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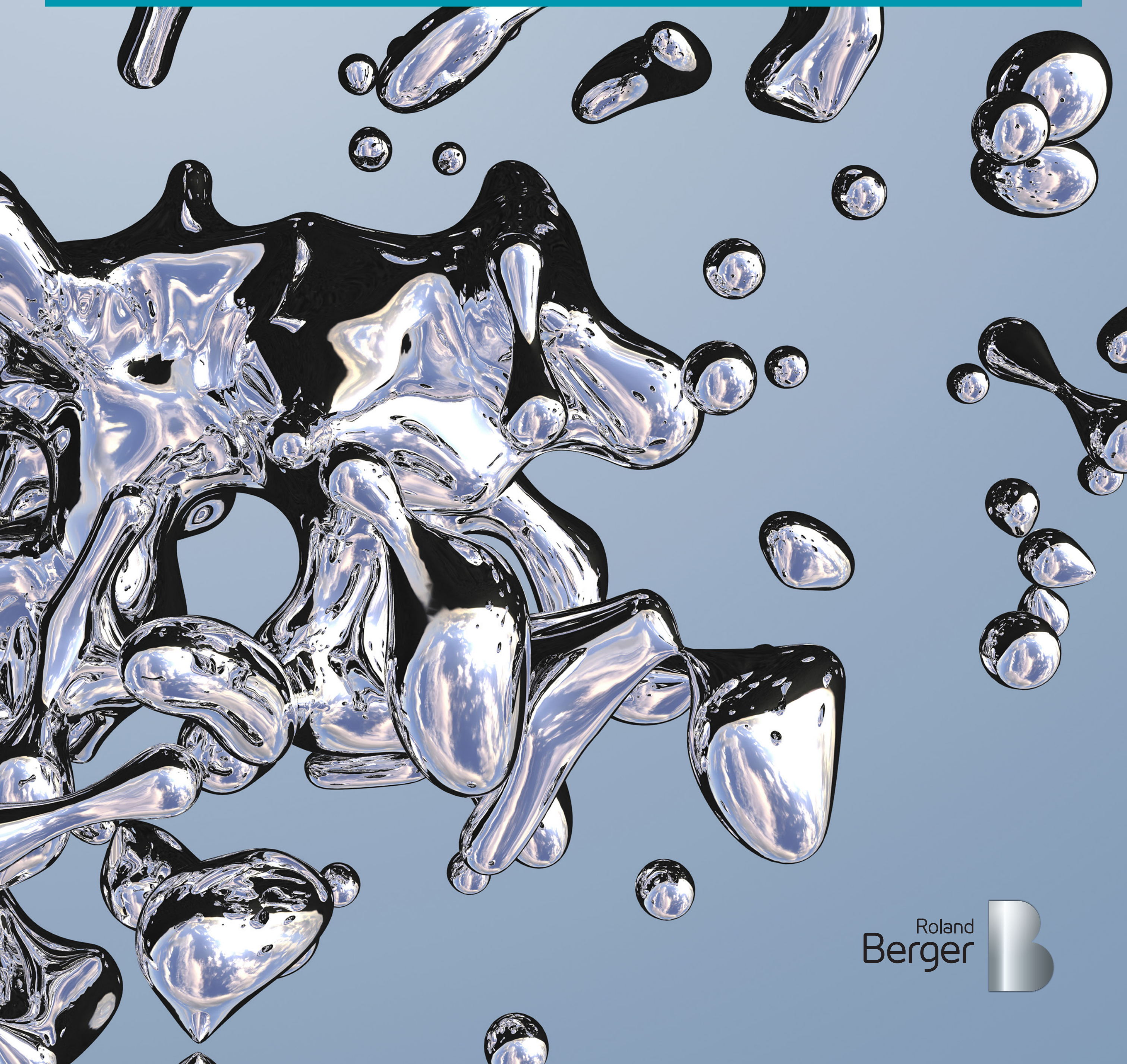
Focus

Roland Berger

Hydrogen | A future fuel for aviation?



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Hydrogen / *A future fuel for aviation?*

The aviation industry is at a crossroads. In the face of pressure to address its impact on climate change, the industry must respond: it must continue to improve current technologies, but also begin investing in greener, potentially revolutionary solutions. Among the many sustainable aviation technologies being considered – from sustainable aviation fuels, to electric aircraft – hydrogen has emerged as a potential aviation fuel of the future, with fuel cells and combustion options offering differing benefits. Which technological path should aerospace and aviation executives embark upon?

Long aircraft development and certification lead times are driving a need for an urgent answer to this question. To help executives navigate through this choice, we investigate the key issues and classify the different sustainable solutions for aviation, from "true zero" solutions to hybrid technologies. We then compare them, not just in terms of their environmental impact, but also their level of compatibility with current engines and aircraft designs. We recognize hydrogen as a genuine contender for power storage – one that is increasingly being used not just in the aviation sector but in other industries too. Most hydrogen-based solutions under development use fuel cells rather than combustion, and we take a detailed look at what exactly each option has to offer.

Shifting to hydrogen as a fuel for aviation is not without its challenges, however. We discuss the implications for aircraft and engine design, the necessity of effective hydrogen storage solutions, the need to produce hydrogen in a sustainable fashion, the infrastructure that will be required, and the associated costs. These are challenges that industry insiders should not – indeed, must not – underestimate. But we see clear potential for hydrogen aircraft, particularly in narrowbody/ Middle-of-the-Market aircraft, which are likely to emerge as the battleground between hydrogen and hybrid-electric technologies.

Hydrogen's future will be informed by technology investment decisions – many of which are to be made very soon – that will shape the industry's future. Industry executives must thus stay abreast of the latest developments, and aware of the issues at stake, in order to shape the future of the industry.

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1

An industry in need of a revolution / *Could hydrogen be the answer?*

The aviation sector is in need of a revolution. Major industries such as energy and automotive are taking steps towards decarbonization, but aviation's emissions continue to increase. Aircraft efficiency is improving, with fuel burn decreasing at approximately one percent a year, but aircraft fleet sizes are growing at around four percent a year. Looking at the net effect, we estimate that aviation may be producing as much as 24 percent of global CO_2 emissions by 2050, compared to roughly three percent today. Even with a hypothetical acceleration of improvements in aircraft efficiency to around 2.5 percent per annum – over twice today's pace – we forecast that aviation could be producing 19 percent of global emissions by 2050. → A

