# Hydrogen-powered aviation

## A fact-based study of hydrogen technology, economics, and climate impact by 2050

May 2020


FCH Fuel Cells and Hydrogen Joint Undertaking

Clean Sky 2

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# Executive summary

**Decarbonization is a major challenge for aviation.** The aviation sector emits more than 900 million tons of carbon dioxide ($CO_2$) per year. Assuming industry growth of 3 to 4 percent per annum (p.a.) and efficiency improvement of 2 percent p.a., emissions would more than double by 2050. In the same time period, the Air Transport Action Group (ATAG) committed to 50 percent $CO_2$ emission reduction (compared to 2005) and the European Union (EU) set with the Green Deal a target to become carbon neutral. Beyond $CO_2$, aircraft impact the climate through emissions of nitrogen oxides ($NO_x$), soot, and water vapor, which create contrails and cirrus clouds. Therefore, the "full" contribution to global warming is significantly higher than just $CO_2$ emissions alone.

$H_2$ combustion could reduce climate impact in flight by 50 to 75 percent, and fuel-cell propulsion by 75 to 90 percent.

**This report assesses the potential of hydrogen ($H_2$) propulsion to reduce aviation's climate impact.** To reduce climate impact, the industry will have to introduce further levers such as radically new technology, significantly scale sustainable aviation fuels (SAF) such as synthetic fuel (synfuel), temporarily rely on offsets in large quantities, or rely on a combination thereof. $H_2$ propulsion is one such technology, and this report assesses its potential in aviation. Developed with input from leading companies and research institutes, it projects the technological development of $H_2$ combustion and fuel cell-powered propulsion, evaluates their technical and economic feasibility, compares them to synfuel, and considers implications on aircraft design, airport infrastructure, and fuel supply chains.

The report's overall conclusion is that **hydrogen propulsion has the potential to be a major part of the future propulsion technology mix.** As a disruptive innovation it **will require significant research and development, investments, and accompanying regulation** to ensure safe, economic $H_2$ aircraft and infrastructure mastering climate impact. The findings and factors supporting this conclusion are:

**$H_2$ propulsion could significantly reduce climate impact.** Hydrogen eliminates $CO_2$ emissions in flight and can be produced carbon-free. Considering also non-$CO_2$ emissions, and taking into account the uncertainties of these effects[1], the latest estimates show that $H_2$ combustion could reduce climate impact in flight by 50 to 75 percent, and fuel-cell propulsion by 75 to 90 percent. This compares to about 30 to 60 percent for synfuels. To scale $H_2$-powered aircraft, several technological unlocks need to happen: enhancing the overall efficiency with lighter tanks (targeting 12 kWh/kg / gravimetric index of 35%) and fuel cell systems (targeting 2 kW/kg incl. cooling), liquid hydrogen ($LH_2$) distribution within the aircraft, turbines capable of burning hydrogen with low-$NO_x$ emissions, and the development of efficient refueling technologies enabling flow rates comparable to kerosene need to be developed. Industry experts project these important advancements are possible within five to ten years.

**Assuming these technical developments, $H_2$ propulsion is best suited for commuter, regional, short-range, and medium-range aircraft.** For commuter and regional aircraft, fuel cell-powered propulsion emerges as the most energy-efficient, climate-friendly, and economic option. Compared to conventional aircraft, operational costs increase by as little as US $5-10 per passenger, about 10 percent per PAX (passenger). This is even before carbon costs and considering all direct infrastructure and CAPEX costs, but not indirect infrastructure costs like potential changes to airport layout that remain highly uncertain. Entry into service could happen within the next eight to fifteen years. For short-range aircraft, a hybrid propulsion approach ($H_2$ combustion and fuel cell) could be best suited, increasing costs per PAX by 20-30 percent. The next largest segment, medium-range aircraft, requires significantly extended fuselages for $LH_2$ storage and thus

[1] The exact climate impact of non-$CO_2$ emissions of aviation is a matter of scientific debate. Please see chapter 1 on climate change for estimates by technology and annex 1 for the methodology and sources behind these estimates.

would consume about 25 percent more energy than conventional aircraft; these aircraft would lead to a cost increase of 30-40 percent per PAX. Considering the amount of climate impact avoided, this translates into costs per abated ton of $CO_2$ equivalent of less than US $60 for regional and commuter and US $70 to $220 for short- and medium-range aircraft. This compares favorably to US $210 to $230 per ton $CO_2$eq for synfuel from direct air capture for short- to long-range aircraft.

**Long-range aircraft require new aircraft designs for hydrogen.** $H_2$ is technically feasible but less suitable for evolutionary long-range aircraft designs from an economic perspective. The hydrogen tanks would increase airframe length and energy demand, resulting in 40 percent to 50 percent higher costs per PAX. Synfuel is likely the more cost-effective decarbonization solution. New aircraft designs (e.g., blended-wing-body) could change that but may be at least 20 years away from entry into service.

**Feasibility and economic analyses show hydrogen can be a major part of aviation's future technology mix.** If $H_2$-powered aircraft are deployed in segments where they are the most cost-efficient means of decarbonization, they could account for 40 percent of all aircraft by 2050, with this share further increasing after 2050. With synfuel and/or biofuels powering the other 60 percent of aircraft, aviation's climate impact would then fall by the equivalent of about 2.7 gigatons of $CO_2$eq versus 5.7 gigatons of $CO_2$eq in a baseline scenario where only efficiency improvements are made. The aviation sector would abate 1.8 gigatons of $CO_2$ in this scenario allowing it to reach carbon reduction targets set by the EU and ATAG.

**Refueling infrastructure is a manageable challenge in early ramp-up years, but will require significant coordination.** In the above-stated scenario, by 2040 aviation's global demand for $LH_2$ would total 10 million tons per annum – 5 percent of projected total global hydrogen demand.[2] Aviation could thus draw on local $H_2$ supply chains that also serve other industries. Liquid fuel trucks could serve most participating airports as demand per airport would likely still be low and only aircraft up to short-range would be converted. Handling and safety regulations would need to be re-assessed for $LH_2$ use in aviation, given the radically different properties versus conventional jet fuel. Fuel companies, airports, airplane manufacturers, and airlines would also need to work together to ensure infrastructure development and aircraft roll-out happens in tandem.

**A more challenging, but not impossible scale-up after 2040 is required.** By 2050, aviation's demand for $LH_2$ would grow to 40 million tons a year, and medium-range $H_2$ aircraft would be introduced, requiring a substantial scale-up in the hydrogen supply chain and airport refueling infrastructure. This scale-up will bring challenges along including finding more scalable refueling technology than refueling trucks, establishing parallel refueling infrastructures at airports, and adapting parking stands to accommodate larger aircraft. While these changes are substantial, there are no fundamental technical constraints that would prevent implementation, if planned and addressed in a timely manner.

An inspiring midterm target could be the introduction of a $H_2$-powered short-range aircraft before 2035.

**Bold steps need to be taken urgently to initiate a path towards decarbonization through hydrogen.** The industry needs to change trajectory today, as commercialization and certification of aircraft can take more than 10 years, and substantial fleet replacement another 10 years. To transition to a new propulsion technology, **a sector roadmap to reduce climate impact, a step-up in Research & Innovation (R&I) activity and funding,** and **a long-term policy framework** will be required. The sector roadmap needs to set the ambition

[2] As projected by the Hydrogen Council

level, align standards, derive safety measures, coordinate infrastructure build-up, overcome market failures and encourage first movers. An inspiring mid-term target could be the introduction of a $H_2$-powered short-range aircraft before 2035. R&I activities and funding should focus on four key areas: $LH_2$ fuel and propulsion components, aircraft systems, infrastructure ramp-up, and the regulatory framework (see Chapter 5 for the R&I roadmap). The long-term policy framework should lay out the rail guards for the sector, including how climate impact will be measured and the roadmap will be implemented. The European Union could first target commuter, regional, and short-range flights as they are covered within its jurisdiction, and then expand this to medium- and long-range aircraft together with its international partners.

In summary, hydrogen propulsion has significant, so far underestimated potential to reduce the climate impact of aviation and contribute to decarbonization objectives. To reap this potential, we must develop and deploy new technologies across the board. R&I must be immediately accelerated before we can transition the aviation sector and the industry into a more efficient and decarbonized future.

# Methodology

This report assesses the state of the art and the potential of hydrogen propulsion technology for the decarbonization of aviation by 2050 as targeted by the European Commission.

The conducted analyses where performed independently by the consultants based on the input from and discussions in two working groups focused on (1) aircraft design and (2) infrastructure. Participants in these working groups were aircraft manufacturers, component suppliers, hydrogen space vehicle and propulsion designers, airlines, airports, hydrogen infrastructure manufacturers, integrators, and research institutes. All meetings were conducted using Chatham House Rules, and participants were invited to review and comment extensively on the analyses and the report. The results do not necessarily reflect the official position by the contributors, and the contributors were not asked to validate all findings of the study, but provide their perspective and feedback to the findings.

Overall, the study followed an eight-step approach:

1. The future climate impact of aviation was forecast, using projected air travel demand development and potential efficiency gains with conventional propulsion technologies.

2. Options to decarbonize aviation were analyzed in terms of climate impact and scalability. The climate impacts of these options were derived based on most recent research and include wide uncertainty ranges, since the effects are still a matter of scientific debate and an industry consensus is not established yet. (See Annex 1.) The study then focused on hydrogen technologies (hydrogen combustion and fuel cells), and compared to them. Technologies that contribute to decarbonization, but are not at-scale solutions, such as batteries, were considered but were not the focus of this study. Furthermore, this study focuses on the use of $LH_2$: Compared to gaseous hydrogen $LH_2$ requires half the volume, causes significantly less tank weight, and potentially faster refueling times. Thus, the correlated tank mass for such gaseous hydrogen systems limits the technological feasibility of larger aircraft.

3. Five segments of commercial aircraft (e.g., short-range segment) were defined. For each of these segments, a "most promising" hydrogen aircraft design was developed with the help of experts and a survey of academic literature. The scope of technologies for this aircraft design included either fuel cells, hydrogen turbines, or a hybrid of hydrogen turbines and fuel cells. Urban air mobility vehicles and general aviation were not considered in this study.

4. The technology performance of key components for these technologies (e.g., power density of fuel cells) as well as cost parameters were projected. These projections were based on a survey of literature, available industry data, and expert input from the contributing organizations.

5. Detailed concept designs for the aircraft were simulated and analyzed together with the German Aerospace Center (DLR) exclusively for the evolutionary $H_2$ short-range and long-range aircraft. In each segment, the aircraft designs were benchmarked against both synfuel (power-to-liquid) powered aircraft and conventional aircraft. Key metrics used in the analysis were energy costs including fuel infrastructure costs, aircraft capital expenditure, maintenance costs, crew costs, fees, $CO_2$ equivalent abatement cost and potential, and flight cost increase per available seat kilometer.

6. Based on all the findings from the concept design phase, estimated entry-into-service dates, and climate abatement potential, two decarbonization scenarios were derived to estimate the total potential decarbonization of the industry via the application of $LH_2$. These scenarios are not actual projections of the future, but were derived to test potential implications on the climate impact of aviation as well as infrastructure roll-out implications.

7. Based on the scenarios, the implications on $LH_2$ infrastructure were identified, including required production technology, critical changes to airport refueling infrastructure and operations and likely cost projections based on learning rates and input from industry members.

8. Drawing on all the findings in the areas of climate impact, aircraft design performance requirements, and critical infrastructure enablers, critical R&I topics were identified. The identified R&I priorities focus on closing the most important knowledge gaps and meeting aircraft design and infrastructure performance targets to make hydrogen aviation a reality.

Across the study no cost of emissions was considered in order to evaluate all technologies like-for-like and in order to estimate abatement costs. To estimate climate impact, all tank-to-thrust emissions and indirect effects of aviation, such as contrail formation, were taken into account over a timeframe until 2100. Emissions beyond tank-to-thrust (e.g., as in a full life cycle analysis) are not considered in the report. Ranges are used to represent the uncertainty inherent in climate impact estimates and projections of technology parameters. To make climate impact comparable, the global warming potentials of each technology were calculated in "$CO_2$ equivalent" units throughout the study. Please see Annex 1 for a detailed explanation, figures, and sources of the methodology used in this report for estimating climate impact.

# List of contributors

Now a part of Cummins Inc.

Statements from these contributors commenting on this report can be found in Annex 2.

# Contents

# 1. Introduction: The challenge of decarbonizing aviation

## Aviation's climate impact is increasing

In December 2019, the European Commission put forth its Green Deal with the objective for decarbonization: net carbon neutrality across all sectors and EU member states by 2050. For aviation, this target is even more ambitious than those from the Air Transport Action Group (ATAG), which call for carbon-neutral growth from 2020 onwards and a 50 percent reduction of emissions by 2050 relative to 2005 levels. Both of these targets put the aviation sector under increasing pressure to decarbonize – and do so quickly.

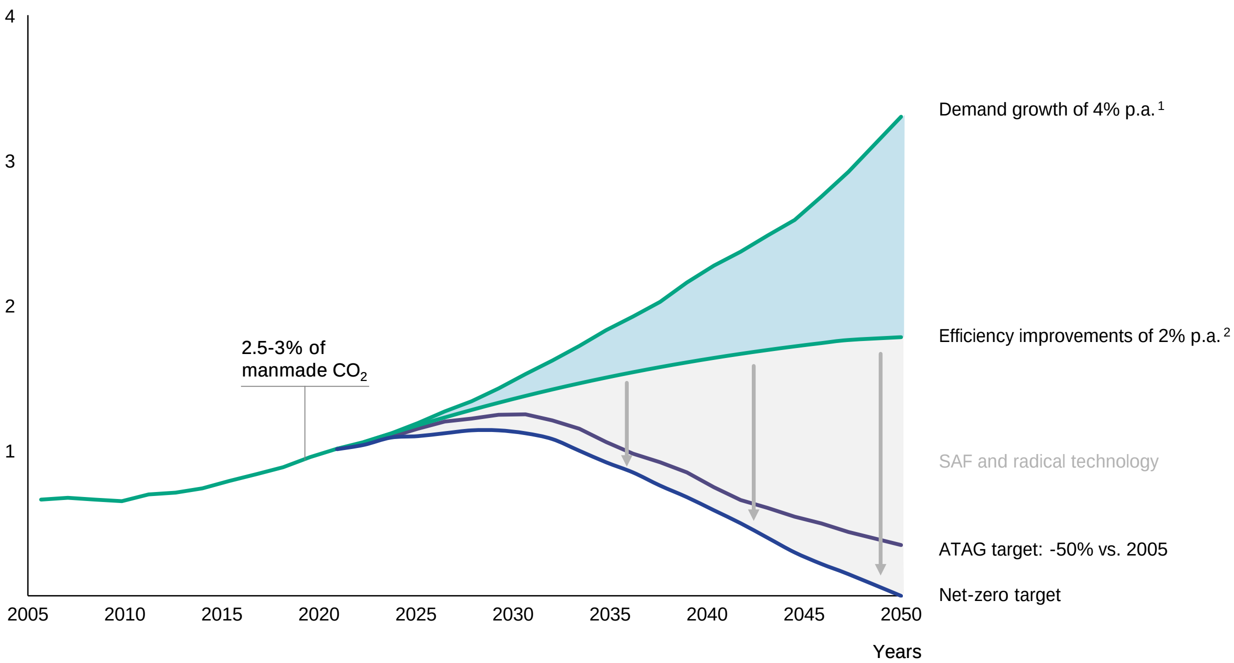
Per passenger, the aviation sector has become more carbon-efficient over the past three decades. Higher seat density and utilization, operational improvements, and technology improvements like higher engine and airframe efficiencies have boosted fuel efficiency per revenue passenger kilometer (the number of kilometers traveled by paying passengers) by approximately 50 percent. Supported by the optimization of flights, flight routing, and airport taxiing, this trend is expected to continue.

**Nevertheless, rising demand for air travel has led to a significant increase in direct $CO_2$ emissions from aviation** – by 34 percent over the past five years. Growing populations and prosperity will further increase demand, with forecasts ranging from 3 to 5 percent per year until 2050.[3] Even if efficiency improvements – currently around 1.5 percent p.a. – accelerate to 2 percent p.a. as targeted by the ICAO, emissions from aviation will double to approximately 1.5-2 gigatons of $CO_2$ emissions by 2050. Given the stated targets from the EU and ATAG, this projection underlines that further decarbonization measures will be required – also in the short-term already applying new fuels such as SAF.

Exhibit 1

### Projection of $CO_2$ emissions from aviation

Gt $CO_2$ emissions from aviation
Does not include compensation schemes




1. Assumption based on growth projections from ATAG, IATA, ICCT, WWF, UN
2. ICAO ambition incl. efficiency improvements in aircraft technology, operations and infrastructure

[3] IATA (2018), WWF (2020)

## Short- and medium-range flights cause two thirds of current aircraft emissions

Roughly two-thirds of today's kerosene consumption – which directly correlates with $CO_2$ emissions – comes from flights operated with short- and medium-range aircraft (flights with fewer than 165 PAX and flights with fewer than 250 PAX, respectively). These aircraft account for 70 percent of the global fleet (Exhibit 2).[4] Less than 5 percent of emissions are caused by regional (fewer than 80 PAX) and commuter (19 PAX or fewer) flights, which are served by about 20 percent of today's aircraft. The remainder of emissions stem from long-range (over 250 PAX) flights, which are served by 10 percent of aircraft.

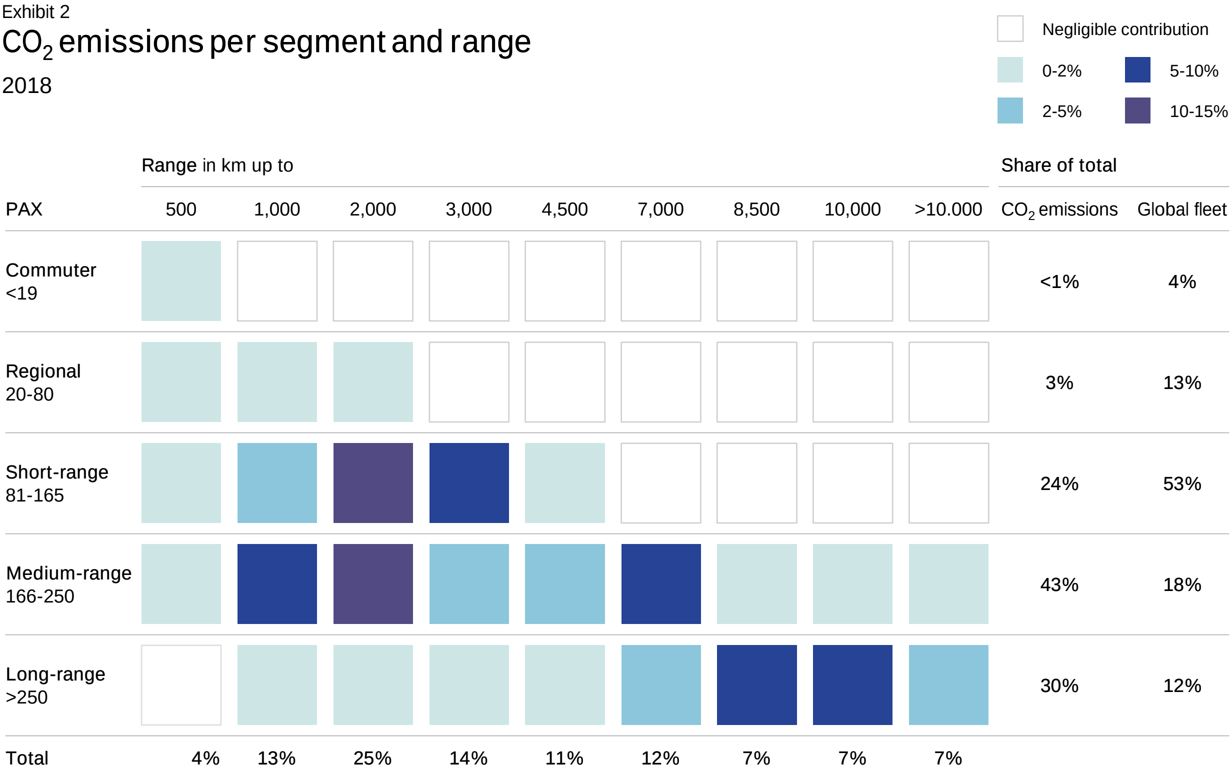
Regarding flight ranges, more than 20 percent of emissions come from flights above 7,000 kilometers, but these only make up less than 5 percent of the total number of flights. By contrast, flights spanning less than 3,000 kilometers and independent from the aircraft size account for more than 50 percent of total aviation $CO_2$ emissions and 90 percent of all flights.

This data indicates that the main focus on decarbonizing aviation should be on short-range aircraft flying less than 2,000 to 3,000 kilometers, as well as on medium- and long-range aircraft.

Exhibit 2

### $CO_2$ emissions per segment and range

2018




4 DiiOMI database and ICCT report (2018)

## Climate impact is not only about $CO_2$ emissions

**$CO_2$ emissions are the best understood and most prevalent way to measure the climate impact of aviation today.** Combustion engines in aircraft emit 3.15 kilograms of $CO_2$ for each kilogram of kerosene burnt in flight.[5] This $CO_2$ stays for 50 to 100 years in the upper atmosphere. However, aircraft also emit $NO_x$, water vapor, and soot at high altitudes. Even though $NO_x$ remains only a few weeks in the atmosphere, it enhance ozone, which could be just as harmful to the climate as $CO_2$ emissions are.[6] Water vapor also directly impacts the climate, because it reflects climate-warming radiation. But it does not last long in high altitudes, and its effects are about ten times less than those of $CO_2$ emissions.

Contrails and cirrus formation are caused by the emission of water vapor, which combines with soot from conventional combustion and particles in the atmosphere. Their formation depends on several factors: the condition of the air (humidity and temperature), the atmosphere the aircraft flies through, the altitude, and the region. When these molecules are emitted into the atmosphere, a "cloud-like carpet" is created at high altitudes, causing radiation and thus climate impact. This effect's full magnitude compared to $CO_2$ emissions is still uncertain, as only a few studies have investigated and tested it. But detailed simulations by leading research institutions support the prediction that the contrail effect could be comparable in magnitude to $CO_2$'s climate impact.[7]

There is no industry-wide standard for translating the different climate impacts of aviation into an aggregate metric and no agreement on which "factors" need to be applied to make this translation.[8] This study uses the concept of GWP as measured in $CO_2$ equivalents. The range of factors that fed into the analyses reflects the uncertainties in the current state of research. (Please see Annex 1 for a description of the methodology, sources, and factors employed.)

Despite the uncertainties, it is evident that non-$CO_2$ emissions and effects are significant contributors to global warming. For kerosene aircraft, and based on the latest scientific evaluations, the total effect could be anywhere between two to four times as large as the impact from $CO_2$ emissions alone (please see Annex 1 on the details of the employed methodology). This means aviation accounts for approximately 3 to 7 percent of global $CO_2$ equivalent emissions, or about two to four gigatons $CO_2$ equivalent. Understanding these effects is particularly important for new propulsion technologies, as they differ significantly in their non-$CO_2$ effects on climate.

## To decarbonize aviation needs new fuels and propulsion technology

It is clear that the aviation industry must make a radical shift if it wants to reduce its climate impact. Evolutionary efficiency improvements that build on existing technology are also required and are a "no-regret-move, but the potential is limited – the ICAO targets, which already propose a significant acceleration of efficiency improvements compared to the last two decades, are set at 2 percent per year. The shift to other transportation modes, e.g., to high-speed rail, is another effect, but addresses only commuter and regional flight distances, which account for less than 5 percent of $CO_2$ emissions in the sector.

