KNCV Chemie & Maatschappij Groep

Can we fly in 2040?

Under what premises could flying be a sustainable means of transport in 2040?

A technical summary for an opinion forming contribution by the members of the Chemical Society Group (CMG) in the Netherlands (English-Dutch)

Cover image: The Flying V is a design by the TU Delft, which could increase fuel efficiency by 20%. (Drawing from TU Delft)

COLOFON

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Summary

The global aviation industry is envisioned to grow by 100% over the coming 20 years. **Depending on the region in the world there is a reduction or a growth in aviation** foreseen. To meet aviation and sustainability goals in western economies a slowdown and reduction in aviation activities is foreseen of 6 to 25% (varying sources). In developing economies on the other hand, a significant growth is foreseen to meet social and economic growth ambitions.

The environmental effects of aviation include more than just CO_2 emissions related to fuel consumption, i.e. fine dust, NOx and water vapor. This broader pallet of atmospheric effects requires attention and needs to be included in the relevant mitigating plans. More attention and related measures are required to control the total GHG effects of aviation.

Recently, the share of green house emission is estimated to be 3.5-5% of global emissions (2018). Therefore, there is a shared viewpoint, amongst environmentalist, COP26 policy makers and EU governments, that there is an urgent and important need to reduce the environmental and climate effects of aviation. This concern has lead in the EU to an aviation policy prescribing clear short and longer term **GHG reduction emission targets** of 55% in 2030 for 90% for 2050 and the prescription of a number of measures related to an increasing percentage of renewable fuels.

Several climate policies have been initiated for aviation, such as the **Emission Trading Scheme** (EU) and **CORSIA** (global), as well as aviation CO_2 and fuel taxation systems that are aimed to increase flight cost and reduce the CO_2 emissions. Also CO_2 compensation schemes are in place providing measures to ensure CO_2 emissions are being recorded and constraint, where the ETS system is being adopted and implemented (Continental EU flights).

Regarding **efficiency**, the aviation industry themselves are taking a number of GHG reduction measurements such ATM (air traffic management) and the implementation of efficient fuel use technologies. These include new airplane design, lighter materials, fuel use and aviation procedures, such as optimal passenger and freight loading and optimum flight routes, landing and off-take procedures. This offers significant opportunities for aviation emission reduction up to 20%.

New aviation and propulsion fuel technologies are being developed. The following technical developments are considered to be potential gamechangers for the aviation industry:

- **Electric flying** would be applicable for short distance aviation and low load airplanes.
- **Hydrogen as propulsion fuel** could become an effective GHG emission reducing fuel. It is however considered to be a rather costly, energy intense and technological challenging. It is envisaged to be a long-term opportunity beyond 2040.
- **E-fuels as propulsion fuel**, created by hydrogen and CO_2, is a high cost and energy intense longer-term option, depending on large amounts of low-cost sustainable electric energy and low-cost high purity CO_2.
- **Synfuels** (syngas based) as propulsion fuel is, depending on feedstock availability (syngas from waste/residual biomass), a rather energy intense and costly, but viable medium/longer-term opportunity with a good direct fit in existing infrastructure and a relative low CO_2 footprint. It is foreseen to start contributing as per as per 2035.
- **Ammonia** as propulsion fuel is an option which has operational pro's as liquid combustion fuel and con's as aggressive, toxic chemical and will remain a farfetched costly proposition. This is due to NOx formation and its dependence of large quantities of low-cost sustainable energy.

- **Primary biofuels** will in the coming years steadily replace kerosine and offers a good opportunity to reduce the environmental burden of flying. This opportunity is for 1st generation biofuels limited to around 20% due to limited access to sustainable food-based bio feedstock. The contribution is envisaged to increase from 5% to 20 % in the year 2030 to 2040.
- **Biofuels based on secondary biomaterials**, including ethanol from starch, are less dependent on feedstock availability. Effective conversion processes are being developed, converting the ethanol and other secondary conversion products by hydro-formulation to unsaturated building blocks that are subsequently processed to drop-in kerosine fuels.

The required CO_2 mitigation cost of several technical viable biobased SAF's technologies shows high values. For food based "drop-in" fuel technologies (sugar cane ethanol and oil based) the CO_2 mitigation cost range from 495 to 550 UD$/Ton CO_2 (assuming certified low risk land use areas) and for the more (strategic) sustainable residue-based technologies these costs range from 185 $/ton to 370 $/Ton CO_2. This cost represents, at a release of 3,15 Ton CO_2 per ton of kerosine, a mitigated CO_2 kerosine fuel cost of 1575 $/Ton to 630 $/Ton. As a reference, the current kerosine costs is around 750 $/Ton.

The cost of flying will go up, depending on the scheme followed. Following the ETS and CORSIA guidelines the ticket cost (on a 30% fuel share cost basis) will go up to 2030, gradually increase from 3% to 15 % due to increase in CO_2 price from 60 $/T to 100 $/t. Following the use of the (first generation) sustainable aviation fuels (SAF) the ticket cost (at 20% SAF) will show an increase of 30+% as per 2035. Following the cost of the higher energy content and more complex manufactured syn-fuels and E-fuels the ticket price will further increase to 200+% from 2035 to 2050.

Way forward: Early international aviation agreements, taxation, CO_2 compensation schemes and early efficiency measurements are foreseen to be the most effective means to reduce the aviation GHG emissions. For the EU clear GHG reduction targets have been set. The employment of new technologies and sustainable aviation fuels is foreseen to have initially a limited impact, but they are envisaged to grow in the period 2030 to 2040. This would lead to substantial reduction in aviation GHG emissions.

The GHG emission reduction contribution of electrical aviation, if any, will only start beyond 2040, following the access to true sustainable electricity. Also H_2 as propulsion fuel in larger aircraft vehicles are not foreseen be a significant contributor before 2040. The first generation SAF biofuels are already contributing at 2.5 % in 2022 and envisaged to grow to 10% in 2030 and max 20% in 2040. The alternative secondary biofuels will become commercially available beyond 2030, while synfuels and E-fuels are envisaged to enter the aviation market in substantial quantities from 2035 and 2040 onwards.
Early development of alternative "drop-in" aviation fuel production technologies, early investment in world scale plants and early agreements within the foreseen global competitive playing field, are all fore seen to be important parameters to curb the longer-term environmental effects of aviation.

Concluding : **There is a clear mismatch between the time based EU GHG emission targets and the implementation of policies, improvements and most importantly the maturity of technology solutions. Speed and urgency seem to be the name of the game to ensure aviation is contributing its fair share to a sustainable future.**

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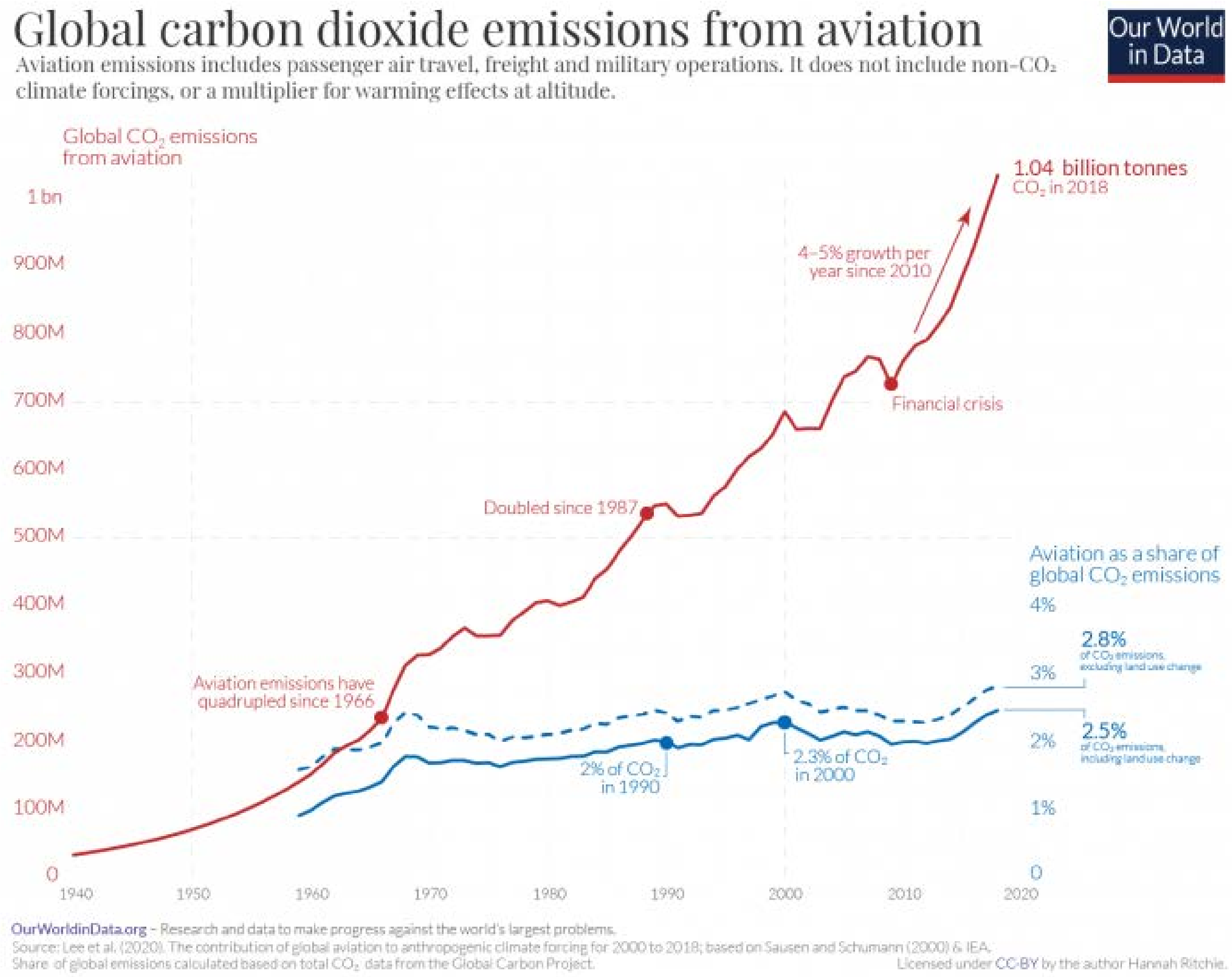
What are the technical sustainable aviation options?