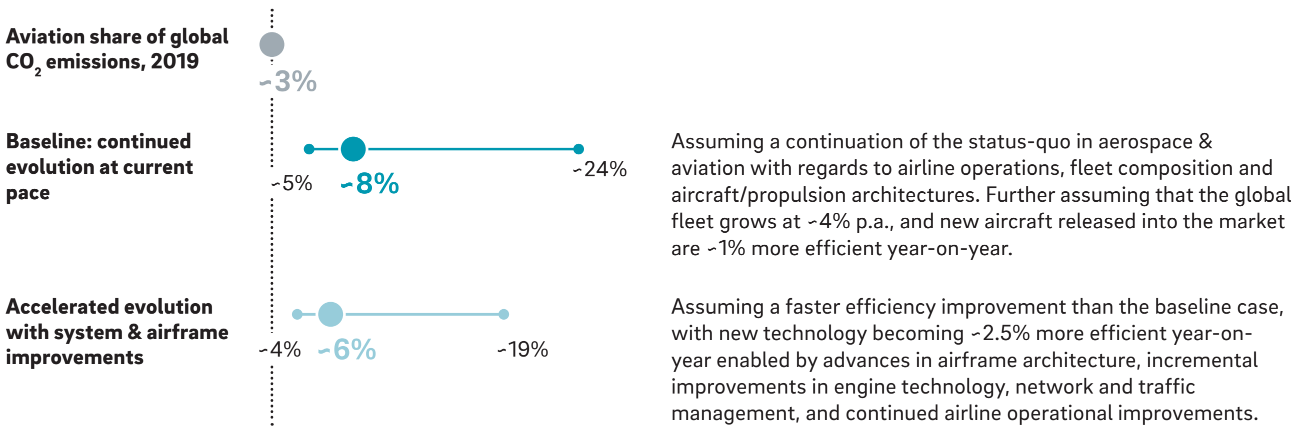
The aviation industry thus finds itself at a crossroads: it can continue to rely on conventionally-fueled gas turbines to propel flight – a path that is likely to see significant resistance – or it can choose to adopt greener modes of propulsion.

In this study we discuss the potential for hydrogen as a fuel for aviation. We begin by comparing the available emission reduction pathways for the aviation sector, including electrification and sustainable fuels. We then present the value proposition of hydrogen and compare the two key hydrogen propulsion methods: combustion and fuel cells. The former involves burning hydrogen instead of kerosene in a modified gas turbine; the latter involves producing electricity from hydrogen and oxygen inputs to power an electric motor that in turn drives a propeller or ducted fan. → B

We then discuss the challenges created by hydrogen, including process efficiency, storage and cost, before finally laying out our expectations for the future of hydrogen propulsion.

A: Two scenarios

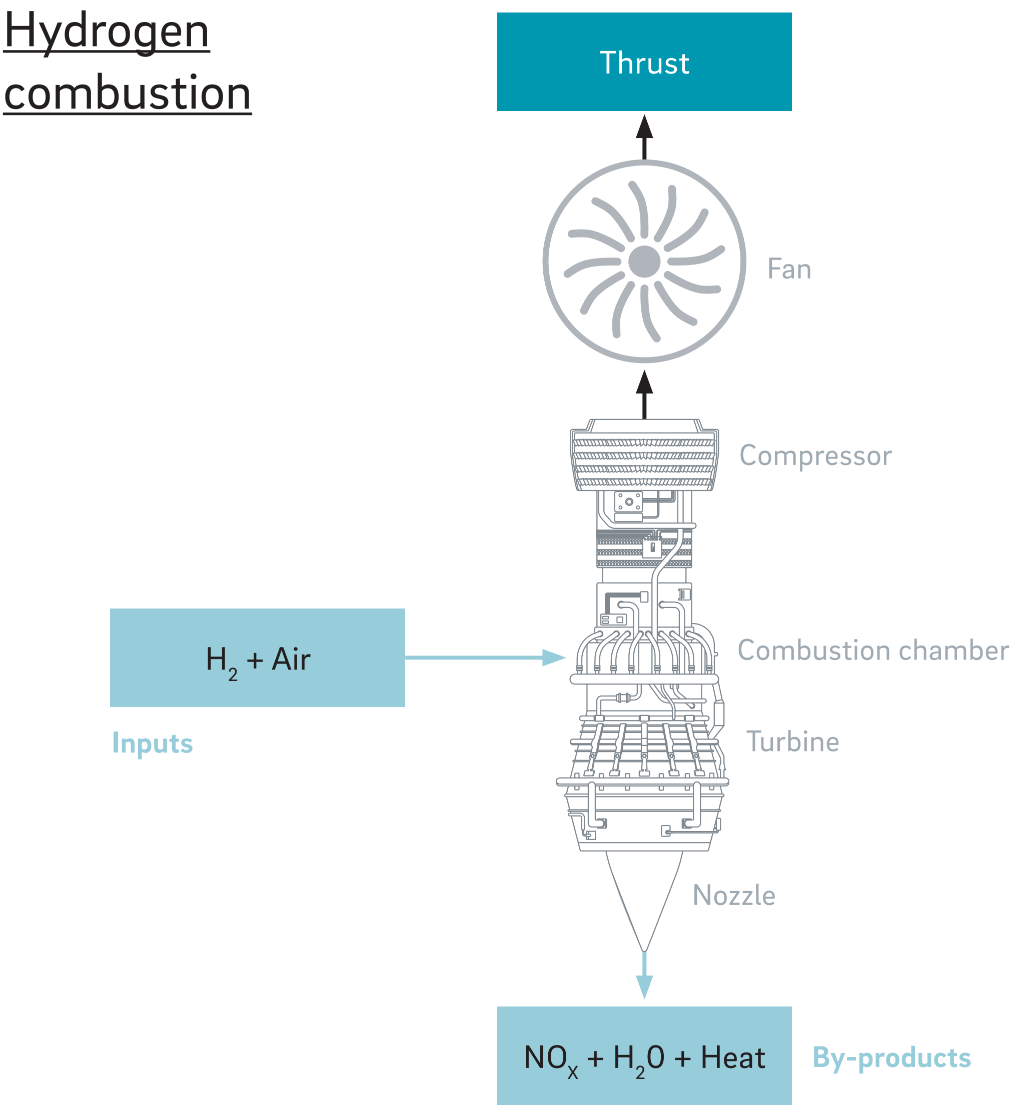
Forecast increase in aviation's share of global CO_2 emissions[1]



[1] For each scenario, the range is obtained by considering different global emissions levels, via the Representative Concentration Pathways. Namely, RCP 2.6 for the maximum value and RCP 8.5 for the minimum value. The average of RCP 4.5 and RCP 6.0 is used to obtain the mean

