Climate Change Impact Analysis of Electric Aviation

CE Delft
Committed to the Environment

Content

1 Management summary

Elysian currently develops the E9X, a zero emissions, battery-electric aircraft designed to transport 90 passengers over distances of 800-1,000 km. The E9X is anticipated to enter the market by approximately 2033.

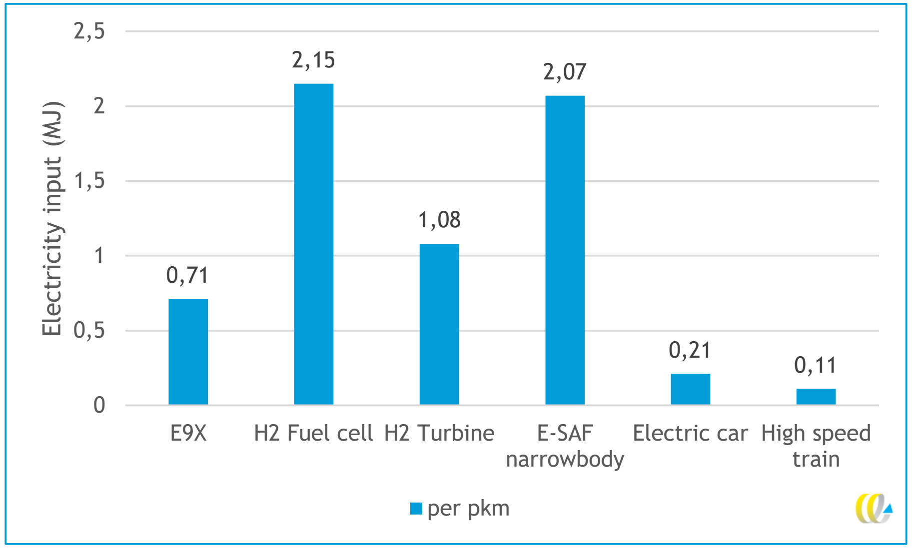
This study compares the E9X with aircraft powered by sustainable aviation fuels (SAF) and hydrogen, projected for 2035. Additionally, the analysis includes comparisons with electric cars and highspeed trains. The evaluation focuses on the following key aspects:

- system energy efficiency;
- life cycle climate impacts including non-CO_2 impacts;
- resources availability and infrastructural impacts.

System energy efficiencies

When comparing the system electricity per person-kilometre (pkm), the highspeed train and electric car demonstrate the lowest electricity demand, requiring 0.11 MJ/pkm and 0.21 MJ/pkm respectively. The E9X requires 0.71 MJ/pkm, while hydrogen-powered aircraft and those using sustainable aviation fuels (e-SAF) require 1.08-2.15 MJ/pkm and 2.07 MJ/pkm respectively (see Figure 1).

Figure 1 - Overview of system energy efficiencies of transportation options per pkm



Life cycle climate impacts

Greenhouse gas (GHG) emissions are generated not only during a vehicle's use or operation but also throughout other life cycle stages, including fuel production, vehicle manufacturing, and infrastructure development. For aviation, an additional significant contributor to climate change comes from non-CO_2 climate impacts. Emissions of nitrogen oxides (NO_x), sulfate aerosols, soot particles, and water vapor at cruising altitudes (~10 km) add to climate change as well. Historically, non-CO_2 impacts account for approximately twothirds of aviation's total climate impact. For this reason, non-CO_2 climate impacts are included in the analysis.

Figure 2 - Climate change impact per persons kilometre of the E9X and competing transport options by air and over land (policy mix for electricity 2035)

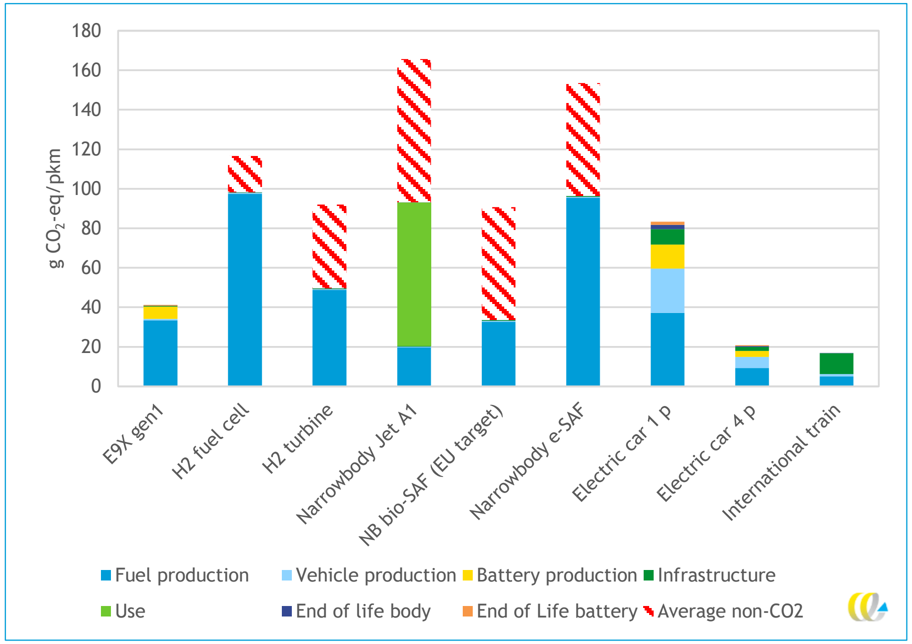
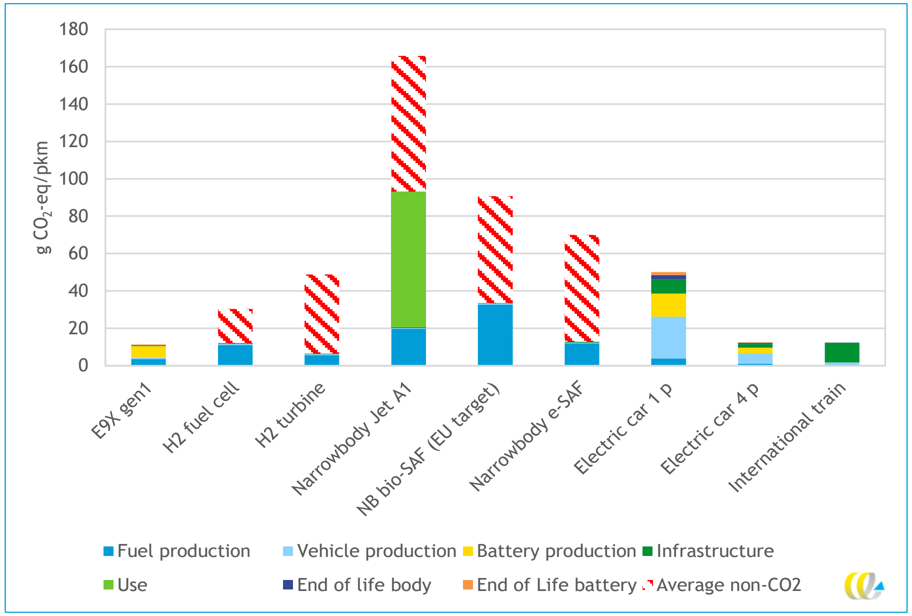


Figure 2presents the results of a climate change impact analysis for 2035. Off all aviation options (the six bars on the left), the E9X has the lowest climate change impact, with its main contribution coming from generation of energy to charge its batteries.

For kerosine Jet A-1, the main contributors are non-CO_2 impacts and fossil CO_2 emissions during operation.

Hydrogen-powered aviation and e-SAF exhibit high GHG emissions due to fuel production. This is due to emissions from grid electricity used to product hydrogen and to capture CO_2, which depends on the grid electricity mix. In addition hydrogen and SAF inhibit much larger non-CO_2 climate effects than electric aviation. SAF production varies significantly depending on the method: for bio-SAF, the EU emission target is applied to model the phase, while E-SAF is modelled using CO_2 captured via direct air capture (DAC) and green hydrogen.

Figure 3 - Future Climate change impact per persons kilometre of the E9X and competing transport options by air and over land (using wind energy as a proxy for 2050)



In a ‘sustainable’ scenario (see Figure 3), emissions from fuel production across all alternatives are significantly reduced. However, non-CO_2 climate impacts remain the largest contributor to climate change (potential reduction of non-CO_2 impacts by operational adjustments is not taken into account here). In this future scenario, the E9X achieves the lowest climate impact among aviation options and is comparable to land-based transportation alternatives.

Resource availability

All climate change mitigation technologies build on specific and often scarce resources. Renewable electricity, in particular, is a critical resource in high demand across various sectors to meet climate targets. Battery-electric aviation, with the lowest electricity demand per passenger-kilometre (pkm), has a clear advantage over other aviation technologies but is only applicable for short haul travel. In addition bio-SAF also requires substantial supply of biomass, which faces even greater competition from other sectors than renewable electricity. In case of scarce resource supply SAF should be used for longer haul travel and battery electric for short-haul flights.

Infrastructural challenges

Switching from fossil kerosene to SAF requires minimal additions to existing fuel and aircraft infrastructure. SAF is a drop-in fuel that can be easily transported and managed using current infrastructure. However, transitioning to battery-electric aviation especially in the Netherlands would most likely necessitate significant upgrades to local electricity grids. These expansions could be challenging to implement by 2035 due to electricity grid capacity constraints. Despite this, the total additional grid capacity required at a national level is expected to remain manageable and not pose significant obstacles.

General conclusions

The challenge of reducing the climate change impacts of the aviation sector is a big undertaking. All improvement technologies discussed should be used to their best advantage to meet this challenge. In this one technology is not necessarily better than the other but all will need to be used in combination. This analysis shows that the application of electric aviation can make a considerate contribution to reducing climate change impacts on the sector in which short haul flights are responsible for 19% of total emissions. When these flights can be covered with electric aviation these emissions can be reduced with ~70% in 2035 and up to 90% in a further future.

Although the E9X is still under development, this comparative assessment of three alternative aviation technologies shows that battery electric aviation is a strong and viable candidate for reducing the aviation sector's climate change impact. The E9X’s high potential to reduce lifecycle climate change impacts is due to the high energy efficiency of the system (lower resource use) and the absence of non-CO_2 climate impacts during its use phase. And although the operational range is smaller than that of conventional aircraft that could use SAF or newly developed hydrogen aircraft, application of the E9X to short range flights offers a great opportunity to reduce the climate change impact of short-haul flights and a considerate part of the climate change impacts of the entire aviation sector.

2 Introduction

Elysian currently develops a zero emissions aircraft, the E9X. This battery electric aircraft is expected to transport 90 passengers over distances of 800-1.000 km and will enter the market around 2035.

This report provides a transparent comparative impact assessment in which the E9X is compared to other long-distance passenger travel options. Different options are compared on system energy efficiency, life cycle climate impacts including non-CO_2 impacts, resource availability and potential infrastructural impacts. The aim of this report is to put different technologies for decarbonization of aviation into perspective in order to obtain insights into how and how much different decarbonization options can contribute to climate targets.

Reading guide

- Chapter 3 elaborates on the climate change impacts of long-distance passenger travel and introduces routes that are currently proposed to reduce these climates impact, with a focus on decarbonization options for aviation.
- Chapter 4 elaborates on the system energy efficiency of different decarbonization routes and shows how much electricity is required for different passenger transportation options.
- Chapter 5 discusses the climate change impact of different long-distance passenger transport options over the entire life cycle in the form of an LCA. The analysis includes non-CO_2 climate impacts from aviation.
- Chapter 6 discusses the broader implications of SAF based decarbonisation of the aviation sector with respect to resource availability, infrastructural requirements and costs.
- Chapter 7 contains a case study on the Dutch electricity grid to understand possible implication of electric aviation on the energy grid.
- Chapter 8 contains a short discussion and the conclusion.

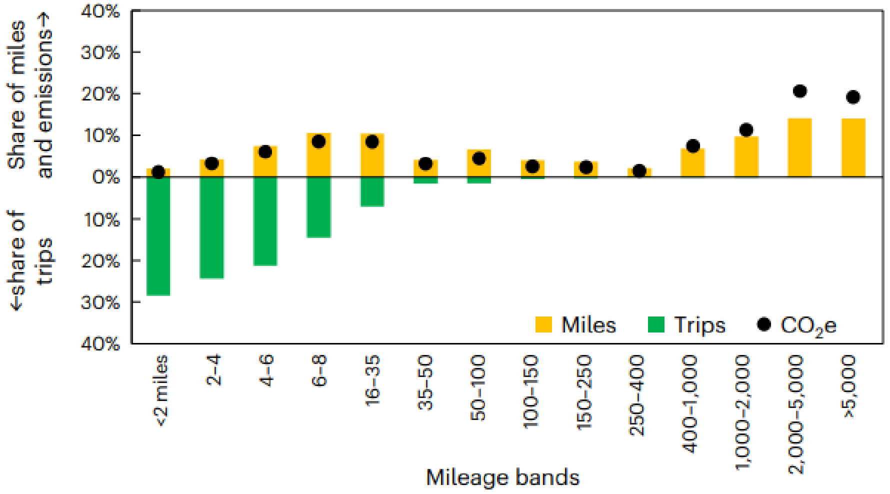
3 Climate impacts of long-distance passenger travel

3.1 Overview long-distance travel

‘Motorised transport by land, sea and air remains dependent on internal combustion engines, generally powered by fossil fuels. Transport accounts for more than one-third of CO_2 emissions from end-use sectors’. (IEA, 2024e)

- Within transport, passenger mobility accounts for 55% and freight transport for 45% of global emissions (IEA, 2024f).
- Long-distance travel (LDT) accounts for a small proportion of total passenger travel but a large proportion of distance travelled and GHG emissions, of which CO_2 is the main source.
- A recent UK study(Wadud et al., 2024) found that in the UK only 2.7% of a person's trips are long-distance (> 50 miles one way), but they account for 61% of the distance travelled and 69% of total GHG emissions from passenger transport.
- As air travel covers the largest distance range, the small share of 0.4% of all trips results in 44% of the distance travelled and 55% of the GHG emissions.

Figure 4 - Distribution of per capita trips (one-way), mileage and GHG emissions at different distance bands



Source: (Wadud et al., 2024).