5 Graver, Zhang, Rutherford (2019)
6 Uncertainty is between 50-150% compared to the effect of $CO_2$ emissions.
7 Grewe, Matthes and Dahlmann (2019), Verstraete (2009), Brewer and Morris (1976), Mital et al (2006), Kallo et al (2010), Steeland (2015)
8 Marquart et al. (2005), Kärcher (2018), Bock and Burkhardt (2019), Burkhardt et al. (2018)

It is clear that the aviation industry must make a radical shift if it wants to reduce its climate impact.

One decarbonization option would offset aviation emissions with “negative emissions” in other sectors. Currently, carbon offsets are comparatively affordable, as many carbon abatement options are available in other sectors. However, in a net-zero scenario carbon offsets can only be gleaned from truly “carbon-negative” activities, such as the sequestration of carbon captured from the air or the expansion of carbon sinks. These offsets will come at a significant cost. Offsetting is also sometimes criticized for the reprieve it gives to consumers, as it relieves the pressure on buyers to reduce their emissions in other ways. The risk of fraud and the scalability of offsetting solutions are also issues.

## Hydrogen propulsion could play a key role in the decarbonization of aviation

To truly decarbonize, the industry needs new, low-carbon propulsion technologies and/or new fuels.[9] As a complement to improvements in advanced kerosene-propulsion systems and other efficiency measures, they include:[10]

- **Sustainable aviation fuels:** The furthest developed among these fuels are biofuels like HEFA from biomass or waste (cooking oils and fats), followed by advanced biofuels that are synthesized from e.g., solid feedstock, biomass like crops, or algae. A third SAF option is power-to-liquid fuels, which are defined in this study as synfuels. These fuels are synthesized from hydrogen and $CO_2$ taken from industrial, biomass or direct-air capture.

- **New propulsion technologies.** These include battery- and turbo-electric technologies, as well as hydrogen combustion in turbines and fuel cells that power electric motors.

The following section compares the most common technologies and fuels – see Exhibit 3 for an overview.

**Sustainable aviation fuels: Biofuels.** These have the advantage of being “drop-in fuels” that do not require changes in aircraft and fuel infrastructure and are applicable across all aircraft segments. The International Renewable Energy Agency (IRENA) projects biofuel availability to be around 100 to 150 exajoules (EJ), which would be sufficient to power a large proportion of aviation.[11] Biofuels are already commercially available – e.g., HEFA fuels. But biofuels’ reliance on feedstock, changes in land use, high water use, and/or monoculture (i.e., the production of a single crop) means that the aviation industry will be competing with other interests that need the feedstock for other purposes.

**Sustainable aviation fuels: Synfuels.** In contrast to biofuels, the main source of synfuels (power-to-liquid) is electricity. This electricity is used to first produce hydrogen and to capture carbon, combining the two into a kerosene-like fuel. Synfuel can also be used in current aircraft engines and the fuel infrastructure, and is hence suitable for all segments.[12]

9 IATA (2018)
10 ICAO (2019), Synder et al. (2009)
11 IRENA (2014)
12 Albrecht et al. (2013), Brynolf et al. (2018), Fasihi et al. (2016)

Exhibit 3

## Comparison of new technology and sustainable aviation fuels and new technologies

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

**New propulsion technologies: Battery-electric and hybrid-electric aircraft.** Battery technology has vastly improved in the last 20 years. For aviation, however, batteries still suffer from low gravimetric energy densities of 0.2 to 0.5 kilowatt-hours per kilogram and limited life-time cycles.[13] This limits their applicability as a sole power source to very short flights (i.e., for commuter and potentially regional aircraft). While energy density is improving, battery technology would need a major breakthrough to be applicable for longer ranges. In addition to that, fast charging or battery exchange systems would require significant changes to the airport infrastructure. Batteries can, however, be applied in combination with hydrogen fuel cells or conventional propulsion ("turbo-electric aircraft").[14] In flight, battery-electric propulsion has the best climate impact because it causes no emissions or emission-related effects.[15]

**New propulsion technologies: Hydrogen aircraft.** Hydrogen can be used as a fuel for aircraft when it is combusted in a $H_2$ burning engine or reacted in a fuel cell powering electric motors. Despite the three times higher gravimetric energy density compared to kerosene, hydrogen's relatively higher volume requires larger volume, which requires larger tanks on-board the aircraft and adjusted aircraft designs. The size and weight of $H_2$ tanks pose major limitations for high energy demand on long-range flights – potentially reducing economics significantly for long-range aircraft.[16] (See Chapters 2 and 4.) From a fuel-supply perspective, hydrogen has other advantages: it can be produced directly from enewable energy and its synergies with other hydrogen-dependent

[13] Hepperle (2012)
[14] Misra (2017), Seitz et al. (2012), Ashcraft et al. (2011), Comincini (2018)
[15] Beyond in-flight emissions, electricity for battery-electric aircraft and the production of batteries also needs to come from renewables for a truly decarbonized solution.
[16] Brewer (1991), Bharozu et al. (2017)

sectors can be realized.[17] A ramp-up in hydrogen demand across sectors would unlock scale effects that would at least partially mitigate the initial cost disadvantages.

**Hydrogen propulsion is projected to be two to three times more effective than synthetic fuels in reducing aviation's climate impact**

Estimating the climate impact of new hydrogen propulsion technologies and new fuels such as synfuels in aviation is a complex, under-researched field. For this study, a survey of available research and expert interviews were used to build a methodology to make their climate impact comparable (see Annex 1 for details, and the R&I roadmap in Chapter 5 for recommendations to close existing gaps in research).

Even at this early stage, a rough order of climate impact can be derived (see Exhibit 4): Aircraft using fuel cell systems can reduce climate impact the most, by an estimated 75 to 90 percent. $H_2$ combustion aircraft are the next best alternative, with 50 to 75 percent reduction. Synfuels using $CO_2$ from direct air capture land at 30 to 60 percent reduction, while reduction potential from synfuels utilizing $CO_2$ from industrial processes depends on the accounting of $CO_2$ emissions. These estimates include $CO_2$ emissions, non-$CO_2$ emissions, and emission-related effects, as explained below.

$CO_2$ emissions. Hydrogen as a fuel does not contain carbon; thus, its combustion does not cause $CO_2$ emissions in flight. Synfuels and biofuels, on the other hand, cause in-flight $CO_2$ emissions that are similar to those of kerosene-powered aircraft.[18] If, for the production of synfuel, carbon is directly extracted from the air, the overall result can be net carbon zero. However, if carbon is captured from an industrial process or something similar to make synfuels, the resulting synfuels are not carbon neutral. If carbon for synfuels is captured from biomass this would also come with the competition in land use and usage for other industries that would "recycle" the carbon. These aspects are the reason why we focus on synfuels with carbon from direct air capture in this study, which promises the highest climate impact reduction.

Non-$CO_2$ emissions. Reducing $NO_x$ comes with a trade-off since it increases fuel burn, raising $CO_2$ emissions. When kerosene aircraft are switched to synfuels, $NO_x$ emissions are expected to remain largely unchanged. However, initial studies of $H_2$-powered aircraft show that $NO_x$ emissions can be reduced by 50 to 80 percent with lean-mixture technology without large reductions in efficiency.[19] Further research and development are required to realize these advantages. (See Chapter 5.) When a fuel-cell propulsion system is used, no $NO_x$ emissions arise in the reaction of hydrogen.

With synfuels, water vapor emissions are expected to be similar to those emitted by kerosene combustion. Fuel-cell systems or hydrogen-direct combustion emits two-and-a-half times as much water vapor.

[17] Only difference for other industries is that additional liquefication capacity will be needed.
[18] Synfuels with about 2 percent higher energy efficiency compared to kerosene combustion, which leads to slightly reduced $CO_2$ emissions.
[19] Perpignan and Rao (2016), Khandelwal et al. (2013)

Exhibit 4

## Comparison of climate impact from $H_2$ propulsion and synfuel

Compared to kerosene-powered aircraft, timeframe until 2100

Ongoing scientific debate about full climate impact, in particular:

- Contrail/cirrus formation
- Aggregate measure

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

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

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

**Emission-related effects.** When the fuel of existing fleets is changed, and flight routes and altitudes are kept the same, initial studies show that synfuels (power-to-liquid) could potentially reduce the climate impact from contrails by 10 to 40 percent. Because synfuels come with fewer aromatics and the combustion causes less soot, properties of contrails are changed and cause slightly lower climate impact. Hydrogen combustion, meanwhile, causes more water vapor but no soot at all. Moreover, initial simulations of $H_2$ direct combustion show that the formed ice crystals of contrails are heavier (i.e., they precipitate faster), and contrails are optically thinner (i.e., they are more "transparent"). As such, these water molecules lead to a lesser, briefer global warming effect – resulting in a 30 to 50 percent reduction in impacts from contrail and cirrus formation compared to kerosene aircraft. No study on contrail formation was found for fuel-cell systems. Nevertheless, when compared to $H_2$ direct combustion, the water vapor emitted by a fuel cell is cooler and fully controllable inside the aircraft. It could be conditioned, depending on the state of the atmosphere in which the aircraft is flying. The requirements for such a system and the conditioning itself have not been developed yet, but there is a potential to explore this idea further to decrease climate impact.

The effect on local air quality should also be considered. It can be enhanced if, when compared to kerosene combustion, less or no $NO_x$, particulate matter (PM), and non-methane volatile organic compounds (NMVOCs) are emitted. With the combustion of synfuels only PM emissions can be reduced, while $H_2$ propulsion would significantly lower all these emissions.

### Hydrogen and synfuels are most scalable decarbonization options for aviation mid- to long-term

Overall, the overview of potential new technologies shows that biofuels and turbo-electric aircraft can already help decarbonize aviation in the short-term. In the long term, the decarbonization of aviation could use a combination of battery-electric power for aircraft (only for very short ranges) and scalable solutions such as $H_2$ propulsion (fuel cell or combustion), synfuels, and biofuels which are also suitable for the larger, higher-emission aircraft segments. This report will further explore hydrogen propulsion and compare it to synfuels with carbon from direct air capture, as it has better potential for climate impact reduction compared to other SAF and our goal is to reduce climate impact.

# A history of $H_2$ aviation

Hydrogen aviation is not a new concept, but no current, complete, and detailed picture of what it will take to capture the potential of $H_2$-powered aviation exists. Most publicly available research concentrates on $H_2$ propulsion components; a few aircraft-level concepts have also been discussed and a few prototypes built. The required infrastructure, however, has rarely been investigated.

In the 1970s, a thorough review highlighted $H_2$-powered aviation's potential and development needs at that time.[20] In the early 2000s, Airbus' Cryoplane study and another research group also assessed climate impact, aircraft design, and such aircraft' required components. However, these efforts were not then pursued.

In terms of civil $H_2$-powered prototype development, the Tupolev T-155, a larger partially $H_2$-powered aircraft, first flew in the late 1980s and was later discontinued. In the last 10 years some early prototypes of $H_2$ aircraft have been developed (e.g., the motorized research glider HY4). Startups such as ZeroAvia are also modifying general aviation aircraft with a zero-emissions hydrogen-fueled powertrain that could be applied to commuter and regional aircraft. Fuel cell systems are being tested as auxiliary power units in commercial aircraft, although they have not been deployed in serial production. $H_2$ propulsion with fuel cell systems is also being tested for urban air mobility (unmanned air vehicles and "taxi"-drones).

All of this research offers significant promise; it also agrees on the greatest technology challenges for components, aircraft systems, and integration into the overall aviation infrastructure.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[20] G. Daniel Brewer, a researcher, revived discussions of civil $H_2$ propulsion technologies in a thorough overview that highlighted $H_2$-powered aviation's potential and development need

## Study objective: To investigate the potential of hydrogen propulsion to decarbonize aviation

As shown, hydrogen propulsion, whether turbines or fuel cells, has the potential to decarbonize aviation at a significant scale. So far, however, these technologies have not been where the EU is focusing its efforts to decarbonize aviation. Globally, there is no overarching, comprehensive view on hydrogen's potential for aviation and its potential implications on climate change and infrastructure.

This study, a joint endeavor by Clean Sky 2 Joint Undertaking and the Fuel Cells and Hydrogen 2 Joint Undertaking, was carried out to evaluate hydrogen as a decarbonization option for aviation – to assess its potential applications, to consider its challenges, and to recommend research priorities going forward. The study is unique, as it draws on the expertise of 24 leading companies and research institutions in the sector and a review of over 100 publications to present the first comprehensive perspective on the topic. Moreover, it:

- Builds a perspective on the performance and commercialization of hydrogen technologies in different aviation segments by synthesizing various organizations' viewpoints.

- Uses scenario-based roadmaps/ramp-ups towards hydrogen and the expected economic/climate impact effects, including a model of the required airport and fuel-supply infrastructure with cost implications.

This introduction provides an overview of the motives for decarbonization in aviation and has briefly explained why hydrogen propulsion is a promising technology for achieving this goal. Chapter 2 will examine the aircraft design implications; and Chapter 3 will expand upon the implications for the fuel-supply infrastructure. The key technology and economic findings are summarized in a roadmap to hydrogen in aviation in Chapter 4. The report then closes with a delineation of critical knowledge gaps and the research priorities needed to inform the industry going forward (Chapter 5).


# 2. Aircraft design: Feasibility and cost of $H_2$ propulsion

This chapter evaluates the feasibility of $H_2$ propulsion in terms of technical feasibility, economics, and commercialization readiness. First, the potential technology development for hydrogen and fuel cell technology was forecasted based on industry perspectives and expert interview. Then, an aircraft design was first defined and then simulated for each of the five aircraft segments – commuter, regional, short-, mid- and long-range. Based on this simulation, total costs for aircraft, both for building and operating them, were estimated.

## Technical feasibility: Energy density, fuel handling and turbines are most important

Hydrogen and fuel cell technology has undergone significant development in the last decades. Based on an extensive literature review, industry perspectives on technology development, and expert interviews, this study built what experts considered an "optimistic and achievable" projection of the performance of $H_2$ propulsion components for the next 5 to 10 years.

The most important components in a hydrogen aircraft are:

- Hydrogen tanks: Hydrogen can be stored as pressurized gas or in liquid form. While gaseous storage can be suitable for shorter flights and is commercially available, this study focuses on liquid hydrogen ($LH_2$) storage tanks as they require roughly half as much volume and consequently, they are significantly lighter than tanks for gaseous hydrogen. This is especially important for short- to long-range segments, where aircraft will carry several tons of hydrogen per flight. Compared to kerosene, $LH_2$ tanks are still about four times as big. Since $LH_2$ needs to remain cold and heat transfer must be minimized to avoid vaporization of

hydrogen, spherical or cylindrical tanks are required to keep losses low.[21] To efficiently integrate the tanks into the aircraft's fuselage, the airframe will need to be extended, which increases the aircraft's operating empty weight.[22]

- A $LH_2$ **fuel system** for the distribution, vaporization, and feeding of $LH_2$ to the fuel cells or turbines: $LH_2$ requires cryogenic cooling down to 20 degrees Kelvin. These temperatures must be handled by pipes, valves, and compressors; boil-off needs to be kept low; and leakage and embrittlement of material avoided.

- **Fuel cells** (for fuel cell powered aircraft): In a fuel-cell powered aircraft hydrogen is converted into electricity that then drives an electric motor and a fan or propeller. Most advanced and suitable for aviation today are low-temperature proton-exchange membrane (PEM) fuel cells. Adding an energy storage such as a battery to this system helps ensure fast load following and power peak shaving to optimize the sizing of the fuel cell system.[23]

- **Hydrogen direct-burning turbines** (for $H_2$ combustion): In $H_2$ combustion airplanes $LH_2$ is directly burned in a turbine, much like kerosene, to create thrust.[24] The use of cryogenic cooling of the fuel is expected to slightly increase efficiency (40 to 50 percent lower heating value [LHV]) compared to conventional engines. This study also considers a hybrid system of $H_2$ turbines and fuel cell systems. Such a system could optimize the higher power densities of turbines with the higher power densities of turbines the higher efficiencies and lower climate impact of fuel cell systems.

21 Rondinelli et al. (2014), Arnold et al. (2007), Verstraete et al. (2010), Gomez and Smith (2019)
22 For aircraft below the short-range segment, storing the hydrogen in pods below the wing could also be an option since the performance is not decreased too much but maintenance, safety, and modularity aspects are much easier to cope with.
23 The potential use of supercapacitors and other storage solutions was not investigated in this study.
24 Corchero and Montanes (2005), Dahl and Suttrop (1998)

The most important technology developments required for $H_2$-powered aircraft are:

- **$LH_2$ tank mass needs to be reduced by 50 percent** compared to current prototypes. There are various levers to reduce the required tank mass, including: boil-off requirements on the ground, which are set by safety regulations; scaling effects for larger volumes; advanced tank designs that integrate into the aircraft fuselage; and the use of lightweight material for double-insulated tank walls and insulation. The tank mass is expressed by the gravimetric index and is defined as the weight of the $LH_2$ fuel mass in relation to the full weight of the $LH_2$ tank filled with maximum $LH_2$ fuel. The latest concepts for commuter aircraft have a gravimetric index of up to 20 percent.[25] For short-range aircraft, an index of 35 percent needs to be achieved, for long-range aircraft 38 percent. Any improvement in this area lowers the weight and volume of the aircraft, which reduces energy demand and therefore improves the economics of building and operating the airplane.

- **Safe and reliable fuel distribution and components** are critical in $H_2$-powered aviation. Safe and reliable systems that also optimize heat management do not exist today and need to be developed, extensively tested, and certified for commercial aviation.

- **$LH_2$ propulsion systems have to be developed for safe operation over a long lifetime.** $H_2$ turbines need to be optimized for climate impact with very low $NO_x$ emissions at the same time they are highly efficient in creating thrust. The new fuel cell system technology will need to achieve up to two to three times more system power density than current fuel cell systems, with an improved density of 1.5-2 kilowatts per kilogram (kW/kg). This new design for the fuel cell system is projected to operate with efficiencies of up to 55 to 60 percent (LHV). For higher power ratings in the megawatt-classes, the cooling of fuel cell systems requires volumetric optimized heat exchangers.

While these advancements are ambitious, projections of technology development and experts considered them achievable within 5 to 10 years.

## The economics (total cost of ownership) of $H_2$ aircraft mostly depend on fuel and $H_2$ aircraft costs

To compare costs of aircraft, the total costs of ownership (TCO) of an aircraft need to be considered. Compared to kerosene aircraft, $H_2$ aircraft have different costs for fuel and related infrastructure, the aircraft itself, and operations. The comparison for synfuels is simpler, as only fuel and related supply infrastructure costs differ from conventional aircraft. In our analysis, fuel costs encapsulate all costs for the production of the fuel and the required infrastructure for distributing, storing, and refueling the airplanes (see Chapter 3 for detailed cost modelling). They do not include indirect second-order effects that are uncertain and difficult to estimate today, such as the potential need to adapt airport gate box sizes to accommodate longer aircraft.

For a short-range aircraft in 2035, costs increase by around 25 percent compared to a 2035-technology adjusted kerosene aircraft (see Exhibit 5). The main cost differences come from higher energy costs, which affect the TCO by 9 percent, higher CAPEX for the aircraft (7 percent), and maintenance costs (6 percent) and other costs (3 percent).

- **Energy costs** depend on the cost of fuel and the required energy to propel the aircraft. Hydrogen aircraft are typically somewhat heavier and/or bulkier, requiring more energy to propel. Hydrogen is also more expensive in

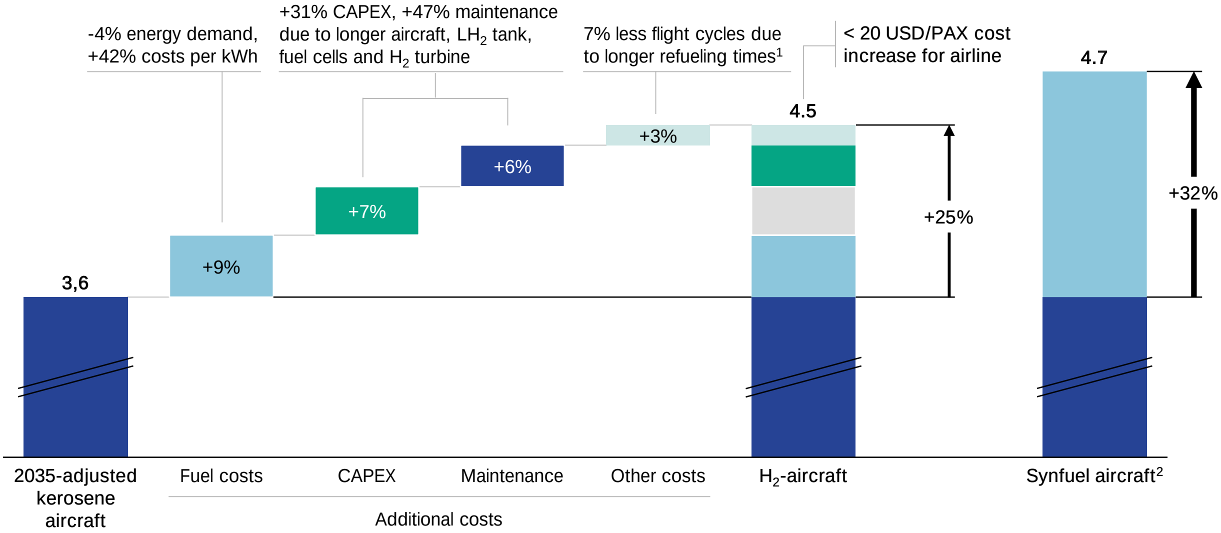
[25] Crespi (2017)

its production compared to kerosene, although its cost is expected to decrease rapidly (see Chapter 3). Due to the higher energy costs for synfuels from direct air capture the TCO increase is higher than with the $H_2$-powered aircraft. In 2050, $LH_2$ fuel prices are expected to approach those of kerosene[26] because of the higher demand for $LH_2$ and associated production cost improvements. While synfuel costs will also drop over time, they will remain structurally more expensive than hydrogen costs as they require an additional process step. Fuel costs will also depend on the changed energy demand for $H_2$-powered aircraft compared to conventional reference aircraft.

Exhibit 5

## Cost comparison of $H_2$ short-range aircraft versus kerosene and synfuel aircraft

USD cents per available seat kilometer (CASK), 2,000 km flight with 165 PAX in 2040




1. As the number of flight cycles decrease, CAPEX and crew costs will increase. Other costs also cover increased fees due to higher MTOW
2. Synfuel from green hydrogen with carbon from direct air capture

- **Aircraft CAPEX and maintenance costs.** CAPEX for $H_2$ aircraft is expected to be higher than for conventional aircraft. This is mainly due to the costs for the $LH_2$ tank structure that is integrated in the fuselage, the increased complexity of the fuel distribution, increased costs for propulsion, and the increased aircraft size. Total maintenance costs for $H_2$ aircraft might rise due to the larger airframe and the $LH_2$ tanks that could require more checks – especially in the first years of introducing $LH_2$ aircraft. In the long term, maintenance costs for the propulsion system might decrease.

- **Other costs including flight cycles.** Current assessments show that refueling times for $H_2$ aircraft might be longer than those of conventional aircraft (Chapter 3). Turnaround times would then increase and around 5 to 10 percent fewer flight cycles could be flown with the same aircraft. This would have a particularly pronounced effect on the aircraft CAPEX costs and on personnel (i.e., crew) costs, which could increase as $H_2$ aircraft potentially fly 5 to 10 percent fewer flights per year. However, it should be an important R&I target to develop technology enabling competitive refueling times with $LH_2$ compared to synfuels until hydrogen aircraft are commercialized. Airport and air traffic control fees mostly depend on the maximum take-off weight (MTOW) of an aircraft. For $LH_2$ aircraft the MTOW will be higher and fees are expected to be marginally higher. However, this assumes that there are no fee subsidies for $H_2$ aircraft and that landing fees will still mainly depend on MTOW in the future. This might be changed in the short-term to encourage the

[26] Depends on the volatility of kerosene prices – current EIA projections, U.S. Energy Information Administration (2019)

development of more climate friendly technologies but would be adjusted in the long term once the roll-out of more decarbonized aviation is more broadly adopted.