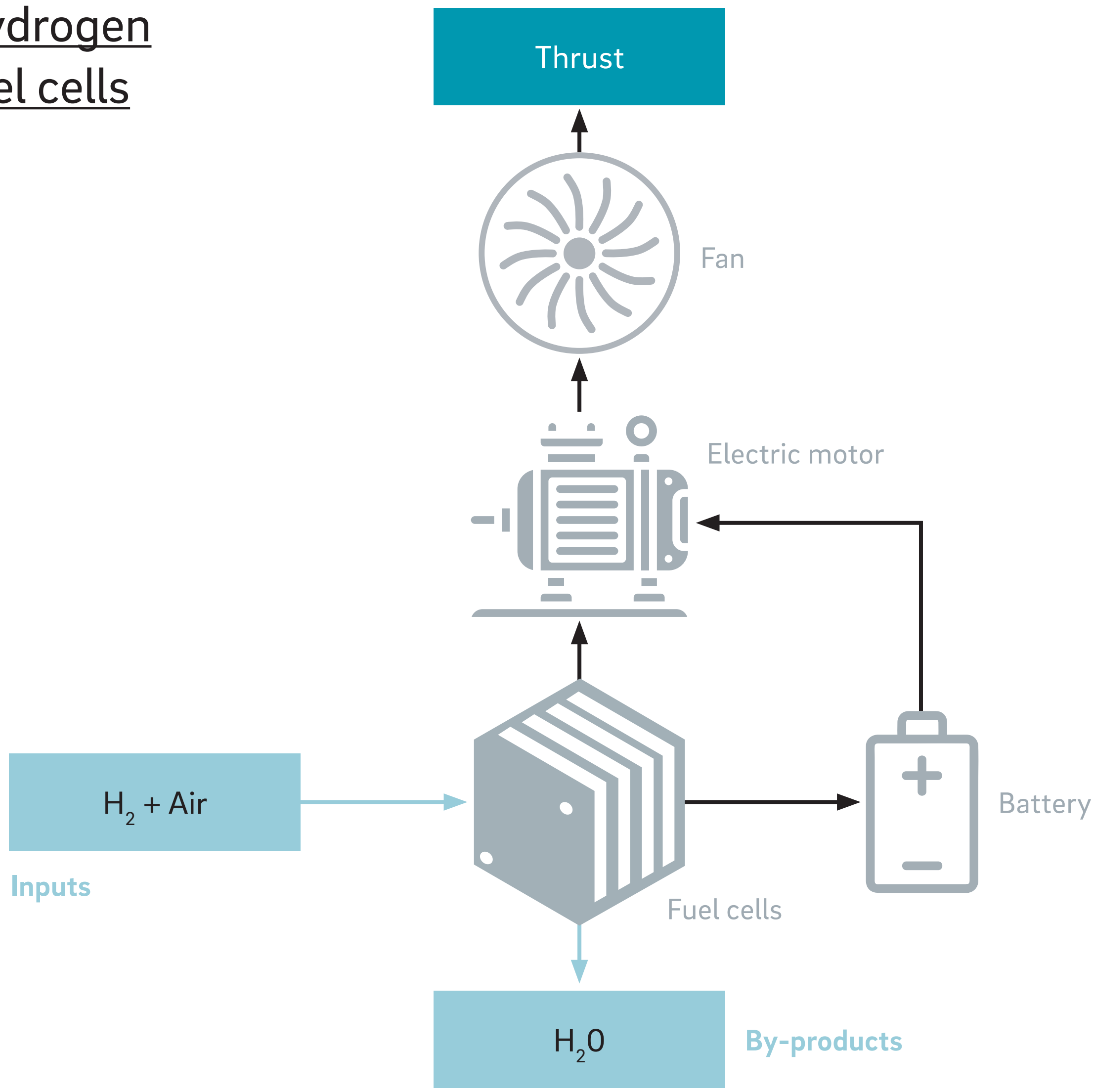
Source: RCP, Secondary research, Roland Berger

B: Two architectures
Using hydrogen power for aircraft thrust



Source: Roland Berger

Hydrogen fuel cells



2

Aviation at a crossroads /

Which is the right path forward?

There are five broad ways in which the aviation industry's emissions can be reduced, each with varying degrees of impact on carbon dioxide, and non-carbon greenhouse effects. → C

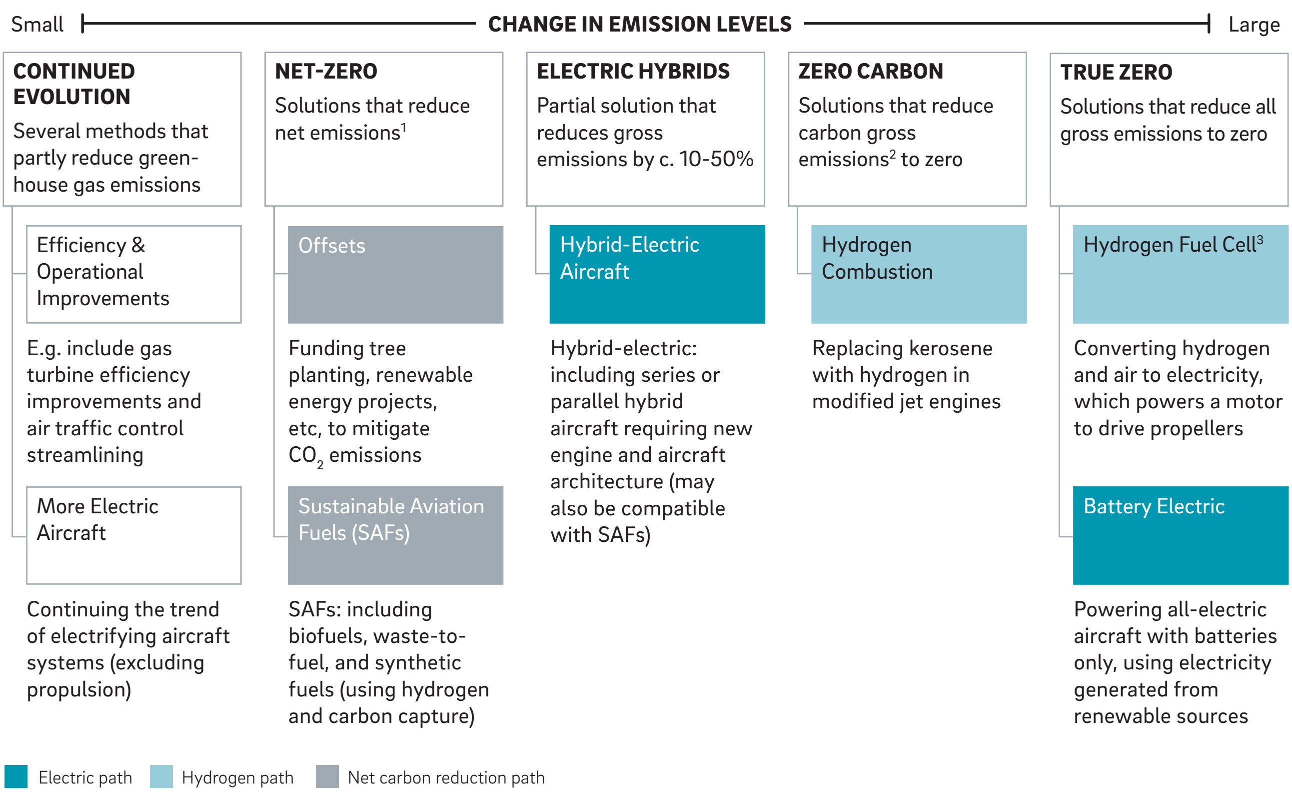
Continued evolution: Solutions that offer incremental improvements on existing technology.