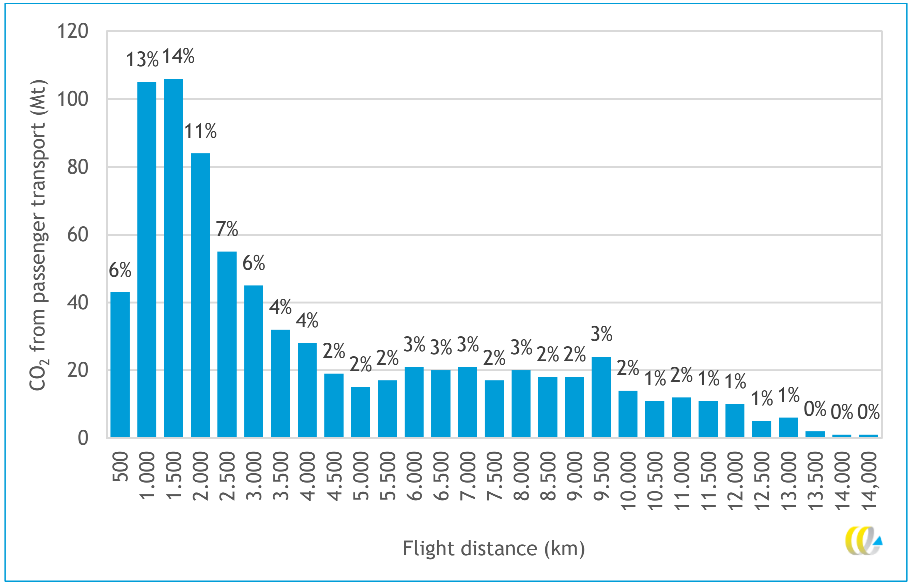
Flying contributes, with only 0.4% of all trips contributing to 55% of per capita travel GHG emissions.

- In recent decades, the volume of long-distance travel, and in particular air travel, has increased at high growth rates that have outperformed efficiency improvements in the aviation sector, resulting in an average annual growth in CO_2 emissions of 4-5%. (see Figure 5).

Figure 5 - Development of global air traffic and efficiency improvements (left) and CO_3 emissions (right) based on (Lee et al., 2021)

- In 2019, aviation's share of global CO_2 emissions was 2.4% (tank-to-wing emissions from fuel combustion) and 3.9% (well-to-wing emissions, including emissions from fuel production and distribution).
- The distribution of emissions by distance class (Figure 6) shows that approximately 50% of CO_2 is emitted on flights of less than 2,500 km, with the remaining half emitted on flights of longer distances.

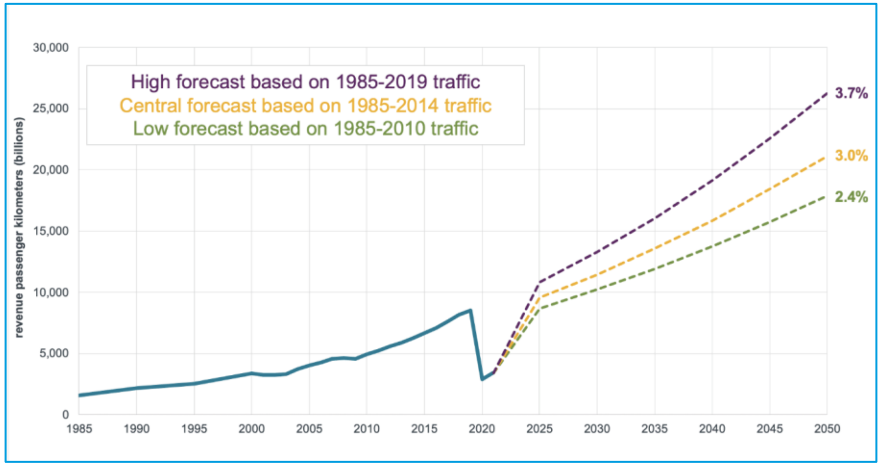
Figure 6 - Global passenger aviation CO_2 emissions in 2019 by flight distance



Source: (ICCT, 2020).

- All demand forecasts and decarbonisation roadmaps (IATA, 2024a) assume growth in global passenger-kilometres (Figure 7 shows an example). The uncertainty in the growth rates depends, among other things, on environmental policies that affect ticket prices.

Figure 7 - Long-term global aviation demand forecast



Source: (Graver, 2022).

3.2 Decarbonization options for aviation

For aviation, generally considered a 'hard to abate' sector, technological decarbonisation options are still being developed. An important recent realisation is that aviation contributes to climate change through so-called non-CO_2 climate impacts (discussed in more detail below). These are emissions of NO_x, sulphate aerosols, soot particles and water vapour at cruising altitudes. These emissions also occur at ground level from other sectors, but only contribute to global warming at high altitudes. The different decarbonisation options for aviation all affect climate change through non-CO_2 climate impacts in different ways.

A shift towards Sustainable Aviation Fuel (SAF)

- Sustainable Aviation Fuel (SAF) can be made from biomass (bio-SAF) or from green hydrogen and CO_2 using renewable electricity (e-SAF).
- SAF is compatible with existing aircraft engines and can be blended with fossil-based fuels. Depending on the certification of the aircraft blending ratios up to 50% are allowed. In the future this ratio will increase to 100%.
- Since it has the same properties as fossil fuel, it can be used for all range of aircraft operations.
- As the fuel infrastructure and aircraft require only minor adaptations, SAF can be considered technically easy to implement.
- Bio-SAF prices are currently 2 to 9 times higher than fossil kerosene prices, and e-SAF prices are 5 to 9 times higher (see subsection 'SAF price projections'). Although these price gaps are expected to decrease over time, SAF will remain an expensive option in the short to medium term.
- SAF is still under development and not widely implemented yet. Currently, SAF accounts for less than 0.1% of all aviation fuels consumed globally, but the IEA's Net Zero Emissions scenario projects 10% SAF use by 2030.

This is much higher than the currently planned production capacity, which will supply 1-2% of jet fuel demand by 2027. This implies a significant increase in investment and capacity (IEA, 2024a).

- The SAF used today is bio-SAF. The current dominantly used biomass feedstocks are oil crops and waste fats and oils. The EU's Renewable Energy Directive puts a cap on the use of these feedstocks. Although 'advanced' biomass feedstocks such as residues from agriculture and forestry may be used as well, their availability is limited and they require other production technologies which are less technologically developed. E-SAF does not require biomass and is expected to play an important role in the longer term.
- The EU has introduced an SAF blending obligation (RefuelEU Aviation) for all commercial flights departing from EU airports. The SAF blending rate increases over time, reaching 70% in 2050, with a sub-target for e-SAF (35% of the total).
- Although the expectations for reducing the climate change impact of aviation are promising, full implementation of SAF is challenging due to availability and competition for resources such as biomass, renewable electricity and technologies that are not yet at scale. The challenges for SAF are discussed further in Chapter 6.

A shift towards hydrogen aircrafts

- Hydrogen produces no CO_2 when burned and can be a zero emission fuel if clean energy is used in the production process (green hydrogen). But does cause non-CO_2 climate impacts (see section on non-CO_2 impacts)
- Hydrogen can be used by direct combustion in jet engines or in fuel cells to generate electricity for electric motors.
- Although the prospects for reducing the climate change impact of aviation by moving to hydrogen-powered aircraft appear promising, there are a number of challenges to the full implementation of hydrogen in aviation.
- The production of green hydrogen needs to be scaled up, the infrastructure to transport it to airports and store it locally needs to be realised, and new hydrogen aircraft are only in the early stages of development. A major challenge is the storage of hydrogen in aircraft, as the volumetric energy density of hydrogen is about four times less than that of kerosene (Piper, 2022). So far, only test flights of hydrogen-powered aircraft have taken place.
- The energy density limits the range of efficient hydrogen aircraft to about 4,000 km, making it not an option for long-haul flights.
- Similar challenges to those identified for SAF could apply to hydrogen, in particular the availability of and competition from renewable energy and the availability of technology and infrastructure on a large scale. These challenges will be discussed further in Chapter 6.

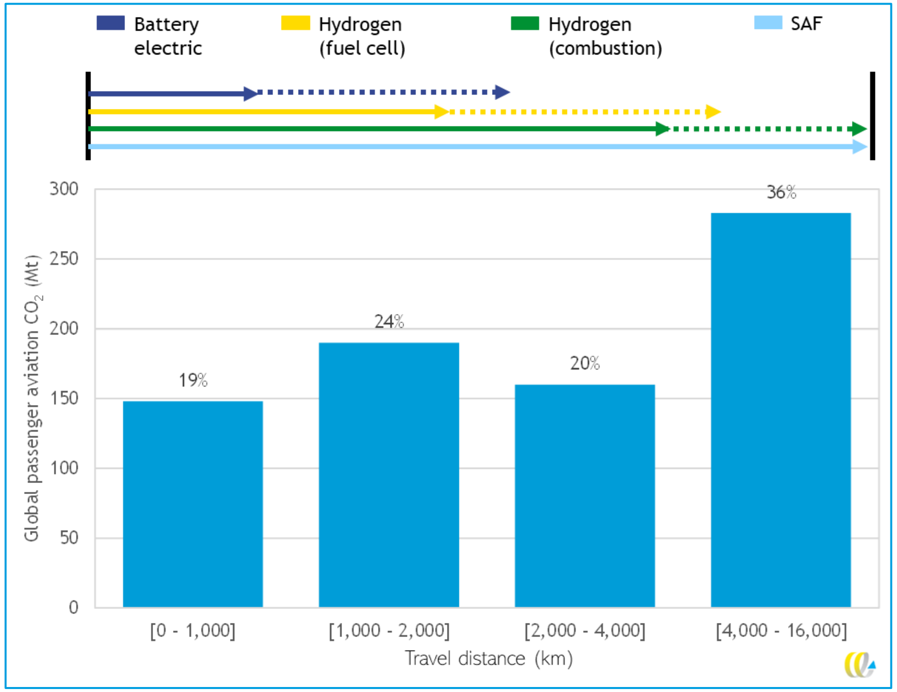
A shift to battery electric aircraft

- A battery electric aircraft has no direct CO_2 emissions during the operation of the aircraft and appears to be an energy efficient option when considering the other options.
- Current battery energy density and weight limit the range of battery electric flights and the size of the aircraft.
- Small two-seater electric aircraft are already in use, but larger electric aircraft have only been tested.
- The Elysian aircraft is an alternative option for ranges up to 1,000 km.
- Challenges for full implementation are the availability of sufficient resources (renewable electricity, technology at scale, energy infrastructure). These challenges will be discussed in more detail in Chapter 6.

Typical operation of decarbonisation options for the aviation sector and their impact on climate change:

- For long-haul flights over 4,000 km, SAF appears to be the only viable decarbonisation option due to the energy density limitations of hydrogen and batteries. SAF-fuelled aircraft are of course technically feasible for shorter distances.
- For the medium-haul range (1,500 km to 4,000 km), hydrogen aircraft appear to be an additional option to SAF. The expected maximum range for hydrogen aircraft is about 3,500 km by 2040 (ICCT, 2022b).
- For short-haul flights (up to 1,500 km), battery electric aviation is also a possibility, with Elysian's E9X expected to be operational around 2033.
- As a future possibility it should be noted that longer travel distances per technology can be achieved when a step-over is considered (see dotted lines in Figure 8). The analysis in this report only considers point to point travel without step-overs.
- Figure 4 shows the global CO_2 emissions from passenger aviation (using almost 100% fossil fuel) by distance class and the corresponding decarbonisation options:
  - short-haul flights up to 1,000 km contribute 19% of global aviation CO_2 emissions;
  - medium-haul flights between 1,000 km and 4,000 km account for 44% of emissions;
  - long-haul flights over 4,000 km account for the remaining 36% of emissions.

Figure 8 - Global passenger aviation CO_2 emissions for 2019 by distance class and technological decarbonisation options



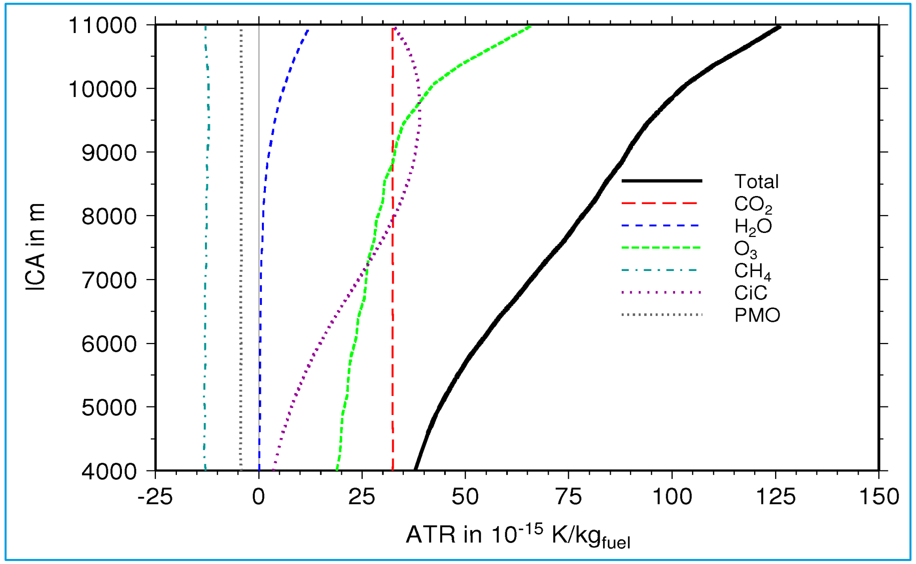
Source: CE Delft analysis based on (ICCT, 2020).

