E-SAF: Techno-Economics of PtL and PtH_2

Focus North America and Europe

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Stakeholder advisory group

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Content

PREFACE

Deutsche Aircraft is developing the D328eco™ powered by 100% Sustainable Aviation Fuel, but we are also engaged in various hydrogen research & technology projects.

We strive to develop solutions that yield the maximum reduction in climate impact and pollution while being aware of the urgent need to bring rapid and economical solutions to market. With the current greenhouse gas emission trajectory, we are about to tip planet Earth into terra incognita, and we need to act now to avoid that we as a society hit the wall during this century.

Hydrogen and power-to-liquids are exciting options due to their scalability and environmental performance. Still, it is often unclear how these fuels perform in an apples-for-apples comparison regarding production costs and their well-to-wake emissions.

While we tackled these questions with extensive in-house modelling, we decided to substantiate our endeavour by seeking independent advice from Ludwig-Bölkow-Systemtechnik (LBST) – globally one of the most reputable PtX consultancies with extensive process know-how and widely cited publications in the field.

Which alternative fuel and at what time will drive the journey towards net zero climate impact is a crucial question that is important not only for us as an aircraft OEM but also for investors, policymakers, and airline customers.

During this research project, we decided to open up the process by involving other stakeholders from the aviation ecosystem. I want to thank all external partners from NGOs, research institutions, fuel producers, airports, consultancies, and OEMs who challenged our assumptions and provided valuable feedback during our partner workshop and the review process. In conjunction with the extensive experience of LBST, their contributions have been vital to enhancing the quality of the study.

Making good decisions under technological and economic uncertainties can only be assured through objective and solid information. With this publication, we hope to bring an essential piece to the often emotionally charged public debate about the most viable decarbonization options for aviation. Collaboration is paramount, and at Deutsche Aircraft, we have diverse partnerships paving the way for this transition. We extend an invitation for you to embark on this journey with us.

Dave Jackson, Chief Executive Officer, Deutsche Aircraft

FUEL FOR THOUGHT – KEY TAKEAWAYS FOR THE AVIATION ECOSYSTEM AND POLICYMAKERS

- From a fuel production and distribution cost point of view, with liquefaction as a significant cost driver, Liquid Hydrogen can undercut Power-to-Liquids at large airports or if demand can be pooled (LH_2 clusters).
- Fuel production and distribution costs for Power-to-Liquids and Liquid Hydrogen show similar orders of magnitude for small-scale applications such as regional airports.
- Power-to-Liquids and Liquid Hydrogen exhibit comparable well-to-wake greenhouse gas emissions according to the employed frameworks.
- Further hydrogen technology maturation at the aircraft level will enable a complete end-to-end view when comparing Liquid Hydrogen and Power-to-Liquids. The favorable energy balance for Liquid Hydrogen compared to Power-to-Liquids on the supply side must be traded against the technological challenges at the aircraft level of airborne hydrogen systems.
- To put aviation on an emissions trajectory in line with the Paris agreement, drop-in SAF must be ramped up now for use in existing aircraft. At the same time, there is a clear need to finalize an ASTM zero-aromatics jet fuel standard for Power-to-Liquids and fossil kerosene to speed up the transition of the global fleet towards alternative fuels optimized for climate impact and local air quality.
- Investments in Power-to-Liquids production plants and overall hydrogen infrastructure require tangible support by policymakers to facilitate scale and cost reduction.
- Aviation will only achieve its environmental targets through e-SAF with an unprecedented ramp-up of renewables. Additional solar and wind energy production capacity is the critical enabler for e-SAF. Increasing the share of renewables in electricity grids will further improve the greenhouse gas emission balance of ancillary e-SAF production processes.
- At the current state of knowledge, the only sustainable and scalable long-term CO_2 source for Power-to-Liquids production is atmospheric CO_2 through direct air capture. Therefore, policymakers need to support investment in direct air capture to ensure future cost competitiveness and sustainability of Power-to-Liquids.
- Further research is needed to conclusively assess non-CO_2 effects, particularly the climate impact of contrails of Liquid hydrogen technologies (H_2 fuel cell, H_2 burn) against Power-to-Liquids.
- An environmentally effective, economically feasible and socially acceptable policy mix is required to guide aviation towards climate neutrality.

1 SETTING THE SCENE

1. SETTING THE SCENE

1.1. Aviation at a crossroads

The success of aviation has been driven by the availability of relatively inexpensive fossil fuels. In the face of rapid climate change, the environmental impact from the combustion of these conventional energy carriers has become a major challenge. Greenhouse gases (GHG) and other harmful emissions continue to rise as air traffic grows, projecting a pessimistic outlook on the sector to achieve climate targets. At the same time, aircraft technology improvements and the uptake of sustainable aviation fuels (SAF) provide possible mitigation options. Figure 1 presents a summary of the sustainability performance and aspirations of the aviation sector.

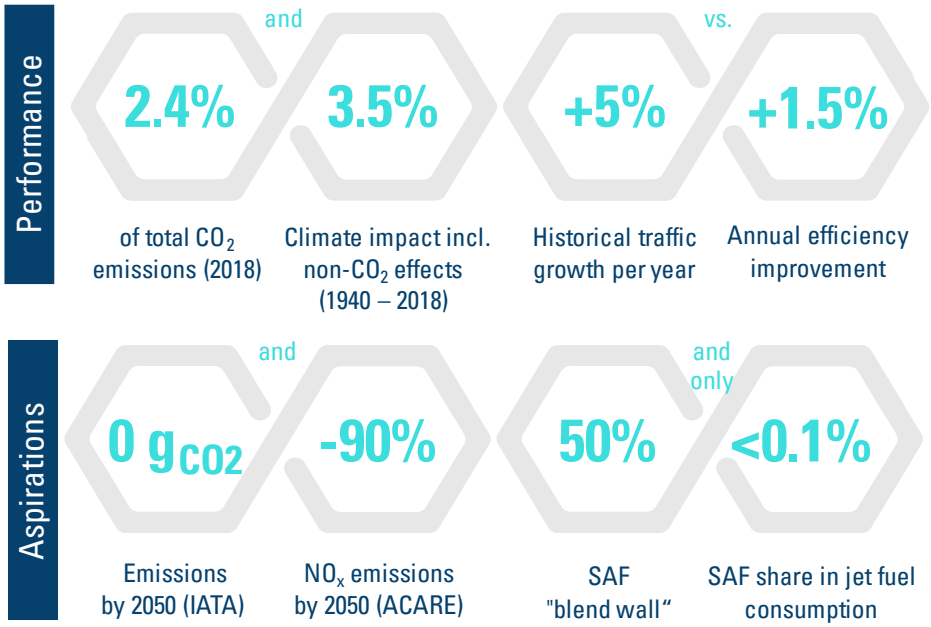


Figure 1: Aviation's sustainability performance and aspirations in figures

In 2018, air transport emitted 2.4% of the total CO_2 emissions in the world. In aviation, besides CO_2 emissions, attention has also shifted towards addressing its high-altitude impact through non-CO_2 effects such as nitrogen oxides and condensation trails (contrails). Taking into account non-CO_2 effects increases the share of aviation in overall GHG emissions.

As a result, the total climate impact of aviation, including non-CO_2 emissions was 3.5% [EESI 2022], [Lee et al. 2021] to 4% [Klöwer et al. 2021][1] pre COVID-19. Additionally, other aviation emissions, including nitrogen oxides (NO_x), volatile organic compounds (VOC), and ultra-fine particles, raise discussions concerning aviation's impact on local air quality.

[1] In 2019 the share of CO_2 from fossil fuel and industry was 64% [IPCC 2022]

Furthermore, growing air travel demand has been outpacing efficiency improvement. In the past, air traffic has increased at about 5% per year on average [EESI 2022]. From 1980 to 2016, the fuel consumption per passenger km decreased slightly less than 1% per year. For the timeframe between 2016 and 2034, an annual decrease of fuel consumption per revenue passenger km of 0.8% to 2.2% may be expected depending on fuel price developments and regulations [ICCT 2016], i.e. 1.5% per year in average.

In face of the climate crisis, the sector is expected to significantly reduce its climate impact. According to ICAO's long-term global aspirational goal (LTAG) for international aviation the greenhouse gas emissions should be net-zero by 2050 [ICAO 2022]. For the same time horizon, the Advisory Council for Aeronautics Research & Innovation in Europe (ACARE) has also set a net-zero CO_2 emissions target and aims to reduce NO_x emissions by 90% relative to the technology introduced in the year of 2000 [ACARE 2023].

Currently the share of SAF including biofuels amounts to less than 0.1% of global jet fuel demand [IEA 2023]. Fuel standards for SAFs so far limit their use to a 50% admixture at most ('blend wall'), i.e. SAFs need to be blended with fossil kerosene (ASTM D7566 Annex 1 and Annex 4). SAF blending mandates set forth in the Refuel EU regulation would only hit 50% at some point between 2045 and 2050. However, the blend wall may be reached earlier in regions with favourable production conditions and stronger regulations, and even the use of 100% SAF is supposable in such regions.

1.2. Pushs and pulls to achieve the Paris climate target

In Europe, the aviation sector is under increasing pressure due to the revision and adoption of regulations/directives under the EU Green Deal, such as the EU Emission Trading Scheme (EU-ETS), the EU Energy Taxation Directive (ETD) and the ReFuelEU Aviation regulation [EC 2023a]. If adopted, the revision of the ETD would set minimum jet fuel taxes across member states [EC 2021]. While pricing emissions at the federal level in North America has been a contentious issue, emission trading schemes have been deployed in some progressive regions [ICAP 2023]. Recently, NGOs have been calling for a frequent flyer levy to generate revenues for decarbonization while ensuring equitable distribution of the cost burden targeting airlines' most profitable market segments [ICCT 2022]. Last but not least, public criticism of the aviation sector (flight shaming) rises due to its impact on climate and local air quality through emissions such as particulate matter (PM) and nitrogen oxides (NO_x).

One way to reduce these impacts is the use of alternative fuels. Power-to-Liquids (PtL), but also other types of SAF benefit in general from increasing support for development and deployment, e.g. through the U.S. Inflation Reduction Act (IRA), and the EU Innovation Fund. Another option is hydrogen-fuelled aircraft (both based on H_2 combustion technologies and fuel cells) that are currently under development. It is clear that, in order to meet the sector's targets, all levers such as SAF deployment, airframe and engine optimization, passenger awareness, and operational measures are necessary to minimise aviation's environmental impacts (Figure 2).