Net-zero: Solutions that rely on the mitigation of carbon emissions elsewhere in the world, but without a reduction in gross emissions.

Electric hybrids: Solutions that move in the direction of electrification, with a partial reduction in all Greenhouse Gas (GHG) emissions.

C: Sustainable options for aviation

Solutions fall into five broad categories



[1] Net emissions = Gross emissions produced by an entity minus any carbon sinks attributed to that entity; [2] Gross emissions = The actual emissions produced by an entity; [3] True zero only if hydrogen is produced from zero carbon sources and if the aircraft is operated appropriately.

Source: Roland Berger

Zero carbon: Solutions that do not emit CO_2, but may emit other GHGs (potentially also causing contrails).

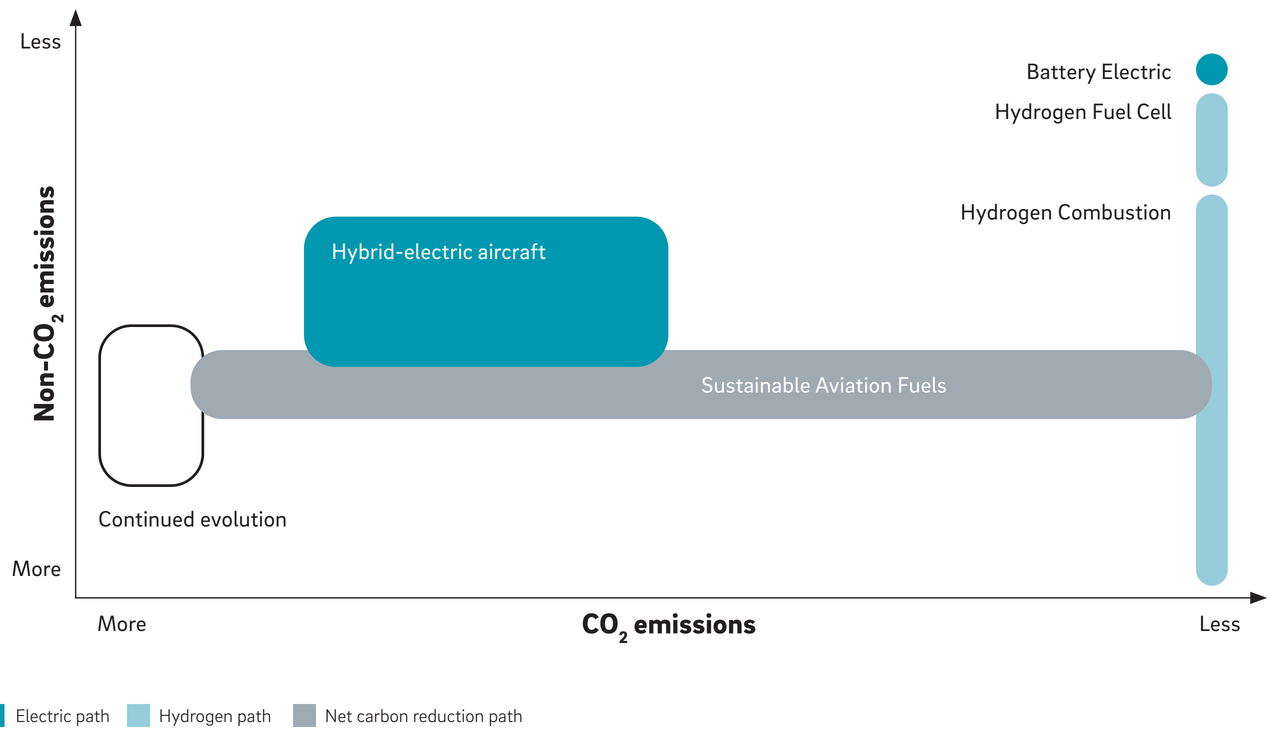
True zero: Solutions that release no greenhouse gases at all during operation.

The least emissions-intensive solutions minimize both CO_2 and non-CO_2 emissions, and are located in the top right of the illustration below. These "true zero" solutions, which – at a high level – include battery electric and hydrogen fuel cell aircraft, offer the greatest potential to reduce emissions from aviation drastically. → D

However, the solutions which offer the greatest emissions reduction also require novel engine or aircraft architectures and/or novel electrical systems. Comparing solutions on compatibility with current engines, requirements for novel design, and technological complexity, battery electric and hydrogen fuel cell designs both require fundamental re-designs. → E

D: Comparing environmental impact

Potential solutions by intensity of CO_2 and non-CO_2 emissions



Source: Roland Berger

E: True zero solutions are also the most complex

The landscape of potential revolutionary aviation solutions[1]

Group	Solution	Effect on GHG emissions	Compatible with conventional engines	Requiring novel engine architectures	Requiring novel aircraft architectures	Requiring novel electrical systems	Complexity[2]
	Sustainable Aviation Fuels (SAFs)	Net-zero carbon solution[3], with all other emissions still present	●				Medium
ELECTRICAL PROPULSION	**Parallel hybrid-electric[4]**	10-20% emissions reduction with conventional fuel		●		◐	Medium
ELECTRICAL PROPULSION	**Series hybrid-electric[4]**	25-50% emissions reduction with conventional fuel		●	●	●	High
ELECTRICAL PROPULSION	**Battery electric**	True zero – No emissions			●	●	Very high
ELECTRICAL PROPULSION / HYDROGEN	**Hydrogen fuel cells**	True zero – If operated appropriately[5]		●	●	●	Very high
HYDROGEN	**Hydrogen combustion**	Zero carbon solution (NO_x and water vapor still emitted)	◐		◐		High

● Required ◐ Partially required

[1] Revolutionary solutions, not considering 'business as usual' solutions arising from continuous technology and operational improvements; [2] Technological complexity considering aircraft/engine/ground infrastructure; [3] When considering the net carbon impact of the full production life cycle of SAFs; [4] Hybrid solutions also compatible with SAFs, offering gross emissions reduction and net-zero carbon emissions; [5] True zero only if operated appropriately to minimize contrails

Source: Roland Berger

3

Hydrogen's value proposition /

What benefits can hydrogen offer?

Despite the modern focus on electrification and batteries for power storage, hydrogen is a genuine contender for aviation. Hydrogen offers several benefits over SAFs and batteries as a power storage technology. → F

First, relative to SAFs (and indeed jet fuel), using hydrogen reduces GHG emissions. In the case of fuel cell propulsion – an almost "true zero" hydrogen solution – the gaseous emissions are limited to water vapor, a by-product of the energy production process. Although water vapor is a greenhouse gas, its harmful effects can be minimized through careful operation. In the case of propulsion via hydrogen combustion – a "zero carbon" solution – NO_x is produced alongside water vapor. Both have radiative forcing effects, but the solution still avoids harmful carbon emissions.