3.3 Non-CO_2 climate impacts in aviation

- In addition to CO_2, aviation emits NO_x, sulphate aerosols, soot particles and water vapour at cruise heights of about 10 km. These emissions are also produced at ground level by other sectors, but only contribute to global warming at high altitudes (see Figure 9) due to chemical and physical processes. The two largest non-CO_2 climate impacts from aviation are
  1. Contrail-induced cloudiness (CiC).
  2. NO_x emissions, which enhance ozone formation (Pro3) and methane (CH_4) depletion.
- The impact of non-CO_2 depends not only on the quantities emitted, but also on the location of the emissions (mainly altitude and latitude) and the actual atmospheric conditions (weather, time of day). For CO_2, the climate impact is independent of the location of the emission.
- In contrast to CO_2, the time horizon of non-CO_2 effects is much shorter, ranging from hours for condensation trails to decades for other types. The different timescales of the CO_2 and non-CO_2 effects make it difficult to compare them with global warming. One attempt to make them comparable is to define CO_2 equivalents (CO_2e), for example by averaging the effects over a hundred years with the GWP100.
- There is still considerable scientific uncertainty about their quantification.
- Best estimates of the total radiative forcing effect are between a factor of 2 and 4 times greater than that of CO_2 (European Commission Directorate-General for Mobility and Transport, 2020). (Lee et al., 2021) have investigated that the cumulative contribution of non-CO_2 effects of aviation between 1940 and 2018 is about 66%. Including aviation's non-CO_2 emissions makes its climate impact assessment more complete.

For current aircraft powered by fossil fuels, the climate impact of the non-CO_2 effects of aviation is twice as great as its CO_2 impact.

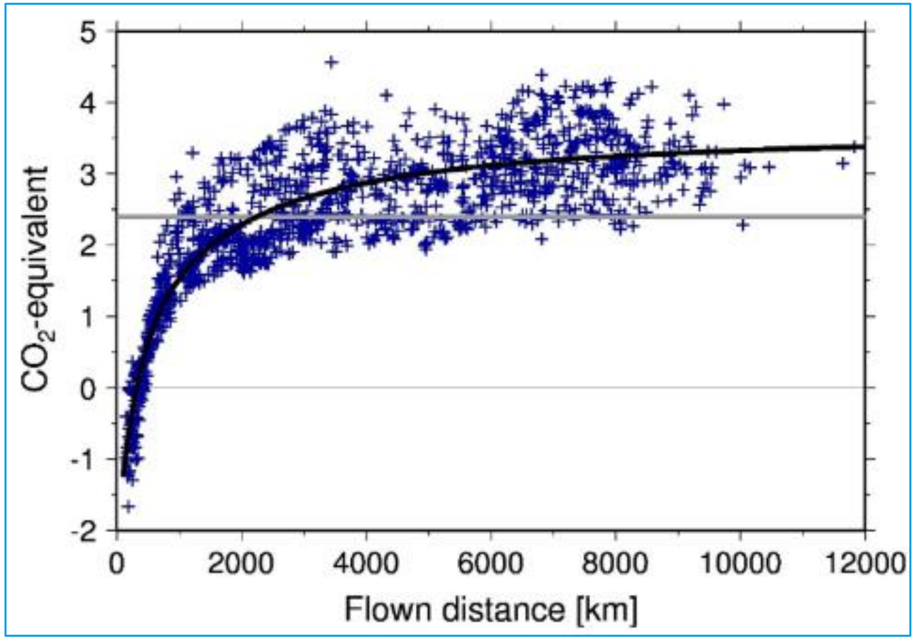
Figure 9 - ATR per kg fuel in dependency of the initial cruise altitude (ICA) for the route DTW-FRA



Source: (Dahlmann et al., 2016).

- The non-CO_2 effect is dependent on flight distance, as shown in Figure 10. his is caused by the fact that shorter flights on average have a lower altitude (a relatively larger part of the flight is take-off, climb, descent and landing). At lower altitudes, the non-CO_2 effects are smaller (see Figure 9).
- or flights between 500 km and 1,000 km (the range of the Elysian aircraft), the non-CO_2 equivalent factor is about 1. This means that the non-CO_2 effect is equal in size to the CO_2 effect.

Figure 10 - Non-CO_2 effect dependency on flight distance in the ATR100 metric. A CO_2 equivalent factor of 2 implies that non-CO_2 effects are twice as large as CO_2 effects



Source: (Dahlmann et al., 2021).

Reduction options for non-CO_2 effects

- It has been suggested that night time flights should be converted to daytime flights to avoid the greater net warming at night and to reduce the impact of linear contrails (Stuber et al., 2006). However, recent measurements combined with contrail cirrus modelling show no net benefit due to observed contrail cirrus lifetimes of up to 18 hours (Newinger & Burkhardt, 2012).

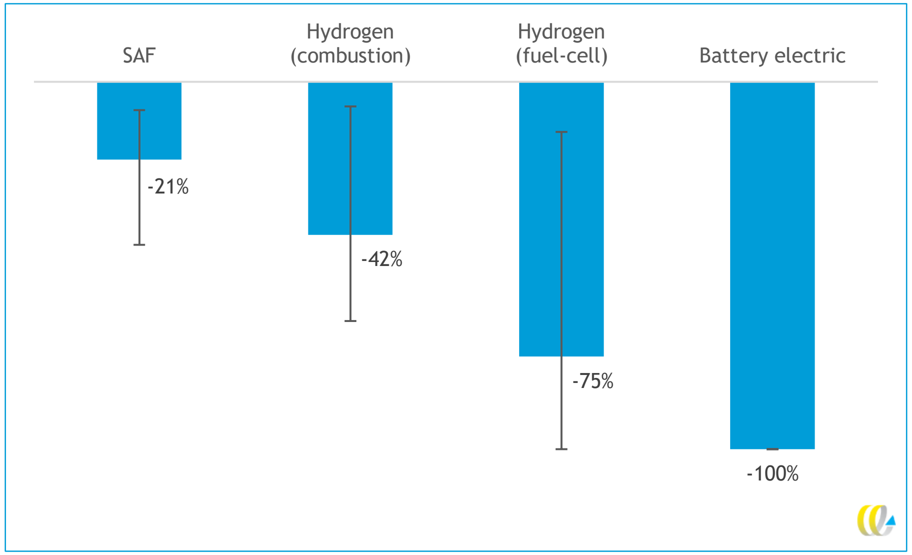
- There is potential for operational adjustments to reduce non-CO_2 effects, such as flying at lower altitudes and avoiding certain atmospheric conditions. Teoh et al. (Teoh et al., 2020) concluded that rerouting 1.7% of flights could reduce contrail energy forcing by 59.3% with only a 0.014% fuel burn penalty.
- Hydrotreating fossil kerosene reduces the concentration of aromatics in the fossil fuel, thereby reducing contrail formation and the non-CO_2 climate impact.

Technologies such as SAF and hydrogen aircraft can reduce non-CO_2 emissions, but battery electric aircraft eliminate all non-CO_2 emissions.

Impact of technological decarbonisation options on non-CO_2 effects

- SAFs generally have a lower concentration of aromatics and therefore also reduce contrail formation (Bräuer et al., 2021; CE Delft et al., 2022).
- Hydrogen aircraft would eliminate soot particle emissions, which stimulate contrail formation. However, the use of hydrogen would increase water vapour emissions compared to fossil kerosene. It is still uncertain whether the net effect would be to reduce or increase contrail formation. NO_x emissions would be eliminated by using hydrogen in a fuel cell, or could be significantly reduced by burning hydrogen. (FlyZero, 2022a; McKinsey, 2020). Battery electric aircraft would eliminate all non-CO_2 emissions (ICCT, 2022c). Figure 11 shows our best estimate of the reduction in non-CO_2 climate impact for the different technological decarbonisation options for aviation.

Figure 11 - Non-CO_2 reduction potential of technological decarbonization options compared to using fossil kerosene



Source: CE Delft analysis based on (Lee et al., 2021), (McKinsey, 2020) and (Märkl et al., 2024).

3.4 Comparison with land-based alternatives

- Since battery electric aviation is only practically feasible on short-haul routes, we compare transportation modes that cover distances up to 1,500 km. For distances within this range, land-based modes of transport like cars, buses or trains are viable options for travellers.
- For cars, buses and trains, electrical alternatives are well-developed and readily available. It is anticipated that they will be widely adopted by 2030:
  - Currently, 18% of cars sold globally are electric. The IEA anticipates that this figure will reach approximately 65% by 2030. (IEA, 2024b)
  - Several countries, including China, have already achieved electric bus sales shares above 50%. However, globally, this figure stands at just 3%. The IEA anticipates that a combination of battery electric, hybrid and fuel cell electric vehicles will account for 46% of bus sales by 2030. (IEA, 2024g)
  - Almost half of the global rail capacity (45%) is already electrically powered. Many countries are investing in their rail infrastructure. China is expanding its network with a focus on high-speed rail, India is concentrating on rapid electrification, and Europe is modernising its rail network. (IEA, 2024c)

Considerations on land-based travel compared to aviation

- It is evident that there are notable distinctions between land-based and air-based modes of transportation:
  - It should be noted that travel over water can be challenging and often necessitates lengthy detours, as evidenced by routes from Southern Europe to Africa or travel between islands in South-East Asia or Central America.
  - Similarly, land-based travel through mountain ranges can be challenging or result in lengthy detours.
  - Furthermore, travel in parts of the world where no road or rail infrastructure is available can be difficult or not possible.
- From a travel time perspective, land-based transportation options are less competitive than aviation. To illustrate, consider the Amsterdam to Vienna route, which is approximately 940 km by great circle distance and thus suitable for electric aircraft. Despite the availability of efficient road and high-speed rail networks, land-based transportation options still require two to five times longer travel times than flying:
  - The flight time is currently estimated to be between 1 hour 40 minutes and 2 hours (Skyscanner, ongoing). Additionally, there will be approximately 2 hours before the flight at the airport and approximately 1 hour at the destination airport to collect luggage. Total: ~5 hours

  - The electric car has an estimated journey time of 11 to 15 hours, depending on traffic and road conditions, but offers a direct arrival at the chosen destination (Google, ongoing)
  - The estimated travel time for the electric bus will be between 16 and 24 hours, depending on the chosen connection (Flixbus, ongoing)
  - Rail journey time is between 11 and 17 hours, depending on the connection (NS International, ongoing)
- The construction and maintenance of rail infrastructure is a costly undertaking. In comparison to the infrastructure of aviation, the cost of rail infrastructure can be three to six times higher, depending on the route (CE Delft, 2023a). Therefore, rail represents a more expensive travel option than flying. These costs can decrease however, by increasing the current low occupancy rate for high speed rail.
- It is important to note that the emissions per passenger kilometre of a passenger car are highly dependent on the occupancy rate of the vehicle. It is likely that the majority of routes considered here (in excess of 80 km but below 1,500 km) will have a higher than average occupancy rate (the average occupancy is approximately 1.3 for a passenger car (CE Delft, 2023b)). Therefore, a vehicle filled with a family of four on holiday will emit three times less per passenger kilometre than a car trip with average occupancy.

4 System energy efficiency of different passenger transportation options

- In this chapter, we define the system energy efficiency as a measure of the amount of grid electricity required to provide 1 MJ at the motor or engine shaft per transportation mode (Figure 12), and the transport efficiency as the quantity of electricity required to transport a single passenger over a distance of 1 km, expressed in pkm (Figure **13**) The first is converted to the second by using the factors presented in Table 6.
- This analysis includes energy losses from transmission and intermediate processes such as hydrogen production and liquefaction. The analysis excludes energy transmission from the shaft of the engine, turbine or motor to the propeller. Efficiency data on different processes and steps vary over the literature. For his analysis, the efficiency data are based on LHV values, taken from public available sources and representing expected values for 2035 (Table 5).
- For hydrogen based aircraft, conceptual designs from FLyZero (DNV, 2022) are taken for reference. Design choices such as capacity and design mission distance do have an influence on the results.

SAF production efficiency

- For this study it is assumed that SAF is produced from hydrogen and CO_2 by using the Fischer-Tropsch (FT) process.
- The production of e-SAF at scale has until now not been proven and there are several factors that influence the efficiency of Fischer-Tropsch fuel production, such as choice of technology, efficiency of the electrolysis process and for example reuse of produced heat. The desired ratio between end products, e.g. diesel, kerosene, wax and gas is also influential on the overall efficiency.
- (Grahn et al., 2022) performed a literature review and reports the efficiency (energy in/energy out) of e-fuel plants to range from ~40% currently to ~50% in around 2050. (Boilley et al., 2024) reports similar efficiencies (~48%) for generic PtL plants but also states that the efficiency of PtL jet fuel plants could be around 38% because of the specific requirements to produce jet fuel from the complete product slate.
- For the SAF production efficiency used in the system energy analysis and for the LCA is consistently assumed to

be 48%. This is considered as a progressive number in order to avoid presenting SAF in a too negative way.

- When the SAF production efficiency is considered 38%, the input of required grid electricity would rise to 6.58 MJ instead of 5.24 MJ.
- Figure 12 shows that in order to obtain a 1 MJ of energy at the shaft of the motor/engine, battery electric aviation is comparable to using a battery electric car or high speed train. A hydrogen aircraft requires 2,3 - 3,5 times as much electricity and using E-SAF requires 4 times as much energy.
- In Figure **13** these numbers are converted into the electricity input required to transport 1 passenger over 1 km (pkm). Here we see that a high speed train (even with an assumed occupancy of only 47% uses the least amount of renewable energy for 1 pkm. After a battery electric car, battery electric aircraft comes in third place. Providing 1 pkm with a hydrogen fuel cell aircraft is the least favourable option when looking at system energy efficiency.