There is increasing evidence about the potential of technical solutions. For short distance and very small aircraft, battery electric propulsion is a potential option, if battery technology improves. Hydrogen is considered for larger aircraft: either featuring fully electric propulsion systems powered by fuel cells for short ranges, or by burning hydrogen in turboengines as a potential long-term option for longer distances. Bridging the time gap until maturity of these technologies, kerosene via PtL is a robust option similar to established jet fuel, both as blend component for drop-in SAF application, as well as zero-aromatics

unblended SAF as soon as the required non-drop-in standard is published. The lead time between launch of a new aircraft project and entry into service ranges between 6 and 12 years [Leeham 2022] and aircraft are generally operated over a period of about 30 years. Therefore, drop-in fuels are a key lever to reduce emissions from the existing aircraft fleet and aircraft entering into service, until novel technologies and fuel standards have reached the necessary maturity.

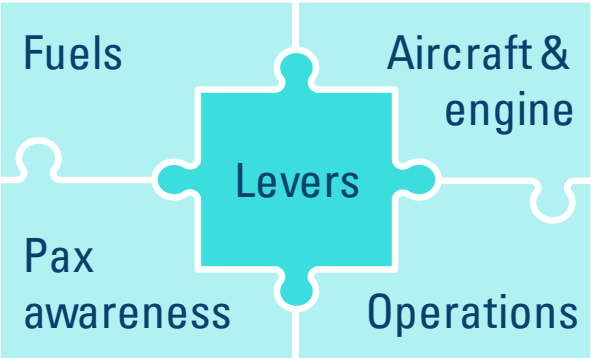


Figure 2: Levers to minimise aviation's environmental impacts

This whitepaper aims to shed light on concrete technology options for aviation fuels, their environmental and economic performance, as well as their respective requirements regarding fuel infrastructure. While advancements in aircraft technology and operational efficiency are essential, more is needed to offset the sector's escalating demand. The lead time for innovation and deployment of new aircraft technologies is considerable. Therefore, the short-term key lever to rapidly reduce climate impact is the fast ramp-up of SAF with sufficient environmental performance for use as drop-in blend component on the in-service fleet. Moreover, the rapid definition of fuel standards is necessary to ensure the compatibility of aircraft entering into service with higher drop-in SAF blends and even non-drop-in SAF options in the future.

This study focuses on drop-in PtL blends, unblended drop-in and non-drop-in PtL, as well as liquid hydrogen (LH_2). PtL and LH_2 are promising alternative fuels due to their long-term scalability and environmental performance while entailing significant technological and economic trade-offs along the whole value chain. The added value of this report is the comparative approach between these two fuel options using consistent techno-economic parameters (cost and GHG balance) to guide the aviation ecosystem and policymakers. Detailed aircraft-specific aspects of the discussed fuel options are beyond the scope of this study. North America and Europe have been chosen as key mature aviation markets with the broadest alternative fuel policy frameworks. Deploying alternative fuels at scale and lowering costs through learning in developed aviation markets is vital for global technology diffusion to curb growing aviation emissions across emerging and developing economies.

2 APPROACH

2. APPROACH

2.1. Pathway description

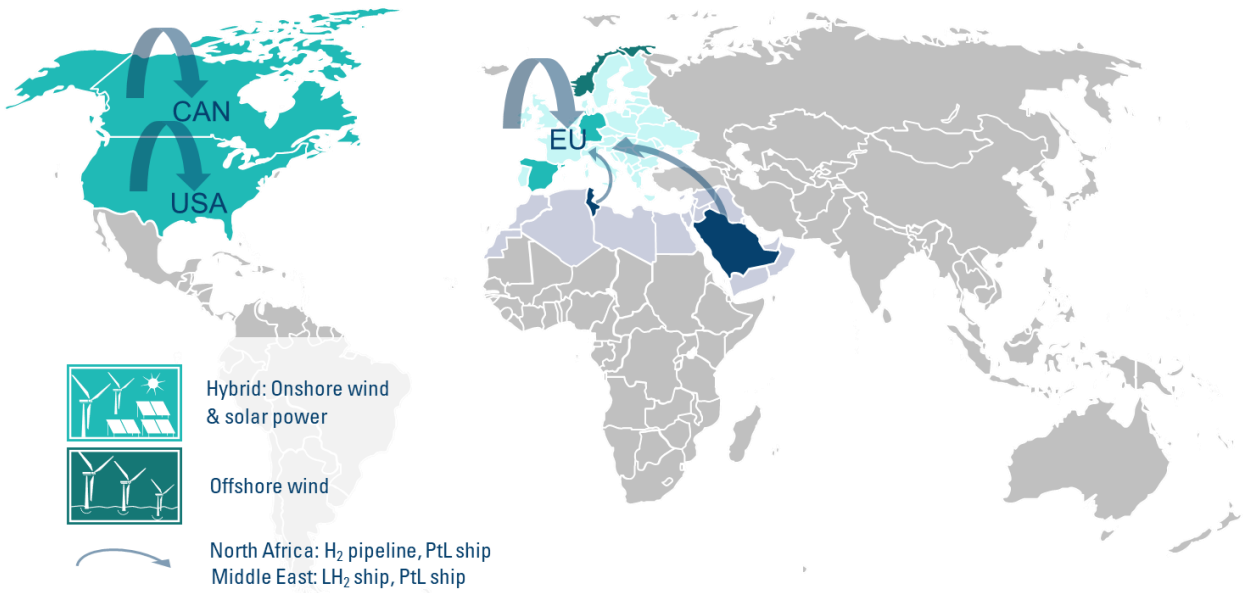


Figure 3: European, North American and import pathways from MENA

The study covers a range of regions, sourcing strategies, fuel qualities and time horizons. Import of PtL and H_2 is only considered for Europe, as North America is assumed to cover its own demand for e-SAF with domestic production due to high potentials of renewable energy sources and a comparatively low population density.

Figure 3 shows the three main regions considered:

1. North American domestic production with the United States of America and Canada as proxy countries
2. European domestic production with Norway, Germany, and Spain as proxy countries
3. Import pathways from Middle East and North Africa (MENA) to Europe with Tunisia and Saudi Arabia as proxy countries

Sources for renewable electricity are selected based on regional economic feasibility. A mix of onshore wind and solar power is assumed in each country, except for Norway, which generates its electricity from offshore wind turbines.

For each pathway, the production of the following fuel types is considered:

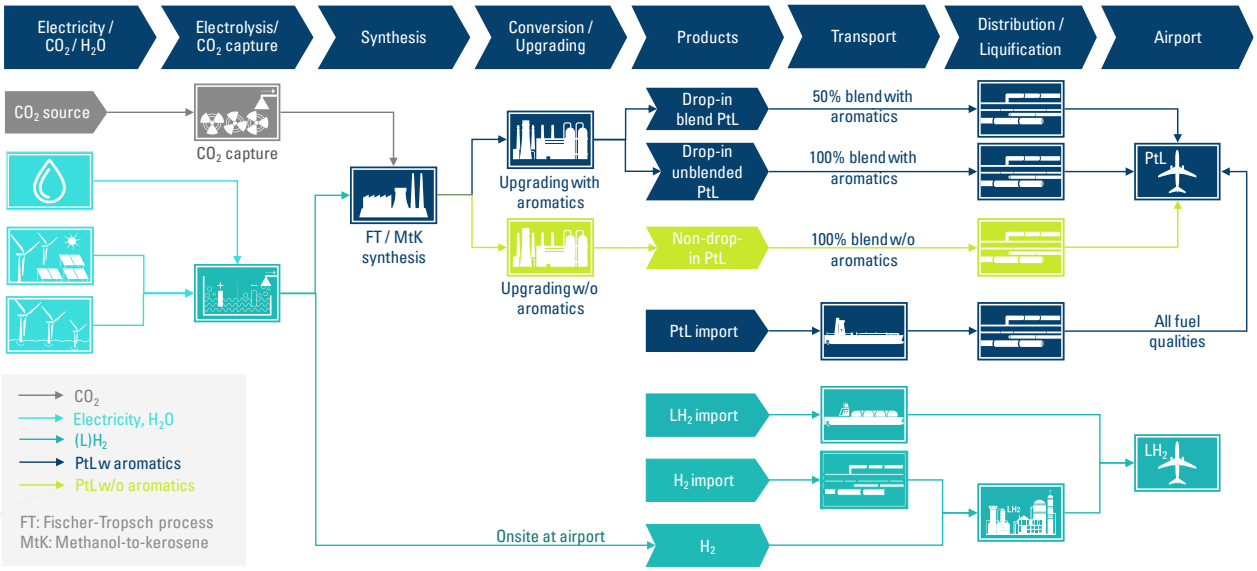
- Drop-in blend PtL (up to 50% blend compatible with existing ASTM standards)
- Drop-in unblended PtL (up to 100% PtL incl. aromatics, assuming a 100% SAF standard accepting synthetic aromatics)
- Non-drop-in PtL (up to 100% PtL without aromatics, assuming a 100% SAF standard implying minor changes in infrastructure and aircraft)
- Liquid hydrogen LH_2 (assuming future standards for LH_2 use in aviation, and entirely new technology in infrastructure and aircraft)

The production of the individual fuels is determined in the respective regions for the time horizons 2030, 2040 and 2050.

2.2. Process description

Drop-in blend PtL (50% blend compatible with existing ASTM); Drop-in unblended PtL (100% with aromatics); Non-drop-in PtL (100% without aromatics)

Figure 4 describes the different pathways and processes for the supply of PtL kerosene and liquid hydrogen (LH_2).



Drop-in blend PtL (50% blend compatible with existing ASTM); Drop-in unblended PtL (100% with aromatics); Non-drop-in PtL (100% without aromatics)

Figure 4: Process description for PtL and LH_2 pathways

To produce PtL, electricity, water, and CO_2 are required. The CO_2 is supplied by a CO_2 capturing plant at a cement kiln for the years 2030 and 2040, or a direct air capture (DAC) plant for the year 2050. The timing for the phase-in of DAC was set in line with expected technology maturity/deployment at scale and EU policy requirements (see Table 4). The potential for concentrated biogenic CO_2 sources is limited. Moreover, while certain fossil point sources remain unavoidable for some time, they represent a net addition of GHG

emissions to the atmosphere. Therefore, DAC is the only long-term option to produce large amounts of e-kerosene. Hydrogen is generated from water and renewable electricity via electrolysis. The third step involves synthesizing liquid hydrocarbons via Fisher-Tropsch synthesis or methanol synthesis with the downstream methanol-to-kerosene process. The raw Fischer-Tropsch synthesis products need to be upgraded to kerosene via hydrocracking, hydrotreating, and isomerization. Since Fischer-Tropsch kerosene generally does not contain aromatics, aromatisation of a part of the product stream or blending of aromatic compounds is required to supply drop-in fuel to meet the ASTM minimum requirement of 8% aromatics content in Jet A1 fuel. For non-drop-in Fischer-Tropsch kerosene, addition of aromatics is not required. The fifth step lists all intermediate products and ready to use electricity-derived sustainable aviation fuels (e-SAF), including gaseous hydrogen produced directly from on-site electrolysis at the airport, and the fuels imported from MENA (e-kerosene, H_2, and LH_2). The imported fuels are transported to the EU either by ship (PtL fuel from MENA and LH_2 from Middle East) or via pipeline (H_2 from North Africa). The PtL fuels are distributed to the airports through pipeline. The hydrogen is liquefied directly at or nearby the airport, except for imported LH_2 from Saudi Arabia.