## Entry-into-service: Commercialization readiness

**It is crucial to optimize time to market for new $H_2$ aircraft** given the objective of reducing the climate impact of aircraft by 2050 and the long ramp-up time from entry-into-service (EIS) of a widespread aircraft rollout. Conventional aircraft development cycles occur about every 15-20 years until a new aircraft platform is introduced. For short-range aircraft, which make up the bulk of emissions, the next window of opportunity is expected to be around 2030-2035. This would be the major chance to introduce new designs in short-range aircraft in order to have an impact on the climate before 2050.

In general, aircraft commercialization starts with an ideation and concept phase, then development, certification, and aircraft handover. For $H_2$ aircraft it will be critical to reach a component technology readiness status of TRL6 as soon as possible to then build a fully functional prototype or representational model. During the same time, all components and the overall aircraft must be certified. Two concept design options, evolutionary and revolutionary, are possible during commercialization; they offer different pros and cons.

- **Evolutionary aircraft** designs will be characterized by the tube-and-wing design of current commercial aircraft. However, this approach would allow for a slightly adapted fuselage and airframe to accommodate the $LH_2$ tanks. It would offer a faster entry-into-service for $H_2$ aircraft and could employ conventional manufacturing and certification techniques. Although less efficient than a fully revolutionary aircraft, the evolutionary aircraft option appears a pragmatic low-carbon one given the short time frame.

- **Revolutionary aircraft** designs would allow new aerodynamic concepts and a better integration of the $LH_2$ storage (e.g., with a blended-wing-body design). One concept that is well suited for smaller aircraft is distributed propulsion. Several propellers on the wing and an adjusted wing layout lead to highly efficient wing aerodynamics.[27] An option for medium- and long-range aircraft with a longer fuselage length could deliver thrust with an aft fuselage fan. The effect of boundary layer ingestion in this approach increases propulsive efficiency. The disadvantage of all radically new aircraft concepts is that they have a long, unpredictable commercialization process with extended development to ensure the aircraft's aerodynamic stability in all flight phases and to optimize cabin design, manufacturing, and operations.

## $H_2$-powered commuter, regional, and short-range aircraft could be commercially available in the next 10-15 years

Detailed analysis was done on potential hydrogen-powered aircraft designs for each segment. Together with industry and research partners, the most promising propulsion technologies were defined for each segment after analyzing each propulsion component and its performance.

[27] Borer et al. (2019), ONERA (2017)

Based on these most promising designs, detailed aircraft design studies were conducted for hydrogen-powered short-range and long-range aircraft. The aircraft concepts were designed using multidisciplinary, iterative sizing processes with several specialized semi-empirical and physics-based models. The design philosophy followed a stepwise approach to capture most of the phenomena that produce the differences in performance. Starting from an existing aircraft, requirements and technologies are then gradually changed, which allows a seamless interpretation of the final results. For instance, conventional aircraft references (Airbus A320neo and Airbus A350-900) were adjusted so they reflected similar conditions such as the technology in 2035 projections, shorter ranges, or lower speeds. The results of the simulation were used to create potential concept designs for medium-range aircraft. An assumption-based approach was chosen for commuter and regional aircraft; several expert discussions and a high-level calculation of $H_2$ propulsion systems and components guided this analysis.

The simulations yielded, for each aircraft design, the resulting energy demand and key technological para-meters. These were then used to project total costs of ownership for each segment and compared to the reference aircraft powered by synfuel.[28]

Aircraft development cycles occur about every 15-20 years until a new aircraft platform is introduced. For short-range aircraft, the next window of opportunity is expected to be around 2030-2035.

[28] This considers a conventional aircraft with the same design mission, technology standards as of 2035 and synfuel costs derived in Chapter 3.

## Commuter segment (19 PAX, 500-kilometer range)

**Block energy reduction of 10 percent with potentially 80-90 percent less climate impact.** A fuel cell system powers the aircraft; it controls the electric motors and includes power management and distribution systems with a battery to buffer transient loads. Each electric motor drives a fan to generate thrust. The fuel cell's high efficiency helps drive the block energy reduction for this aircraft type. Since the flight altitude is below 30,000 feet, contrail formation is unlikely and climate impact is even lower compared to short-range and larger $H_2$ aircraft.

**Feasible segment and time to market within 10 years.** This segment uses a revolutionary design concept. As current $H_2$ aviation projects already demonstrate the feasibility of more evolutionary-like concepts, we assume that the development of a more radical design change could be feasible. This revolutionary commuter could incorporate a new wing to increases efficiency with a lift-optimized design with distributed propulsion. The integration of the liquid hydrogen tank, the fuel distribution system, and the electricity distribution still need to be dealt with. A development of an evolutionary $H_2$ aircraft design and tests with gaseous hydrogen tanks might enable even faster commercialization and might come with different economics which were not investigated in this study.

**Cost increases by 0 to 5 percent** based on cost per available seat kilometer (CASK). Although the energy costs will increase compared to the conventional design, the purchasing and total maintenance costs for the $H_2$-powered commuter are expected to be slightly lower. Based on a cost comparison with the adopted reference aircraft powered by synfuel, the $H_2$ commuter would be 10 to 15 percent less expensive.

**In the long term, this is a stepping stone to larger hydrogen aircraft,** as the commuter aircraft will play only a minor role in the overall climate impact reduction of the aviation sector.

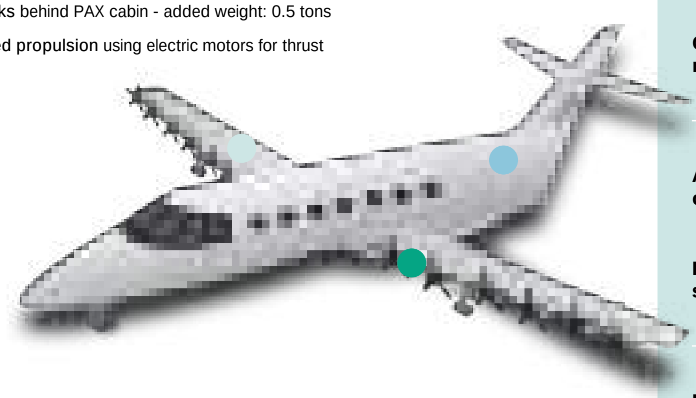
Exhibit 6

### Commuter aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 19 PAX, 500 km range, cruise speed 500 km/h

- Highly efficient wing
- 2 $LH_2$ tanks behind PAX cabin - added weight: 0.5 tons
- Distributed propulsion using electric motors for thrust



| | |
|---|---|
| **Energy demand**[1] | -10% |
| **$CO_2$ reduction** | 100% |
| **Climate impact reduction** | 80-90% |
| **Additional cost** | 0-5% CASK[2] |
| **Entry into service** | <10 years |
| **Propulsion power** | Fuel cell system |
| **MTOW**[3] | +15% |

1. Major assumptions: 25% gravimetric index of $LH_2$ tank, 90% useable $LH_2$ fuel, FCS mass 1.5 kW/kg (incl. cooling) and 58% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg
2. Cost per available seat kilometer
3. Maximum take off weight

## Regional segment (80 PAX, 1,000-kilometer range)

**Block energy reduction of 8 percent with potentially 80-90 percent less climate impact.** Regional $H_2$ aircraft are equipped with a fuel cell system. As with commuter aircraft, the climate impact is highly reduced due to the high system efficiency and no contrails formed.

**Feasible segment and time to market within 10 to 15 years.** This segment uses a revolutionary design concept with a highly-efficient wing design with distributed propulsion.[29] The integration of the liquid hydrogen tank, the fuel distribution system, the high power fuel cell systems, and the electricity distribution remains a challenge that will need to be overcome.

**CASK increases by 5 to 15 percent.** The higher energy and aircraft costs are the main drivers for this increase when compared to conventional designs. Compared to the reference aircraft (extended design based on an ATR 72) powered by synfuel, the $H_2$ regional aircraft would be 10 percent less expensive.

**In the long term, the regional segment is important for the rollout of hydrogen aviation within a geographic region.** Even though it is a minor contributor, it could play an increasing role in the overall climate impact reduction of the aviation sector if it replaces the lower end of the short-range segment.

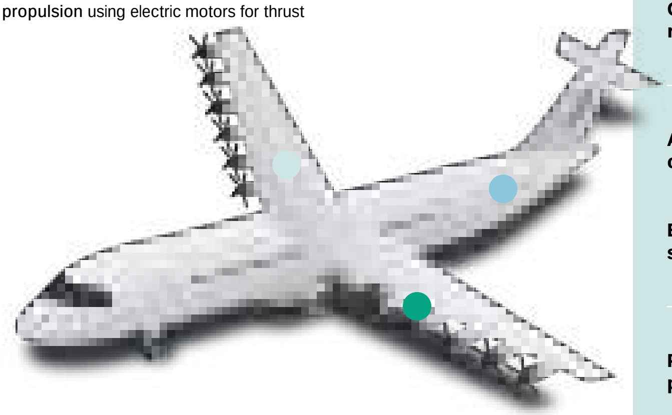
Exhibit 7

### Regional aircraft powered by fuel cells

Revolutionary aircraft

**Design mission:** 80 PAX, 1,000 km range, cruise speed Mach 0.44

- **Highly efficient** wing
- 2 $LH_2$ **tanks behind PAX cabin** - added weight: 2 tons
- **Distributed propulsion** using electric motors for thrust



| | | |
|---|---|---|
| **Energy demand**[1] | | -8% |
| **$CO_2$ reduction** | | 100% |
| **Climate impact reduction** | | 80-90% |
| **Additional cost** | | 5-15% CASK[2] |
| **Entry into service** | | 10-15 years |
| **Propulsion power** | | Fuel cell system |
| **MTOW**[3] | | +10% |

1. Major assumptions: 30% gravimetric index of $LH_2$ tank, 90% useable $LH_2$ fuel, FCS mass 1.75 kW/kg (incl. cooling) and 59% peak efficiency (LHV), e-motors and PMAD with 97%
2. Cost per available seat kilometer
3. Maximum take off weight

[29] Seeckt (2010)

## Short-range segment (165 PAX, 2,000-kilometer range)

**Long design ranges and high cruise speeds could limit the application of the new, heavier propulsion technologies** because they increase the aircraft's energy and power requirements. For $H_2$ aircraft, the design range will need to be reduced by approximately 25 to 50 percent for short-, medium-, and long-range concepts. To make it possible to apply the power-sensible fuel cell system in a $H_2$ short-range plane, the design speed will also be reduced to Mach 0.72, which increases the flight time by approximately 5 to 15 percent.[30]

**Block energy reduction of 4 percent and potentially 70 to 80 percent less climate impact.** A hybrid system of $H_2$ turbines and a fuel cell system powers the aircraft; the fuel cell is the major power source for cruise. The $H_2$ turbine is sized to deliver the major thrust for takeoff and climb. This operation strategy reduces energy and climate impact because of the higher efficiency of fuel cell systems and since they do not emit $NO_x$ and could lead to less contrails.

**Feasible segment and time to market within 15 years.** An evolutionary tube and wing aircraft design was chosen to ensure faster commercialization. The fuselage is extended by approximately five meters to integrate the two $LH_2$ tanks behind the passenger cabin. However, this design still has issues that must be addressed. A system needs to be created that will distribute the $LH_2$ safely and reliably from the back of the fuselage to the two wing-mounted engines. Second, the fuel cell system has a power rating greater than 10 megawatts (MW), requiring even more efficient heat exchangers or other cooling concepts. Third, the use of a parallel hybrid system adds complexity to the development and certification of the propulsion system.

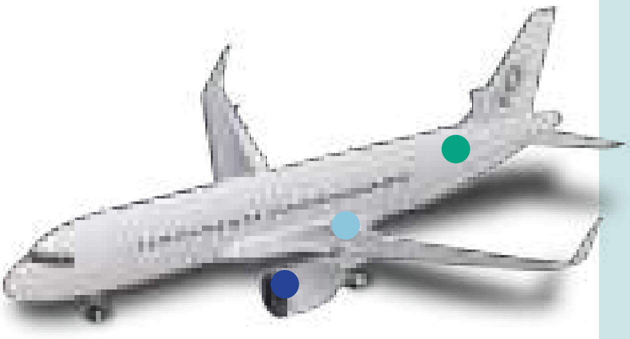
Exhibit 8

### Short-range aircraft powered by hybrid $H_2$ propulsion

Revolutionary aircraft

**Design mission:** 165 PAX, 2,000 km range, cruise speed Mach 0.72

- 2 $LH_2$ tanks behind PAX cabin -added weight: 4 tons
- Fuel cell system (11 MW) powering electric motors
- Electric motor driving main turbine fan shaft during cruise, while $H_2$ turbine is turned off



| | |
|---|---|
| **Energy demand**[1] | -4% |
| **$CO_2$ reduction** | 100% |
| **Climate impact reduction** | 70-80% |
| **Additional cost** | 20-30% CASK[2] |
| **Entry into service** | 15 years |
| **Propulsion power** | Hybrid |
| **MTOW**[3] | +14% |

1. Major assumptions: 35% gravimetric index of $LH_2$ tank, 91% useable $LH_2$ fuel, FCS mass 2 kW/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg, $H_2$-turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

[30] All design mission changes (range and speed) are also applied to the new conventional reference aircraft to ensure comparability.

**CASK increases by 20 to 30 percent.** With the longer fuselage and the approximately five tons of heavy tanks the aircraft's costs will increase. However, the increase in energy cost is relatively moderate because the aircraft is more energy efficient. Compared to synfuel aircraft, the $H_2$ short-range aircraft would be 5 to 10 percent less expensive.

**In the long term a revolutionary** short-range aircraft design could lead to even higher energy improvements (5 to 10 percent greater) but would require longer time to market and higher development risks for the aircraft manufacturers. From a technology point of view, the application of boundary layer ingestion or partially distributed propulsion could be pathways towards this but will require further analysis.[31]

$H_2$ propulsion could be less expensive up to medium-range aircraft segments compared to synfuels. These would be more cost competitive for long-range aircraft.

## Medium- to long-range $H_2$ aircraft are technologically feasible, but will have higher costs

### Medium-range segment (250 PAX, 7,000-kilometer range)

**Block energy increases of 22 percent and potentially 50 to 60 percent less climate impact.** The aircraft is powered by $H_2$ turbines, as fuel cells with their correlated cooling requirements would be too heavy. The energy requirement is higher than that of a conventional kerosene aircraft because the weight of the hydrogen tanks must

[31] Page et al. (2018)

be carried over the long flight distance. Even though more energy is needed for the flight, this concept still offers a significant climate impact reduction.

**Feasible segment and time to market within 20 years.** An evolutionary tube and wing aircraft design will ensure faster commercialization. The fuselage is extended by about 10 meters to integrate the two $LH_2$ tanks behind and in front of the passenger cabin. However, several issues need to be worked out. Liquid hydrogen storage tanks with a gravimetric index[32] of 35 percent or higher must be developed, tested, and certified. The $LH_2$ tanks have to be integrated into the airframe. The means to safely and reliably distribute the $LH_2$ from the back and front of the fuselage to the two wing-mounted engines must be identified.

**CASK increases by 30 to 40 percent.** Because of the increased block energy requirement, the energy costs increase significantly for this concept. With the longer fuselage and the tank weight of about 30 tons, other costs also increase. Compared to synfuel aircraft, the $H_2$ medium-range aircraft would be 0 to 5 percent less expensive.

**In the long term, a revolutionary** medium-range aircraft design could lead to even higher energy improvements by taking out another 5 to 10 percent but would require longer time to market and higher development risks for aircraft manufacturers. From a technology point of view, the application of a blended-wing-body (BWB) with partially distributed propulsion could be a pathway toward this but would require further analysis.[33]

Exhibit 9

## Medium-range aircraft powered by $H_2$ turbines

Evolutionary aircraft

**Design mission:** 250 PAX, 7,000 km range, cruise speed Mach 0.82

- 2 $LH_2$ tanks in front and back of PAX cabin - added weight: 29 tons
- $H_2$ turbines generating propulsion power

| | |
|---|---|
| **Energy demand[1]** | +22% |
| **$CO_2$ reduction** | 100% |
| **Climate impact reduction** | 50-60% |
| **Additional cost** | 30-40% CASK[2] |
| **Entry into service** | 20 years |
| **Propulsion power** | $H_2$ turbine |
| **MTOW[3]** | +12% |

1. Major assumptions: 37% gravimetric index of $LH_2$ tank, 92% useable $LH_2$ fuel, 47% $H_2$ turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

[32] The gravimetric index of a tank is calculated by dividing the mass of the stored hydrogen by the sum of the mass of the stored hydrogen and the empty tank weight. A gravimetric index of 50 percent means that the empty tank is as heavy as the stored hydrogen.

[33] Guynn et al. (2004), Marino et al. (2015)

## Long-range segment (325 PAX, 10,000-kilometer range)

**Block energy increases of 42 percent but with potentially 40 to 50 percent less climate impact.** The aircraft is powered by $H_2$ turbines because fuel cells with their correlated cooling requirements would be too heavy. The energy requirements are higher than those in a conventional kerosene aircraft because the weight of the hydrogen tanks must be carried over the long flight. Even though more energy is needed for the flight, this concept still provides a significant climate impact reduction.

**Feasible segment and time to market within 20 to 25 years.** An evolutionary tube and wing aircraft design ensures faster commercialization. The fuselage is extended by about 30 percent to integrate the two $LH_2$ tanks behind and in front of the passenger cabin. However, several other obstacles must be overcome. Liquid hydrogen storage tanks with a gravimetric index of 38 percent or higher must be developed, tested, and certified. The $LH_2$ tanks must be integrated into the airframe. A system to safely and reliably distribute $LH_2$ from the back and front of the fuselage to the two wing-mounted engines must also be developed.

**CASK increases by 40 to 50 percent.** The energy costs increase significantly for this concept due to the higher block energy requirement. The longer fuselage and the tank weight of approximately 50 tons increase costs as well. Compared to synfuel aircraft, the $H_2$ long-range aircraft would be 0 to 10 percent more expensive.

**In the long term, only a huge breakthrough in $LH_2$ tank development or a revolutionary** long-range aircraft design could lead to a very competitive aircraft design. Such a revolutionary design could further improve energy by another 15 to 25 percent but would require longer time to market and higher development risks for aircraft manufacturers.[34] From a technology point of view, the application of a blended-wing-body with partially distributed propulsion could be a pathway toward this, but further analysis is required.

Exhibit 10

### Long-range aircraft powered by $H_2$ turbines

Evolutionary aircraft

**Design mission:** 325 PAX, 10,000 km range, cruise speed Mach 0.85

- 2 $LH_2$ **tanks** in front and back of PAX cabin - added weight: 52 tons
- $H_2$ **turbines** generating propulsion power

| | |
|---|---|
| **Energy demand**[1] | +42% |
| **$CO_2$ reduction** | 100% |
| **Climate impact reduction** | 40-50% |
| **Additional cost** | 40-50% CASK[2] |
| **Entry into service** | 20-25 years |
| **Propulsion power** | $H_2$ turbine |
| **MTOW**[3] | +23% |

1. Major assumptions: 38% gravimetric index of $LH_2$ tank, 92% useable $LH_2$ fuel, 50% $H_2$ turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

[34] Airbus (2020)


LIQUID HYDROGEN
H2

# 3. Infrastructure: Liquid hydrogen supply and refueling challenges

Beyond the implications for aircraft design discussed in the prior chapter, switching to $LH_2$ would have major implications for the fuel supply chain, airport infrastructure and operations, and the air travel system as a whole. This chapter analyzes two key concerns around this infrastructure. First, we look at whether the infrastructure to produce, liquify, and dispense the hydrogen can feasibly be built and operated – both in the early years of deployment and in the long term, at scale. Second, we examine the resulting cost of liquid hydrogen to the airplane operator, which should account for all infrastructure investments; the overall cost-competitiveness of hydrogen propulsion in aviation pivots on this cost.

## Two scenarios for hydrogen aircraft deployment

To analyze the required infrastructure, we consider two scenarios for aircraft deployment.[35] In the **efficient decarbonization** scenario, hydrogen plays a role where it is the most cost-efficient means of decarbonization. In this scenario, aircraft up to medium-range will start to be replaced with hydrogen aircraft by 2030-2040, representing the earliest potential entry-into-service dates of aircraft in each segment. After a ramp-up of manufacturing capacity over three to four years, all new aircraft in commuter and short-range and 50% of medium-range aircraft would be powered by hydrogen. In this scenario, 40 percent of all aircraft are switched to $LH_2$ by 2050, while the remainder would be powered by other sustainable aviation fuels like synfuel and/or biofuels.

In a maximum decarbonization scenario, hydrogen aircraft would start to replace all aircraft for ranges of up to 10,000 kilometers after 2028-2038, representing the first conceivable entry-into-service dates with ambitious assumptions. After a ramp-up of manufacturing capacity over three to four years, all new aircraft up to a 10,000 km range would be powered by hydrogen. In this scenario, 60 percent of all aircraft are switched to $LH_2$ by 2050, and the rest would be powered by synfuel and/or biofuels.

In the two scenarios, the global demand for hydrogen would reach approximately 10 or 40 million tons of $LH_2$ by 2040 per annum, and approximately 40 or 130 million tons by 2050, as illustrated in Exhibit 11 below. This amount represents 5 or 20 percent of the total global demand for hydrogen projected by the Hydrogen Council by 2040, and 10 or 25 percent of global demand by 2050.

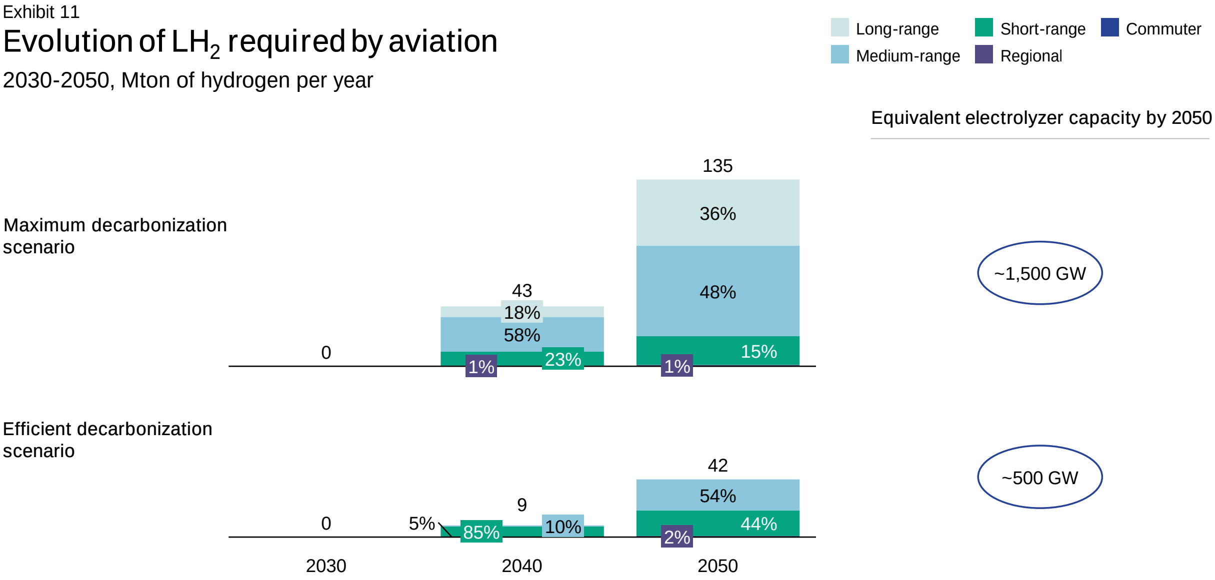
**40% of all aircraft** are switched to $LH_2$ by 2050 in an efficient decarbonization scenario - remainder of fleet powered by sustainable aviation fuels.