Figure 12 – System energy efficiency of selected transportation options for 2035

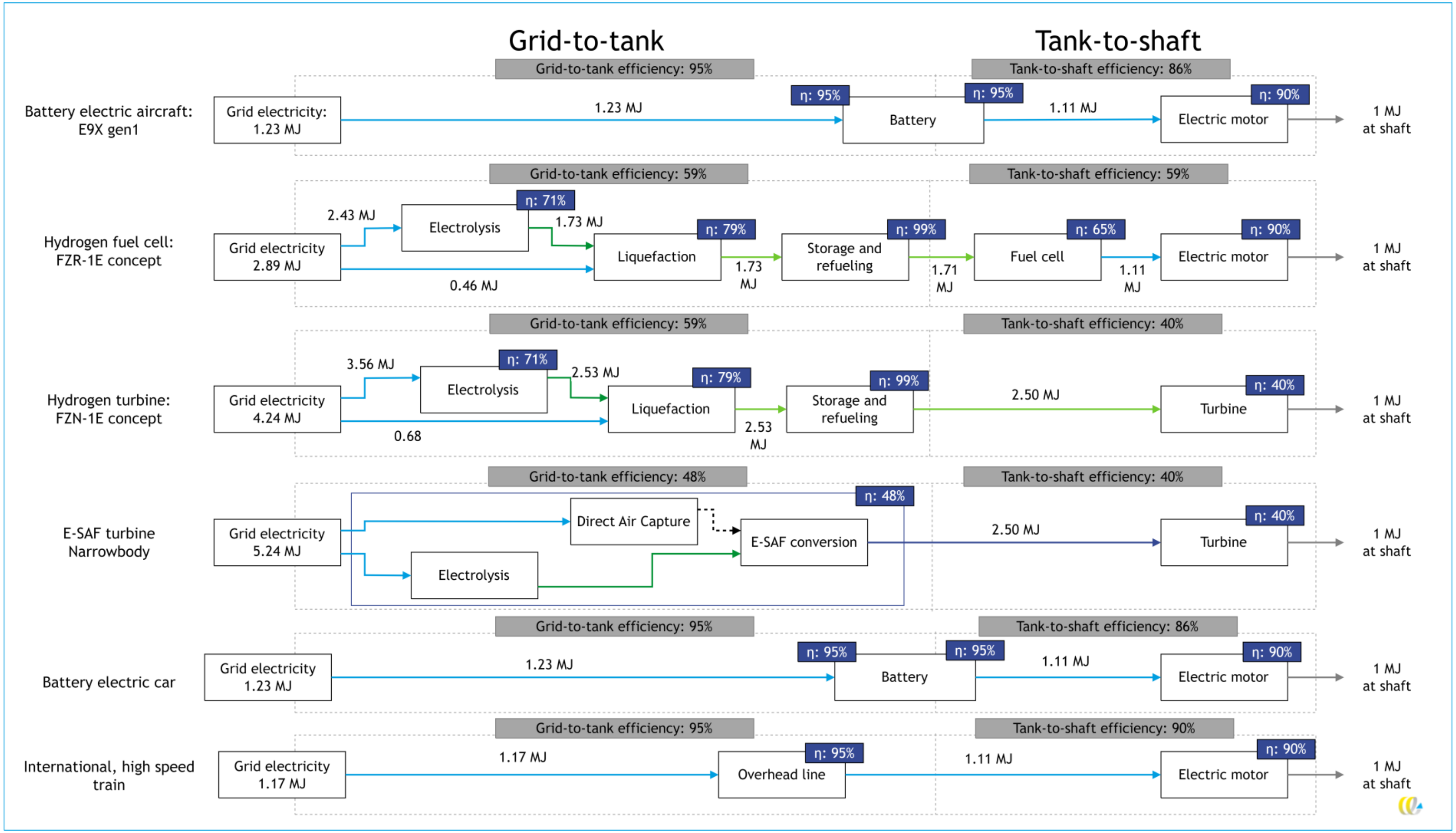
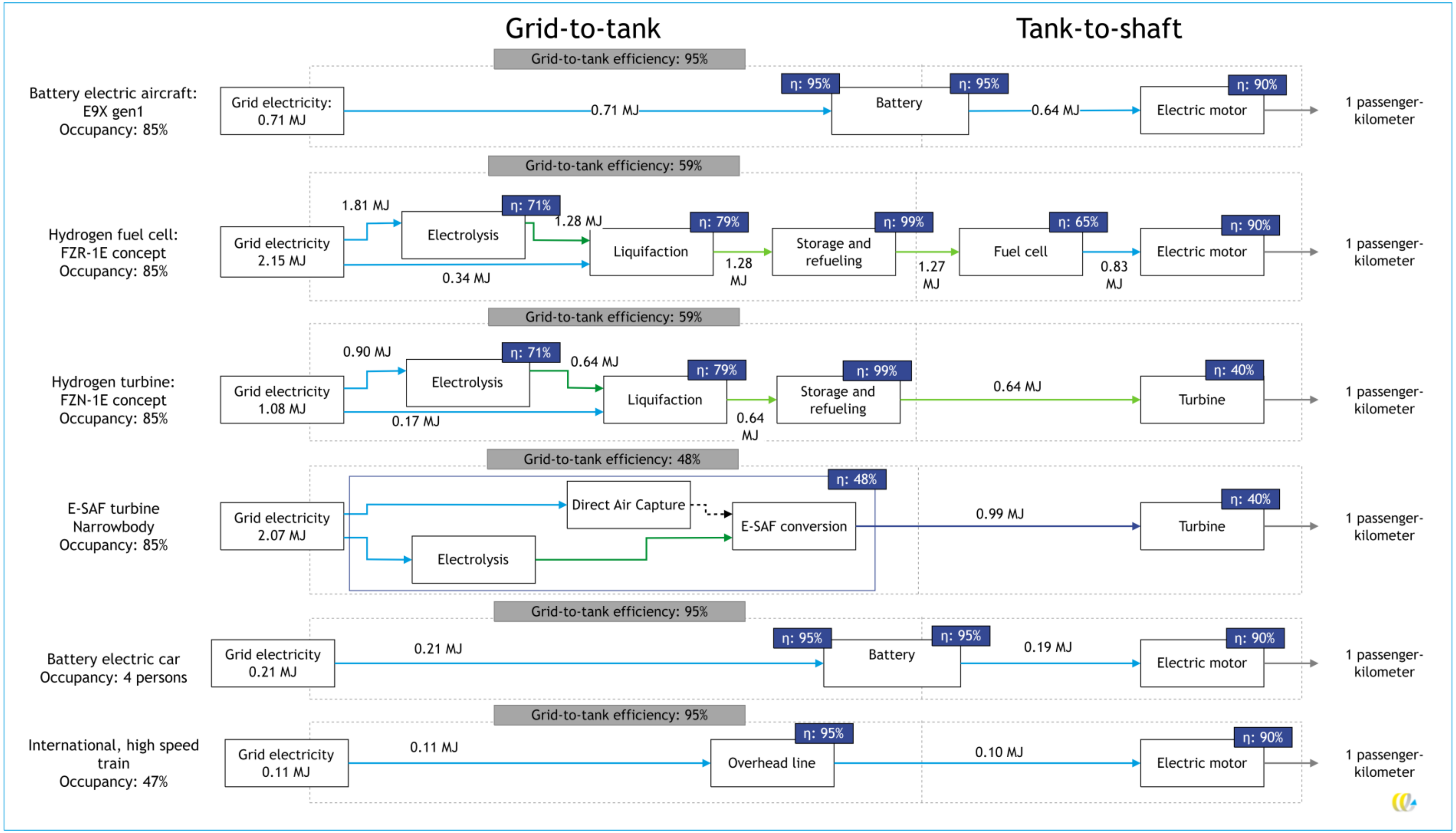
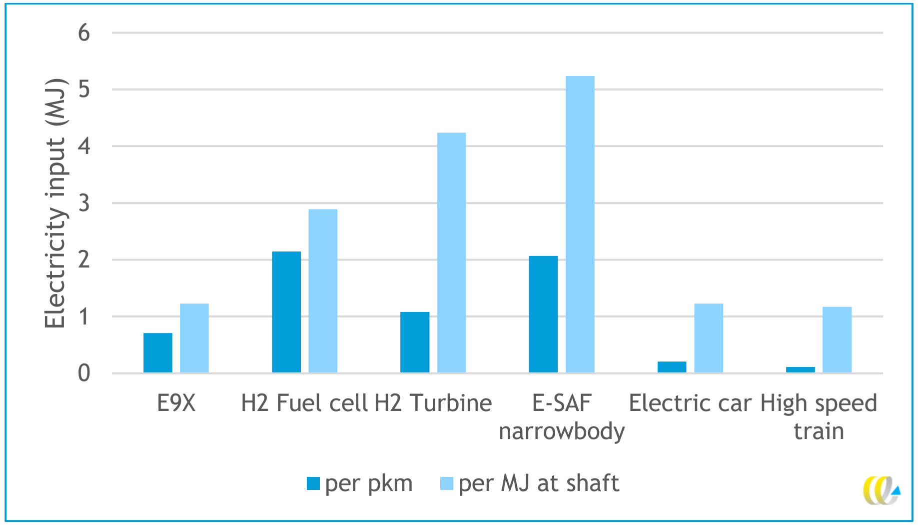


Figure 13 – Transport efficiency of technological decarbonization options for 2035



- Figure 14 provides a graphical overview of the system efficiencies analysed. When regarding system energy efficiency, we can conclude battery electric aviation is on par with highspeed trains and electric cars when looking at the relation between energy in- and output (per MJ at shaft). When looking at energy required per pkm, the electric car and high speed train score best and battery electric aviation scores best when compared to other air-based transport.

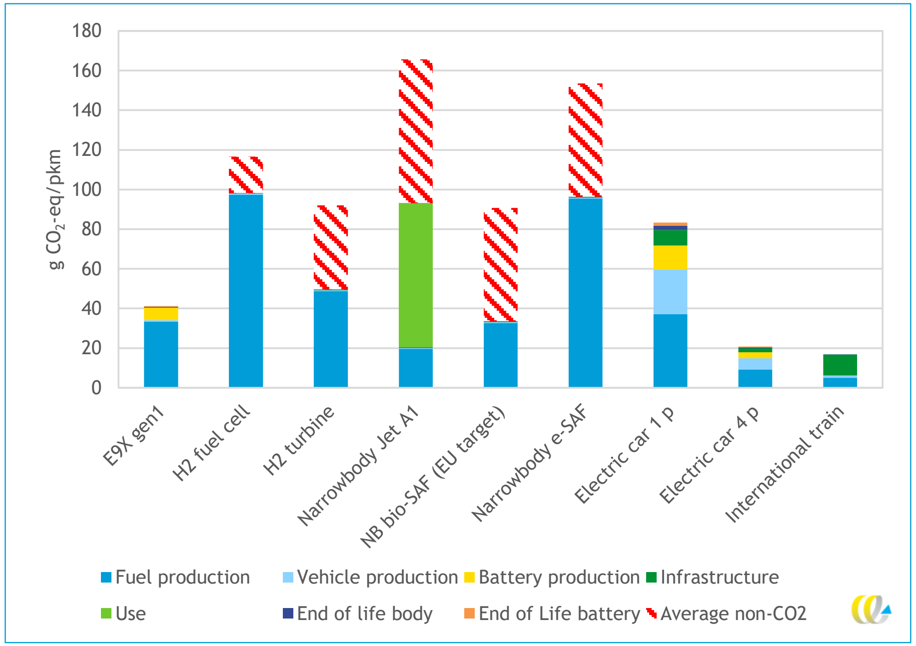
Figure 14 - Overview of system energy efficiencies



5 Climate change impacts of different passenger transportation options

- It is important to recognise that the impact of climate change caused by passenger transportation is not solely a result of greenhouse gas (GHG) emissions during the operational phase of transportation modes. In fact, the life cycle of a transportation system can also contribute to this impact. To illustrate, a battery electric vehicle does not emit GHGs during operation. However, GHGs may be emitted when the electricity is generated or when the aircraft is constructed. It is therefore important to assess the GHG emissions and related climate change impacts over the entire life cycle. Data used for the energy efficiency is similar to the data use for the LCA. Further details on the data use in the LCA can be found in Appendix B.
- The following activities are included in the analysis: fuel production, vehicle/craft production, battery production, infrastructure, use, and end-of-life. In addition, the use phase of aircraft is included in the assessment, with non-CO_2 emissions (as defined in Figure 8) also taken into account.
- The results are expressed per pkm for an 800 km trip and presented for both 2035 (Figure **15**) and 2050 (Figure 16). In 2035, the EU policy mix is used as a reference point (0.045 kg CO_2-eq./MJ), while in 2050, a cleaner energy supply is assumed, with wind energy used as a proxy (0.0047 kg CO_2-eq./MJ).

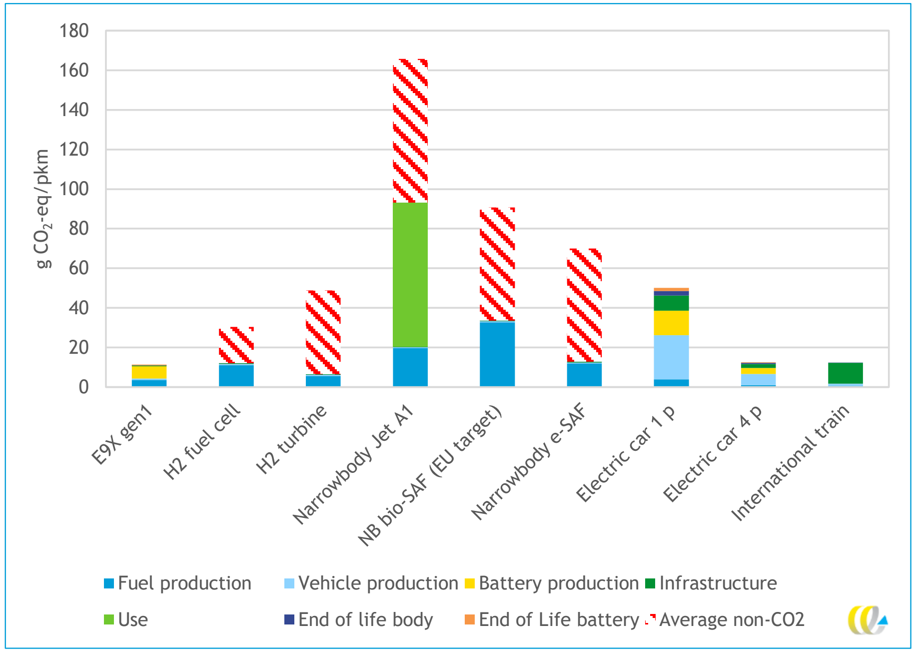
Figure 15 - **Climate change impact per persons kilometre of the E9X and competing transport options by air and over land (policy mix for electricity 2035)**



From Figure 15 we conclude the following:

- The provision of one pkm with a narrow-body aircraft using Jet A1 demonstrates the greatest climate change impact. Approximately 45% (green) of this impact is attributed to the emission of fossil CO_2 in the use phase. Another 45% is caused by non-CO_2 climate impacts that occur in the use phase.
- E-SAF demonstrates a modest reduction in the overall climate change impact. Grid-mixed production of E-SAF accounts for ~60% of the climate change impact, with the remaining impact predominantly resulting from non-CO_2 climate emissions.
- Bio-SAF, based on UCO HEFA, has a climate change impact that is more than 50% lower than that of JetA1. However, UCO is only available in limited quantities and will only cover a small proportion of the total fuel demand of the aviation sector.
- The use of hydrogen in a fuel cell or turbine results in significantly reduced climate change impacts when compared to Jet A1. In the case of the fuel cell, larger emissions are produced in the production of the hydrogen used for one passenger kilometre, while fewer emissions are caused by non-CO_2 emissions. The opposite is true for the hydrogen turbine.
- The E9X has the lowest climate change impact of all aviation options, comparable to an electric car with 2 persons.
- Figure 16 shows the potential climate change impacts in a future where the electricity supply is expected to be 'green'. The graph illustrates that all alternative aviation options (battery electric, hydrogen and SAF) demonstrate even lower climate change impacts, due to minimal GHG emissions in fuel production, which is now conducted using 'green' energy. While the emissions from fuel production for all alternatives are reduced and almost similar for all options, non-CO_2 climate change impacts are the primary contributor to climate change. The E9X exhibits the lowest climate change impact of all aviation options. It should be noted that potential reduction of non CO_2 climate impacts by operational adjustments is not taken into account here.

