Danish Energy Agency

Technology review on aviation

Technical assessments of technologies in future aviation

Technology review on aviation

ISBN: 978-87-94447-27-0

Published April 2025 by

Danish Energy Agency
Carsten Niebuhrs Gade 43
DK-1577 Copenhagen

Phone: +45 3392 6700
E-mail: ens@ens.dk

ens.dk

Preface

Commercial aviation is an important element of the global economy and a core part of the transport systems, enabling time efficient transport for both passengers and freight services. However, the aviation sector faces significant challenges, particularly in the context of environmental sustainability.

This report provides an exploratory and introductory analysis of two subjects; the current state of the aviation sector and the developing technologies and fuels to replace conventional aviation operation.

Recognizing the novelty of the transition towards sustainable aviation, the limited data and experience available, this report does not cover a full comprehensive investigation of the technologies part of the transition of the aviation sector. Instead, it aims to foster an understanding about the emerging technologies potentially contributing to the transition of aviation. The included technologies are battery electric propulsion, hybrid electric propulsion, hydrogen fuel cells and Sustainable Aviation Fuels (SAF).

This report extends perspectives on future technical perspectives and planning challenges associated with the adoption of these technologies. The report also examines the environmental and climate-related impacts, economic implications, and technical requirements.

Content

Abbreviations & terminology

APRON	Area of an airport where aircraft are parked, unloaded or loaded, refuelled, boarded, or maintained
AR	Aspect Ration – for an aerofoil the ratio between the length and the average width of the surface
ASK	Available Seat Kilometres
AtJ	Alcohol-to-jet
BPR	The ratio of the mass of air that bypasses the engine core to the mass of air that passes through the core.
BtJ	Biomass-to-Jet
CO	Carbon monoxide
CO_2	Carbon dioxide
CTW	Conventional Tube-and-Wing design
EPR	Engine Pressure Ratio - is the ratio of the turbine discharge pressure divided by the compressor inlet pressure
ETOPS	Extended-range Twin-engine Operations Performance Standards
FT	Fischer-Tropsch
GWP	Global warming potential
H_2	Hydrogen
HBR	High Bypass Ratio (HBR) engines
HEFA	Hydroprocessed Esters and Fatty Acids
ILUC	Indirect land use change
Ktas	Knots true airspeed. A measure for the speed of an aircraft, taking speed and air density into account
LCA	Life-cycle assessment

Mach	Ratio of the speed of an aircraft to the speed of sound. A value of 1 corresponds to the speed of sound
MEA	More electric aircraft
MEW	Manufacturers Empty Weight
MTOW	Maximum take-off weight. The maximum mass at which the aircraft is certified for take-off due to structural or other limits
NOx	Nitrogen oxide
OEW	Operating empty weight
OPR	overall pressure ratio
OPR	Overall pressure ratio
PBTJ	Power-and-Biomass-to-Jet
PtJ	Power-to-Jet
R&D	Research and development
RPK	Revenue Passenger Kilometres measures the total distance flown by paying passengers (not flight crew). RPK = Number of (paying) passengers * distance
SOx	Sulphur oxide
v/v	Volume over volume

1 Introduction & scope

Commercial aviation involves everything from design, development, production and operation of aircraft to design and operations of infrastructure and airports. Aviation serves different purposes within various sectors including commercial passenger and cargo flights, private aviation and military purposes.

The scope of this report concerns the alternative fuels and propulsion systems that are projected to be of relevance in the transition away from the current fossil-fuel based commercial aviation sector towards net zero aviation. The main objective of the analysis is focused on fixed-wing aircraft designed for *commercial passenger- and cargo transport*.

From a societal perspective, there are many important and positive effects of aviation. Commercial aviation is an important element of the global economy and a core part of the transport systems, enabling convenient and time efficient transport for both passengers and commercial freight services over vast distances.

Nevertheless, aviation also has significant negative climate and environmental impacts. The global society seeks to mitigate climate change, while demand for aviation passenger transport is expected to double by 2050 (ATAG, 2021). Therefore, a shift from the sector's dependency on fossil fuels towards energy carriers based on renewable energy sources and net zero technologies becomes inevitable.

Future technologies in aviation must mitigate the negative climate and environmental effects, while supporting and meeting specific technological requirements enabling airborne transport.

IATA[1] has committed to a target of achieving net zero CO_2 emissions by 2050. And ICAO[2] has adopted a

What is a Technology Review?

The Danish Energy Agency publishes this **Technology Review** in extension of our two existing Technology Catalogues on heavy duty transport for road and sea, respectively. The aim is to communicate latest knowledge about current and future heavy-duty technologies in the transport sector.

It introduces technologies relevant for the energy transition away from fossil fuels in the aviation sector.

While sharing some key parameters with our technology catalogues. The format of this report will differ from a technology catalogue, as it concerns a subject of much lower empirical experience and available data. Therefore, this product does not include data sheets, unlike a technology catalogue.

[1] The International Air Transport Association (IATA) is the trade association for the world's airlines, representing some 330 airlines over 80% of global air traffic.
2 The International Civil Aviation Organization (ICAO) is a United Nations agency which helps 193 member states to coordinate the principles and techniques of international air navigation.

collective long-term global aspirational goal (LTAG) of net-zero carbon emissions by 2050. Achieving a target of net zero aviation by 2050 is a challenge of immense magnitude and there are many difficult challenges that need to be overcome.

Currently, there are multiple technologies in play to substitute the conventional aviation technologies and fuels. These technologies are at different development stages and characterized by their own advantages and disadvantages, with the common denominator that their technical performance and/or economic traits are yet not at the benchmark set by modern conventional aviation.

1.1 Report content

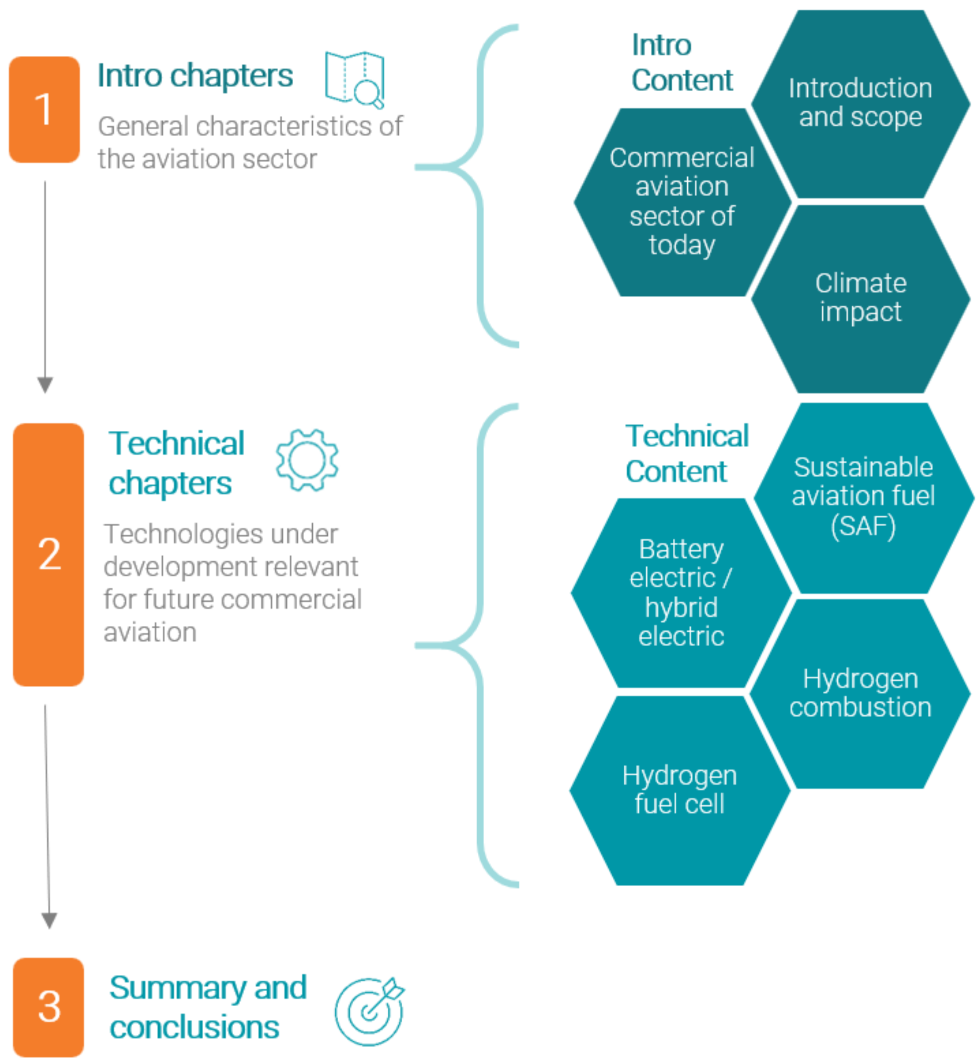
The initial chapters introduce 1) the concept of the report, 2) the current state of the aviation sector and 3) the climate impact of aviation. These chapters set the scene for the content of the following technical and technology specific chapters.

As such, the subsequent chapters are structured to mimic the technology catalogues. These chapters are inherently more technical and each chapter is dedicated to a given technology, as shown in the figure.

The final chapter summarises learnings and compares technical values where possible.

Figure 1 indicates the structure of the report and is created as an overview of the report content.

Figure 1 Structure of this Technology review on aviation. Illustration by the Danish Energy Agency.



2 Commercial aviation today

For the purpose of this report, understanding the current state of commercial aviation is a step towards recognizing and identifying the framework against which any new alternative technology will be compared. Decades of gradual improvements in commercial aviation, have led to aircraft with much improved energy efficiencies and decreased carbon-intensity. In addition, improvements have been made to the whole logistical system connected to airports and air traffic. Nevertheless, the current reliance on fossil jet fuel requires new technologies and solutions to move aviation towards a more sustainable trajectory and enable the achievement of IATA and ICAO goals and ambitions.

There are several 'tough-to-beat' advantages of modern aviation and the existing value chains behind it. Existing technology is superior when it comes to fuel characteristics, fuelling infrastructure, aircraft design, costs and flight speeds. These are the strengths that enable a fossil fuel-based aviation sector to deliver safe, fast, long-distance travel at affordable costs. Consequently, this sets a high benchmark for any competing technologies, that may in turn rectify sustainability issues.

2.1 Global fleet of fixed-wing aircraft

The current world fleet of fixed-wing aircraft[3] for commercial comprises approximately 28,000 aircraft. With the expected increase of passengers, the fleet of aircraft could grow to about 36,000 in 2034.

Table 1 Number of aircraft by type and forecast (OliverWyman, 2024).

World fleet (number of aircraft)	2024	2029	2034	Increase 2024-2034
All	28,396	31,396	36,396	28%
Narrow body	17,264	19,786	22,976	33%
Regional Jet	3,042	3,171	3,468	14%
Turboprop	2,333	2,272	2,566	10%
Widebody	5,757	6,705	7,402	29%

Prices for a commercial turbofan aircraft from e.g. Boeing or Airbus range from about 70 mil. EUR to around 400 mil. EUR (Axon Aviation Group, 2025) with regional turboprop planes from e.g. ATR or Bombardier being much less costly at around 30 mil. EUR (FlyRadius, 2025). The typical life span for a commercial aircraft is about 20-30 years. And while age of the aircraft is one aspect, the life span is also highly dependent on flight hours, flight cycles, sufficient maintenance and replacement of all the different components from control systems, airframe,

[3] A fixed-wing aircraft is an aircraft with rigid wings that generate lift. Unlike rotary-wing aircraft, such as helicopters, which rely on rotating blades for lift, fixed-wing aircraft achieve flight through aerodynamic forces acting on their wings. Fixed-wing aircraft are known for their efficiency in long-distance travel, higher speeds, and greater payload capacity compared to other types of aircraft.

engines etc. In praxis, the life span of aircraft will either be determined by the cost of maintenance and fuel cost or the so-called *limit of validity* (LOV) which is part of the type approval of aircraft issued by the aviation authorities. The LOV is the limit before widespread fatigue damage occur, as long as the required maintenance schedule is followed (Hansman, 2014).

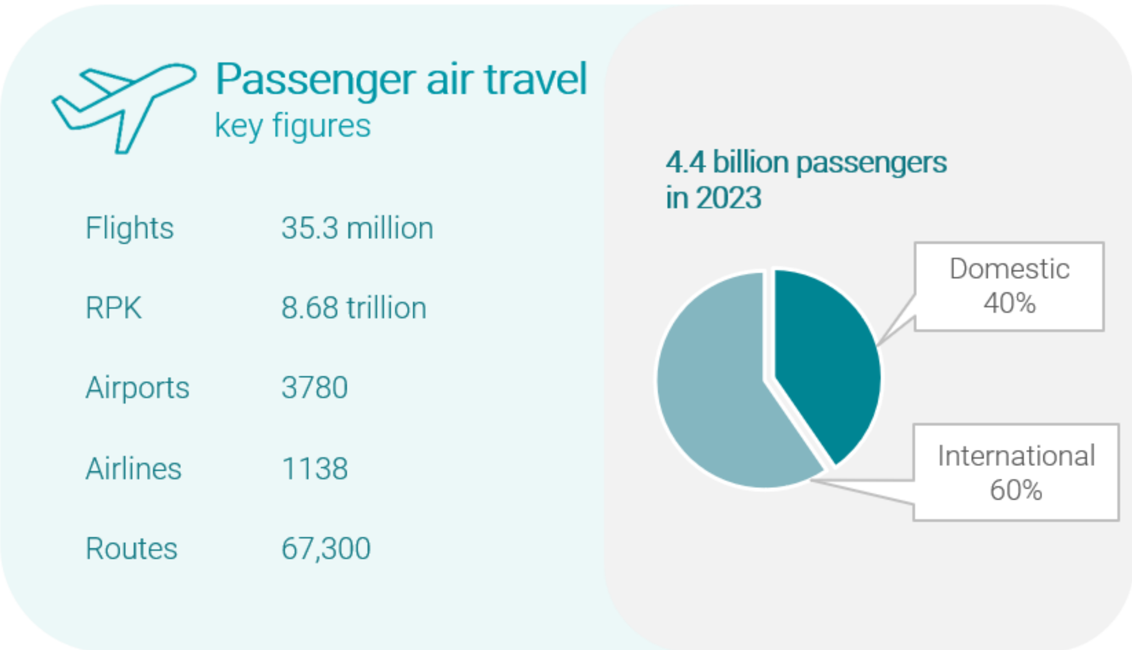
2.2 Flight activities

The activities of modern aviation can be deduced from a couple of common performance indicators regarding kilometres flown, tonnes of goods moved and passenger count etc. As aviation has become fundamental in modern transport systems for carrying goods and passengers, these numbers show significant activity levels. This section briefly describes key metric within cargo- and passenger flight.

2.2.1 Passenger flights

In 2023, the total global passenger count was 4.5 billion passengers, resulting in a total of 8.68 trillion RPK[4]. Figure 2, based on an overview by ATAG (2024) shows the general level of activities in passenger air transport.

Figure 2 Key figures for passenger air travel of 2023. Illustration by the Danish Energy Agency, based on ATAG (2024).



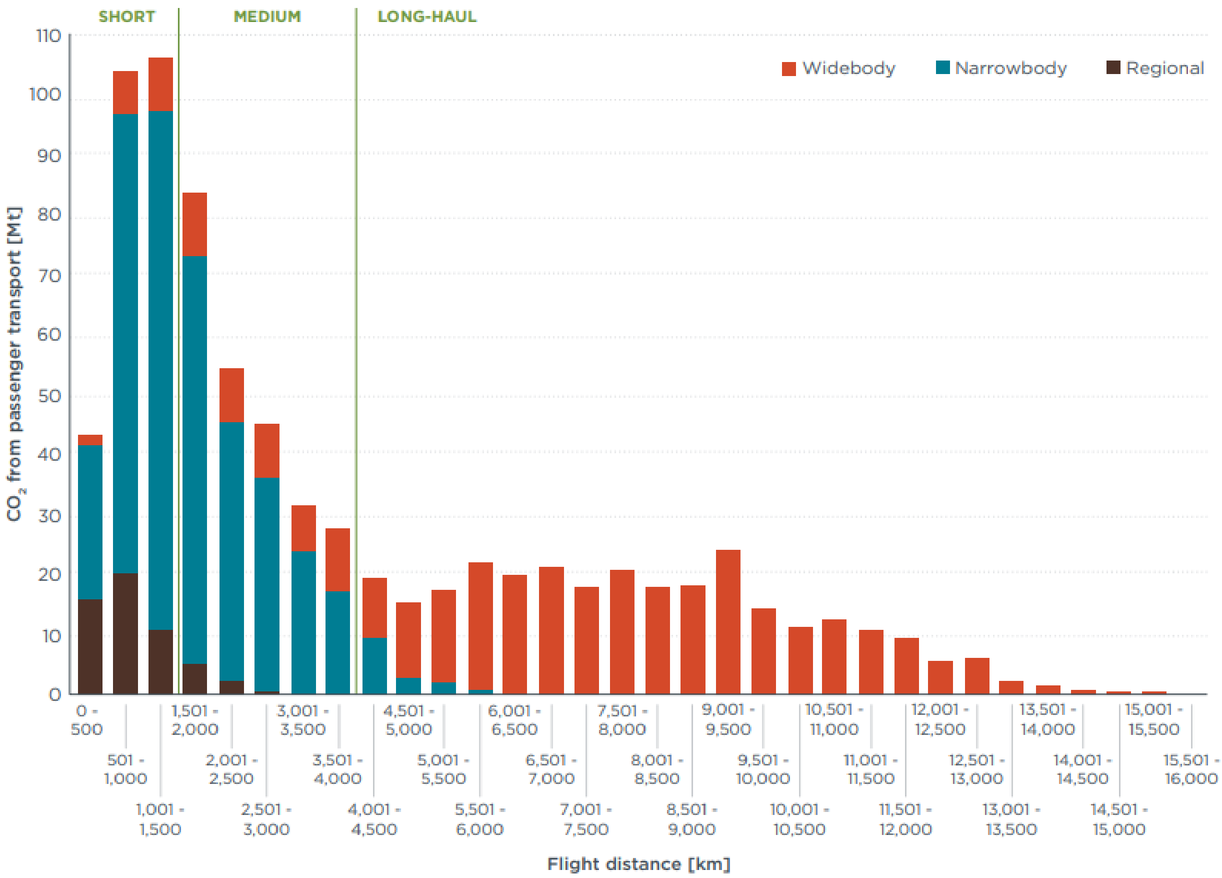
The figure illustrates the values of 2023, where 4.4 billion passengers were transported through commercial aviation (ATAG, 2024).

[4] Revenue Passenger Kilometre (RPK) is metric measuring the total distance travelled by paying passengers. It is calculated by multiplying the number of revenue-paying passengers by the distance flown in kilometres.

2.2.2 Short-, medium- and long-haul passenger flight activity

Passenger flight can be categorised by flight distance, determined as regional/short-haul, medium-haul and long-haul purposes. ICCT (2020) analysed the global passenger flights of 2019 to determine the share flights performed across increasing flight leg distances. The result is shown in Figure 3.

Figure 3 Share of passenger air transport CO_2 emissions by trip length and type of aircraft (ICCT, 2020).

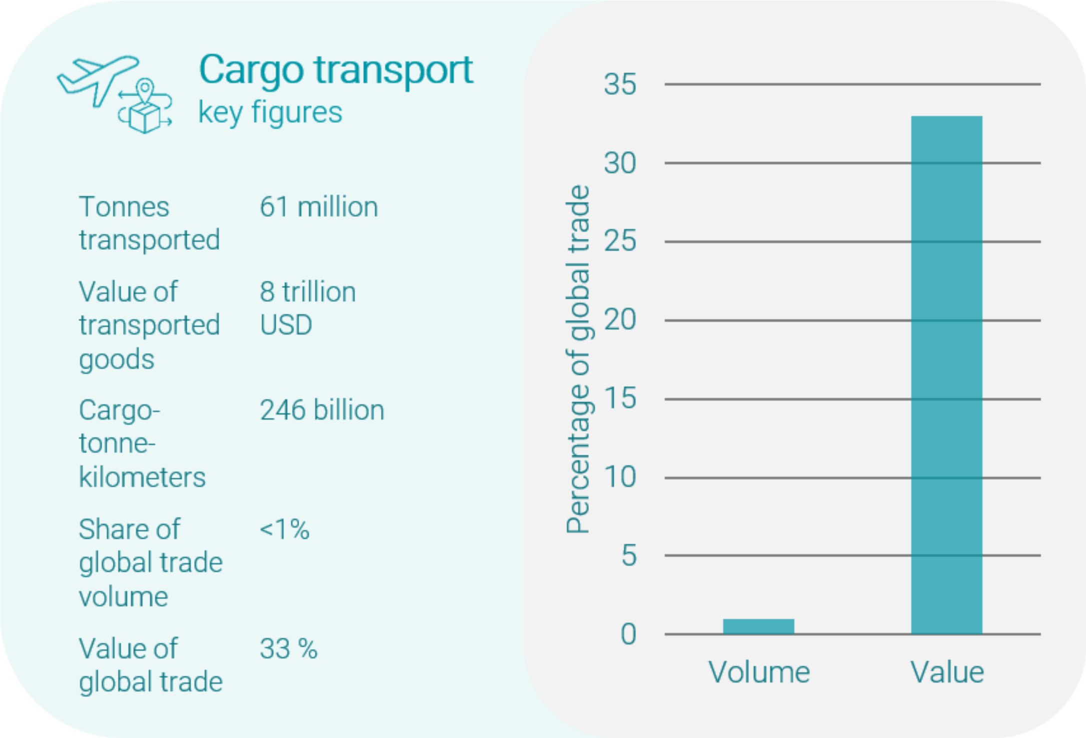


The figure highlights how short to medium-haul flights emit significant shares of the total CO_2 emissions from aircraft. With each stage length group responsible for about one third. Each of the three categories (short-, medium- and long-haul) make up approximately one third of total emissions.

2.2.3 Cargo flights

With a similar view on cargo flights, the significance of total distance flown is less pronounced, compared to passenger flights. However, the value of goods moved is substantial. In fact, air cargo represents a relatively small share of global trade by volume, but it accounts for a disproportionately large share by value. The faster delivery times and flexibility of air freight, may cater to transport high-value goods or goods sensitive to delivery times. Figure 4 shows an overview, based on ATAG (2024).

Figure 4 Key figures for airborne cargo transport in 2023. Illustration by the Danish Energy Agency, based on ATAG (2024).

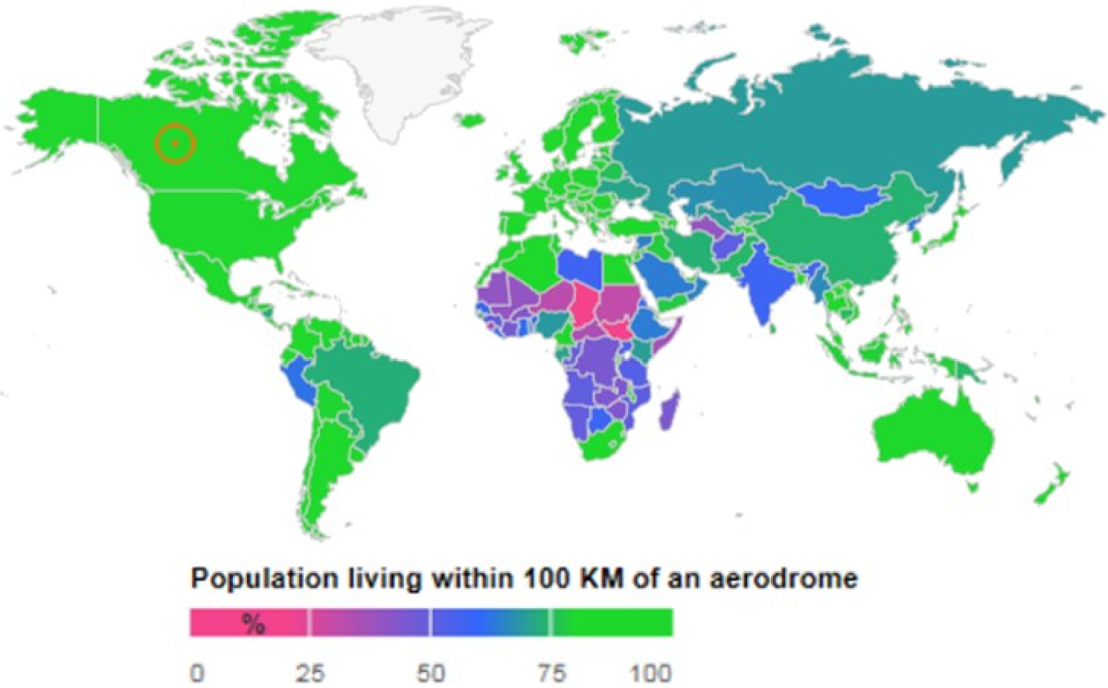


The figure indicates how even the small trade volumes can have significant economic impact. The numbers showcase the value of cargo flights, despite the annual cargo flight activities being significantly lower, compared to passenger flights (ICCT, 2020).

2.3 Airports

An extensive network of airports, allows the aviation sector to connect people and goods across regions and continents. The growing number of airports, coupled with increasing urbanisation, means that a significant share of the global population now lives within 100 kilometres of the nearest airport, as shown in Figure 5.

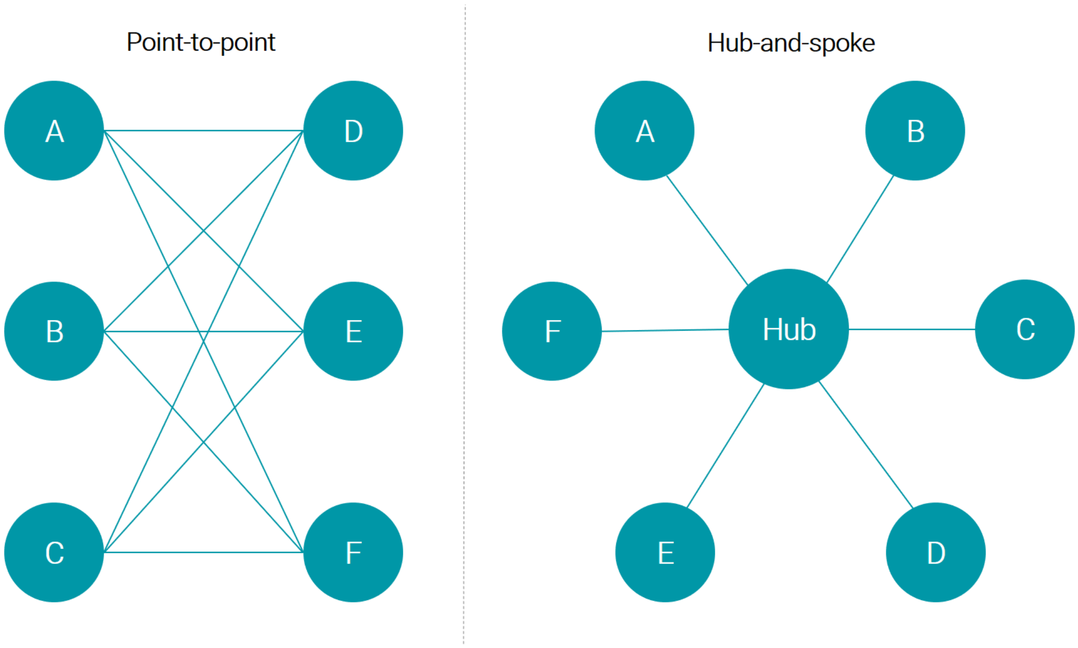
Figure 5 Airport availability, adjusted from ICAO (2024).



2.3.1 Airport networks: Hub-and-spoke and point-to-point

The aviation system is supported by different types of airports, ranging from major international hubs to smaller regional airports and cargo-specific facilities. Whether an airport is designed for large international planes or smaller regional ones affects the runway layout and which planes are able to operate at the airport. Accordingly, airports are strategically designed to meet the specific demands, including all necessary infrastructures for fuelling, safety, and maintenance, repair and technical support of aircraft, and their roles are shaped by whether they function primarily within a point-to-point or hub-and-spoke network. The two types of airport networks are illustrated in Figure 6.

Figure 6 Concepts of point-to-point versus hub-to-spoke networks in aviation. Illustration by the Danish Energy Agency.



