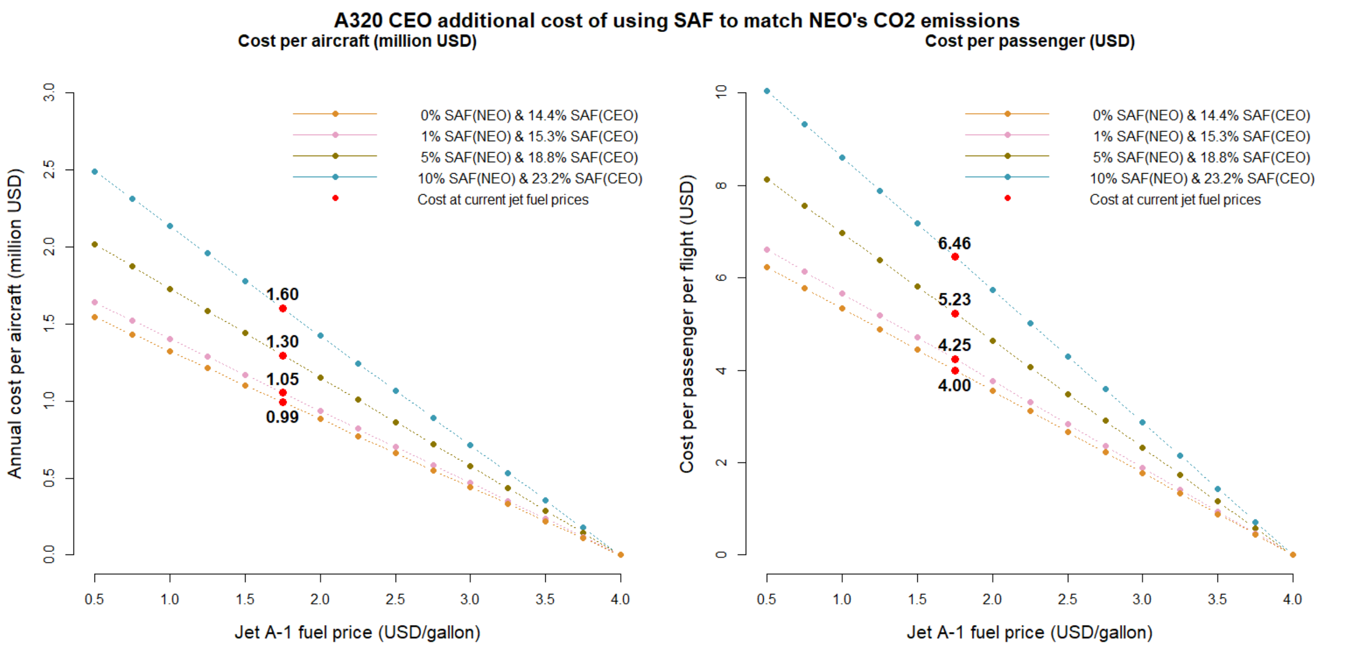

Figure 2. Simulation results: the additional cost for an A320 CEO to match the emission reduction in an A320 NEO, which uses no SAF, 1%, 5%, and 10% SAF. The A320 CEO must use a large quantity of SAF (14.4%) to offset the additional fuel consumption compared to the A320 NEO. The additional baseline cost for the A320 CEO is ~1 million USD per aircraft or ~4 USD per passenger per flight.