Figure 16 - Future Climate change impact per persons kilometre of the E9X and competing transport options by air and over land (using wind energy as a proxy for 2050)



6 Contextual challenges for SAF based decarbonisation

This chapter discusses the role of resource availability, production capacity and production costs of the bio-SAF and e-SAF decarbonisation options. First, the demand for SAF is discussed (Paragraph 6.1). Second, the required resources for SAF production and their availability is discussed (Paragraph 6.2). Third, an overview of SAF production availability is provided (Paragraph 6.3) and a discussion on production costs and SAF prices closes of this chapter (Paragraph 6.4). Paragraph 6.5 gives an overall conclusion on the finding presented in this chapter.

6.1 Demand for SAF

- Aviation is not the only sector that needs clean energy and biomass to reduce its emissions. Renewable electricity is a scarce commodity and demand for biomass is highly competitive, with various sectors - such as the chemical and energy industries - pursuing biobased pathways to drive sustainable development.

For the decarbonisation of aviation, the aviation sector is heavily focused on the transition from fossil fuels to Sustainable Aviation Fuels (SAFs). In the medium term, these are mainly biofuels (bio-SAF), while in the long term the share of e-fuels (e-SAF) is expected to increase significantly due to regulatory mandates like ReFuelEU Aviation.

- The current fuel demand of the global aviation sector is about 11 EJ/year. This demand is expected to increase with global prosperity to 14-18 EJ in 2035 and 15-24 EJ in 2050(IEA, 2024h).
- The global SAF consumption is expected to be 0.064 EJ in 2024, covering 0.53% of global aviation fuel consumption (IATA, 2024d). To meet the sum of mandates and aspirational targets for SAF use in 2030, global demand for SAF would need to increase to 0.69 EJ in 2030 (SkyNRG, 2024) about 6% of total fuel demand. Demand for 2050 has been estimated assuming that 50% of aviation energy demand is met by SAF, resulting in a value of 9.8 EJ.
- EU aviation fuel demand was calculated in the ReFuelEU Aviation impact assessment to be around 1.9 EJ in both the short and longer term (EC, 2021). ReFuelEU Aviation includes a SAF target of 20% in 2035 and 70% in 2050, which implies an SAF demand of 0.39 EJ in 2035 and 1.3 EJ in 2050. For 2030, it is assumed that 50% of the 2035 target is achieved in 2030, resulting in an SAF demand of 0.19 EJ in 2030. See Table 1 .

Table 1 - Estimation of SAF demand worldwide and in the EU, for 2030 and 2050

		EU		World	
	Unit	2030	2050	2030	2050
Expected SAF demand	EJ	0.19	1.3	0.69	9.8
	Mtonne	4.5	31	16	228

6.2 Resource availability

- Biofuels are made from biomass crops or biomass residues. E-fuels use two building blocks: hydrogen and CO_2. The hydrogen is produced by water electrolysis. If renewable electricity is used, the hydrogen is considered 'green'. The required CO_2 can be captured from industrial emissions, from the air (Direct Air Capture (DAC)) or from seawater.
- The use of energy crops or residues from land or forest (primary residues) for bio-SAF production competes with land used for natural carbon sequestration and other land uses, such as food crop production. It can also lead to indirect land use change (ILUC). See Textbox 1 . Biomass residues from industrial processes or waste streams are generally considered sustainable, but their availability is limited by the magnitude of biobased production and consumption volumes.

Textbox 1 - Environmental impacts associated with biomass

> Two main categories of biomass are biomass residues and biomass crops. Primary residues from agriculture and forestry are considered sustainable if sufficient primary residues are left on the land to maintain soil quality. Energy crops have a significant impact on land use and compete with food production. Non-food crops grown on marginal land may have less negative impacts on the local environment, but this still depends on local conditions and the intensity of crop production. In addition, forest biomass has a significant time lag in carbon sequestration, leading to a debate about whether biofuels are truly carbon-neutral if produced using clean energy.

- In an analysis of twelve aviation roadmaps to net-zero GHG emissions from global aviation in 2050, (Becken et al., 2023) found an average global aviation fuel demand in 2050 of 18.2 EJ, an average estimated biomass demand for global bio-SAF production of 15 EJ, and a demand for renewable electricity for e-SAF production of 20 EJ.
- As part of its Net Zero Emissions (NZE) scenario, the IEA projects a global sustainable biomass supply, excluding food and feed crops, of 102 EJ in 2050. However, a maximum potential estimate based on reduced meat consumption and increased agricultural yields is 120 EJ. On the other hand, other literature sources using stricter sustainability criteria have estimated a global biomass supply of 50 EJ in 2050 (Becken et al., 2023).
- The IEA has projected that the global renewable electricity supply will grow from 60 EJ in 2030 (IEA, 2024d) to 137 EJ in 2035 (IEA, 2024h), and to 260 EJ in 2050 (IEA, 2021). However, (Becken et al., 2023) find a minimum estimation of 224 EJ in aviation roadmaps.

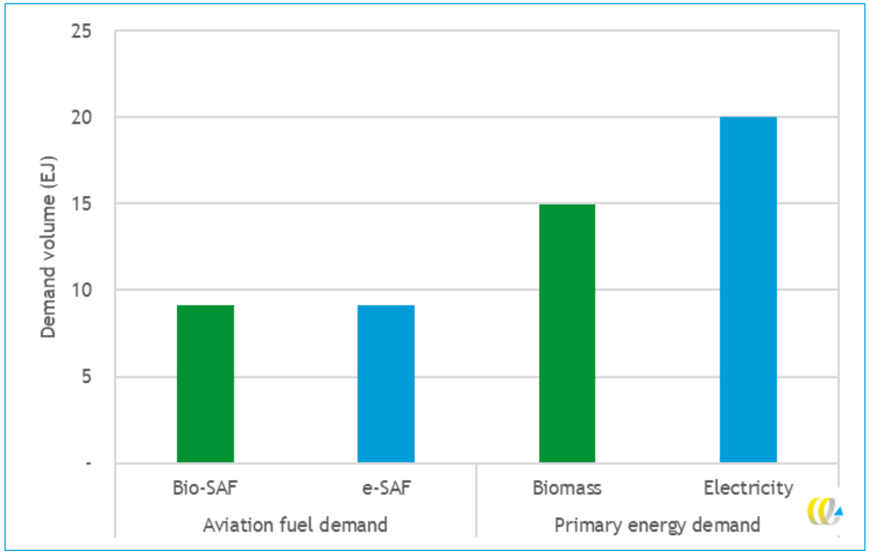
- Combining the above information, the required share of available biomass for global aviation in 2050 can be estimated to be in the range of 13-30%. For renewable electricity, the range is 8-9%. See Table 2. The bio-SAF and e-SAF demand volumes and required biomass and renewable electricity are also visualised in Figure 17.

Table 2 - SAF demand and required primary energy share, worldwide in 2050

	Low primary energy supply		High primary energy supply	
	Bio-SAF	e-SAF	Bio-SAF	e-SAF
SAF demand (EJ)	9	9	9	9
SAF demand (Mtonne)	213	213	213	213
Primary energy demand (EJ)	15	20	15	20
Primary energy supply (EJ)	50	224	120	260
Required share for SAF production	30%	9%	13%	8%

Note: 'Primary energy' relates to the energy contained in the biomass resources (in the case of bio-SAF) or the electrical energy produced with renewable energy sources such as wind and solar (in the case of e-SAF). It is assumed that the global aviation fuel demand in 2050 is 18.2 EJ (Becken et al., 2023), and that this is met by 50% bio-SAF and 50% e-SAF.

Figure 17 - SAF demand and required primary energy demand, worldwide in 2050



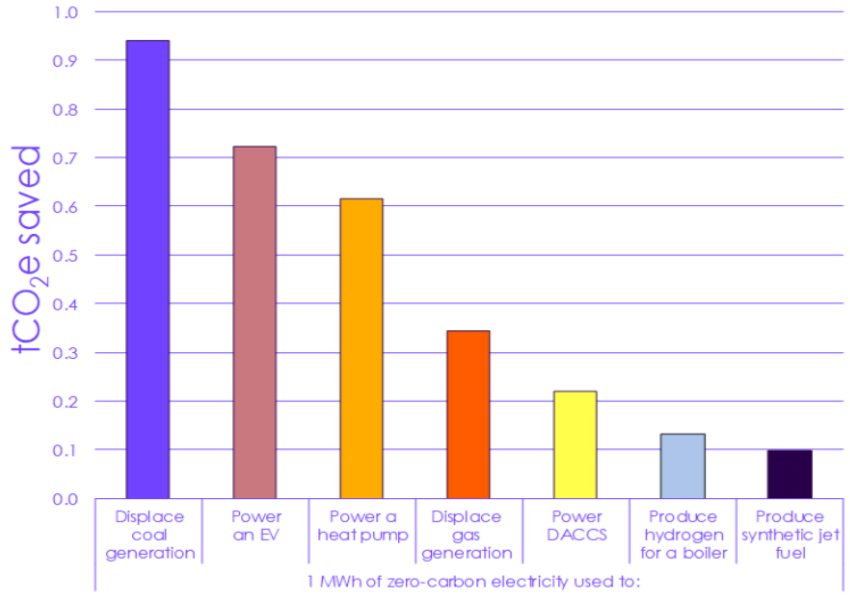
- The current share of aviation in total global energy demand is about 2.4% (assuming a global primary energy demand of 620 EJ (Energy Institute, 2024) and a jet fuel demand of 15 EJ, or 348 Mtonne, in 2024). Although the future share of aviation in total energy demand may be higher, the required shares of biomass and renewable electricity suggest an excessive resource use by aviation in 2050.
- In the short term, the use of renewable electricity for e-SAF production for aviation is not energy efficient and results in lower GHG emission reductions compared to other uses, as shown in Textbox 2. Therefore, if renewable

electricity is scarce, its use in other sectors than aviation would contribute more to climate objectives.

Textbox 2 - GHG emissions reduction for different renewable electricity applications

The below figure shows the CO_2-eq. emissions saved with 1 MWh of low-carbon electricity across different sectors. Many applications such as displacing coal generation, powering an EV or even powering DACCS constitute a more effective use of clean energy in terms of GHG emissions saved than e-SAF (synthetic jet fuel) production and use.

Emissions saved with 1 MWh of low-carbon electricity across sectors (Climate Change Committee, 2020)



Note: synthetic jet fuel is e-SAF.

6.3 SAF production capacity

- The development of sufficient SAF production capacity is another prerequisite for growing SAF production. Current SAF production capacity only produces bio-SAF; the production of e-SAF is expected to gradually grow over time. The SAF production capacity in 2024 was about 0.04 EJ, which was 0.3% of global jet fuel production. SAF volumes are growing ‘disappointingly slowly’ (IATA, 2024b). Investors need a steady business case, but low prices of fossil kerosene, global competition between airline companies and regulatory uncertainty are barriers to this.
- The expected development of SAF's global production capacity will be slower than the total amount of announced production plans would suggest: Most production facilities are still in the feasibility study or design phase. The estimate of SAF's expected production capacity takes into account that a large proportion of the announced projects will not be realised.
- Global SAF production capacity is expected to increase to 0.74EJ in 2030 (SkyNRG, 2024), and 13 EJ in 2050 (Becken et al., 2023).
- For the EU, SAF capacity is expected to grow to 0.16 EJ in 2030 (SkyNRG, 2024), which is sufficient to meet the 6% ReFuelEU Aviation SAF target for 2030 (which amounts to 0.12 EJ). We estimated the capacity in 2050 based on the

global estimate for 2050 and the 2030 estimate. This resulted in a capacity of 2.9 EJ, which easily meets the SAF target of 70% in 2050 (which amounts to 1.3 EJ).[1] The above estimates are presented in Table 3, together with the SAF demand estimated earlier in this chapter.

Table 3 - Estimation of expected SAF production capacity compared to demand (EJ)

		EU		World	
	Unit	**2030**	**2050**	**2030**	**2050**
Expected SAF production capacity	EJ	0.16	2.9	0.74	13
	Mtonne	3.8	68	17	308
*Required number of SAF plants**	EJ	*10*	*176*	*45*	*800*
	Mtonne	231	4,103	1,051	18,680
Expected SAF demand	EJ	0.19	1.3	0.69	10
	Mtonne	4.5	31	16	228

*: Calculated using an average of 650 SAF required plants for 250 Mt (~11 EJ) of SAF (SkyNRG, 2024).

- The estimates of SAF production and demand show that expected SAF production capacity is similar to expected SAF demand, both globally and in the EU, and for both 2030 and 2050. This shows that SAF production capacity is expected to follow SAF demand and that no implementation bottlenecks have been identified in the literature on SAF supply development.
- However, there are still many uncertainties about the technological readiness of large-scale direct air capture (DAC), which is required for e-SAF production, which is expected to take over the majority of bio-SAF between 2030 and 2050. At present, only small-scale DAC pilot plants have been developed and scale-up to industrial scale requires time and large investments. Validation of large-scale operation is still lacking or even unplanned (Bisotti et al., 2024), making it uncertain whether the technology will be available in time and at the required scale.
- Furthermore, a recent ACER report concludes that the growth of electrolysis capacity in the EU is slow, making it difficult to achieve the 2030 renewable hydrogen targets. Although many electrolysis projects have been announced, few have reached a final investment decision because renewable hydrogen is three to four times more expensive than fossil-based hydrogen and demand is uncertain (ACER, 2024). The slow development of the electrolysis market is a barrier to the development of e-SAF production capacity.