Major international hubs[5] like Atlanta, Dubai, Heathrow etc. are central to the global aviation system, accommodating significant volumes of both passenger and cargo traffic. These airports support hub-and-spoke operations, where flights from smaller regional airports (the spokes) connect through central transfer points (the hubs). This model allows airlines to consolidate traffic and maximize aircraft utilization, efficiently connecting numerous destinations through a few major hubs (Cook & Goodwin, 2008).

Some airlines have specialized in the alternative point-to-point approach. In this case, aircraft navigate between departure and final destination with no stops during their trip. This approach minimizes the need for transfers at major hubs, reducing travel time and operational costs, especially for low-cost carriers. The primary advantage of the point-to-point model in long-haul operations is reduced total travel time. By eliminating layovers, airlines improve the passenger experience while reducing the number of take-offs and landings, which are the most fuel-intensive phases of a flight. However, this model also presents challenges. Long-haul point-to-point routes require sufficient direct passenger demand to remain economically viable. Unlike hub-and-spoke operations, which pool travellers from multiple locations, direct long-haul routes depend entirely on the traffic between the two cities. As a result, such routes are typically more feasible between large population centres or highly frequented destinations.

[5] more than 100 million passengers per year.

3 Climate impact

Globally, aviation emitted for approx. 2.5 percent of global CO_2 emissions, in 2023[6]. Demand for passenger air travel has kept growing in recent decades. This is expected to continue to increase towards 2050. ICAO has (including covid-19 effects) estimated the global annual growth in passenger demand for air transport to be between 2.9 - 4.2 per cent. per year until 2050 measured in RPK (ICAO, 2022). This growth corresponds to a tripling in 2050 compared to the 2018 level.

A similar development is expected in relation to air freight. Thus, it is also expected that emissions will grow rapidly and already in 2025 exceed the level of 2019 (IEA, 2024a).

In addition to the direct CO_2-emissions, it is recognized that aviation has an indirect heating effect on the atmosphere. This is caused by non-CO_2 effects that have been found to have a significant climate heating effect related to the combustion of fuel at high altitude (EASA, 2020b; IPCC, 1999). The effects are complicated to determine, and there is still no international consensus on the most appropriate calculation method. Furthermore, non-CO_2 effects are not part of current regulation[7]. However, the role of non-CO_2, in the net-effects of climate effects, from aviation cannot be neglected. The non-CO_2 effects are reviewed in section 3.2.

3.1 Emissions

In an ideal combustion process involving hydrocarbons, the only by-products would be water (H_2O) and carbon dioxide (CO_2). However, the continued use of kerosene as the primary aviation fuel ensures that real-world combustion processes remain far from perfect. Due to the high-temperature and high-pressure conditions in jet engines, incomplete combustion occurs, leading to the persistent release of additional harmful emissions. These include sulphur oxides (SO_x), nitrogen oxides (NO_x), unburned hydrocarbons, and soot particles.

Over time, the ongoing reliance on kerosene-based fuels not only sustains the production of these emissions but also exacerbates their cumulative impact on the atmosphere. CO_2 remains the most significant emission due to its long atmospheric lifetime and direct contribution to climate change (Chevron, 2007). The CO_2 emissions from conventional aviation is elaborated in 4.3.1. In addition, the impacts of water vapor and other non-CO_2 emissions from kerosene combustion are becoming increasingly evident. At high altitudes,

[6] The post-2019 level of activity was strongly affected by the covid-19 pandemic, and CO_2 emissions fell as a result in 2020 by almost 43 per cent. Emissions have since increased, and in 2022 were emissions back to approx. 90 per cent of the level in 2019 (IEA, 2025) .

[7] The European Union has introduced a Monitoring, Reporting, and Verification (MRV) system, effective from January 1, 2025, requiring airlines to report non-CO_2 emissions for each flight. By the end of 2027, the European Commission will evaluate the MRV system and may propose additional legislation to mitigate non-CO_2 effects (European Commision, n.d.).

water vapor released by aircraft forms contrails and cirrus clouds, which have a significant warming effect.

3.2 Non-CO_2 effects

Non-CO_2 effects, while highly complex, are scientifically accepted as a significant additional driver of the global warming potential (GWP) from aviation. It began as a subject of research in the 1960's and has become more mainstream since it was addressed by IPCC (1999).

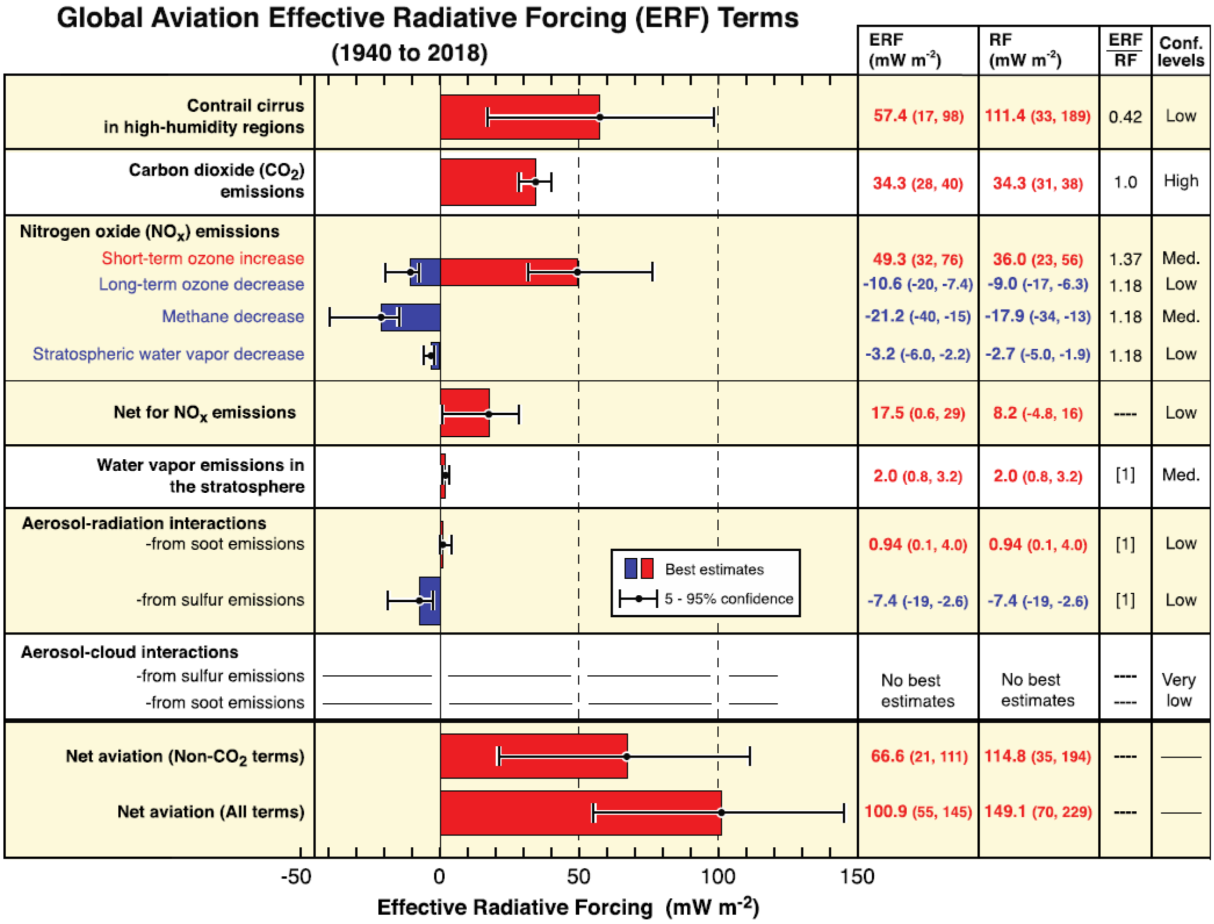
The GWP of non-CO_2 is significant. EASA estimated 66% of total aviation climate forcing to originate from non-CO_2-effects, in 2018 (EASA, 2020b). The additional effect is caused by emissions of nitrogen oxides (NOx), water vapor, soot and sulphate aerosols, and increased cloudiness due to contrail formation. This additional heating effect of aviation is referred to as non-CO_2 climate impacts (Lee, et al., 2021).

Figure 7 indicates the complex nature of non-CO_2, where different factors weigh differently in the overall warming potential on surface temperature (mW/m^2).

Definition: Non-CO_2

The non-CO_2 effects arise from emissions of oxides of nitrogen (NOx), soot particles, oxidised sulphur species and water vapour. These emissions cause in changes in the chemical composition of the global atmosphere and cloudiness, perturbing the earth-atmosphere radiation budget. The net impact of aviation non-CO_2 emissions is a positive radiative forcing (warming), although there are a number of both individual positive (warming) and negative (cooling) forcing arising from respective aviation non-CO_2 emissions, for which large uncertainties remain (EASA, 2020b).

Figure 7 Effective Radiative forcing from CO_2 and non-CO_2 (EASA, 2020b).



As indicated, there are both cooling and heating factors of the non-CO_2 effects. The issue of non-CO_2 effects may add layers of regulatory and technical complexities to the planning for climate mitigation of the aviation sector.

Regulating non-CO_2 effects

The EU Emission Trading System has addressed direct carbon emissions from aviation since 2012. However, the EU have modified the MRV regulation to require mandatory monitoring and reporting of non-CO_2-effects, starting January 2025. The EU has developed a model for both large and small actors in the aviation sector to calculate the impact of their non-CO_2-emissions. By 2027, the European Commission will deliver a report on the results of the monitored data and whether a legislative proposal to address the issue is appropriate (European Commision, 2024).

Depending on whether non-CO_2 effects will be part of future life-cycle-assessments on aviation technology, it may play a role in determining the operation and technology choice for cleaner aviation.

For this technology review and its scope, the topic of non-CO_2 is too complex and comprehensive to cover. Therefore, following EASA (2020b) and the conclusions from their report, produced for the EU, the following can be outlined:

1) Non-CO_2 emissions consist of multiple parameters that leads to conflicting effects on surface temperature. Some aspects of non-CO_2 have a warming potential while other effects have a cooling effect, but the net-effect of non-CO_2 is a warming effect (net positive). EASA finds that given the right circumstances, the net-effect from non-CO_2 may even turn net-negative (cooling).
    a. The strongest impactors of non-CO_2 are those from net-NOx[8] emissions and cirrus clouds. The knowledge on this area is subject to significant uncertainties.
2) Avoiding cirrus clouds requires further studies on the subject and better tools to predict ice-supersaturation at least 24 hours ahead of time.
3) Aromatic content of fuel is of significant importance in relation to the severity of non-CO_2 effects occurring in relation to conventional aviation. Higher values of aromatic content increase ice particles formed behind an aircraft, and vice-versa.
4) Formulating aviation emissions equivalencies for short-lived climate forcers (e.g. non-CO_2 impacts) with the long-lived greenhouse gas (e.g. CO_2), presents scientific and policy challenges.
5) Some of the measures that can reduce the non-CO_2 effects may simultaneously increase CO_2 emissions – for example when changing flight height.

Mitigating non-CO_2 effects

Many studies are looking into the potential efforts that may reduce the occurrence of non-CO_2 emissions. There are both technical and operational approaches to minimize the effects of non-CO_2 emissions.

1) Operationally, academia has looked into the option of managing the altitude and route of certain planes. The re-routing of an aircraft does add marginally to the fuel consumption of a plane, but can, if implemented correctly, reduce the net climate forcing of the given flight (Lee, et al., 2021).
2) As a more technical solution, the modification of the existing combustion processes can reduce NOx emissions. The fuel consumption (fuel efficiency) and NOx does, however, have conflicting effects on the net-effect on climate effects from an aircraft. This is because higher engine temperatures allow for more efficient combustion, but also produces more NOx – and vice versa. A study found that the breakeven-point of such modifications would have to acquire a 20% NOx reduction for a 0.5% increase in CO_2 emissions (Freeman, Lee, Ling, Agnieszka, & De León, 2018).

---

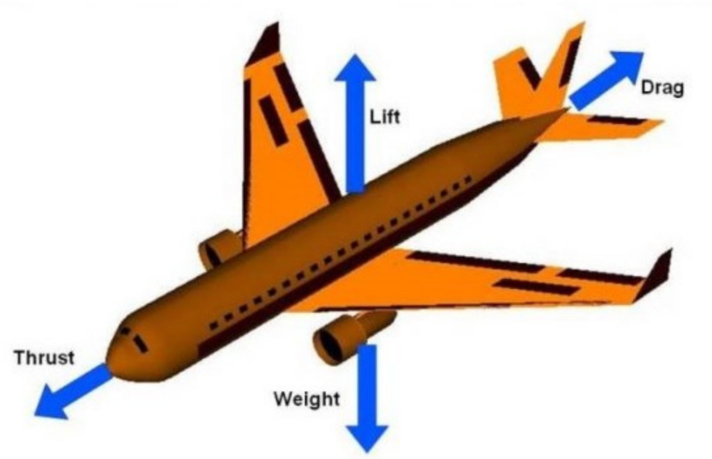
[8] NOx is not a direct GHG (greenhouse gas) per se, but its emission results in changes in the chemical balance of the atmosphere to ozone and methane which have radiative impacts, quantified as a 'net-NOx ' effect (EASA, 2020b).

Additionally, it has been identified lowering the aromatic content of jet fuel as a way to reduce the non-CO_2 effects. This approach involves monitoring and potentially regulating the aromatic content within jet fuel standards to ensure a reduction in non-CO_2 climate impacts. Sustainable Aviation Fuel (SAF) is found to have lower aromatic concentrations meaning that SAF, in addition to the CO_2 benefits, also helps reducing the impacts of non-CO_2. Potentially, adjusting aromatic content of fossil kerosene can reduce contrail formation by 50%, with further 80% reduction in soot particle emissions (EASA, 2020b). This is discussed in more detail in chapter 5.12.

4 Technology of today - aircraft characteristics

Today's commercial aircraft designs are the outcome of a century's development within private, military and commercial aviation. While there are many different iterations of aircraft, some characteristics are general for all modern fixed-wing aircraft. Four fundamental forces act on an aircraft in flight: Lift, the upward acting force; weight, the downward acting force; thrust, the forward acting force; and drag, the backward acting force. The impact of the forces is visualised in Figure 8.

Figure 8 The four forces on an aircraft (Glenn Research Center, 2022b).



Each force has its own direction, opposing force, and factors that affect its effect. These forces balance the trajectory of the aircraft where lift opposes weight and thrust opposes drag. The four forces are explained in the table below.

Table 2 The physical forces affecting flight, summarised from Glenn Research Center.

Force	Description
Lift	Enables an aircraft to climb and remain airborne by counteracting the effect of gravity. Lift is generated by a complex interplay of physics and is influenced by airspeed, angle of attack (the angle between the forward motion of the aircraft and the airstream), shape and size of wing and air density (Glenn Research Center, 2022a).
Weight	Exerted by gravity on the aircraft. It acts downward towards the centre of the Earth and is dependent on the mass of the aircraft and the acceleration due to gravity. The impact of weight depends on the total mass of a given aircraft. Weight must be counterbalanced by sufficient lift for the aircraft to achieve and maintain flight.
Drag	A resistance force that opposes an aircraft's forward motion through the air. Drag is influenced by factors such as airspeed, air density, shape of the aircraft, and surface roughness. There are two main types of drag: parasitic drag (which includes form drag, skin friction, and interference drag) and induced drag (which is associated with generating lift).
Thrust	The force produced by the aircraft's engines to propel it forward. Thrust must overcome drag for the aircraft to accelerate. In jet engines, thrust is generated by expelling exhaust gases backward, creating a forward push. In propeller-driven aircraft, thrust is produced by the propeller blades pushing air backward (Glenn Research Center, 2022b).

These are the paramount forces when designing an aircraft. The ideal setup balances the aircrafts manoeuvrability, fuel efficiency, cargo volumes and/or passenger capacities as well as safety requirements.

4.1 Propulsion

As explained in Table 2, lift is a required force to maintain flight for a heavier-than-air aircraft. All aircraft engines, whether they are piston engines, jet engines, gas turbines, or electric motors, use the same fundamental principle to generate thrust: By accelerating air backwards relative to the engine, and thereby a reaction force that drives the aircraft forward. In other words, thrust is the displacement of ‘working fluid’ (in this case atmospheric air) in opposite direction of a plane’s path and can be described as (Fehrm, 2024):

Thrust = Air Massflow through the engine * Air Overspeed (the speed of the accelerated air compared to the surrounding air

Thrust can be generated by either accelerating a large air mass flow to a low overspeed or accelerating a small air mass flow to a high overspeed. At no or low speed (e.g. when the aircraft is taking off), it requires less power to accelerate a lot of air to a low overspeed than less air to a high overspeed. The higher the air mass flow and the lower the overspeed, the higher the engines propulsive efficiency. However, as speed of the aircraft increases, the case with a large air mass flow at a low overspeed will have the overspeed reduced proportionally faster than the second case. The effect is called speed lapse of thrust, and it affects engine designs with low overspeed more adversely. Therefore, the ideal propulsion system varies between different applications, dependent on operation speeds, routes, distances and altitudes (Fehrm, 2024).

The most common engine types used in modern commercial aviation are turboprop engines (gas turbine engine that mechanically powers a propeller) and turbofan engines (gas turbine engine driving a ducted fan and produces a jet propulsion).

These two engine types are advantageous due to due to their traits of efficiency and reliability and the subsequent sections elaborates on these engine types of modern aviation. There is a variety of other engine types used in different aircraft applications e.g. military or experimental aircraft, such as pulse jet, ramjet and scramjet engines, but they are of less or no relevance for commercial aviation, due to their strengths being high-velocity rather than noise- and fuel-efficient operation required in commercial aviation.

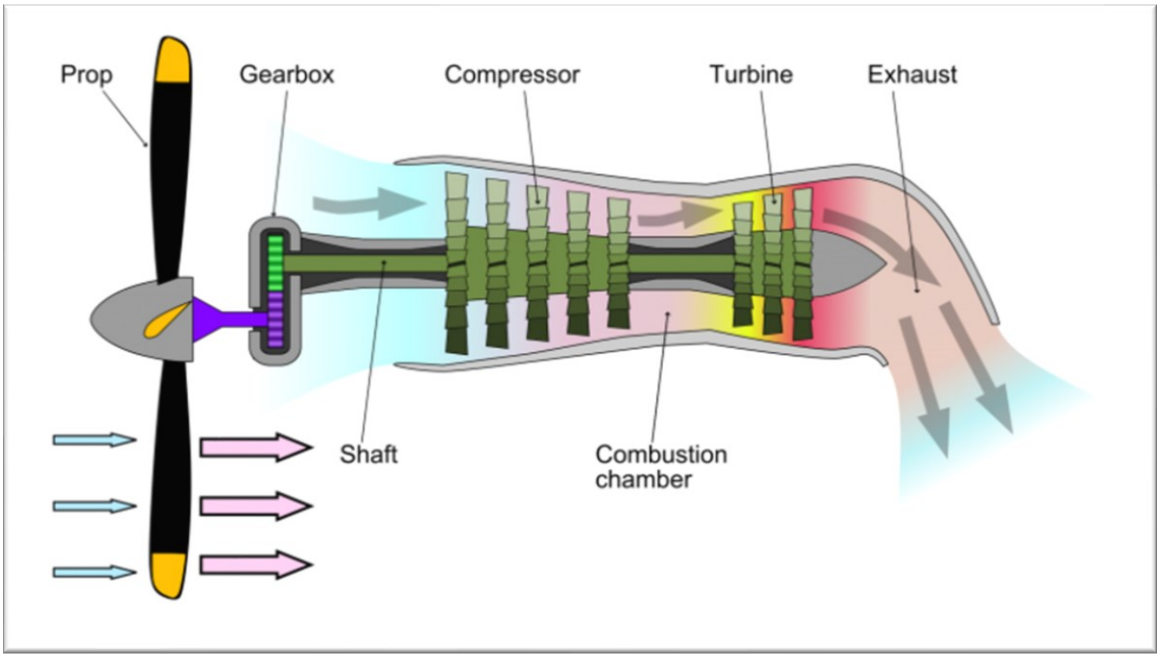
Considerations for the choice of a given engine include economic aspects such as investment and maintenance costs and reliability, etc. as well as technical aspects including safety, fuel efficiency, cruise speed and noise levels. Both engine types are explained in the following two sections.

4.1.1 Turboprop engines (regional and short-haul at lower speeds)

The turboprop engine has a shaft driven propeller, driven by a gas turbine (Embry-Riddle Aeronautical University, 2024b). The propellers generate thrust by displacing a large air mass flow to a low overspeed, pushing the plane forward, making the turboprop engine an efficient engine solution for low speed aircraft. The propellers of a turbo prop engine generate more than 90 % of their total thrust, while exhaust gas generates the remaining share.

Smaller turboprop engines deliver 500-2,000 shaft horsepower and larger ones up to 5,000 shaft horsepower (U.S. Department of Transportation, 2023). Figure 9 shows a design of a turboprop engine.

Figure 9 Visualisation of a turboprop engine with propellers (Embry-Riddle Aeronautical University, 2024b).



The inherent characteristics of the turboprop makes it an efficient engine type for short- and medium-haul distances at lower altitudes compared to alternative propulsion technologies. The engine type also allows for lower noise levels as well as take-off and landing at shorter runways (European Aviation School, 2023). The current turboprop aircraft in operation are typically smaller commuter-class aircraft with 40 to 90 seats, with a maximum leg-length about 1,600-1,800 km with flights taking 3.5-4.5 hours. They are frequently used for shorter flights well under the maximum range.

Figure 10 Picture of a plane with turboprop engines. Photo credit: Unsplash.

Turboprop engines, while efficient for certain types of flight operations, have notable limitations, particularly related to speed and altitude. Such constraints influence suitability of turboprop engines for long-distance, high-speed routes. The limit of flight speed is due to energy efficiency. As aircraft speed increases, the efficiency of turboprop engines decreases significantly. This is primarily due to the propeller blades encountering greater aerodynamic resistance, reducing propulsion efficiency. Therefore, turboprop passenger aircraft typically cruise at speeds around 500 km/h (275 knots), which is significantly slower compared to aircraft equipped with turbofans.

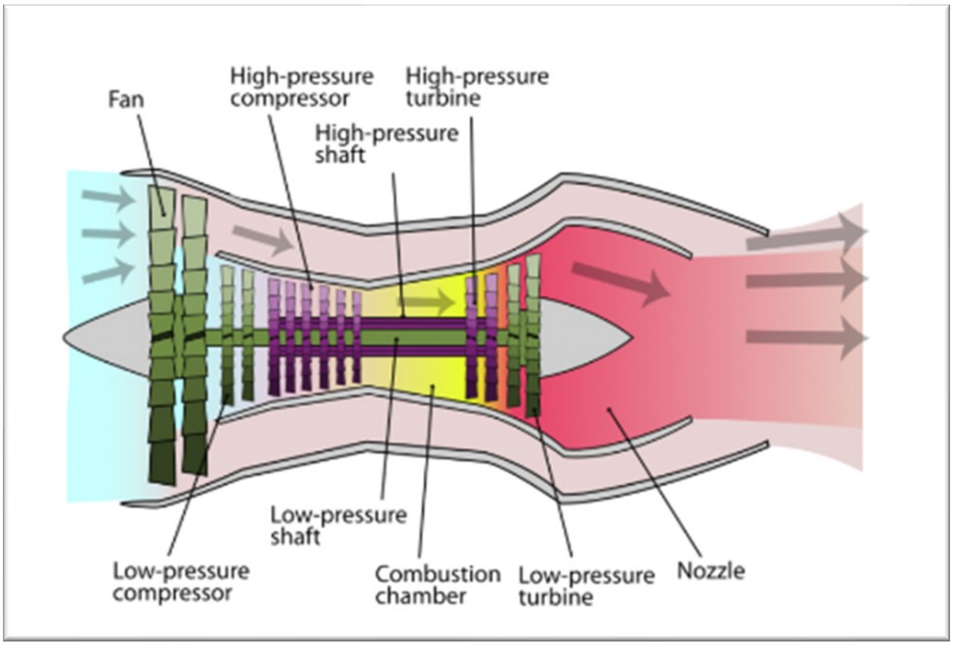
The limitation of altitude is due to air density – this limitation is referred to as service ceiling. The maximum cruising altitude, or service ceiling, for turboprop aircraft generally ranges between 25,000 and 30,000 feet (approximately 7.6 km to 9.1 km). Air density decreases with altitude, which negatively impacts the performance of the propeller. As propellers rely on displacing air to generate thrust; in low-density air, the propellers are at a disadvantage at higher altitudes, compared to turbofan engines.

4.1.2 Turbofan engines (short-, medium- and long-haul at high speed)

The turbofan jet engine is an iteration of the turbojet engine, where a large fan is placed within a duct, called the diffuser, and is driven by the turbine. The turbofan directs two airflows: one that leads air into the compressor, and further into the combustion chamber and turbine stages and leaves the engine through the exhaust nozzle at high velocity. The second airflow is directed around the core of the engine and does not enter the combustion. This flow accelerates a large air mass to a low overspeed generating thrust. The airflow that diverts the core is defined as 'bypass air'. The bypassing air is measured in a bypass ratio[9] (BPR) indicating the ratio of air entering the fan that is directed around the core combustion turbine engine. As much as 70% of thrust is generated from the BPR (Embry-Riddle Aeronautical University, 2024a). This design dramatically increases efficiency and reduces noise levels (U.S. Department of Transportation, 2023). During the last decades of development turbofans have increased in size, to maximize the benefits of higher BPR by increasing fuel efficiency. However, this trend towards bigger fans and BPR is challenged by drawbacks to the efficiency of aircraft itself, since bigger fans/nacelles also increases the weight of the engine. The rotation speed of the fan-tip increases with the size, and this also poses a challenge since the fan blades only function at tip speeds below the speed of sound. Finally, the fan size is limited practically by the ground clearance (the distance between the runway and the bottom of the engine). Figure 11 illustrates a turbofan and how it directs the airflow both into and around its core.

[9] The bypass ratio (BPR) of an aircraft engine is the ratio of the mass of air bypassing the engine core to the mass of air passing through the core.

Figure 11 Illustration of a turbofan (Embry-Riddle Aeronautical University, 2024b).



Conceptually, a jet engine consists of an inlet, a compressor, a combustion chamber, a turbine, and an exhaust nozzle. Its functions by drawing air into the engine through the inlet and compresses and heats the air in the compressor. The compressed air is mixed with fuel, and ignited, which generates an enormous amount of energy, which both drives the turbines (that drives the compressor) and provides forward thrust as the exhaust gas accelerated to high speed passes through the nozzle. Therefore, traditional turbojet aircraft work on the principle of accelerating a relatively small mass of air to a high overspeed.

The overall efficiency of a turbofan jet engine is directly connected with engine fuel consumption, which can be measured as Thrust Specific Fuel Consumption[10] (TSFC) (lb/lbf/h). Fuel efficiency improved with about 2 pct. per annum between 1960 and 1995, where it reached a plateau. However, the research later picked up with high BRP engine designs (Adu-Gyámfi & Good, 2022). Today the most efficient turbofan engines consume 60% fuel less in comparison with the first design using this architecture. Such improvement has mainly been achieved by a significant increase in BPR and OPR (Overall Pressure Ratio) parameters (Michal Kuropatwa, 2022).

Turbofan engines are used for both short-, medium- and long-haul flight and are the only option for long, high capacity flights at high speed and high altitude (European Aviation School, 2023).

[10] The mass of fuel expressed in pounds [lb] consumed in the time expressed in hours [h] when the engine generates a unit level of thrust expressed in pounds of force [lbf].

Figure 12 Picture of a plane with turbofans. Photo credit: Unsplash.

Turbofan vs turboprop

There are trade-offs for the turbofans. While their strengths are efficiency at higher altitudes and higher speeds, their weaknesses (compared to a turbo-prop) are the opposites, meaning lower efficiency at lower speeds and altitudes. In these areas the turboprop engines perform better and can be selected as the preferred engine for servicing short-haul routes.

Table 3 Typical characteristics of turboprop and turbofan engines (Airplane Academy, 2025; FlyVolato, 2025).