An overview of considerations and public measures and references.

A.1. The case for action in aviation to reduce GHG emissions.

The expectations of various organizations are that aviation industry will grow significantly over the coming 20 years. The CAGR predicts between 2018 and 2038 an increase in flight activities ranging from 3% to 5.5% per year, depending on the global region, which leads to a doubling of aviation activities as per 2040[ref.56]. The FAA in the US predicts doubling of the passenger's flight activities as per 2040[ref.57]. The ICAO predicts a growth of over 100% of the CO_2 emissions from aviation fuels, even after further improvements in ATM, infrastructure, fuel efficiencies and technology improvements.


Global carbon dioxide emissions from aviation

Aviation emissions includes passenger air travel, freight and military operations. It does not include non-CO_2 climate forcings, or a multiplier for warming effects at altitude.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Lee et al. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018; based on Sausen and Schumann (2000) & IEA.
Share of global emissions calculated based on total CO_2 data from the Global Carbon Project.
Licensed under CC-BY by the author Hannah Ritchie.

Figure 1 Climate change and flying: what share of global CO_3 emissions come from aviation? From ref.12

The outlook seems however not to take into account envisaged higher flight costs and pricings due to use of more costly and energy intense sustainable aviation fuels, CO_2 pricing and compensation schemes and alternative aviation reducing measures as developed in the EU. To mitigate this envisaged growth in CO_2 emission, it assumes the employment of 100% renewable aviation fuels, i.e. SAF's[ref.58]. All in all, a reason to look more closely at different means to reduce the aviation emission in the period to come.

A.2. Social and economic relevance of flying: is there still a need to fly, can we reduce flying substantially.

Why do we fly?

- Personal development by traveling for adventure, curiosity and cultural exchange
- Personal relaxation to visit a new place
- Taking care of relations with family and friends
- High quality meetings for knowledge exchange and forming agreements for business or society that require physical presence
- To ship products, equipment and resources over the globe
- To provide human support and aid to deprived regions and catastrophes

Is flying a pre requisite for “the well-being of humanity”?

- Information exchange by internet can reduce the need for physical exchange, taking into account that Virtual reality will improve digital group meetings. We are meeting much more digital on MS Teams, Zoom or Google Meet. However physical meetings are still needed in certain cases.
- Regional and local production can reduce the needs for product by air. It is important to take into consideration which products do require extreme fast travel. Will production shift more continentally when full carbon price is paid on air and sea travel?

What trends and measures will affect the environmental impact of flying?

- Alternative transport means (digitalization, boat, train transport) will reduce the need for flying
- The envisaged global economic growth in the emerging markets will increase aviation
- Different sustainability measures in aviation will have a substantial footprint impact.

Main issues and opportunities:

We may assume that flying can and will be reduced in some areas due to alternative and more effective communication means, whilst in other regions it will still show growth. So overall there will remain a substantial flying activity in the future.

The global flying activity will be determined by the growth and the future “total cost of flying”, based on the “all in” cost of sustainable transport means including:

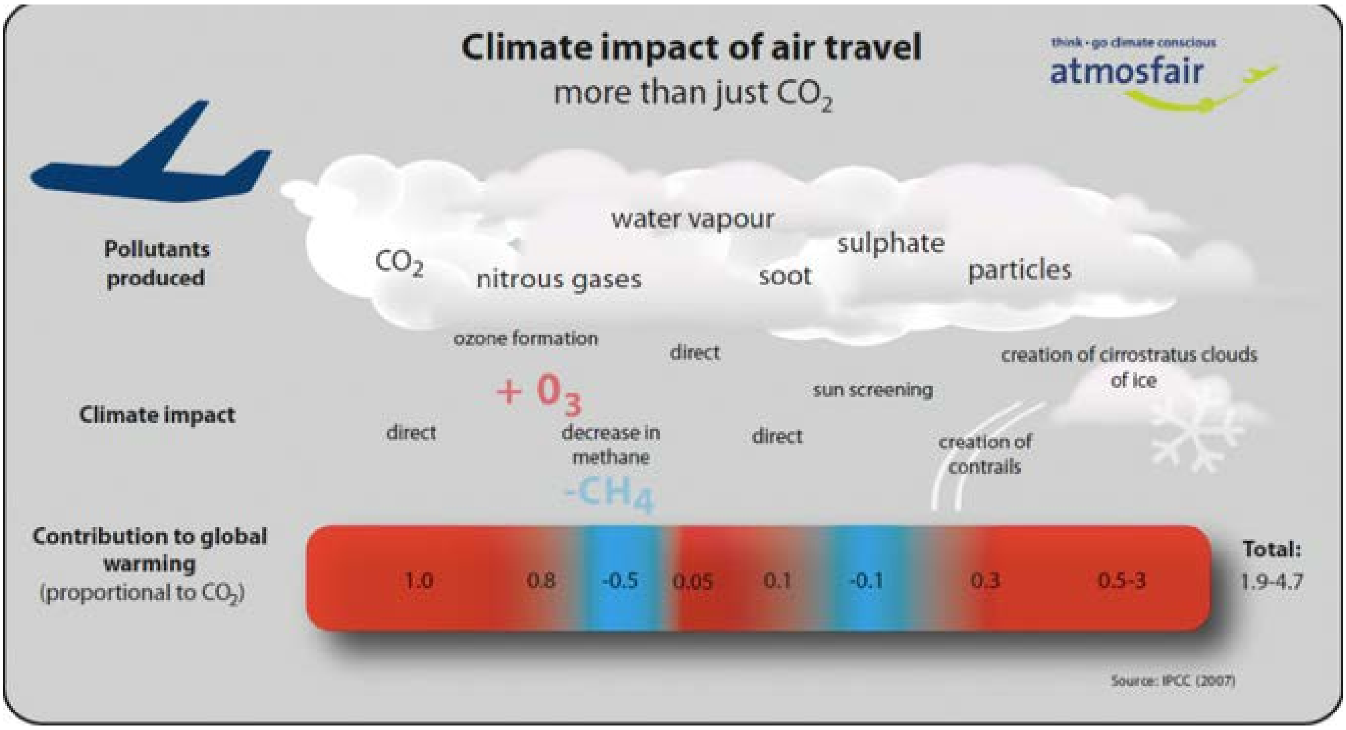
1. CO_2 compensation schemes;
2. cost of sustainable fuels;
3. cost for new propulsion concepts.

Given the slow implementation of sustainability measures, the envisaged time and the cost of the technology transition to more sustainable means of flying, it is foreseen that the contribution to the reduction in GHG emissions will initially be negative and only in the longer run will lead to reducing effects and a contribution to the global energy GHG reduction schemes.

A.3. Aviation emissions: CO_2 is not the only GHG emission. The emissions vary from 2.5 to 3,5 % on total when other effects are included. The emissions are on global basis foreseen to grow.

There are, other than CO_2, aviation emission effects such as NOx, particulates and curtail cirrus that need to be taken into account. They are responsible for 66% additional radiative effects. See also “this chart” in reference[ref.12].

The aviation emissions consist of more than then just CO2 and are, based on current predictions and the aviation growth, foreseen to become more important. See also figure in reference[ref.13].