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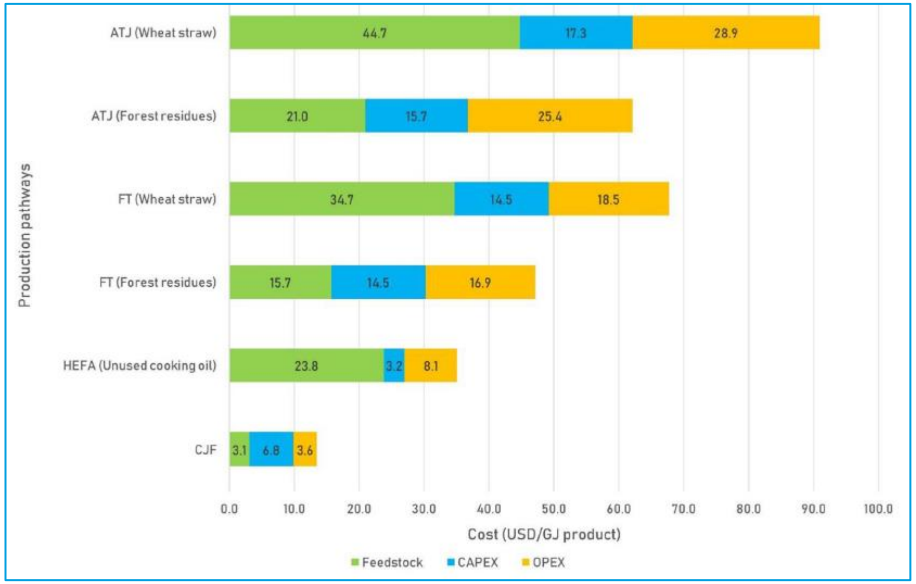
[1] The aviation fuel demand estimates that were used to calculate the EU SAF fuel demand in 2030 and 2050 stem from the ReFuelEU Aviation impact assessment EC (2021).

6.4 Cost breakdown of SAF

- Before discussing price projections, we first provide an indication of the cost breakdown of SAF, i.e. the cost components that make up the production cost of SAF and their relative proportions.
- For bio-SAF, a basic cost breakdown can be made between biomass feedstock costs, capital expenditure (CAPEX) and operating expenditure (OPEX). The proportions of these three components in the production costs of bio-SAF are largely determined by the assumed feedstock type(s) and production technology. Easily collected, abundant and lower quality biomass feedstocks are generally cheaper. If these are used for bio-SAF production, the share of feedstock costs in total production costs is likely to be lower than if scarce and high quality feedstocks are used. In addition, the use of newer technologies (which have not yet benefited from the cost reductions of mass production) often corresponds to a relatively high CAPEX cost component, while high external energy use results in a higher OPEX cost component.
- This dependence of the cost breakdown of bio-SAF on feedstock type and technology is illustrated in an overview from Doliente et al. (2020) (see Figure 18). While the feedstock cost is relatively small for conventional jet fuel (fossil kerosene), it accounts for the vast majority of the production cost for bio-SAF made from used cooking oil (UCO) using the HEFA production route. It can also be seen that wheat straw is more expensive than forest residues, that the OPEX share of the Alcohol-to-Jet (ATJ) route is slightly higher than for the Fischer-Tropsch (FT) route, and that the CAPEX share of the HEFA-UCO route is quite low compared to the other production routes.

Figure 18 - Cost breakdown of production cost of bio-SAF (Doliente et al., 2020)

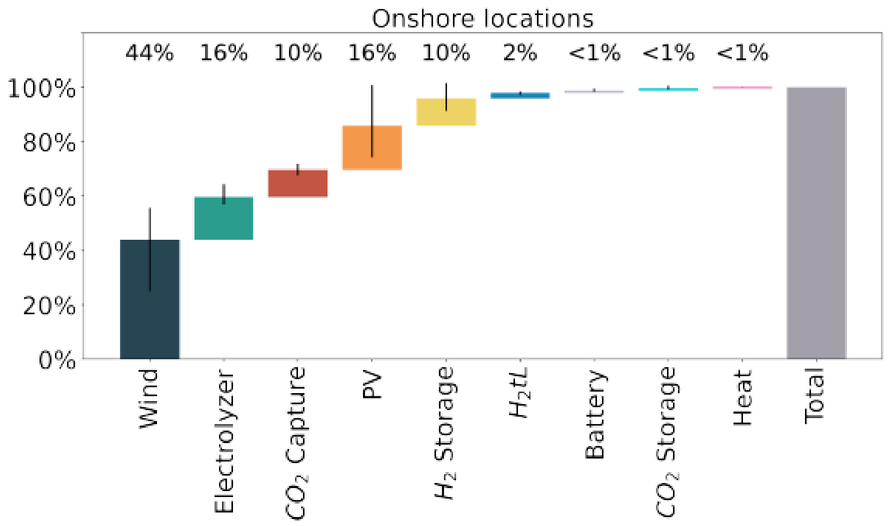


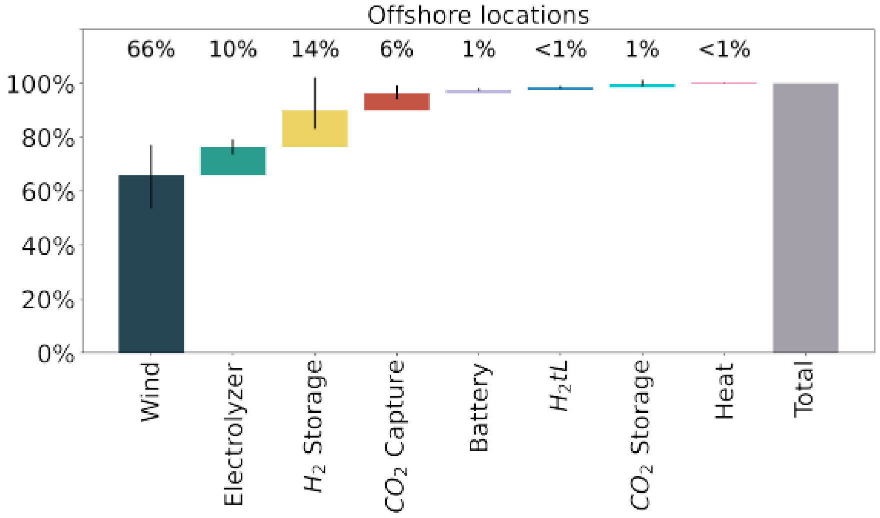
Note: CJF = conventional jet fuel; ATJ = alcohol-to-jet; FT = Fischer-Tropsch, HEFA = hydro processed esters and fatty acids.

- In the cost breakdown of e-SAF, the cost of renewable electricity required for electrolysis, synthesis and CO_2

capture is the main cost component. In a modelling study of the production costs of future e-SAF plants in Europe using wind and solar power, Seymour et al. (2024) present a cost breakdown for different future years. In this study, wind turbines and solar PV panels are assumed to be part of the overall production system. The share of wind turbine CAPEX in total e-SAF production costs in future years ranges from 40% (for onshore wind and PV) to 70% (for offshore wind). Other major cost components are the CAPEX of the electrolyser, CO_2 capture, solar PV and hydrogen storage. See Figure 19.

Figure 19 – Cost breakdown of production cost of e-SAF (Seymour et al., 2024)





Note: Share of e-SAF cost components in 2040 for onshore (top) and offshore renewable electricity production (Longbottom). Wind turbines and solar PV systems are part of the overall e-SAF production system.

6.5 SAF price projections

- The above discussion of the cost breakdown of SAF production costs shows that these costs are highly dependent on biofeedstock costs and production routes (in the case of bio-SAF) and electricity costs (in the case of e-SAF). This implies that the future development of SAF production costs will depend on the technologies adopted, and the feedstocks used, but also that technological progress in production routes and the scaling and learning effects of large-scale development of SAF plants will have a major influence on future production costs. These developments are highly uncertain.

- We have conducted a literature review of bio-SAF and e-SAF production cost projections and fossil kerosene price estimates for the current situation, 2035 and 2050. The results are presented in Figure 20. We emphasize that estimations of future costs and prices are very uncertain, and that these values should be seen as possible developments rather than predictions.
- Literature studies typically provide projections of SAF production *costs* rather than market *prices*. In contrast, literature sources show fossil kerosene market *prices* (which reflect the oil market prices[2]) rather than production costs. Therefore, a literature-based financial comparison of fossil kerosene and SAF is usually a skewed comparison of kerosene *market prices* and *SAF production costs*.
- SAF market prices are the result of matching supply and demand, and are therefore higher than production costs. In situations of scarcity, SAF producers can benefit by increasing their sales prices. In spot markets for SAF trade, the market price (market clearing price) will equal the price of the highest accepted supply bid to meet SAF demand. In situations where both bio-SAF and e-SAF can be used to meet demand (which is not the case when for example fulfilling the ReFuelEU Aviation e-SAF target), SAF market prices may be set by the most expensive SAF type, if bids of this type were accepted at market clearing. Therefore, in the shorter term, the e-SAF price may also be the price for which the cheaper bio-SAF is sold. This mechanism results in SAF market prices that could be much higher than actual SAF production costs, which causes the ‘price gap’ between SAF and fossil kerosene to be underestimated. In other words, the actual price gaps between SAF and fossil kerosene are larger than is reflected by the difference between SAF production costs and fossil kerosine prices that is shown in Figure 20.
- The fossil kerosene prices in Figure 20 already include CO_2 costs, which lead to an increased competitiveness of SAF.[3] CO_2 prices may need to become as high as $252 per tonne of CO_2 to make the cheaper SAFs competitive with fossil kerosene (BloombergNEF, 2021), whereas the EU-ETS CO_2 allowance price fluctuated between 50 and 80 euro per tonne in 2024.[4]

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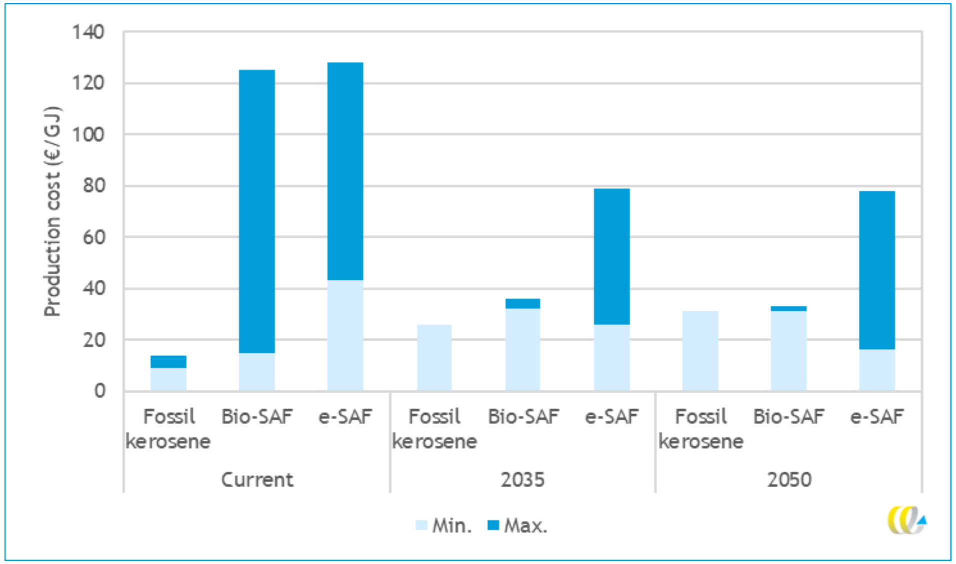
[2] The global fossil kerosene price development follows the same pattern as the oil price, with the spread between both ranging between 15% and 25% of the kerosene price over the last few years, (IATA, 2024c)

[3] The EU-ETS costs for the aviation sector, which are borne by the aircraft operators, are not included in the fossil kerosene market prices, but are redistributed through flight ticket prices. This means that the estimated fossil kerosene prices in Figure 20 are higher than the actual market clearing prices would be.

[4] https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/, accessed in January 2025.

- In a discounted cash flow analysis of the evolution of e-kerosene production costs in the US and Europe, ICCT (2022a) finds that e-SAF is currently 7 to 10 times more expensive than fossil kerosene and 2 to 3 times more expensive than bio-SAF using the HEFA production route. However, the gap between SAF and fossil kerosene is expected to narrow over time as fossil kerosene prices could double by 2050 while SAF production technologies advance and the market matures (ICCT, 2022a).
- While the ICCT (2022a) concludes that the cost of e-kerosene will still not be cost-competitive with fossil kerosene or bio-SAF by 2050, PwC's Green Aviation study finds that the costs of e-SAF, HEFA bio-SAF and bio-SAF produced from advanced feedstocks will converge to "very similar levels" by 2050 (PwC, 2022). Given the large uncertainties associated with price projections in 2050 and the large number of assumptions required to model production cost trajectories, it is not surprising that studies come to different conclusions. Nevertheless, PwC (2022) also expects SAF prices to remain more expensive than fossil kerosene until 2040.

Figure 20 - Production cost estimations of bio-SAF and e-SAF from literature compared to the fossil kerosene price, for the current situation, 2035 and 2050



Sources: (Concawe, 2024; ICCT, 2022a; PwC, 2022; RMI, 2024; Transport & Environment, 2023). Note: The dark blue bar indicates the production cost margin found in the literature. Where only a light blue bar is shown, a single value was found.

- The results of the literature review of SAF production costs and fossil kerosene prices are visualised in Figure 20, showing minimum and maximum estimates found for the current situation, 2035 and 2050. We find that:
  - Bio-SAF is currently 2 to 9 times more expensive than fossil kerosene, but is estimated to reach cost parity with fossil kerosene in 2050.

- e-SAF is currently 5 to 9 times more expensive than fossil kerosene. In 2050, it is estimated to be at most 2.5 times more expensive or, in the most favourable estimate, 2 times cheaper.
- There are very large differences in the production cost estimates (shown by the dark blue bars), the causes of which have been discussed above.
- The higher ends of the SAF production cost ranges correspond to a future where biomass and renewable electricity are scarce and technologies and markets are not fully mature.