Characteristic	Turboprop Engine	Turbofan Engine
Optimal Speed Range	Best below 400 knots (460 mph or 740 km/h)	Best at 500–600 knots (575–690 mph or 925–1,100 km/h)
Fuel Efficiency	Higher at lower speeds and lower altitudes	Higher at higher speeds and altitudes
Weight	Generally lighter	Generally heavier
Operating Costs (OPEX)	Lower due to fuel efficiency and simpler maintenance	Higher due to more complex maintenance and fuel consumption
Capital Expenditure (CAPEX)	Lower initial purchase cost	Higher initial purchase cost
Runway Requirements	Suitable for short, unpaved runways (grass, gravel, etc.)	Requires longer, paved runways
Altitude Efficiency	More efficient below 25,000 feet	More efficient above 30,000 feet
Noise Levels	Louder, especially at take-off	Quieter, especially modern high-bypass engines
Payload Capacity	Lower, suitable for smaller aircraft	Higher, suitable for larger, high-capacity aircraft
Range	Shorter range, typically for regional flights	Longer range, suitable for medium to long-haul flights
Passenger Comfort	More vibration and noise	Smoother and quieter flight
Types of routes	Regional, remote and rugged areas	Major airports, long-distance travel, but also commonly used in short-haul flights.

4.2 Dimensions and utility of the airframe

There is a wide range of sizes of aircraft within both passenger- and cargo transport. Transporting passengers and cargo are two different tasks with different demands. Airborne cargo can be transported either in the cargo-section of a passenger aircraft (belly freight) or in an aircraft specialized for transporting cargo, rather than people (known as cargo planes or 'freighters'). In passenger aircraft, the cargo volumes are smaller, as their main purpose is to carry passengers. The cargo is located in the lower deck below where the passengers are seated. This allows airlines to carry some cargo, in addition to the passengers as their main service. Freighters are not restricted to use only a lower deck for cargo, as seat capacity is compromised for cargo volume, and will hence more cargo, with only a few crew members on board.

Passenger flights

For short- and medium haul flights, two of the most common aircraft are the Airbus A320 series and the Boeing B737 series (these two series of aircraft make up 50 pct. of all current commercial aircraft). The two models have come in many configurations and have, respectively, been developed since the 1980's and 1960's.

Table 4 table below gathers general details of some of the most common types of commercial aircraft. The table shows the traits of two turboprop aircraft, two narrow body medium-sized planes, and two wide body twin aisle aircraft for long-haul routes. The aircraft come in many versions and iterations and any specific aircraft may differ from the values presented below. The table should be read as general indications of the given aircraft characteristics.

Table 4 Specifications of two single-aisle (narrow body) aircraft dominant within short- and medium-haul flights and two twin aisle wide body aircraft used for long haul l flights (lufthansagroup, 2024a; Hunt and Palmer, 2024; Boeing, 2024a; Boeing, 2024b; Ultimate Specs, 2025; Airbus, 2024b; Airliners, 2025).

	Commuter/regional/Short haul - Turboprop		Regional/medium/ short haul - Turbofan		Long haul - Turbofan	
Aircraft example	ATR-72-600	Bombardier Dash 8-400	Airbus A320neo	Boeing 737-MAX 8	Airbus A350-900	Boeing 777-300ER
Passengers	70	78	165	178	300-350	365-550
Length (meters)	27.2	32.8	37.6	39.5	66.8	73.9
Wingspan (meters)	27.1	28.4	35.8	35.9	64.8	64.8
Height (meters)	7.65	8.3	11.8	12.3	17.1	18.5
Max take-off weight (tonnes)	22.8	29.2	78.5	82.2	269	351
Max Landing weight (tonnes)	22.3	28	67.4	69.3	205	251
Max range (km)	1,528	2,522	6,297	6,480	15,742	13,649
Fuel capacity (litres)	5,930	6,616	27,200	26,035	138,000	181,283
Fuel consumption (kg/km)*	1.56*	2.16*	2.79**	2.71**	6.52***	8.49***
Cruise speed (km/h)	510	667	833	839	912	905

** Commuter flights (560 km)*
*** medium flight (1,900 km)*
**** Long haul flights (9.300-13,000 km)* (Wikipedia, 2025).

Cargo aircraft

Figure 13 A cargo aircraft with its distinctive design optimized for cargo transport. Photo credit: Unsplash.

These planes can make use of the entire cabin for cargo. The following table highlights values for common cargo aircraft types.

The placement of wings on cargo aircraft driven by the unique requirements of cargo operations. High-wing configurations offer practical advantages such as increased ground clearance, better weight distribution, and improved operational capabilities on diverse runways. These benefits make high-wing designs well-suited for cargo transport, where flexibility and efficiency in loading and unloading are paramount. In contrast, passenger aircraft prioritize aerodynamic efficiency, fuel economy and passenger comfort, often leading to low or mid-wing placements. An example of a cargo plane (Antonov An-124) is shown in the picture, there are visible variations compared a common passenger plane:

- Wing placement is higher on the fuselage
- There are no side windows, as there are no passengers
- More landing wheels to support balance during heavy landings

In addition to these visible variances, some key addition differences, not visible in the picture, include larger doors allowing larger cargo to enter the cabin. Some designs enable opening the nose of the plane, in order to allow for easier access. However, the Airbus A300 or Boeing 747 freighter are commonly used, with exterior looks being closer to those of passenger aircraft.

The following table compares the specifications of two cargo planes, in order to benchmark on modern cargo plane designs.

Table 5 Specifications for common freighters (Air Bridge Cargo Airlines, 2020; Boeing, 2024; Antonov, 2024).

Cargo aircraft	Antonov An-124-100	Boeing 747-8F
Max payload (tons)	120	139
Length (meters)	69.1	76.3
Wingspan (meters)	73.3	68.5
Height (meters)	21	19.4
Max take-off weight (tons)	402	447.7
Max landing weight (tons)	330	329.8
Maximum payload (tons)	150	135
Fuel Capacity (litres)	262,715	226,118
Range (km)*	8,400	8,130
Cruise speed (km/h)	865	898

*Range is dependent on payload carriage and flight conditions.

4.3 CO_2 emissions

CO_2-emissions are central in international aviation regulation, aiming to manage climate change impact. The emitted CO_2 is a by-product from the burning of carbon-based fuel.

Figure 14 Pathway for CO_2 emissions to net zero emissions 2050 (scenario from aspirational and aggressive technology perspective) (ATAG, 2021).

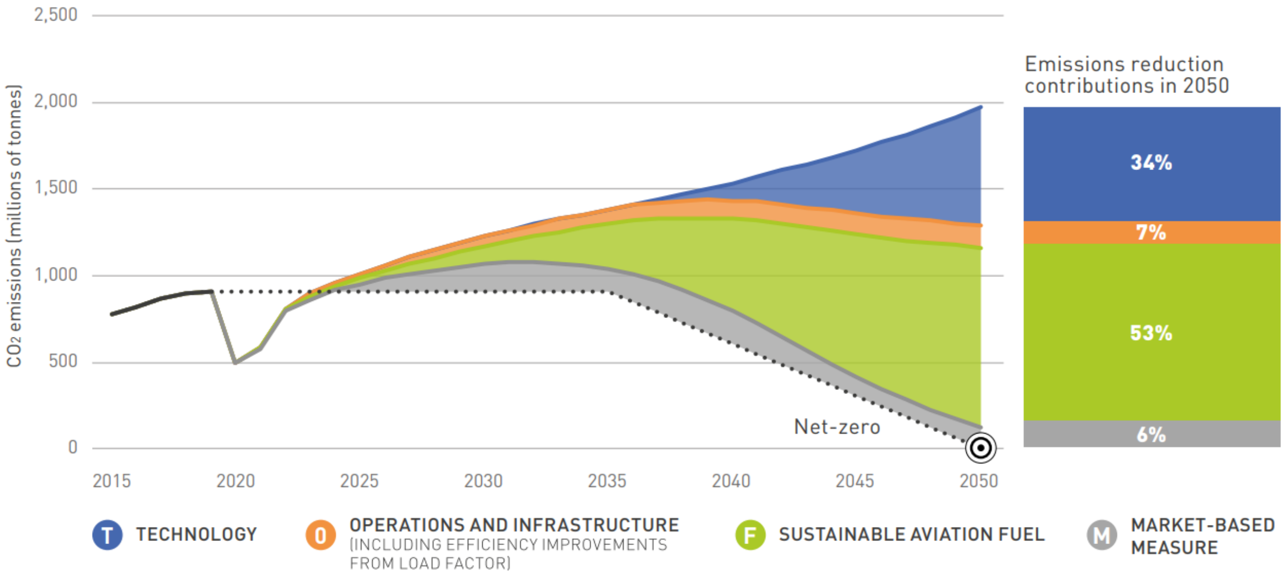


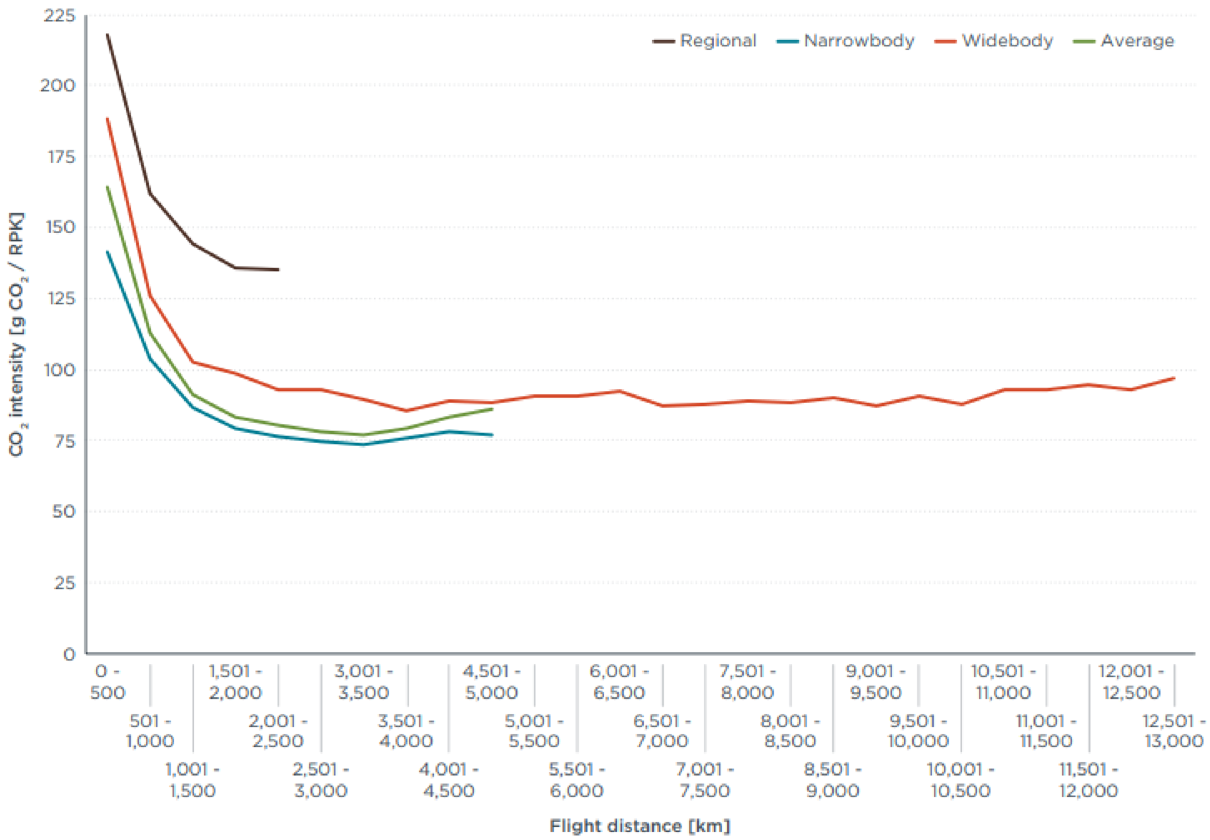
Figure 14 shows projected emissions in ATAGs Waypoint 2050 scenario 3, relying heavily on new technologies including electric aircraft up to 100 seats, zero emissions aircraft for 100-200 seat and hybrid electric powered unconventional larger aircraft. According to this scenario at substantial part of the necessary CO_2 emission reduction would even with extensive use of new technologies have to come from the use of sustainable aviation fuels.

4.3.1 CO_2 emissions by aircraft size

There are many factors affecting the emission of CO_2 from the exhaust of an aircraft and various metrics used to establish the carbon-intensity of a given flight. For example, accounting for emissions per kilometre flown (favouring smaller planes) or per RPK (favouring larger planes with a higher seat count).

Figure 15 shows the RPK carbon-intensity of distances ranging from short-haul to the longest international flights, as well as for regional planes, narrow-body and wide-body aircraft.

Figure 15 Range of passenger aircraft and the subsequent CO_2-intensity per RPK (ICCT, 2020).



The graph from ICCT (2020) shows the CO_2 intensity across different flight distances for the three categories of aircraft. The three categories can be defined as the following:

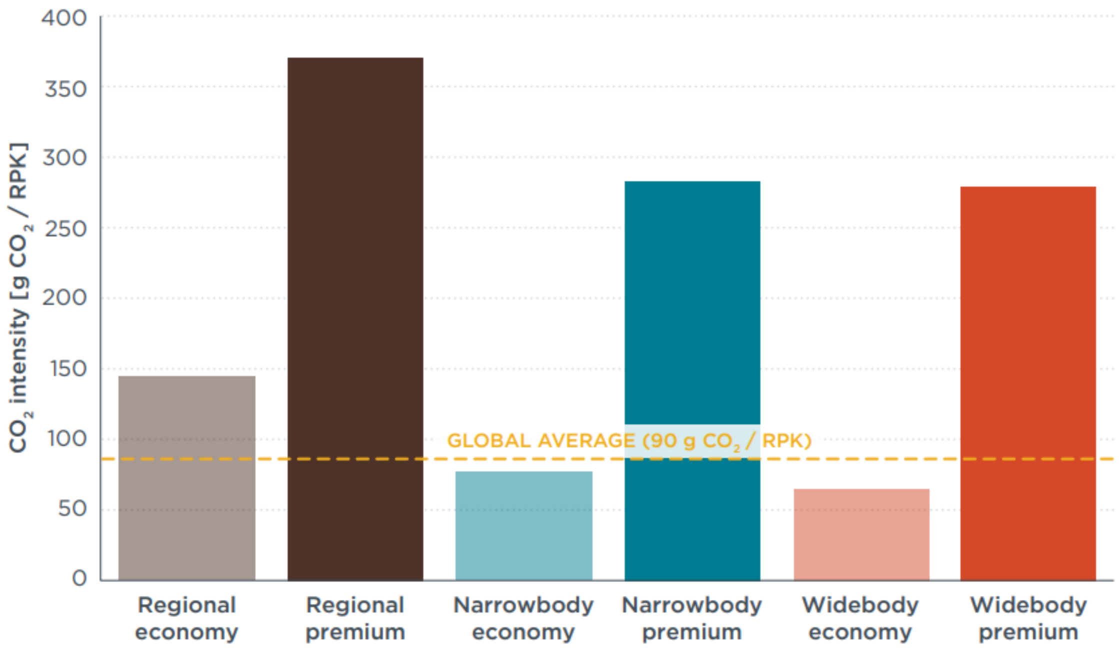
1) Regional aircraft. Small to medium-sized planes designed for short-haul flights. Usually seating below 100 passengers.
2) Narrow body aircraft. Single aisle medium sized planes designed for short- to medium-haul flights. Typically seats between 100-220 passengers.
3) Wide body aircraft. Twin-aisle aircraft, larger in size, planes designed for long-haul flights. Seats up to around 400 passengers – and in cases up to 850. However, a design for less than 400 passengers is more common.

The level of emissions ranges from around 75 – 220 g CO_2/RPK across the categories and flight ranges. Generally, shorter trips are more energy and carbon intensive with narrow body aircraft being the most efficient of the three categories. Derived by the figure, after a certain point, around 3,500 – 4,000 km, the carbon intensity stabilises.

4.3.2 Seat capacity and carbon-intensity

Intuitively, increasing the number of seats on a plane also decreases the emissions per seat. By splitting the emissions tied to the individual passenger, depending on their seating (economy or premium), the results portrayed in Figure 16 can be deduced.

Figure 16 CO_2-intensity by RPK, categorised in seating classes (ICCT, 2020).



The trend is clearly showing economy seating being significantly less carbon-intensive compared to the premium options (first- and business class). Load factors in this context are based on the average for each seating class. The trend shows higher load factors for economy seating than for premium seating. A higher load factors lowers the carbon intensity per RPK (Bofinger & Strand, 2013).

4.4 Design and engineering of new aircraft series

The development of a new conventional aircraft is a comprehensive task both in terms of the technical engineering but also the whole approval process making it extremely costly and time consuming. Therefore, the full product cycle from initial ideas and developing of design to first in-service flight of a new aircraft span across several years.

For instance, Airbus has not launched an all-new commercial aircraft since the A350 in 2013 and Boeing since the 787 in 2003, though Embraer on the other hand have developed several new aircraft within the last decade (Hamilton 2024).

The actual production time of an aircraft, once the development, test and type approval phases are finalised, is on the other hand relatively fast, e.g. the Boeing 777 takes 49 days in the factory to build, followed by 30 days of testing, summing up to 79 days (Brown, 2012).

For all new aircraft designs, a similar economy of scale and production pace will not be expected for many years to come.

4.5 Energy efficiencies of current technology and potential improvements

As of 2024, fuels estimated to account for 31% of all operating costs (IATA, 2024). Hence, fuel efficiency of commercial air transport has been a main focus and improved vastly at a rapid rate over the last 60 years. The gains from fine tuning of current technologies have slowed down and new more radical concepts are getting increased attention.

Today's large turbofan engines generate thrust with an efficiency of around 40%, where combustor irreversibility (incomplete combustion and heat loss to surroundings), core exhaust heat loss and bypass exhaust kinetic energy, accounts for more than 80% of the energy losses (Grönstadt, et al., 2016). Efficiency can be increased by optimization of engine core thermal efficiency, which is directly correlated with compressor system and overall pressure ratio (OPR), and developing new materials that can sustain greater temperatures are part of this. Another key way to attain better efficiency is to increase BPR even more than today (current best in class engine has BPR=12.7), and expectations are, that significant improvements can be accomplished introducing ultra-high bypass ratio geared fan engines etc. However, increasing the engine fan also necessitates bigger casing/nacelles, increasing weight, aerodynamic drag and eventually making the physical clearance under the aircraft wings a factor.

The future of engine development therefore looks into more radical design like the open-rotor concepts. An open rotor, also known as a propfan, is an engine design that was first tested in the 1980's, but was laid aside due to technical challenges e.g. issues with noise and vibrations, meanwhile turbo-props and turbofan increasingly dominated markets. Still, to this day, the propfan is deemed an attractive prospect of technological advancement, as it may reach up to 30% reduction in energy use, compared to 2000 levels (Clean Sky, 2016). The design concept is inspired by the turbo-prop but allows for higher speeds while maintaining efficient operation. More recently, in 2021, CFM International announced the beginning of a new engine program, RISE (Revolutionary Innovation for Sustainable Engines), that work on a large diameter open fan operating with low rotation speed and expectation of a BPR up to 75 (CFM Aeroengines, 2025).

More Electric Aircraft (MEA) is another path that has been, and still is being, exploited towards more efficient but still conventional aircraft. The overall idea with MEA is to minimize mechanical drive systems by electrification of pneumatic and hydraulics systems thereby improving aircraft system efficiency. This has been deployed to a large extent in e.g. the Boeing 787 Dreamliner and the Airbus A350. The additional loads from these electrical systems have significantly increased the power consumption of the aircraft and divided the aircraft into several power sections (Cano, et al., 2021).

4.6 An alternative trend

While the aviation sector is focusing on reducing energy consumption and emissions from flights by improving the turbofan and turboprop technologies and transit to new low or zero emissions technologies, some companies are working intensively on technologies to increase the speed and reduce travel times. E.g. the company Boom Technology, which is working on a supersonic aircraft that could lead to travellers flying between New York and London in just over 3½ hours (similar time as the Concorde in service from 1976-2003). The aircraft are projected to reach a max range of just under 5,000 miles, with a 60,000-foot cruising altitude and accommodation of up to 80 passengers.

However supersonic commercial flight is, due to issues of energy consumption and noise, expected to be a niche of future aviation and will not be discussed further in this review.

4.7 Mid-report status

The modern aviation sector is a complex environment of many actors, technologies and regulatory perspectives. For any competing technology to thrive in this system, there are specific requirements that they will be benchmarked against. The remaining chapters of this report delve into the alternative aviation technologies and how they perform in their current state also indicating their future performances.

As a conclusion of this report (Chapter 8) these benchmarks will used to plot the technical performances of the alternative technologies (and SAF as a drop-in fuel) described in the following chapters.

5 Sustainable Aviation Fuel

5.1 Introduction

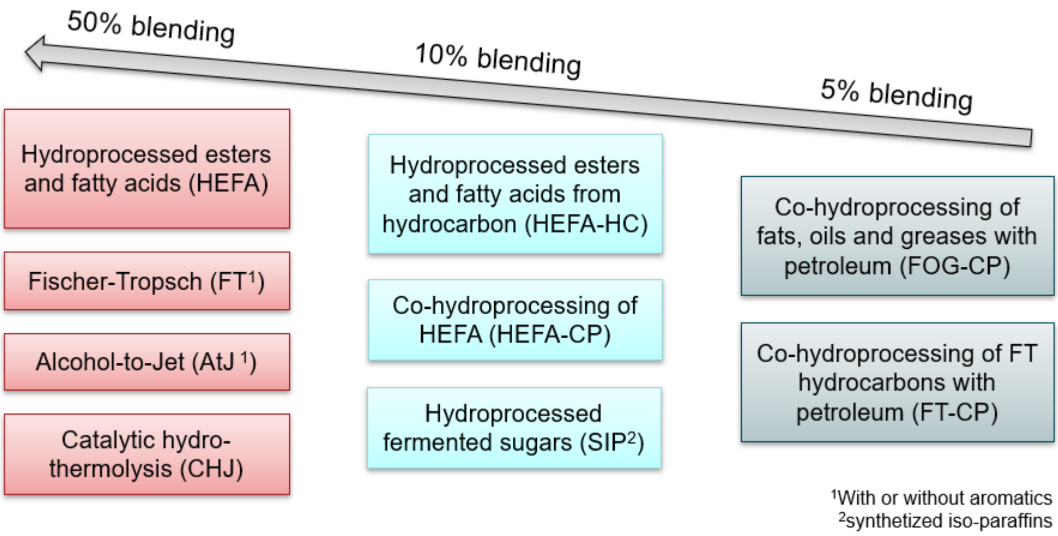
The major benefit of sustainable aviation fuels (SAF), and what makes them key contenders in the transition away from conventional aviation fuels, is the drop-in fuel characteristic. SAF can replace 50% of the jet fuel today, under the current state of certification, while in the future airplanes will be able to use up to 100% SAF[11]. However, SAF production is currently expensive and less widespread due to the cost and complexity of sourcing sustainable feedstock for the fuel production. The viability of SAF as a solution is largely revolving around the prices and volume of production, rather than aircraft designs or infrastructure in the airports as SAF essentially is the same type of fuel as fossil jet fuel, but sourced in a sustainable manner.

There are different types of SAF, that can be split into two main categories; bioSAF and eSAF. BioSAF are focused on biomass production pathways, while eSAF relies on hydrogen from

[11] Two tracks are being pursued, one with 100% SAF in modified jet engines without aromatics in the fuel content and another 100% track with 8% aromatics in non-modified jet engines.

electrolysis and biogenic carbon from carbon capture. There are also hybrid pathways combining the benefits (and challenges) of bioSAF and eSAF, blending biomass and hydrogen in the production process. Therefore, there is a wide range of routes to produce SAF, although relative few of these pathways have yet received the ASTM[12] approval for commercial use. Currently the maximum blend level of these fuels is 50% (v/v)[13] according to this regulation as shown in the figure below.

Figure 17 ASTM approved pathways and the maximum blending potential



5.2 The most prominent sorts of SAF-products

The development of SAF production requires dedicated plants at a considerable scale and geographical distribution if the expected large future demands from aviation should be meet. SAF pathways with low blending limits have low scaling potential, such as co-processing with fossil fuels, because only limited amounts of biogenic products can be mixed in fossil fuel refineries. The actual scaling lies in the pathways that can blend to 50% with fossil fuels, as in the future, many of these blends have the potential to reach 100% SAF.

In general, no SAF pathway can be a silver bullet to fully replace all fossil jet fuel. Therefore, to fulfil the decarbonisation goals for the aviation sector by the use of SAF, a mix of different pathways might be required. The choice of these pathways will depend on their scaling potential, or more precisely on the availability of the different feedstocks. Moreover, this report handles 2nd generation and advanced biofuels and e-fuel SAF pathways, excluding 1st generation biofuels that rely on food products or recycled carbon aviation fuels (produced from fossil waste streams). For these reasons, this chapter highlights the following pathways:

---

[12] ASTM International, formerly known as American Society for Testing and Materials, serves as the international standard for jet fuel quality. ASTM has a key role in ensuring safety, quality, and reliability of fuels. ASTM does not define when a fuel is sustainable, but strictly focuses on the chemical properties of aviation fuel.

[13] Volume over volume

Table 6. SAF production pathways included in this report.

Production pathway	Category
HEFA (Hydroprocessed Esters and Fatty Acids)	BioSAF
BtJ (Biomass-to-Jet) via Fischer-Tropsch or Methanol Synthesis	BioSAF
AtJ (Alcohol-to-Jet) via cellulosic ethanol	BioSAF
PtJ (Power-to-Jet) via Fischer Tropsch or Methanol Synthesis	E-SAF
PBtJ (Power-and-Biomass-to-Jet) via Fischer Tropsch or Methanol Synthesis	Hybrid (Bio-SAF + E-SAF)

Each of the subsequent descriptions include an assessment of the current and expected efficiencies for each pathway. Annex I includes an overview of these assumptions.

5.3 HEFA

Producing HEFA is the most mature among all SAF routes. Also known as HVO (Hydrogenated Vegetable Oil), it uses used cooking oils and purposefully grown plants as oil trees or oil seed bearing herbs as feedstocks. In addition to the fats and oils, it also needs hydrogen, electricity, thermal energy and catalysts (World Economic Forum, 2020; Danish Energy Agency, 2017). This pathway is ASTM certified to blending of up to 50%, but there is also the possibility of producing HEFA from algae, although this pathway is only certified to 10% blending.

The pathway is primarily split in two main steps, catalytic hydrogenation and cracking and isomerization. Hydrogen is used throughout each of these steps. The final output is essentially a mix of jet fuel, naphtha, diesel and other light-end gases, with jet fuel as the primary product with at least 50% jet fuel yield of the total input (Wei, et al., 2019). This has the potential for increasing to 70%, although this may affect the economics of the production plant. This review uses a jet fuel yield of 66% of the total input (Danish Energy Agency, 2017).

In general, the conversion rate of the primary feedstocks is high, where up to 85% of the input oils and fats can be converted to jet fuel. Despite the high conversion rate and maturity, the upscaling potential of this pathways is limited because of the type of feedstocks it uses. The used cooking oils, animal fats and other oily plants can only replace a limited amount of fossil jet fuel, estimated to 5-10% of the total demands, both in Europe and internationally (O'Malley, Pavlenko, & Searle, 2021; World Economic Forum, 2020).

5.4 Biomass-to-Jet via Fischer-Tropsch or Methanol Synthesis

The biomass-to-jet is pathways have reached is at commercial pilot level maturity (World Economic Forum 2020) and it relies on cellulosic feedstock from agriculture, forestry or energy crops. In addition, it can gasify municipal. They rely on cellulosic feedstock from agriculture, forestry, energy crops and can also use municipal solid waste or biogas plant digestate, which some companies are pursuing working on. Unlike HEFA, the BtJ is pathways can benefit from more abundant feedstocks, as lignocellulosic wastes and residues. However, the supply chains to collect these feedstocks are challenged by the unevenly distributed availability of resources, the poor collection potential of large amounts of sustainable feedstock, and not the least, the concurrent use of biomass for energy and non-energy purposes.

The BtJ pathways rely on the thermal gasification of biomass. This is a high-temperature chemical process placed between combustion and pyrolysis. While combustion requires oxygen and pyrolysis requires an oxygen-free environment, gasification requires only a partial oxidation of the biomass. It produces a raw producer gas: a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, water and other impurities, depending on the properties of the process and feedstock. The producer gas must be cleaned and adjusted to a mixture containing hydrogen and carbon monoxide in a stoichiometric ratio of 2 for methanol production (Danish Energy Agency, 2017) and slightly higher than 2 for Fischer-Tropsch (Korberg, 2021).