For reference and ETS purpose, a CO_2-e factor, that represents all aviation effects, is described. Mitigating options to reduce the aviation radiative effects are also reviewed.
Sustainable aviation fuels with low aromaticity show promise, due to their low particulate emissions and reduced condense formation. Other measures such as NOx limits and avoidance of ice-super saturated routes are also envisaged to help to reduce the non-CO_2 radiative effects. Aviation emissions can have a disproportional large influence, as they occur in relative clean regions in the atmosphere[ref.14].

Alternative aviation fuels, technologies are not going to resolve the whole problem related to the variety of GHG effects (ranging from 2,5% to 5,9%). The majority of the technical options are either not sustainable (electrical aviation and primary biofuels) or not realistic in terms of energy efficiency (H_2, E-fuels). The latter would consume sustainable electrical energy in amounts that equal the current (2018) total global amount of sustainable energy produced.

The main conclusion is we should significantly reduce aviation holiday-, busines- and transport- activities now and into the future to reduce the undesirable aviation GHG effects on our environment[ref.15].

Main issues and opportunities:

To assess the effects of aviation on the atmosphere there is a need to include the effects beyond CO_2 i.e. NOX, particulates, curtail cirrus as they all contribute to the overall global warming effects. The suggestion that the required aviation fuels for the aviation growth can be sourced from energy intense processes (H_2, E-fuels) and / or the access to low-cost CO_2 (Sabatier E-fuels) is doubted. A reduction in aviation transport activities is foreseen to be the only realistic way forward in the short and medium term.

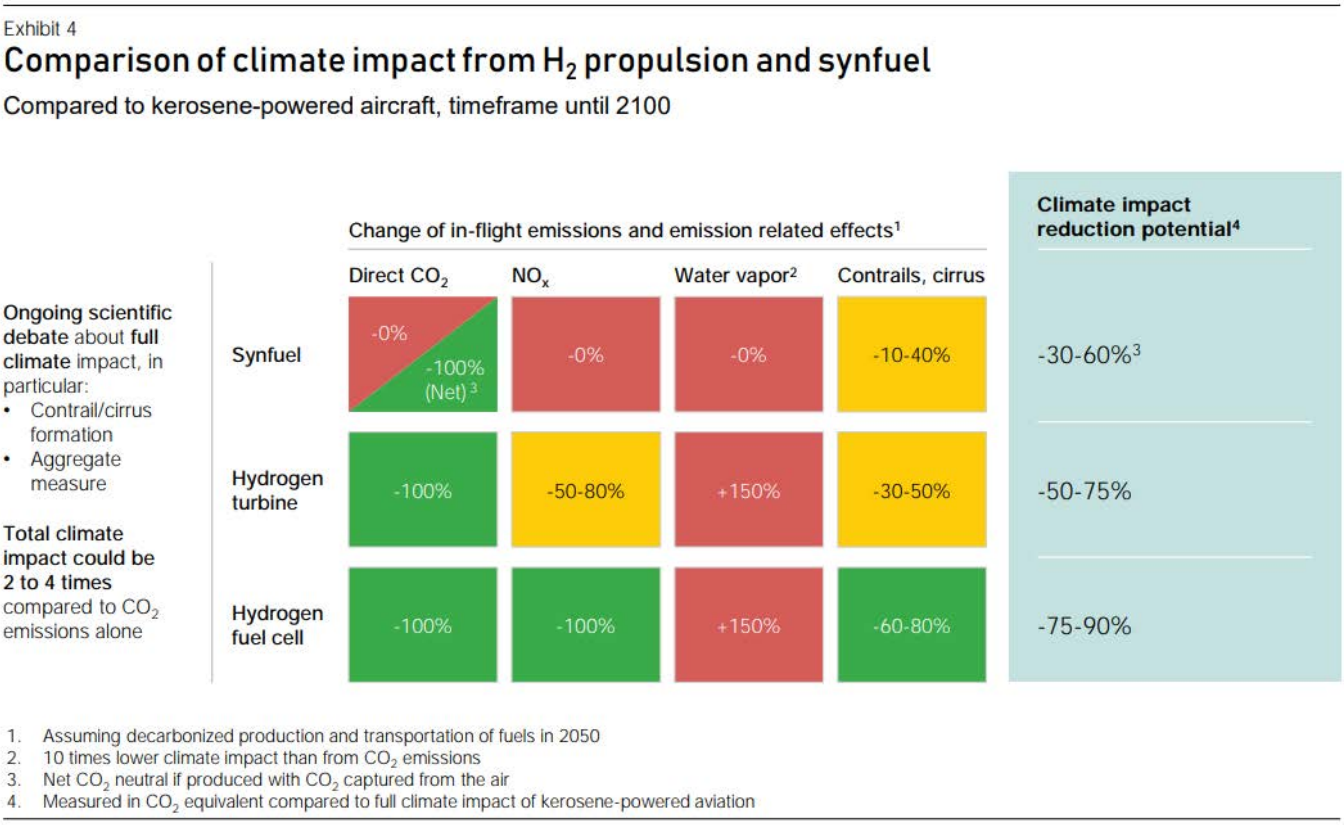


Exhibit 4

Comparison of climate impact from H_2 propulsion and synfuel

Compared to kerosene-powered aircraft, timeframe until 2100

Ongoing scientific debate about **full climate** impact, in particular:
- Contrail/cirrus formation
- Aggregate measure

Total climate impact could be 2 to 4 times compared to CO_2 emissions alone

	Change of in-flight emissions and emission related effects[1]				**Climate impact reduction potential[4]**
	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	
Synfuel	-0% -100% (Net)[3]	-0%	-0%	-10-40%	-30-60%[3]
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

1. Assuming decarbonized production and transportation of fuels in 2050
2. 10 times lower climate impact than from CO_2 emissions
3. Net CO_2 neutral if produced with CO_2 captured from the air
4. Measured in CO_2 equivalent compared to full climate impact of kerosene-powered aviation

Figure 2: Taking into account all GHG factors for all fuel types

A.4. What are the main policy guidelines for the reduction of aviation emissions?

EU approach: 55% GHG reduction as per 2030 and 90% GHG emission reduction per 2050. Main themes; technology and operational improvements, sustainable fuels and CORSIA (a CO_2 off setting program)[ref.7]. Explicit and detailed EU emission reduction guidelines stipulate SAF content and Synfuel /E-fuel content. The EU mandate describes a GHG emission reduction of 55% as per 2030, a SAF fuel content 5% by 2030, 32% by 2040 and 63% by 2050 and synthetic aviation fuel content, starting at 0.7% in 2030, increasing to 8% in 2040 and 28% in 2050. In case of non-conformance, substantial penalties ranging from 1000 to 6000 EU/ton will apply[ref.8].

Clean sky 2 EU program aims to increase the aircraft fuel efficiency, thus reducing CO_2 emissions by 20-30% compared to 'state-of-the-art' aircraft and reducing aircraft NOx, particulates and noise emissions by 20-30% compared to 'state-of-the-art' aircraft[ref.9].
Clean aviation, an EU program for cleaner and new aviation technologies foresee for regional aviation the use of hybrid electric aircrafts, a 50% fuel reduction and 90% emission reduction as per 2035 and for short-medium range ultra-efficient aircrafts, a 30% fuel reduction and 86% emission reduction as per 2035. Disruptive technologies to enable hydrogen-powered aircraft are also allowed for[ref.10].

Sustainable and smart mobility strategy: EU concentrates on rail inter-operability for goods and passengers and invests heavily in rail infrastructure and inland shipping as a way to reduce local /regional air transport[ref.11].

Main issues and opportunities:

The EU distinguishes between short and longer haul flights and sees transport over land as a logical step forward for short and regional passenger and goods transport. For longer distances they promote CO_2 off-setting via CORSIA and CO_2 pricing via a new ETS program and via taxation. At the same time the EU supports innovation in aviation technology, efficiency and new aviation concept, so the EU is basically working on many fronts to support the reduction of the emissions from aviation.