6.6 SAF analysis conclusion

- The aviation sector focusses on sustainable aviation fuels (SAF) to decarbonize. Regulatory mandates like ReFuelEU make that the demand for SAF needs to increase significantly. Where current SAF consumption is about 0.5% of the global aviation fuel consumption, ReFuelEU targets are 20% SAF in 2035 and 70% in 2050.
- For the production of SAF, the aviation is in competition with other economic sectors for renewable electricity and biomass. The required share for the production of SAF in 2050 of biomass is 13-30% of available biomass and 8-9% of available renewable electricity. The current share of aviation in the global energy demand is about 2.4% which suggests a relatively high use of resources for decarbonization of the aviation sector via adoption of SAF.
- Currently only bio-SAF is produced which covers ~0.3% of the global jet fuel demand. The production capacity is reported to grow ‘disappointingly slow’ (IATA, 2024b). Although SAF production capacity planned seems sufficient to keep up with demand, most of the planned SAF production plants are currently still in their design phase or feasibility studies are being performed. Expectations are that a large part of the proposed SAF production projects will not be realized. Uncertainties around technology readiness and large scale production are high. In addition, DAC technology and electrolysis capacity which are both required to supply feedstock for e-SAF production are not expected to be available at the required scale in the timeframe considered.
- Where feedstock costs for conventional fuel are relatively small, it accounts for the vast majority of production costs of bio-SAF. For e-SAF the costs of electricity is the main component in the production costs, followed by capital costs for electrolysers and CO_2 capture.
- Production costs for SAF are highly dependent on availability of feedstocks and production technology, which are also in high demand by other economic sectors. The future availability of SAF production facilities is therefore uncertain.
- SAF market prices will be higher than SAF production costs reported in literature due to competition for the required

biomass and renewable electricity and the produced renewable fuels. Where production costs of e-SAF are expected to be higher than the currently produced bio-SAF, it can be expected that a generic SAF price will follow the high e-SAF production costs. This makes that the price difference between SAF and fossil kerosine is likely to be underestimated in literature.

- Projections from literature show that bio-SAF prices might reach cost parity with fossil kerosine in 2050 and that e-SAF will be 2.5 times more expensive than fossil kerosine making SAF not preferable from a price perspective.
- The successful implementation of SAF in the aviation sector at the required scale to reduce climate change impact in the aviation sector is uncertain. And while application SAF does reduce direct CO_2 climate impacts, the reduction of non-CO_2 climate impacts is limited. SAF will play a role in the decarbonisation of the aviation sector, however additional aviation decarbonisation routes like hydrogen and electric aviation will also be highly needed to reach reduction targets.

7 Impact of electric aviation on the energy grid (Dutch case study)

- Historically, the electricity grid in the Netherlands has had a lower capacity than in other countries because local heat supply has been provided by natural gas rather than electricity. The Dutch case therefore potentially requires more effort than other countries in a transition towards higher electricity use and is considered a ‘not the best case scenario’ for electrification, meaning that challenges in other countries are expected to be less cumbersome than in The Netherlands.
- The transition from fossil fuels to renewable energy, often in the form of electricity, is creating a challenge in the form of grid congestion. Grid congestion is a situation where the capacity of the existing electricity transmission network is insufficient to handle the distribution and supply and demand of electricity.
- As the development of electrification and renewable energy grows faster than the development of the grid, many new applications for grid connections and transport capacity cannot be met. The question is whether a shift to electric aviation will also have an impact on existing grid congestion problems.
  If the Netherlands faces significant grid congestion challenges compared to other EU countries, this could also be an issue in other countries, and we believe that the main observations and conclusions apply to other countries as well.

Characteristics of battery electric aviation

- The typical power of an electric aircraft charging station is expected to be around 20 MW. The battery of the electric aircraft will have a capacity of 15 MWh, which means that a charge cycle takes about 45 minutes (at full power).
- Regional airports will need about two of these charging points, for a total of 40 MW. However, it is unlikely that both chargers will use maximum power at the same time. It is therefore expected that a grid connection of 20-30 MW will be sufficient.
- An international airport such as Schiphol will need around six charging points and a grid connection of around 60 MW.
- The impact of charging batteries from the grid can be reduced by using smart charging and shifting demand to times when the grid is less loaded. The flexibility of shifting demand is limited due to operational requirements (aircraft need to be charged on time).

Putting the demand in perspective

- At a national level, the additional grid capacity required for electric aircraft charging points is marginal. However, at a local level, the charging points can lead to a significant increase in the electricity demand of airports, which has an impact on the local electricity grids. It is therefore expected that additional grid reinforcements will be needed to support the electricity demand of the charging points.
- The average electricity demand in the Netherlands is expected to be 25 GW in 2030. The demand per airport is therefore less than 0.1% of the total electricity demand in the Netherlands.
- 20 MW corresponds to the average demand of around 20,000 to 30,000 households (excluding electric vehicles and heat pumps), and the electricity demand of large industrial clusters is expected to be in the order of several GW after electrification.
- The average demand of charging points at an airport is 20 to 60 MW. The current electricity demand of Schiphol Airport is around 80 MW and is expected to grow to 160 MW by 2030. This means that the demand of the charging points is significant compared to the current and future electricity demand of the airport, and would therefore require an extension of the existing grid connections.
  - A typical substation on the distribution network has a maximum capacity of around 250 MW, which clearly shows that an additional demand of 20 to 60 MW can have a significant impact on the existing grid.

Expectations for grid congestion

- The exact impact on the electricity grid depends on the hourly demand from the charging points and the hourly load profile of the local grid and the nearby electricity substation. It can be assumed that the load on the grid will increase as the charging points will require electricity for a large part of the day and the flexibility of the demand (the ability to shift this demand) is limited.
- Grid congestion seems to be a temporary problem that will be solved in the near future. Network operators have investment plans that include all the investments they expect to be needed to facilitate all the expected developments. If these plans are implemented on time, all congestion should be solved in the next 10 years. The current investment plans of the network operators have a time horizon of ten years, which means that the current problems should be solved by then. These investment plans are reviewed every two years.
- The investment plans of the grid operators are based on the connection requests received. In order to ensure that the planned grid reinforcements are sufficient for the demand of the charging points, it is important that the grid operators are informed in time by the energy users. It is therefore advisable to request additional grid capacity at an early stage.

- While current investment plans are expected to resolve current grid congestion problems in about 10 years' time, it is not expected that all necessary grid expansions can be implemented on time due to limited human resources and long lead times. Recent studies have estimated that around 30% of the planned grid expansions will not be delivered on time.
- There are alternative ways of facilitating additional grid capacity in times of congestion. Firstly, parties can enter into 'conditional contracts' for capacity on the grid. These contracts limit access to the grid when it is expected to be overloaded, which can affect electric aircraft charging schemes. Secondly, battery storage can be used to meet electricity demand during hours when access to the grid is restricted. In this case, the charging schemes are not affected (see also battery reuse below)

Potential re-use of battery packages as grid-connected batteries

- The battery packs of the electric aircraft reach the end of their life after about 9 months of use. At this point, these batteries can still be used for energy functions such as grid balancing or trading on electricity markets.
- Batteries connected to the grid can have several functions. Firstly, load balancing behind the meter. In this case, the demand from the charging points can be spread out over time. This can lead to a lower peak demand and therefore a lower connection to the grid. This may be necessary in times of grid congestion with a conditional grid capacity contract (see previous section). It can also be used to obtain a smaller grid connection, which reduces grid charges.
- Second, local grid balancing. In this case, the battery is used to reduce the load on the local electricity grid. It is expected that grid operators will pay for this service in the future.
- Third, balancing supply and demand at national level. Within a bidding zone (the Netherlands is a bidding zone), supply and demand must be balanced at all times of the year. Various electricity markets (such as the day-ahead market and the balancing markets) ensure this balance, and grid batteries can earn money by trading on these markets (arbitrage). This is currently the main revenue model for grid-connected batteries. This can lead to additional revenues. However, the number of grid-connected batteries is growing rapidly, which could lead to a saturated market by 2035. This will lead to lower revenues.

- There are two main challenges in connecting end-of-life batteries to the grid: First, the limited size of the grid connection can be a limiting factor for the operation of grid-connected batteries. While the grid connection is used for the charging aircraft, the limited capacity does not allow the grid-connected batteries to be charged simultaneously. A larger grid connection may be an option, but is costly.

- Secondly, it is to be expected that a used battery pack cannot easily be used as a grid battery. Considerable additional technical additions (auxiliary equipment, advanced measurement and control systems, etc.). What exactly is required depends on the specific situation and the quality of the battery.

Relative system costs of green hydrogen and renewable electricity

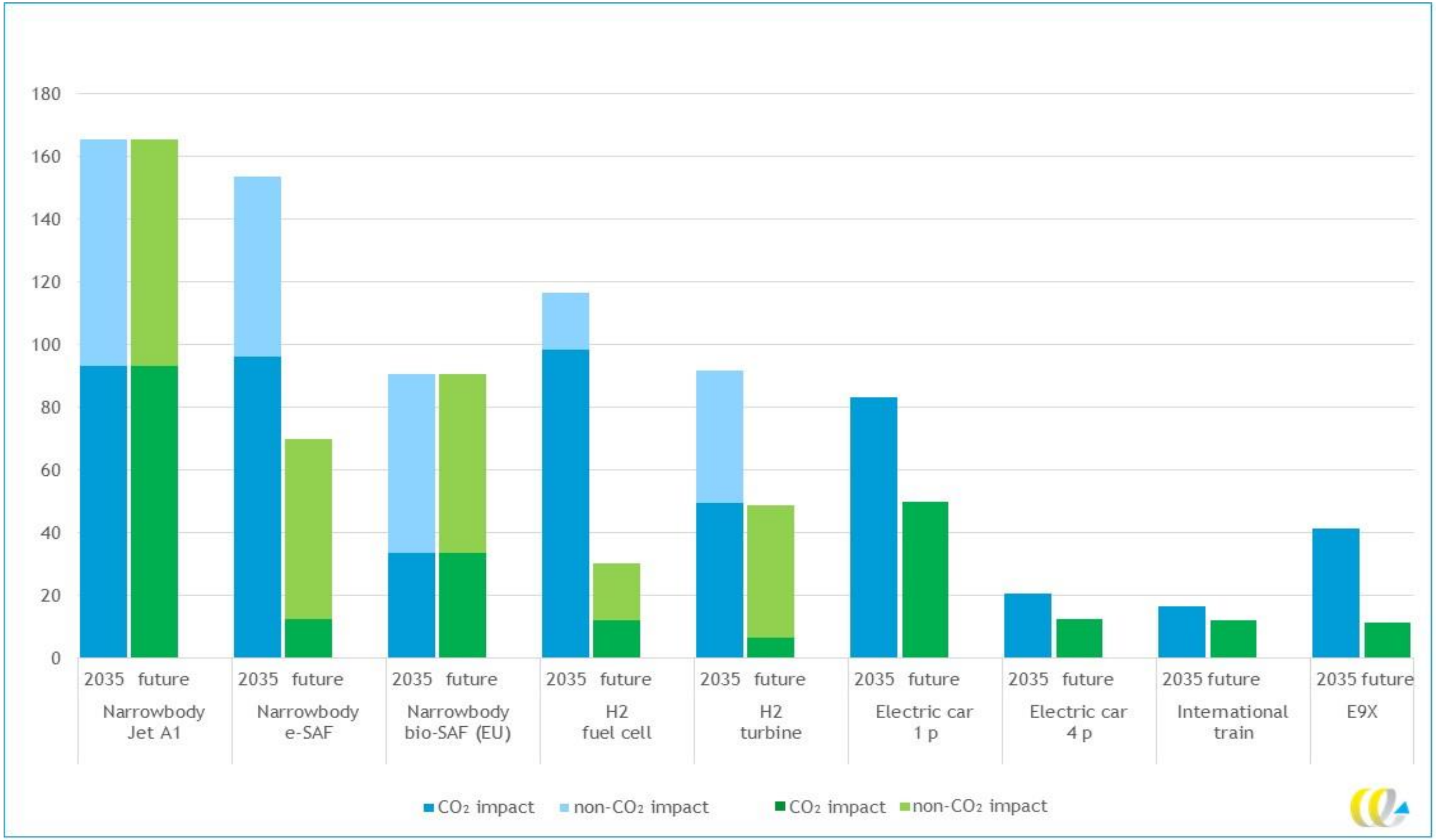
- In general, green electricity production costs are lower than green hydrogen production costs, while hydrogen infrastructure costs per unit of energy are a factor of 10 lower than electricity infrastructure costs (CE Delft & Witteveen+Bos, 2024).
- Centralised hydrogen production at a location where (renewable) electricity is available or imported hydrogen does not require an extension of the electricity grid. However, it does require a connection to a hydrogen network, which often has to be built from scratch.
- Local hydrogen production (at the airport) requires additional electricity grid capacity (similar points to grid congestion). The additional advantage that hydrogen is easier to store locally than electricity is likely to be limited.
- At a system level, the use of renewable electricity has lower costs, especially where direct use applications are possible. Green hydrogen has higher costs, but it may be feasible in situations where electricity is not practical.

8 Discussion and conclusion

Three alternatives ways of air transport to the use of fossil-based kerosene have been considered and compared. A summary of this comparison for 2035 is given in Table 4:

1. The three technologies considered in the analysis all have the potential to reduce a specific proportion of the total climate change impact of the aviation sector over their potential operating ranges. The Electrical E9X is expected to be operational by 2035 and to have a significant market share by 2050. Hydrogen-powered aircraft with comparable operational characteristics (passengers and range) are also expected to enter the market from 2030 onwards. The use of SAF is expected earlier. ReFuelEU targets 20% SAF in 2030 and 70% SAF in 2050.
2. In terms of system energy (MJ/MJ) and transport efficiency (MJ/pkm), battery electric aviation clearly outperforms hydrogen and SAF. This shows that in a world where the efficient use of renewable electricity is an issue, battery electric aviation has an advantage over the other technologies.
3. Battery electric aviation reduces life cycle climate impacts (including non-CO_2 climate impacts) by 70% compared to fossil kerosene in 2035 and even more than 90% when a green future is assumed. Hydrogen and SAF-based aviation show lower reductions, 15-35% and 10-45% respectively, in 2035. This is mainly due to the absence of non-CO_2 climate impacts (Figure 21).