35 It is important to note that these scenarios do not represent expected future growth or market projections but serve as a tool for analyzing the required infrastructure.

Exhibit 11

## Evolution of $LH_2$ required by aviation

2030-2050, Mton of hydrogen per year




For the purpose of analysis, we looked at the required infrastructure in two distinct phases: 1) the early ramp-up years until 2035 or 2040 (depending on the scenario), when only airplanes up to short range would be replaced by $LH_2$ aircraft; and 2) the infrastructure required at scale by around 2050. The first phase seeks to understand what is required to get started, while the second seeks to identify any constraints to scaling $LH_2$ to a large share of aircraft.

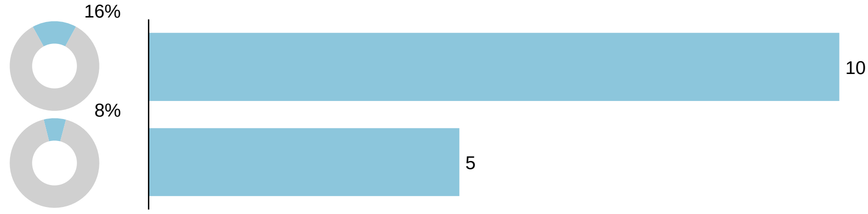
## Early years: No major technical infrastructure roadblocks foreseen for $LH_2$ aviation ramp-up

Until 2035 in the maximum decarbonization scenario and 2040 in the efficient decarbonization scenario, hydrogen aircraft will first penetrate the smaller segments, from commuter to short-range aircraft. In these early years, the total amount of aircraft and therefore the total demand for $LH_2$ are still limited (about five to ten million tons of $LH_2$) as shown in Exhibit 12 below.

Exhibit 12

## Key facts during early ramp-up years

| Scenario | Time frame | Share of fleet replaced | $LH_2$ demanded Mton |
|---|---|---|---|
| Efficient decarbonization | 2040 | 16% | 10 |
| Maximum decarbonization | 2035 | 8% | 5 |



**Deployment pathways**

There are multiple deployment pathways one could imagine for the roll-out of hydrogen aviation. In one possible deployment pathway, regional airports would lead the innovation in hydrogen-powered commuter and regional flights during the early years. An initial infrastructure could, for instance, be established to serve certain point-to-point flights (as trial routes) or a tight regional network of smaller airports. Airports with competitive access to the low-cost renewable energy needed to produce green hydrogen would particularly benefit – for example, an airport serving an island group with access to hydropower, airports along the North Sea coast with access to wind power, and airports in Southern Europe with access to solar and wind power. Smaller airports would also make good starting points, because they tend to serve a relatively low number of other airports and to have fewer congestion problems and spatial constraints, thereby allowing for the gradual introduction and testing of $H_2$ infrastructure. For instance, $LH_2$ supply trucks could supply these airports relatively easily, and finding space for liquefaction plants and liquid storage would prove less difficult than at larger, busier airports.

After these early days, other airports in the broader region or continent could follow based on the results of the initial trials. $LH_2$ for short-range flights would be introduced, and applications would move from point-to-point flights to full roll-out across a regional network. To ensure a competitive offering, a subset of flights in one region would need to switch to $LH_2$ almost simultaneously so that routes could be flexibly scheduled. This larger roll-out would require the expansion of the $LH_2$ infrastructure to include small airports that have not yet participated as well as larger airport hubs.

**Implications for the fuel supply chain**

To understand the potential implications to the fuel supply chain, we must first understand what the $LH_2$ supply chain might look like. Hydrogen must come from a low-carbon source to be used for decarbonization. The most common ways to produce low-carbon hydrogen are electrolysis of water, which is carbon-free if powered by renewable energy ("CertifHy Green $H_2$", also known as "green $H_2$"), and carbon-neutral if produced through reformation of natural gas combined with carbon capture and storage ("CertifHy Low Carbon $H_2$", also known as "blue $H_2$"). Both of these are conceivable pathways and could exist in parallel.

Once produced, the hydrogen would need to be either compressed or liquified and then distributed to the airports, through either liquid or compressed hydrogen truck trailers for smaller airports or through a pipeline for larger airports. It can also be shipped in liquid form or converted (e.g., into ammonia or liquid organic hydrogen carriers). Once at the airport, the hydrogen would be liquified (if not already liquefied at the source), stored, and ultimately transferred to airplanes via refueling trucks or an alternative refueling method like refueling platforms or aircraft "fuel station" plots.

Synfuel would also draw on hydrogen electrolysis, or hydrogen from natural gas reforming plus carbon capture and storage, to provide low carbon hydrogen for its needs. Additionally, synfuel requires the capturing of $CO_2$ (either from the air, biomass, or existing industrial processes), which must then be combined with the hydrogen to produce synfuel. This process takes three times the amount of overall energy required to produce hydrogen fuel in the case of direct air capture and twice the amount of energy if $CO_2$ is captured from biomass or industrial processes. After production, however, synfuel can use the same supply routes that kerosene uses today.

**By 2035 or 2040,** there would likely be enough hydrogen supply infrastructure in place for LH2 aviation to take-off.

By 2035 or 2040, there would likely be enough hydrogen supply infrastructure in place for $LH_2$ aviation to take off, excluding any dedicated liquefaction capacity required at large airports. In the efficient decarbonization scenario, 10 million tons of $LH_2$ would be needed by 2040. This amount represents only 5 percent of the total projected global demand for hydrogen by 2040. This means that aviation could likely tap into a scaled-up hydrogen supply infrastructure. Here synfuel would actually be at a disadvantage, as any scale-up in synfuel production would have to be driven entirely by demand from aviation, meaning synfuels would capture less cost reductions from scaling up production than the $LH_2$ route.

Exhibit 13

## Overview of fuel supply chain for $LH_2$ and Synfuels

✓ Always applicable
(✓) Sometimes applicable

| | Description | Energy | $H_2$ production | $CO_2$ capture + fuel synthesis | $H_2$ liquefaction | Shipping | Distribution | $H_2$ liquefaction | Storage | Refueling |
|---|---|---|---|---|---|---|---|---|---|---|
| Main $H_2$ pathways | Off-site + truck | ✓ | ✓ | | ✓ | (✓) | ✓ | | ✓ | ✓ |
| | Off-site + pipeline | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| | On-site | ✓ | ✓ | | | | | ✓ | ✓ | ✓ |
| Main SF pathways | Off-site | ✓✓✓ | ✓✓ | ✓ | | (✓) | ✓ | | ✓ | ✓ |
| | On-site | ✓✓✓ | ✓✓ | ✓ | | | | | ✓ | ✓ |

Synfuel from air capture requires roughly 3x energy and 1.5x the amount of hydrogen for same energy content

To illustrate the potential impact on airport fuel supply chains, the projected demand for $LH_2$ by 2040 is equivalent to the demand that would be generated if all regional airports today were to switch 10 percent of their fuel infrastructure to $LH_2$ and if major hubs were to switch 5 percent. For an average regional airport, this change would necessitate a supply of around 5,000 tons of $LH_2$ per year, or about 10 tons per day. With an average $LH_2$ distribution truck carrying four tons of $LH_2$, a regional airport would thus need about 2.5 truckloads per day.[36] For these regional airports, the subset of aircraft powered by $H_2$ could be supplied directly by $LH_2$ trucks from central production plants that already exist for other $H_2$ uses, in most cases likely relying on an existing $LH_2$ supply chain. Alternatively, a local electrolysis unit of 50 megawatts could serve the need for this fuel as well.

For larger hubs, a 5 percent switch of fuel infrastructure would require the supply of around 40,000 tons of $LH_2$ per year, or about 100 tons per day. The 25 truckloads required to supply those needs would still be feasible

[36] To put it in perspective, at an assumed distance of 1,500 kilometers flown with a short-range aircraft, those flights each need about 1,500 kilograms of $LH_2$, with one trailer being capable of delivering about 4,000 kilograms of $LH_2$. Therefore, these truckloads could cover about 20 short-range flight refueling events a day.

(with trucks most likely traveling at night to avoid congested roads); a gaseous pipeline from a nearby electrolysis unit of around 500 megawatts might prove to be another viable option but would require the construction of dedicated liquefaction capacity on large airports.

In the maximum decarbonization scenario, the same conclusions can be drawn for the early years of ramp-up, except that they would occur about five years sooner.

**Implications for airport refueling infrastructure and operations**

In the early years, given the amount of refueling required and the primary focus on regional airports – which already often use refueling trucks – a major overhaul of the refueling infrastructure at airports is not likely to be needed. The number of refueling trucks required is roughly double the number needed for kerosene or synfu-el but comprises only a small share of the total existing refueling fleet in this time frame, so the implications on ground traffic would be limited. These $LH_2$ refueling trucks are very different to existing refueling trucks and would require a different training and a safety assurance framework for operations, but these are manageable challenges to overcome.

In addition, refueling times would likely stay within the required turnaround times of shorter-range aircraft. $LH_2$ hoses could attain the same flow rate in the short-term as kerosene/synfuel hoses – about 900 liters per minute – if the right investments are made to accommodate the hoses' heavier weight and lower maneuverability. Given $LH_2$'s lower volumetric density, $LH_2$ refueling would still be much slower, but if the amount of hoses were doubled from one to two, the refueling of a sample short-range airplane would take 20 to 30 minutes, which would still be within turnaround times. The major remaining question concerns safety and taking the necessary precautions when refueling, which could potentially compromise the ability to conduct parallel operations during the turnaround. This could potentially have a major impact: Losing more than 10 minutes of turnaround time three to four times per day means that short-haul aircraft could lose the ability to perform a flight sector during an 18-hour operating period per day, which has a negative revenue impact. We explore the required research needs related to this further in the R&D roadmap (Chapter 5).

There are a few other airport infrastructure implications, that seem to be manageable on the shorter term. Short-range aircraft designs may be about five meters longer. Not all airport boxes[37] are designed with a buffer to accommodate this. Yet, given the low number of gates required to serve hydrogen aircraft in this shorter-term time frame, it is likely that this will result in minimal infrastructure update requirements. If $LH_2$ is trucked in from outside, liquefaction would not have to take place at the airport. The needed three-day storage of $LH_2$ (around 90 tons for regional airports) would require only limited space (about 100 square meters). The size of the required safety perimeter around this storage space – as mandated by the SEVESO Directive in the EU, which regulates hazardous chemicals – is not yet known, but the regional airports that would likely be early movers tend to have more space and might accommodate this additional infrastructure more easily. Finally, in early years when not

[37] Parking area for airplane at gate

all airports have an $LH_2$ infrastructure, it is worth noting that flights that are diverted may get stuck at an airfield waiting for $LH_2$ resupply by truck if that airfield is not cleared for $LH_2$ refueling. Diversions are common across the industry, so this would be an early stage-challenge.

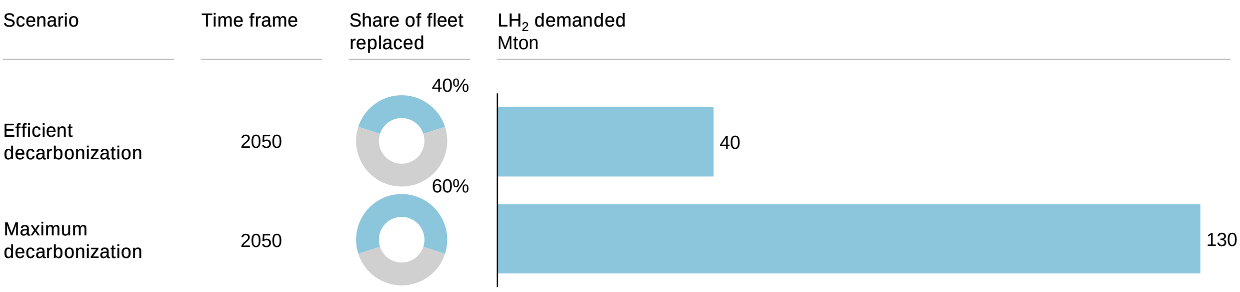
While these challenges exist, all in all, the technical feasibility of establishing $LH_2$ infrastructure in the early years (up to 2040 in the efficient decarbonization scenario and 2035 in the maximum decarbonization scenario) is strong, even within the constraints of the current infrastructure. The major challenge will likely be in ensuring the required coordination between fuel providers, airports, aircraft manufacturers, and airlines as they develop the new industry in tandem.

## At-scale deployment: Significant but manageable technical and investment challenges to overcome in the decade up to 2050

In the decade up to 2050, $LH_2$ adoption increases in the commuter to short-range segments – exceeding 50 percent of the fleet – and penetrates the medium-range segment (and, in the maximum decarbonization scenario, the long-range segment as well). By 2050 $LH_2$ demand will have reached about 40 million tons in the efficient decarbonization scenario and about 130 million tons in the maximum decarbonization scenario. The key parameters of this time frame are delineated in Exhibit 14 below.

Exhibit 14

### Key facts during at-scale deployment




**Deployment pathways**

This scale-up will require new infrastructure around the globe. Single regions cannot make this change alone, as medium- and long-range aircraft will require refueling infrastructure across continents to operate – especially since tank sizes will not be large enough to allow for extra refueling in single locations, as is sometimes the practice today.

Certain regions could lead the way, while others follow. For instance, the EU could establish a cross-continental network with some airports in the US and Asia, while emerging markets would work to scale up their hydrogen infrastructure.

Particularly when compared to the initial phase, multiple challenges will arise in this phase as new infrastructure is developed in parallel with the existing kerosene refueling infrastructure - comparable to the challenges of other transportation segments where a switch to low carbon alternatives is required. Below we lay out these challenges, which involve the fuel supply chain, the airport refueling infrastructure and operations, and other system-wide implications.

### Implications for the fuel supply chain

The projected $LH_2$ demand of 40 million tons in the efficient decarbonization scenario and of 130 million tons in the maximum decarbonization scenario would comprise 10 and 25 percent of total projected global hydrogen demand by 2050, respectively. All the produced $H_2$ would need to be liquefied, which would likely multiply the required liquefaction capacity around the world as aviation would be one of the only large users of $H_2$ in liquid form, possibly in addition to shipping.

To illustrate, the demand for $LH_2$ in the efficient decarbonization scenario would be equivalent to the demand that would be generated if all regional airports today were to switch 50 percent of their fuel infrastructure to $LH_2$ and if major hubs were to switch 25 percent. An average regional airport would need around 20,000 tons of $LH_2$ per year, or about 60 tons per day. If the airport needed to be supplied from a central production facility, it would require 15 truckloads a day. This arrangement is still feasible for most regional airports.

Larger hubs would face bigger supply challenges. A 25 percent switch of these hubs' fuel infrastructure would require the supply of around 200,000 tons of $LH_2$ per year for an average hub, or about 500 tons per day. The 125 truckloads required to supply those needs would probably pose a safety hazard to supply airports whose feeder roads are already congested. From this point of view, and considering economies of scale, a larger-scale supply route would be favorable. While in some situations delivery by train or barge may be an option, a truly at-scale solution would probably necessitate the introduction of gaseous pipeline delivery. Existing natural gas pipelines would thus need to be rehabilitated, or new, dedicated hydrogen pipelines constructed. The first option could be cost-technically attractive if gas pipeline assets would be otherwise stranded in a decarbonized future. Alternatively, in location with good access to renewable energy (e.g., Southwest US, Australia, Norway), airports could be served directly via near-site electrolysis plants. Where this is possible, this may be a far more competitive alternative.

The amount of hydrogen needed at large hubs also affects the required set-up for fuel production. The average hub airport assumed above would require about two gigawatts of electrolysis to supply its $LH_2$ fuel needs by 2050. If these electrolysis units had to be powered by offshore wind, four large offshore wind parks of 500 megawatts (the higher end of offshore wind parks today) would be necessary to supply just one airport. However, this set-up falls within the range of scales for offshore wind parks and electrolysis projects that have been announced for the 2030s.

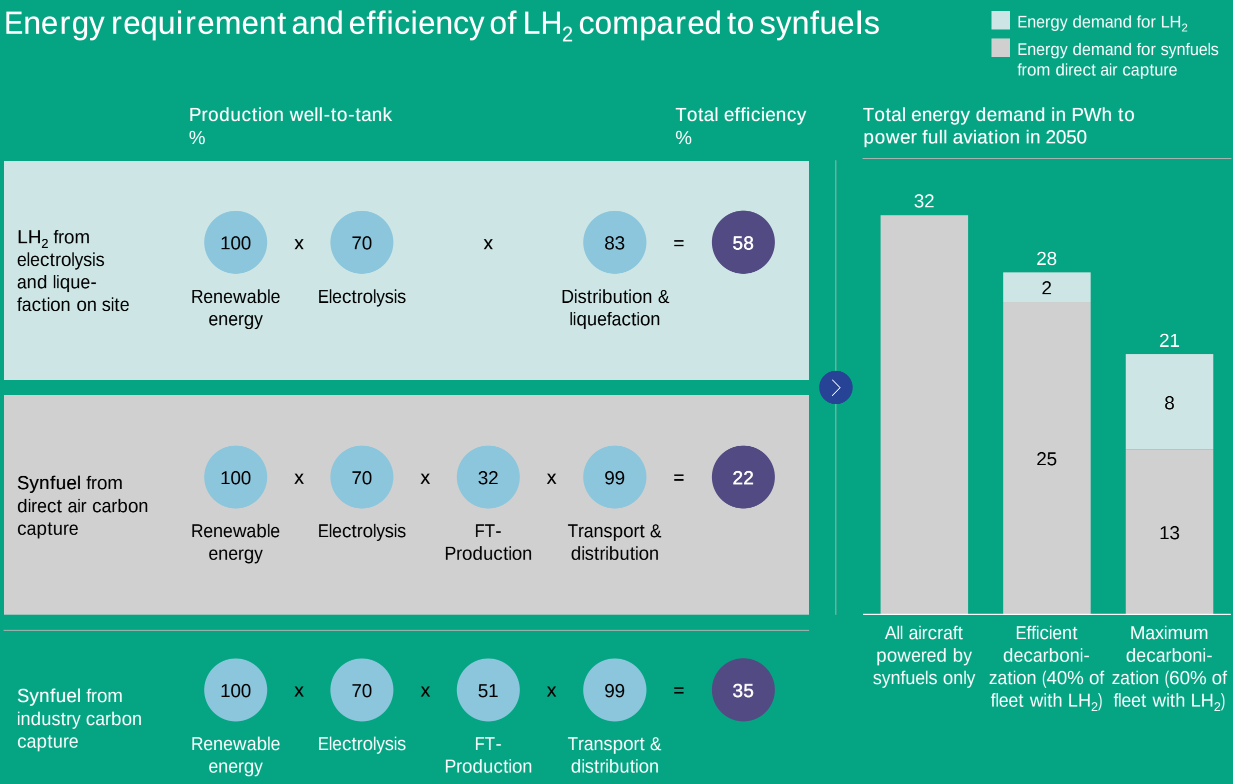
The full global demand for $LH_2$ in aviation would require as much as 500 or 1,500 gigawatts of renewable energy capacity, depending on the scenario assumed, or about 20 or 60 percent of the total capacity of renewable energy available today.[38] Scaling up to this capacity would obviously raise significant planning challenges. That being said, if an energy-equivalent amount of synfuel from direct air capture were produced, it would require about three times the amount of renewable energy and one and a half times the amount of electrolysis. This is a significant drawback for synfuel, as the global energy system will already be challenged to scale up enough renewable energy to make the overall energy transition a success as illustrated in the box on the next page.

[38] IRENA (2020)

# Energy demand of different decarbonization technologies and scenarios

Exhibit 15

## Energy requirement and efficiency of $LH_2$ compared to synfuels




So-called "well-to-tank" efficiencies will differ between decarbonized aviation fuels. Comparing $LH_2$ and synfuel, synfuel will require significantly more input energy to produce and distribute. Synfuel uses low carbon hydrogen as one of its inputs. Additionally, synfuel requires the capturing of $CO_2$ either from the air, biomass, or existing industrial processes. These inputs are then synthesized into synfuel. All of these processes require energy input. As such, it takes roughly twice the amount of energy to produce and distribute an energy-equivalent amount of synfuel compared to $LH_2$ if $CO_2$ is captured from biomass or industrial processes. Given the energy-intensity of $CO_2$ air capture, synfuel produced in this way requires roughly three times the amount of energy to produce and distribute than an energy-equivalent amount of $LH_2$. Synfuel from direct air capture is the main comparison fuel in this study. The exact energy efficiencies can be observed in Exhibit 15.

Based on these energy efficiencies, we can estimate the total amount of clean energy required for each of our decarbonization scenarios proposed in this study. In the efficient decarbonization where 40% of aircraft would be powered by $LH_2$ and the rest via synfuel by 2050, total energy demand to supply the aviation industry would be around 28 petawatt hours. Decarbonizing the aviation sector via $LH_2$ and synfuel would thus triple to quintuple the renewable energy produced globally today – in other words, demand for renewable energy would be 20-30 times as high as renewable energy produced in Europe.

The implications are clear: To go to net zero, renewable energy capacity will need to be scaled in an unprecedented way. If $LH_2$ could help to limit the required scale-up, this would make scaling up alternative fuel production comparatively easier – even if this does imply investing in a new distribution infrastructure to handle this new alternative fuel.

**Implications for airport refueling infrastructure and operations**

While supply-side challenges will be significant in 2050, they will not be unique in a future energy system that partially relies on hydrogen. (By some estimates, hydrogen could play a role in about 18 percent of final energy demand, with 24% in Europe by 2050.[39]) The challenges affecting the airport refueling infrastructure and operations are unique, however, and will require significant development and planning to overcome. They include searching for scalable refueling technology, optimizing refueling practices, and re-configuring airport infrastructure to introduce parallel fuel systems.

The first challenge is developing scalable refueling technologies. In many large airports today, hydrant pipelines are used to refuel aircraft. These pipelines could be easily adapted to synfuel. To the contrary, by 2040 cryogenic hydrant refueling systems for $LH_2$ seem to be cost-technically infeasible, as their cost may be as much as five times the cost of conventional hydrant systems. Given this fact, the most viable near-term $LH_2$ refueling technology seems to be the $LH_2$ refueling truck. These trucks work well at smaller airports, where kerosene refueling trucks are used today, but at larger airports they could greatly increase ground traffic and pose logistical challenges.

For now, the optimal solution is unclear. Larger mobile refueling platforms or even refueling station lots away from boarding gates may be an option. The latter may sound cost-technically infeasible given today's required turnaround times but considering the lengthier refueling times needed for medium- and long-range $LH_2$ aircraft discussed below, an economic case could be made for refueling station lots if they greatly optimize refueling times. In the longer term, $LH_2$ hydrant pipeline systems may become a viable solution.

Refueling practices and operations will also need to be reviewed. Unlike shorter-range aircraft segments, refueling times for long-range aircraft may extend beyond their current standard turnaround times. For instance, if a long-range plane has a tank that is 75 percent empty, refueling the tank with kerosene/synfuel using two hoses may take up to 65 minutes, assuming a flow rate of 900 liters per minute per hose. Assuming the same flow rates for $LH_2$, even with twice as many hoses, refueling would take 140 minutes. The standard turnaround time for a large jumbo jet is about 120 minutes today. Further research and development will be important to develop economic solutions to push refueling flow rates above 1,000 liters per minute per hose. For large aircraft refueling, automated tank solutions that can handle higher weights of hoses for higher refueling rates may even allow for flow rates at multiples of kerosene today.

Beyond longer refueling times, it is unclear whether all or some of the usual turnaround operations could happen in parallel. First, doubling the amount of hoses will cause additional spatial constraints around the aircraft and leave less room for other operations to take place. In addition, it is not certain which turnaround operations would be permitted from a regulatory and safety perspective. Experts agree that new regulations will need to be developed to ensure adequate and safe handling of low temperature $LH_2$ and its unique properties – for instance, the possible spontaneous ignition on contact with water, asphyxiation risk, and vertical dispersion. The impact on aspects such as ignition free zones around refueling trucks is as yet unclear. For example, some experts suggest that the periphery required around refueling trucks may even be smaller, as $LH_2$ would not form a pool on the ground but rather evaporate upwards in the air. This shows that safety considerations are still highly preliminary and need to be refined through further research and on-the-ground testing.