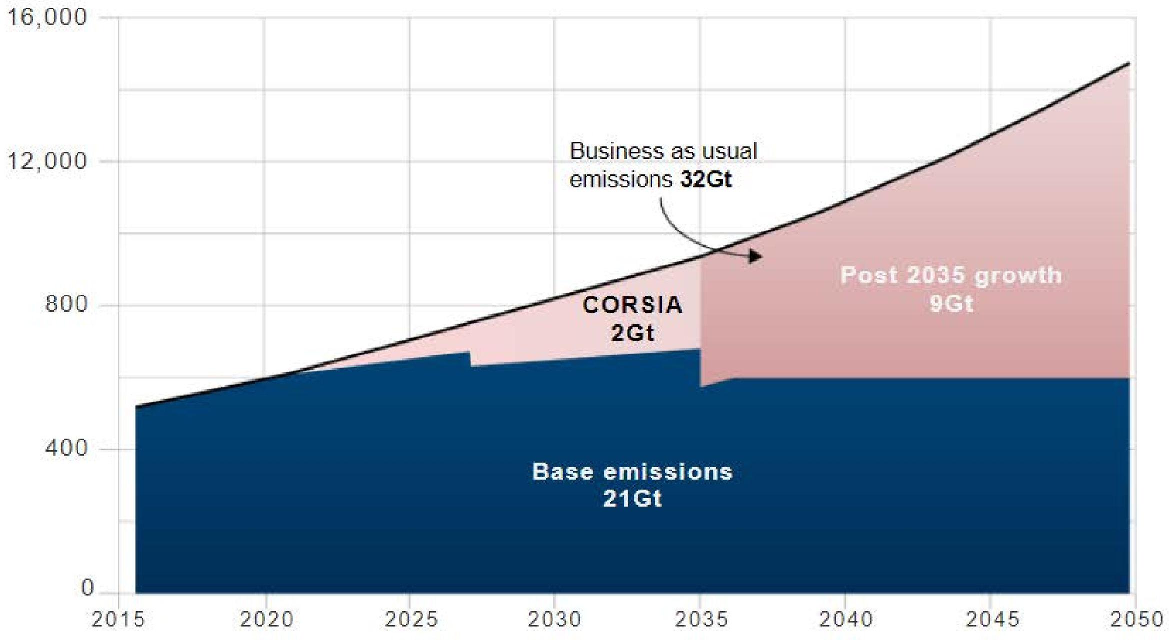
A.5. Is CO_2 pricing, CO_2 offsetting & CO_2 compensation a means to reduce the overall emission effects?

A broadly accepted tool shows the significant CO_2 effect of flying on personal footprint[ref.16]. The EU will implement the EU-ETS (emission trading system) for aviation as per 2024. CO_2 represents in the EU 3,8% of total emission. The aim is to reduce the emission effects with 90% from 1990 levels as per 2050. EU ruling is envisaged to offset 80% of the emission growth starting per 2020[ref.17].

The marginal abatement costs MAC (60-321 EUR/t CO_2) is higher in most scenarios until 2050 than the social CO_2 costs SCC (120-202 EUR/t CO_2). However, the total prevention costs (432-547 billion EUR) are substantially lower over the entire thirty-year period than the total damage costs (770 billion EUR). So internalization of the prevention costs is more cost-efficient. The EU ETS or a fuel tax is the best policy instrument to internalize these costs. This would lead to ticket price increases of 8-34% and a downwards impact of 6-25% on the demand for aviation, compared to “business as usual”[ref.18].

The fly-green program described does not lead to a CO_2 reduction but it compensates the CO_2 emission elsewhere i.e., solar projects India, coking stoves Africa and planting of trees. The latter contribution is debated, because of the absence of long term guarantees and the very long-term contribution periods (40 years)[ref.19].

The CORSIA program is an UN initiative to make the post-growth in aviation CO_2 emissions neutral as per 2020. To realize this climate neutral European aviation sector aim, a change over period is required from fossil fuels (kerosine) to sustainable fuels. The total cost for this transition is, up till 2050, lower than the penalty costs related to the CO_2 emission without this transition.



Annual and cumulative CO2 emissions from international aviation, 2015 to 2050. This data assumes China will partake from the pilot phase. As the chart shows, base emissions continue to grow under Corsia due to uncovered traffic. Offsetting requirements then increase in 2027 when the Corsia obligations become mandatory for all ICAO members. Source: ICCT 2018

Figure 3: Corsia compensation is currently only tackling 6% of the cummalitve projected emissions. Ref.20

This approach holds for biobased fuels till 2032 and for E- and Syn- fuels beyond this year.
The required CO_2 price for the economic transition is 200 euro per ton in 2025 and ranges from 60-240 euro per ton in 2050[ref.20].

Main issues and opportunities:

CO_2 pricing, CO_2 offsetting or CO_2 compensation is an effective tool in reducing the environmental impact of flying today. The effects can potentially be large by increasing CO_2 costs and certified CO_2 compensation schemes. The EU ETS system is envisaged to be an effective tool. The compensation approach is considered by others to be a debatable transition means and not a long-term viable way to motivate the sector to bring down the overall CO_2 emissions of aviation.

A.6. Expert interviews on sustainable aviation issues and options

- A Dutch podcast on the question: should I reduce or even stop flying? The viability of flying in the future[ref.1].
- A Dutch podcast on aviation subsidies, the KLM feeling and the technical options of the future and their costs effects[ref.2].
- A Trouw article reviews the increase in the global population it is foreseen that global CO_2-emissies will increase strongly, Synfuels are the only solution. The economic importance of KLM needs to included in the considerations of the future. Kerosine becomes possibly 4 to 6 times as expensive which will make flying in. the future also a lot more expensive[ref.3].
- A University of the Netherlands Podcast explains that high speed trains/ train connections are not an effective sustainable new alternative for regional flying, flying less is though[ref.4].
- A BNR Podcast reviews alternative technical flying options suggesting, flying efficiency offers part of the solution, limitations of electrical and hydrogen flying suggest however that synfuels & biofuels are the way forward[ref.5].
- An overview article from Duurzaam MBO on the CO_2 footprint of flying, the growth and alternative aviation options and some key figures[ref.6].

B. What are the technical sustainable aviation options

B.1 Do Electric fueled planes have a future?

After initial development testing, demonstration and certification efforts the Airbus E-fanX project was stopped[ref.21]. A special report on different electric airplane designs show different prospects, all aimed at small size, small scale, low load and short distances[ref.22].
The Weflywright company claims, as one of the few, to come up with a four-engine, 100 passengers airplane that can perform 1-hour electric flights by 2026. The electric plane is based on existing airplane technology. It is unclear whether this is a dream or reality[ref.23].
The IEEE, a professional organization for advanced technology, states that electrical fueled planes will not contribute to short- & long-range air travel in the coming decennium due to inherent limitations of (current) battery systems[ref.24].

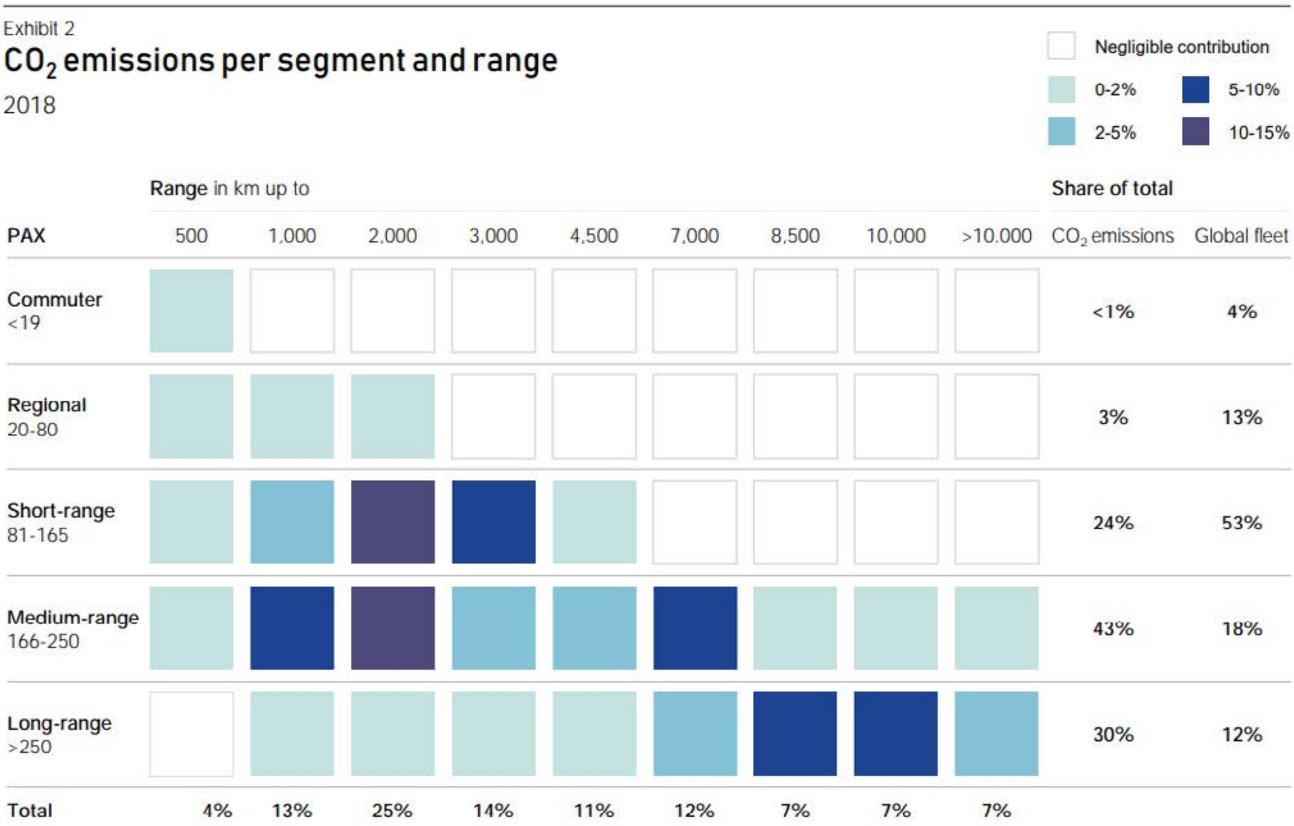


Figure 4: Distribution of GHG emissions from size of planes (PAX = Passengers Approximated) and flight lengths

Main issues and opportunities:

Only short haul flights with limited number of passengers seem viable. Battery weight, energy density, costs, recharging time, are major issues. Certification of technology is another challenge as it concerns a new technology. There is a discrepancy in the literature between claims on time of introduction and the readiness of technology.
Conclusion electrical planes are not going to form a significant part of the solution in the coming decennium as they are not able to fulfill the main needs of the current aviation industry in terms of transport volume/weight (passengers, freight) and relevant transport distances. Hybrid electrical planes (electrical and fuel driven) are however foreseen to contribute to lower fuel consumption and are as such a relevant short-term step towards more sustainable aviation.