Second, especially relative to SAFs, hydrogen is likely to penetrate into other industries, too, which could speed up the development of fuel cells and storage systems, promote downstream infrastructure and push down production costs. This would benefit the aviation industry, as the R&D and infrastructure development costs would be partially borne by other industries (see Box feature: "Hydrogen in other sectors").

Third, relative to batteries, hydrogen has a gravimetric energy density three times that of kerosene (33 kWh/kg). Heavy storage tanks weaken this benefit, with aviation storage systems currently being investigated that employ 30-65 percent in hydrogen weight share, reducing future expected stored hydrogen densities to 10-21 kWh/kg. Nevertheless, hydrogen remains superior to conventional fuel in terms of power density by unit weight. This is highly relevant for flight, a weight-critical application, as it offers a Maximum Take-off Weight (MTOW) advantage over all other energy storage alternatives. The main drawback of hydrogen is that, due to its low volumetric density, it requires four to five times the volume of conventional fuel to carry the same

F: Competitive advantages
Comparison of hydrogen with other energy storage options for sustainable aviation

BENEFIT OVER SAFs?

1. Ability to reduce aviation's GHG emissions ✓
2. Potential to leverage scale from other industries ✓

BENEFIT OVER BATTERIES?

3. High gravimetric density ✓
4. Relatively fast refueling capability ✓

Source: Roland Berger

G: Energy densities
Comparison of energy carriers and storage solutions

	GRAVIMETRIC ENERGY DENSITY [KWH/KG][1]	VOLUMETRIC ENERGY DENSITY [KWH/L][1]
Fuel	12.0	10.4
Jet fuel + storage system	~8.9	~9.5
Current batteries	~0.3	~0.8
Hydrogen (Liquid)	~33	~2.4
Potential future hydrogen + storage system (Liquid)[2]	~10-21	~1.6-2.1

[1] 1 kWh is equivalent to 3.6 MJ; [2] Based on aviation grade liquid hydrogen storage systems under study

Source: US DoE, Leibniz University Hannover, Secondary Research, Roland Berger

onboard energy. Nevertheless, hydrogen still offers advantages over battery storage in energy density, both in gravimetric (batteries currently offer 0.3 kWh/kg) and volumetric measures. → G

Fourth, refueling aircraft with hydrogen is likely to be quicker than recharging batteries, enabling faster turnaround times. Similarities in the refueling process between hydrogen and kerosene could ease the transition between new and old processes: hydrogen would only require different piping and potentially different temperatures of fluid. By contrast, recharging batteries entails a completely different process, requiring ultra-fast charging or rapid battery replacement options and localized energy distribution infrastructure.

Box feature

HYDROGEN IN OTHER SECTORS

Hydrogen is primed to be a key contributor to reducing emissions and noise pollution in various sectors of the economy. End-users in mobility, energy and industry alike will look to hydrogen as a zero-emission energy source, for example, in fuel cell electric powertrains for automotive, stationary fuel cells for distributed cogeneration of electricity, and for heating applications and feedstock in industrial production processes.

The lifecycle emissions impact of hydrogen use – e.g., the "well-to-wheel" emissions for fuel cells – depends on the underlying hydrogen production method. Hydrogen is classified as "gray" if it is produced using fossil fuels causing carbon emissions, "blue" if those emissions are captured or offset, and "green" if it is generated by renewable energy with no carbon emissions. "Green" hydrogen can also act as a clean energy storage option for excess electricity from intermittent renewable power generation.

However, production capacity will depend on demand, which will likely be driven by policies and regulations creating incentives for sectors to decarbonize. The adoption of hydrogen will thus be most widespread where it represents a cost-efficient pathway compared to alternatives (e.g., electrification, biofuels or carbon capture & storage) and where the enabling hydrogen supply infrastructure becomes available.

Long-range/heavy-duty ground transportation

Hydrogen fuel cells based on Polymer Electrolyte Membrane (PEM) technology are likely to become the zero-emission powertrain of choice for long-range and heavy-duty transportation applications. This could encompass trains on non-electrified rail lines, heavy-duty trucks, urban and interurban buses, and certain long-range segments of passenger vehicles, including fleets. In these segments, hydrogen can overcome the range, charging-time and payload issues faced by battery-electric vehicles. Moreover, most use cases operate with captive fleets with dedicated hydrogen refueling infrastructure.

Use cases have already been demonstrated: the first multiple-unit, regional hydrogen trains in Germany entered service in 2018, heavy-duty hydrogen trucks have already commenced operations in Norway, hundreds of fuel-cell buses are in service in China and Europe, and more than 16,000 fuel-cell passenger cars are on the road around the world. To drive this uptake, governments in leading markets such as Japan, Korea and the United States have set combined targets for deployment as high as 2.5 million vehicles by 2030.

Beyond road and rail mobility, maritime transportation is a key follower that will benefit from further innovation in powertrain technology (including hydrogen storage) as well as overall fuel cost reduction. The first demonstration projects with fuel-cell ferries are already underway.

Industrials

Hydrogen plays an essential role as a feedstock in various manufacturing and chemical processing processes, for example, ammonia production and refinery processes. Decarbonizing these processes would be relatively straightforward using "green" hydrogen. For instance, steel production requiring Direct Reduction of Iron (DRI) using hydrogen is likely to adopt such a change, driven by regulation. This, in turn, may prompt the steel industry to push into hydrogen R&D for "clean DRI" steel production.

Driven by growing demand from these end-user applications, clean hydrogen production is gaining traction. Project announcements for new electrolyzers (electrolytic hydrogen production plants) have grown in both number and size. Global electrolyzer capacity currently stands at just over 100 MW, with many new plants planned and some concepts in development for GW scale capacity.

Overall, the hydrogen value chain is rapidly maturing and growing, as influential sectors look to hydrogen as a pathway to decarbonization. Aerospace and aviation could stand to benefit significantly from these advances.

4

Hydrogen in aviation /

Fuel cells or combustion?