The final challenge is finding the capacity to set up two parallel refueling systems at busy, spatially constrained hubs. Spatial requirements are likely to be moderate; for example, if hydrogen production happens off-site, large airports using 500 tons of $LH_2$ would need less than 25,000 square meters for liquefaction and storage

[39] Hydrogen Council (2017); FCHJU (2019)

equipment, or about 0.2 percent of Heathrow's footprint today. However, additional capacity may be needed if refueling lots must be installed away from gates and/or gate space is locked for longer periods due to longer refueling times. Finally, airport box sizes may not always be able to accommodate the additional 10 to 15 meters in length needed for the suggested $LH_2$ medium-range and long-range aircraft designs, which could potentially lead to the need for sizable infrastructure investments. Alternatively, this could lead to constraints on aircraft gate assignments, which would further increase turnaround times and reduce overall infrastructure flexibility.

### Synergies with other airport infrastructure

While the scaling up of $LH_2$ infrastructure to power $LH_2$ aviation involves many challenges, the establishment of this infrastructure would create several potential synergies with other energy offtakes at airports. First, ground vehicle hydrogen refueling stations could draw on the same supply of hydrogen. Having access to such a large, efficient source of hydrogen could provide a cost advantage of up to US $0.50 per kilogram of hydrogen over other supply sources, which may make this the most cost competitive option for ground traffic in the near future. $CO_2$ emissions from ground traffic on airports comprise well below 1% of total emissions related to aviation but mitigating these in this way would be an additional cost-efficient way of climate impact reduction in the industry.

Second, the hydrogen supply infrastructure could also potentially provide airports' heating and electricity needs through boilers and fuel cells. While a grid connection may be preferable in many locations to balance supply and demand with other off-takers, such a solution could provide a competitive alternative in airports located in remote locations.

Finally, the industries around an airport may benefit from the available hydrogen. The production of ammonia, methanol, and – potentially in the future – steel relies heavily on hydrogen. Having a cheap, reliable source of supply along with a nearby airport could give these producers a competitive advantage. In return, the diversification afforded by their offtake demand would increase the security of the airport's supply.

### Further system-level implications

In addition to the challenges and opportunities related to supply chain and refueling logistics, two important, broader system implications arise from introducing $LH_2$ in aviation and airports. First, in the maximum decarbonization scenario, the introduction of $LH_2$ in the long-range aircraft segment will reduce their maximum range to 10,000 kilometers. If all flights would need to be served by $H_2$-powered aircraft, flight patterns would then have to change; for instance, a flight from Los Angeles to London would have to make a stopover in New York.

In a similar vein, the introduction of $LH_2$ in aviation may provoke a thorough review of the type of aircraft that are used to serve each segment. In today's system, many routes are served by larger, longer-range aircraft with higher fuel consumption. The introduction of $LH_2$, then, could become an opportunity to reoptimize the entire air traffic system.

### Fuel cost implications

The required infrastructure for $LH_2$ in aviation ultimately is reflected in the cost of fuel to aircraft operators. This cost is also a key driver of an airplane's competitiveness.

At scale by 2040, the cost of $LH_2$ produced in Europe may be as low as US $2.60 to $3.50 per kilogram of $LH_2$ at the refueling hose.[40] The range will depend on the supply route chosen, as illustrated in Exhibit 16 below. On-site production will be cheapest if a source of competitive, low-carbon energy is close by – if an airport is located

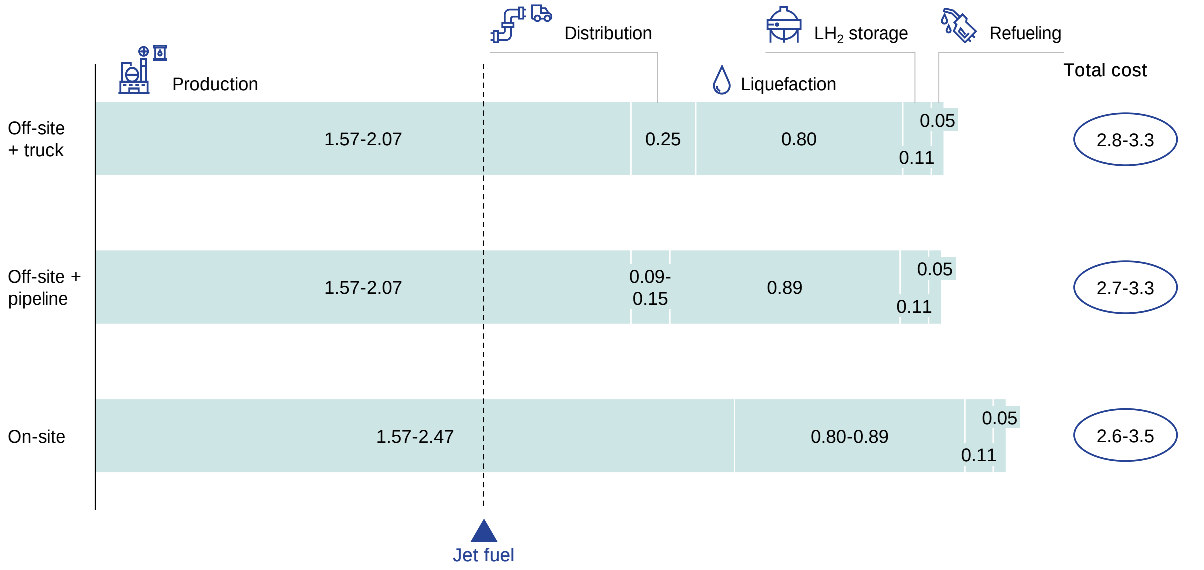
[40] The cost estimations in this chapter are built on industry projections of possible cost reductions in the production, liquefaction, distribution, and dispensing of hydrogen. They incorporate also all losses along the supply chain, including 5 percent loss on distribution, up to 4 percent loss of hydrogen in liquefaction, and other inefficiencies.

close to the shore, for instance. Off-site production and liquefaction could be competitive at a lower scale. At a larger scale, using a pipeline to transmit the hydrogen to the airport might be more cost-effective. Costs of producing hydrogen would still be more expensive than kerosene, which would cost US $1.90 per kilogram of $LH_2$ in energy-equivalent costs (assuming the flat development of kerosene costs). However, in its International Energy Outlook 2019, the U.S. Energy Information Administration (EIA)'s oil price reference case predicts that kerosene prices may increase.

Exhibit 16

## Cost overview of three hydrogen supply pathways

USD per kg of $H_2$ in 2040




If we compare likely costs of synfuel supply expressed in US $/kg of $LH_2$, we find that it would cost US $4.10 per kilogram of $LH_2$ to supply synfuel via industry $CO_2$ capture and US $6.80 per kilogram of $LH_2$ to supply synfuel via direct air capture at scale by 2040. $LH_2$ would thus be cheaper than the energy-equivalent cost of synfuel, even without considering the additional energy efficiency of fuel cells versus turbines. The main reason for this conclusion is the "well-to-tank" energy efficiency difference of the decarbonization pathways. Green $LH_2$ requires about 1.7 kilowatt hours of input energy to produce one kilowatt hour of fuel energy (supply and distribution included). For synfuel from industry $CO_2$ capture, this figure is closer to 2.8 kilowatt hours, and for direct air capture, 4.6 kilowatt hours – mainly because the process to capture $CO_2$ for synfuel production is quite energy-intensive, and further processing the hydrogen into synfuel requires an additional fuel synthesis step.

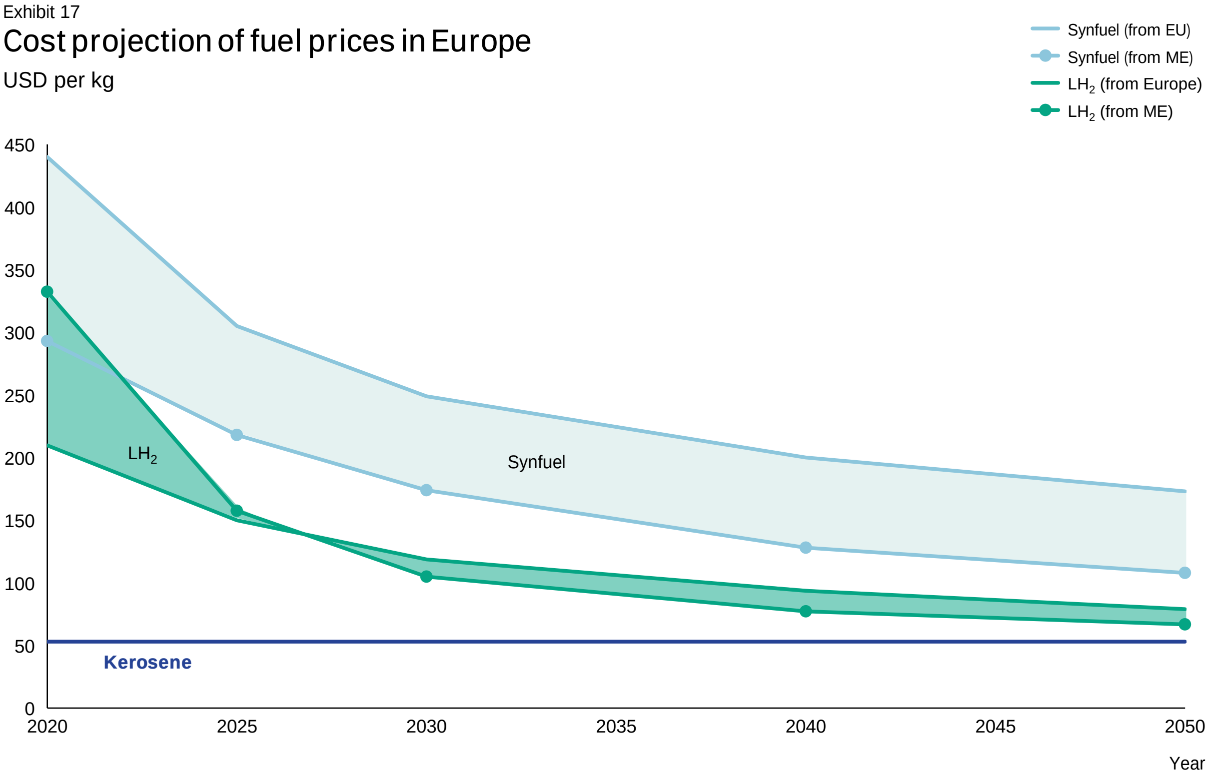
Given that both $LH_2$ and synfuel are energy-intensive to produce, one way to lower costs would be to produce in a location with access to competitive renewable energy – for instance, the Middle East. This step would lower the levelized cost of energy from US $36 per megawatt hour (MWh) for offshore wind in Europe (including grid fees) to US $14/MWh in the Middle East. For synfuel, moving production would lower the total cost of synfuel via direct air capture to US $4.30 per kilogram of $LH_2$ – down from US $6.80. $LH_2$ could also be produced more cheaply in the Middle East, but given the expected high shipping costs of about US $0.40 per kilogram, costs would only drop to about US $2.40 per kilogram of $LH_2$.

No matter the fuel type or source, over time costs are expected to fall as the supply chain scales up. This scale-up will occur thanks to manufacturing learning rates, more optimal utilization of infrastructure, and increased process efficiency. Exhibit 17 below shows the steep cost-down trajectory expected for each of the alternative fuels from different sources (landed costs at EU airports). No matter the source, alternative fuels will become increasingly competitive against kerosene today; for its part, $LH_2$ will drop from four times the cost of kerosene today to roughly the same cost by 2050.

Exhibit 17

## Cost projection of fuel prices in Europe

USD per kg



$LH_2$ price projected to drop by factor

4

from today to roughly the same cost per unit energy as for kerosene by 2050.

# 4. Roadmap: Key findings and decarbonization scenarios

Our assessment of the feasibility of hydrogen aircraft has shown that, while these aircraft require significant technological developments and changes to infrastructure, they have the potential to become a leading propulsion system for short- to medium-range flights. For long-range flights with more than 250 passengers and traveling more than 10,000 kilometers, however, the additional weight of the liquid hydrogen tank makes hydrogen propulsion an impractical choice. Unless revolutionary aircraft designs are available for long-range flights and assuming no change to current air traffic patterns, synfuels seem to be the better option in the path toward decarbonization. This chapter analyzes the factors at play in the choice between synfuels and hydrogen are analyzed.

## $H_2$ propulsion greatest potential for commuter to medium-range aircraft, synfuels for long-distance aircraft

The factors used to evaluate hydrogen and synfuels are climate impact, aircraft design, aircraft operations, airport infrastructure, fuel supply chain, and costs (see Exhibit 18).

**Climate impact**
The detailed analysis of projected climate impact in Chapter 1 emphasized that $H_2$ propulsion with fuel cell systems offers the highest reduction potential up to 75 to 90 percent, followed by $H_2$ turbines with 50 to 75 percent – both technologies do not cause $CO_2$ emissions in flight. Synfuels from direct air capture can achieve net carbon zero, but their potential of reducing climate impact is less – 30 to 60 percent.

**Aircraft design**
The switch to hydrogen requires a redesign to incorporate large, heavy $LH_2$ tanks. For commuter to medium-range aircraft, our analysis showed feasible designs, if major technology unlocks are realized. In contrast, for long-range aircraft, the heavier weight greatly increases energy consumption and thus costs. In the long-term, revolutionary aircraft designs could improve the economics for longer ranges, but their commercialization might be beyond 2050. Synfuels, on the other hand, only need to be certified and tested to be used as fuel in existing aircraft, with little or no design modifications required.

**Aircraft operations**
The most important change in aircraft operations is the refueling and the on-ground handling. Because $LH_2$ has greater volume than kerosene for the same energy content, the refueling of a $H_2$ aircraft might take up to two times longer for commuter, regional, and short-range aircraft segments and as much as three times longer for medium- and long-range aircraft, even if the aircraft has double the usual number of refueling points. This is true if we consider similar flow rates to kerosene today, but technological development may ultimately allow for higher flow rates. Handling a new fuel will also call for new safety regulations, which could potentially inhibit parallel operations. In contrast, if synfuels are certified and classified with safety precautions that are similar to those applied to kerosene aircraft, the synfuel aircraft operation for refueling and ground-handling would be comparable to kerosene aircraft operations today.

**Airport infrastructure**
Hydrogen requires infrastructure changes at airports, including the addition of $LH_2$ refueling technologies, liquefaction facilities, and liquid hydrogen storage. For the foreseeable future, $LH_2$ hydrant refueling systems seem to be technically and economically infeasible, calling for other refueling technology at scale – such as refueling trucks, mobile refueling platforms, or refueling slots away from boxes. Synfuels, meanwhile, are compatible with the existing, truck-based refueling and storage infrastructure at airports.

Exhibit 18

## Comparison of hydrogen technology and synfuel

Major advantages (shaded teal) / Major challenges (shaded grey)

| | $H_2$ fuel cell | $H_2$ turbine | Synfuel |
|---|---|---|---|
| Climate impact | 75-90% reduction | 50-75% reduction | 30-60% reduction[1] |
| Aircraft design | Only feasible for commuter to short-range segment | Feasible for all segments except for flights >10,000km | Only minor changes |
| Aircraft operations | 1-2x longer refueling times for up to short-range | 2-3x longer refueling times for medium- and long-range | Same turnaround times |
| Airport infrastructure | $LH_2$ distribution and storage required | | Existing infrastructure can be used |
| Fuel supply chain | 1.7x energy[2] required for fuel production | | 4.6x energy[3] required for fuel production |
| Cost comparison between $H_2$ and synfuel | Lower for commuter to short-range aircraft | Lower for medium-, higher for short-range aircraft | Higher than $H_2$ aircraft for commuter - medium-range |

1. $CO_2$ from direct air capture assumed
2. Assuming PEM electrolysis, compression, pipeline transport, liquefication, storage and distribution
3. Assuming PEM electrolysis, $CO_2$ direct air capture, synthesis, pipeline transport, and distribution

### Fuel supply chain

$LH_2$ production is more efficient than synfuel production. $LH_2$ has a high "well-to-tank" efficiency of approximately 60 percent. Synfuels using $CO_2$ from direct air capture have a low "well-to-tank" efficiency of approximately 20 percent, which means that their production requires about three times as much input energy as liquid hydrogen fuel. Consequently, when compared to the direct usage of $LH_2$ in aircraft propulsion, a significantly larger scale-up of green energy sources would be required for synfuels to decarbonize aviation. This is a critical shortcoming of synfuels in a global setting, especially since renewable energy capacity may not be installed equally in all regions by 2050.

### Cost comparison between hydrogen and synfuel

The total costs of ownership for $H_2$ aircraft operations were assessed, with detailed analyses of fuel and related infrastructure costs, the increased cost of aircraft, and other operational costs. In 2040, the cost difference between the envisioned hydrogen aircraft and a conventional aircraft could be as little as 25 percent for short-range flights. For a flight from Brussels to Athens on a typical 165-seat airplane, this additional operational cost could amount to about US $15 to $20 per ticket. This added amount would cover all costs and savings along the value chain – the production of required energy, fuel distribution, the cost difference in aircraft operations, additional costs per airplane, and the resulting energy efficiency of the aircraft. These incremental costs are lowest for short-distance segments. In the medium-range segment, the cost difference climbs to 35 percent, driven by the addition of larger and heavier tanks and even up to 50 percent for long-range aircraft. Compared to $H_2$ aircraft TCO, synfuels from direct air capture come with higher TCO for commuter to short-range segments, about equal TCO in the medium-range, and potentially lower TCO for long-range segments (Chapter 2).

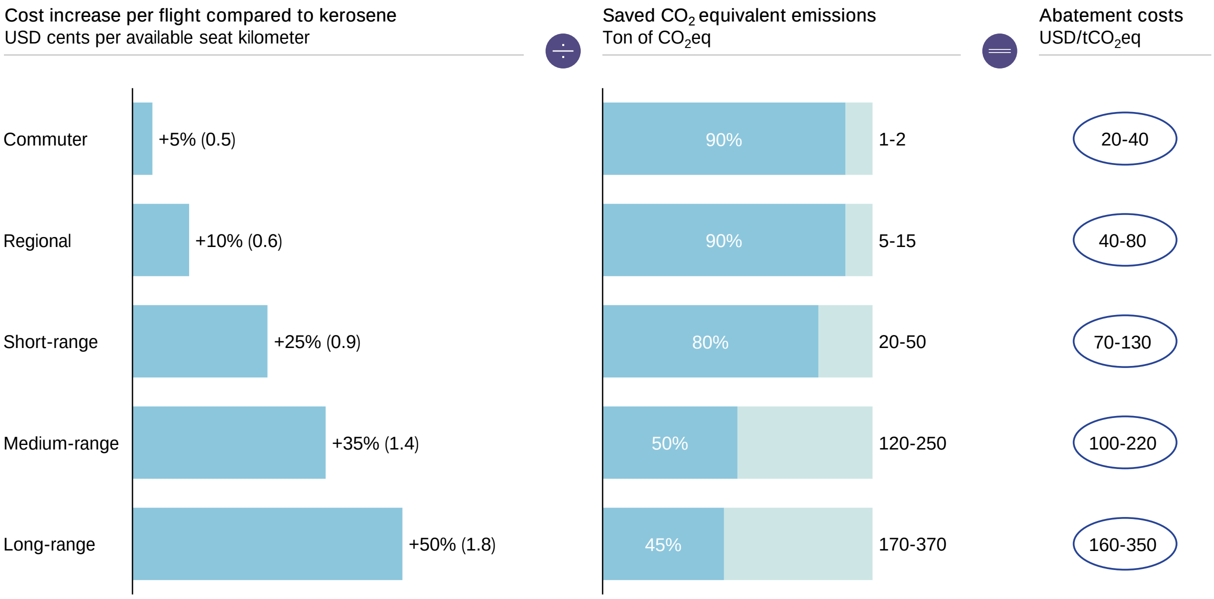
## Economically, $H_2$ propulsion could trump synfuels for short and medium distances in abating climate impact

A fair cost comparison between hydrogen and synfuels must consider both technologies' total climate impact and not only $CO_2$ emissions. (See the box on page 56) The additional costs related to a reduction in $CO_2$ equivalent climate impact are called "climate impact abatement costs" (Exhibit 19).

Exhibit 19

### Added costs and reduced emissions compared to kerosene in 2040

COSTS SHOWN FOR 2040 NUMBERS SHOWN FOR AVERAGE CLIMATE IMPACT




Since hydrogen propulsion would necessitate segment-specific new aircraft designs and changes in performance, the abatement costs associated with using $H_2$ differ by segment. Synfuels would not require changes in aircraft design and come with the same price premium of fuel per kilogram consumed for each segment, so their abatement costs only depend on the reduction of climate impact per segment.

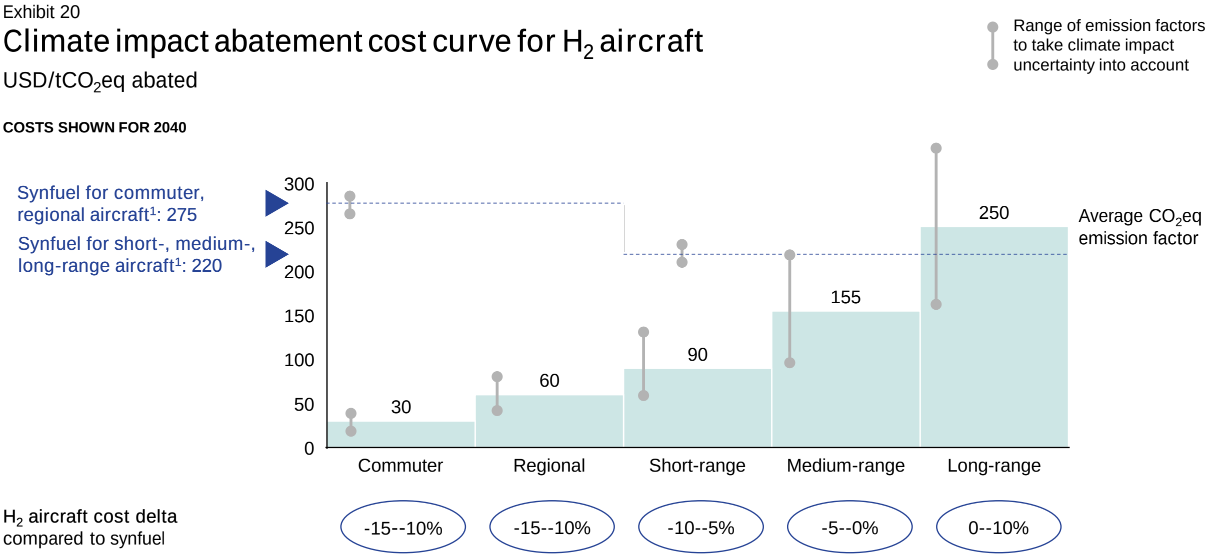
For short-range segments, abatement costs for hydrogen propulsion could be as low as US $70 to $130 per ton of $CO_2$-equivalent saved in 2040 (Exhibit 20). For commuter aircraft, these costs could be as low as US $20 to $40 per ton of $CO_2$ equivalent. To put these figures into perspective, evaluations of a 1.5-degree scenario expect that the social cost of carbon could reach US $170 to $250 per ton of $CO_2$ equivalent in 2040-2050. Hydrogen's abatement costs would be well within this range for shorter-range aircraft. Even for a medium-range aircraft, the $CO_2$ equivalent abatement costs would still be competitive at US $100-$220 per ton of $CO_2$ equivalent saved. Synfuels from direct air capture on the other hand – not requiring modifications to the aircraft or fuel distribution systems – come with abatement costs of US $210 to $230 per ton of $CO_2$ equivalent abated for short- to long-range aircraft.