B.2 Do Hydrogen fueled planes have a future?

The claim is that hydrogen fueled airplanes, in which the existing kerosine motors are replaced with hydro-electric H_2 motors, will allow for >50 passengers and >1000 NM as per 2026 and allow for >200 passenger and >5000 NM as per 2040[ref.25]. The NLR claims that hydrogen, as energy /fuel carrier, has a future in the longer term, also for larger aircrafts. Solutions need to be found for the installations on board and there will be a requirement for very large quantities sustainable electricity to make the H_2.

The EU has made a budget available of 2.1 billion EU for the Clean Aviation program[ref.26].
Mc Kinsey reports: Hydrogen fueled aircrafts are feasible, but H_2 cost, H_2 volume and availability as per 2040 is an issue. For the time being the concept is only suitable for shorter distances with 4 passengers. Hydrogen combustion could reduce climate impact per flight by 50 to 75 percent and improve fuel-cell propulsion by 75 to 90 percent. The additional cost for short distance flights are foreseen to be low i.e. 10 to 20$/flight and the foreseen CO_2 abatement cost range from 60 to 150 $/ton for commuter flights to short distance flights[ref.27].

The BBC Future Planet states that the availability of H_2, the H_2 energy production efficiency and the H_2 transport cost (2x) are major issues related to the use of H_2. The low energy density H_2/liter compared to kerosine (25%) creates the need for large size (highly pressurized) fuel tanks, but the high energy content

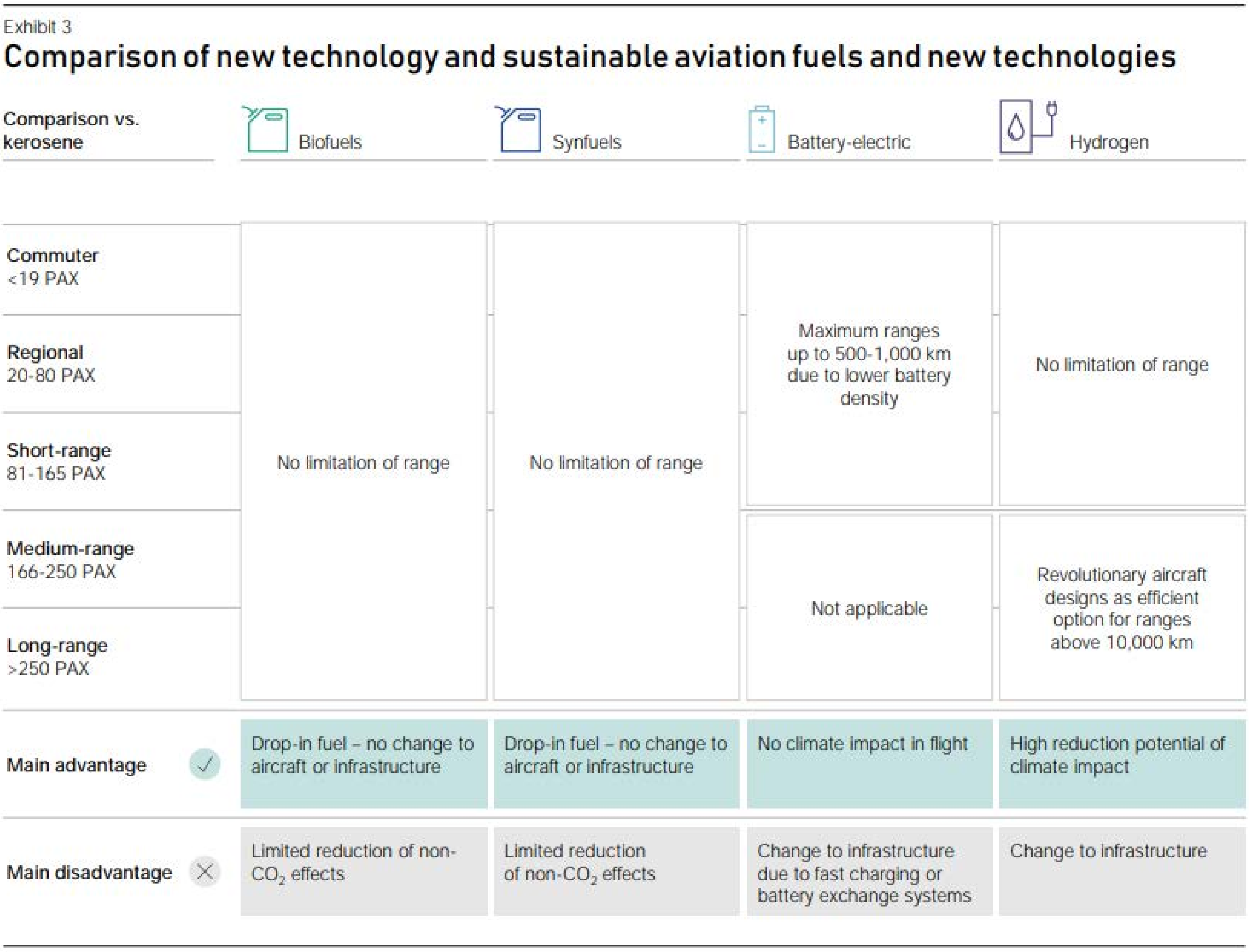


Exhibit 3

Comparison of new technology and sustainable aviation fuels and new technologies

Comparison vs. kerosene	Biofuels	Synfuels	Battery-electric	Hydrogen
Commuter <19 PAX	No limitation of range	No limitation of range	Maximum ranges up to 500-1,000 km due to lower battery density	No limitation of range
Regional 20-80 PAX				
Short-range 81-165 PAX				
Medium-range 166-250 PAX			Not applicable	Revolutionary aircraft designs as efficient option for ranges above 10,000 km
Long-range >250 PAX				
Main advantage ✓	Drop-in fuel – no change to aircraft or infrastructure	Drop-in fuel – no change to aircraft or infrastructure	No climate impact in flight	High reduction potential of climate impact
Main disadvantage ✕	Limited reduction of non-CO_2 effects	Limited reduction of non-CO_2 effects	Change to infrastructure due to fast charging or battery exchange systems	Change to infrastructure

Figure 5: Comparison of fuel types. Ref.27

of H_2/kg = 2,5 X more energy/kg compared to kerosine, can compensate to some extend for the earlier disadvantage[ref.28].

The if's and but's of hydrogen as aviation propulsion fluid are discussed by IATA. The conclusion is that certification of new aircraft technology and hydrogen availability at low cost, will be a major challenge[ref.29].

Main issues and opportunities:

Pressured H_2 production inefficiency (40%) leads to relative high costs fuel per kg H_2. The availability of H_2 for aviation depends on electrolysis capacity (10% of total global capacity need) is competing with others H_2 end-users. On the short term, the H_2 airplanes are limited to 100 passengers. Beyond 2040, larger aircrafts are foreseen to be feasible. H_2 is a costly, rather energy inefficient but (GHG) environmentally attractive long term aviation propulsion fuel option.

B.3. What about ammonia (NH_3) as aviation fuel?

In an interview Ad van Wijk and others propose ammonia as propulsion fuel for container ships, but for airplanes it is fore seen to be less attractive[ref.30]. New conversion processes to make green ammonia are being developed. Science direct reports that current cost of these processes are still very high 718$/ton to potentially 450$/ton. Generation 3 ammonia technology shows promise as via a renewable electrolysis process ammonia can be derived from water (H_2) and N_2, the potential interesting process is in early stages of its development[ref.31].
“Interesting Engineering” reviews a new ammonia-based aircraft concept which is 70% more powerful than liquid H_2, but it might contribute to smoggy skies and acid rain. Whether ammonia offers a sensible GHG reducing option needs further investigation[ref.32].

