Target True Zero
Unlocking Sustainable Battery and Hydrogen-Powered Flight

INSIGHT REPORT

JULY 2022

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Contents

Foreword 5

Executive summary 6

Introduction 8

1 Opportunities for alternative propulsion 11

1.1 The environmental case for alternative propulsion 12

1.2 Applications of alternative propulsion technologies 16

1.3 Unlocking alternative propulsion 19

2 Technology unlocks 20

2.1 Technology unlock 1: Ensuring aviation batteries are charged with renewable energy 21

2.2 Technology unlock 2: Accelerating the introduction of green hydrogen 22

2.3 Technology unlock 3: Improving battery life cycles and management for aviation 24

2.4 Technology unlock 4: Improving battery-electric aircraft energy density 25

2.5 Technology unlock 5: Developing lighter fuel cell systems 26

2.6 Technology unlock 6: Developing lighter storage tanks for liquid hydrogen 28

2.7 Technology unlock 7: Redesigning aircraft for optimized hydrogen performance 30

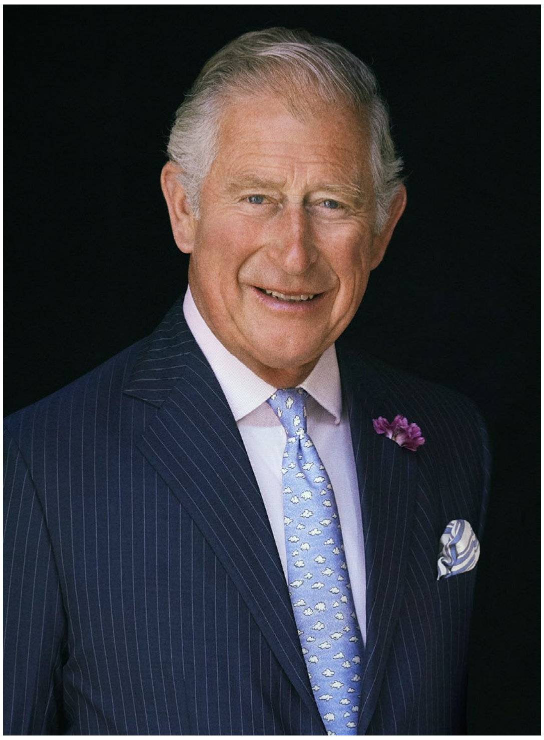
2.8 Technology unlock 8: Contrail research and mitigation 31

Conclusion 33

Contributors 34

Endnotes 35

Foreword



His Royal Highness The Prince of Wales

CLARENCE HOUSE

We have a particular opportunity at this precise moment in time. The current 'business as usual' position for sectors like aviation is increasingly understood to be unsustainable and untenable, but at the same time we are seeing an explosion of new thinking, new ideas and approaches that can allow us to reinvent that status quo.

This is the challenge in front of us – to end the climate impact of aviation so that we can retain the immense benefits of air travel to our economies and societies.

Through my Sustainable Markets Initiative, I have been working to bring together the forerunners in multiple sectors, including the aviation sector, to find ways to roll out new approaches and new thinking at scale. I have been deeply encouraged by the appetite and commitment from companies in that sector to face up to this challenge – to admit that the current approaches are not working.

But the need for change is urgent. For more years than I care to remember, I have been urging businesses and governments to recognize the scale of the climate and Nature crises we are facing, and while it is encouraging that so many have now recognized these issues, we have precious little time left to respond.

This is why it is essential to have the best possible information about what solutions have the best potential to deliver change at speed and scale.

This report, from the World Economic Forum's Target True Zero project and the University of Cambridge's Aviation Impact Accelerator, sheds much-needed light on the potential of new technologies like hydrogen and battery electric aviation to offer new forms of air travel without the same environmental impact.

I can only urge everyone interested in thinking about the future of the aviation sector, of the economy and, most of all, of our planet, to study its findings and consider them most seriously.

Charles

Executive summary

As industries and governments take increasing steps to address the threat of climate change, much focus is being placed on the transition that hard-to-abate sectors such as aviation will need to make to fit in with wider climate goals. Sustainable aviation fuels (SAFs) offer a promising solution for allowing the industry to reach net-zero CO_2 emissions by the middle of this century. Yet, concerns remain regarding whether SAFs can ever be sufficiently scaled to enable the full decarbonization of aviation while also being economically viable and environmentally sustainable. For this reason, voices within and outside the industry are urging the need to explore more radical solutions.

At present, there is uncertainty about the role these new technologies will play in the sector's overall climate plans. Produced in conjunction with the University of Cambridge's Aviation Impact Accelerator, this report marks the first step of the World Economic Forum's Target True Zero coalition, answering some of the questions that must be addressed if industry and governments are to make informed decisions about alternative propulsion in the future.