For long-range segments, though, abatement costs for synfuels are likely to be more economical than those for $H_2$ propulsion: $H_2$ long-range aircraft would abate climate impact at US $160 to $350 per ton of $CO_2$ equivalent abated.

Exhibit 20

## Climate impact abatement cost curve for $H_2$ aircraft

USD/t$CO_2$eq abated




1. Synfuel costs depend on climate impact – no contrail and cirrus formation assumed for commuter and regional aircraft.

The cost assessments shown here at scale assume that hydrogen propulsion (and synfuels) has been widely adopted, and that the needed infrastructure and fuel supply system are available and properly utilized. In the years leading up to this change, costs per flight and costs per ton of carbon abated will be significantly higher. Chapter 3 describes the required investments and challenges for this transition in more detail.

The comparison above uses synfuels that are "net-neutral" on $CO_2$. This means that, during their production, as much $CO_2$ is extracted from the atmosphere as is burned later in the turbine. One alternative to this practice is to use carbon that is captured from industrial processes. Such synfuels are not net-carbon-neutral, because the carbon cycle is not closed – i.e., the emitted carbon ends up in the atmosphere. The carbon is "recycled" for one more use in the aircraft. To illustrate, if we assume that 50 percent of the abatement is counted towards use in the airplane, such synfuels would cost about US $1.00 per kilogram (compared to US $1.60 per kilogram), and the abatement cost would drop to US $130 to $150 per ton of $CO_2$ equivalent. Such synfuels would then only reduce about 15 to 35 percent of $CO_2$ equivalent climate impact for that flight, with the rest requiring offsets. This scenario is obviously only a feasible option if there are carbon-emitting industrial processes at a sufficient scale and in the right location for synfuel production. Such synfuels could serve as a "bridge" in the transition to decarbonization, but ultimately their cost-effectiveness depends on the cost development of direct air capture compared to the cost development of offsets.

## Abatement cost sensitivity analysis

The economics and abatement costs associated with hydrogen and synfuels in this report are projections and sensitive to several input factors. The most critical sensitivities are the cost of liquid hydrogen, aircraft CAPEX and turbine lifetime, and their impact on refueling times. These could alter the results, but not so radically that they would fundamentally change the results as illustrated below.

**Cost of liquid hydrogen:** The report assumes an $LH_2$ input price of US $2.60 per kilogram for hydrogen shipped to the EU from the Middle East. If the hydrogen was produced in Europe, it could cost up to US $3.00 per kilogram at the nozzle. $CO_2$ equivalent abatement costs for a short-range aircraft would increase by 20 percent, for example.

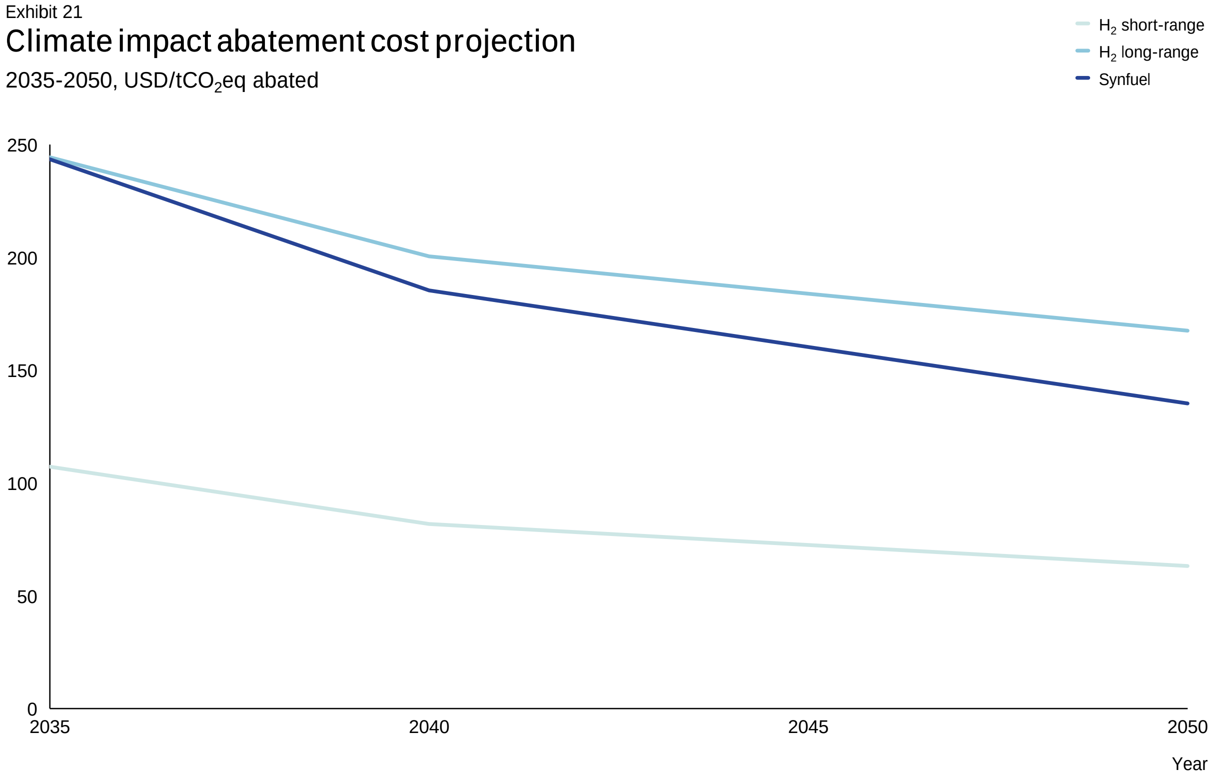
**Aircraft CAPEX and turbine lifetime:** A 10 percent increase in the CAPEX of short-range hydrogen aircraft would result in a 12 percent increase in $CO_2$ equivalent abatement costs. Furthermore, an increase of 10 percent in the current $H_2$ turbine lifetime of 30,000 hours would decrease $CO_2$ equivalent abatement costs by 2 percent.

**Impact on refueling times:** An increase in $LH_2$ refueling time from 20 minutes to 30 minutes for a short-range aircraft results in a 9 percent increase in $CO_2$ equivalent abatement costs.

Exhibit 21

## Climate impact abatement cost projection

2035-2050, USD/$tCO_2$eq abated



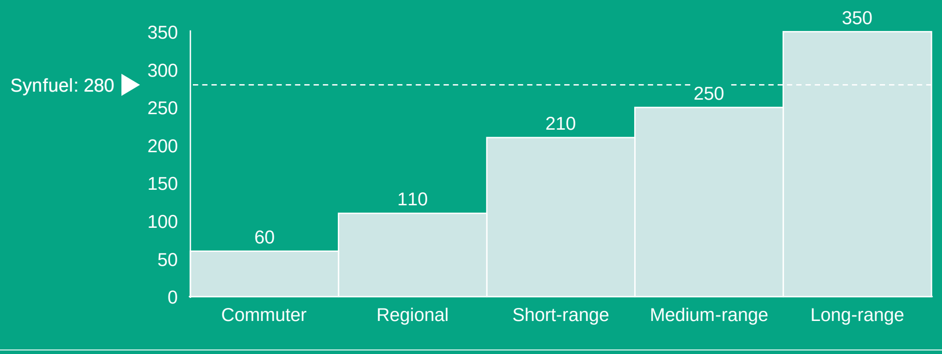

Finally, our analysis assumes a timeframe of 2040. The $CO_2$ equivalent abatement costs in 2050 could potentially be lower – as shown in Exhibit 21 – as scaling and the lessons of experience lead to reductions in $LH_2$ costs, as well as slightly lower hydrogen storage and propulsion costs. Similar cost reductions could be achieved for synfuel.

# $CO_2$ abatement costs

Exhibit 22

## $CO_2$ abatement cost curve for $H_2$ aircraft

USD/t$CO_2$ abated




Since aviation is currently measuring $CO_2$ emissions only, hydrogen propulsion and synfuel from direct air capture would both ensure a full decarbonization of aviation.[41] Nonetheless, hydrogen propulsion would still be a more economic choice than synfuels for commuter to medium-range aircraft. The abatement costs associated with an $H_2$-powered commuter aircraft would be US \$40 to \$80 per ton of $CO_2$, and a regional aircraft would have abatement costs of US \$90 to \$135 per ton of $CO_2$.

A short-range aircraft's abatement costs would range from US \$170 to \$250 per ton $CO_2$. At US \$200 to \$300 per ton of $CO_2$, an $H_2$-powered medium-range aircraft's abatement costs might be less expensive or roughly equal to those of a synfuel-powered craft, at US \$280 per ton of $CO_2$. An $H_2$-powered long-range aircraft, however, would be more expensive than a synfuel-powered one at US \$280 to \$420 per ton of $CO_2$ (Exhibit 22).

[41] Synfuels from direct air capture are the focus here, as the debate is still ongoing about accounting for $CO_2$ emissions from industrial $CO_2$ capture and the risk of double-counting abatement costs.

## Scenarios for hydrogen's role in the decarbonization of aviation shows the abatement potential could be 45-50 percent by 2050

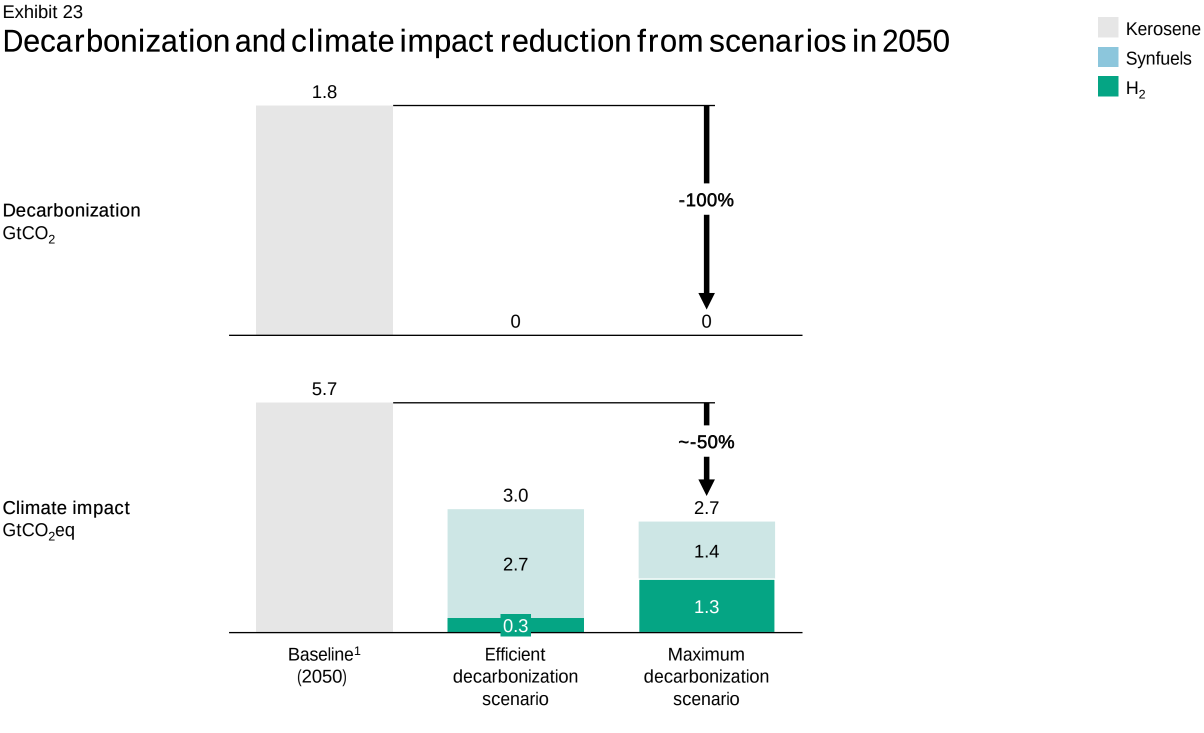
Having illustrated the potential of $LH_2$ to decarbonize aviation in a cost-competitive way, the key question remaining is how much of greenhouse gas emissions related to aviation could possibly be abated with the help of hydrogen. As discussed in the chapter on infrastructure implications, based on the conceivable entry-into-service dates of various liquid hydrogen aircraft designs, we have projected two possible $H_2$ aircraft ramp-up scenarios.

In the efficient decarbonization scenario, hydrogen would replace aircraft in the commuter to short-range segment and 50 percent of the medium-range segment as the most cost-efficient means of decarbonization after initial entry-into-service. At typical replacement rates, 40 percent of all aircraft would switch to $LH_2$ by 2050; the remainder would be powered by synfuels and/or biofuels.

In the maximum decarbonization scenario, all planes that could technically be replaced by hydrogen-powered aircraft would be replaced at the earliest possible entry-into-service date. In this case, 60 percent of all aircraft would switch to $LH_2$ by 2050 at standard replacement rates, while the remainder would be powered by synfuels and/or biofuels.

Exhibit 23

### Decarbonization and climate impact reduction from scenarios in 2050




1. Including anticipated efficiency improvements of 2% p.a.

Based on the above scenarios, we can estimate the size of the potential $CO_2$ equivalent abatement in hydrogen-powered aviation future (Exhibit 23). Taking into account different technologies' estimated, full $CO_2$ equivalent impact, the efficient decarbonization scenario would reduce 1.8 gigatons of $CO_2$ emissions projected in 2050 and total $CO_2$ equivalent emissions by about 2.7 gigatons. This reduction is 45 percent greater than the reduction expected in a baseline scenario, in which only efficiency improvements are made to airplanes. In the maximum decarbonization scenario, $CO_2$ equivalent emissions would fall by about 3.0 gigatons, a 50 percent reduction compared to the baseline scenario in which only efficiency improvements are made to conventional aircraft. In both cases the carbon reduction targets from the EU and ATAG would be achieved.

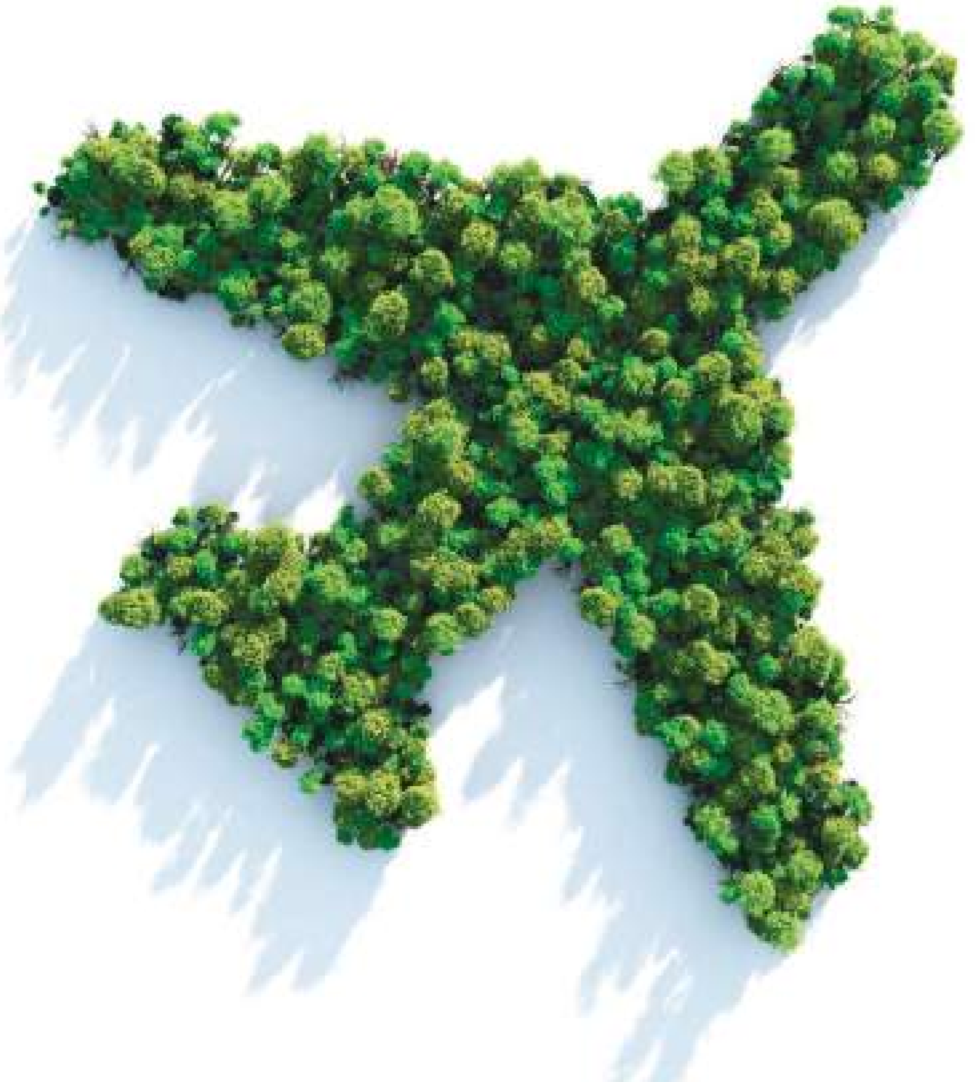
In 2050, the efficient decarbonization scenario would come at an increased TCO for the aircraft fleet of about 27% versus the baseline scenario using conventional airplanes – not taking into account potential carbon taxes on conventional fuel propulsion. Total aircraft fleet TCO if we replaced the entire fleet with synfuel would be roughly similar, but would have 15 percent lower abatement potential. The total aircraft fleet TCO of the maximum decarbonization scenario would be 31% higher than the baseline scenario, but this would buy 10 percent more abatement potential compared to the efficient decarbonization scenario.

The carbon reduction targets from the EU and ATAG could be achieved.

While these scenarios illustrate $LH_2$'s potential role in the decarbonization of the aviation sector by 2050, they also show that, even if $LH_2$ aircraft replaced 100 percent of aircraft in all segments from the first conceivable entry-into-service date plus manufacturing ramp-up, only 60 percent of the total fleet would be replaced by 2050. The rest would have to be powered by synfuel, biofuel or another sustainable aviation fuel. Consequently, while full decarbonization is achieved, the climate impact of the aviation sector will remain significant.

The only way to achieve a 100 percent penetration of $LH_2$-powered aircraft by 2050 is to overproduce planes at much greater rates than current replacement rates, which would lead to an over-supply of airplanes by 2050. Assuming this situation is to be avoided, a full fleet replacement with $LH_2$-powered planes could be achieved by ~2060. The sector's $CO_2$ equivalent abatement could then approach nearly 65 percent. Zero climate impact could not be achieved via hydrogen propulsion, nor is there any other conceivable cost-technically feasible technology that could ensure zero climate impact from aviation.

Whichever pathway is chosen, $LH_2$ clearly has the potential to significantly decarbonize aviation and reduce its climate impact. Yet the projected scenarios also illuminate the formidable challenges the industry must overcome to reach its decarbonization goal. We turn to the research agenda to tackle some of these critical challenges next.



# 5. Recommendations: Advancing $H_2$-powered aviation

As this report has shown, hydrogen propulsion has the potential to be a significant part of the propulsion mix by 2050 and to play a key role in the decarbonization of aviation. To do so requires a step-up in research, innovation, and development activity to develop the underlying technologies, integrate them into airplanes, and develop the necessary infrastructure. These research activities will also yield better insights into the feasibility, economics, and climate impact of future technologies. They will address many of the uncertainties identified in this study, validate and invalidate the taken assumptions, and help to refine this roadmap towards decarbonized aviation.

## The need to act now

There is an urgent need to act now. Depending on the size of the aircraft the introduction of larger new aircraft typically takes around 15 to 20 years, and broad deployment across the fleet another 10 years. The last generation of short-range aircraft, responsible for roughly one quarter of total climate impact of the sector, was introduced around 2015 (e.g., the A320neo family of aircraft). This opens a window of opportunity between 2030 and 2035 for a new, decarbonized aircraft in this segment. The next generation in this segment would then be expected only between 2045 and 2050 which would be too late to achieve the decarbonization objectives for this segment set by the EU and ATAG targets. Regional and/or commuter pilots could be introduced before, and the short-range aircraft could become a stepping stone towards introduction in medium-range aircraft (see Chapter 4).

Three aspects are required to guide this transition for the sector:

1. A sector roadmap to guide the transition

2. A step-up in Research & Innovation (R&I) activity and funding

3. A long-term policy framework

The sector roadmap needs to set clear ambitions, align standards, coordinate infrastructure build-up, overcome market failures, and encourage first movers. An inspiring mid-term target could be, for example, the introduction of a $H_2$-powered short-range aircraft before 2035. The long-term policy framework should lay out the rail guards for the sector, including how climate impact will be measured and the roadmap will be implemented. The European Union could first target commuter, regional, and short-range flights as they are covered within its jurisdiction, and then expand this to medium- and long-range aircraft together with its international partners.

The R&I activities both lay the groundwork for the sector roadmap and long-term policy framework, as well as spur the technology development required to bring hydrogen aircraft into service.

## Research and innovation roadmap

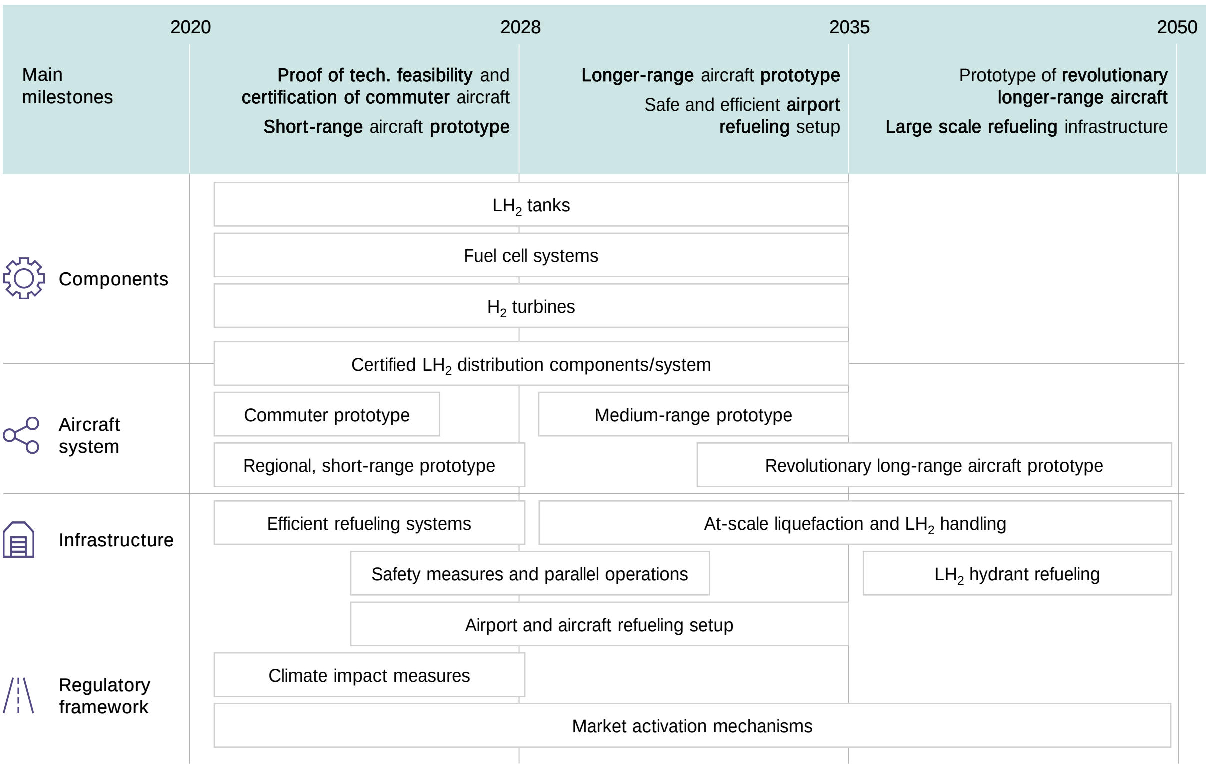
Based on the feasibility analysis of the technology, the critical cost drivers, uncertainties and barriers to introduction, the following R&I roadmap has been derived (see Exhibit 24). It is structured in four areas: the development of key $H_2$ propulsion components, the development of $H_2$ aircraft systems (including new aircraft designs), addressing infrastructure barriers, and establishing a governance framework. All of these areas include certification and standardization aspects as major enablers for clear guidance in R&I and require the involvement of civil aviation certification authorities. Key activities occur in three phases:

- The objective in years 2020 to 2028 is to develop the technology fundamentals, bring commuter aircraft to certification, pilot hydrogen aircraft in regional and short-range segments, and create the roadmap and underlying body of work for regulations on everything from safety to market activation mechanisms.
- In the second phase from 2028 to 2035, R&I activities should focus on scaling up these components, applying them to medium-range aircraft, and getting them ready for entry into service, as well as preparing the second wave of hydrogen aviation, which includes a safe and efficient airport refueling setup.
- In the long-term from 2035 to 2050, concepts and first prototypes for medium- and possibly long-range segments, including new revolutionary aircraft designs and new technology for large scale fuel supply and fast refueling, must be developed.