3 COSTS

3. COSTS

3.1. Fuel cost corridors

In line with the study objective of comparing different sustainable aviation fuels and pathways, a full cost assessment from the renewable power production to the final e-fuel dispensing has been carried out. Hence, no business case analysis, no net present value (NPV), or return on invest (ROI) have been calculated. Therefore, neither taxes/levies nor exemptions thereof are considered, and cost figures are given in today's purchasing power. Learning curves have been considered for technologies with potential for cost reductions from series production. Cost effects on aircraft design and operations are explicitly excluded from this study.

CAPEX is converted to an annual annuity assuming an interest rate of 6% as a baseline and a repayment time in line with the process-specific lifetime (typically 25-30 years). Annual costs for maintenance and repair are added. The resulting annual costs divided by the average annual production volume result in the specific product costs. The specific costs are aggregated according to pathway definition and expressed in € per unit of final energy in kerosene equivalents.

All facilities, such as plants for power generation, synthesis, and conversion/upgrading, are newly built (from scratch). The same applies for vehicles used for the transport of the final fuel.

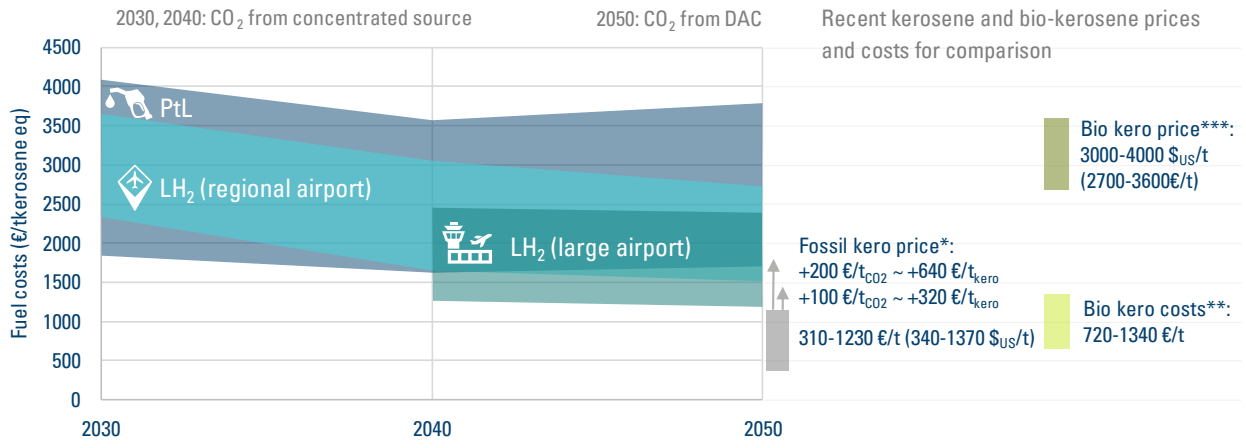
The interest rate is assumed to be 6% as base case. For the sensitivity assessment the minimum interest rate is assumed to be 4% and the maximum interest rate is 10%. We use an asymmetric sensitivity around the baseline interest rate to account for potential country-specific risk factors in the import pathways and to consider that the upside is higher than the downside.

In 2030 and 2040 a cement kiln is used as CO_2 source for e-kerosene production, for 2050 DAC is assumed as CO_2 source. Therefore, under conservative assumptions, PtL costs slightly increase between 2040 and 2050.

The economics of PtL is mainly driven by production scale and not by the scale of distribution. Therefore, we assumed large PtL plants and do not differentiate between airport sizes. For LH_2, on the other hand, the distribution scale does matter. We consider two different airport sizes for LH_2 to assess the cost impact of liquefaction. We assume only regional traffic (below 100 PAX aircraft) can be encountered at the regional airport, while we assume all aircraft classes to be present at the large airport. In conjunction with a market penetration scenario for potential LH_2 aircraft, we estimate LH_2 quantities for each airport class (Table 7 in Annex).

Figure 5 shows the cost corridors for the supply of electricity-based aviation fuel over time and recent kerosene prices, as well as biogenic kerosene costs and prices for reference. Costs for e-kerosene are higher than recent fossil jet fuel price levels (~340-1370 US$/t or ~310-1230 €/t in the time frame from January in 2016 to July in 2023 excluding the COVID 19 effect in 2020 according to [IATA 07/2023]). LH_2 costs would converge to recent fossil kerosene prices in the long-term when used at large scale and under optimistic assumptions.

Figure 5 shows the cost corridors for the supply of electricity-based aviation fuel over time.



* Min/max in the timeframe 01/2016-07/2023 based on market data by [IATA 07/2023]

** BtL via Fischer-Tropsch synthesis of gasified woody biomass from short-rotation forestry, Data by [IEA 2020]

*** Data by [Argus 05/2023]

Figure 5: Fuel cost corridors for electricity-based aviation fuel over time, recent fossil jet fuel prices including potential CO_2 taxes, recent biogenic kerosene costs and prices in €/t of kerosene equivalent based on the lower heating value

The production costs of e-kerosene are competitive with the recent prices of bio-jet fuels (3,000-4,000 US$/t or 2,700-3,600 €/t in April 2022 to April 2023 according to [Argus 05/2023]). However, additional measures such as subsidies, taxes, or tightening emission trading schemes are necessary to close the cost gap with fossil fuels. Our analysis shows, for instance, that CO_2 prices of 100 to 200 €/t would achieve parity in 2050 and potentially 2040 between e-SAF production costs under optimistic assumptions and recent fossil kerosene prices (see Figure 5). Indeed, the revision of the EU-ETS under the EU Green Deal will increase the linear reduction factor determining the annual adjustment of the emission cap. Moreover, free allocations of allowances for airlines will be fully phased out from 2026 [UBA 2023]. In the USA, the Inflation Reduction Act will provide subsidies through tax credits to SAF producers once their fuels meet minimum GHG reduction thresholds. Blending mandates can foster the uptake of e-SAF, especially in the absence of sufficiently high emission taxes and allowance prices, but do not close the cost gap. Indeed, allowance prices in the EU-ETS had been too low to incentivize airlines to uptake SAF. Therefore, the ReFuel EU Aviation regulation will mandate increasing minimum SAF shares in the European jet fuel mix to create a market for SAF and in particular PtL through a dedicated sub-quota [EC 2023a].

In case of LH_2 as aviation fuel, the most significant cost reductions are expected to be achieved through the scale-up of liquefier technology for conditioning H_2. Smaller hydrogen liquefaction capacities lead to fuel costs that are within the range of e-kerosene production costs. On the other hand, larger LH_2 production capacities have the potential to achieve costs below those of e-kerosene. Complexity and technology risk of LH_2 aircraft drive research and technology projects towards smaller aircraft classes. LH_2, on the other hand, can be provisioned in the most cost-efficient manner at scale, as our analysis demonstrates by comparing regional and large airports. This result reinforces the need for integrated hydrogen clusters combining demand from various sectors to provide hydrogen at small scales to specific users economically. Nevertheless, hydrogen clusters can only partly provide for the necessary liquefaction scale, as gaseous hydrogen may be sufficient for many sectors outside of aviation. The other conclusion that could be drawn is that LH_2 should be used in larger aircraft classes to harness the significant economies of scale in liquefaction.

The production costs of e-kerosene in Southern EU, North America, North Africa, and the Middle East are similar, falling within the range of uncertainty.

3.2. Cost breakdown

Table 1 shows the estimated total costs for the supply of e-kerosene. Figure 6 show the cost contributions for the supply of e-kerosene in 2040 and 2050.

Table 1: Costs of e-kerosene (base case)

Region	2030 (€/$t_{kerosene\ eq}$)	2040 (€/$t_{kerosene\ eq}$)	2050 (€/$t_{kerosene\ eq}$)
USA	2150	1860	2020
Saudi Arabia (KSA)	2120	1840	2010
Spain (ESP)	2190	1880	2030
Norway (NOR))	3130	2650	2860

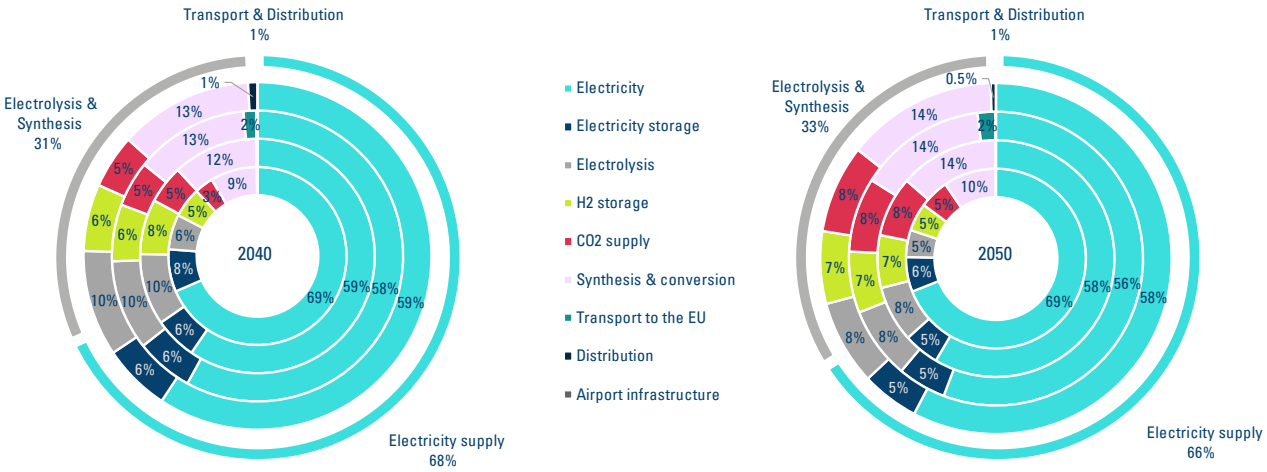


Figure 6: Cost contribution for kerosene via PtL in 2040 and 2050

In the production and supply costs of e-kerosene, the dominant cost component is the cost of electricity, accounting for 56-69% of the total. When considering sweet-spot regions, namely Southern Europe, MENA, and North America, there are no significant cost differences compared to the range of uncertainty. Between the years 2040 and 2050, there will be changes in the contribution of CO_2 supply to the PtL plant due to different sources of CO_2. In 2040, the CO_2 is assumed to come from cement kilns, while in 2050, it will be sourced from DAC. The transportation of e-kerosene to the EU has a minor impact on fuel costs because these fuels have a high energy density, making the transportation relatively efficient. The handling of LH_2 at airports is more complex than that for e-kerosene leading to higher costs for airport infrastructure.