Using the Aviation Impact Accelerator's whole system model, this report takes a new approach in assessing the complete climate impact of these new technologies and identifies critical areas of uncertainty. It also determines what the technical capabilities of these new technologies will mean and their role in the aviation sector's decarbonization efforts.

Battery-powered aircraft would eliminate CO_2 as well as all other in-flight emissions. When powered by fully renewable or low-carbon energy, the electricity used to power these aircraft would have minimal climate impact. There are, however, challenges that will need to be overcome to avoid charging batteries directly from electrical grids, which in many parts of the world will remain reliant on fossil fuels for decades to come, as well as managing climate impacts currently associated with the production of batteries.

Based on forecast battery gravimetric energy densities, the maximum operating range of lithium-ion battery-electric aircraft by 2035 is expected to be around 400 km, rising to 600 km in 2050. Extending the range of these aircraft beyond this limit would require the use of breakthrough battery technologies, the development and commercialization of which are extremely difficult to forecast.

Hydrogen fuel cell electric would eliminate the majority of emissions but could still release water vapour into the atmosphere, which might lead to significant contrail formation – though there is considerable uncertainty here. Certain design decisions and the low temperatures at which fuel cells operate could create the potential to condense any water vapour into a liquid in the exhaust that would likely eliminate the chance of contrail formation. Still, the overall uncertainty about the impact of contrails from these aircraft makes it especially difficult to assess their full climate impact. Fuel cell technology would allow aircraft to be designed for a much longer range than battery electric aircraft – around 2,000 km by 2030, and a possibility of reaching 4,000 km by 2035.

Hydrogen combustion aircraft would eliminate CO_2 and soot emissions in-flight but still produce nitrogen oxides (NO_x) emissions, resulting in increased water vapour compared to jet fuel. As with fuel cell aircraft, assessing the total climate impact of hydrogen combustion aircraft is especially difficult due to the high uncertainty about the impact of hydrogen contrails. Even if the impact of these contrails were greater than those produced from flying on jet fuel, there remains the possibility that changes to aircraft operations could be used to reduce or eliminate contrail formation from both hydrogen and traditional jet fuel aircraft. By 2035, hydrogen aircraft may be able to operate over the same distances as jet engines, meaning they offer the potential to replace current jet fuel-powered aircraft at any range and are a viable option for decarbonizing the longest-range flights.

This report identifies eight key unlocks that are necessary for realizing the potential of alternative propulsion for moving us towards an aviation system with a true zero climate impact:

1. Ensuring aviation batteries are charged with renewable energy
2. Accelerating the introduction of green hydrogen
3. Improving battery life cycles and management for aviation
4. Improving battery-electric aircraft energy density
5. Developing lighter fuel cell systems
6. Developing lighter storage tanks for liquid hydrogen
7. Redesigning aircraft for optimized hydrogen performance
8. Contrail research and mitigation.

The Target True Zero coalition will build on this report by working with stakeholders to advance these unlocks and other areas necessary for realizing how alternative propulsion can contribute to a future of sustainable flight.

Introduction

The aviation industry must adopt transformative technologies to reach net-zero emissions goals.

Before the COVID-19 pandemic, aviation accounted for around 2% of global CO_2 emissions, with its overall contribution to climate change believed to be about 5%, with the impact of non-CO_2 emissions considered.[1,2] This share will only rise as other sectors transition to sustainable energy sources. The aviation industry and governments worldwide have responded to this challenge by committing to a range of measures to reduce aviation CO_2 emissions, including a global commitment by the industry to reach a climate target of net-zero emissions by 2050.[3]

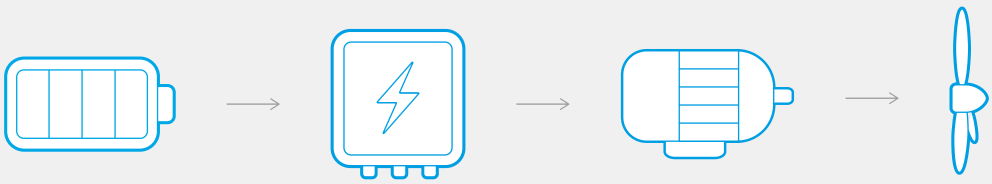
Many recent efforts have focused on how the industry can transition to using sustainable aviation fuels (SAFs). These can reduce aviation's net carbon impacts without requiring significant changes to aircraft in operation today. Yet, questions remain about the degree to which they can be produced at a sufficient scale, the sustainability of certain types of SAFs, and whether they will ever be economically competitive. Transformational technologies like battery- and hydrogen-powered aircraft have been touted as alternative solutions. Unlike SAFs, which are composed of hydrocarbons and have properties that replicate traditional jet fuel, these alternative propulsion technologies do not emit CO_2 into the atmosphere during flight. While there is excitement about what these technologies could mean for aviation, more certainty is needed about how these could be used by the sector and the costs and benefits compared to SAF-based climate solutions. Taking steps now to build this certainty is essential so that industry and governments can start planning for the significant changes these disruptive technologies would entail.