Figure 21 – CO_2 and non-CO_2 climate change impact of transport per personskm (g CO_2-eq./pkm) per technology in 2035 and in a green future



- In reducing its impact on climate change, the aviation sector competes with other economic sectors for key resources such as biomass and renewable electricity. The limited availability of these resources creates an economic allocation problem.
- Where battery electric aviation has a significantly lower electricity consumption per pkm, it has a clear advantage over SAF and hydrogen based aviation when electricity scarcity is an issue.
- An additional challenge, not present for battery electric aviation but present for bio-SAF, is competition for available biomass.
- All three technologies considered require additional development and scale up before fully implemented. This however, does not give one specific technology a clear advantage over the others.
- Increased demand for renewable electricity might have an impact on local electricity grids. This is particularly true for battery electric aviation and hydrogen based aviation, where hydrogen is produced locally. However, these challenges are expected to be limited when these technologies are expected to be fully operational.

Conclusion

- The challenge of reducing the climate change impacts of the aviation sector is a big undertaking. All improvement technologies discussed should be used to their best advantage to meet this challenge. In this one technology is not necessarily better than the other ,but all will need to be used in combination. This analysis shows that the application of electric aviation can make a considerate contribution to reducing climate change impacts on the sector, in which short haul flights are responsible for 19% of total emissions. When these flights can be covered with electric aviation, these emissions can be reduced with ~70% in 2035 and up to 90% in a further future.
- Although the E9X is still under development, this comparative assessment of three alternative aviation technologies shows that battery electric aviation is a strong and viable candidate for reducing the aviation sector's climate change impact.
- The E9X’s high potential to reduce lifecycle climate change impacts is due to the high energy efficiency of the system (lower resource use) and the absence of non-CO_2 climate impacts during its use phase. And although the operational range is smaller than that of conventional aircraft that could use SAF or newly developed hydrogen aircraft, application of the E9X to short range flights offers a great opportunity to reduce the climate change impact of short-haul flights and a considerate part of the climate change impacts of the entire aviation sector.

Table 4 – Comparison of alternatives for aviation in 2035

	Battery electric (E9X)	Hydrogen	Sustainable Aviation Fuel (SAF)
Operational range	0-1,000km	0-2,000km (fuel cell) 0-4,000km (turbine)	0-16,000km
Potential share of total GHG emissions aviation sector (2019)	19% (148 Mt)	24% (fuel cell) (190 Mt) 20% (turbine) (160 (Mt)	36% (283 Mt)
System energy efficiency	1.23 MJ/MJ,	2.89MJ/MJ (fuel cell) 2.61MJ/MJ (turbine)	3,22 MJ/MJ (e-SAF)
Transport system efficiency	0.74 MJ/pkm	2.15MJ/pkm (fuel cell) 1.08MJ/pkm (turbine)	1,68MJ/pkm (e-SAF)
Decrease in life cycle climate impacts compared to fossil kerosine	70%	15% (fuel cell) 35% (turbine)	45% (bio-SAF), 10% (e-SAF) (Average of 28% when considering 50-50 share)
Decrease in non-CO_2 climate impacts compared to fossil kerosine	100%	75% (fuel cell) 42% (turbine)	21%
Technology readiness	E9X no yet proven on operational scale. Expected on the market in 2035.	Hydrogen aircraft not yet proven on operational scale. Expected on the market in 2030.	SAF is a drop in fuel and proven technology. SAF production is expected to be sufficient in the future, however capacity for hydrogen and CO_2 supply in FT routes can a challenge.
Resource availability	Demand for renewable electricity is in competition with other sectors. Higher system efficiency than other aviation options provides a preference for battery electric aviation.	The growth of electrolysis capacity for green hydrogen production is slow. This makes it difficult to meet the 2030 green hydrogen targets.	Most SAF production facilities are still in the planning phase. In 2050, SAF production is expected to meet SAF demand. In the short term, the availability of CO_2 via DAC and the supply of green hydrogen are challenging. The required shares of biomass and renewable electricity suggest too high a resource consumption for aviation in 2050.
Infrastructural challenges	In the Dutch situation, which is a case in which a transition towards using more electricity requires considerate additional efforts, no big challenges have been identified. Expectations are that this will also be the case for other countries.	Local hydrogen production requires local grid expansion comparable to battery electric. Centralised hydrogen production requires a transport infrastructure that depends on the local situation.	Uses existing infrastructure.

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Annexes

CE Delft

Committed to the Environment

A Energy efficiency background

Table 5 - Energy efficiencies (on LHV basis) used in this study

Poduction step	Efficiency (LHV)	Source	Rationale
Battery charging	95%	de Vries et al. (2024).	Data assumed to be valid for 2035
Battery discharging	95%	de Vries et al. (2024).	Data assumed to be valid for 2035
Electric motor	90%	Assumed to be same as aircraft.	Data assumed to be valid for 2035
Hydrogen electrolysis	71%	Krishnan et al. (2024).	Assumed to be PEM electrolyser for 2035, data from Krishnan for 2030
Hydrogen Liquefaction	79%	Zhang et al. (2023).	Average value for short to medium term
Hydrogen Storage and refuelling	99%	Zhang et al. (2023).	Assumption that hydrogen will not be stored longer than 1 day
Fuel cell	65%	Wallington et al. (2024)	2035 value, converted from HHV to LHV
Turbine motor	40%	de Vries et al. (2024).	Lower efficiency than most other literature because of suboptimal range for this type of aircraft.
E-SAF conversion (Grid-to-liquid)	48% (38%)	Grahn et al. (2022) and Boilley (2024)	48% as a progressive assumption to not present SAF in too negative manner compared to electric aviation. 38% is a lower efficiency reported in literature with which a sensitivity analysis is performed in the analysis.
Feed cable	95%	Wallington et al. (2024), 2035 value.	

Table 6 - Conversion factors from MJ to pkm (specific for 800 km distance)

Transport	Energy from grid per passenger-kilometre (in MJ)	Energy from tank per passenger-kilometre (in MJ (LHV))	Source energy from tank:
Battery electric aircraft	**0.74**	**0.70**	**de Vries et al. (2024)**
Hydrogen fuel cell	**2.13**	**1.27**	**FlyZero (2022b), adjusted by Vries (2024) for 800km**
Hydrogen turbine	**1.07**	**0.64**	**FlyZero (2022b)**
Jet fuel turbine	**2.07**	**0.99**	**Emission calculator EEA (2023),** [5]
Battery electric car (4 passengers)	**0.21**	**0.18**	**CE Delft (2024)**
Train	**0.11**	**0.10**	**CE Delft (2024)**

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[5] Input data: 800 km flight, a320neo, assumed occupancy 85%.

B LCA background

To calculate the life cycle climate change impact, the ISO 14040-44 guidelines were followed for the structure. The analysis was performed using SimaPro 9.6.0.1 LCA software, using the Ecoinvent 3.10 LCA database for background data. The foreground data used in the analysis are described below. The impact assessment method used is IPCC 2021 GWP100 V1.03 in SimaPro. The analysis is based on readily available data and extensive data checks have not been performed. The analysis has not been externally verified.

B.1 Goal and scope of the analysis

Goal of the LCA

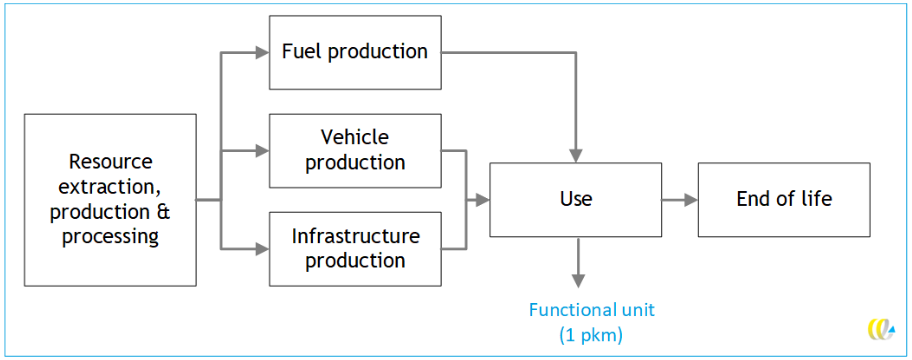
Assess the climate change impact of different modes of passenger transport over their life cycle in order to make a fair comparison.

Scope

The analysis compares the impact of the following transportation modes per person-kilometre (pkm) for the expected situation in 2035:

- Elysian E9X first generation;
- Fuel cell H2 aircraft;
- Turbine H2 aircraft;
- Narrow body (A320neo) JetA1;
- Narrow body (A320neo) bio-Saf;
- Narrow body (A320neo) e-Saf;
- Electric passenger car;
- High speed train (electric).

Figure 22 - System under study



The LCA is a cradle-to-grave analysis, which means that all emissions from resource extraction, material processing, use and end-of-life (EoL) treatment are considered. The analysis is divided into the following parts:

- fuel production (well to tank emissions);
- vehicle production;
- infrastructure production;
- use (tank to wake emissions);
- end of life;

- (emissions from resource extraction are included in the categories above).

For the use phase of aviation, non-CO_2 impacts are included in the analysis.

B.2 Inventory data

Fuel production

Electricity, liquid hydrogen and e-SAF are modelled based on literature sources. For bio-SAF, the carbon footprint was assumed to be 65% lower than fossil, as required by RED II (EU, 2018). For electricity, two scenarios are included, the expected European grid mix of 2035 (CF: 0.045 kg CO_2-eq./MJ) and a mix of only wind energy (CF: 0.0047 kg CO_2-eq./MJ). These electricity mixes are also used for the production of liquid hydrogen and e-SAF. The gaseous hydrogen model is based on the PEM electrolyser (future configuration) of Krishnan et al. (2024). This gives an energy use of 48 kWh/kg gaseous hydrogen. Liquefaction is based on Zhang et al. (2023). The energy use for liquefaction is 9 kWh/kg hydrogen. In addition to (gaseous) hydrogen, CO is a major input for e-fuel production. This CO is produced from CO_2 from DAC, modelled after Ottenbros et al. (2024). Here 1,500 kWh per ton CO_2 is assumed for full scale production in 2030. The production of syngas and synthesis to e-SAF is based on Van Der Giesen et al. (2014) and (Tremel et al., 2015). The conversion efficiency from hydrogen to e-SAF is 83% on LHV basis, making the PtL efficiency ~48%. The production of fuels includes not only the energy demand but also the infrastructure.

Vehicle production and EoL

Aircraft body production is modelled by using the weight of the aircraft multiplied by the expected material composition taken from Cox (2018). This gives a rough indication of the impact of materials. The assumed weights are given in Table 7.

Table 7 - Aircraft weight estimation in 2035

	Aircraft weight (tons)	Battery weight (tons)	Battery type	Source
E9X gen1 (excl. battery)	32	35	Li-ion	de Vries et al. (2024)
H2 fuel cell	19.8			FlyZero (2022b)
H2 turbine	48			FlyZero (2022b)
Narrowbody	41.5			FlyZero (2022b)

For trains and electric vehicles, the Ecoinvent data for vehicle production is used as is.

The impacts of vehicle production, EoL and infrastructure use are divided by the expected total person-kilometres over the lifetime. For aircraft, the total passenger-kilometres are calculated using lifetime, average flight distance, available seats and average occupancy.

Table 8 - Total pkm estimation for aircraft

	Available seats	Average occupancy	Average flight distance	Total flight cycles	Total pkm (in millions)
E9X gen1	90	85%	800	Body: 40,000	2,448
				Battery: 1,500	92
H2 fuel cell	75	85%	800	40,000	2,040
H2 turbine	180	85%	800	40,000	4,896
Narrowbody	180	85%	800	40,000	4,896

For the train and the electric car, data from Ecoinvent are used (150,000 km for the car and 100,000 for the battery), adjusted for an assumed occupancy of 1 and 4 passengers per electric car and a train occupancy of 47%.

Infrastructure production

Specific infrastructure required for transport (roads, railways, airports) is included. For the transport of electricity and fuel, Ecoinvent data has been used. Energy consumption of infrastructure (road lighting and airport operation) is excluded. Specific additional infrastructure related to fuel use (battery chargers, hydrogen storage) is not yet included.

Fuel use

Fuel consumption per pkm for Elysian aircraft is based on Elysian data. For the narrow-body aircraft, the EEA Aviation Master Emission Calculator (EEA, 2023) is used to estimate the fuel consumption of an A320 neo for a flight of 800 km. This is not the optimised distance for a narrow-body but considered the most realistic alternative for a flight distance of 800 km. Table 9 gives an overview of the direct fuel consumption per pkm for all the transport options included in this analysis. It is assumed that all aircraft are filled to 85% capacity.

Table 9 - Energy consumption per passenger-kilometre

	Energy type	Energy from tank per passenger-kilometre (in MJ (LHV))	Source
E9X gen1	Electricity	0.70	de Vries et al. (2024)
H2 fuel cell	Hydrogen	1.27	FlyZero (2022b)
H2 turbine	Hydrogen	0.64	FlyZero (2022b)
Narrowbody	Jet A1, 100% bio-SAF or 100% e-SAF	0.99	Emission calculator EEA (2023), [6]
Electric car (1 person)	Electricity	0.72	CE Delft (2024)
Electric car (4 persons)	Electricity	0.18	CE Delft (2024)
Train	Electricity	0.11	CE Delft (2024)

For fossil kerosene, direct CO_2 emissions are included based on a factor of 0.733 kg CO_2-eq. per MJ of kerosene used. Non-CO_2 climate impact are based on the factors described earlier in the report. For simplicity, aircraft are assumed to use 100% SAF.

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[6] Input data: 800 km flight, a320neo.

Uncertainties

The following uncertainties that should be taken into account when using the results:

- For non-air transport, vehicle and infrastructure production have a large contribution to the results. The use of infrastructure varies between routes and vehicle occupancy. For certain routes the differences can therefore be significant.
- The background data used in the LCA represent the production of materials using current technologies. It is possible that the carbon footprint will be different in the future.
- In order to ensure a 'fair' comparison with Elysian, the best case has been assumed for the alternatives wherever possible. The results for the alternatives should therefore only be used for comparison with Elysian.

Colophon

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