The following sections detail out the areas for research in each of these research areas.

Exhibit 24

### Research & Innovation roadmap – 4 main research areas




## Component engineering: Safe and reliable $LH_2$ storage, distribution, and propulsion

The immediate priority for components is to develop and engineer lightweight tank systems, reliable fuel distribution components, $H_2$ propulsion turbines with low-$NO_x$ emissions and long lifetimes, and high-power fuel cell systems. To guide research and development, certification requirements must be decided for each component.

### Lightweight and safe $LH_2$ tanks

**Objective:** Decrease weight of $LH_2$ tanks to enable more efficient $H_2$-powered aircraft and better economics – potentially enabling competitive economics for long-range aircraft

**Target:** 35% gravimetric index for short-range (5 tons of $LH_2$ stored), 38%+ for long-range aircraft (more than 30 tons of $LH_2$)
Cost target in 2050: <550 US $/kg $LH_2$

**Where we are today:** 15-20% gravimetric index (for tank with less than one ton of $LH_2$)

**Research timeline:** For short-range in the next 5 years, longer-range aircraft in next 10 years to ensure on time development of first aircraft prototypes

The $LH_2$ tank with appropriate volume and weight is a key enabler of technologically feasible and economic $H_2$-powered aviation. A sensitivity analysis shows how the economics depend on the gravimetric tank index. This is especially important for the long-range segment: an index increase from 38 percent to 55 percent would make $LH_2$-powered aircraft competitive with synfuel-powered aircraft thanks to a 44 percent decrease in $CO_2$ equivalent abatement costs.

To achieve a gravimetric index of 35 percent for a short-range aircraft and 38 percent or more for a long-range aircraft, the R&I of $LH_2$ tanks needs to link strongly to that of aircraft manufacturers and certification authorities. It should focus on:

- Synergistic tank design and integration into fuselage – testing new and also non-cylindrical or spherical shapes as well as advanced materials for safe and light tank walls.
- Safety and certification procedures and requirements adapted to $LH_2$ tank standards including specified boil-off requirements for on-ground handling. If no or reduced boil-off requirements on ground can be adjusted to still ensure safe ground handling or storage of aircraft, tank walls could be built lighter.
- Reliable components with focus on cooling equipment such as cryogenic pumps, pipes, and valves, and sensors including condition-monitoring capabilities. These components and the tank walls should also be designed to last at least as long as the aircraft's lifetime, with the least amount of maintenance possible.

### On-board $LH_2$ distribution components and system

**Objective:** Ensure a kerosene level of safety and reliability for $LH_2$ distribution

**Target:** Safe, certified distribution architecture with minimized weight and maintenance costs

**Where we are today:** Pilots exist, no designs for commercial aircraft standards yet

**Research timeline:** For short-range in the next 5 to 8 years, longer-range aircraft in next 10 to 15 years to ensure on time development of first aircraft prototypes

Safe, reliable, and redundant $LH_2$ fuel distribution is the key to ensure feasibility and certification of $LH_2$-powered aircraft. Cryogenic fuels have never been used in commercial aviation so far – in an environment where safety, low weight, and a long lifetime is very important. Since hydrogen is stored in liquid form but must be injected into the fuel chamber in high-pressure, gaseous form, the architecture must be designed to handle the vaporization of the hydrogen. $LH_2$ fuel system and component manufacturers together with certification authorities should focus on:

- **Safe and light $LH_2$ fuel components** such as double-insulated fuel pipes with cryogenic cooling, compressors, and heat exchangers.

- **Reliable and optimized $LH_2$ system layout** with redundancy, highly durable components, leakage and venting management, and optimized point of vaporization – including **certification procedures** adapted to $LH_2$ equipment standards.

The above-described components and architecture design must ensure that maintenance costs are kept as low as possible.

### High-power, lifetime-optimized fuel cell system, including cooling concepts

**Objective:** Enable the use of fuel-cell propulsion since it has higher potential to reduce climate impact than $H_2$ combustion

| | |
|---|---|
| **Target:** 1.7 kW/kg for up to regional aircraft (<5 MW), 2 kW/kg for short-range and larger aircraft<br>Cost target in 2050: <250 US $/kW | **Where we are today:** ~0.75 kW/kg power density on system level (incl. balance of plant) |

**Research timeline:** In next 5 years for regional and short-range, until 2035 for longer-range aircraft as hybrid propulsion concept

Research on how to increase the power density of fuel cells by threefold is crucial for larger fuel-cell aircraft designs. If fuel cells' power density cannot be increased, the energy-saving potential of the concept studies on commuter, regional, and short-range aircraft cannot be realized.

A major limiting factor of fuel cell systems with higher installed power – more than 10 to 20 megawatts – is the resulting rise in heat, which requires large, heavy heat exchangers to cool the system. Consequently, fuel cell manufacturers should focus on:

- **Scaling of systems** through synergies in weight and cooling due to potentially optimized modularization, higher operating temperatures, and light heat exchangers.

- **Reliable components** with an extended lifetime (of about 25,000 operating hours or more) by optimizing operation regimes, and using lightweight materials.

- **In-flight $H_2O$ treatment** on-board in order to minimize climate impact.

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### Highly efficient, low-NOx-emitting $H_2$ combustion turbine

**Objective:** Optimize energy demand and climate impact of $H_2$ turbine combustion to ensure economics

**Target:** ~40-50% efficiency while reducing 50-80% of $NO_x$ emissions
Cost target in 2050: <115% compared to kerosene

**Where we are today:** ~35-40% efficiency

**Research timeline:** In next 5 years for short-range, until 2035 for longer-range aircraft

$H_2$ turbines with high combustion efficiency, lower $NO_x$ emissions, and a reliable, long-lasting turbine are required to make hydrogen aircraft for short-range, mid-range, and long-range aircraft a reality. Higher efficiencies and reliability enable economic competitiveness, while lower $NO_x$ emissions improve climate impact. Engine manufacturers should develop:

- **Combustion chambers** with new designs tailored to hydrogen's combustion properties, cryogenic compressors, and optimized fuel inflow.
- **Control system** tailored to $LH_2$ properties to regulate fuel flow and lean injection technology to reduce $NO_x$ emissions. Substantial research projects such as ENABLEH2 (EU-funded) are already investigating the potential of new lean-mix technology for $H_2$ turbines.
- **Cooling system** for high-temperature turbine stages by using cold hydrogen flows to further increase efficiency.

## $H_2$ aircraft system: Efficient, reliable system architecture and prototype development

Once developed and tested, the above-described components need to be integrated into a **$H_2$ aircraft system.** The priority in this area is to develop safe, reliable fuel distribution for both routine and critical conditions. The fuel distribution system should then be integrated into an airframe with $LH_2$ tanks in a manner that maximizes efficiency. Only in this way can $H_2$ aircraft achieve competitive operational costs (e.g., aircraft CAPEX and maintenance costs).

Toward the end of the initial phase, the aviation industry should create a prototype for short-range and smaller aircraft and work closely with various authorities during development to ensure the prototype's certification. In the medium term (2028-2035), the component and aircraft system development and prototyping must also be applied to larger aircraft (e.g., the mid-range and some of the long-range segments). For all segments it will be critical to develop and ensure certification-ready prototypes with an overall focus on airframe designs with highly efficient aerodynamics and lightweight structures that enable a modular integration of safe, reliable hydrogen components which also minimize maintenance lead times.

### Commuter prototype

**Objective:** Proof of $H_2$ aircraft concept and establishment of certification and standardization for $H_2$ propulsion

**Target:** Commuter prototype, first standardization of $(L)H_2$ certification

**Where we are today:** First $H_2$ demonstrators in general aviation segment

**Research timeline:** 2020-2025

With a prototype in the commuter segment, $H_2$ propulsion components and a safe, reliable integration of the $H_2$ system will be developed and tested in real flight conditions. For a faster development and early testing, gaseous hydrogen for propulsion of such smaller aircraft could also be used. In parallel, airframe and system development should focus on more radical designs such as distributed propulsion, test the aerodynamics and evaluate efficiency benefits.

### Regional, short-range prototype

**Objective:** Evaluate technological feasibility and economics of $H_2$-powered aviation in regional and short-range segments as a stepping stone for commercialization

**Target:** Regional and short-range prototype in TRL 6 and ready for certification

**Where we are today:** N/A

**Research timeline:** 2020-2028

Since this short window of opportunity necessitates rapid development of $H_2$ propulsion components, demonstrations should have the scale of a regional or short-range aircraft so that relevant safety features can be tested as soon as possible. A well-known aircraft platform (e.g., Bae 146, ATR 72, Airbus A320) could be used to first

develop and test the components independently as part of a conventional system and then be integrated as a system into a new, optimized airframe. Developments in the hybrid-electric field showed a similar approach: Airbus and Rolls Royce built the E-Fan X demonstration based on a Bae 146 aircraft with four engines, with one engine replaced by an electric-powered engine. After successfully finishing such demonstrations, a full evaluation of $H_2$ propulsion's potential (including economic factors such as efficiency, lifetime of components, etc.) should be conducted to ensure certification and mitigate the risk of new aircraft design. Compared to the commuter prototype it will be important to prove the scalability of the $LH_2$ components for larger megawatts and several tons of $LH_2$ storage. Therefore, the suggested hybrid propulsion architecture should be developed and expected efficiency improvements and improved economics validated.

### Medium-range prototype

**Objective:** Proof of large scale $LH_2$ aircraft concept and economic feasibility

**Target:** Medium-range prototype in TRL 6 and ready for certification

**Where we are today:** N/A

**Research timeline:** 2028-2035

In the medium-range segment, an $LH_2$-powered prototype would be required to demonstrate the feasibility of high-power $H_2$ turbines and very large scale $LH_2$ tanks integrated in front and behind the passenger cabin. It will be key to achieve synergistic fuel tank designs integrated into the fuselage and further ensuring safe and economic operation.

### Next revolutionary generation of aircraft

**Objective:** Further exploit energy efficiency and better economics with more aerodynamically efficient aircraft concepts

**Target:** Revolutionary (medium-) and long-range aircraft demonstrated before 2050

**Where we are today:** First concepts existing from e.g., Airbus, NASA, TU Delft

**Research timeline:** Focus years 2028-2035 for short-range, until 2050 for longer-range aircraft

Over the medium and long term, the industry could develop an aircraft system that is based on energy-optimized, certification-ready, radical designs. These designs could lead to a new wave of more efficient, economical $H_2$-powered aircraft. But developing a new propulsion system and completely new airframe, with significant changes in aerodynamics, will take a great deal of time. This effort must address:

- Revolutionary design fully tailored and optimized to specific properties, the constraints of hydrogen propulsion, and the integration of a pressurized passenger cabin.


- **Prototypes and flight-testing** to validate simulated aerodynamic and propulsion efficiency improvements as well as aircraft controllability.

- **Manufacturing** chain adapted and ready for scaled up production of radically new concepts.

New certification guidelines will be needed for both the integration of the new propulsion system and for the new aerodynamic principles. Moreover, aircraft manufacturers will have to take on additional risk as they make substantial investments in this new aircraft, as it will completely change aircraft design, aircraft families, and manufacturing. However, the significant increases in energy efficiency and cost savings afforded by such a design could offset this risk.

## Refueling infrastructure: Refueling systems, safety, and liquefaction

Another key to unlocking the potential of $LH_2$ aviation is developing the necessary refueling infrastructure. Most of the required technologies are commercially available today, so the challenge lies mainly in scaling and building parallel infrastructures during the transition to new aircraft systems. Nevertheless, some critical R&I challenges need to be resolved. The outcome of tackling these challenges could “make or break” the competitiveness of $LH_2$ flight.

In the short term, new refueling strategies and technologies must accelerate the refueling process to compete with conventional refueling rates. At the same time, the industry must establish bespoke safety measures for $LH_2$ and review their potential impact on parallel operations. The airport refueling set-up may also need to be reviewed in light of parallel infrastructure needs.

Over the medium and long terms, installing at-scale $LH_2$ supply and liquefication at airports will be a key R&D challenge. In the longer term, it may prove fruitful to explore if and how $LH_2$ hydrant refueling systems could play a role in at-scale $LH_2$ refueling.

### Efficient refueling systems

**Objective:** Reduce $LH_2$ refueling times to minimize impact on turnaround times

| | |
|---|---|
| **Target:** >1,000 liters per minute | **Where we are today:** ~500 liters per minute |

**Research timeline:** 2020-2028

Because longer turnaround times greatly increase costs, research into more efficient refueling systems is critical. Merely extending turnaround times by 10 minutes could increase the cost of a short-range flight by 2 percent. R&D should focus on ways to optimize flow rates through $LH_2$ hoses and ensure that refueling can initially achieve flow rates comparable to kerosene (900 liters/minute) or even higher. This will require research in at least 4 areas:

- **Hose designs** that allow for maximum flow rates while keeping weight of insulation low and maneuverability optimal (especially if they go above 1,000 liter per minute).

- **New, more efficient hose connection** systems to ensure compatibility with unconventional tank set-ups (e.g., overhead, from the top) and ensure reliable, safe connections through self-closing quick couplings.

- **Automation** incl. experimentation with autonomous, mechanically-enabled hoses and/or exoskeletons. While current flow rate may not require this, hoses with flow rates well above 1,000 liters/minute could be enabled by such solutions.

- **Optimal aircraft refueling set-up and handling standards**, especially given the fact that lengthier refueling times are likely, even with additional hoses.

**Safety measures and parallel operations**

**Objective:** Ensure adequate safety standards for $LH_2$ refueling while minimizing impact on turnaround times

**Target:** Enabled parallel operations maintaining same minimal tolerance for incidents as today

**Where we are today:** N/A

**Research timeline:** 2024-2032

As turnaround time is critical to competitiveness, the potential impact of a worst-case refueling event around the airplane, as well as the required safety (i.e., ignition-free) zone around refueling operations, should be better understood. Having this knowledge will help to determine which operations can take place in parallel during aircraft turnarounds.

Priority research topics concerning safety measures and parallel operations include:

- **Scan of potential safety issues**, including leakages during refueling and the range of potential impacts.

- **Leakage management** and countermeasures that can allow parallel operations during turnaround.

- **Safety standards and regulations**, including a new regulatory framework to guarantee safe handling and refueling with $LH_2$.

- **Required ignition-free zone around $LH_2$ refueling equipment** and safety buffer zone to assess whether parallel operations during turnaround can be allowed.

Ultimately, two questions must be answered: what safety standards are needed to guarantee the same, minimal tolerance for failures that is in place today; and could passengers board while other airplane services are in operation.

### Airport and aircraft refueling set-up

**Objective:** Develop a refueling infrastructure with minimal disruptions to current airport operations

**Target:** Refueling truck concept fully optimized for airport refueling commercially available by 2030; at-scale modular refueling setup able to operate in parallel with existing refueling infrastructure at airports by 2035

**Where we are today:** $LH_2$ refueling trucks designed for long-distance transfer with low boil-off

**Research timeline:** 2024-2035

In the short term, $LH_2$ refueling trucks will be able to serve aircraft at smaller regional airports directly. With some potential adaptations to hose (connection) systems, current systems are adequately set up to enable early innovation. But in the longer term, alternatives may be needed to curtail interference with on-ground operations and the existing airport refueling infrastructure. This raises the following research topics:

- Optimized refueling truck concept: Smaller airports could continue to rely on $LH_2$ refueling trucks, but research is needed to develop $LH_2$ refueling truck concepts optimized for at-airport refueling operations – including updates to hose connection systems, new safety standards, etc.

- Modular set-up, including the optimal organization of ground operations and infrastructure to allow parallel refueling systems. For instance, would an airport need to be divided into different zones.

At-scale refueling systems: The cost of $LH_2$ hydrant refueling systems would be at least five times the current cost of hydrant refueling systems, making them cost-technically infeasible, at least until 2040. The question to explore, then, is which systems could serve larger airports' $LH_2$ refueling needs at scale. Automated refueling trucks with mechanically operated refueling hoses, mobile refueling platforms, and refueling lots away from the plane are all options.

### At-scale liquefaction and $LH_2$ handling

**Objective:** Optimize distribution infrastructure to supply airports with lowest-cost $LH_2$ in most efficient way

**Target:** $LH_2$ available at <100 US $/MWh by 2030; and <60 US $/MWh by 2050

**Where we are today:** $LH_2$ available at >200 US $/MWh

**Research timeline:** 2028-2050

Fuel costs will play a fundamental role in determining the competitive viability of $LH_2$ aviation. While aviation's hydrogen demand will increase hydrogen demand overall only by about 10 to 25 percent in our scenarios, the demand for liquid hydrogen could grow by multiples, requiring an unprecedented scale-up in liquefaction capacity. This scale-up will be a critical sensitivity in fuel competitiveness; if liquefaction costs could be reduced by another 10 percent by 2040, fuel cost could be reduced by another US $1.50 per megawatt hour versus US $77.20 per megawatt hour projected. This would in turn make an average short-range flight 1 percent cheaper. R&D could help the industry greatly improve efficiency and reduce CAPEX. We see three priority research areas:

- **Liquefaction equipment efficiency** and CAPEX through improved designs, large-scale manufacturing setups, and optimized sourcing.

- **Optimization of $LH_2$ supply**: Beyond optimizing liquefaction, the competitiveness of $LH_2$ aviation will also hinge on supplying airports efficiently. In many locations, supplying with trucks may not be optimal, as the resulting congestion might compromise safety. In these cases, a dedicated gaseous hydrogen pipeline network could be set up, or old gas pipelines could be retrofitted, but pipelines would have to be sufficiently utilized to recoup the cost of these measures. In parallel, this would require the development of on-site liquefaction facilities at airports. Alternatively, on-site production would require access to large amounts of water and electricity, which may not be practical at some airports. This optimization exercise should be performed for every type of airport.

- **$H_2$ shipping optimization** including assessing and scaling the most efficient shipping solution incl. $LH_2$, ammonia, and/or LOHCs. Key questions will revolve around what is the most efficient supply route under what conditions.

### $LH_2$ hydrant refueling infrastructure

**Objective:** Determine whether $LH_2$ hydrant refueling infrastructure is cost-technically possible and could enable economies of scale at large airports

**Target:** Hydrant refueling system costs at par with refueling trucks

**Where we are today:** Prohibitive costs. Costs >5x those of standard hydrant systems

**Research timeline:** 2035-2050

Today, many large airports rely on hydrant refueling systems to supply aircraft with kerosene. Although it is not feasible in the short term, cryogenically-insulated hydrant refueling systems for $LH_2$ could potentially reduce liquid-handling costs at airports and alleviate congestion. While this topic is not a top priority for research on $LH_2$ aviation, resolving this question could help overcome some fundamental scaling challenges in the long run. It includes two research priorities:

- **Performance assessment of potential systems,** evaluating what benefits a hydrant system brings compared to trucks from an operational and cost perspective (economies of scale).

- **Technical layout,** which includes the design and integration of a cryogenically-cooled system with minimum disruption to existing operations.

## Regulatory framework: Climate impact research and market activation mechanisms

To manage the transition a long-term regulatory framework is required. R&I is needed to provide the basis upon which this transition policy can be crafted. This requires a better understanding of the climate impact of aviation, the levers to reduce that climate impact, a sector roadmap that lays out the different transition paths and their economics, and research into market activation mechanisms.

### Climate impact measurement

**Objective:** Develop a holistic and detailed understanding of the climate impact of aviation from conventional aircraft and new propulsion technologies and fuels

**Target:** Standardized definition for the full climate impact of aviation, and methodologies to measure and track climate impact for new technologies and fuels

**Where we are today:** $CO_2$ emissions measured, no standard measurement including non-$CO_2$ emissions and effects

**Research timeline:** Immediate focus in the next years

The climate impact of aviation is still not thoroughly understood, making target setting, measuring of efforts, and comparisons of technology pathways challenging. Future technology decisions will depend heavily on a better understanding of how non-$CO_2$ emissions and their related effects impact global warming. These would include the lifetime impacts of $CO_2$, non-$CO_2$ emissions, and emission-related effects. The differences between the climate impact of new propulsion systems and fuels and of conventional aviation need to be clear if the industry and manufacturers are to make well-informed decisions.

New models, simulations, and flight tests will also be needed to evaluate the impact that new fuels such as synfuels or hydrogen combustion will have on the climate. The initial studies on changes in $NO_x$ emission from synfuels and $H_2$ turbine combustion need be validated and compared to the effects of conventional turbines. Additionally, the industry needs to explore how these technologies produce water vapor, soot, and correlated contrails. No fuel cell combustion models or simulations currently exist to assess the effect on contrails and cirrus formation. Potential methods for reusing or conditioning water vapor to avoid contrail formation need to be designed and tested as well. Finally, all of these effects should be evaluated for different aircraft sizes at different flight altitudes.

Further climate-related topics should also be investigated, including a detailed life-cycle analysis of upstream emissions from the various fuels and technologies, as well as an examination of potential mitigation levers, such as changing flight routes and altitudes to reduce the formation of contrails.

**Deployment roadmap and market activation mechanisms**

**Objective:** Develop a roadmap for the aviation sector to transition towards net zero

**Target:** Roadmap with concrete targets, a plan for deployment and infrastructure rollout, and the foundation to build a long-term policy framework for this roadmap

**Where we are today:** Limited target setting (ATAG has set -50% $CO_2$ emission target), but lack intermediate targets, technology pathways, deployment path and supporting policy framework

**Research timeline:** All time horizons

The aviation sector needs a roadmap with clear long-, mid- and short-term targets for decarbonization to reduce uncertainty and align efforts of individual actors. A long-term perspective strengthens the ability to plan, invest and develop future technologies. This certainty attracts investments in innovation and scale-up and enables infrastructure to be developed.

A roadmap is not a monolithic, single piece of research: it contains technology evaluations and comparisons including safety and certification requirements, scenario planning for infrastructure and deployment scenarios, and research into suitable support mechanisms and market activation policies. It needs to be developed and regularly updated and adjusted to ensure deployment. As the technology matures, efforts need to shift from crafting the long-term plan to more mid-term policies. It provides the foundation upon which to craft policies to enact the roadmap. These could be funding for R&I activities, targeted subsidies for more climate-friendly aircraft, supporting the development and deployment of infrastructure through PPPs, funding mechanisms, and many more. Ultimately, the sector needs a fair and long-term regulatory framework, similar to other industries with the ETS and transport with fleet targets, in which the secondary costs of climate change are internalized in the cost of using an aircraft to fly goods or people. Such policy will need careful analysis and deliberation to move forward with an effective and efficient transition.