In the methanol route, the syngas mixture is converted to raw methanol in a synthesis unit to raw methanol. Then, the raw methanol is dehydrated to methanol. In the next steps methanol is converted to jet fuel, which consists of several steps, as olefin synthesis, oligomerization and hydrotreating.

In the case of Fischer-Tropsch, the syngas is converted to a range of liquid hydrocarbons that can be optimized to produce more jet fuel along with other by-products as diesel, naphtha, alcohols or gases.

The pathways have a lower expected conversion rate to jet fuel than HEFA, with up to 45-50% of the biomass to be converted to jet fuels, depending on the efficiency of the gasifier, the moisture level of the biomass and the selectivity to jet fuel. On the longer term, with more optimized production the efficiency may increase, although this is not reflected in the calculations made for this report (Skov & Abid, 2024).

5.5 Alcohol-to-Jet via cellulosic ethanol

Alcohol-to-Jet route is a fuel production pathway at a commercial pilot level (World Economic Forum, 2020). The main input to the conversion is C_2 to C_5 alcohols, either as single or in combination between these alcohols, such as ethanol, butanol or isobutanol (Wei, et al., 2019). The alcohols can be obtained from the fermentation of different sources of biogenic or non-biogenic origin, with ethanol as the most common intermediate. Traditionally, ethanol is produced from food crops as corn, wheat or sugar cane, also known as the 1st generation ethanol. Non-food based sources are also sought nowadays in the form of cellulosic feedstocks from agriculture, forestry or purposely-grown energy crops and are the focus in this report.

The pathway can therefore be split into two components, namely ethanol production from fermentation and jet fuel production. Biogenic ethanol production generally has a low energy efficiency, where only up to 30-40% of the energy in biomass converts to ethanol (Danish Energy Agency, 2017).

The AtJ route is one of the few certified pathways to 50% blending by ASTM. It is a less complex pathway, with fewer conversion steps than the other bioSAF routes. It involves the dehydration of ethanol to ethylene and then the oligomerization to desired yields. The conversion is however more efficient, where about 50-60% of the ethanol can be converted to jet fuel. In total, this can stand for yields of about 20% feedstock to jet-fuel, making it the most biomass-intensive pathway among the five described in this chapter.

5.6 Power-to-Jet via Fischer-Tropsch or Methanol Synthesis

The two PtJ pathways that are currently in development share similarities with the BtJ route, with the exception that the syngas mixture comes from electrolysis and carbon capture. Unlike the BtJ pathways, the PtJ pathways have the potential to meet larger parts of the jet fuel demands if they can access low-cost large-scale wind or solar production, making them less constrained, in theory, by feedstock availability unlike the biomass-based routes. On the other hand, access to enough carbon can often be a limitation in the deployment of such plants.

The carbon can originate from various sources at different costs and energy intensities. Current common sources are industrial flue gas from industry, power and heat production, cement factories, biogas methanation plants or in general any other point source which allows for capture of CO_2. Direct air capture (DAC) is another alternative in the longer term, although the costs and energy intensity of this process can make it less attractive for producing cost-competitive eSAF.

The hydrogen component should originate from renewable energy sources, such as wind or solar. An electrolyser converts the electricity and water into hydrogen. Various types of electrolysers exist, such as alkaline electrolyser cells (AEC), proton-exchange membrane electrolyser cells (PEMEC) and solid oxide electrolyser cells (SOEC). The different types operate at various efficiencies ranging from 50% (electricity-to-hydrogen) and upwards, depending on the technology and system setup.

The PtJ pathways are still in development and face challenges, among others the access to large amounts of low-cost renewable electricity, water and suitable carbon sources. Moreover, there is a challenge of making a mix of components as fluctuating electricity production, electrolysis, and a high-temperature Fischer Tropsch work as a whole from an economic and technological perspective.

Fischer Tropsch pathway has been used for several decades in combination with coal gasification and the jet fuel from this pathway is already certified, giving more certainty to future producers. On the other hand, jet fuel from methanol is in process of being approved and is an international commodity with multiple applications in the chemical sector or shipping sector, which also finds it a promising solution for decarbonize shipping (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021).

In Denmark, notable PtJ projects are Arcadia eFuels and Fjord PtX, both of which are planning to use the Fischer Tropsch pathway. On the methanol side several companies are working on first of their kind plants, to be ready by the end of the decade, such as Metafuels Aerobrew in Denmark and ExxonMobile Methanol-to-Jet Fuel technology.

In general, producing any kind of hydrocarbons (including eSAF) from CO_2 and water is an energy intensive process. In optimized plants using carbon captured from a point-source, around 35% of the electricity used in both pathways will end up as jet-fuel. Some sources find the efficiency of the Fischer Tropsch pathway significantly lower at 18% electricity-to-jet fuel efficiency (World Economic Forum, 2020), while other reviews find this pathway to be 42% efficient, with potential to reach 50% efficiency with future technology development (Skov & Abid, Renewable Aviation e-SAF Catalogue and System Impacts, 2024).

5.7 Power-and-Biomass-to-Jet via Fischer Tropsch or Methanol Synthesis

Carbon capture can be replaced by biomass in a hybrid setup that mixes biomass gasification and hydrogen enhancement so that all carbon in biomass is converted to SAF, unlike biomass gasification alone, which cannot make use of all carbon in the biomass. These routes can apply to both the Fischer Tropsch and Methanol pathways, with two main advantages: avoiding the need for an external carbon source to the plant and less electrolytic hydrogen to achieve the same effect, because a significant share of hydrogen can be sourced from biomass. Such hybrid solutions are more carbon-efficient and electricity-efficient per unit of fuel produced compared to their bioSAF and eSAF counterparts (Aviation Impact Accelerator, 2024). On the downside, such a combined pathway would have to deal with the combined challenges specific to the pathways described for BtJ and PtJ.

Like all SAF production, the combined energy efficiency still remains low however, sitting in between BtJ and PtJ pathways, with around 40% efficiency for electricity and biomass to SAF. Same as with the BtJ and PtJ routes, there is potential for efficiency improvements.

5.8 Insights into the proportions of SAF demands

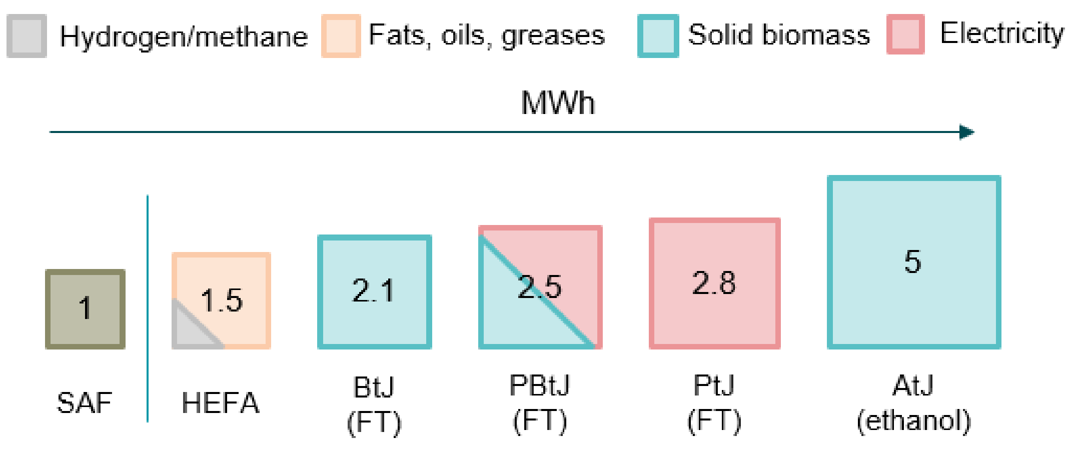
The current global annual demand for aviation fuel is approximately 300 Mt of kerosene. This is the equivalent of about 4,000 TWh of energy and the future growing aviation sector demand is expected to increase twofold. If this demand shall be meet by PtJ alone, it would need about 24,000 TWh of electricity. To put that into perspective, the current global renewable electricity generation is about 9,000 TWh (IRENA, 2024).

Therefore, the replacement of the existing jet fuels with SAF will incur major sustainable feedstock demand - feedstock that is currently used for different purposes (e.g. biomass for combustion, chemical industry or agriculture), are collected in a fragmented manner, or currently do not exist yet in sufficient quantities (such as solid biomass or electricity for green fuel production).

The production of SAF is and will remain an energy intensive process, subject to significant losses because the energy in biomass or in electricity must be converted in multiple steps to chemical energy, i.e. high-density liquid fuels that can live up to the quality requirements of the aviation industry.

Figure 18 intends to show input (MWh) needed to produce 1 MWh of SAF through each of the five production pathways described above. It shows that the HEFA route requires moderate amounts of feedstock, making it the most efficient production route. However, the necessary feedstocks for producing HEFA are also the scarcest among the pathways investigated here.

Figure 18 Energy consumption and feedstock type for the production of 1 MWh SAF



The BtJ pathways are the next most efficient routes. They require at least double the energy in feedstocks to produce the equivalent unit of jet fuel. The PtJ routes are considerably more energy intensive, at a factor of 3, but the hybrid option that combines the two pathways into PBtJ finds itself in between, with less biomass and electricity demand than the BtJ and PtJ pathways.

Finally, the AtJ remains the most energy intensive route when accounting for the whole value chain, since ethanol is not a feedstock, but the product of a fermentation process from biomass or other resources. If taken separately, the AtJ process lies between HEFA and BtJ, estimating that it requires 1.8 MWh of ethanol to produce 1 MWh of jet fuel.

Based on the assumptions found in Annex I starting from primary feedstock (electricity is assumed to come from wind or solar). HEFA requires hydrogenation and refining similar to a fossil fuel refinery, hence the additional 20% on top of the main feedstocks. The BtJ, PBtJ and PtJ pathways reflect the Fischer Tropsch route, although the amount of energy consumed would be similar to the methanol route. The PBtJ via methanol has a higher proportion of biomass consumption than electricity, although the total primary energy demand is similar. The AtJ route uses bioethanol, which in turn is produced from solid biomass (primary feedstock).

5.9 Quantitative analysis for EU and international demands

None of the described SAF routes alone can replace all jet fuel used today in aviation, even less when with the expected doubling of the fuel demands by 2050. This also means that there will be a mix of technologies and production routes in the future.

The assessment below aims to provide a perspective over the needed resources if only 50% of the current aviation demands would be replaced. More specifically, 50% of the EU aviation demand represents approximately 23-24 Mt of SAF, while 50% of the global demands represent approximately 164 Mt of SAF (figures representative for 2019, assuming the aviation demand remains the same). The table below provides the answer to the following question:

Can any of the proposed SAF pathways cover 50% of the EU and global SAF demands?* If yes, what is the impact on resources?

*Relative to 2019 jet fuel demand. In the future, this demand may double.

Table 7 Comparison of the feedstock availability of the various SAF production methods and whether these are able to cover 50% of EU and global demand respectively.

	Can it cover 50 % of EU demand?	Can it cover 50 % of Global demand
HEFA	**No**, it can only cover limited amounts. Up to 10% can be supplied by 2030, potentially marginally more by 2050 (SkyNRG, 2024)	**No**, it can only cover limited amounts. Up to 5% by 2030 and around 10% by 2050 (SkyNRG, 2024)
BtJ	**Yes**, there is a need for about **110 Mt of dry biomass.** Total EU biomass supply for all uses suitable for this pathway in a conservative scenario is	**Yes**, there is a need for about **800 Mt (15 EJ) of dry biomass.** A conservative global biomass supply for all uses is estimated at

	estimated at 400 Mt (Soler, Alba, 2022).	50 EJ (Aviation Impact Accelerator, 2024).
PBtJ	**Yes**, there is a need for about **50-70 Mt of dry biomass** depending on the choice between methanol or Fischer Tropsch routes and **70-80 GW of offshore wind** (with capacity factor 55%, and electrolysis at 62% LHV). As reference, the Esbjerg declaration targets 65 GW offshore wind by 2030 (Ministry of Climate, Energy and Utlities, Denmark, 2023).	**Yes**, there is a need for approximately **500 Mt (7-8 EJ) of dry biomass** depending on the choice between methanol or Fischer Tropsch routes and **550-650 GW of offshore wind** (with capacity factor 55%, and electrolysis at 62% LHV). As reference, the global installed offshore wind capacity in 2023 is 73 GW (IRENA, 2024).
PtJ	**Yes**, however it would require about **170 GW offshore wind** (with capacity factor 55%, and electrolysis at 62% LHV). As reference, the Esbjerg declaration targets 150 GW offshore wind by 2050.	**Yes**, however it would require about **1,200 GW offshore wind** (with capacity factor 55%, and electrolysis at 62% LHV). In 2023, the global installed capacity was 73 GW offshore wind (IRENA, 2024).
AtJ	**Yes**, however this requires **260 Mt or 5 EJ of dry biomass.** Total EU biomass supply for all uses suitable for this pathway in a conservative scenario is estimated at 400 Mt (Soler, Alba, 2022).	**Yes**, however this requires **1,800 Mt or 35 EJ of dry biomass**. A conservative global biomass supply is estimated at 50 EJ (Aviation Impact Accelerator, 2024).

Despite the apparent sufficiency of cellulosic biomass for the pathways presented above, biomass consumption in bioSAF is underpinned by two important considerations:

1. **Biomass is limited** and it is based on the collection of different types of waste biomass in specific geographical areas. Overall, the availability could be higher with improved collection or with additional energy crops.
2. **Multiple sectors compete for the same biomass** - even in efficient scenarios with high levels of electrification, biomass is still necessary for sectors as shipping, chemical industry, wood products, pulp and paper. That also means that aviation is just one of the sectors that can tap into it.

Furthermore, an aviation sector based primarily on eSAF would take an extraordinary renewable capacity buildout to cover even 50% of the current jet fuel demands (without considering that future jet fuel demand will increase), or even more if offshore wind is replaced by onshore wind or photovoltaics due to their lower capacity factors. Same as with bioSAF, such a buildout will likely face economic, technical or environmental challenges in a green transition where all sectors require more renewables. Beyond that, capturing enough biogenic carbon (another limited product), transporting, storing and ensuring a suitable flow in price optimized PtJ plants will add another layer of challenges.

None of the pathways presented is challenge-free. BtJ solutions for bioSAF require large amounts of biomass with streamlined collection, while eSAF from PtJ requires abundant electricity synchronized with suitable carbon supply. The hybrid PBtJ solutions can solve some of the issues regarding the effective use of carbon in the biomass (that BtJ alone cannot) and an extreme renewable capacity buildout (since a large share of hydrogen can come from biomass), but it will also share the challenges of both pathways.

The table below summarizes the advantages and disadvantages for the pathways presented in this report.

Table 8 Approximate technological maturity of SAF pathways.

	HEFA	BtJ	PBtJ	PtJ	AtJ
Technology maturity					
Scaling potential					
Energy efficiency					
Carbon efficiency					
Production cost					

5.10 Regulations regarding SAF

For a fuel to be recognized as a sustainable aviation fuel by International Civil Aviation Organization, ICAO, it must both live up to some technical specifications as well as specific sustainability criteria.

ASTM International provide a set of technical specifications for aviation fuels outlined in ASTM D1655 and ASTM D7566. Other technical specifications include DEF STAN 91-091 and CTSO-2C701. ASTM are not responsible for the definition of the fuel sustainability, but rather for the chemical properties of any given SAF.

For a fuel to be recognized as sustainable, it must live up to some standards outlined in *ICAO International Standard and Recommended Practices – Annex 16 to the Convention on*

International Civil Aviation, Volume IV Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and its related documents. This includes requirements to the feedstock, production pathway and transportation when it comes to both carbon emissions, environmental considerations and socio-economic aspects. One important criterion that must be met for a SAF to be CORSIA certified is that the net greenhouse gas emissions must be reduced by at least 10%. This is compared to the emission of conventional aviation fuel on a life cycle basis and is defined as 89 gCO_2e/MJ (CORSIA, 2022).

The ReFuelEU Aviation (European Commission, 2023) also defines SAF with sustainability criteria and limits for cradle-to-grave emissions for e.g. eSAF. ReFuelEU applies to all fuel delivered to EU airports and the same definitions apply in the EU ETS Aviation.

5.10.1 Technical specifications

Jet A1 and Jet A are both used for civil aviation, however Jet A is predominantly used in the United states (Oldani, Solecki, & Tonghun, 2022). Conventional Jet A1 and Jet A fuel are regulated by ASTM Internationals Standard Specification for Aviation Turbine Fuels, D1655. As the chemical composition of fossil jet fuels vary depending on the hydrocarbons from which it is refined, the specifications are primarily focused on fuel properties such as volatility, fluidity, combustion properties and thermal stability. However, maximum amounts of sulphur, potassium hydroxide, and aromatics are also included in the standards, with the maximum aromatic allowed content being 25% (v/v).

Like any other jet fuel, SAF is also regulated under ASTM International Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, D7566, which covers fuel-blends of conventional and synthetic components. The fuel requirements are in most cases identical to those of unblended conventional fuel, however, a minimum level for the aromatic content of 8 % (v/v) is included, as most SAF is characterized by a lower sulphur and aromatic content than fossil-based jet-fuel. This is also the reason that 100% SAF is not allowed in aircraft today and all SAF must be mixed with conventional aviation fuel before use.

Aromatics are known to help seals in the aircraft fuel and piping systems swell and soften as well as provide lubrication. The minimum content of 8% (v/v) has therefore been introduced for safety reasons to ensure functionality of the seals. However, some newer engines have sealings which are not dependent on aromatics to stay intact (Faber, Király, Lee, Owen, & O'Leary, 2022).

5.11 Approved pathways and blends

Currently, 11 different conversion processes have been approved by the ASTM and are thus qualified for commercial use and 11 others are in the certification process, including methanol-to-jet.

The 11 existing conversion processes are illustrated in Figure 17. Most can be blended with conventional fuel in ratios up to 50% (v/v). The remaining processes are so-called co-processing methods meaning that the alternative feedstock is processed and refined together with conventionally sourced hydrocarbons. These are defined in ASTM D1655 and have maximum blend ratios of 5-10% (v/v) in the product.

The 11 new conversion processes including the work on increasing the co-processing blend ratio are:

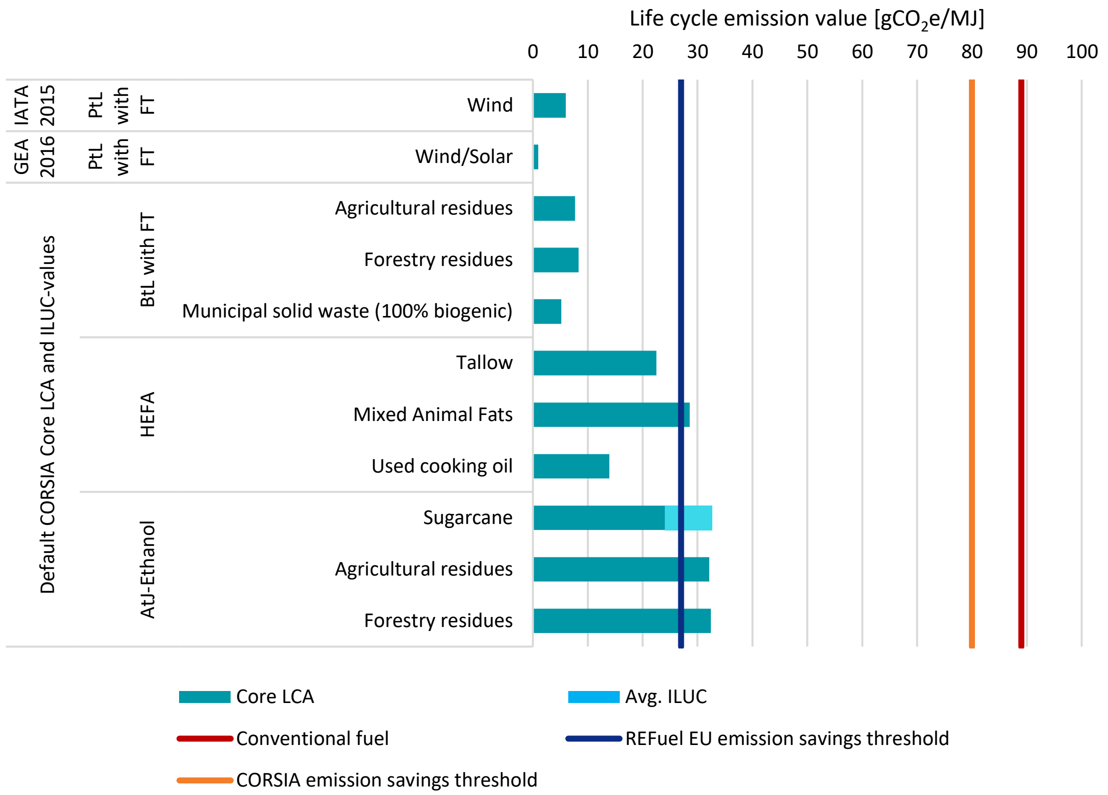
- Methanol-to-Jet
- Increase in fatty acid/ester co-processing from 5% to 30%
- Biomass pyrolysis
- Biomass/Waste pyrolysis
- Pyrolysis of non-recyclable plastics
- Co-processing of pyrolysis oil from used tires
- Integrated hydropyrolysis and hydroconversion
- HEFA with higher cycloparaffins
- Synthetized aromatic kerosene
- Cycloalkanes from ethanol
- Single Reactor HEFA

Work is also being done to allow using 100% SAF in aircraft as this possibility would be easiest achievable for blending components already containing aromatics (ICAO, 2024b).

5.12 Environmental aspects of SAF

From a lifetime perspective, SAF generally benefit from lower carbon emissions. This goes for both bioSAF and eSAF. Additionally, all SAF can also help mitigate negative non-CO_2-effects, as they often have a lower content of aromatics.

Figure 19: Life cycle emissions values for different SAF-pathways and feedstocks broken down by Core LCA and ILUC value. If multiple places of production are listed in 'CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels' (ICAO, 2024), an average ILUC value is used.



5.12.1 CO_2-reduction potential

In order to deem SAF as sustainable, fuels must meet a criterion for a certain level of CO_2 emission reductions compared to conventional jet fuel, benchmarked by CORSIA at 89 g CO2/MJ. According to the same scheme, a net greenhouse gas reduction of minimum 10% is required for a synthetic aviation fuel to be certified as sustainable, while the EU has a much higher threshold in its Refuel EU regulation, where SAF must have at least 70% emission savings (European Commission, 2023). The emission reduction is determined by calculating a Life Cycle Emission value that includes both a core LCA[14] value and an ILUC[15] value (the EU excludes fuels with ILUC). For the different processes, the emission-reduction potential will depend on the feedstock used and the place of production, both of which can have an impact

[14] LCA: Life cycle assessment (Life cycle analysis). An assessment of the environmental effects of a product throughout its entire lifecycle.
[15] ILUC: Induced land use change (Indirect land use change). Accounts for potential emissions from the displacement of food of feed production as a result of land use for crops grown for biofuels or energy.

on the ILUC value. In Figure 19: Life cycle emissions values for different SAF-pathways and feedstocks broken down by Core LCA and ILUC value. If multiple places of production are listed in 'CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels' , an average ILUC value is used.Figure 19, the life cycle emission value based on default CORSIA Core LCA and ILUC-values can be seen (ICAO, 2024). Generally, gasification with Fischer-Tropsch and have better reduction potential than both HEFA and AtJ. For e-SAF, the emission reduction is expected to be close to 100% or even above, depending on the source of CO_2 (Skov & Abid, 2024; IATA, 2015; Schmidt & Weindorf, 2016; IATA, 2015; Agora Verkehrswende, 2024).

5.12.2 Non-CO_2 effects

Due to the different feedstocks and production pathways, most SAFs are characterized by lower levels of sulphur and practically no aromatics. This gives SAF the potential to help mitigate non-CO_2 effects. When burning conventional fuels, typically with an aromatic content of 12-20%, an incomplete combustion takes place resulting in the emission of not just CO_2 and water, but also other harmful compounds such as NOx, SOx, and soot particles (Faber, Király, Lee, Owen, & O'Leary, 2022). Emission of the latter is associated with formation of contrails and cirrus clouds which occur when water vapour condenses on the particles and freezes to ice crystals (Dyk & Saddler, 2024). A lower aromatic content of the fuel has the potential to result in smaller soot number concentrations. This consequently results in fewer, but larger, ice crystals which is essentially modelled to reduce the Effective Radiative Forcing (ERF). Studies by NASA[16] and DLR[17] have found the soot number reductions when using SAF blends with lower aromatic concentrations to be 45-53% for HEFA and ~50% for Fischer Tropsch fuel, resulting in 45-74% lower ice crystal emission indices (Voigt et. al., 2021).

However, as previously discussed, a minimum level of aromatics in SAF fuel blends of 8% (v/v) is required to ensure safety, as it is essential for the seals to stay intact.
Some sustainable aviation fuels have added aromatics in their compositions. This could potentially ease the path to allow 100% use of these specific SAFs in existing aircraft, however, the reduction of non-CO_2 effects would be lower than for SAFs with no aromatics. To use SAF with no aromatics unblended, new seals that do not require aromatics for swelling would be required, which will, nevertheless, still take time before all aircraft globally can support this (Dyk & Saddler, 2024).

[16] NASA Langley Research Center
[17] Deutsches Zentrum für Luft- und Raumfahrt

6 Battery electric aircraft

6.1 Introduction

Electric aviation has become an important area of research lead by the fast growth of the aviation industry coupled with the growing need to reduce CO_2 emissions. Electrification of aircraft is subject to projects ranging from small start-up companies to the largest legacy companies in the industry. The feasibility of electric aviation is not yet fully covered and the development of this technology is still pre-commercial.

Electric propulsion does show promising potential for emission reductions, but they face severe limitations, only truly relieved through significant advancements in batteries.

At the time of writing, just one electric fixed wing aircraft model is certified by EASA – the Pipistrel Velis Electro, which can be seen in Figure 20.

EVTOLs

Electric vertical take-off and landing (EVTOL) aircraft, covering a variety of different types of small aircraft, are somewhat closer to markets and have the potential for introducing all new electric applications in aviation enabling completely new airborne services and all new transport patterns. These are, however, not expected to replace any significant shares of existing passenger air travel demand.

Figure 20 Picture of a Pipistrel Velis Electro (Pipistrel, 2024) .

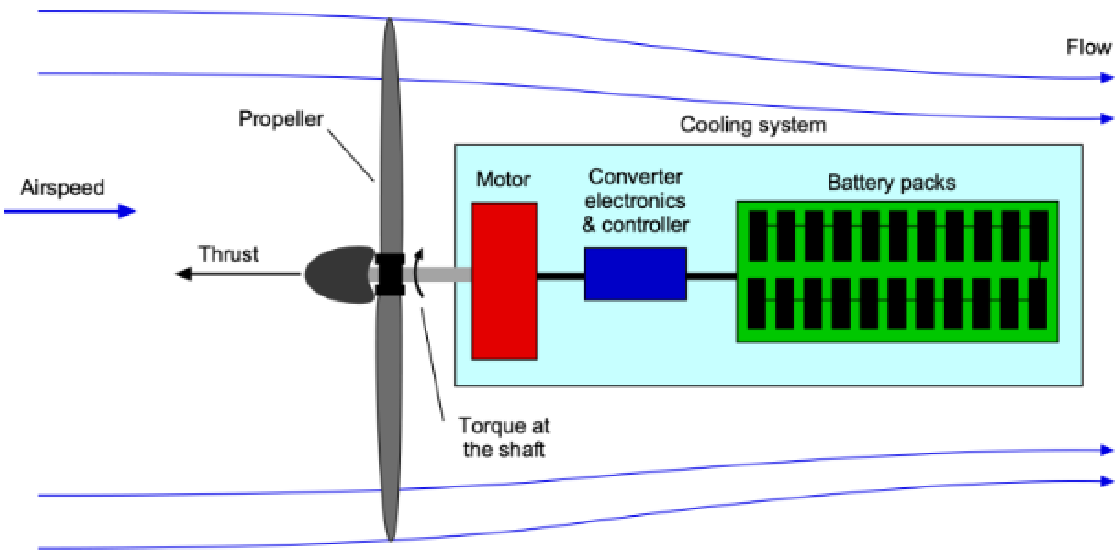
This model is a small two-seater aircraft mainly intended for pilot training with a battery capacity sufficient for up to 50 minutes of flight. Due to its intended use and small size, this aircraft has no relevance to commercial aircraft designed for passenger transport (EASA, 2020a). But this electric plane is the first example of an approved electric aircraft. As such it can be a step, in building experience with regulation and approval processes.