For LH_2 as aviation fuel, the hydrogen liquefaction plant is located at the airport except in case of LH_2 imported via LH_2 carrier from Saudi Arabia. As a result, the capacity of the liquefaction plants for regional and large airports is different, leading to different cost contributions. In the case of LH_2 produced in Saudi Arabia, a large H_2 liquefaction capacity has been applied for all time horizons and across airport types to sufficiently utilize a large LH2 carrier with a capacity of 140,000 m³.

In 2040, the capacity of the hydrogen liquefaction plant amounts to about 8 t of LH_2 per day in the case of the regional airport and about 127 t of LH_2 per day in case of the large airport. Regarding the LH_2 imported from Saudi Arabia, a large hydrogen liquefaction plant is installed at the electrolysis plant. Both specific electricity consumption and capex of hydrogen liquefaction plants strongly decrease with increasing capacity. Furthermore, the costs of renewable electricity used for hydrogen liquefaction in Saudi Arabia also leads to lower costs for LH_2 supply.

Table 2 shows the total costs for LH_2 as aviation fuel in 2040. Figure 7 shows the cost contributions for the supply of LH_2 in 2040.

Table 2: Costs of LH_2 as aviation fuel in 2040 (base case)

Region	Regional airport (€/$t_{kerosene\ eq}$)	Large airport (€/$t_{kerosene\ eq}$)
USA	2140	1470
Tunisia (TUN)	2380	1740
Saudi Arabia (KSA)	2020	1890
Spain (ESP)	2080	1420

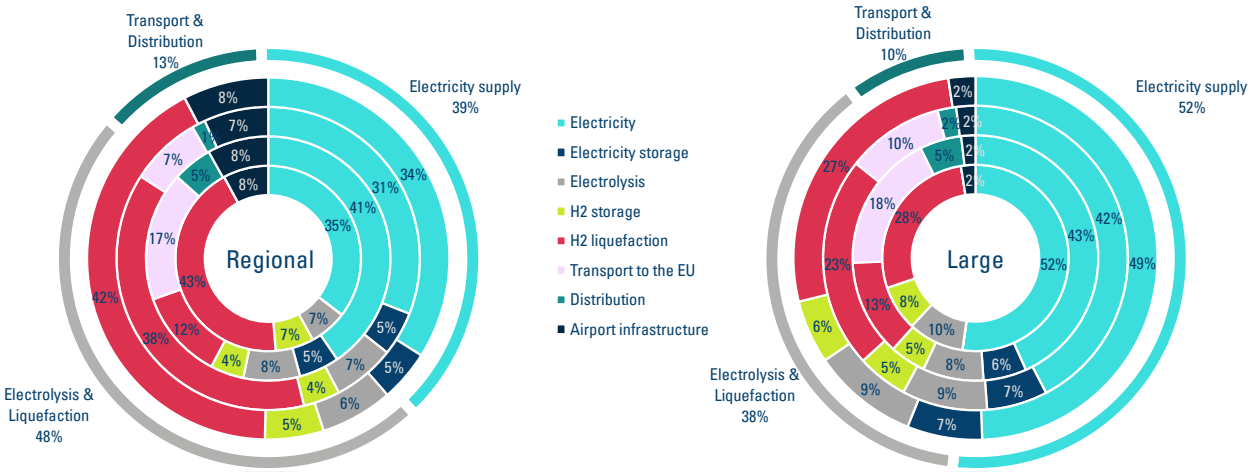


Figure 7: Cost contribution for LH_2 for regional airports in 2040

The use of large hydrogen liquefaction plants results in lower fuel costs compared to small-scale liquefiers. When comparing domestic production in Spain (inner circle) to imports from Saudi Arabia (middle circle) and Tunisia (outer circle), the transportation of LH_2 becomes a significant cost driver in contrast to PtL. For large airports, most domestic pathways except LH_2 from offshore wind in Norway are more cost competitive than shipping LH_2. The reason is that no maritime LH_2 transport is required, and large airports require large hydrogen liquefaction plants (economies of scale). Importing H_2 through pipelines and performing liquefaction at large airports leads to lower fuel costs compared to LH_2 imports over longer distances. In the case of the regional airport, the opposite is true. The capacity of the hydrogen liquefaction at the airport is lower, leading to higher unit costs (economies of scale).

4 EMISSIONS

4. EMISSIONS

4.1. RED II vs. CORSIA GHG – why slightly different results?

The GHG calculations of the different regions are calculated according to two different methodologies. For the North American countries, the calculation of the GHG emissions is based on CORSIA and for the European region, including the import from MENA, based on RED II.

Table 3 shows the differences between the two regulations.

Table 3: Differences between RED II and CORSIA GHG calculation methodologies

	RED II	CORSIA
Region	EU	Global
Calculation of GHG emissions	GWP 100 in IPCC Assessment Report 4 (AR4)	GWP 100 in IPCC Assessment Report 5 (AR5)
Allocation based on	Exergy (excess heat) and energy (other)	Energy
Minimum savings	65% (biofuels) and 70% (e-fuels) in relation to 94 g CO_{2eq}/MJ reference	10% in relation to 89 g CO_{2eq}/MJ reference
Land-use change (LUC)	Direct LUC	Default indirect LUC value + Core LCA value

Both methodologies do not (yet) consider grey/capex-related emissions, meaning the GHG emissions from the manufacturing of power plants, fuel production facilities, vehicles, etc. The climate impact from fugitive H_2 emissions and non-CO_2 climate impacts for aviation are not considered either.

In addition to the requirements of the regulations, the following assumptions were made. In 2030 and 2040, a cement kiln serves as the CO_2 source, while in 2050, a direct air capture plant is used. The national electricity mix is used for auxiliary processes (see data annex).

4.2. CO_2 sources

For 2030 and 2040, the CO_2 for e-kerosene production is derived from a cement kiln. The CO_2 concentration of the flue gas in today's cement kilns using fossil fuel amounts to about 22% [Gardarsdottir et al. 2019]. The flue gas from future electrically heated rotary cement kilns can reach a CO_2 concentration of almost 100% and the amount of CO_2 emitted from cement manufacture will decrease at about 50% [VTT 2022]. For 2050 CO_2 from DAC is assumed. The required temperature of the heat required for regeneration of the adsorbents used in the DAC plant for CO_2 capture from the Swiss manufacturer Climeworks amounts to about 100°C. As a result, the heat released by the Fischer-Tropsch synthesis plant (~220°C) can be used to supply heat to the DAC plant. The DAC plant of another manufacturer Carbon Engineering requires heat

with a temperature of about 900°C. Therefore, the heat and electricity consumption are based on data from Climeworks published in [Beuttler et al. 2019].

Combustion of fossil fuels leads to emission of CO_2 and thus increases its concentration in the atmosphere. Using CO_2 from fossil CO_2 sources such as coal power stations can lead to a technology lock-in, posing barriers to the adoption of more sustainable alternatives. The potential for concentrated CO_2 sources such as biogas upgrading plants and biomass power stations is limited. Therefore, CO_2 from DAC will be the dominant CO_2 source for large-scale e-kerosene production in the long run. Table 4 shows the sustainability aspects for various CO_2 sources.

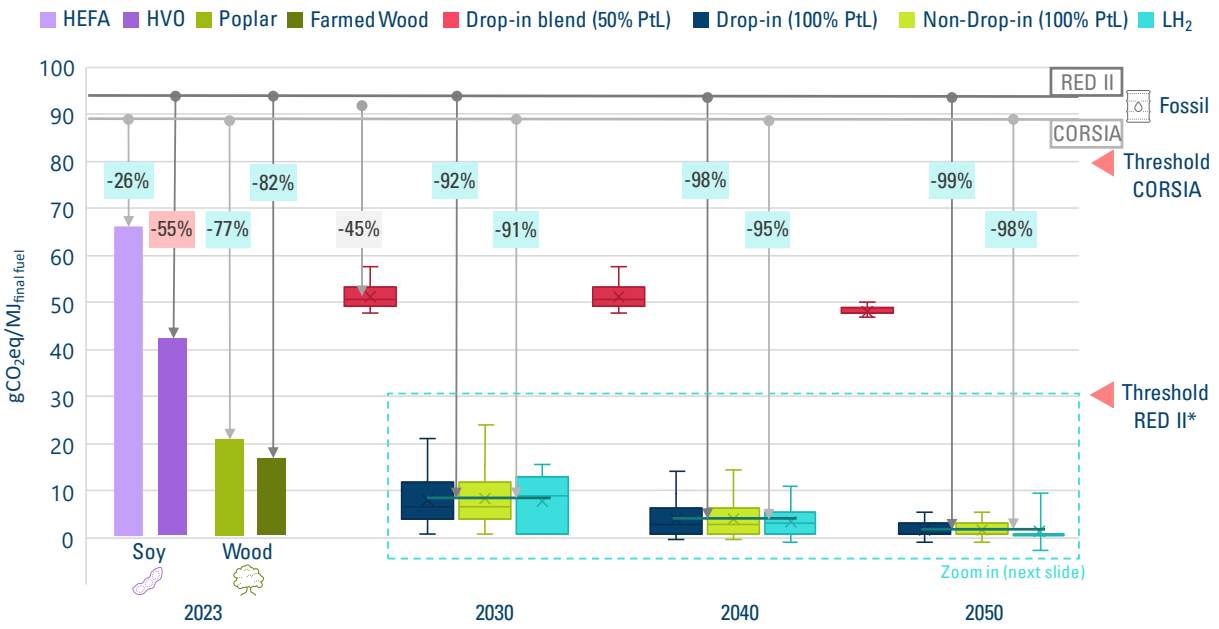
For the GHG calculation with CORSIA methodology it was assumed that CO_2 from fossil CO_2 sources is accounted as in RED II (0 gCO_{2eq}/gCO_2 before 2041), because CORSIA does not yet cover the use of CO_2 for SAF production. Furthermore, CO_2 from cement kilns in Saudi Arabia and Tunisia is accounted as in Europe.