Main issues opportunities:

Compared to the conventional aviation with a fuel energy content of 11.9 MWh per ton ammonia has a lower energy content of 5.2 MWh per ton. Ammonia is toxic for humans and rather corrosive for the existing steel systems. It would require adaptation of facilities and motors. During combustion ammonia produces substantial amounts of NOx, so additional (expensive) catalysts are required to ensure NOx free combustion. Although ammonia (NH_3) has twice the energy density compared to H_2/liter, this is of limited relevance given the large energy need of fuels in aircrafts and the potential availability of high pressured H_2.

On the other hand, ammonia is easy to store, transport at H_2/NH_3 production locations and is applicable as fuel in existing combustion motors (with minor adjustments). Both elements lead to a low total delivered fuel costs compared to many alternatives. All in all, ammonia as aviation propulsion fuel is technical viable. However, its low energy density and corrosive chemical nature gives it less chance to be adopted as fuel.

B.4. Electrofuels ‘E-fuels’

The production concept is to produce H_2 via electrolysis of water, capture CO_2 from existing industrial processes and to convert both via Sabatier (methanation) and the derived syngas via Fischer-Tropsch to methane and kerosine type E-fuels. E-fuels are gaseous and liquid fuels such as hydrogen, methane, synthetic petrol, diesel and kerosine type fuels generated from electricity. H_2 can sustainably be obtained from renewable energy resources and CO_2 from biobased heat conversion process.

Compared to alternatives like Green H_2, E-methanol, E-ammonia and E-LNG, only
E-kerosine is regarded to be the real E-fuel option for aviation. All other E-fuels deviate significantly from E-kerosene and are unacceptable due to a too high loss of passenger and load capacity and large investments in new airplane/engine designs and infrastructure[ref.33].

The estimated demand of renewable electricity for the entire transport sector in 2050 is ten times larger than the current annual renewable electricity generation capacity in the EU. Over 80% of this future capacity will be consumed for e-fuel production. The costs of e-fuels are high (up to 4.50 € per liter diesel equivalent). Target costs of approximately 1 € per liter diesel equivalent appear possible with imports of low costs electricity or H_2 from regions with very good solar and wind power conditions[ref.34].

E-fuels are manufactured on basis of solar/wind energy and CO_2 via an energy intense process Power2Liquid with around 50% energy loss. The access to abundant solar and or wind energy is questioned, the intermittency of solar/wind requires energy back-up facilities and most importantly the total required amount for E-fuels would be too high i.e., requiring more than the current global available renewable electricity production[ref.15, 35].

Main issues and opportunities:

Production conversion losses are high i.e., 50%. The cost of liquified CO_2, obtained via amine capture process, is high. This cost ranges for CO_2 ranges from 40 to 200 EU/ton, and at 30 to 50 EU/MWh for electricity the E-fuel production costs range between 27 - 48 €/MWh.
The concept builds on existing aviation propulsion technology and infrastructure, which facilitates implementation. The availability of “neutral” CO_2 is an issue, but it can be resolved. The requirement for renewable energy, H_2 and stored energy is very significant.

B.5. Synthetic fuels on basis of ‘synthesis gas’

This approach involves a two stage process, in which Syngas (CO and H_2) is produced from (biomass) waste. Via the Fischer-Tropsch (FT) process (with additional H_2 to hydrotreat/hydrocrack) higher molecular weight kerosine type of products “syn-fuels” are produced that meet the “drop-in” requirements of the current aviation industry. The feedstock is diverse in terms of composition. Nevertheless, the FT process requires a high purity feedstock. The presence of contaminants (particulates, tars, sulfur, CO_2, nitrogen and chlorine, alkali metals, etc.) require complex and expensive cleaning operations before the (clean)feedstock can be fed to the FT process. The FT process is energy intense (30% loss)

In this Science direct article different bio based and waste to syngas technologies and operations are reviewed. It highlights, in an extensive way, the various issues to come to a clean syn-kerosine’s for aviation[ref.36].

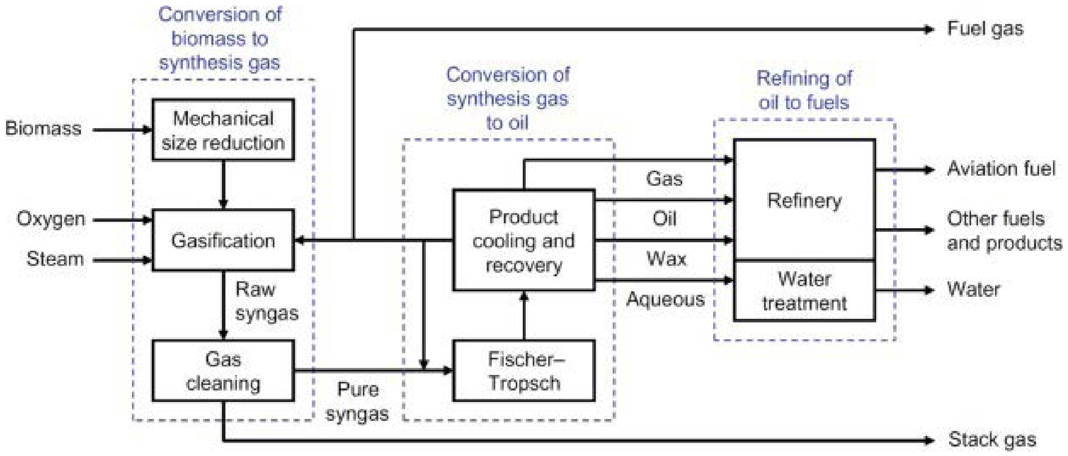


Figure 6: Simplified process scheme of synfuel production and synthesis

Main issues and opportunities:

A challenge is the access to large quantities of waste/biomass, whilst ensuring CO_2 neutrality. To make these products economical viable, in particular in the case of waste as feedstock, large scale, complex and capital intense operations are required. The resulting product can be used in existing airplanes and related infrastructure. The feedstocks are in principle low costs, and the syngas manufacturing operation may be very complex and quite costly, but given access to the derived pure syngas the operation is less complex compared to E-fuels. The overall CO_2 mitigation cost of synfuels is low compared to alternative biobased routes

B.6. Biofuels

There are different concepts of sustainable aviation fuels (SAF’s)

- HEFA: hydrotreated esters of fatty acids an oleochemical conversion processes, by hydro-processing of lipid feedstocks obtained from oilseed crops, algae or tallow.
- SIP: biochemical conversion of biomass (sugars, starches or lignocellulose-derived feedstocks) to longer chain alcohols and hydrocarbons.
- ATJ: alcohol to jet fuel, a “hybrid” biochemical /thermochemical technology; the fermentation of biomass carbohydrates to alcohols and the catalytic hydro-formulation of these products to jet fuel.

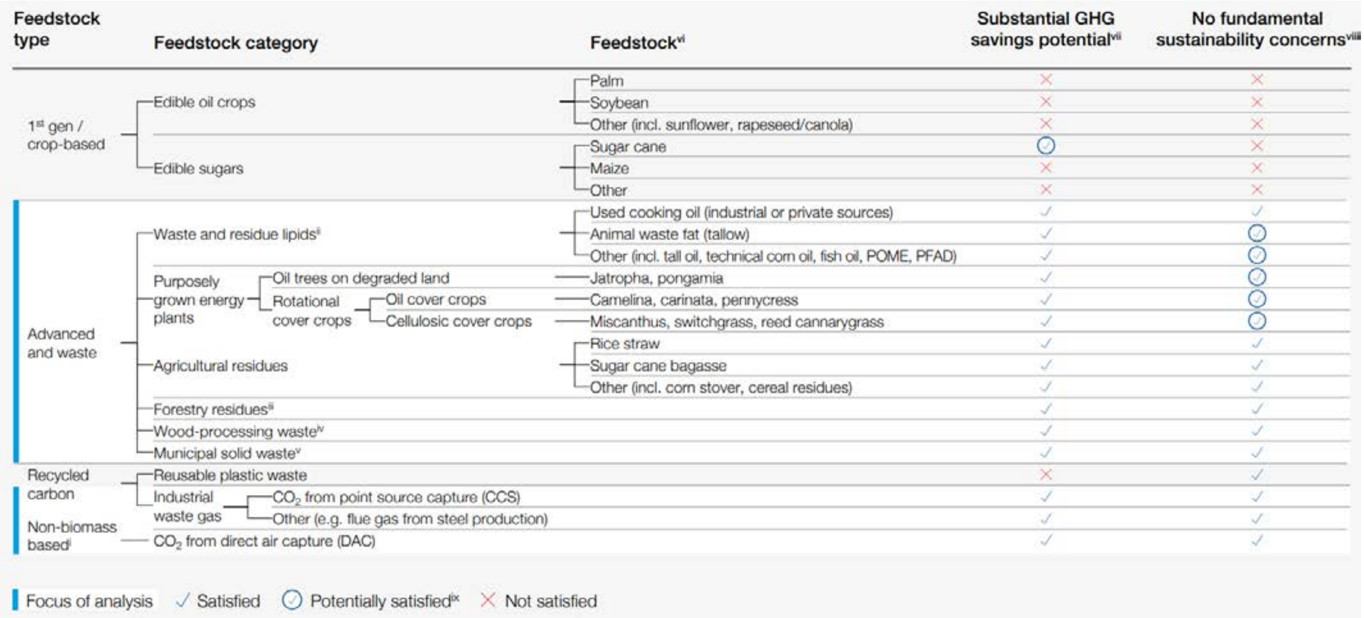
This WEF report, which is made by Mc Kinsey, provides a longer term view on Biofuels. Aviation fuels lag behind with regard to the envisaged CO_2 reduction targets. The volume of aviation fuels is envisaged to grow substantially, the fuel use efficiency will also improve and a 5% reduction in growth will contribute to a lower then envisaged CO_2 emission.