Several companies like e.g. Heart Aerospace and Elysian are working on developing electric passenger aircraft, aiming at 19-90 seat capacities, with an aim of servicing regular passenger flights. EASA expects to certify several electric aircraft in the future, with the earliest models with relevance for commercial use, set to reach markets before 2030 (EASA, 2020a). Vitally, the size and seat capacities of these aircraft are significantly lower than the conventional alternatives, at around 19-30 passengers. The Achilles heel of battery electric aviation is the required energy demand onboard the aircraft. Accordingly, it is necessary to recognize the physical and technical limitations imposed by the battery technology, when analysing the near- to medium term technical potential in aviation.

6.2 Propulsion

Battery electric aircraft rely on electric motors to rotate propellers or fans to generate thrust, with batteries as the source of energy. An example is illustrated in Figure 21.

Figure 21 Example of an electric propulsion system based on a simple propeller setup (Embry-Riddle Aeronautical University, 2024c).



As shown in the figure, thrust is solely generated from the propellers and hence shares conceptual traits with the propellers of a conventional turboprop. As there is no combustion process there is also no exhaust to generate additional thrust, as is the case of the turbofan or, to a lesser degree, the turboprop engine (Embry-Riddle Aeronautical University, 2024c).

A great advantage of electric motors is their inherently high energy efficiency, with efficiencies of the motor of more than 90%. This introduces a significant improvement over corresponding efficiencies of modern combustion aircraft engines aircraft (Leishman, 2023).

From a technical perspective, the technology of electric motors is well understood and the motors are not a limitation in terms producing sufficient thrust (Embry-Riddle Aeronautical University 2024a). Electric motors are weight-efficient due to their high power density. The power density of current state-of-the-art electric motors is 5-7 kW/kg – but start-ups like

Wright electrics or H3X are working on new motors with between 16-19 kW/kg making them much more power dense than piston or turboprop engines – with typical designs spanning around 1-5 kW/kg. The higher values compared to modern liquid fuelled engines, meaning the electric motor provides more power output per weight (Embry-Riddle Aeronautical University, 2024c).

Comparing electric propulsion directly with a turbofan is more complicated (than comparing it to a turboprop) as the force of the turbofan is measured in thrust – e.g. a force measured in kilo newtons (kN), and not as a shaft power (kW). Even though electric motors for stationary or marine use can be scaled to very significant power levels, they are less relevant when compared to turbofans used on large aircraft. Turbofan jet engines typically operate with very high thrust capacity. Current energy density of batteries makes electric aircraft unable to achieve this amount of thrust for a sustained amount of time.

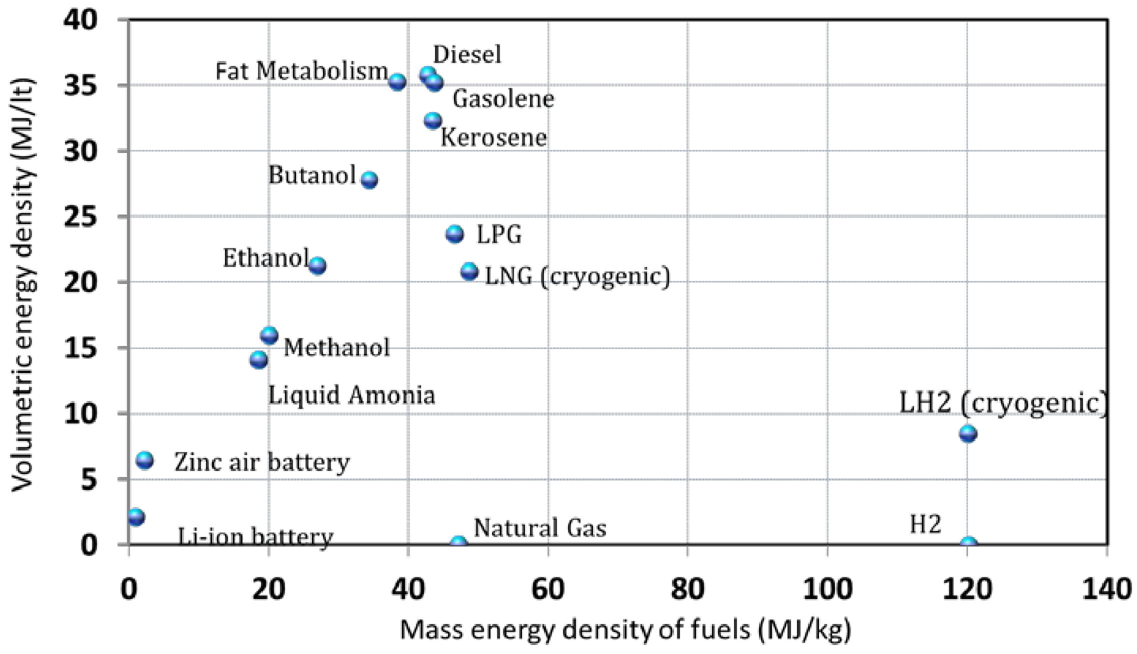
In addition to the high energy efficiency of the electric motor itself, the lightweight and the possibility for more compact and lighter designs of the airframe e.g. pylons, reduces drag of the aircraft and therefore further contributes to reduce energy consumption.

6.3 Battery energy storage

As mentioned, the primary hindrance for the viability of battery electric aircraft is the low energy density of batteries, making their designs heavy and bulky, compared to energy stored as liquid in a fuel tank.

Jet fuel or kerosene has an energy density of around 43 MJ/kg. Figure 22 indicates how li-ion batteries compare to other energy carriers, when plotting the gravimetric and volumetric energy densities of different energy carriers.

Figure 22 Energy density of different fuels, plotted as MJ/L (y-axis) and MJ/kg (x-axis) (Rao, 2015).



As shown, both weight and volume of batteries are very high, relative to the energy volumes they hold. Even with electric propulsion being inherently more energy efficient compared to combustion engines the lower energy density is a deal breaking barrier for widespread electric applications in modern commercial aviation.

The aspect of the weight penalty of batteries is further worsened by the fact that the weight of batteries is constant throughout the flight. In contrast, when conventional aircraft travel, they become lighter as they burn fuel – hence significantly lowering the weight of the aircraft and, hence, the fuel consumption. This is important as maximum landing weight (MLW) for a modern aircraft is significantly lower than its maximum take-off weight (MTOW) e.g. the Boeing 737-7 has a MTOW of 82 tons and an MLW of 69 tons (Boeing, 2019). The difference between MTOW and MLW is a design choice that balances the aircraft's operational needs, structural integrity, and regulatory requirements to ensure safe and efficient flight operations. Accordingly, the whole design and engineering of the aircraft takes advantage of the weight reduction during flight, and the difference ensures that the aircraft can land safely without causing excessive stress on the landing gear, brakes, or airframe, maintaining the safety and structural integrity of the plane (Pilotinstitute, 2024). A battery electric plane design must compensate for its constant weight, in this regard.

Researches have modelled a series of optimized 180-passenger aircraft based on the Airbus A320neo configuration, evaluated them at 200–1,600 NM, relying on batteries with energy densities ranging from 400-2,000 Wh/kg. They compared them to advanced conventionally-powered aircraft. They found that a factor of four increase in battery pack specific energy from initial values of 200 Wh/kg to 800 Wh/kg would enable 500 NM flights (926 km) (Gnadt, Speth, Sabnis, & Barrett, 2019). Consequently, design aspects such as long-distance range, large airframes with high payload/passenger capacities and high speeds are not technically feasible with current battery technology.

The more near-term appliance of electric aircraft is instead, presently, restricted to specific use-cases revolving around smaller planes, with relatively small payload capacity, shorter range and lower speeds. An important path for battery-powered commercial airliners would therefore be to deploy them strategically, based on applications where the electric range is sufficient. As described in 2.2.2, there are significant flight emissions originating from flights shorter than 1,000 km, where some routes could potentially be electrified.

The largest fully electric or hybrid aircraft that are known to be under development, have passenger carrying capacities around 9-30 passengers. Comparing a fully electric plane (Alice) to the ES-30 (hybrid electric) can indicate the compromises required to allow for fully electric flight even for medium distances.

Table 9 General technical values for Alice (fully electric) and ES-30 (hybrid) (Heart Aerospace, 2024; Eviation, 2024; Lambrecht, 2023).

Model	Alice	ES-30
Development status	On-hold [18]	Ongoing
Electric/hybrid	Fully electric	Hybrid electric
Passenger seats	9	30
Motor power output (kW)	2 x 700	N.A.
Battery size (kWh)	900	N.A.
Range (km)	463	200 (electric) 400 (hybrid)
Battery weight (kg)	3,600	N.A.
Expected release year	2027 (development on-hold)	2029

As both aircraft in the table are under development, a full insight to their final technical details are not yet publicly available or finally determined. The table is primarily an indication of the parameters announced, highlighting the limited size imposed by current battery technology.

Lithium-ion batteries are the standard battery-type within electrified transport today (Fraunhofer, 2023b). But the theoretical limits on energy density for the commercially available batteries are not sufficient to let battery-electric planes replace even smaller conventional jets. The large OEMs of the EV-industry have estimates following energy densities of their batteries, in this decade (Fraunhofer, 2023a).

[18] As of February 2025, this project was put on-hold and the majority of staff was laid off, due to lack of funding (Ostrower, 2025).

Table 10 Expected energy cell-level densities for lithium ion batteries reached within this decade, as communicated by OEMs.

Energy density	2025	2030
Wh/kg	300 – 350	350 – 400
Wh/L	700 – 800	800 – 1000

The values in Table 10 set a benchmark as to what can be expected from the existing battery technologies. And while developments will allow for longer range light- and heavy-duty vehicles, it will still be a limiting factor on the application of electric aviation. Even for flights of a couple hundred kilometres, an energy density of more than 300 Wh/kg is required (Fraunhofer, 2023a). In recognition of the challenge of energy density of current batteries, NASA is one of the actors developing a solid-state battery with the aim of achieving 500 Wh/kg (Gould, 2022).

New battery types are under development. Advancements in battery technology, including the development of solid-state batteries but also other high-density energy storage solutions, are expected to significantly increase energy density of batteries. While raising interest due to their technological promises compared to current commercial battery technology, they are still in the development phases. It is yet uncertain which of the future battery technologies may be the best fit for aviation.

6.3.1 Cell-level and pack-level energy density

Understanding the distinction between cell energy density and pack energy density is crucial for evaluating the performance and feasibility of battery systems.

Cell-level energy density refers to the amount of energy stored (kWh) across cells (either litres or kg). As such, the cell-level perspective does not take the packaging and the full battery weight into account. Rather, this approach can determine the actual energy density of the cells, which has a justified use, especially when measuring advancements in the battery industry.

When batteries are applied the cells are assembled into a battery pack for a specific use, and this is why the pack energy density becomes the defining parameter, when measuring the actual energy density of an aircraft battery. Pack energy density considers the additional components such as the battery management system (BMS), cooling systems, structural elements, and other necessary electronics. These components add weight and volume, reducing the overall energy density of the pack compared to the energy density of cells alone. While increasing cell-level energy densities does improve pack-level energy density, these two distinctions should not be confused.

6.3.2 Battery charging & battery swapping

The energy for battery electric flight is supplied through charging. However, battery electric aircraft require significant charging capacities, and the charging has to be available at the airport.

Current electric aircraft designs rely on the CCS[19] charge plug providing charging capabilities of up to 350 kW (Bernard, Tankou, Hongyang, & Ragon, 2022). While this this charging rate is more than the majority commercially available light-duty-vehicles in road transport are able to support, it does limit the charging times for larger applications within heavy duty transport, where significantly larger battery packs must be charged – and often over short charging durations. Therefore, more potent charging options are required, surpassing current charging rates of 350 kW for larger vessels, such as aircraft. This development is already well underway, as electric transport modes both on land, sea and in the air demand higher charging rates, shown in Figure 23.

Figure 23 New charging systems under development and close to commercialisation (Bernard, Tankou, Hongyang, & Ragon, 2022).

Standard name	Organization(s) in charge	Market	Max voltage and amperage	Maximum power	Timeline	Compatibility
ChaoJi	China Electricity Council and CHAdeMO	First used in China and Japan	1,500V and 600A	900 kW		Backward compatibility with all current global standards.
MegaWatt Charging system (MCS) CharIN	Industry Task Force set up by CharIN	Europe and North America	1,250V and 3,000A	3.75 MW	Pilot projects in 2023, planned commercialization in 2024.	Compatible with the CCS infrastructure.

The upcoming MCS (Megawatt charging system) will reduce charging times and expand the range of possible applications for electric aircraft. Whether a given aircraft is able to utilize the full potential charging capacity of 3.75 MW depends on a wide range of aspects, and may not prove more than sufficient for the smaller electric aircraft.

As an alternative to battery charging, battery swapping may also be a viable solution. Battery swapping is an approach where a depleted, rechargeable battery is replaced with a fully charged one. This requires a different setup at the airport, as large batteries will need to be transported all the way inside an aircraft, but it also changes and lessens the requirement for charging equipment to be situated at in a given proximity of the aircraft. This method can potentially reduce the turnaround time for aircraft compared to traditional charging, as charging rate, expectedly, will be of a lesser impact for the time-sensitivity of operation.

6.3.3 Range

The flight range of electric planes remains one of the largest challenges. This is due to the limitations on energy density for current battery designs. Current announced fully electric

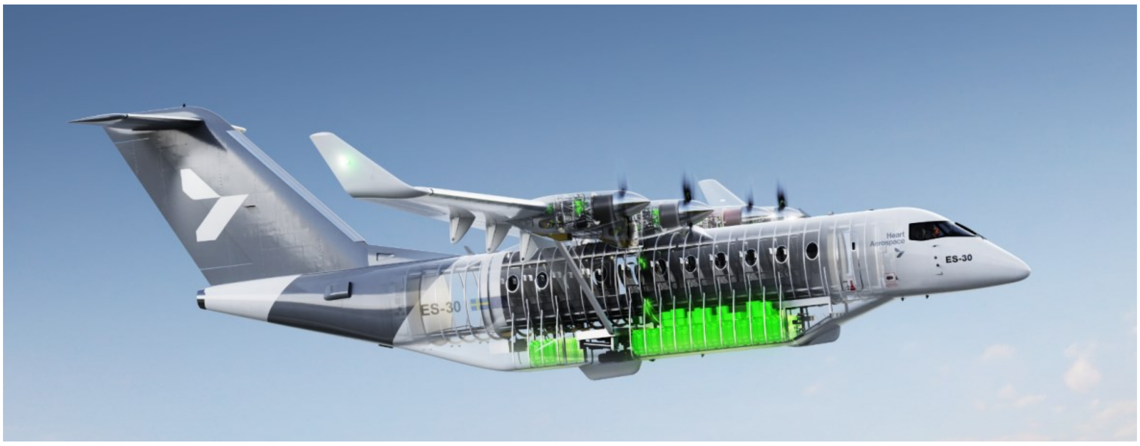
[19] Combined Charging System (CCS) is a widely adopted charging connector standard seen in both light- and heavy-duty electric vehicles. It supports both AC and DC charging for electric vehicles, though DC charging is required for high-speed charging.

planes have ranges of up to around 450 km[20] while hybrid solution offer a variety of ranges, largely depending on the share of mechanical energy delivered by electric propulsion.

6.4 Airframe

In electric planes, the airframe design undergoes significant adaptations to accommodate the unique requirements of electric propulsion systems. One of the most significant differences in the airframes of electric planes is the integration of battery systems. Due to the weight of batteries and space requirements, the electric aircraft airframes tend to be bulkier and heavier. An example of how the airframe integrates the battery can be seen on the ES-30, shown in Figure 24.

Figure 24 Battery storage placement (marked with green colour) on an ES-30. Animation credit: Heart Aerospace (2024).



The battery is located as low as possible. In addition, illustration also shows how the wings are attached through a high-wing concept on the fuselage, similar to the configuration on conventional turboprop aircraft.

6.5 Safety

In addition to the existing safety measures in aviation, some of the primary safety concerns specifically for battery electric aircraft revolve around thermal runaway (fire hazard) and safety-critical power supply. Batteries will, during their use-phase, be subject to degradation affecting total energy capacity, internal resistance, power fade and short circuits (Sripad, Bills, & Viswanathan, 2021). Therefore, a monitoring of the battery health is vital for safe operation. The two subjects are elaborated in the follow two sections.

6.5.1 Fire hazard

A central concern for batteries is their thermal stability. In case of a thermal runaway, a battery can cause a fire hazard, posing an alarming risk for an aircraft in flight. Therefore, fire hazards in batteries is a cardinal issue to regulate. In the past two decades, several cases concerning

[20] As seen for the electric aircraft 'Alice' (Eviation, 2024).

thermal runaway in lithium batteries being transported in the cargo compartment have let to both serious and even fatal accidents (Flight Safety Foundation, 2024).

Significant safety improvements may be achieved by the introduction of solid-state batteries. Without the liquid electrolyte, the fire hazards are decreased considerably, though without eliminating them entirely (Sripad, Bills, & Viswanathan, 2021).

6.5.2 Safety critical power supply and fuel requirement

The gradual degradation of batteries will be a subject of concern, in relation to effective range and ICAOs current legal requirements of “Alternate fuel” and “Final Reserve Fuel”. Alternate Fuel and Final Reserve Fuel refers to the additional quantity of fuel that an aircraft carries beyond the planned fuel necessary for completing a flight. This precautionary measure is carefully calculated to ensure an aircraft's ability to navigate unforeseen circumstances safely. Such scenarios include unexpected delays, diversions to alternate airports, or changes in flight conditions that could increase fuel consumption (GlobeAir, 2025).

These requirements add to the challenge of having sufficient amounts of energy stored on board. The gradual battery degradation of batteries affects force extra precaution and buffer-capacity and may imply careful surveillance and replacement might be needed regularly. It might also mean that different regulations will be needed for electric aircraft (Sripad, Bills, & Viswanathan, 2021).

6.6 Costs

The economic feasibility of electric aviation is still unknown, as the development of this technology at a pre-commercial stage. One expected benefit has been seen in other sectors where electric vehicles are introduced - the technology’s lower complexity, with fewer moving parts, helping to lower maintenance costs and low fuel costs.

Expectedly, the battery costs and scale-of-production of commercial electric plane airframes will reduce costs, compared to initial costs of the pilot projects within electric aviation.

BNEF estimated a weighted average of 115 USD/kWh (cell-level) in 2022 which is a significant price decrease compared to earlier cost levels. This is the result of more than a decade of significant cost-reductions. The tendency is expected to continue, meaning future battery costs will continue their decline. OEMs estimate cell costs (per kWh) and pack costs (per kWh) as shown in Table 11.

Table 11 Expected development in cell- and pack level costs per kWh li-ion batteries (Fraunhofer, 2023a).

	2023	2025	2030
Av. cell costs in EUR_{2020}/kWh	~120 €/kWh	~90 €/kWh	~70 €/kWh
Av. pack costs in EUR_{2020}/kWh	~150 €/kWh	~110 €/kWh	~80 €/kWh

This development points to lower expenses tied to the batteries, especially closer to 2030, when batteries on pack-level are cheaper and closer to cell level costs.

6.7 Climate and environment

The possibility of zero emission aviation of electric aircraft is the strongest argument for electric aviation. An important point is that this is not only the elimination of CO_2, assuming all charging of batteries is based on renewable energy sources, but also the complete elimination of high-altitude non-CO_2 effects (Gnadt, Speth, Sabnis, & Barrett, 2019). It also reduces the local air pollution of great importance to airports and ground personal. No alternative technology can compete with these technology strengths.

The stand-out component of an electric aircraft, in an environmental perspective, is the battery. LCA-perspectives will show different climate- and environment-impacts for different battery chemistries. Depending on the given battery chemistry being used in electric aviation will be of key relevance for the overall environmental footprint of the aircraft over its lifetime.

6.8 Hybrid electric aircraft

Hybrid-electric aircraft (HEA) setups rely on both liquid fuel and electric propulsion. This approach may turn out to be a promising technology, as it enables electric propulsion being applied on longer flights, compared to fully electric planes. The ES-30 by Heart Aerospace, is an example of a HEA. In order to maximize carbon reductions, the liquid fuel can be replaced with SAF. In this tech review, hybrid electric propulsion is not allocated a separate chapter. But the strengths and weaknesses of both the conventional fuels and the battery electric systems, can largely be extracted from the respective chapters on these subjects, indicating the potentials and challenges for hybrid-electric planes. This section briefly reflects the current state of hybrid-electric planes.

Several aircraft and engine manufacturers are working on concepts for hybrid electric aircraft, ranging from mild hybridisations, where the electric propulsion is designed just for the taxi-part of take-off and landing to concepts where the aircraft relies fully on electric motor propulsion but where batteries are coupled with range extending fuel combustion generators (serial hybrid solutions).

6.8.1 Example of a hybrid-electric aircraft in development

Heart Aerospace is currently developing the previously mentioned 30-seat hybrid-plane (ES-30) with propulsion from four sets of electric motors and propellers. Heart Aerospace has 250 aircraft in order, indicating a significant interest, but they are yet to be certified – which accordingly to their website is a target for 2029, where the plane is expected to be market-ready (Aerospace Global News, 2024). Additionally, the ES-30 has not completed a test flight cycle, but has recently been set to start on-ground testing followed by airborne testing, starting in 2025 (Military Aerospace Electronics, 2024).

The ES-30, if realised with the claimed technical specifications, will be able to serve shorter routes conventionally operated by conventional turbo-prop planes. A comparable turbo-prop plane, widely used, is the ATR-42, used to serve shorter regional routes. Table 12 compares technical aspects of the two plane types. A larger version of the ATR42 (the ATR72) has overtaken the ATR42 in active aircraft, indicating that the ATR42 and hence the ES-30 are smaller than current preferred designs.

Table 12 Comparison of the ES-30 and an ATR42, based on Heart Aerospace (2024) and ATR (n.d.).

	ES-30	ATR-42-600
Seats / passenger capacity	30	48
Range	200 km (fully electric), 400 km (hybrid)	1,345 km
Propulsion / engine	Electric motors (propellers)	Turbo-prop (propeller)
Wing span (meters)	32	24.6
Max take-off weight (kg)	N.A.	18,600 kg
Max landing weight (kg)	N.A.	18,300 kg
May payload (kg)	N.A.	5250 kg
Cruise speed (km/h)	350	535
Max altitude (feet)	20,000	25,000
Runway length (m)	1,100	890
Charging time (min)	30	-
Fuel capacity (kg)	N.A	4,500
Engine power (kW)	N.A.	2 x 1,800

* The ATR42 was originally designed for passenger 42 seats but has been modified in several designs, allowing for more seats.

The table shows the few available data for the ES-30 compared to specs of the ATR-42, but has 18 fewer seats and much shorter range in fully electric mode. According to Heart Aerospace, the expected battery technology improvements will increase range performance of the ES-30 (30 PAX) by mid-2030's to 300 km/500 km[21] and by late-2030's to 400 km/600 km (Heart Aerospace, 2024).

[21] 300/500 indicates 300 km fully electric range and 500 km hybrid range.

7 Hydrogen as aviation fuel

7.1 Introduction

Hydrogen holds potential to play a fundamental role in the transition towards zero emission aviation. Hydrogen can power electric motors through fuel cells or directly as a combustion fuel in gas turbine engines. The comprehensive FlyZero project led by Aerospace Technology Institute concluded that green hydrogen is the most viable path to zero carbon emission aviation, with the potential of scaling to large aircraft (Aygin, et al., 2022). This chapter describes the main characteristics of the two propulsion systems, their effects on aircraft design and the common challenges related to hydrogen as an aviation fuel.

Hydrogen is the smallest, lightest and most abundant element in the universe. At the same time hydrogen is rarely found naturally in its pure form (H_2) on Earth, since it is often bound in molecules, such as water (H_2O) (Bagarello S, 2024). Hydrogen is not a primary energy source, but rather an energy carrier. In relation to transition of aviation towards net zero emissions the primary energy source becomes important, e.g. hydrogen must be sourced from renewable energy generation, in order for it to be classified as 'green'. The use of hydrogen highlights the importance of the whole value chain, the demand from other sectors and the system energy efficiency.

7.2 Hydrogen – chemical and physical properties

The advantages but also the challenges for hydrogen as fuel for aircraft are closely linked to the basic chemical and physical properties of hydrogen.

Fundamentally, hydrogen is an energy carrier just like jet fuel, but unlike jet fuel, it does not contain carbon, and therefore causes no carbon emissions upon consumption in either a fuel cell or combustion engine.

Hydrogen has an extremely low boiling point at 20.28 K (- 252.9 °C). This physical trait introduces innate requirements to hydrogen storage. But even in a cryogenic liquid state, hydrogen has a low volumetric energy density holding only about 25% of the energy compared to the same volume of jet fuel. In other words, cryogenic hydrogen takes up 4 times more space than jet fuel, therefore demanding larger fuel tanks. Using compressed hydrogen at a pressure of 700 bar as an alternative to cryogenic liquid hydrogen requires even more space – more than 7 times the space of jet fuel (Jayant & Rutherford, 2022).

The zero carbon properties of hydrogen and the weight advantage means that hydrogen also has substantial advantages over jet fuel, holding nearly 3 times the energy per unit weight (Yusaf, et al., 2023). Hydrogen's zero carbon properties, and the weight advantage makes hydrogen a potential way of tackling the CO_2 emissions of aviation. But the properties of hydrogen like its flammability, storage requirements, and the need for advanced materials and cooling systems pose great engineering and economical challenges and involves major changes to the current design and technical configuration of aircraft. An overview comparing properties of jet fuel and hydrogen can be seen in the following table.

Table 13 Comparison of Jet fuel with cryogenic hydrogen in the context of properties (Yusaf, et al., 2023; Jayant & Rutherford, 2022).

Property	Hydrogen (Cryogenic)	Kerosene (Jet fuel)	Hydrogen/Kerosene
Density liquid (kg/m^3)	70.79	810.53	≈ 0.1
Melting temperature (K)	14.01	225-573	-
Boiling temperature (K)	20.28	423-573	-
Energy density (volumetric) kWh/m^3	2,359	9,637	≈ 0.25
Energy density (gravimetric) (kWh/kg)	33.33	11.89	≈ 3

7.3 Hydrogen production

The sustainability of hydrogen as an energy carrier, is tied to the method behind obtaining hydrogen. Today, the primary method and also cheapest way to produce hydrogen is referred to as *gray hydrogen* (see Table 14). In this process, hydrogen is extracted through steam-methane reforming. This method depends on fossil fuels (natural gas, coal or oil) and is therefore not a solution to reduce CO_2. Conceptually, steam reforming can be combined with carbon capture[22], which will then again improve the potential sustainability benefits of hydrogen, while also increasing production costs. As of 2021, the use of fossil fuels dominated hydrogen production, making up 96% of total production (IRENA, 2022; Bagarello S, 2024).

- 47% stemmed from natural gas
- 27% stemmed from coal
- 22% stemmed from oil

Instead, a clean fuel alternative to conventional fuels is present when hydrogen is produced through an electrolyser and with renewable electricity as input. IRENA (2022) estimates just 4% of global hydrogen demand was met through the use of electrolysers. This technology cannot yet compete with the conventional production of hydrogen. IEA (2023) estimates costs per kg H_2 to range widely, depending on the production method:

- 1-3 USD per kg H_2 from natural gas reformation
- 3.4-12 USD per kg H_2 from electrolysers[23]

Accordingly, there is a high uncertainty of the costs of hydrogen, as a fuel. In addition to the direct fuel costs comes the costs of handling and storage. For hydrogen to play an essential role in aviation, whether through electrolysis or other methods, it needs to be scaled up and sourced from renewable energy to be truly sustainable. Different pathways for production of hydrogen are shown in Table 14.

[22] Referred to as blue hydrogen.
[23] Marksel and Brdnik (2023) cites price estimations of 2.8-8 EUR per kg H_2.

Table 14 Overview of the colours of hydrogen, based on their production method. Illustration by the Danish Energy Agency. Source: (National Grid, 2024; Florian Osselin, 2025).