Table 4: Sustainability of CO_2 sources

CO_2 sources	Renew-ability	Environmental sustainability	Alternative CO_2 uses	Towards carbon-neutrality; Risks	Eligible under EU RED II [EC 2023b]
Extraction from air		Subject to renewable energy			
Biogas upgrading		Subject to feedstock & process	Power-to-methane	Other land or sustainable biomass uses	Complies with sustainability and greenhouse gas savings criteria/ CO_2 capture did not receive credits for emission savings
Solid biomass fired heat (& power) plants			Bio-CCS		
Fermentation to alcohols			e.g., beverage industry		
Geothermal sources		Subject to geo-physical CO_2 cycle	CO_2 re-injection (closed loop)	Hot dry rock a potential no-go	CO_2 was previously released naturally
Cement, burnt lime or glass production		Subject to energy input; process-related emissions	Power-to-chemicals	Shift to alternative materials, recycling; Technology lock-in	CO_2 has been captured from an EU-ETS activity and has been taken into account upstream in an effective carbon pricing system and is incorporated in the chemical composition of the fuel before 2041 (2036 for combustion of fossil fuels for electricity generation). No fuel combustion for the specific purpose of producing CO_2.
Steel production (coke-based)		Subject to feedstock & process	Top gas for heating and reduction	Shift to direct reduction with H_2, recycling, alternative materials; Technology lock-in	
Fossil fuel firing			CCS	Phase-out; Technology lock-in	

4.3. Fuel GHG emissions and reduction values

The calculation was conducted using the E3database and carried out in compliance with the RED II/CORSIA framework (excluding hydrogen slip, capex related GHG emissions, and high-altitude climate impacts).



* Average between -65% for biofuels and -70% for RFNBO (PtX fuels) related to 100% SAF
MeOH/FT and regions are within bandwidths
Well-to-wake, according to RED II/CORSIA (assuming accounting of CO_2 for MeOH/FT synthesis according to RED II), without H_2 slip, no capex GHG, no high-altitude climate impacts

Figure 8: Greenhouse gas emission reductions by fuel type and year

Figure 8 shows the GHG emissions and reduction values for all four fuel types, along with the typical values of bio-kerosene (soybean HEFA and wood-based kerosene via gasification and Fischer-Tropsch synthesis) compared to the Fossil Fuel Comparator (FFC) baselines of RED II and CORSIA. A marginal reduction in GHG emissions is discernible between 2030 and 2050, denoting a reduction of seven percentage points. There were also only marginal GHG differences between the methanol synthesis with downstream methanol-to-kerosene process and the Fischer-Tropsch production pathway. The type of synthesis as well as the regions of production, fall within the bandwidths depicted in the boxplots. Notably, the potential reduction achievable reaches 99% when compared with the RED II FFC benchmark and 98% compared to the CORSIA threshold. In contrast, the 50% PtL drop-in blend fuel delivers only half the GHG reduction of its 100% PtL counterpart, as would be the case for all SAFs used in drop-in blends.

Both drop-in fuels, non-drop-in fuels, and LH_2 offer higher greenhouse gas reduction potentials than the biomass-to-Liquid (BtL) options. The GHG intensity of the analyzed fuels also has financial implications. Within the IRA, tax credits to support the ramp-up of SAF in the USA apply from 2023 until 2027 under certain conditions. On average, the analyzed PtL fuels achieve a GHG reduction of approximately 90% in 2030 and close to 100% in 2050 against the fossil fuel baseline in a 100% blend. With a 90% reduction in GHG emissions and assuming that no other state-level subsidies apply, these fuels would hypothetically be

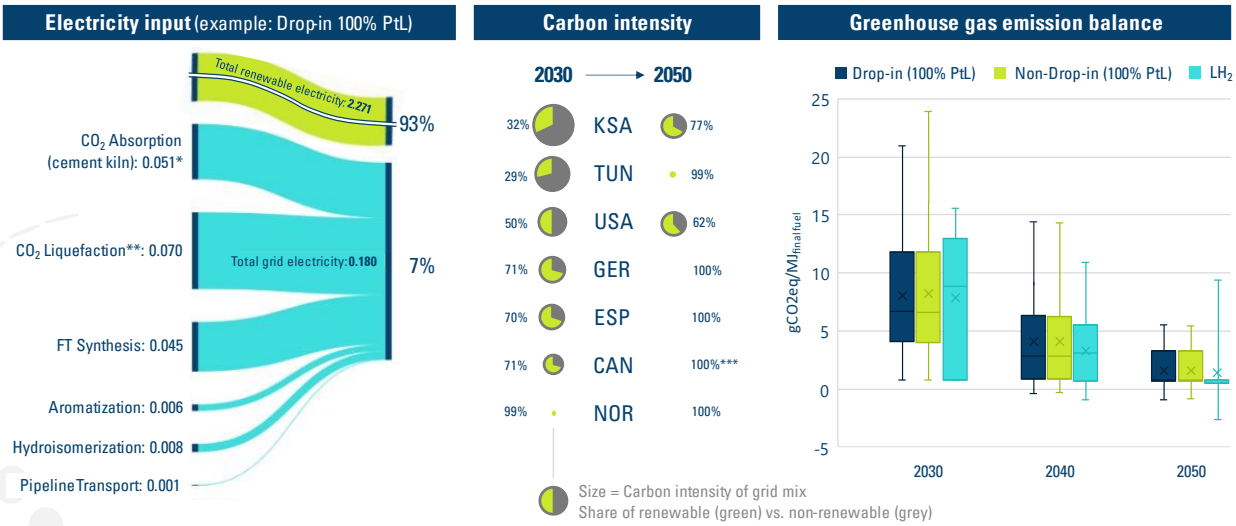
eligible for a 1.65 USD/gal Sustainable Aviation Fuel Tax Credit from 2023 to 2024 if produced domestically [DOE 2022] and applicable ASTM fuel standards would already include 100% drop-in and non-drop-in PtL fuels. In addition to specific SAF tax credits, the IRA supports hydrogen by providing subsidies for green hydrogen production and its main input, renewable electricity, until 2032, ultimately also lowering the costs of PtL [ICCT 2023].

As Corsia and RED II do not consider contrails, a detailed examination of the greenhouse gas (GHG) emissions reveals marginal differences when comparing PtL supply scenarios with or without aromatics driven by slightly different energy requirements. Likewise, the Fischer-Tropsch and methanol routes do not yield any significant differences from a GHG point of view.

The most significant GHG contributor is emissions resulting from the use of grid electricity for auxiliary process such as liquefaction, pipeline transport, and syntheses. This crucial factor is illustrated in Figure 9 emphasizing the overarching influence of electricity sourcing on the overall emissions outcome.

Turning our focus to the European landscape, the feasibility of bio jet fuels encounters distinctive challenges. First generation biofuels such as oil crops, while partly still permissible in road transportation, fall short of achieving the prescribed RED II GHG threshold and are thus not accepted in aviation. Moreover, EU policymakers have agreed on a food and feed feedstock phase-out for transportation fuels. Feedstocks based on waste, such as used cooking oil, exhibit limited global potential, illustrating the complex interplay between feedstock availability and sustainability considerations.

The influence of indirect land use change (ILUC) values is reflected in the CORSIA default values for certain feedstocks. ILUC describes CO_2 emissions from an extension of agricultural land as a consequence of diverting existing areas to biofuel production, that have been previously used for food and feed production. For instance, ILUC considerations contribute to 8.6 out of 20.8 g CO_2 equivalent per MJ of final fuel in the case of poplar and 25.8 out of 66.2 g CO_2 equivalent per MJ of final fuel for soybean oil. Neither PtL nor LH_2 cause ILUC emissions.



* 0.137 kWh for DAC ** Assumed for purification purposes depending on CO_2 source in combination with buffer storage
*** Net negative carbon intensity of Canadian grid mix due to planned BECCS [CER 2023]

Figure 9: Influence of electricity input on GWP results

Hydrogen is an indirect greenhouse gas because it influences the concentration of hydroxyl (OH^-) radicals which influences the degradation of methane in the atmosphere. [Warwick et al 2022] estimates the global warming potential of hydrogen of about 11±5 g CO_2 equivalent per g for a 100-year time horizon (GWP 100). Other sources, e.g. [Sand et al. 2023], indicate 11.6±2.8 g CO_2 equivalent per g. Figure 10 shows the impact of fugitive H_2 emissions on the overall GHG emissions balance. The global warming potential of H_2 emissions is expected to become a standard element in greenhouse gas emission calculations, but is not yet included in RED II and CORSIA calculation methodologies.

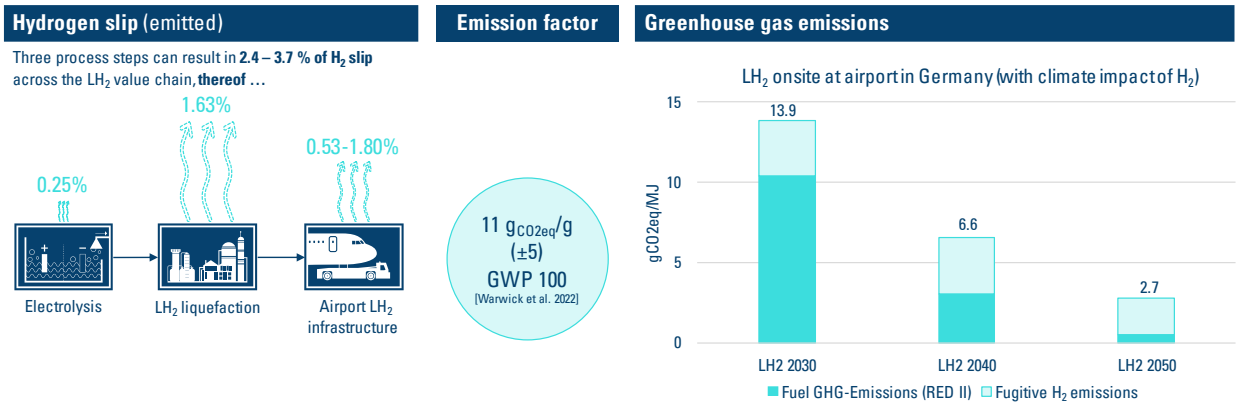


Figure 10: Climate impacts of H_2 fugitive emissions

Water electrolysis splits water into hydrogen (H_2) and oxygen (O_2). O_2 is vented, while some of the H_2 moves through the membrane to be released to the atmosphere together with O_2 if no prior recombination to water through for instance catalytic burning is induced. Subject to the design of hydrogen purification process, purging can occur to remove impurities. A further source of H_2 emissions can be leakages through casing and pipework and venting during start-up and shutdown [Frazer-Nash 2022]. Meanwhile there are H_2 purifiers for electrolysers where no purging is required [ReiCat 2022]. In this study, the hydrogen emissions from water electrolysis are derived from [Frazer-Nash 2022] where full recombination of hydrogen from purging and crossover is assumed leading to hydrogen emissions to atmosphere of about 0.25% (best available technology based on the cited reference).