A comparison of future aviation fuels includes: SAF (Lipids) and biomass to alcohols, biomass (via gasification and FT) to Syn-fuels and $CO_2 + H_2$ (via power to liquid) to E-fuels.
The SAF fuels are initially envisaged to be double the price of conventional fuels but the price will come down. Major implementation issues relate to technology challenges, scale up, regulatory frame works and innovative financing solutions.

The SAF climate impact is foreseen to lead to 73-84 % GHG reduction. The actual fit as replacement fuel is very good. The transition is envisaged to go gradual from 10% to 50% to 100% aviation fuel replacement. The main issue for SAF’s (HEFA) is the availability. Although it is a good potential fit the accessible volume is limited to around 20% of total needs in million-ton oil equivalents, see fig 11[ref.37].

This IRENA report distinguishes several generations of biofuels.

1. First generation biofuels are derived from traditional food crops.
2. Second generation biofuels are made from agricultural residues from food crops, or dedicated non-food biofuel crops, or food waste such as cooking oils.



Feedstock type	Feedstock category			Feedstock[vi]	Substantial GHG savings potential[vii]	No fundamental sustainability concerns[viii]
1st gen / crop-based	Edible oil crops			Palm	✗	✗
				Soybean	✗	✗
				Other (incl. sunflower, rapeseed/canola)	✗	✗
	Edible sugars			Sugar cane	○	✗
				Maize	✗	✗
				Other	✗	✗
Advanced and waste	Waste and residue lipids[ii]			Used cooking oil (industrial or private sources)	✓	✓
				Animal waste fat (tallow)	✓	○
				Other (incl. tall oil, technical corn oil, fish oil, POME, PFAD)	✓	○
	Purposely grown energy plants	Oil trees on degraded land		Jatropha, pongamia	✓	○
		Rotational cover crops	Oil cover crops	Camelina, carinata, pennycress	✓	○
			Cellulosic cover crops	Miscanthus, switchgrass, reed cannarygrass	✓	○
	Agricultural residues			Rice straw	✓	✓
				Sugar cane bagasse	✓	✓
				Other (incl. corn stover, cereal residues)	✓	✓
	Forestry residues[iii]				✓	✓
	Wood-processing waste[iv]				✓	✓
	Municipal solid waste[v]				✓	✓
Recycled carbon	Reusable plastic waste				✗	✓
	Industrial waste gas	CO_2 from point source capture (CCS)			✓	✓
		Other (e.g. flue gas from steel production)			✓	✓
Non-biomass based[i]	CO_2 from direct air capture (DAC)				✓	✓

▌ Focus of analysis ✓ Satisfied ○ Potentially satisfied[ix] ✗ Not satisfied

Figure 7: Various biobased sources for aviation fuels. Ref.37

3. Third generation biofuels can be produced from algae
4. Fourth generation biofuels are envisaged to be made from genetically modified feedstocks.

Depending on the feedstock different processes are used to come to the desired aviation fuel. The primary extracted fats or lipids from the biomass, waste cooking oil /tallow or algae can be converted by hydroprocessing (3% H_2) to “drop-in” aviation fuels.

The access of this food feedstock is an issue and it also for seen to be limited in volume. The secondary biomass can be converted via hydrolysis to various sugars which upon fermentation lead to higher alcohols which after hydroprocessing lead to aviation fuel additives i.e. not “drop-in” aviation fuels. The secondary biomass can also be converted into pyrolysis oil which is via catalytic hydrotreatment (H_2) and hydroprocessing (H_2) converted to aviation fuels. The process to upgrade this oxygenated oil is costly, merely due to the need of large quantities of H_2.

Alternatively, the secondary biomass is gasified to syngas, which after cleanup (costly) is converted with Fischer-Tropsch (H_2) to FT liquids, which by hydroprocessing (H_2) leads to aviation fuels (40%) and other middle distillates products (60%). The prospects for effective cost reduction on larger scale are there, but need to confirmed on commercial scale[ref.38].

The foreseen replacement of kerosine with first generation SAF biofuels may amount up to 20% in 2040 according to the IEA. This is much slower than current EU regulation goals. So other more expensive biobased fuels and synfuels or E-fuels will have to close the gap. The first generation biofuels (HEFA) are two times as expensive to produce whilst the more advanced biofuels are for seen to be at least four times as expensive[ref.39].

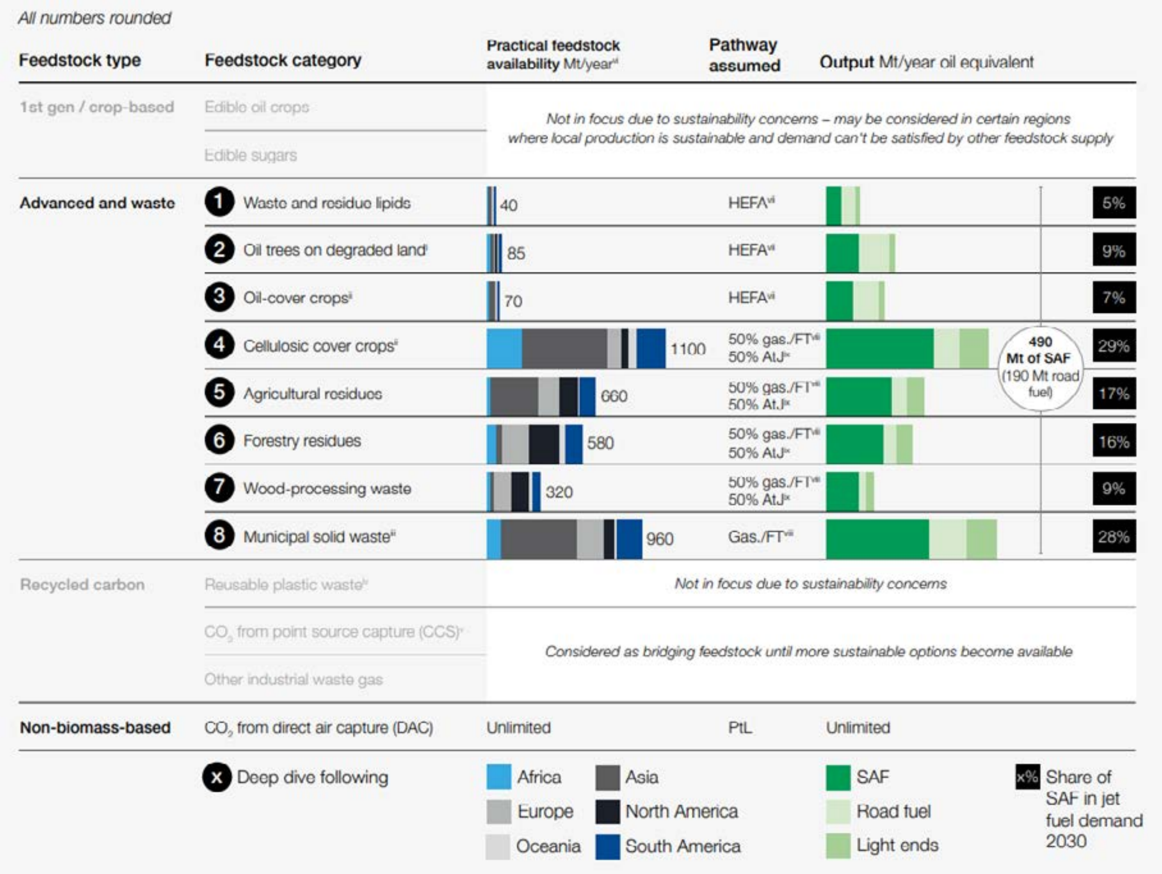


Figure 8: Overview of feedstock availability and projected output in 2030. Ref.37

This type of second generation aviation biofuel show prospects. The AtJ concept converts ethanol derived from organic waste into unsaturated building blocks that can be oligomerized into drop-in kerosine fuels. In contrast to the first generation biofuels there are no concerns regarding feedstock availability. The technology is however in its early phase and overall process economics, conversion yield, waste handling, hydrogen and energy use need be assessed[ref.40].