Green hydrogen	• Produced though electrolysis from renewable energy sources.
Blue hydrogen	• Produced mainly from natural gas, through steam reforming, CO2 is produced as a by-product in this process, but is isolated by the use of CCS (carbon capture and storage).
Gray hydrogen	• The most common form of hydrogen production. Over 95% of the world's hydrogen consumption is currently grey hydrogen, using steam methane reformation but without capturing the greenhouse gases made in the process.
Orange hydrogen	• The name refers to the colour of oxidized iron. Production, follows the same principles of White hydrogen and looks to make the Earth provide most of the work for hydrogen production.
Black/brown hydrogen	• Produced by coal gasification. The black and brown colours sometimes indicate the coal type: bituminous (black) and lignite (brown). This process generates significant CO2 emissions.
Pink hydrogen	• Produced through electrolysis powered by nuclear energy.
Turqoise hydrogen	• Relies a process called methane pyrolysis to produce hydrogen and solid carbon. Turquoise hydrogen may be valued as a low-emission hydrogen, dependent on the thermal process being powered with renewable energy and the carbon being permanently stored or used.
Yellow hydrogen	• Hydrogen made through electrolysis using solar power.
White hydrogen	• White hydrogen is a naturally occurring, geological hydrogen found in underground deposits and created through fracking. There are no strategies to exploit this hydrogen at present.

There is a global market for hydrogen, as it is already being used in refineries for hydrocracking and desulphurization purposes, in agriculture for fertilizer production and in ammonia and methanol production, food processing etc. (Moradi & Groth, 2019). Current global production of hydrogen for all uses is around 75 million tonnes (IRENA, 2022). To put the potential need for low or zero emission hydrogen in aviation into perspective e.g. FlyZero estimates that in certain scenarios, more than 70 million tonnes of liquefied hydrogen would be required in 2050.

7.4 Storage of hydrogen on board aircraft

To make up for the low energy density by volume, hydrogen used in today's industries and freight sector (as transported goods) is stored either as a gas under pressure (up to 700 bars) or as a cryogenic liquid (LH_2). This makes handling hydrogen a complex operation both for the airports in relation to distribution and fuelling and for the systems on board the aircraft.

The weight and volume of compressed hydrogen are makes in unfeasible for commercial aviation, except for very short-haul flight like island hopping (Fehrm, 2022). This is due to the fact that compressed hydrogen only has a gravity efficiency of around 5 pct., which expresses the ratio between usable fuel mass and the total mass of fuel tanks, fuel system, pumps, equipment, pipework and cooling (Svensson, Oliveira, & Grönstedt, 2024).

As an example, a DASH 8 that holds 4,600 kg of jet fuel would need a fuel/tank system weighing 26,700 kg if designed for compressed hydrogen at 700 bars (Fehrm, 2022). Much higher gravimetric efficiencies are achieved for LH_2, where efficiencies of around 47-58% by 2026 are suggested (Fly Zero, 2022) and Svensson, Oliveria and Grönstedt (2024).

Assuming a gravimetric efficiency of 35 % would mean that a DASH 8 that holds 4,600 kg of jet fuel would need a fuel system of similar 4,600 kg if designed for LH_2 (Fehrm, 2022).

The design of LH_2 tanks requires complex solutions, as the materials of the tanks have to withstand significant temperature fluctuations and the mechanical stress from flight cycles, including take-off, cruising and landing, as well as emergency landings and other operations outside of the normal. They also have to minimize permeable conditions and thermal conductivity. The insulation is crucial, as it must be effective enough to prevent external heat from causing vaporization and internal pressure increases. One litre of LH_2 will expand to 845 litres if vaporised at ambient pressure (Postma-Kurlanc, Leadbetter, & Pickard, 2022). Therefore, storage tanks need to be equipped with pressure sensors and relief valves to avoid overpressure, which otherwise could lead to the catastrophic failure of the aircraft.

Minimizing the weight of the tanks becomes an important design target vital for the efficiency of the aircraft (Svensson, Oliveira, & Grönstedt, 2024). The primary weight reductions on LH_2 tanks are expected through improvements on pipework structures and insulation. The increased efficiency is then driven by lighter tanks but also larger tank volumes and composite materials replacing aluminium. Future tank designs could lead to gravimetric efficiencies of 61-72% in 2030 (Fly Zero, 2022).

Table 15 Gravimetric efficiencies for hydrogen compared with kerosene.

Parameter	Unit	LH_2	H_2 gaseous	Kerosene
Normal storage condition	Pressure (bar)	1.5	700	1
Specific energy	Gravimetric Efficiency (%) (current technology)	47-58	<5	<98

There are other possibilities of storing hydrogen without the need for high pressure tanks or the need to manage a cryogenic liquid, e.g. material storage such as metallic alloys that absorbs hydrogen, chemical carriers like ammonia or carbon nanotubes that are capable of storing hydrogen within the tube structure (Colozza, 2002; Massaro, et al., 2023). These methods are, however, further away from any practical applications in aviation.

Cryo-compressed hydrogen, where hydrogen is stored as gaseous hydrogen at cold temperatures (-230 to -200 °C) under high pressure (up to 100 bar) is an area of research (Ebrahimi, Rolt, Jafari, & Anton, 2024). Verne and ZeroAvia are looking into this technology for aviation applications that could increase the volumetric energy density by 40 percent compared to liquid hydrogen. There is however a challenging trade off, as high-pressure storage demands pressure vessels of reinforced high strength materials, which adversely affect gravimetric density, cost and safety levels (Massaro, et al., 2023).

7.5 Airframe

The technical issues concerning LH_2 storage calls for new or redesigned airframes in order optimize the overall energy efficiency of the aircraft.

In order to hold enough LH_2 storage tanks need to be spherical or cylindrical with a relatively large diameter. This means they cannot be placed in the wings, as is the case for the main fuel tanks for jet fuel in conventional aircraft which is a design advantage as the weight of jet fuel thereby is close to the centre of lift and gravity, and the structure holding the fuel has little negative influence on the aircraft weight (Fehrm, 2020). Instead LH_2 tanks must be incorporated into the fuselage of the aircraft thereby changing the whole aircraft design, the weight distribution, and cargo/passenger capacity (Jayant Mukhopadhaya, 2023). An illustration is shown in the figure below.

Figure 25 Placement of fuel tanks marked with orange for kerosene and turquoise for hydrogen. Illustration by Danish Energy Agency, based on image by macrovector on Freepik.

The need for fitting hydrogen tanks inside the fuselage in a CTW design (Conventional Tube-and-Wing Design) significantly increases the wetted area compared to volume for passenger and cargo, leading to increased parasitic drag, which will reduce the efficiency of the aircraft.

The presence of fuel tanks in the fuselage, however, has an impact on more than just the size and weight of the fuselage. Because the fuel is not stored in the wing as jet fuel normally is, the bending moment alleviation effect of the fuel weight is no longer present, resulting in a need for strengthening the wing increasing the weight of the hydrogen aircraft (Yusaf, et al., 2023).

Figure 26 Blended wing body (BWB) hydrogen aircraft concept. Courtesy: Airbus.

Making aircraft design more efficient (increasing the lift/drag ratio) is one way of meeting some the challenges of hydrogen concerning volume and range. Novel and radical aircraft design like Lockheed Martin’s box-wing concept (Mehedi, Redonnet, & Hernadi, 2021), Boeing’s transonic truss-braced concept (Boeing, 2023) or the Blended Wing Body (BWB) that companies like JetZero and Airbus are working on[24] are all concepts that could dramatically increase the efficiency of aircraft. The BWB has a distinct wing and body structure, but the structures are blended together. The BWB is hugely relevant in relation to hydrogen, since the design allows for more internal storage volume for cargo, fuel and passengers compared to the wetted area meaning relative less parasitic drag. Furthermore, the BWB offers a large surface area to generate lift in flight and an improved balanced between lift and weight. This means that the BWB design could prove more efficient than conventional CTW aircraft.

Besides the efficiency gains there are other advantages of BWB like a relative higher payload/capacity ratio, wider cabin space, comfortable seating, faster boarding and evacuation procedures. The BWB design however also involves challenges of its own. The BWB is an inherent unstable design, making it fully dependent on sophisticated computer control surfaces. This is unlike the CTW design that has a passive stability effect on the aircraft without any inputs from control surfaces. The BWB also has a less optimal fuselage in relation to pressure loading of the cabin, and new airport designs might be necessary due to the different dimensions and accesses to the aircraft.

7.6 Safety

Safety is of paramount importance in aviation, and safety measures are one of the key development aspects of hydrogen as a fuel in aviation. Therefore, in addition to the safety protocols of conventional aviation, where many existing regulations can be applied to hydrogen aircraft, a series of new aspects come into play in terms of new aircraft certifications, but also regulation in relations to production sites, transporting, distribution, storage and refuelling (Department for Business, Energy and Industrial Strategy, 2022).

Under normal conditions, hydrogen is a non-corrosive, non-toxic, colourless, odourless, tasteless gas that is both combustible and explosive. And just like kerosene, hydrogen is a considered a flammable hazardous substance. While certain characteristics of hydrogen make it safer as a fuel than kerosene, other characteristics make it more dangerous (IATA, 2019). A conclusion from the CRYOPLANE project was that the overall safety level of hydrogen aircraft will not be worse than for kerosene aircraft (Airbus Deutschland GmbH, 2003).

7.6.1 Flammability and auto ignition

A key aspect of combustible fuels is their flammability meaning the ease with which they can be ignited, combust or even explode. The lower flammability limit represents the lowest air to fuel vapour concentration required for combustion when ignited by an external source. Likewise, the upper flammability limit represents the highest concentration at which combustion can take place. Kerosene has a low, but narrow flammability range of 0.6% to 4.7 % while hydrogen has wide flammability from 4.3 % to 75% by volume (Mohamed A. Habib & Qasem, 2024; Chevron, 2007). Hydrogen therefore needs three times higher concentration

[24] "Flying wing" configurations that are very close to the BWB concept have been used on military aircraft like the B-2 bomber.

than kerosene to ignite, but the high upper flammability limit of hydrogen means that hydrogen can ignite under much higher concentrations and in a variety of different situations.

This hazard risk becomes evident as hydrogen at the same time has a very low minimum ignition energy of only 0.017 MJ, meaning a weak spark can cause ignition - e.g. mechanical spark from rapidly closing valves, electrostatic discharges, sparks from electrical equipment, catalyst particles, heating equipment, atmospheric discharge near a vent stack, etc. (IATA, 2019; SES Hydrogen, 2022). However, at volumetric concentrations below 10 pct. the ignition energy is actually similar to the ignition energy of natural gas and gasoline (U.S. Departement of Energy, 2024).

The auto ignition temperature for hydrogen, meaning the temperature for spontaneous ignition, is 574 °C is much higher than kerosene's 210 °C.

7.6.2 Leakage and detection

Leakage is a serious risk for handling hydrogen both in relation to handling and fuelling at the airport but especially in the aircraft. This is especially critical as the hydrogen molecules are so small they easily leak through tiny cracks or pores, fuel lines, fittings, flanges, threads, gaskets, porous materials (SES Hydrogen, 2022). Leak detection therefore becomes a critical safety concern.

This is further complicated since hydrogen at standard temperature and pressure, is a colourless, odourless, and tasteless gas making it difficult to detect. Furthermore, a hydrogen flame is invisible to humans, increasing the risk that a hydrogen fire can go undetected. This calls for advanced hydrogen sensors and leak detection systems that will quickly identify and address any leaks. Redundant safety systems can further enhance detection and response capabilities, ensuring rapid intervention in case of a leak (IATA 2019).

In case of leakage, the lightness of hydrogen becomes a safety advantage since hydrogen, if vented to the surrounding environment, quickly will diffuse and mix with air to below the lower flammability concentration.

7.6.3 LH_2 storage tanks

LH_2 tanks require special attention in terms of safety. Like mentioned the on board LH_2 tanks must be very robust to withstand mechanical stress and violent abuse in case of emergency landings or even crashes. But the integration of them in the fuselage actually provides some safety advantages since they have a much smaller area for frontal impact than wing tanks and are protected by a significant amount of structure, both ahead and beneath them (Yusaf, et al., 2023).

The insulation of the tanks must be effective enough to reduce external heat from causing vaporization and internal pressure increases. Pressure release valves must handle the boil off gas and it must be vented securely – this could be for explicit use in axillary units. These technical solutions also have to function at high altitudes, where the challenges of LH_2 are amplified by low ambient pressures and temperatures.

Handling cryogenic liquid hydrogen can cause severe freeze burns on humans if the liquid comes in contact with skin. Equipment to keep hydrogen ultra-cold must be robust and designed to vent hydrogen safely in gaseous form if a breach is detected. Along with redundant safety features this should dramatically reduce the likelihood for human contact with the cryogenic hydrogen (U.S. Departement of Energy, 2024).

7.6.4 Embrittlement

Hydrogen embrittlement (HE) degrade metals and alloys, reducing their fracture toughness, fatigue resistance and ductility. HE in metals presents a serious challenge for the use of high strength materials in engineering practice and the phenomenon is a major obstacle for deployment of hydrogen energy infrastructure (Yi-Sheng Chen, 2024). The HE phenomenon is vital in relation to aviation, where HE can lead to fatigue and failure of important on-board structures such as hydrogen tanks, vessels, fuel lines etc.

The phenomenon of HE has been known for almost 150 years and research is still required to further advance the understanding of HE and development of HE-resistant alloys (Yi-Sheng Chen, 2024). (Bagarello S, 2024)

7.6.5 Flame, heat and spills

Even though flame temperature is higher for hydrogen flames they emit significant less heat than kerosene and are therefore less likely to cause secondary fires (U.S. Departement of Energy, 2024). The low heat radiant and invisible flame makes hydrogen flames difficult to sense for humans until there is direct contact with the flame, which in itself poses a risk.

The ENABLE H_2 study indicate that, in the event of fuel spill, LH_2 has some safety advantages over kerosene/jet fuel. Modelling have shown that LH_2 pool fires exhibits smaller thermal radiation hazardous distance and deliver a lower thermal dose than those found for a comparable kerosene pool fire (Ingram, Benson, & Battersby, 2020). Due to the lightness of hydrogen, it quickly rises and diffuses rapidly, which means when released into the ambient air it dilutes into non-flammable concentrations. This also means that LH_2 spills produce short duration fires such that the fuel spills will completely evaporate and burn-out rapidly. Hydrogen fires will also be clean burning such that no toxic smoke is produced (unless other materials become involved). However, the use of LH_2 fuel will also introduce new additional hazards associated with e.g. dense gas cloud dispersion behaviour.

7.7 Fuelling – infrastructure

LH_2 whether used for electro-chemical conversion in fuel cells or thermal conversion in combustion engines, will require substantial and costly technical modifications to the airport infrastructure (J. Hoelzen, 2022; Bagarello S, 2024). This includes the whole supply chain from production and delivery of hydrogen to the airport, or alternatively on- site hydrogen production, liquefaction and storage facilities that will match the demand for hydrogen fuel, advanced facilities and specialized equipment for refuelling aircraft with liquid hydrogen, including on site distribution pipelines, special trucks and fuelling towers etc. This also includes training and education of ground personal to ensure safe procedures for handling cryogenic hydrogen (ACI, 2021b).

A major challenge is how to ensure hydrogen availability at the airport. Hydrogen could be trucked from production sites in liquid state, or it could be piped as compressed gas from production sites to the airport and then liquefied at the airport.

Alternatively, hydrogen could be produced on-site at the airport using renewable energy sources. However, large airport like Heathrow could need about 10 GW of electric power for onsite production and liquefaction of hydrogen, even if only half of the aircraft in Heathrow uses LH_2 (Rolt, Lundbladh, & Williamson, 2022).

To ensure continuity of fuel supply, and to minimize on-site storage, airports might need multiple sources of hydrogen either LH_2 or GH_2 with liquefaction (Rolt, Lundbladh, & Williamson, 2022).

In an early ramp up period, hydrogen demand will be small, and will most likely be delivered in liquid form via trucks. One single truck can carry up to 5 t of hydrogen which would be enough to cater for about five hydrogen-powered turbo-prop aircraft (short haul) or one narrow body aircraft on a medium-haul mission (ACI, 2021b). Trucking liquefied hydrogen seems the least capital- intensive solution, but for any large airport it would mean a massive logistic challenge as a total switch to hydrogen could mean 500 truck deliveries a day to a major airport (Postma-Kurlanc, Leadbetter, & Pickard, 2022). Besides the question of physical space needed for handling hydrogen, other considerations for airports in relation to serve hydrogen aircraft is longer fuelling times, and different stand sizes due to different airframes (ACI, 2021a).

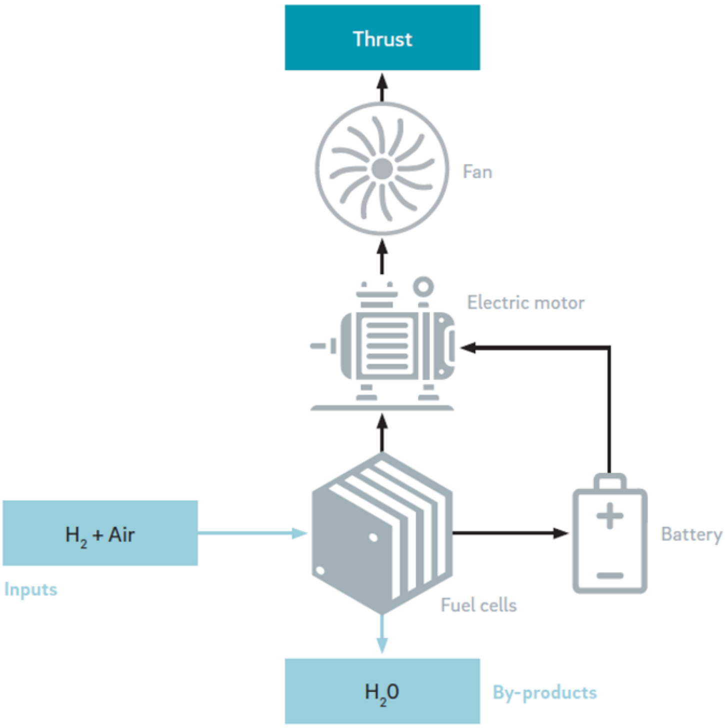
7.8 Fuel Cell Aircraft

Hydrogen fuel cell aircraft (FC-aircraft) are electric aircraft relying on fuel cells to deliver electricity for the electric motors that generates propulsion, and this is where they vary significantly from battery-electric planes. The fuel cells are electrochemical devices that produces electricity from the chemical energy contained in hydrogen. FC aircraft share the same benefits and challenges as battery-electric aircraft, regarding the propulsion technology (See chapter 6). But unlike battery-electric aircraft, FC-aircraft avoid heavy batteries and long charging times, as energy is stored hydrogen. As previously described, the storage volume of hydrogen is a challenge limiting range and size of FC aircraft within a foreseeable timescale, FC aircraft are considered better suited for short and regional flights that are currently operated by conventional turboprops.

Fuel cell technology has been known for more than a century and is applied in different contexts. There are thousands of stationary uses of fuel cells. Nevertheless, the concept of fuel cell propulsion systems in aviation involves a range of new challenges to be overcome, prior to commercialisation, with the very first FC aviation solutions aiming at market entrance before 2030. As for type of fuel cell, the PEM (Proton Exchange Membrane) fuel cells seems most relevant for aviation uses do to its power-related criteria such as specific power, power density, and power capacity (Murat Ayar, 2023).

The propulsion systems of FC aircraft are similar to those of battery-electric aircraft where propulsion is generated through propellers or ducted fans. A fuel cell propulsion system is visualised in Figure 27.

Figure 27 Hydrogen fuel cell propulsion system (Roland Berger, 2020).



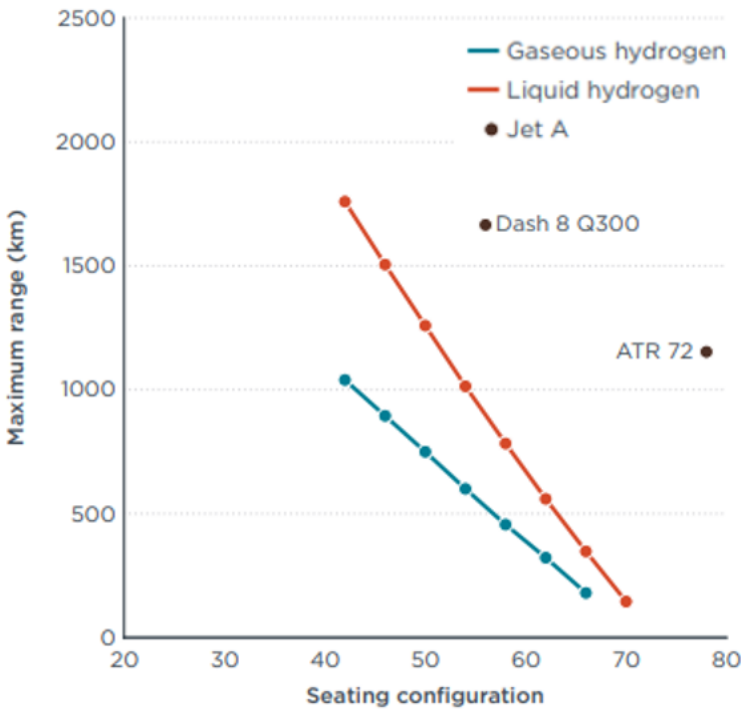
As indicated in the figure, thrust is generated through a fan (or propeller) driven by an electric motor, in a fuel cell propulsion setup. The electric motor is powered by the fuel cell and a buffer battery. The battery supports the system during peak power demands like during take-off or transient conditions, ensuring smooth operation alongside the fuel cell. The hydrogen storage is the backbone of the setup, as it is the energy source for the fuel cell that converts the chemical energy into electricity. H_2 and air is the only input in the process. The H_2 is provided from storage tanks and the O2 is drawn directly from the air surrounding the aircraft. The by-product of this process is water (H_2O). The efficiency is estimated at 45-50% (Roland Berger, 2020).

7.8.1 Fuel Cell aircraft – Efficiency

The FC aircraft having efficient electric motors opens up for great efficiency gains over conventional technologies. A study by ICCT (2023) based on a simulation, indicated that a specific fuel cell electric plane had an energy consumption of 0.61 MJ/ASK compared to 0.90

MJ/ASK for a kerosene fuelled plane of similar size. This is an indicator of the efficiency gains possible through fuel cell powered propulsion.

Figure 28 Modelled maximum range of a fuel cell retrofitted ATR 72, fuelled by gaseous hydrogen and LH_2, respectively. From a study by ICCT (2023).



The study looked into the retrofitting of an ATR 72. This aircraft is not originally designed for hydrogen storage and electric propulsion. As a consequence, the results may not translate with the exact same trends, in cases of aircraft designed specifically for the purpose of fuel cell electric propulsion. The trend observed in the figure indicates how the range of a FC-aircraft declines with an increasing number of seats. In this given study, a hydrogen tank was added for every row of seat removed – hence the tendency observed in the figure. This illustrates one of the inherent challenges of low volumetric energy density. Compared to a conventional ATR 72, the fuel cell hydrogen fitted model must compromise either seat count or maximum range, in order to match the ATR 72 in either of the parameters.

The conclusion is that while the FC-modified plane enabled improvements to energy efficiency, it did suffer space for passenger seats, due to the required space for hydrogen tanks. Despite the increased energy efficiency, the FC-setup does restraint either carrying capacity or range of the aircraft, compared to a conventional benchmark. In the given example of the study, the conventional turboprop plane achieved a range of 1650 km with 78 passengers, while the FC-modified (with LH_2) plane was limited at 783 km with 58 passengers (ICCT, 2023).

7.8.2 Fuel Cell aircraft - climate and environmental properties

From a sustainability point of view, FC-aircraft offer attractive traits such as "true-zero" flight, with just water vapour as a by-product. This true-zero trait is a strength shared with the battery electric planes, that is unique for these propulsion systems. The consequences of the water vapour from fuel cells is still unknown to which degree and if the water vapour emissions are worse for FC-planes compared to combustion engines. Though the contrail and cirrus cloud formation are expected to be reduced due to the purity of hydrogen, while eliminating emissions of CO_2, NOx, CO, HC and soot, it will not be true-zero until the heating effects of contrails and cirrus clouds are avoided fully.

Additionally, hydrogen fuel cells offer the potential for reduced noise and more efficient flight operations compared to traditional combustion engines (Roland Berger 2020).

7.8.3 Fuel Cell aircraft – applications

The ICCT study (2023) indicated that a fuel cell aircraft based on the ATR 72, with a reduced seat capacity down to 50 seats (for gaseous hydrogen) and 58 seats (for LH_2) would be able to service 14% and 16% of global turboprop ASK. Vitally, this would correspond to just 0.1% of global ASK demand in commercial aviation. Therefore, as current fuel cell technology is not able to generate sufficient thrust to power narrow body plane, the application seems limited to regional turboprop aircraft (ICCT, 2023).

The flight range of FC-aircraft is one of the key areas where they separate from current battery-electric aircraft, as the energy-to-mass ratio is significantly better. The grade of this advantage will depend on the commercialisation of LH_2, affecting the operation range of FC-aircraft. Regardless, FC-aircraft are best suited for smaller aircraft and routes of limited range and, as storage tanks does require significant space of the vessel and their airspeed is lower than alternatives. For longer flights and larger aircraft, many analyses point to hydrogen combustion, in the case of hydrogen flight (see chapter 7).

Airbus ZEROe project, launched in 2020, had a 100-seat fuel cell propeller aircraft with a 1,000 nm (1,852 km) range as part of their conceptual 'ZEROe' project line-up (Airbus, 2023). Airbus has since developed the concept further and in 2023 they demonstrated a 1.2 MW fuel cell power unit and in 2024, completed test of an integrated fuel cell stack, electric motors, gearboxes, inverters and heat exchangers. Airbus has set a target of service for the technology in the second half of the 2030s (Airbus, 2025). The ZEROe project can, arguably, be viewed as an important signpost as to how a FC aircraft may be a realistic technology within the next 10-15 years. It also means the application of FC aircraft are limited to a very small share of the global aviation demand – but may be efficient at certain routes.

7.9 Hydrogen combustion aircraft

As an alternative to fuel cell aircraft, hydrogen can be used as fuel in combustion setups such as turboprops and turbofans. The concept of using hydrogen as a combustion fuel is centuries old, and has been used as fuel in space rockets. Hydrogen has also been used in air breathing engines in experimental/low volume cars since the 1970´s (BMW AG, 2024). More notably the Russian TU-155 aircraft in 1988 was an experimental testbed passenger aircraft that flew with one of three engines on LH_2. As hydrogen is a not a drop-in fuel like SAF, it demands substantial changes to the aircraft design, airframe, engines, storage and fuelling systems.

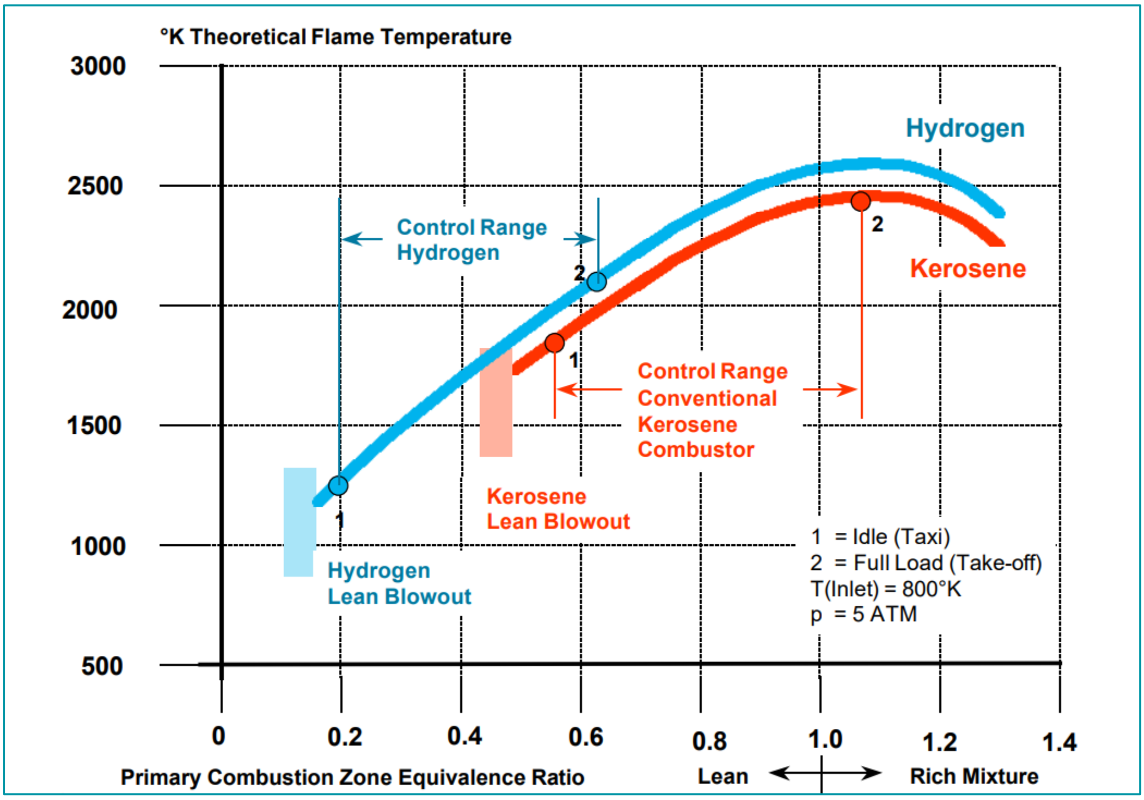
The development of new conventional gas turbine engines is a tremendous engineering task taking manufacturers years to accomplish. Following final approvals and taken into service, it typically takes several more years of practical experience to iron out all problems and honing it into fully reliable and efficient engines (Fehrm, 2024). To develop effective hydrogen combustion gas turbine engines and reach same level of in-service reliability will likely be considerably more demanding.