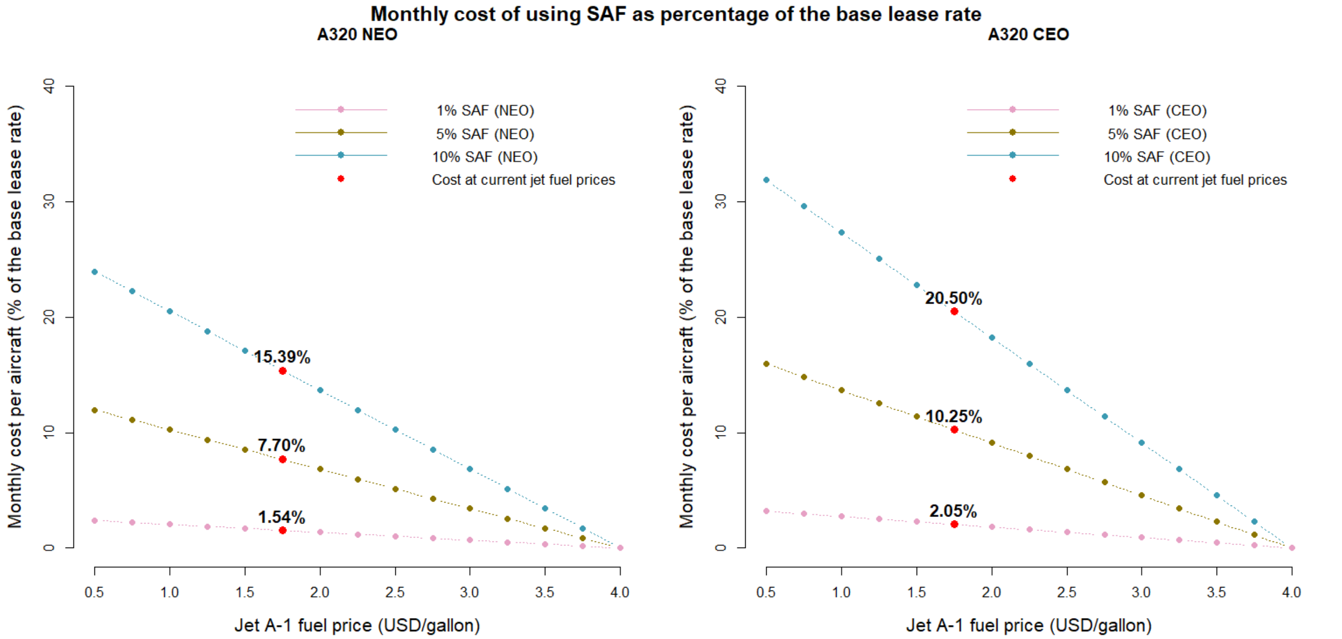

Figure 3. Simulation results: the additional cost of SAF if transferred to an operating lease for A320 CEO and A320 NEO, calculated as a percentage of the base lease rate. Each aircraft uses 1%, 5%, and 10% SAF of their respective fuel consumption.