BOX 1 | **Alternative propulsion technologies**

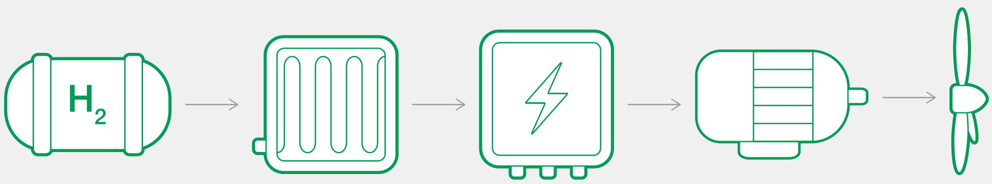
Target True Zero has identified three potential alternative propulsion technologies as having the greatest potential to reduce aviation's climate impact; electrification using either batteries or hydrogen fuel cells and hydrogen combustion using gas turbines.

Electrification

Electrification creates new opportunities for aircraft design. The efficiency of a jet engine increases as its power rises, which is why most aircraft have only two engines. Conversely, the efficiency of electric motors is not dependent on their power. This leads to a new degree of freedom when designing an aircraft, allowing a larger number of smaller propulsors to be mounted along the wings or around the fuselage at locations that maximize the overall efficiency of the propulsion system and minimize the aircraft's drag in what is known as "distributed propulsion". Such an approach could reduce cruise power consumption by up to 20%[4] and provide extra redundancy in the event of one motor failure, as the additional power requirements can be split over a high number of remaining motors.

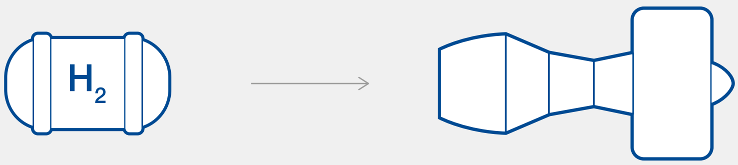


Battery-electric: Batteries can be used to power electric motors, which power a propeller directly.



Hydrogen fuel cell electric: Hydrogen can be used in a fuel cell to convert hydrogen and air into water and electricity using an electrochemical process. The electricity generated can power electric motors, which power a propeller. The hydrogen can be stored as a liquid at a low temperature or as a compressed gas at high pressure.

Hydrogen combustion



Hydrogen combustion: Hydrogen can also be used directly to power aircraft by burning it in a gas turbine engine, as jet fuel is today. Once again, the hydrogen can be stored on board the aircraft as a liquid at a low temperature or as a compressed gas at high pressure.

Each of these technologies can be used as the sole propulsion system on board an aircraft or can instead be used in conjunction with another alternative or conventional propulsion system – either in a hybrid configuration, where different propulsion technologies augment each other's performance, or in a dual fuel configuration where different fuels are used in the same propulsion technology. By increasing flexibility, using a combination of technologies could help accelerate the deployment and scaling of these technologies. The application of combined technologies is not explicitly addressed in this publication but will remain a future focus of the Target True Zero coalition.

Other forms of carbon-free propulsion, such as ammonia, have been suggested as a solution for aviation's climate impact. The practicalities of using ammonia as a fuel for aviation are considered more problematic than other solutions and Target True Zero is not currently focused on such applications.

Aiming for true zero aviation

The World Economic Forum is building on previous work undertaken to advance the aviation sector's decarbonization through its Clean Skies for Tomorrow (CST) coalition. CST has been at the forefront of efforts to enable the transition to SAFs. To ensure appropriate focus is given to all levers that can help eliminate the climate impacts of flying, the Forum believes it is necessary to also look at the role alternative propulsion technologies such as battery and hydrogen-powered aircraft can play and what is needed to scale and accelerate their adoption. Through its Target True Zero coalition – supported by knowledge partners the University of Cambridge's Aviation Impact Accelerator (AIA), the Aviation Environment Federation, and McKinsey & Company, and with generous support from Breakthrough Energy and the Quadrature Climate Foundation – the World Economic Forum has brought together leaders from across the aviation sector to begin to answer these questions.

This initial Target True Zero report is intended to serve as a knowledge base for future decisions on alternative propulsion by providing policy-makers and the industry with an understanding of the opportunities these technologies offer for addressing climate change and the technological and scientific advances needed to make this a reality. Section one of the report will assess the total climate impact of aviation, both in terms of assessing its whole life cycle (e.g. infrastructure, fuel production, aircraft manufacture) and including all types of climate impact (e.g. hydrogen leakage, nitrogen oxides, soot, condensation trails), and identifies how they can be used across the global aviation network to reduce emissions. From these insights, eight key unlocks for enabling sustainable alternative propulsion at scale are identified and explored in the subsequent section. This report does not address wider factors that will also be important considerations for the future of alternative propulsion – such as industry dynamics and economics, infrastructure, and policy and regulation – but these will be examined in future Target True Zero work.