The EU Higfly program is involved in the development of second generation sustainable biofuels for aviation. Biobased (forestry and biomass waste) fuels such as furfural and bio-oxygenates allow for 90% reduction in CO_2 emissions and can ultimately replace 20% of existing aviation fuels. The EU supports early phase development of this project[ref.41].

Neste SAF is one of the few well developed drop-in sustainable aviation fuels at commercial scale increasing from 100 kilotons to 1,5 Million kilotons per 2023. Nest SAF is based for 100% on organic waste streams, leading to a 80% lower CO_2 emitting fuel, showing significant lower NOx, particulates and sulphur emission than conventional kerosine[ref.42].

A Science direct overview article shows the development stage of different sustainable aviation fuels. HEFA (hydrotreated esters of fatty acids) is most mature route (TRL 9), supplying around 2% of total aviation supply needs. The other biobased routes, based on lignocellulose, biomass, algae are in development stage. The thermochemical routes are likely to provide the largest volume, but are in early phase (TRL 6-8) and are dependent on feedstock availability and are technically and economically challenging. The envisaged cost are 2 to 7 times higher suggesting that HEFA is economically the most promising type of biofuel. Supporting biofuels policies are a prerequisite[ref.43].

There will be a substantial shortage of secondary bio mass based biofuels fuels in the Netherlands to meet the currently envisaged sustainable aviation fuels mounts in 2050. For synfuels based on CO_2 capture volumes, the potential volume per 2050 is more in line with the needs[ref.44].

Main issues and opportunities:

Access to large quantities of waste/biomass, whilst ensuring CO_2 neutrality. There is limited amount of feedstocks for primary aviation biofuels available. This will limit its application to a max 20%, the CO_2 neutrality is regular questioned and needs to be secured.

Secondary bio aviation biofuels have good prospects, but the majority of the processes are in early stage of development and require large scale, complex and capital intense operations.
Similar as for synfuels and E fuels, the secondary aviation biofuel routes require H_2 for their processes. This means that the majority of the viable alternative aviation fuel routes will put a large claim on the future H_2 competing with alternative markets for sustainable H_2.

In terms of maximum affordable H_2 cost the order is as follows:
1. chemical feedstocks (H_2 = 5-10 $/Kg),
2. H_2 transport mobility (H_2 as combustion fuel/ H_2 fuel cell systems H_2 = 3,0-4,5 $/Kg),
3. processing aid to prepare sustainable aviation fuels (H_2 = 1,80 -2,75 $/Kg)
4. as heating fuel (H_2 = 1 $/Kg)[ref.59]

B.7. What about the contribution of fuel efficiency measures in aviation?

Fuel efficiency has improved over the years with 45% (1968-2014), 2.6% over the last few years and further improvements are foreseen for the years to come[ref.45]. Clean sky foresee a 20-30% reduction in CO_2, NOx emission as a result of a range of recent technical innovations[ref.46]. Further efficiency improvements are envisaged by taking a holistic approach towards aviation efficiency and including technology innovation (5-50%), operational efficiency (up to 15%), infra-structural improvements and economic measures[ref.47].

EU aviation sector claims in their Destination 2050 a pathway to reduce aviation emission by industry and governments on four themes.

1. Improvements in aircraft and engine technologies: 37%
2. Deployment of SAF's (sustainable aviation fuels) can make a difference: 34%
3. Application of SEM (smart economic measures) such ETS can make a difference: 8%
4. ATM (air traffic management) and aircraft operations can make a difference: 6%[ref.48].

Wikipedia indicates a significant improvement in aviation fuel economy was realized from 2016 at 3,23 L/100 km till 2021 1,75 L/100 km. Important parameters are offtake and decent procedures, direct routing, reduced thrust on landing, load and passenger optimization. Up till 10-12% savings can be realized this way. Policies and regulation need to be put in place to make it happen[ref.49]. Prescouter.com reviews the 6 top technologies for aviation efficiency improvement. New design aims for 27% more efficient, 15% weight reduction, 20% more lift to drag ratio, 27% less thrust[ref.50].

Main issues and opportunities:

A lot of efficiency improvements have been realized over the last few decades. Additional aviation fuel efficiency measures, consisting of new airplane design and improved operational procedures and loadings, can also in the future contribute significantly reducing the environmental impact of flying with 15 till 30%.

B.8. CO_2 mitigation cost, related fuels cost and ticket price increase.

Several technical viable food based and residue based SAF's were evaluated in terms of CO_2 mitigation costs. The technologies are HEFA (hydrotreated vegetable oils), UCO (used cooking oil and tallow waste oil), AT (dehydrated and oligomerized ethanol) from sugar cane and its waste residues, and other organic residues such as the (TCC) thermal chemical conversion the HTL (Hydrothermal liquefaction process) and FT(Fischer Tropsch) process to make synfuels.

For food based technologies (sugar cane ethanol and oil based) the CO_2 cost range from 495 to 550 $/Ton CO_2 (assuming certified and low risk land use area's) and for the more (strategic) sustainable residue-based technologies from 185 $/ton to 370 $/Ton CO_2. All viable SAF's technologies, lead to a substantial increase in "all in" flying costs, affecting the economic attractiveness of aviation as a transport means.

Above CO_2 mitigation cost appear factors higher than the current CO_2 market value (ETS Dec 2021 of 100 $/Ton) and not in line with the current CORSIA carbon offsetting cost of Oct 2021 of around 25 EU/ton[ref.51]. The cost of offsetting CO_2 at CORSIA indication of Oct 2021 is 25 €/Ton. This leads at a kerosine cost of 750 $/ton and a CO_2 release of 3,15 Ton CO_2 per ton of kerosine to an additional cost of 87 $/Ton for emission allowances i.e. a 12 % increase in "all in" fuel costs. The current ETS guidelines of 100 $/Ton would increase this percentage to 45% increase in "all in" fuel costs. A (strategic) environmental SAF fuel based on waste, with a CO_2 mitigation cost of 200 $/Ton would bring the mitigation costs to 3,15*200 = 630 $/ton fuel. Whether this fuel needs further processing and or adaptation to aviation specification is not clear.

The more directly available but potentially less sustainable "drop-in" SAF's based on food technologies (vegetable oils) would lead to a 2,5 times higher CO2 mitigated fuel costs i.e., to around 1500 $/ton, which is in the ultimate case a doubling of the current kerosine fuel costs[ref.52].

Fuel is 30% of the overall passenger/tickets cost for a short flight. The other cost relate to maintenance 15%, ground handling 10%, landing 5%, crew 10%, aircraft ownership 10%, overhead 10% , pax cost (catering, reservation, insurance) 10%, excluding 25% tax. So doubling of fuels cost as indicated above to include all environmental costs may lead to an overall ticket price increase of around 30% assuming that the "other costs" are not a direct function of sustainable measures[ref.53].

There is a public willingness to pay more than the current 7 EU tax for the use of sustainable biofuels in aviation. Up to 84% of the public is prepared to pay an increase of up to 25%[ref.54].

Also the carbon footprint calculation suggest noticeable penalties based on CO_2 footprint per person. For instance, for an Amsterdam-Durban (SA) flight a CO_2 footprint of 2,67 Ton of CO_2 per person is foreseen. This would lead for the various scenario's above to a fuel price increase ranging from 66 $ (CORSIA) to 267 $(ETS) and to a fully CO_2 mitigated fuel cost ranging from 2,67*500 to 2,67*200 =1340 $ to 534 $ for the "current" available SAF's and the "future" Syn-fuels respectively[ref.55].

Main issues and opportunities:

It is considered viable to come to more sustainable aviation transport means at a noticeable but acceptable cost increase. Systems need to be put in place to allocate for this increase in aviation cost and to secure a fair global competitive playing field. More important however is the early implementation of:

- accessible sustainable aviation technologies

- efficiency measures
- facilitate the investments in the foreseen high capex facilities
- start the allocation/access to relevant feedstocks for the early production of SAF's on a commercial and economic scale.

E-fuels based on H_2 and CO_2 are not included in the above, but remain an option depending on access to low-cost sustainable energy and low-cost CO_2 feedstocks. Cost indicators suggest that these fuels may cost up to 4000 EU/ton based on liquid CO_2 at 200 EU/Ton and H_2 at 3000 EU/Ton. These fuel costs, which currently represent 30% of flying ticket, would give rise to a price ticket increase of a factor 2.2.

C: Conclusion

We welcome your opinion and comments on the above and look forward to a broad reflection on the main issues and opportunities to help us all, as interested audience to further improve the perspective on the tittle subject, “will we be flying in 2040”?

Potentially interested parties /responders

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