At the hydrogen liquefaction plant hydrogen leakages occur at the feed gas compressor (1.5%), regeneration of adsorber at the pre-cooling step (0.1%), and the flash gas compressor (0.025%) according to [IDEALHY 2013]. Improvement of sealings of the compressors potentially can reduce the H_2 emissions from the feed gas compressor (not assumed in this study due to lack of data).

Hydrogen emissions from airport infrastructure are assumed to be about 1.8% in 2030 decreasing to about 0.5% in 2050 due to the application of clean-break coupling [Hoelzen et al. 2022]. According to [Frazer-Nash 2022] stationary gas turbines have low H_2 emissions (0.01%). It is assumed that the same H_2 emissions occur at H_2 fuelled jet engines.

Altogether, best available technology (BAT) and operational practices can significantly reduce fugitive emissions in hydrogen value chains.

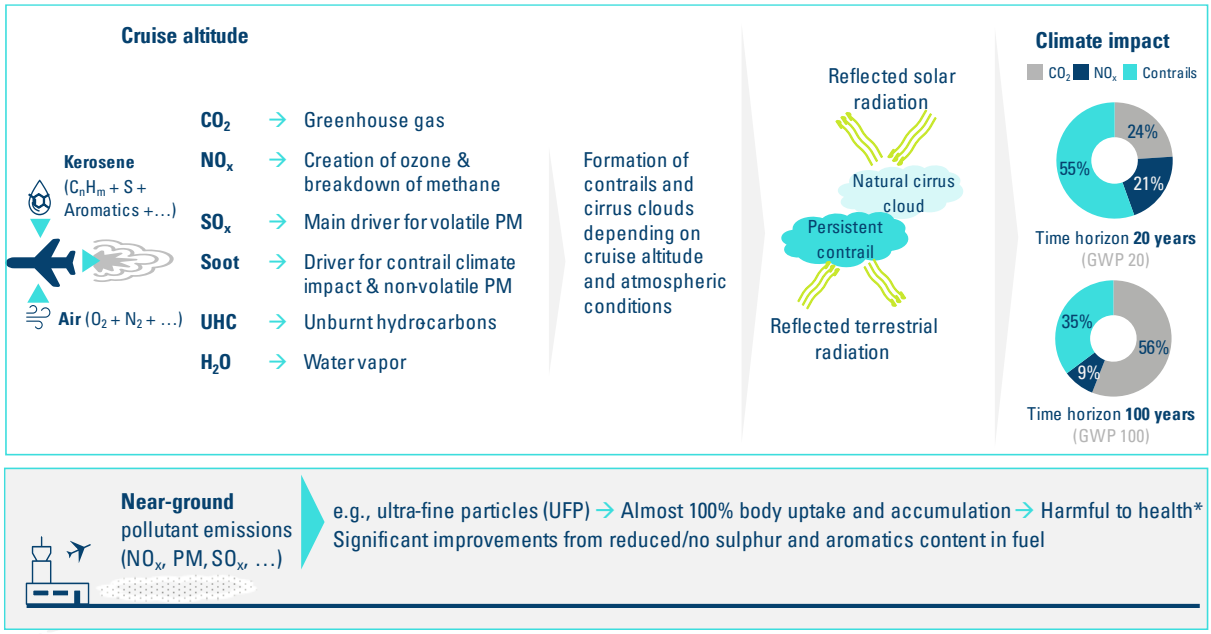
4.4. Deep Dive: PtL pollutant emissions & non-CO_2 impacts

Current jet fuel standard ASTM D7566 mandates an aromatics content of 8% to 25%. Today's jet fuels contain around 17% aromatics, of which approximately 2% are naphthalene [Voigt et al. 2021].

Among others [Lee et al. 2021] and [Voigt et al. 2021] indicate that particulate matter (PM) emissions such as soot from aircraft, largely influenced by the aromatics content of jet fuels, are significant triggers for contrail formation and their characteristics. Contrails, along with their subsequent cirrus cloud formation, have been identified as a potent factor in aviation's overall climate impact. These clouds reflect terrestrial radiation, leading to a warming effect, thus exacerbating the overall climate impact of aviation.

In addition, the aromatics content in jet fuels leads to more near-ground polluting emissions. Particularly ultra fine particles (UFP) can be hazardous to human health. These tiny particles, often less than 100 nanometres in size, can penetrate deep into the respiratory system upon inhalation. [Janssen et al. 2022] have shown that UFP can have adverse effects on the cardiovascular and respiratory systems, and worsen conditions such as asthma, chronic bronchitis, and cardiovascular diseases.

Figure 11 shows the pollutant emissions and the non-CO_2 impacts of kerosene at high altitude.



Graphic: LBST based on [Lee et al. 2021]; [BDL 2020]; [Janssen et al. 2022]; [Teoh et.al. 2022]
* Particularly if UFPs in combination with sulphur

Figure 11: Pollutant emissions and non-CO_2 impacts of kerosene

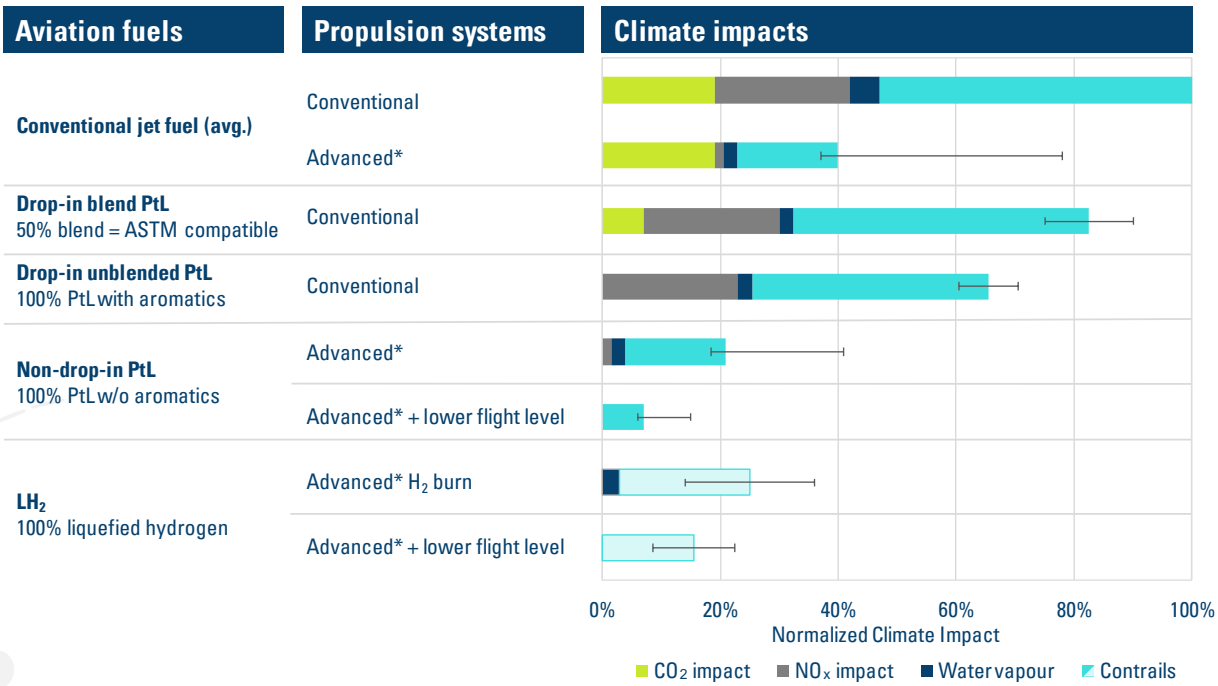
Improving aviation fuel composition is one effective strategy to reduce near-ground pollutant emissions. If aromatics and sulphur content are minimized in aviation fuels, aviation engines emit significantly less particulate matter and soot. Bringing aromatics and sulphur content closer to the minimum thresholds defined in current fuel standards presents an attainable and impactful option to improve local air quality and reduce the climate impact of aviation [CE Delft 2022].

In addition to optimizing currently used jet fuels, the use of PtL and LH_2 can offer further environmental benefits. PtL jet fuels produced from renewable energy lower the CO_2 emission balance of aviation. With further reductions or complete elimination of aromatics content, PtL fuels also significantly decrease soot emissions, making their non-CO_2 climate impacts even lower.

Hydrogen can be used in two principal ways as fuel for propulsion: Hydrogen burn in engines, or in fuel cells. In case of fuel cell electric propulsion, no soot emissions and no NO_x emissions occur. Only water vapour is emitted. Contrails from fuel cell electric aircraft will be formed even at lower altitudes but they are expected to be short lived and less dense [Gierens 2021].

Hydrogen-powered aircraft produce no soot emissions. The effect of hydrogen combustion induced contrail formation and characteristics is expected to be investigated in the upcoming years [Airbus 2022]: More water emissions would imply more contrails, but the lack of exhaust particles means less dense and short-lived contrails, reducing their climate impact. Overall, the current working hypothesis is that hydrogen contrails have less climate impact than those of fossil kerosene. When comparing the non-CO_2 impacts of hydrogen burn and PtL, we assume a similar performance and potentially slightly lower non-CO_2 effects of hydrogen, which still need to be confirmed by empirical results.

Reduction of NO_x emissions to ultra-low levels can be achieved via flameless oxidation, which is assumed in [Silberhorn et al. 2022] for future 'advanced' combustion technology shown in Figure 12. Today, flameless oxidation (FLOX) is used in stationary combustors for heat supply. The Institute of Combustion Technology at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) is working on FLOX burners for gas turbines [DLR 2023].



Graphic: LBST based on normalized global emissions of B767 aircraft fleet [Silberhorn et. al. 2022]
* Advanced = low-NO_x/low-soot combustion technology
** Only fuel cells eliminate NO_x entirely

Figure 12: Normalised climate impact of aviation fuels

A technology to decrease the NO_x emissions from hydrogen fuelled aircraft engines is steam injection. Pratt & Whitney develops a hydrogen steam injected inter-cooled turbine engine (HySIITE). The technology offers NO_x emission reduction by up to 80% and a decrease of fuel consumption by 35% compared to conventional aircraft engines [Pratt & Whitney 2022]. MTU develops the water-enhanced turbofan (WET) concept both for kerosene and hydrogen as fuel. Residual heat from the exhaust gas is used to generate steam, which is injected into the combustor. The water for steam generation is extracted from the exhaust gas by means of a condenser and then separated. [Kaiser et al. 2022] state a reduction of climate impact by 80% compared to an aircraft engine from the year 2000 if sustainable aviation fuels (e. g. PtL) or hydrogen are used. The market launch for the water-enhanced turbofan concept is planned for 2035 [Henrich 1/2022].