# Annex 1: Approach and metrics to assess climate impact of aviation

The assessment of the climate impact of commercial aviation is essential to the future technology decisions aimed at making aviation more environmentally-friendly. According to current scientific understanding, not only do **direct emissions** such as $CO_2$, $NO_x$, and water vapor emissions cause severe climate impact, but **emission-related effects** such as contrails and cirrus have a significant impact as well.

Before we can quantify and compare them, climate metrics need to be defined. Common metrics found in literature and industry are "radiative forcing," "global warming potential," "global temperature change potential," and "average temperature response." Metrics can be expressed in absolute units or in relative terms that are compared to a reference emission. To accurately assess climate impact, these metrics must be considered over a specified **time horizon,** since emissions and related effects have different atmospheric lifetimes. For most metrics, a time horizon of 20 to 100 years is used. This annex explains the **chosen metrics, assumptions, and approach on which this report's climate impact study is built.**

**$CO_2$ equivalent ($CO_2$eq) is used as a benchmarking metric.** Throughout the report, $CO_2$eq is the main metric used to compare and quantify the climate impact of $CO_2$, $NO_x$ and water vapor emissions, and emission-related effects such as contrails and cirrus formation.[42] The metric of $CO_2$eq emissions fully relies on the concept of a "global warming potential" metric, which will be defined and discussed in detail below. This metric is widely used as it allows easy comparison between different industries. For instance, in shipping industry the concept of $CO_2$eq is used to map emissions of non-$CO_2$ climate pollutants like black carbon, CH4, and $N_2O$ which are emitted when burning fossil marine fuels.[43] In automotive, $CO_2$eq is widely used to express the climate impact of tailpipe emissions ($CO_2$, CH4, and $N_2O$) in a single number.[44]

**In measuring and comparing climate impact, this report follows the methodology below:**

- **Radiative forcing was used to derive values of global warming potential.** One of the most widely used metrics, radiative forcing, indicates warming and heating effects with relatively strong scientific certainty. It measures the net radiative energy flux-change (power) into or out of the earth's system caused by an imposed emission of gas into the atmosphere. Although definitions vary, radiative forcing is usually expressed in watts per square meter averaged over a specific time period. Based on available research and expert interviews, e.g. with DLR, global warming potential values were derived.

- **Global warming potential (GWP) was used as the metric to transfer emissions and related effects to a common scale of $CO_2$ equivalent.** GWP is a measure of how well an emitted gas traps heat in the atmosphere compared to $CO_2$. It is defined as the time-integrated radiative forcing of an emitted gas or the related effect, relative to the effects created by an equal mass of emitted $CO_2$.[45] GWP is thus expressed as a dimensionless ratio and is always assessed over a time horizon. The chosen time horizon in this report is until 2100, mainly to consider the full, long-term effect of $CO_2$.[46] Per this definition, we define the GWP for $CO_2$ as "1." Ranges of uncertainty for the different effects are taken into account based on literature references and expert discussions. The $CO_2$ equivalent emissions for a specific flight are determined by multiplying the

42 Azar and Johansson (2011)
43 ICCT (2017)
44 United States Environmental Protection Agency (2018)
45 Myhre et al (2014)
46 Niklass et al (2019)

GWP of emissions of the fuel used, the emission factor of kerosene (0.0733 $kgCO_2eq/MJ$), and the total energy demand (in megajoules, or MJ) needed for that flight.[47]

- **To compare the climate impact of kerosene-powered aircraft to the impact of new technologies and fuels, benchmarking studies and expert interviews were used.** For each propulsion technology and fuel, relative changes in climate effects were determined using kerosene-powered aircraft as a reference. These relative changes are based on benchmarking studies comparing climate impact, incl. atmospheric lifetimes. Furthermore, effects that have not yet been investigated in climate research were assessed during expert interviews. Based on the relative changes for new technologies and fuels compared to kerosene-powered aircraft, the range of the absolute factor GWP was calculated for each effect.

- **The approach including contrail effects holds for short-, medium- and long-range aircraft flying at altitudes above 30,000 feet.** The properties of contrails and the likelihood of contrail formation depend on the condition of the air the aircraft is flying through. Contrails are formed when hot, humid water vapor mixes with soot particles and aerosols at low-pressure and low-temperature air at high altitudes. At low altitudes (typically less than 30,000 feet) contrails are less likely to form. Therefore, the climate effects of contrails for commuter and regional aircraft are assumed to be negligible. However, for short-range, medium-range and long-range aircraft which fly at altitudes above 30,000 feet, contrails have a significant climate impact. Further research is required to test the climate impact of different aircraft segments.

- **Net-carbon neutrality was assumed for synfuel from direct air capture.** The production of synfuels by direct air capture, as well as carbon net-zero production of $H_2$ and electricity, is assumed. In terms of climate impact, this assumption significantly increases synfuels' competitiveness in comparison to other fuels and propulsion technologies.

Based on the above methodology and assumptions, this report studies the climate impacts and assesses the relative change in emissions effects when new technology and fuels are used in place of kerosene. The GWP of kerosene emissions is used as a reference for comparison. By multiplying the GWP of kerosene emissions with the relative changes corresponding with each technology, and fuel, absolute GWP values can be determined for each climate effect, technology and fuel.[48,49] The absolute GWP values of the four effects and for each technology and fuel can be summarized in the following table:

| **Average values** | **$CO_2$** | **$NO_x$** | **Water vapor** | **Contrails** | **Total** |
|---|---|---|---|---|---|
| **Kerosene** | 100% | 100% | 10% | 100% | **310%** |
| **Synfuel** | 0% | 100% | 10% | 75% | **185%** |
| **$H_2$ turbine** | 0% | 35% | 25% | 60% | **120%** |
| **$H_2$ fuel cell** | 0% | 0% | 25% | 30% | **55%** |

[47] Brander (2012)
[48] Efficiency improvements of new aircraft designs were not included in deriving the GWP for new technologies – applied in a second step when considering energy requirements per aircraft.
[49] Grewe (2019)

**However, this report uses ranges to account for uncertainties** as the scientific understanding of certain aspects of emission effects is not yet comprehensive. These ranges are based on extensive discussions with climate and industry experts, as well as a detailed review of available literature.

Detailed discussions of each climate effect:

- **$CO_2$ emissions** originate from the combustion of hydrocarbon fuels such as kerosene and SAF. In general, their climate impact is relatively well-known. The climate impact of $CO_2$ kerosene emissions is used as a benchmark for comparing the impact of other effects: the GWP of $CO_2$ has a value of 1 or 100 percent. For synfuels, despite emitting $CO_2$ during combustion, no $CO_2$ emissions were taken into account as net-carbon-neutrality was assumed (using renewable energy and carbon from direct air capture from atmosphere). $H_2$ turbines and fuel cells generate no $CO_2$ in the propulsion of aircraft.

- **$NO_x$ emissions** arise from chemical reactions at high temperatures in the combustion chamber of jet engines. Therefore, $NO_x$ emissions depend on the design of the engine and a trade-off between fuel-burn efficiency ($CO_2$ emissions) and $NO_x$ emissions exists. The climate effect of $NO_x$ is less certain than for $CO_2$ as $NO_x$ influences atmospheric methane and ozone concentrations. Conventional kerosene, synfuels, and $H_2$ turbine aircraft rely on combustion processes and hence emit $NO_x$, albeit in different quantities. For synfuels, equal $NO_x$ emissions are assumed as for kerosene, as synfuels are "drop-in" fuels that go into the same turbine used for kerosene combustion. For $H_2$ turbines (vs. kerosene), hydrogen's wider flammability limits enable leaner combustion that results in lower flame temperatures. In addition, higher burning velocities and diffusivity allow for higher reaction rates and faster mixing respectively, resulting in lower residence time. These factors cumulatively contribute to lower thermal $NO_x$ and allow for shorter combustor designs. As the total amount of $NO_x$ reduction is promising but still uncertain, a range of 50 percent to 80 percent compared to kerosene was considered. Translating this to GWP and in reference to kerosene aircraft, we used a range of GWP for $NO_x$ from $H_2$ turbines of 10 percent (lower limit) to 75 percent (upper limit), resulting in an average GWP value of 35 percent (see table). With fuel cells, no $NO_x$ is emitted, so there is no associated climate impact.

- **Water vapor** is the most abundant greenhouse gas in the atmosphere, both by weight and volume. All of the considered propulsion technologies and fuels emit water vapor. Both kerosene and synfuel are characterized by relatively low contributions of water vapor, as found in the literature.[50] For H2 turbines and fuel cells, as they use $H_2$ as fuel, 2.55 times more water vapor is formed compared to kerosene combustion (for the same energy content).[51]

- **Contrails and cirrus,** as described above, are emission-related effects that usually form at very high altitudes (usually above 30,000 feet) where the air is extremely cold (less than about 40 degrees Celsius).[52] They originate when hot, humid exhaust gases, soot particles, and aerosols combine in the low temperature and pressure conditions of high altitudes. Since all propulsion technologies emit water vapor (see above), and particles are often already present in the atmosphere, it is likely that all technologies and fuels lead to contrail formation. For synfuels, a lower contrail effect is assumed compared to kerosene as particle mass concentration in the exhaust gases is lower.[53] $H_2$ turbines emit less soot compared to kerosene; therefore, their emission leads to optically thinner ice crystals and thus lower climate impact.[54] Based on expert interviews, the effect of contrails for $H_2$ fuel cells is considered to be slightly lower given the possibility that water vapor can

50 Caiazzo, Agarwal, Speth and Barrett (2017)
51 Gauss, Isaksen, Wong and Wang (2003)
52 NASA (2020)
53 Snijders and Melkert (2011)
54 Marquart, Ponater, Ström and Klaus (2005)

be collected and conditioned, thus mitigating contrails. The precise climate impact of contrails is not yet well understood and needs to be clarified by future scientific studies.

The described findings and assumptions were translated into ranges of GWP for each effect (see below). **The lower limit of the uncertainty range** correlates with the lower importance of NOx, water vapor, and contrail and cirrus formation relative to $CO_2$ emissions. The **higher limit of the uncertainty range** correlates with the relatively high importance of $NO_x$, water vapor, and contrail and cirrus relative to $CO_2$ emissions.

| **Lower limit values** | **$CO_2$** | **$NO_x$** | **Water vapor** | **Contrails** | **Total** |
|---|---|---|---|---|---|
| **Kerosene** | 100% | 50% | 5% | 50% | **205%** |
| **Synfuel** | 0% | 50% | 5% | 30% | **85%** |
| **$H_2$ turbine** | 0% | 10% | 15% | 25% | **50%** |
| **$H_2$ fuel cell** | 0% | 0% | 15% | 10% | **25%** |

| **Upper limit values** | **$CO_2$** | **$NO_x$** | **Water vapor** | **Contrails** | **Total** |
|---|---|---|---|---|---|
| **Kerosene** | 100% | 150% | 15% | 150% | **415%** |
| **Synfuel** | 0% | 150% | 15% | 135% | **300%** |
| **$H_2$ turbine** | 0% | 75% | 40% | 105% | **220%** |
| **$H_2$ fuel cell** | 0% | 0% | 40% | 60% | **100%** |

# Annex 2: Statements of contributors

As referred in the list of contributors, the following statements were written by the contributing organizations and not modified by the authors.

## Airbus

"Airbus is committed to researching and developing technologies which allow the decarbonization of the aviation industry. Already, Airbus' newest generation of aircraft use up to 25% less energy. In addition, Airbus has certified all aircraft in service to fly with up to 50% of Sustainable Aviation Fuel (SAF) on board. In the short term, these are huge levers to significantly reduce aviation's $CO_2$ emissions.

In addition, Airbus is investing in disruptive solutions which have the potential to significantly increase aircraft efficiency with the ambition to eliminate climate impact. Hydrogen is one of those pathways which along with the huge opportunity, also comes with many challenges. Through cross-industry and public-private research partnerships, Airbus believes that together we can bring competitive climate neutral solutions to the future of flying."

## Air Liquide

"The future of aviation, like the future of our society, is carbon neutral.

Facing the climate emergency, aviation took a pioneering attitude towards sustainability with ambitious goals of decarbonisation. A systemic strategy and a clear roadmap are necessary to identify where and how to act on aviation.

All stakeholders have already taken actions such as: increase operational and fuel efficiency, optimize air traffic management. These levers will not suffice to achieve the goal targeted of "Net-zero climate impact" as they don't reduce carbon dioxide emissions sufficiently. The only way to be zero carbon emission is to shift rapidly to innovative technologies for electrical and hydrogen propulsion. Given battery limitations, the decarbonisation of aviation carbon emissions will rely heavily on hydrogen. The introduction of such innovation will impact all the value chains, requiring an integrated approach to define a common strategy to strengthen the ability of different stakeholders to timely act together. Air Liquide is committed to work with all the stakeholders to build together the path forward to cleaner and greener aviation.

Air Liquide believes that hydrogen ($H_2$) is a major opportunity to shape the future of cleaner aviation based on our expertise, know-how and certifications in the aerospace industry, ability to launch liquid hydrogen systems in space, fuel cell technologies mastery, hydrogen infrastructures as well as, low-carbon (blue) hydrogen production and liquefaction.

In particular, Air Liquide has been working on introducing hydrogen in aviation since the early 2010s. A project supported by the European Union (EU), launched in 2013, demonstrated the feasibility of an airborne gaseous hydrogen tank to power fuel cells. It has clearly demonstrated gaseous hydrogen was not the solution for the propulsion of aircraft, given the large quantities required (several tons aboard) and that liquid hydrogen ($LH_2$) is the only way forward. We now believe that it is urgent to use flight demonstrators as the principal means of evaluating, maturing and validating the technology and the procedures required to use liquid hydrogen. This is the goal of the Heaven project, granted by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), where Air Liquide is in charge of the storage while the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) will modify its existing "HY4" R&D platform by switching from a gaseous to a liquid hydrogen storage. The first flight will occur in 2022 and it will be the world's first passenger aircraft powered by fuel cells fed with liquid hydrogen.

Three main advantages are worth to be mentioned :

- Hydrogen propulsion is two to three times more effective than synthetic fuels in reducing aviation's climate impact.
- Hydrogen can be produced directly using renewable energy.
- Aviation, with an energy intensive captive fleet, is an ideal candidate for the expansion of liquid hydrogen supply chain.

Because hydrogen will play a key role in the energy transition, a large market for Hydrogen Energy is foreseen starting from the mid-2020s. "Scaling up existing hydrogen technologies will deliver competitive low-carbon solutions across a wide range of applications by 2030 and may even offer competitive low-carbon alternatives to conventional fuels in some segments." (source: Path to Hydrogen competitiveness / Hydrogen Council January, 2020)."

## ArianeGroup

"ArianeGroup essential business is access to space, and also making the related space technologies available to anyone. As a designer and maker of hydrogen powered space vehicles, ArianeGroup engineering background, skills and technologies can be adapted at the benefit of clean aviation.

While mastering the design, manufacturing and operation of $LH_2$ powered Launch Vehicles since decades, ArianeGroup has the particular position of being in the role of vehicle designer, motorist and operator, therefore tackling the issues, engineering and producing:

- Cryogenic fuel vehicles ($LH_2$ & LOX as operational space rockets)
- Cryogenic propellant tanking and propulsion system
- Cryogenic ($LH_2$, LCH4 and LOX) engines
- $LH_2$, LCH4, LOX ground infrastructure (requirement, design or procurement, operations), including engines and cryogenic equipment stage facilities.

A large network of Hydrogen-technology proven suppliers, contractors, and partners (industrial and academic) has been built and is part of the industrialization.

ArianeGroup is also at the cross-road of Space and Aeronautics, as a results of intensive studies, pre-development and sub-systems demonstrators (tested) for innovative passenger transport vehicle with cryogenic fueled on-board rocket propulsion as Sub-Orbital SpacePlane, designed for civil aircraft-like (EASA) certification, and more advanced high-speed transport concept (as ZHEST or follow-ons).

The design-to-safety/certification approach developed on this occasion, coupled to the competence in accommodating a CryoFuel (as $LH_2$) system in an aircraft-like vehicle is also an additional valuable contribution that can be made available for the development of LH2 as fuel in clean aviation."

## Bauhaus Luftfahrt

"This report emphasises the potential of using renewable hydrogen as a large-scale future fuel supply option for aviation. Hydrogen as an energy carrier in commercial aircraft is not a new idea, and even the aircraft design may not seem particularly radical at first glance. In combination with various technologies and operational adaptions, however, hydrogen can enable the desired reduction in emissions, especially on long-haul routes. A crucial rationale for the introduction of hydrogen is given by the reduced effort for liquid hydrogen production compared to electricity-derived hydrocarbon fuels (PtL); no carbon source is needed, less process steps are required, and no major by-product streams are generated. These advantages can overcompensate the higher cost and the boil-off losses along representative $LH_2$ supply chains."

## Boeing

"Boeing appreciates the opportunity to participate in this study and is committed to sustainable aviation growth. While the potential for hydrogen in aviation is encouraging, there are still significant challenges ahead. In addition to using hydrogen for launch vehicle and space applications, Boeing has been working on hydrogen and fuel cell applications for aviation for more than 15 years, including three flight demonstration programs. Based on our experience, we recommend research into the complete lifecycle impacts of hydrogen production and emissions, fuel system technologies, infrastructure development, development timelines, and certification. If successful, hydrogen could have a place alongside other technologies such as sustainable aviation fuels and electrified aircraft. We look forward to working together with the other contributors in the future."

## easyJet

"At easyJet we fully acknowledge the challenge and urgency of decarbonising aviation. Whilst committed to optimising the efficiency of our direct emissions, and proud to be operating net-zero carbon flights by offsetting all fuel used on our flights, we realise that the long-term solution lies in reinventing aviation. Hence our interest in contributing to this study and in its clear conclusion that hydrogen has the potential for a major role in aviation's future technology mix."

## German Aerospace Center (DLR)

"The German Aerospace Center DLR supported this study in several working group sessions regarding future $H_2$ and fuel-cell technology assumptions and the integration studies on aircraft level for the evolutionary short/medium-range and long-range $H_2$ aircraft vehicle concepts. In order to reduce the environmental impact of aviation, hydrogen in combination with highly efficient aircraft configurations will play an increasingly important role as a fuel due to its high energy density and its significant potential for emission reduction. Its climate impact however is highly dependent on the fuel production pathway and how, where and when the non-$CO_2$ emissions occur. Prospective use cases are burning the hydrogen in a gas turbine or its electrochemical conversion in an onboard fuel cell system as energy source for an electric propulsion unit."

## GKN Aerospace

“Hydrogen offers the potential for emission free flight, with no $CO_2$, particulate matter and when reacted within a Fuel Cell, no $NO_x$. As identified in this report, whether combusted within a gas turbine or reacted within a Fuel Cell, it therefore has the potential to significantly reduce the climate impact of air transport as well as improve air quality. The approach of scaling hydrogen production for shorter range aircraft, as well as ‘synfuels’, ensures a staged path to acceptance and large scale availability of hydrogen for medium and long range aircraft. In addition to other necessary aircraft research and development programmes with and for our customers, e.g. lightweight multifunctional structures, natural laminar flow (NLF), composite fan static modules, integrated antennas etc, GKN Aerospace has planned a substantial research and development project into emission free hydrogen power systems planned for 2020 and beyond supporting our industries most significant decarbonisation opportunity leading to cleaner and more sustainable aviation.”

## Plug Power

“Plug Power strongly believes that hydrogen and fuel cell technologies will play a significant role in the future of aviation’s propulsion systems, resulting in a dramatic reduction of overall climate impact from commercial aircraft. Today, our team is actively engaged in the development of these technologies and we look forward to a bright, zero-emission future throughout our skies.”

## Safran

“The reduction of environmental footprint of aviation in is key for the future of our industry, and environmental aspects will be crucial in the future.

In order to meet the ambitious targets set by industry (ATAG goals) but also by national/ international policies (see EU Green Deal for instance), aviation industry has to propose an ambitious roadmap, based on a combination of radical improvements of aircraft efficiency, optimization of operations and low-carbon sustainable aviation fuels (SAF).

Among the various potential SAF pathways, conventional drop-in solutions (biofuels) have a strong potential as they allow a decarbonization of existing fleets and can be massively deployed without modification of existing aircraft and airport infrastructure. They are nevertheless limited by biomass availability and complex sustainability criteria. Advanced synthetic fuels (e.g. Power-to-Liquid pathways), produced from low carbon electricity and $CO_2$, have also a strong potential but need to increase their technological maturity ($CO_2$ capture).

Last, but not least, Hydrogen (provided it is produced from low carbon electricity) seems to have an interesting potential due to its foreseen availability, and the strong environmental potential ($CO_2$, particles, $NO_x$). Nevertheless, due to its low volumetric energy density, hydrogen will need to be liquid (cryogenic) for aviation usage: its deployment for aviation will need deep changes in the aircraft architecture, but also airport infrastructure and operations. These changes will be radical and fundamental questions are still on the table on the technical feasibility of such developments: liquefied hydrogen ($LH_2$) logistics and operations, development and certification of $LH_2$ aircraft (including key technological bricks such as pumps, heat exchangers, and global propulsive system optimization). Such uncertainties imply the need to launch fundamental low TRL R&T projects, potentially in collaboration between aviation industry and hydrogen production industry, in order to answer to fundamental key questions: definition of a global $LH_2$ propulsive system, definition of hydrogen A/C optimal design, development of key technological bricks, definition of airport logistics and operations, first steps in certification of $LH_2$ aircraft and assessment of environmental benefits. All these low TRL developments are compulsory in order to be able to envisage an industrial development, the certification and the entry into service, which is consequently difficult to envisage before 2040.

This last point is fundamental and will require specific studies: the better understanding of global environmental impact of aviation, and especially of non-$CO_2$ impact, is key in order to fully assess the potential of new technologies / fuels. The complex phenomena occurring in high atmosphere are far from being perfectly well known, which leads to a huge uncertainty in the comprehensive environmental evaluation of new pathways and can lead to biased messages."

## ZeroAvia

"We at ZeroAvia are very happy to see this new report by CleanSky, and the FCH JU. It is great to see the aviation industry picking up on the potential of hydrogen in aviation – something we have believed in from the very beginning of our efforts at ZeroAvia 2.5 years ago. We continue to push boundaries already today to make sure the first zero-emission, hydrogen-electric aircraft can be commercially operating before mid-decade, with better economics than today's commuter aircraft."

# Glossary

| | |
|---|---|
| BWB | Blended-wing-body |
| CAPEX | Capital expenditures |
| CASK | Cost per available seat kilometer |
| CH4 | Methane |
| $CO_2$ | Carbon dioxide, greenhouse gas |
| $CO_2eq$ | $CO_2$ equivalent |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center |
| EIA | United States Energy Information Administration |
| EIS | Entry-into-service |
| EU | European Union |
| FCS | Fuel cell system |
| Gt | Gigaton |
| GWP | Global warming potential |
| $H_2$ | Hydrogen |
| $H_20$ | Water |
| HEFA | Hydro processed esters and fatty acids |
| IATA | International Air Transport Association |
| kW/MW | Kilowatt, megawatt (unit of power, 1 Watt = 1 J per s) |
| kWh | Kilowatt-hour |
| $LH_2$ | Liquid hydrogen |
| LHV | Lower heating value |
| LOHC | Liquid organic hydrogen carriers |
| LT-PEM | Low-temperature proton-exchange membrane |
| ME | Middle East |
| Mton | Megaton (10^6 metric tons) |
| MTOW | Maximum take-off weight |
| NMVOC | Non-methane volatile organic compounds |
| $NO_x$ | Nitrogen oxides |
| PAX | Passenger |
| PEM | Proton-exchange Membrane |
| PM | Particle matter |
| PMAD | Power management and distribution |
| PP | Percentage point |
| R&D | Research and development |
| R&I | Research and Innovation |
| SAF | Sustainable aviation fuels |
| TCO | Total cost of ownership |
| t $CO_2eq$ | Metric tons carbon dioxide equivalent |
| TRL6 | Technology readiness level 6 |
| US $ | United States Dollar |

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