7.9.1 H_2 combustion aircraft – Efficiency

Hydrogen gas turbine engines are largely similar to kerosene gas turbine engines. However, due to the different thermal and chemical properties of hydrogen, conventional engine design and fuel delivery systems must be thoroughly modified (Ling-Chin, et al., 2024). Hydrogen engines must be able to handle higher flame speed, greater diffusivity and wider range of flammability, and the materials must withstand higher temperatures, requiring advanced cooling techniques or materials. This includes further development of new technologies such as heat exchangers that pre heat the hydrogen from liquid to gaseous state before entry to the combustion chamber, the geometry of combustion chambers, advanced multi point injectors, and many other changes (Patrao, Xisto, Jonsson, & Lundbladh, 2023).

Different studies of hydrogen combustion have shown potential efficiency gains (Enmine Ogue, 2024). Thermodynamic efficiency of an engine depends on how effectively the heat from combustion can be utilized to do work. Hydrogen gas turbines can lead to greater temperature gradient between the combustion gases and the turbine components and potentially more efficient conversion of thermal energy into mechanical energy. Also benefits from the cryogenic cooling and heat exchangers can cool engine oil, turbine and other component, and hydrogens wider flammability, that enables leaner mixture leaves potential for improved efficiency compared to the kerosene engines (see Figure 29) (Ebrahimi, Rolt, Jafari, & Anton, 2024; Ling-Chin, et al., 2024). The figure shows how hydrogen can be controllable combusted at lower concentrations than kerosene, which also lowers the flame temperature and the fuel consumption.

Figure 29 Combustion process and control ranges for hydrogen and kerosene (Fass, 2001).



However, as described in section 7.5 the space needed for fuel storage, the weight of storage tanks and the complex cooling systems to keep hydrogen at cryogenic level affects the design of aircraft. For conventional CWT aircraft design this would lead to increased fuselages with negative effects on drag. Different research projects have come to different conclusions regarding the total efficiency of hydrogen combustion aircraft.

The Cryoplane study from 2000 concluded that the energy consumption of hydrogen-fuelled aircraft would be 9–14% higher than kerosene-fuelled aircraft due to the excessive tank volume required for liquid hydrogen (LH_2). Other studies, have found efficiency gains of 11 % for hydrogen combustion aircraft (Habib, Abdulrahman, Alquaity, & Qasem, 2024). Different results are likely due to the different approaches to aircraft designs (Yusaf, et al., 2023).

More recently Pratt Whitney have provided a promising potential from its Hydrogen Steam Injected, Inter-cooled Turbine Engine (HySIITE) program that was launched in 2022. The system basically feeds water from the exhaust back into the combustion chamber. From their latest results Pratt & Whitney have stated that the HySIITE system could improve energy efficiency by 35% compared to current single-aisle aircraft powerplants while reducing NOx emissions by 99.3 pct. These advantageous effects are reached from the water injection increasing the mass density of the air stream in the engine increasing the power extraction in the turbines (Fehrm, 2025; Pratt & Whitney, 2025).

7.9.2 H_2 combustion aircraft - climate and environmental properties

NOx

Combustion of hydrogen emits no CO_2 but does lead to emissions of water. Nevertheless, when hydrogen in used in an air breathing engine the ambient air is used for the combustion and since air contains nitrogen, the combustion also emits NOx (Yusaf, et al., 2023). There are different approaches to reduce NOx emissions from hydrogen combustion engines. Higher burning velocities and diffusivity allow for higher reaction rates and faster mixing respectively, resulting in lower residence time in the combustion chamber, which leads to lower NOx emission. Studies have shown reduction of NOx emission by 50-80% (CleanSky2, 2020). As mentioned, the Pratt & Whitney HySIITE concept could also dramatically reduce NOx emission from hydrogen combustion.

Reducing the altitude of flight operations with 2 to 3 km can also reduce the amount of nitrogen oxides produced (Maciorowski, Ludwiczak, & Kozakiewicz, 2024). In turn, lower altitudes introduce more drag, and hence energy consumption, due to higher air densities.

Contrails

Water vapor from a hydrogen combustion jet engine could lead to about 2.6 times higher water emissions than from a jet engine using kerosene or SAF (IATA 2019), but is believed to form different contrails. There is no published data on this subject to date, but the contrails from hydrogen combustion will likely be optically thinner and less persistent due to the absence of particulates in the exhaust (cleaner combustion) (Department for Business, Energy and Industrial Strategy 2022).

7.9.3 H_2 combustion aircraft – applications

The option of hydrogen combustion is expected to enable applications that are operationally close to conventional commercial planes in terms of range, cruise speed and payload. Hydrogen combustion planes are tied to fewer practical restrains, compared to, for example, battery-electric and fuel cell electric aircraft. As such hydrogen combustion can be used in similar applications as traditional turboprops and turbofans, seen from a theoretical perspective. Besides the option of using SAF, hydrogen combustion also seems a relevant alternative for long range high capacity flights. Studies have found that lower passenger capacity of a hydrogen plains may require a larger fleet of aircraft to meet the demand on long haul fights (Ebrahimi, Rolt, Jafari, & Anton, 2024).

Rolls Royce has worked on hydrogen gas turbine engines for stationary appliances for several years and is now collaborating with EasyJet on hydrogen combustion turbofan jet engines capable of powering a range of aircraft, including narrow body aircraft. Currently, they have conducted successful ground tests on a converted AE 2100-A regional aircraft engine and a Pearl 15 business jet engine showing hydrogen can safely and efficiently deliver power for small- and mid -size aircraft.

Nevertheless, the cost efficiency, safety regulation/certification and how they compare to other alternatives, will highly affect whether hydrogen combustion will play a role in future aviation.

From the current projects by Airbus etc. the hydrogen combustion is foremost seen as relevant in the range of medium regional flight up to 2.000 nm from 2035 and onwards. The ENABLEH2 and FlyZero projects have predicted that long range LH_2 aircraft will become feasible well before 2050 (Ebrahimi, Rolt, Jafari, & Anton, 2024).

An ICCT study on hydrogen powered aircraft looked into performance, fuel related costs and emissions for LH_2 aircraft with the perspective of entering service by 2035[25]. The study found that that LH_2 could contribute to the aviation sector's 2050 climate goals. Though having a shorter range than comparable fossil-fuel aircraft the ICCT study estimated that evolutionary LH_2 narrow-body aircraft could transport 165 passengers up to 3,400 km and LH_2-powered turboprop aircraft could transport 70 passengers up to 1,400 km. This would cover about two thirds of all RPK (Revenue passenger kilometres) serviced by narrow-body aircraft and about 90% of all RPKs serviced by turboprops. Together, this would cover about one-third of all passenger aviation traffic, as measured by RPK. (Jayant & Rutherford, 2022).

7.10 Economics of hydrogen

High uncertainty revolves around costs of fuel cell electric aircraft. The technology is still in its infancy and will require significant innovation before market viability is a possibility. Yet, there have been studies conducted estimating the current or achievable costs. A study comparing a conventional 19-seat aircraft with a corresponding fuel cell aircraft identified some metrics trying to highlight the economic viability of fuel cell electric aircraft. The 19-seat configuration was chosen, as an aircraft this size is subject to less stringent regulation[26] (Marksel & Brdnik, 2023). In this study it was assumed that only the engines groups were different between the conventional benchmark and the fuel cell electric alternative, as there is not yet an actual 19-seat fuel cell electric aircraft to otherwise compare.

The Clean Sky 2 project found, that for commuter and regional aircraft, fuel cell-powered propulsion compared to conventional aircraft, would increase operational costs by as little as US $5-10 per passenger, about 10 percent per PAX (passenger).

The ICCT study on hydrogen aircraft estimated that a carbon price of about $250/tonne-CO2e would be needed for fuel price parity for LH_2-powered aircraft in the United States in 2035, falling to $100/tonne-CO2e in 2050 (Jayant & Rutherford, 2022).

[25] As of 2025 Airbus have scaled back on their expectations for fuel cell aircraft by 2050. They still hold the 2035 ambition of introducing an airborne concept aircraft, but estimates that development is 5-10 years behind to reach the 2035 target (Hepher, 2025) .
[26] FAR–23/EASA CS-23 regarding air worthiness and compliance.

Entry into service could happen within the next eight to fifteen years. For short-range aircraft, a hybrid propulsion approach (H_2 combustion and fuel cell) could be best suited, increasing costs per PAX by 20-30 percent. The next largest segment, medium-range aircraft, requires significantly extended fuselages for LH_2 storage and thus would consume about 25 percent more energy than conventional aircraft; these aircraft would lead to a cost increase of 30-40 percent per PAX. Considering the amount of climate impact avoided, this translates into costs per abated ton of CO_2 equivalent of less than US $60 for regional and commuter and US $70 to $220 for short- and medium-range aircraft. This compares favourably to US $210 to $230 per ton CO_2eq for synthetic fuel from direct air capture for short- to long-range aircraft.

8 Recap of aviation technologies

This review has highlighted aspects of the technologies being developed in the aviation sector for its transition away from conventional fuels. Conventional aircraft have significantly improved their performance and efficiency through decades of continuous incremental improvements. Therefore, conventional aircraft place a high benchmark for any competing technology, in terms of costs, reliability and safety, which are crucial aspects for penetrating the markets. The aviation industry is built around synergies of aircraft, infrastructure, supply chains and airports, which affects the design and technologies of new aircraft concepts.

This chapter highlights the key strengths and weaknesses of the technologies discussed in this report. The visualizations presented in this chapter illustrate learnings from previous chapters but are also subject to significant uncertainties and simplifications. Future technological breakthroughs and advancements in fuel production methods may significantly alter the potential of these technologies, reshaping the perspectives illustrated.

In essence, SAF can with relative ease, replace kerosene and hence potentially mitigate the issues of CO_2 emissions from the aviation industry if only to a smaller extend the non-CO_2 issues, seen from a technical perspective. The drop-in characteristic of SAF eases the introduction of the technology, in an industry with technological lock-ins in place. SAF allows for the same technical advantages as kerosene, hence permitting a continued operation similar to the aviation sector of today.

SAF is challenged by feedstock availability, sustainability and high costs, meaning pathways for production becomes essential. As shown in chapter 5, there are great differences in prices and availability of feedstock resources for the different pathways. Securing a sustainable and abundant source of carbon for production is vital and together with high costs and non-CO_2 effects this rise concerns for SAF as the sole solution to decarbonisation of aviation.

As described in chapter 6 and 7, battery-electric, fuel cell electric and hydrogen combustion aircraft have their strengths and weaknesses and are facing different challenges. These alternative technologies, unlike SAF, require substantial changes and modification to the aviation sector of today. This includes completely new configurations of aircraft designs, different performances and capacities including fewer seats, shorter range lower speeds (for electric and fuel cell electric aircraft) and large investments in redesign of airports and fuelling infrastructure. Nevertheless, these aircraft types allow for carbon-free flight, which greatly limits the climate change impacts of aviation but also improves local pollution in airports.

This chapter highlights the central figures and assessments based on this technology review. The chapter recaps empirical content but also reflects on the potential use of the included aviation technologies of this technology review.

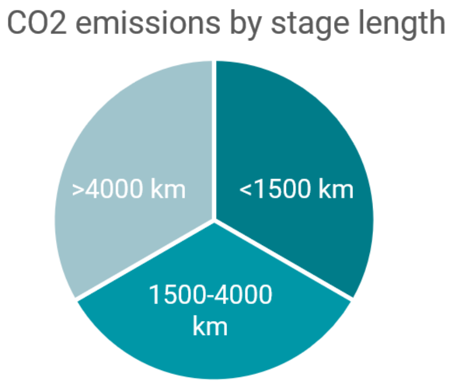
8.1 Key figures of the current aviation sector

Global aviation emissions are dominated by passenger flight. Consequently, this is where the majority of GHG-emission reduction must take place, when decarbonizing the sector. The passenger flight segment today consists of four overall aircraft segments totalling a global fleet of nearly 30.000 commercial fixed-wing aircraft (OliverWyman, 2024):

1) Narrow body (17,264)
2) Wide body (5,757)
3) Regional jet (3,043)
4) Turboprop (2,334)

Narrow- and wide body aircraft make up a significant share of all aircraft, due to their versatility and advantages in terms of speed, range and capacities compared to smaller regional jets and turboprops.

Figure 30 Approximate CO_2 emissions grouped by stage length. Figure by the Danish Energy Agency, based on ICCT (2020).



As seen in Figure 30, the emissions of aviation can be roughly divided into three categories each responsible for a third of global CO_2 passenger flight emissions. Narrow body aircraft are the dominant segment for short- and medium-haul flights (<4000 km). In contrast, longer flights of >4,000 km are primarily serviced by wide body aircraft. Regional flights of <500 km accounted for ~6% of total aviation emissions, in 2018. With an average lifespan of 27 years, many of the aircraft produced today will still be in operation by 2050 (ICCT, 2020).

The figure signals both the potentials and limits of decarbonizing, for example, shorter distances of <1500 km, where the electric (whether fuel cell electric or battery electric) could play a role if developments of these technologies proceed as stated. With a third of emissions stemming from this category, the decarbonizing of this group is not negligible but is also not enough to reach the stated 2050 targets. Therefore, the longer flights and the fuels able to provide the energy necessary, is a vital area of research and investments.

8.2 2040 Narrow body aircraft example

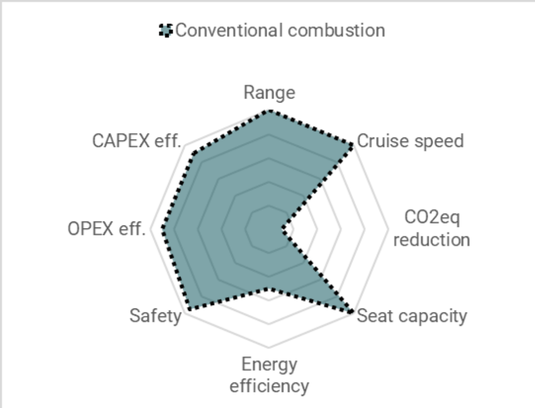
Some general characteristics can be deduced, following the technical chapters of this review. The following six figures present the propulsion technologies included in this review on eight key aspects: Range, cruise speed, CO_2eq-reduction, seat capacity, energy efficiency, safety, OPEX efficiency and CAPEX efficiency.

The scores in the figures are measured against on what is known from the sector today (current optimal flight speed, maximum common seat capacity etc.). As such, these diagrams plot the alternative technologies and their performance compared to a conventional narrow body fixed wing passenger aircraft by 2040.

8.2.1 Conventional aircraft (fossil kerosene)

These aircraft are the all-dominant market standard, hence setting a benchmark for alternative technologies or fuels to compete with. They excel in performance parameters such as range and speed. Furthermore, the decades of innovation and optimization are expressed in high scores in CAPEX, OPEX and safety. OPEX may increase, as regulation is enforced to reduce emissions. The most significant, and inherent, challenge remains to be CO_2eq-emissions, originating from the use of fossil kerosene. Despite continuous efficiency gains and the induced CO_2eq-reductions conventional technologies cannot comply with stated targets for reducing climate change effects from aviation.

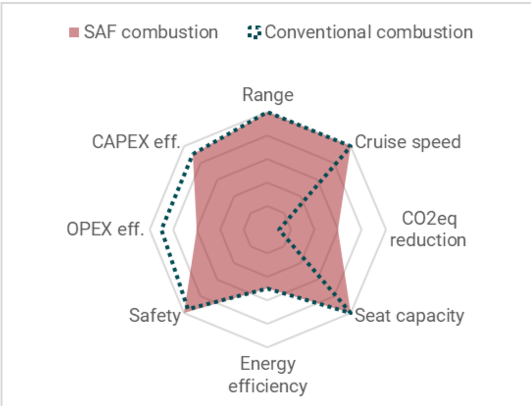
Figure 31 Technical aspects of conventional kerosene combustion aircraft. Estimation and illustration by the Danish Energy Agency.



8.2.2 SAF combustion

Similar to conventional aircraft in almost every aspect, except the origins of the fuel, SAF is a solution that imitates the strengths of fossil kerosene. This includes high performance scores in range, speed, seat count, CAPEX and safety. The use of SAF adds the key benefit of potentially significant CO_2-reductions, and also benefits from potentially lower non-CO_2 effects. On the other hand, all SAF products involve added fuel costs, and therefore lowers the OPEX score (higher costs = lower score), compared to kerosene. However, as SAF can be produced by various pathways and methods at different costs, there is significant uncertainty about the OPEX score.

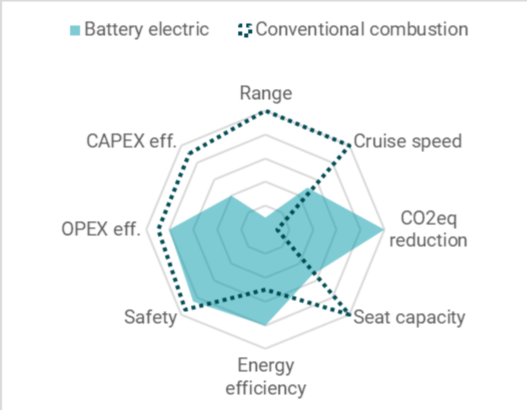
Figure 32 Technical aspects of SAF combustion aircraft. Estimation and illustration by the Danish Energy Agency.



8.2.3 Battery electric aircraft

This technology is fundamentally different from the conventional aircraft using combustion engines. The strongest asset of electric aircraft is the possibility of true zero emission flights meaning no CO_2 emissions and no non-CO_2 effects. The OPEX will be highly influenced on the origins of the liquid fuel used. The low specific energy of batteries brings weight limits the attainable range and the use of propellers for thrust limits cruise speed and altitude of these aircraft. The battery weight issue of electric aircraft also limits sizes of aircraft and seat capacities, and in the end restricts electric aircraft to short/medium range low capacity flights cruising at lower speeds.

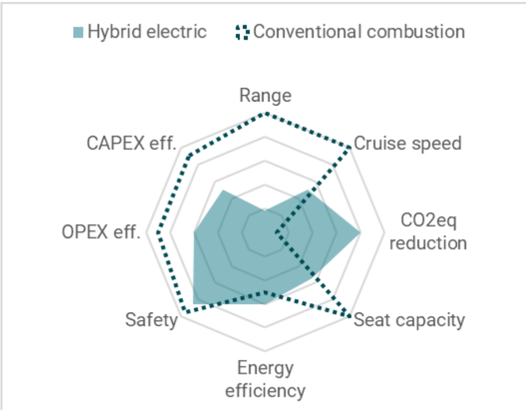
Figure 33 Technical aspects of battery electric aircraft. Estimation and illustration by the Danish Energy Agency.



8.2.4 Hybrid battery electric aircraft

These aircraft share traits with both traditional combustion aircraft and battery electric aircraft. They can utilize both liquid fuels as well as electric power from a battery. They have reduced weight from batteries compared to fully electric aircraft, as they store some of their energy in much more energy dense liquid fuel. Therefore, these aircraft allow for longer range, at the cost of lower energy efficiency, higher emissions and higher OPEX, in comparison to full battery electric aircraft. Depending on the type of liquid fuel used (either conventional kerosene or SAF) the CO_2-reduction potential will vary greatly. Design wise, and in order to maximize the electric propulsion, these aircraft are kept smaller and optimized for slower speeds and shorter range, compared to conventional aircraft.

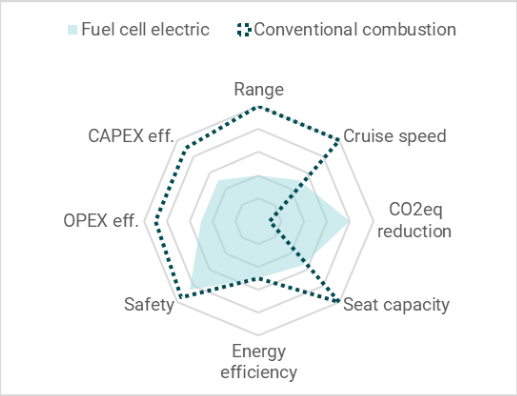
Figure 34 Technical aspects of hybrid battery electric aircraft. Estimation and illustration by the Danish Energy Agency.



8.2.5 Hydrogen fuel cell aircraft

This is the first of two options to utilize hydrogen in aviation. Relying on propellers powered by electric motors, the fuel cell electric aircraft share many traits with battery electric aircraft. However, due to their energy carrier being compressed or cryogenic hydrogen instead of chemical energy stored in batteries, they can carry significantly more energy on board, allowing for a longer range. A substantial advantage of hydrogen is that it is a carbon-free fuel with zero CO_2 emissions during flight, meaning they have a great CO_2eq-reduction potential. The cost-perspective of this tehcnology is currently largely unknown, and the viability of the technology will depend on costs of hydrogen and the storage and fuelling systems. The effect of water as a by-product from the fuel cells remains uncertain at this point, but will be an important metric in the overall climate-performance of this type of aircraft. Hydrogen is in some aspects safer than kerosene while in others it has disadvantages. Even though hydrogen might be as safe as kerosene or even better there will for a long time be less experience with handling hydrogen, meaning hydrogen valued concerning safety than conventional aircraft.

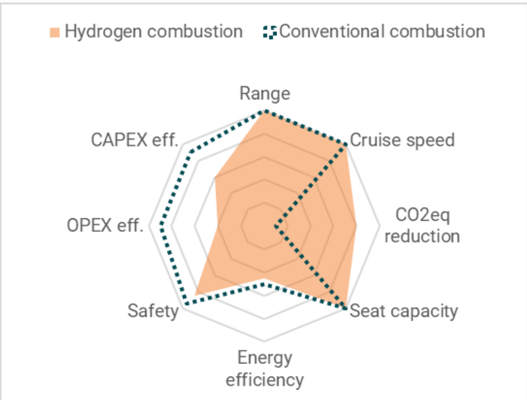
Figure 35 Technical aspects of fuel cell electric aircraft. Estimation and illustration by the Danish Energy Agency.



8.2.6 Hydrogen combustion aircraft

This is the second of the two options for utilizing hydrogen in aviation. The main similarity to fuel cell aircraft is the energy storage systems suited for cryogen liquid hydrogen (LH_2). Hydrogen combustion technology shares many aspects with kerosene (or SAF) combustion. Compared to electric aircraft this technology is expected to perform well in terms of range, cruise speed and passenger capacity. As such, these aircraft are well suited to service medium and even longer haul routes flown by the most popular conventional narrow body aircraft of today. The low volumetric energy content of hydrogen compared to kerosene or SAF, their flight range may however not reach the same figures as SAF or kerosene. Hydrogen combustions means CO_2-free flight, though NOx emissions and water vapor are potential issues. A significant advantage of hydrogen is the potential absence of issues with carbon-availability and sustainability, if produced through electrolysis with green electricity. Like mentioned under fuel cell electric aircraft hydrogen is in some aspects

Figure 36 Technical aspects of hydrogen combustion aircraft. Estimation and illustration by the Danish Energy Agency.



safer than kerosene while in others it has disadvantages. Even though hydrogen might be as safe as kerosene or even better the lack of experience handling hydrogen, leads to hydrogen scoring slightly lower safe score than conventional aircraft.

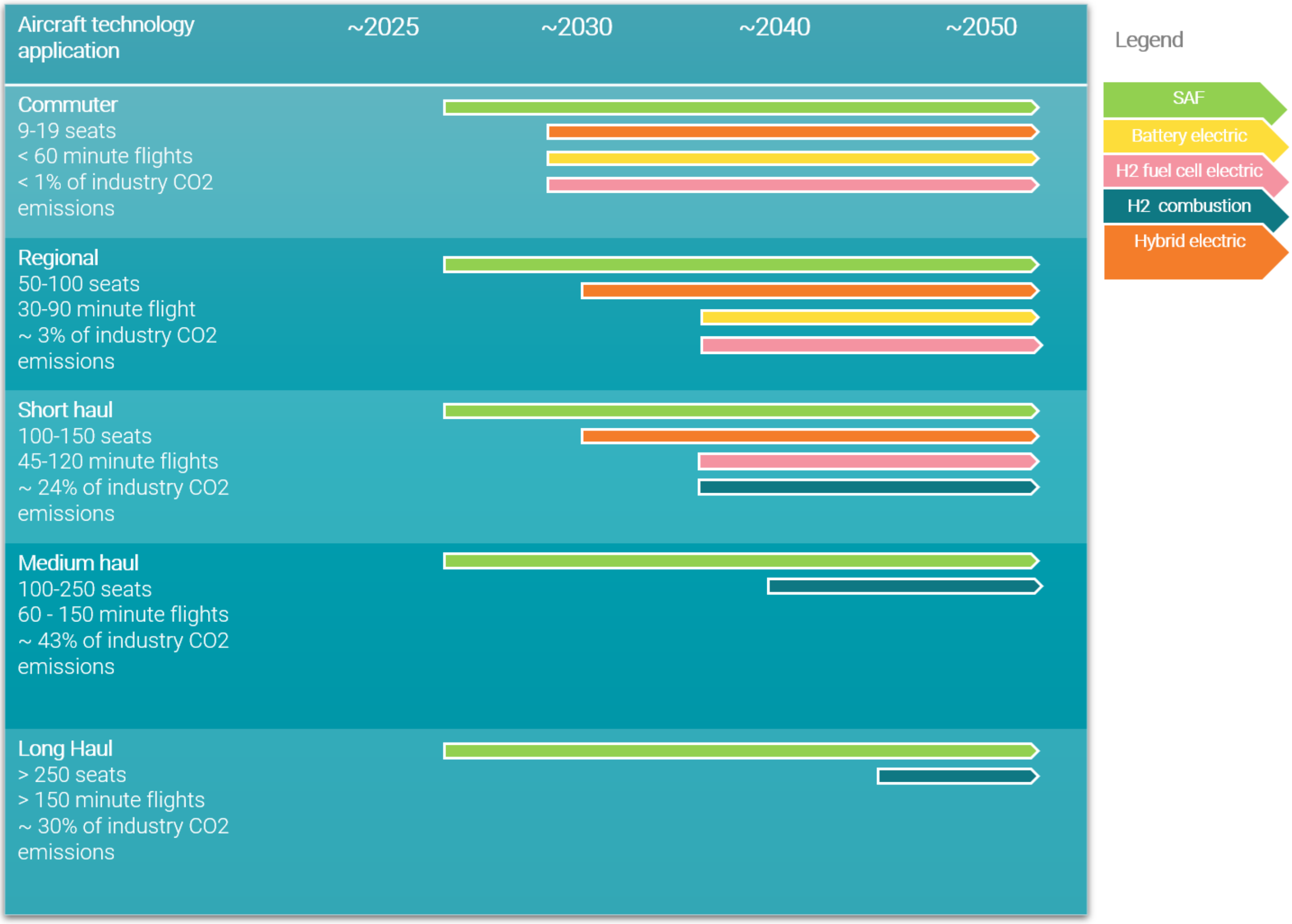
8.3 Technology application timeline

Knowing the strengths and weaknesses of each technology helps identifying the potential applications in the sector. A reoccurring phrase within the transition of the aviation sector is that “there are no silver bullets” – pointing to the fact that different technologies may excel under different circumstances. The ideal aircraft would score maximum score in all aspects shown in section 8.2. But as indicated, there is no such aircraft technology. This is due to the individual technologies each having their own pros and cons, causing trade-offs in costs, sustainability and technical performance. Safety will be high priority, as it has been throughout the development in aircraft and commercial aviation. As described in the chapters for each technology, there are both factors increasing and decreasing risks and hazards compared to conventional kerosene. The certifications required prior to any commercialization will set very high demands to safety. The remaining significant factors for which technologies may be applied will then be technical feasibility, environmental/climate impact as well as economics.