If a standard combustor design is applied, there are effects that increase NO_x emissions and others that decrease NO_x emissions. Combustion dynamics change if hydrogen is used as aviation fuel. On the one hand, more thermal NO_x forms due to higher combustion temperatures of hydrogen. On the other hand, gaseous hydrogen does not need to be vaporized, avoiding hot spots in the combustion chamber forming NO_x. Furthermore, water has a higher heat capacity, lowering temperatures and decreasing NO_x. The opposing effects could lead to similar NO_x emissions compared to kerosene combustion. Further research should provide clarity. Zero NO_x emissions are only possible with fuel cell electric aircraft.

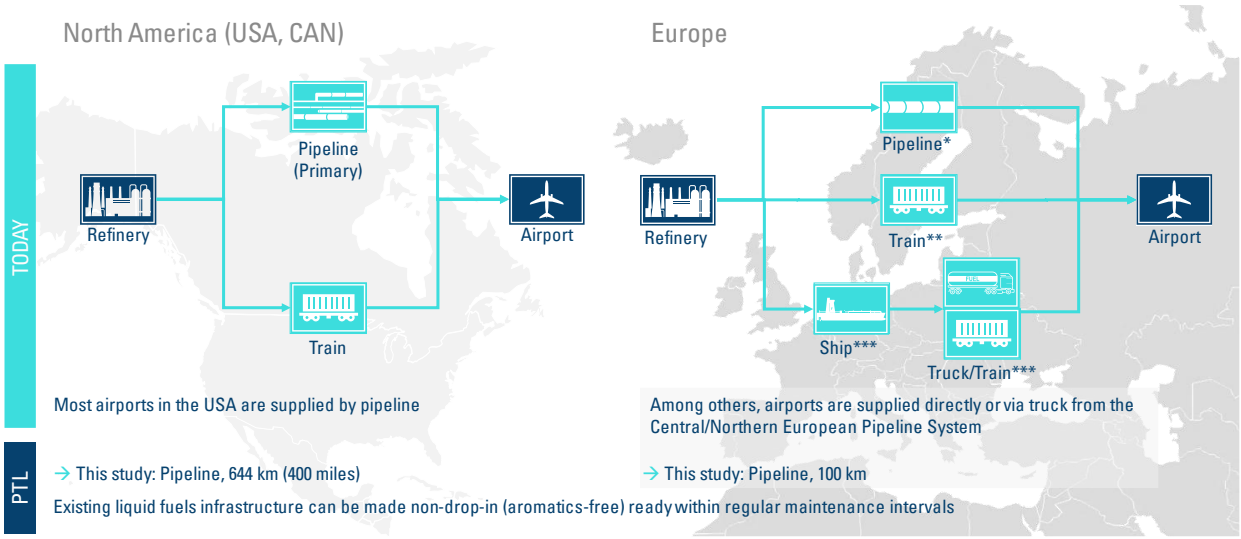
Beyond progress in fuel composition, standards, and production, adjusting flight time and routing (see Figure 12) can further reduce non-CO_2 climate impacts according to [Teoh et.al. 2022]. By strategically planning flights and considering factors like altitudes and weather patterns, airlines can minimize their overall climate impact. By including specific meteorological data in the tactical flight planning, airlines can minimize their overall climate impact, taking into account non-CO_2 effects. Scientific understanding for such climate-optimized trajectories still needs further improvement.

5 FUEL INFRASTRUCTURE

5. FUEL INFRASTRUCTURE

5.1. Deep dive: PtL logistics - distribution to/at airports

Jet fuels can be transported to and at airports in various ways as shown in Figure 13. In Europe, kerosene is supplied to the airports mainly via pipeline. To some airports, kerosene is delivered via ship, train, and truck.



* Pipeline, e.g. Germany (MUC, ~100 km, FRA, 22/80 km), Netherlands (AMS, 16 km), Austria (VIE, ~10 km)
** Train, e.g. Switzerland (ZRH, ~150 km) *** Ship + truck/train, e.g. Denmark, Norway, Sweden

Figure 13: Jet fuel delivery pathways in North America (left) and Europe (right)

PtL plants are not necessarily going to coincide with the location of today's crude oil refineries. PtL plants are rather going to be collocated with large renewable energy potentials. In Europe, there is an extensive kerosene pipeline grid [NATO 2009]. Therefore, this study assumes that the PtL is transported to the airports via pipeline over an average distance of 100 km.

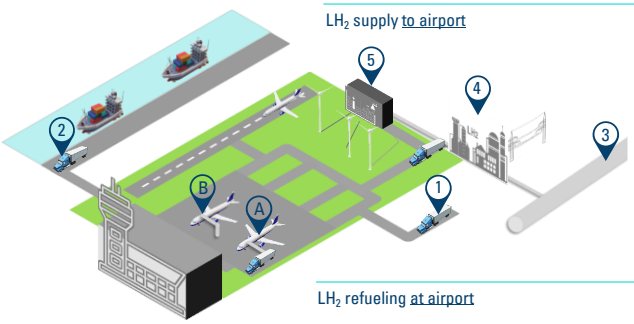
In the USA kerosene is also mainly transported via pipeline [A4A 2018], [Moriarty et al. 2021]. As a rough estimate, the pipeline distance is assumed to be 400 miles (644 km) as indicated for oil products in [GREET 2016] for the USA.

For the transport of unblended aromatics-free jet fuel via existing pipelines, regulations need to be updated [Moriarty et al. 2021]. Blends of fossil jet fuel and SAF compliant with ASTM D7566 are designated as ASTM D1655 jet fuel and can consequently be transported in pipelines [Moriarty & Kvien 2021].

Airport fuel infrastructure has to be upgraded to ensure compatibility with aromatics-free jet fuel. When drop-in and non-drop-in fuels are used at the same time at airports, it has to be ensured that they are kept separate and not co-mingled. Therefore, dedicated or dual-use tanks, refueling trucks, hydrant systems and updated operational measures may be required. The adaption of airport infrastructure to aromatics-free kerosene (e. g. replacement of sealings) can be carried out within regular maintenance intervals.

5.2. Deep dive: LH_2 distribution at airports

At the airport, the aircraft refuelling can be carried out by a LH_2 refuelling truck or by a LH_2 pipeline and hydrant system (Figure 14).



#		2030	2040	2050
1	LH_2 delivery to airport via truck (160 km)	Regional airport	-	-
2	LH_2 import via ship (7350 km), truck transport (50 km) to airport	KSA	KSA	KSA
3	H_2 import via long-distance pipeline (2500 km)	TUN	TUN	TUN
4	H_2 delivery to airport via local pipeline (100 km), H_2 liquefaction at airport	-	GER, TUN	GER, TUN
5	H_2 production and liquefaction at airport	-	NOR, ESP, USA, CAN	NOR, ESP, USA, CAN
A	Aircraft refuelling via LH_2 trailer	Regional airport	Regional airport	Regional airport
B	Aircraft refuelling via LH_2 hydrant system & dispenser truck	-	Large airport	Large airport

GER = Germany; NOR = Norway; KSA = Saudi Arabia; TUN = Tunisa; ESP = Spain; USA = United States of America; CAN = Canada

Figure 14: Overview of LH_2 proxy infrastructure and pathway applicability

For small volumes, a universal approach is LH_2 supply via truck trailer from the nearest liquefier (central) and/or LH_2 import (break bulk) combined with aircraft refuelling via refuelling truck. For the supply of first prototype LH_2 aircraft, a small-scale H_2 liquefier onboard a truck may be an option [H2Tech 2023]. For significantly larger volumes, a LH_2 pipeline and hydrant system can be applied.

A future European H_2 pipeline system (e.g. the scheduled European Hydrogen Backbone) will facilitate H_2 supply to H_2 liquefiers at or nearby the airport [EHB 2022].

H_2 losses into the atmosphere can occur in the LH_2 pipeline system and during refueling of the aircraft. Clean-break coupling can avoid H_2 losses during the refueling procedure [Hoelzen et al. 2022]. The LH_2 boil-off rate of comparatively small LH_2 tanks (e. g. the LH_2 tanks installed at Tanegashima Space Center in Japan with a capacity of 540 m³ of LH_2) is below 0.18% per day [Kamiya et al. 2015]. Larger LH_2 tanks planned for export and import terminals with a capacity of 3,000 to 50,000 m³ of LH_2 can achieve even lower LH_2 boil-off rates due to the lower ratio of surface to volume (e. g. LH_2 tank with a capacity of 10,000 m³ of LH_2: 0.1 % per day) [Kawasaki 2020] or even lower (4700 m³ of LH_2: 0.048% per day) [Fesmire & Swanger 2021]. The boiled-off LH_2 leads to a pressure increase and is released into the atmosphere if the maximum allowable pressure is reached. For large LH_2 tanks the dormancy time (time until hydrogen is released) can be up to several weeks depending on the design. Instead of releasing the boiled-off LH_2 into the atmosphere, it can be returned to liquefaction or used for other purposes (e. g. compressed gaseous hydrogen refueling stations for road vehicles or stationary electricity generation).

Less than 0.8% of the H_2 throughput is emitted into the atmosphere from LH_2 storage at the airport [Hoelzen et al. 2022]. A standard for aircraft LH_2 refuelling is still pending.