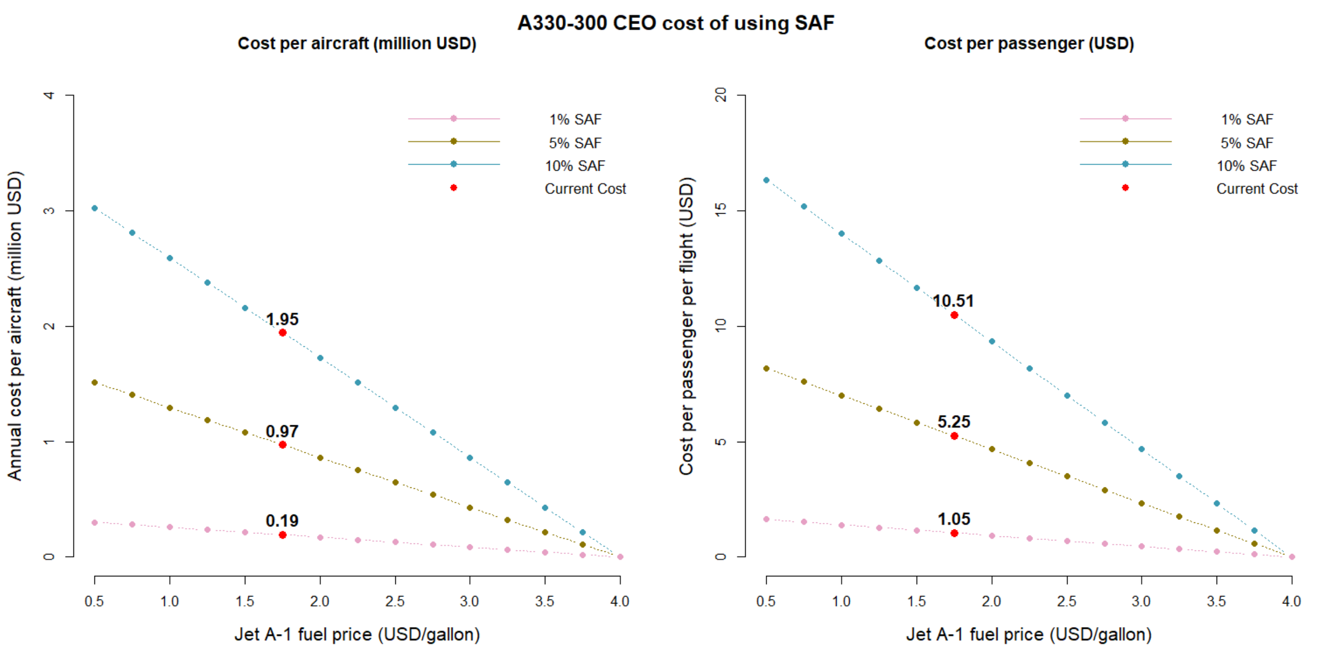

Figure 4. Simulation results: the additional cost for A330 CEO when using SAF blended with Jet A-1. SAF blending rates of 1%, 5%, and 10%. Each 1% SAF leads to a cost increase of ~ 200,000 USD per aircraft per year, or equivalently 1.05 USD per passenger per flight at 80% load factors.

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APPENDIX

There are diverse pathways to deriving sustainable aviation fuels and initiatives to derive SAFs in full development worldwide. Technical considerations for each pathway are detailed in ASTM D7566 (2021).

A1. FT-SPK (Fischer-Tropsch – Synthesised Paraffinic Kerosene) is the first synthetic fuel approved by ASTM International. FT-SPK is a thermochemical process consisting of gasification at high temperatures of diverse biomass based on lignocellulosic materials (woody residues such as bark and sawmill by-products, corn stover). The result of the gasification, referred to as syngas, is a combination of carbon monoxide (CO) and hydrogen (H_2). The syngas is further synthesised via the FT process to obtain jet fuel. Notable producers are Fulcrum, Red Rock, Velocys.

A2. HEFA (Hydrotreated Esters and Fatty Acids) have initially been referenced as "HVO" (Hydrotreated Vegetable Oil) when derived from only vegetable oils. HEFA uses as feedstock: used cooking oil, animal fat, common vegetable oils or some non-food oils like jatropha and algae, which are hydrotreated and produce synthetic paraffinic kerosene. HEFA fuels have similar molecular composition to FT-SPK. The technology for deriving HEFA fuel is the only one commercially available at an industrial scale. Notable producers are Neste, SkyNRG, Total, World Energy.

A3. HFS-SIP (Hydroprocessed Fermented Sugar - Synthesized Iso-Paraffins) or DSHC (Direct Sugar to Hydrocarbon) converts sugars (sugarcane juice) by fermentation into farnesane. This biofuel has a molecular composition different from FT-SPK and HEFA and consists of a single molecule, which is why this biofuel is limited to 10% blends. To date, the development of this biofuel has been only announced by Amyris (Brazil) in collaboration with Total (France).

A4. FT-SPK/A (Fischer-Tropsch Synthetic Kerosene with Aromatics), a variation of Annex A1, refers to synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources.

A5. ATJ-SPK (Alcohol to Jet – Synthetic Paraffinic Kerosene) consists of two independent stages, one that converts carbohydrates from biomass (corn, sugarcane, agricultural residue) into alcohol (ethanol or isobutanol) and a second one that upgrades the alcohol into a mix of hydrocarbons from which the jet fuel can be separated. The companies developing ATJ are:

a. LanzaTech (US, China, India) can produce ethanol-based jet fuel using sustainable ethanol from steel mill emissions as feedstock.
b. Gevo (US) uses a diverse feedstock to derive ATJ-SPK (corn crops, sorghum, beets, wood, wood residues, cellulosic MSW, certain food wastes, cane sugar, etc. molasses).

A6. CHJ (Catalytic Hydrothermolysis Jet) was developed by Applied Research Associates (ARA) and Chevron Lummus Global (CLG). Their biofuel, named ReadiJet, is derived from waste fats, oils and greases. ReadiJet contains a uniform distribution of all hydrocarbon types commonly observed in fossil fuels, including aromatics; thus, making it another promising replacement for fossil fuel.

A7. HC-HEFA SPK (Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthesised Paraffinic Kerosene) was developed by IHI NeoG Algae IHI Corporation together with Gene and Gene Technology and Neo-Morgan Laboratory. The biofuel is derived by hydrotreating the oil extracted from a particular strain (Enomoto) of fast-growing algae which can double its volume in only two days. Its growth rate is 1,000 times faster than the general family of algae, Botryococcus Braunii, to which Enomoto algae belongs.

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