Hydrogen combustion aircraft and **hydrogen fuel cell aircraft** are the two broad hydrogen propulsion systems under consideration. Seven publicly known hydrogen-propelled aircraft are currently in development, all of which employ fuel cells. These are informed by older feasibility studies, such as those by Airbus and NASA. Just one of these aircraft has already flown using hydrogen fuel, while the others remain at lower technology readiness levels. → H

HYDROGEN COMBUSTION AIRCRAFT

Thrust is generated through the combustion of hydrogen in a modified jet engine. This process eliminates the CO_2, CO, SO_x and the majority of soot emissions generated by conventional jet engines. NO_x and water vapor are still emitted, representing some contribution to atmospheric GHG levels. With respect to NO_x, two different combustor designs are under consideration to manage its production: Lean Direct Injection (LDI),

H: Current hydrogen aircraft developments

Details and status of hydrogen aircraft projects

	YEAR ANNOUNCED	POWER	DESCRIPTION	STORAGE SYSTEM	RANGE [KM]	STATUS
HY4	2015	Hydrogen fuel cells and electric batteries	Four seat fixed wing aircraft, single propeller, twin fuselage	Gas	1,000	**Flown**
HES Element One	2018	Hydrogen fuel cells	Four seat, fixed wing aircraft, 14 propellers	Gas/liquid	500-5,000	**Under development**
Alaka'i Skai	2019	Hydrogen fuel cells	Five seat futuristic "air-taxi" rotorcraft, six rotors	Liquid	640	
Apus i-2	2019	Hydrogen fuel cells	Four seat fixed wing aircraft, two propellers	Gas	1,000	
NASA CHEETA	2019	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	n/a	
Pipistrel E-STOL	2019	Hydrogen fuel cells	19 seat, fixed wing aircraft	n/a	n/a	
ZeroAvia[1]	2019	Hydrogen fuel cells	10-20 seat fixed wing aircraft, two propellers	Gas	800	
Airbus Cryoplane	2003	Hydrogen combustion	Large commercial aircraft	Liquid	n/a	**Feasibility study**
NASA Concept B	2004	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	6,500	

[1] Flown to test powertrain only

Source: Roland Berger

which has been shown to limit NO_x emissions to the same level as modern kerosene engines, and Micro-Mix Combustors (MMC), which could produce lower levels of NO_x than modern kerosene engines.

Crucially, contrails and Aviation Induced Cloudiness (AIC) may still be produced due to the release of water vapor, though there is an ongoing debate as to whether these would be better or worse than those created by conventionally fueled gas turbines. With conventional gas turbines, soot particles in the exhaust behave as nucleation points for water vapor, leading to longer-lasting contrails and the potential formation of cirrus clouds. With hydrogen, if any fuel impurities can be eliminated, this nucleation could be reduced significantly, leading to lower optical density and thus less impact due to contrails formed, although contrail lifetime may be increased due to higher water vapor emission levels. The relative impact of these two factors remains unclear, and thus the debate on this topic is expected to continue.

Conversion to hydrogen combustion would require changes to the engine, fuel storage and fuel delivery elements of conventional aircraft. Whilst this would necessitate new designs and a lengthy certification process, the transition would require much less redesign than hydrogen fuel cell or other electric aircraft options. As the result, a move to hydrogen combustion could be less disruptive to the current setup of the aerospace industry relative to alternatives.

HYDROGEN FUEL CELL (HFC) AIRCRAFT

HFC aircraft could potentially offer a "true zero" solution for GHG emissions. The only output of fuel cells is water, which eliminates CO_2, NO_x, SO_x, CO, HC and soot emissions. However, the water produced – around nine kilograms for every one kilogram of hydrogen reacted – would have to be released, and water vapor is also a GHG with the potential to cause contrails and Aviation Induced Cloudiness (AIC).

This is critical as hydrogen fuel cell aircraft can only be considered "true zero" solutions if they eliminate contrail/AIC emissions. Research suggests that due to the pure nature of the hydrogen and oxygen electrolysis reaction in a fuel cell, any impurities are likely to be minimal, significantly reducing the density of nucleation points and thus the impact of contrail/AIC formation. Furthermore, flying at lower altitudes could make the impact of the water vapor on global radiative forcing less significant, by constraining flights to remain within the troposphere where water vapor emissions are much less harmful (below 8-12 kilometers in altitude, varying by latitude and time of year). Additionally, unlike hydrogen combustion aircraft, HFC aircraft could be designed to store some of the water produced and release it in conditions conducive to low contrail/AIC formation (though this is not yet fully understood). Nevertheless, though there are proposed solutions, further research is required to prove contrail/AIC elimination.

Experts also believe that hydrogen fuel cell aircraft would be more efficient than hydrogen combustion designs, needing to carry 20-40 percent less fuel, driven by two factors. First, fuel cell propulsion can provide more efficient energy conversion – around 45-50 percent due to the combination of fuel cell efficiency (55 percent) and electric powertrain efficiency (90 percent) – versus around 40 percent for hydrogen combustion efficiency. Second, by virtue of being electric, fuel cell aircraft can benefit from distributed propulsion, which could deliver an extra 20-30 percent in fuel savings, considering improvements like boundary layer ingestion and flow control technologies.

Fuel cell aircraft would also share many other attributes with electric aircraft, including a need for high-voltage/high-power cabling, power electronics and an electric motor. The system therefore benefits from compatibility with the rapidly developing electric powertrain supply chain in both the automotive and aerospace sectors, as well as advancing design thinking on how best to maximize the benefits of distributed propulsion. As with electric aircraft, hydrogen fuel cell aircraft could also be less noisy than both conventional and hydrogen combustion designs. → I

I: Combustion vs. fuel cells

Comparison of hydrogen propulsion options

	COMBUSTION	FUEL CELLS
Description	• A gas turbine engine burns hydrogen and oxygen (from air) to rotate a turbine • The turbine rotates a fan to generate thrust	• A fuel cell converts hydrogen and oxygen (from air) into electricity • The electricity powers a motor that spins a propeller or ducted fan to generate thrust
Efficiency	~40%	~45-50%
Environmental footprint	• Reduced environmental impact – "zero carbon" solution • Zero CO_2, CO, SO_X, HC • NO_X emissions present • Water vapor emissions: more emissions than in an engine with comparable thrust • Contrail/cirrus cloud formation: due to the high purity of liquid hydrogen, nucleation of ice crystals will be reduced, although lifetime may be increased	• Minimal environmental impact – potential for "true zero" solution • Zero CO_2, CO, NO_X, SO_X, HC, soot emissions • Water vapor emissions: more emissions than in an engine with comparable thrust • Contrail/cirrus cloud formation: due to the high purity of liquid hydrogen, nucleation of ice crystals will be reduced, although lifetime may be increased
Technological barriers	• Redesign of engines for hydrogen as a fuel • Updated aircraft design to accommodate safe, light storage of liquid hydrogen	• Development of aviation-ready, efficient, power-dense fuel cells • Improved electric motors, power electronics, cabling and other electrical components • Updated aircraft design to accommodate safe, light storage of liquid hydrogen • Full benefits require entirely new aircraft design that leverages distributed propulsion • Effective thermal management
Advantages	• "Zero carbon" solution • Propulsion system very similar to conventional aircraft • Significantly less emissions • More compatible with current aerospace supply chain, with minimal architectural and design changes	• "True zero" solution • Compatible with electric propulsion, with potential to benefit from distributed propulsion • 20-40% more efficient than hydrogen combustion
Disadvantages	• Requires a redesign of today's aircraft to accommodate the additional volume required for hydrogen fuel tanks • Still produces NO_X and water vapor emissions so contributes to global warming • Increased water vapor emissions have an unclear impact on contrails/cirrus cloud formation	• Requires drastic aircraft redesign to accommodate the distributed propulsion system, full suite of new electric subsystems and significant hydrogen storage • Increased water vapor emissions have an unclear impact on contrails/cirrus cloud formation

Source: Roland Berger

5

Five key barriers / *Where do the challenges lie?*

For hydrogen technology to become a viable solution for aviation, the industry needs to overcome five key barriers. Two of these relate to aerospace design, namely aircraft and engine redesign, and hydrogen storage. The remaining three relate to factors in the hydrogen supply chain: sustainable production, infrastructure and cost.