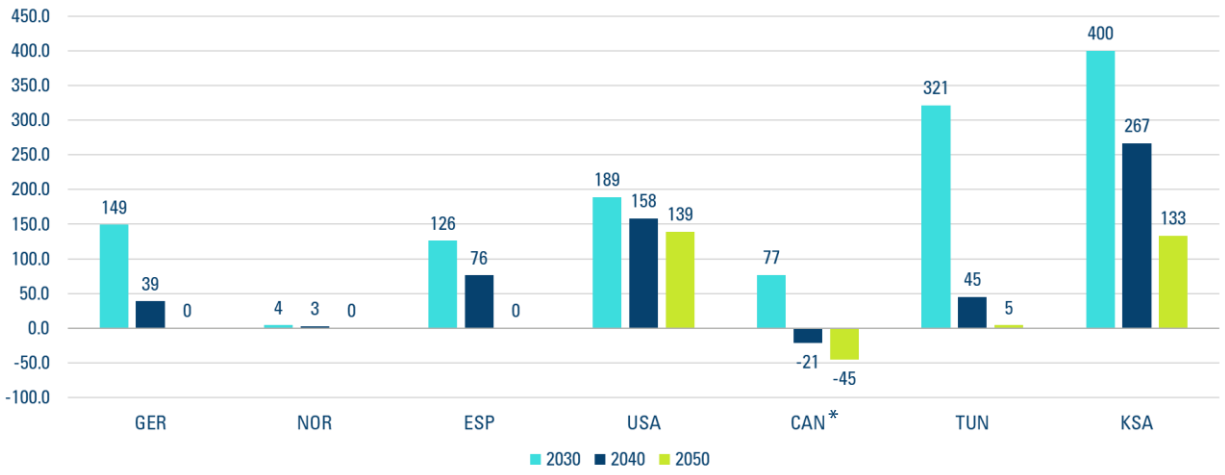
6 SUMMARY

6. SUMMARY

- Switching aviation fuels to a **renewable electricity** base is an indispensable step to reduce sector greenhouse gas emissions.
- Reducing **pollutant emissions** from aviation could already be realized with reasonable effort by lowering the aromatics content and eliminating the sulphur content of conventional jet fuel.
- In addition to adjusting fuel composition, switching to alternative fuels is a way to further reduce climate impact. LH_2 consumed in fuel cells even eliminates NO_x emissions, otherwise LH_2 and PtL may show similar benefits in **CO_2 emissions and non-CO_2 effects**. The average carbon intensities of Drop-in and Non-Drop-in PtL decrease from 9.8 in 2030 to 1.8 gCO_{2eq}/MJ in 2050.
- From a production and distribution point of view, LH_2 exhibits a lower primary **energy demand** than PtL per energy content including transport (~1.6 to 2.0 MJ per MJ of LH_2 versus ~2.5 to 2.8 MJ per MJ of e-kerosene via Fischer-Tropsch synthesis depending on electrolysis efficiency, electricity mix for auxiliaries, and CO_2 source). The higher energy efficiency of LH_2 must be traded against aircraft design parameters, such as higher system mass and volume requirements to accommodate LH_2 onboard the aircraft. While this study can shed light on the production and distribution side, further research by aircraft and propulsion OEMs must confirm the specific primary end-to-end energy requirements of LH_2 aircraft (MJ per passenger kilometer).
- PtL costs range from around 1640 € to 4100 €/t of kerosene equivalent from 2030 to 2050. Costs for LH_2 from regional airports drop continually from 2350 – 3660 €/t in 2030 to 1560 – 2750 €/t in 2050. LH_2, owing to its energy efficiency and liquefaction economics, holds the potential for **cost competitiveness** at scale with minimal costs as low as 1140 €/t. However, this advantage is facing challenges by the need for considerable aircraft redesign and infrastructure investments, which are not required for drop-in PtL.
- **Non-drop-in SAF** options, which are characterized by zero-aromatics content, need only marginal investments for modifications in fuel infrastructure and on the aircraft system side. Transitioning to these zero-aromatics fuels mid-term is integral to climate impact and pollution reduction. In the short-term, the massive scale-up of drop-in SAF production capacity will still be critical to reduce the climate impact of the existing fleet and aircraft entering into service, until the non-drop-in fuel standard is available and implemented. Aircraft which go into service today will still be operated in 2050.
- **Fuel standards** assume paramount importance, intertwining with climate policy imperatives. To this end, regulatory bodies should support fossil and sustainable aviation fuel (SAF) standards, both devoid of aromatics, alongside existing drop-in SAF standards. In the future, LH_2 standards are also required.
- Due to the cost gap, a portfolio of **policy measures** is needed for the uptake of renewable electricity-based fuels through incentive-based instruments (e. g. taxes and subsidies), direct regulatory instruments (e. g. mandates), and sustainability safeguards for SAF feedstocks.
- **In summary**, our research highlights the multi-faceted nature of improving aviation sustainability. When supported through effective policies, the aviation industry can chart a comprehensive and practical course towards a greener and more responsible future by recalibrating fuel composition, harnessing technological advances, and promoting infrastructure.

ANNEX

ANNEX



* Net negative emissions due to planed BECCS [CER 2023]

Figure 15: Summary of the carbon intensity of grid electricity in the proxy countries (in g_{CO2eq}/kWh_e)

Table 5: Efficiency and inputs for alkaline water electrolysis

	Unit	2030	2040	2050
Efficiency (LHV)	-	68%	72%	75%
Electricity	MJ/kg_{H2}	49.0	46.3	44.4
Water	kg/kg_{H2}	8.94	8.94	8.94

Table 6: Inputs for CO_2 capture

	Unit	Cement kiln	DAC
CO_2 concentration		22%	0.04%
Electricity	MJ/kg_{CO2}	0.535	1.44
Heat	MJ/kg_{CO2}	3.78	5.76
T (heat)	°C		100
Reference		Voldsund et al. 2019	Beuttler et al. 2019

Table 7: Capacity H_2 liquefaction plants at airports

Parameter	Unit	2030	2040	2050
Regional airport	t_{LH2}/d	*	8.1	16.3
	MW_{LH2}	*	11.3	22.6
Large airport	t_{LH2}/d	**	127	349
	MW_{LH2}	**	176	484

* Central liquefaction

** Larger LH_2-aircraft entry into service after 2030

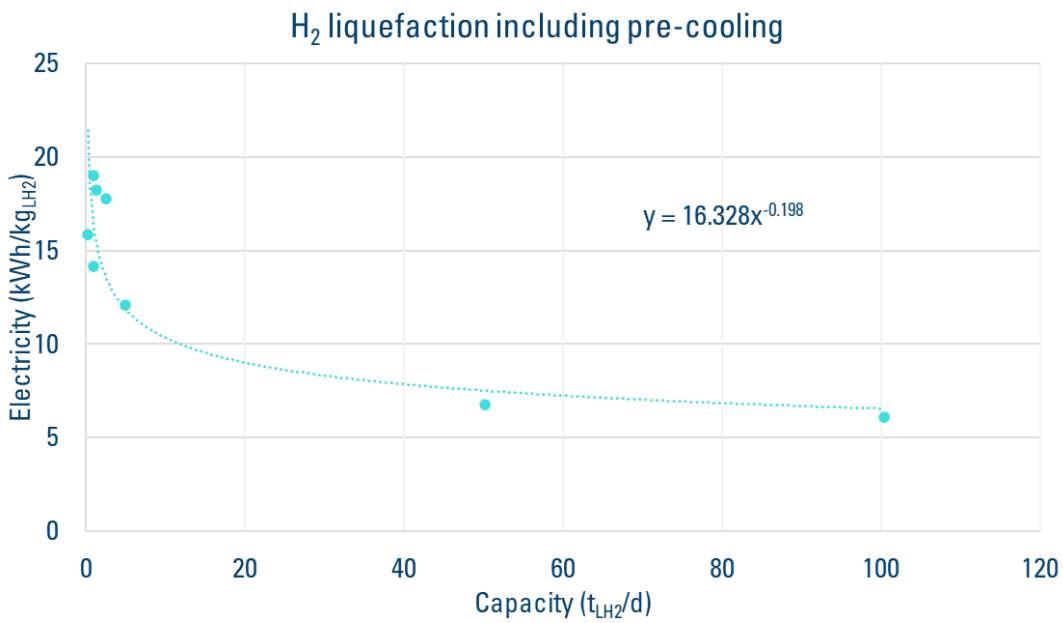


Figure 16: Electricity consumption from liquefication

The higher the capacity, the lower the electricity consumption per unit of hydrogen. Because of low LH_2 demand from aviation in 2030, it is assumed that the LH_2 is delivered via truck to the airport over 160 km from a central H_2 liquefaction plant. In 2040 and 2050, H_2 liquefaction is carried out at the airport except in case of LH_2 imports.

Table 8: Techno-economics for PtL production in 2030 as example for cost assumptions (CO_2 from cement kiln)

Parameter	Unit	NOR domestic	ESP domestic	Import from KSA
Electricity costs	€/MWh_e	74.2	43.8	41.9
Electricity input	TWh/yr	5.6	5.6	5.6
Fuel output	kt/yr	200	200	200
	TWh_{LHV}/yr	2.4	2.4	2.4
Efficiency (LHV)		43%	43%	43%
CAPEX				
Electricity storage system	M€	561	303	322
Electrolysis	M€	744	824	815
H_2 storage loading compressor	M€	101	111	110
H_2 storage	M€	654	630	484
CO_2 supply	M€	253	278	259
Synthesis and conditioning	M€	588	574	613
Total	**M€**	**2900**	**2720**	**2603**
O&M				
Water costs	M€/yr	1	1	1
Maintenance & repair, labour	M€/yr	52	52	52
Total	**M€/yr**	**53**	**53**	**53**
Specific fuel costs				
Total	**€/GJ_{LHV}**	**72.5**	**50.7**	**49.1**
	€/$t_{kerosene}$	**3129**	**2187**	**2118**

The contribution of electricity costs shown in Figure 7 includes electricity required for electrolysis, H_2 compression for H_2 buffer storage, and electricity for H_2 liquefaction in Saudi Arabia. In case of H_2 liquefaction at or nearby airports the costs of electricity are included in the H_2 liquefaction costs category. The costs for the electrolysis include CAPEX, maintenance, repair, labour, and other costs other than electricity. The costs of maritime LH_2 transport include CAPEX for the LH_2 carrier and LH_2 infrastructure at ports such as LH_2 terminals, costs for fuel other than vaporized hydrogen, the labour costs for the ship crew, maintenance, and repair of the LH_2 carriers.

TABLES

FIGURES

ACRONYMS & ABBREVIATIONS

ACARE	Advisory Council for Aeronautics Research & Innovation in Europe
AR4	IPCC Assessment Report 4
AR5	IPCC Assessment Report 5
BECCS	Bioenergy with Carbon Capture and Storage
BtL	Biomass-to-Liquid
CAN	Canada
CCS	Carbon Capture and Storage
CGH_2	Compressed gaseous hydrogen
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
DE	Deutschland (Germany)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
e-SAF	Electricity-derived Sustainable Aviation Fuel
ESP	Spain
ETS	Emission Trading System
FLOX	Flameless oxidation
FT	Fischer-Tropsch
GER	Germany
GHG	Greenhouse gas
GWP	Global warming potential
H_2	Hydrogen
HEFA	Hydro-processed esters and fatty acids
HySIITE	Hydrogen steam injected inter-cooled turbine engine
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICAP	International Carbon Action Partnership
ILUC	Indirect land use change
IRA	Inflation Reduction Act
KSA	Kingdom of Saudi Arabia
LCA	Life-cycle assessment
LH_2	Liquid Hydrogen
LHV	Lower heating value

LTAG	Long-term global aspirational goal
MeOH	Methanol
MtK	Methanol-to-Kerosene
N_2O	Nitrous oxide
NOR	Norway
NO_x	Nitrogen oxides
O_2	Oxygen
OH-	Hydroxyl
PAX	Passenger seats
PM	Particulate matter
PtH_2	Power-to-Hydrogen
PtL	Power-to-Liquid
RED II	Renewable Energy Directive II
RFNBO	Renewable liquid and gaseous fuels of non-biological origin
SAF	Sustainable Aviation Fuel
TUN	Tunisia
UFP	Ultra fine particles
VOC	Volatile organic compounds
WET	Water-enhanced turbofan

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