8.3.1 Technical feasibility

A general overview is presented in the figure below – indicating the potential applications of the various technologies presented in this technology review. Inspired by ATAG (2021), this figure is not a suggestion on which technologies will dominate the given routes. Rather, it should be seen as a perspective on which technologies may enter given route types, by a given timeframe.

Figure 37 Estimated potential technology application by year. Based on ATAG (2021).

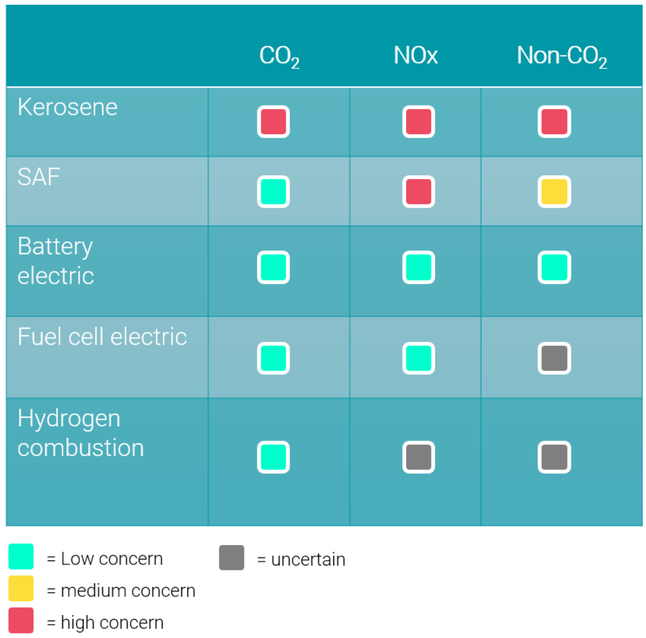


The figure illustrates how multiple technologies possess technical feasibility for shorter distances. However, these shorter routes are responsible for just few percent of the global emissions from passenger air traffic. The figure includes an estimate of the share of global CO_2-emissions from the given flight leg length. This is an indication of how battery electric, fuel cell electric and hybrid electric, while possibly well suited for some operations, are not competing to assist transitioning the longer routes, with larger aircraft, shown in the bottom rows of the figure. LH_2 combustion aircraft seems to be the only option to assist SAF for longer routes. SAF on the other hand, excels in its versatility and ability to mimic the use of conventional fuels. SAF appears as the only option for the longest flight in wide body aircraft, accounting for roughly 30% of industry emissions. The figure does not include perspectives on the availability of the fuels – but this is a key consideration. Especially SAF, that while technically versatile, may suffer from feedstock availability.

8.3.2 Environmental and climate related concerns

The different technologies introduce different areas of concern, in terms of emissions. Combustion at high temperatures leads to NOx emissions, which makes it an inherent challenge for propulsion systems relying on combustion. An overview can be seen in Figure 38.

Figure 38 Main emissions and contrail formation by each technology included in this review. Illustration by the Danish Energy Agency.



Kerosene is the propulsion technology with the highest concerns, both for CO_2, NOx and non-CO_2-effects. SAF improves the aspect of CO_2-emissions significantly, while still causing NOx emissions form the combustion process. The impact of non-CO_2-effects are deemed to be of medium concern for SAF, however this is very uncertain and depending on type of SAF. Battery electric propulsion systems excels in this perspective of emission concerns, as they avoid emissions entirely. Hydrogen is similarly tied to a complete CO_2-free operation. The aspect of non-CO_2-effects and NOx from H_2 remains uncertain, with current literature showing a wide range of possible outcomes depending on specific technology developments.

8.4 Future aviation trends

This technology review and the literature behind it, largely considers the aviation industry 'as is', with expectations of how alternative energy carriers may be able to assist a decarbonization of the sector. Arguably, there are new technologies, regulations or behaviours outside aviation that may affect the current and future demand. People may choose different transport modes to reach a given destination – especially if the increased costs from alternative aircraft technology makes alternative transport modes, such as high-speed trains more competitive.

Even within the aviation sector, new trends may emerge. As briefly covered in this review, electric vertical take-off and landing (eVTOL) aircraft are increasingly subject to research and development. And while these are not in position to replace the flight tasks of the type of lights included in this review – especially counting for narrow- and wide body aircraft, they may generate a demand of their own.

Following current projections from actors and organizations within the industry, there is reason to believe a continued growth with increased flight activities. This includes a continued trend of a higher number of flights, more passenger and more cargo. Consequently, the demand for fuel will continue to increase, further enforcing the need for zero or low-carbon alternatives in the sector.

9 References

ACI. (2021a). *Sustainable Energy Sources for Aviation: An Airport Perspective.* Airports Council International.

ACI. (2021b). *Integration of Hydrogen Aircrafts into the Air Transport System.* Airports Council International.

Adu-Gyámfi, B. A., & Good, C. (2022). Electric aviation: A review of concepts and enabling technologies. *Transport Engineering*.

Aerospace Global News. (2024). *ES-30: Getting to the Heart of the matter*. Retrieved from https://aerospaceglobalnews.com/news/es-30-getting-to-the-heart-of-the-matter/

Agora Verkehrswende. (2024). *Defossilising aviation with e-SAF – An introduction to technologies, policies, and markets for sustainable aviation fuels.* Berlin: Agora Verkehrswende.

Air Bridge Cargo Airlines. (2020). *airbridgecargo.com.* Retrieved from https://www.airbridgecargo.com/files/flipbook/2021/CargoAircraftGuideENG_2020_10NOV20_LR.pdf

Airbus. (2023). *At Airbus, hydrogen power gathers pace*. Retrieved april 2025, from https://www.airbus.com/en/newsroom/stories/2023-06-at-airbus-hydrogen-power-gathers-pace

Airbus. (2024b). *A350-900*. Retrieved from A350-900: https://aircraft.airbus.com/en/aircraft/a350-clean-sheet-clean-start/a350-900

Airbus. (2025). *Airbus showcases hydrogen aircraft technologies during its 2025 Airbus Summit*. Retrieved from https://www.airbus.com/en/newsroom/press-releases/2025-03-airbus-showcases-hydrogen-aircraft-technologies-during-its-2025

Airbus Deutschland GmbH. (2003). *CRYOPLANE - Liquid Hydrogen Fuelled Aircraft - System Analysis.*

Airliners, M. (2025). *Modern Airliners*. Retrieved from https://www.modernairliners.com/airbus-a350-xwb

Airplane Academy. (2025). *Turboprop vs. Turbofan: Safety, Efficiency, and Performance*. Retrieved from https://airplaneacademy.com/turboprop-vs-turbofan-safety-efficiency-and-performance/

Antonov. (2024). *An-124 Ruslan*. Retrieved from https://www.antonov.com/en/history/an-124-ruslan

ATAG. (2021). *Waypoint 2050, second edition september 2021.* ATAG: ATAG.

ATAG. (2024). *Aviation Benefits Beyond Borders.*

ATR. (n.d.). *The idea local commuter.* Retrieved from https://www.atr-aircraft.com/wp-content/uploads/2022/06/ATR_Fiche42-600-3.pdf

Aviation Impact Accelerator. (2024). *2030 Sustainable Aviation Goals.* University of Cambridge.

Axon Aviation Group. (2025). *AXON Aviation*. Retrieved april 2025, from http://www.axonaviation.com/commercial-aircraft/aircraft-data/aircraft-pricing/

Aygin, E., Town, N., Burrows, E., Hadnum, L., Whilier, M., & Milne, K. (2022). *Advanced Manufactuering - a key enabler for zero carbon emission commercial flight.* Fly Zero - Aerospace Technology Institute.

Bagarello S, C. D. (2024, August 06). A survey on hydrogen tanks for sustainable aviation. *Green Energy and Intelligent Transportation*, p. https://doi.org/10.1016/j.geits.2024.100224.

Bernard, M. R., Tankou, A., Hongyang, C., & Ragon, P.-L. (2022). *Charging solutions for battery-electric trucks.* International Council on Clean Transportation.

BMW AG. (2024). *Pioneering spirit for the mobility of the future.* https://www.bmw.com/en/electric-future/hydrogen-milestones-pioneering-spirit-for-the-mobility-of-the-future.html.

Boeing. (2019). 737 MAX Airplaine Characteristics for Airport Planning. D6-38A004 p 2-7.

Boeing. (2023). X66A Braced for the Next Bing Wing. *Innovation Quaterly*, Volume 7 issue 26.

Boeing. (2024). *boeing.com*. Retrieved from https://www.boeing.com/commercial/747-8/design-highlights#economy-and-performance

Boeing. (2024a). *About the Boeing 737 MAX family*. Retrieved from 737 MAX: https://www.boeing.com/commercial/737max#overview

Boeing. (2024b). *Boing 777*. Retrieved from Boeing 777: https://www.boeing.com/commercial/777#Anchor2

Bofinger, H., & Strand, J. (2013). *Calculating the carbon footprint from different classes of air travel.* The World Bank.

Brown, D. P. (2012). How long does it take to build a Boeing 777? *Airline Reporter*.

Cano, T. C., Castro, I., Rodriguez, A., Diego, L. G., Khalil, Y. F., Albiol-Tendillo, L., & Kshirsagar, P. (2021). Future of Electrical Aircraft Energy Power Systems: An Architecture Review. *IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION,*.

CFM Aeroengines. (2025). *Test Progress Builds Confidence in Open Fan Engine Architecture for the Future of More Sustainable Air Transport*. Retrieved from https://www.cfmaeroengines.com/press-articles/test-progress-builds-confidence-in-open-fan-engine-architecture-for-the-future-of-more-sustainable-air-transport/

Chevron. (2007). *Aviation Fuels - technical review.* Technical Review. Retrieved from https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf

Clean Sky. (2016). *Innovation takes off.*

CleanSky2. (2020). Hydrogen-powered aviation a fact based study of hydrogen technology, economics and climate impactby 2050.

Colozza, A. J. (2002). *Hydrogen Storage for Aircraft Applications Overview.* NASA - Glenn Research Center.

Cook, G. N., & Goodwin, J. (2008). *Airline networks: A Comparison of Hub-and-spoke and Point-to-Point Systems.* Journal of Aviation/Aerospace.

CORSIA. (2022). *CORSIA Eligible Fuels – Life Cycle Assessment Methodology*.

Danish Energy Agency. (2017). *Technology Data - Renewable Fuels.* Copenhagen: Danish Energy Agency.

Department for Business, Energy and Industrial Strategy. (2022). Our Vision for Zero Carbon Emission Air Travel.

Dyk, S. v., & Saddler, J. (2024). *Progress in commercialization of biojet/sustainable aviation fuels (SAF).* IEA Bioenergy, task 39.

EA Energy Analyses. (2018). *Biomass Statistics: Wood waste.* Copenhagen: Danish Energy Agency.

EASA. (2020a). *EASA certifies electric aircraft, first type certification for fully electric plane world-wide*. Retrieved from https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-certifies-electric-aircraft-first-type-certification-fully

EASA. (2020b). *Report from the Commission to the European Parliament and the Council - Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4).* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020SC0277

Ebrahimi, A., Rolt, A., Jafari, S., & Anton, J. H. (2024). A review on liquid hydrogen fuel systems in aircraft applications for gas turbine engines. *International Journal of Hydrogen Energy*, pp. 88-105.

Embry-Riddle Aeronautical University. (2024a). *Fundamentals of propulsion systems*. Retrieved from https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/introduction-to-propulsion-systems/

Embry-Riddle Aeronautical University. (2024b). Retrieved from Turbofan & turboprop engines: https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/turbofan-turboprop-engines/

Embry-Riddle Aeronautical University. (2024c). *Electrically-powered aircraft.* Retrieved from eaglepubs.erau.edu: https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/electric-aircraft/

Enmine Ogue, A. K. (2024). Thermodynamic, economi and environmental analysis of a hydrogen powered turbofan engine at varying altitudes. *International Jounal of Hydrogen Energy*.

European Aviation School. (2023). Retrieved from Aircraft engines: types and characteristics: https://easbcn.com/en/aircraft-engines-types-and-characteristics/

European Commision. (2024). *Reducing emissions from aviation*. Retrieved from climate.ec.europa.eu: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en

European Commision. (n.d.). *Reducing emissions from aviation.* Retrieved from https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en

European Commission. (2023). *EUR-lex - ReFuelEU Aviation*. Retrieved 03 17, 2025, from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202302405

Eviation. (2024). *Alice - The All-Electric Game Changer*. Retrieved from https://www.eviation.com/aircraft/

Faber, J., Király, J., Lee, D., Owen, B., & O'Leary, A. (2022). *Potential for reducing aviation non-CO2 emissions through cleaner jet fuel.* CE delft.

Fass, D. R. (2001). *CRYOLPLANE Flugzeuge mit Wasserstoffantrieb.* Airbus Deutchland GmbH. Retrieved from https://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2001_12_06_Cryoplane.pdf

Fehrm, B. (2020). The challenges of Hydrogen. Part 4. Hydrogen safety. *Bjorns Corner*, https://leehamnews.com/2020/08/14/bjorns-corner-the-challenges-of-hydrogen-part-4-hydrogen-safety/.

Fehrm, B. (2022). Bjorn's Corner: Sustainable Air Transport. Part 12. Hydrogen storage. *Leeham News*.

Fehrm, B. (2024). New Engine delevelopment, part 2, Thrust generation. https://leehamnews.com/2024/04/05/bjorn-s-corner-new-engine-development-part-1-thrust-generation/.

Fehrm, B. (2024). New engine development. Part 23. New versus old, GTF vs V2500.

Fehrm, B. (2025). *Air Transport's route to 2050.* Retrieved April 02, 2025, from https://leehamnews.com/2025/03/07/bjorns-corner-air-transports-route-to-2050-part-12/

Flight Safety Foundation. (2024). Database. *Aviation Safety Network*, https://asn.flightsafety.org/asndb/321248.

Florian Osselin, C. S. (2025). Orange hydrogen is the new green. *Nature Geoscience*, 15, pp 765-769, HAL Id: insu-03858117.

Fly Zero. (2022). *Cryogenic hydrogen fuel - system and storage.* Roadmap.

FlyRadius. (2025). Bombardier Q400 price. pp. https://www.flyradius.com/bombardier-q400/price.

FlyVolato. (2025). *urboprop plane vs. jet: Speed, altitude, efficiency differences.* Retrieved from https://flyvolato.com/turboprop-plane-vs-jet/

Fraunhofer. (2023a). *Lithium-Ion Battery Roadmap - Industrialization Perspectives toward 2030.* Fraunhofer ISI.

Fraunhofer. (2023b). *Alternative Battery Technologies Roadmap 2030+.* Fraunhofer ISI.

Freeman, S., Lee, D. S., Ling, L. L., Agnieszka, S., & De León, R. R. (2018). *Trading off Aircraft Fuel Burn and NOx Emissions for Optimal ClimatePolicy.* ACS.

Glenn Research Center. (2022a). *Glenn Research Center*. Retrieved from Airplane Parts and Function: https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/learn-about-aerodynamics/

Glenn Research Center. (2022b). Retrieved from Four forces on an Airplane: https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/four-forces-on-an-airplane/

GlobeAir. (2025). *Reserve Fuel*. Retrieved from https://www.globeair.com/g/reserve-fuel

Gnadt, A. R., Speth, R. L., Sabnis, J. S., & Barrett, S. R. (2019). Technical and environmental assessment of all electric 180 -passenger commercial aircraft. *Progress in Aerospace Science*.

Gould, J. (2022). *nasa.gov.* Retrieved from NASA: https://www.nasa.gov/aeronautics/nasas-solid-state-battery-research-exceeds-initial-goals-draws-interest/

Grönstadt, T., Xisto, C., Sethi, V., Rolt, A., Rosa, N. G., Yakinthos, K., . . . ahha, h. (2016). Ulra Low Emissions Technology Innovations for Mid Century Aircraft Turbine Engines.

Habib, M., Abdulrahman, G. A., Alquaity, A. B., & Qasem, N. A. (2024). Hydrogen combustion, production and applications: A review. *Alexandria Engineering Journal* , pp. (100) 2024 182-207 .

Hansman, R. J. (2014). *Analysis of Impacts of Aircraft Age on Safety for Air Transport Jet Airplanes.* MIT International Center for Air Tranpsortation, Department of Aerionautics and Astronautics.

Heart Aerospace. (2024). *Introducing the ES-30*. Retrieved from https://heartaerospace.com/es-30/

Hepher, T. (2025). Reuters. *Airbus postpones development of new hydrogen aircraft*. Retrieved from https://www.reuters.com/business/aerospace-defense/airbus-postpones-development-new-hydrogen-aircraft-2025-02-07/

Hillestad, M., Mohammad, O., Gonzalo, A. S., Erling, R., Bjørn, A., John, P., & Odne, B. (2018). Improving carbon efficiency and profitability of the biomass to liquid process with hydrogen from renewable power. *Fuel*, 20.

Hunt and Palmer. (2024). *Commercial airliners*. Retrieved from https://www.huntandpalmer.com/aircraft-guide/commercial-airliners/

IATA. (2015). *Report on Alternative Fuels.* Montreal-Geneva: International Air Transport Association.

IATA. (2019). *Liquid hydrogen as a potential low-carbon fuel for aviation.* International Air Transport Association.

IATA. (2024). Air Profitability Outlook Improves for 2024. pp. https://www.iata.org/en/pressroom/2024-releases/2024-06-03-01/.

ICAO. (2022). *REPORT ON THE UPDATED LONG-TERM TRAFFIC FORECASTS WITH POST-COVID-19.* International Civil Aviation Organization.

ICAO. (2024). *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels.* ICAO. Retrieved from https://www.icao.int/environmental-protection/Pages/SAF_RULESOFTHUMB.aspx

ICAO. (2024b). *Conversion processes*. Retrieved from https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

ICCT. (2020). *CO2 emissions from commercial aviation.* International Council on Clean Transportation.

ICCT. (2023). *Performance analysis of fuel cell treofit aircraft.* White paper.

IEA. (2023). *Global Hydrogen Review 2023.* International Energy Agency.

IEA. (2025). *Aviation*. Retrieved from Aviation: https://www.iea.org/energy-system/transport/aviation

Ingram, J., Benson, C., & Battersby, P. (2020). *Test Report on Hydrogen Flammability, Ignition and Release.* ENABLEH2.

IPCC. (1999). *Aviation and the Global Atmosphere.* Intergovernmental Panel on Climate Change.

IRENA. (2022). *Hydrogen*. Retrieved from https://www.irena.org/Energy-Transition/Technology/Hydrogen

IRENA. (2024). *Renewable energy highlights.* IRENA.

IRENA. (2024). *Wind energy*. Retrieved 12 16, 2024, from https://www.irena.org/Energy-Transition/Technology/Wind-energy

J. Hoelzen, D. S.-R. (2022). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure e Review and research gaps. *International Journal of Hydrogen Energy*, pp. 3108-3130.

Jayant Mukhopadhaya, P. (2023). *Performance analysis of Fuel Cell Retrofit Aircraft.* ICCT.

Jayant, M., & Rutherford, D. (2022). *Performance analyses og evolutionary hydrogen powered aircraft.* ICCT.

Korberg, A. D. (2021). The role of biomass gasification in low-carbon energy and transport systems. *Smart Energy*, 12.

Lambrecht, A. (2023). *Eviation CEO talks electrifying the skies with its upcoming plane.* Insideevs.

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C., Lim, L. L., . . . Sausen, R. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Elsivier.

Leishman, J. G. (2023). *Introduction to Aerospace Flight Vehicles.* Embry-Riddle Aeronautical University.

Ling-Chin, J., Giampieri, A., Wilks, M., Shiew, W., Bacon, E., Sheppard, I., . . . P. Roskilly, A. (2024). Technology roadmap for hydrogen fuelled transportation in the UK. *International Journal of Hydrogen Energy*, pp. 705-733.

lufthansagroup. (2024a). *Lufthansa Group*. Retrieved from https://www.lufthansagroup.com/en/company/fleet/brussels-airlines.html

Maciorowski, D., Ludwiczak, A., & Kozakiewicz, A. (2024). Hydrogen, the future aviation. *Combustion Engines*, 126-131 https://doi.org/10.19206/CE-178375.

Marksel, M., & Brdnik, A. P. (2023). Comparative analysis of direct operating costs: Conventional vs. hydrogen fuel cell 19-seat aircraft. *MDPI*.

Massaro, M. C., Biga, R., Kolisnichenko, A., Marocco, P., Monteverde, A. H., & Santarelli, M. (2023). Potential and technical challenges of on board hydrogen storage technologies coupled with fuel cell systems for aircraft electrification. *Journal of Power Sources*.

Mehedi, H., Redonnet, S., & Hernadi, A. (2021). Computational Investigation of Novel Box Wing Aircraft Concepts. *Applied Sciences*, https://doi.org/10.3390/app12020752.

Michal Kuropatwa, J. K. (2022). Turbofan engines efficiency, historical trends, and future predictions. A Review.

Military Aerospace Electronics. (2024). *Heart Aerospace debuts its first full-scale demonstrator*. Retrieved from https://www.militaryaerospace.com/commercial-aerospace/article/55139918/heart-aerospace-debuts-its-first-full-scale-demonstrator

Ministry of Climate, Energy and Utlities, Denmark. (2023). *The Esbjerg Declaration.*

Mohamed A. Habib, G. A., & Qasem. (2024). Hydrogen combustion, production, and applications: A reivew. *Alexandria Engineering Journal* , pp. 182-207.

Moradi, R., & Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal f Hydrogen Energy*, pp. 12254-12269.

Murat Ayar, T. H. (2023). Decision mechanism between fuel cell types: A case study for small aircrafts. *International journal of hydrogen energy*, 23159-23167.

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021). *Position Paper Fuel Option Scenarios.* Copenhagen: MMMCZCS.

National Grid. (2024). The hydrogen colour spectrum. pp. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.

Oldani, A. L., Solecki, A. E., & Tonghun, L. (2022). *Evaluation of physicochemical variability of sustainable aviation fuels.*

OliverWyman. (2024). *Global fleet and MRO market forecast 2024-2034.*

O'Malley, J., Pavlenko, N., & Searle, S. (2021). *Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand.* International Council on Clean Transportation.

Ostrower, J. (2025). *The Air Current.* Retrieved from https://theaircurrent.com/aircraft-development/electric-airplane-eviation-lays-off-most-staff-alice/

Patrao, A. C., Xisto, C., Jonsson, I., & Lundbladh, A. (2023). *ENABLEH2 – enablinging cryogenic Hydrogen-based CO2-free air transport.* H2020-MG-2016-2017/H2020-MG-2017-Two-Stages.

Pilotinstitute. (2024). Airplane Weight & Balance Explained.

Pipistrel. (2024). *electric pioneer*. Retrieved from https://www.pipistrel-aircraft.com/products/velis-electro/

Postma-Kurlanc, A., Leadbetter, H., & Pickard, C. (2022). *Hydrogen Infrastructure and operations.* Flyzero.

Pratt & Whitney. (2025). *Alternative Fuel*. Retrieved from https://www.prattwhitney.com/future-of-flight/alternative-fuel

Rao, A. G. (2015). *Ahead: Paving the Way for Next Generation Aircraft and Engine.* Research Gate.

Roland Berger. (2020). *Hydrogen a future fuel for aviation?*

Rolt, A., Lundbladh, A., & Williamson, I. (2022). *ENABLE H2 D5.2: Roadmap for the Introduction and Transition to Liquid Hydrogen for Civil Aviation.*

Schmidt, P., & Weindorf, W. (2016). *Power-to-Liquids Potentials and Perspectives for the Future Renewable.* Dessau-Roßlau: German Environment Agency GEA.

SES Hydrogen. (2022). H2 Safety #1: Understanding hydrogen. Physical and chemical properties of the fuel of the future. *SES Hydrogen New Letter*, https://seshydrogen.com/en/safety-of-hydrogen-systems/.

Skov, I. R., & Abid, H. (2024). *Renewable Aviation e-SAF Catalogue and System Impacts.* Copenhagen: Aalborg University.

Skov, I. R., & Abid, H. (2024). *Renewable Aviation e-SAF Catalogue and System Impacts.*

SkyNRG. (2024, November). Gering for the Market Deployment of SAF. Amsterdam.

Soler, Alba. (2022). *Sustainable biomass availability in the EU towards 2050 (RED II Annex IX, Parts A and B).* Concawe.

Sripad, S., Bills, A., & Viswanathan, V. (2021). *A review of safety considerations for batteries in aircraft with electric propulsion.*

Svensson, C., Oliveira, A. A., & Grönstedt, T. (2024). Hydrogen fuel cell aircraft for the Nordic market. 650-663.

U.S. Departement of Energy. (2024). *Hydrogen Safety*. Retrieved from https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheet.pdf

U.S. Department of Transportation. (2023). *Aviation Maintenance Technician handbook - Powerplant.* Federal Aviation Administration.

Ultimate Specs. (2025). Retrieved from https://www.ultimatespecs.com/aircraft-specs/boeing/boeing-737-max-8-2014

Voigt et. al. (2021). *Cleaner bruning aviation fuels can reduce contrail cloudiness.*

Wei, H., Liu, W., Chen, X., Yang, Q., Li, J., & Chen, H. (2019). Renewable bio-jet fuel production for aviation: A review. *Fuel*, 16.

Wikipedia. (2025). *Fuel Economy in Aircraft*. Retrieved from https://en.wikipedia.org/wiki/Fuel_economy_in_aircraft

World Economic Forum. (2020). *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.* World Economic Forum.

Yi-Sheng Chen, e. a.-Y.-W.-P. (2024). Hydrogen Trapping and embrittlement in metlas - A review. *International Journal of Hydrogen Energy*, p. https://doi.org/10.1016/j.ijhydene.2024.04.076.

Yusaf, T., Mahamude, A. S., Kadirgama, K., Ramasamy, D., Farhana, K., Dhadad, H. D., & Talib, A. A. (2023). *Sustainable hydrogen energy in avatioan - A narrative review.* Internation Journal of Hydrogen Energy.

10 Annex I

Assumptions for SAF calculations on efficiency and feedstock consumption

Fischer Tropsch selectivity to kerosene (%)	82%	(Skov & Abid, 2024)
Methanol to Jet efficiency (%)	74%	(Skov & Abid, 2024)
FT liquids of H_2 input PtJ setup (%)	70%	(Danish Energy Agency, 2017)
Methanol of H_2 input PtJ setup (%)	78%	(Danish Energy Agency, 2017)
Alkaline electrolysis efficiency (%) 2030 data	62%	(Danish Energy Agency, 2017)
Offshore wind capacity factor	55%	(Danish Energy Agency, 2017)
Offshore wind availability	97%	(Danish Energy Agency, 2017)
Syngas to FT liquids ratio	0,60	(Skov & Abid, 2024)
Hydrogen to FT liquids ratio	0,74	(Skov & Abid, 2024)
Syngas to methanol ratio	0,73	(Skov & Abid, 2024)
Hydrogen to methanol ratio	0,61	(Skov & Abid, 2024)
FT liquids of syngas input	75%	Based on (Hillestad, et al., 2018)
Gasifier efficiency (%)	77%	(Danish Energy Agency, 2017)
Energy content dry biomass (MJ/kg)	19	(EA Energy Analyses, 2018)

Alcohol-to-Jet efficiency (%)	55%	Estimated incl. product selectivity
HEFA from FOG inputs + refining	84%	(Danish Energy Agency, 2017)

Technology review on aviation

ISBN: 978-87-94447-27-0

Published April 2025 by

Danish Energy Agency
Carsten Niebuhrs Gade 43
DK-1577 Copenhagen

Phone: +45 3392 6700
E-mail: ens@ens.dk

ens.dk