#1 AIRCRAFT AND ENGINE REDESIGN

To exploit the full benefits of hydrogen, aircraft must change substantially. This could amount to a redesign of almost all the components of the aircraft, from the propulsion system and the form of the fuselage to the fuel storage. Hydrogen combustion requires a partial redesign of the aircraft, while fuel cells require a complete redesign.

Hydrogen combustion aircraft will rely on modified conventional thrust systems. Major changes will result from fuel delivery and storage, and additional fuel storage volume in the fuselage will be required given the reduced volumetric density relative to jet fuel. This will necessitate an increased fuselage size, generating additional drag, or a complete redesign of the aircraft structure, such as a move to blended wing bodies, with significant enclosed storage volume.

In addition to storage considerations, hydrogen fuel cell propulsion will require a redesign of the thrust systems to integrate distributed electrical propulsion, involving high voltage/high power electrical systems. The form and function of such aircraft will require a complete change from contemporary tube and wings architecture, and mirrors the design shift required for series hybrid or all-electric flight at the aircraft level.

#2 HYDROGEN STORAGE

Effective storage solutions are key to unlocking hydrogen's high gravimetric energy density and will need to be refined to address the issue of low volumetric energy density. Storage in the liquid state is currently the most promising option, offering high volumetric density relative to the gaseous alternative. The drawback of liquid storage is the requirement for cryogenic cooling (below -253 degrees Celsius). Cooling uses as much as 45 percent of the stored energy content, meaning there is a significant loss of energy between energy stored and delivered for thrust (tank-to-wing efficiency). This demonstrates the trade-off that must be made between maintaining high volumetric density alongside high tank-to-wing efficiency.

Additionally, the cryogenic requirement necessitates the inclusion of cooling systems and significant insulation. This leads to complex and heavy tank designs that consequently reduce the effective gravimetric energy density of the fuel. To take full advantage of hydrogen's high energy density, significant progress must be made in light-weighting storage tanks and advancing cryogenic cooling systems.

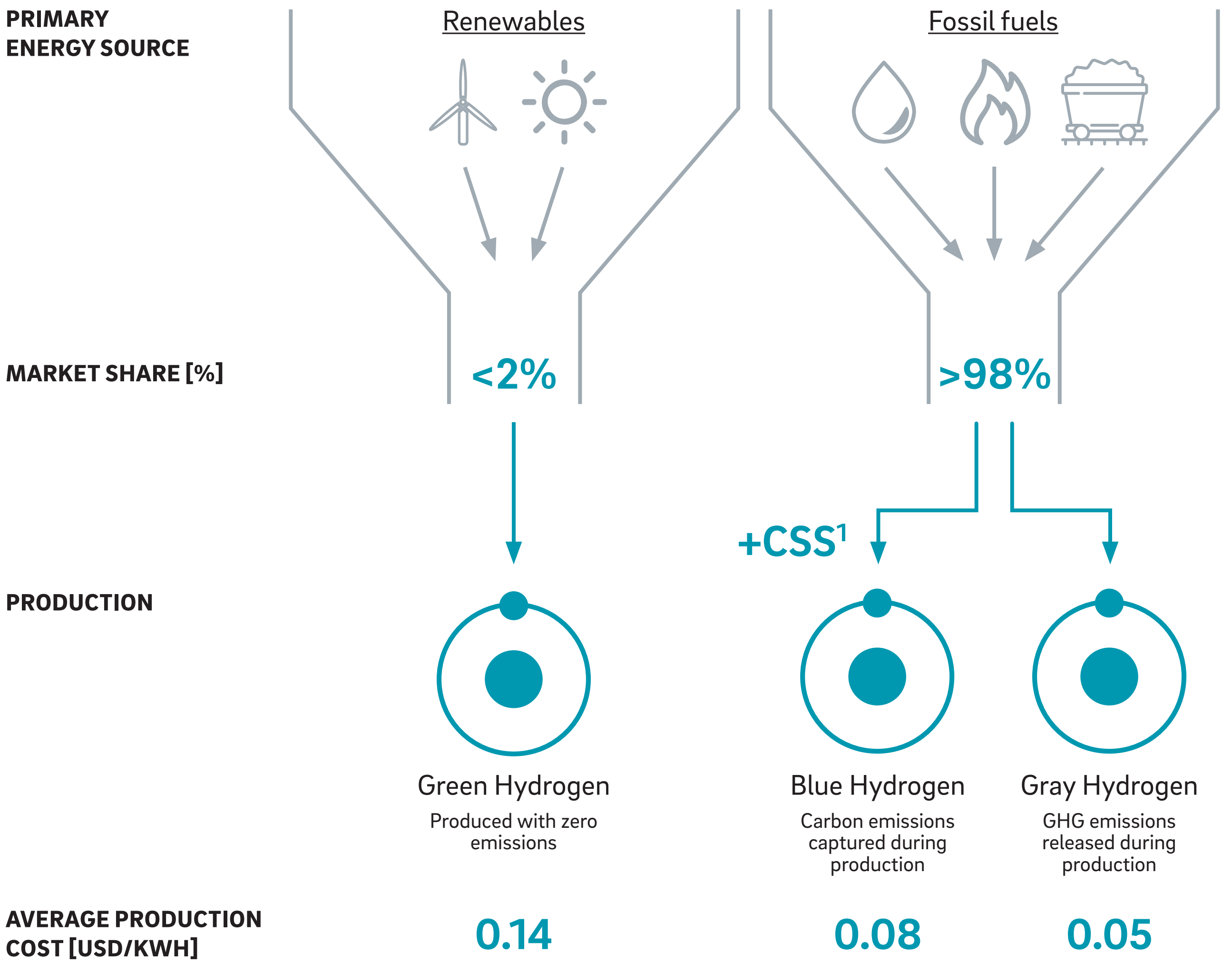
#3 SUSTAINABLE HYDROGEN PRODUCTION

A significant ramp-up in "green" hydrogen production or Carbon Capture and Storage (CCS) for "blue" hydrogen production will be necessary to produce volumes sufficient for the aviation industry in a sustainable manner. Current production is dominated by "gray" hydrogen processes, with 96 percent of hydrogen produced directly from CO_2-emitting processes such as steam methane reforming or coal gasification. The remaining four percent is generated via electrolysis, which only produces "green" hydrogen if renewables are used. Of the 70 million tons of hydrogen produced today, only around one million tons is currently "green". → J

Fortunately, a clear pathway to sustainable hydrogen exists. The solution in this case is likely to be driven by the energy sector as the transition to peak load renewables may produce a need for energy supply-side management and surplus energy capture, with hydrogen storage a viable solution. This source, alongside wider

J: Hydrogen production methods

Energy source, market share and production cost



[1] Carbon Capture & Storage

Source: Shell, IEA, HYSAFE, IATA, Roland Berger deployment of CCS driven by carbon taxes, may lead to growth of sustainable hydrogen production and an associated decrease in its price.

#4 INFRASTRUCTURE

Hydrogen infrastructure improvements will need to move in lockstep with technology to enable exploitation of hydrogen by aviation. Two key areas here are fuel delivery to airports and airport refueling infrastructure.

One option for fuel delivery will be via existing gas networks. A good example of this is the Leeds City Gate study, which shows that it will be possible to convert existing natural gas networks for the transportation of hydrogen gas. This is promising for the basic building blocks of hydrogen infrastructure, but significant investment will be needed by all sectors involved. The long-distance transportation of hydrogen must also be considered, especially given the disconnect between where hydrogen is produced (renewable energy plants with excess capacity and hydrogen production sites) and where it will be used (airports).

At airports, there could be an additional requirement to liquefy hydrogen on site, assuming that the infrastructure will be in place to deliver hydrogen gas. This will require local electricity generation or a reliable grid connection to ensure no network disruption costs arise.

#5 COST

Hydrogen is more expensive than kerosene on a kWh basis: excluding storage costs, average production costs are 0.14 USD/kWh for "green" hydrogen and 0.05 USD/kWh for "gray" hydrogen. The latter is on par with kerosene, but as "green" hydrogen would be necessary for "true zero" or "zero carbon" sustainable aviation, the price of these production methods must fall to compete on a cost basis. → J

Underlying overall production cost is "grid-to-wing" efficiency. Hydrogen production is often criticized for requiring too many power conversion steps, each of which diminish its overall production efficiency (and increase cost). For example, converting electricity into hydrogen may seem like a redundant step, to simply convert it back into electricity in a fuel cell. By contrast, employing a battery to power an aircraft would seem simpler and more efficient. However, if battery improvements plateau at a point insufficient for mid- to long-haul flight, hydrogen may remain the only "zero carbon" or "true zero" option. Furthermore, the question of production efficiencies quickly resolves into a question of cost alone: if hydrogen combustion can be cheap, does it matter how many steps it takes?

Once again, other sectors may provide the solution. As demand for hydrogen from other transportation sectors increases, and supply rises in line with renewable energy capacity, costs will likely fall. For example, projects are under development in Australia, Saudi Arabia and North Africa where "green" hydrogen is expected to cost as little as 0.07 USD/kWh in the future. Technology improvements in electrolyzers and hydrogen compression methods are also likely to contribute further to cost reduction, as the improved efficiency of such processes will reduce the energy input per ton of hydrogen produced.

More important than the decreasing cost of hydrogen may be the increasing cost of carbon. If greater emissions sanctions are imposed on aviation, such as ETS and CORSIA, the operating cost of burning jet fuel will rise. The aviation industry should therefore be careful to monitor price trends for both hydrogen and kerosene, as an inversion in the cost differential between the two fuels would improve the business case for investing in hydrogen.

6

Looking ahead / *What does the future hold?*

Keeping in mind the competitive advantages and constraints of the various sustainable solutions available, we expect to see the emergence of three different technological segments of aircraft with different sizes and ranges.

First, **smaller aircraft with shorter ranges** will likely become all-electric, with battery gravimetric densities expected to achieve the minimum thresholds to cater for these missions.

Second, **larger, long-haul aircraft** can be expected to have to rely upon Sustainable Aviation Fuels (SAFs), as all-electric, hybrid-electric or hydrogen solutions will face gravimetric and volumetric power density challenges at the required weights and ranges.

Third, and in between these two extremes, **regional and narrowbody/Middle-of-the-Market aircraft** will likely be the battleground where hydrogen will compete against hybrid-electric.

Within the narrowbody/Middle-of-the-Market category, hydrogen offers several advantages over hybrid-electric. It can do away with all carbon emissions, while hybrids only partially reduce carbon. It will remain significantly more power dense by weight than batteries, which will limit the degree to which hybrids can move away from kerosene as their primary power source. And hydrogen combustion, in particular (and unlike series hybrid-electric) does not require a wholesale redesign of the aircraft to deliver meaningful sustainability improvements.

But hydrogen technologies also have several drawbacks compared to hybrid-electric solutions. The science is not yet clear on whether the total impact of GHGs produced by hydrogen aircraft (water vapor emissions, contrails, aviation induced cloudiness, and NO_x for hydrogen combustion) are better or worse than efficient hybrids. Further, hybrids do not require investment in a hydrogen supply chain, and are compatible with SAFs, unlike hydrogen aircraft. And series hybrids with distributed electrical propulsion designs, for example, would be future-proof, with the ability to transition to all-electric if battery technology improves sufficiently, by replacing the turbo-electric generator with power-dense batteries.

So, will it be hydrogen fuel cells or hydrogen combustion aircraft that win out? As hydrogen combustion requires less of a technological leap than hydrogen fuel cell aircraft, we expect to see hydrogen combustion emerging first – potentially as a pioneering design, helping to build the hydrogen supply chain in aviation. This could lay the groundwork for the more efficient fuel cell aircraft that will likely come along later.

Now is a unique time when the pressure on the industry to become sustainable is high, a range of options exists, and long-term capital decisions have not yet been made. Indeed, stakeholders across the value chain – including OEMs, suppliers, airports, airlines and governments – can influence the future direction of the industry. Executives making investment decisions on future propulsion technologies should thus seriously consider allocating resources to explore the potential of hydrogen technology, diversify their technology risk, and help overcome the barriers to hydrogen propulsion.

Conclusion

Despite several decades of broad technological homogeneity in aerospace and aviation, the future looks more complex as the industry grapples with the challenge of sustainability. While smaller aircraft can electrify, and long ranged aircraft will likely be constrained to Sustainable Aviation Fuels, it will be the all-important narrowbody/Middle-of-the-Market sector where hydrogen will be a strong candidate for future propulsion. In this category, OEMs will have to prove that hydrogen is more viable than hybrid-electric solutions, and airlines will have to verify that the cost of adopting this technology is justified amidst growing sustainability concerns. Alongside Electrical Propulsion and SAFs, we see a clear role for hydrogen in helping address the challenge of sustainable aviation, and executives should allocate resources to ensure its potential is explored.

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