This report has been produced by the World Economic Forum and the AIA, an international group of academics and practitioners convened by the University of Cambridge. It draws on a multi-disciplinary range of expertise to develop interactive, evidence-based models, simulations and visualizations that provide tools for decision-makers and the wider public to understand and engage in developing the pathways to net-zero flight. The AIA's whole aviation sector model produced the findings within this report. The data set on which the model is based was assembled using responses from technology questionnaires filled in by a wide range of expert technologists from industry and universities worldwide and data from peer-reviewed journal articles.

1 Opportunities for alternative propulsion

Finding alternatives to traditional jet fuel and addressing emissions are prime concerns for the aviation industry.

❝ Several companies are already flying prototype aircraft, and it is possible that a large hydrogen airliner could be in operation by the middle of the next decade.

With the attention that has been focused on the climate impacts of aviation in recent years, finding solutions for addressing emissions has become a top priority for the industry as it looks to achieve net-zero emissions by 2050. While it is accepted that SAFs may deliver a significant share of emissions reductions by 2050, a growing number of industry leaders believe that new technologies could allow aviation to move away from hydrocarbon fuels completely.

The beginnings of this transition can already be seen. Advances in battery technology and aircraft design capabilities have resulted in an explosion of electric aircraft concepts – from electrical vertical take-off and landing vehicles envisioned as a solution for urban and regional air mobility to larger aircraft that more closely resemble those we are used to today. Other companies see hydrogen (H_2) as better suited to longer-distance flights. Several companies are already flying prototype aircraft, and it is possible that a large hydrogen airliner could be in operation by the middle of the next decade.

While these advances demonstrate that these underlying technologies are viable for aircraft, their suitability for decarbonizing the overall sector is still a subject of debate. Several dimensions to this issue will need to be addressed in coming years – not least the economics of these technologies across the full value chain compared to sustainable aviation fuels. This report, however, is focused on providing an authoritative fact base on the opportunities for alternative propulsion from a technological perspective. Little work has been done to date to understand the full climate impact of these new technologies beyond the emissions savings achieved during flight. Similarly, competing views remain about the extent to which aircraft powered by alternative propulsion technologies can match the capabilities of existing aircraft powered by jet fuel, and thereby their capacity to offer a feasible solution for helping to decarbonize the sector. This section seeks to clarify these questions so that industry and government decision-makers understand the opportunities these technologies could provide for decarbonizing the aviation sector.

1.1 The environmental case for alternative propulsion

Electric and hydrogen-powered aircraft are sometimes called zero-emission aircraft because they eliminate all CO_2 emissions during flight. However, both the generation of electricity and the production of hydrogen require energy as an input – which, depending on its source, results in different climate impacts upstream. SAFs, by contrast, still emit the same amount of CO_2 during flight as conventional jet fuel, however, life cycle CO_2 savings are achieved elsewhere (see Box 2). To fully understand how alternatives to fossil fuels can help the aviation sector address its contribution to climate change, a necessary step is to examine the full range of climate impacts associated with fuel production and flight.

A necessary second step is to consider the impact of the emissions aircraft release in-flight other than CO_2 – namely water vapour and condensation trails (contrails) – which are formed under certain conditions from condensed water vapour released at altitude – soot and nitrogen oxide (NO_x). These are released high up in the atmosphere and so are a much more significant climate concern for aviation than sectors with ground-based emissions. It is believed that the total climate warming impact of aviation today, when these emissions are considered, could be two to four times higher than that of CO_2 alone.[5] While fully electric aircraft would not produce any in-flight emissions, these are a potential concern for hydrogen-powered aviation and must be considered.

It should be noted that a significant part of aviation's total climate impact is believed to result from the effects of contrail formation. Though these are thought to have lifetime impacts of just a few hours instead of hundreds of years like CO_2, there remains significant scientific uncertainty about their overall impact.[6] There are techniques available that allow the formation of contrails to be avoided, such as changing the time, route or altitude of a flight.[7] These often lead to a slight increase in fuel burn and, therefore, an associated increase in CO_2 emissions. While flying with fossil fuels, it is essential to balance the removal of contrails – which might have a large but highly uncertain climate impact – with the definite increase in CO_2 emissions due to higher fuel burn. This balance lies in favour of contrail avoidance when flying with fuels of minimal CO_2 impact. While it is important at this stage to consider the impact of contrails when assessing the climate impacts of different propulsion technologies, in the future, it may be possible to eliminate any negative impact on the climate so that they are no longer a concern.

BOX 2 | Sustainable aviation fuels (SAFs)

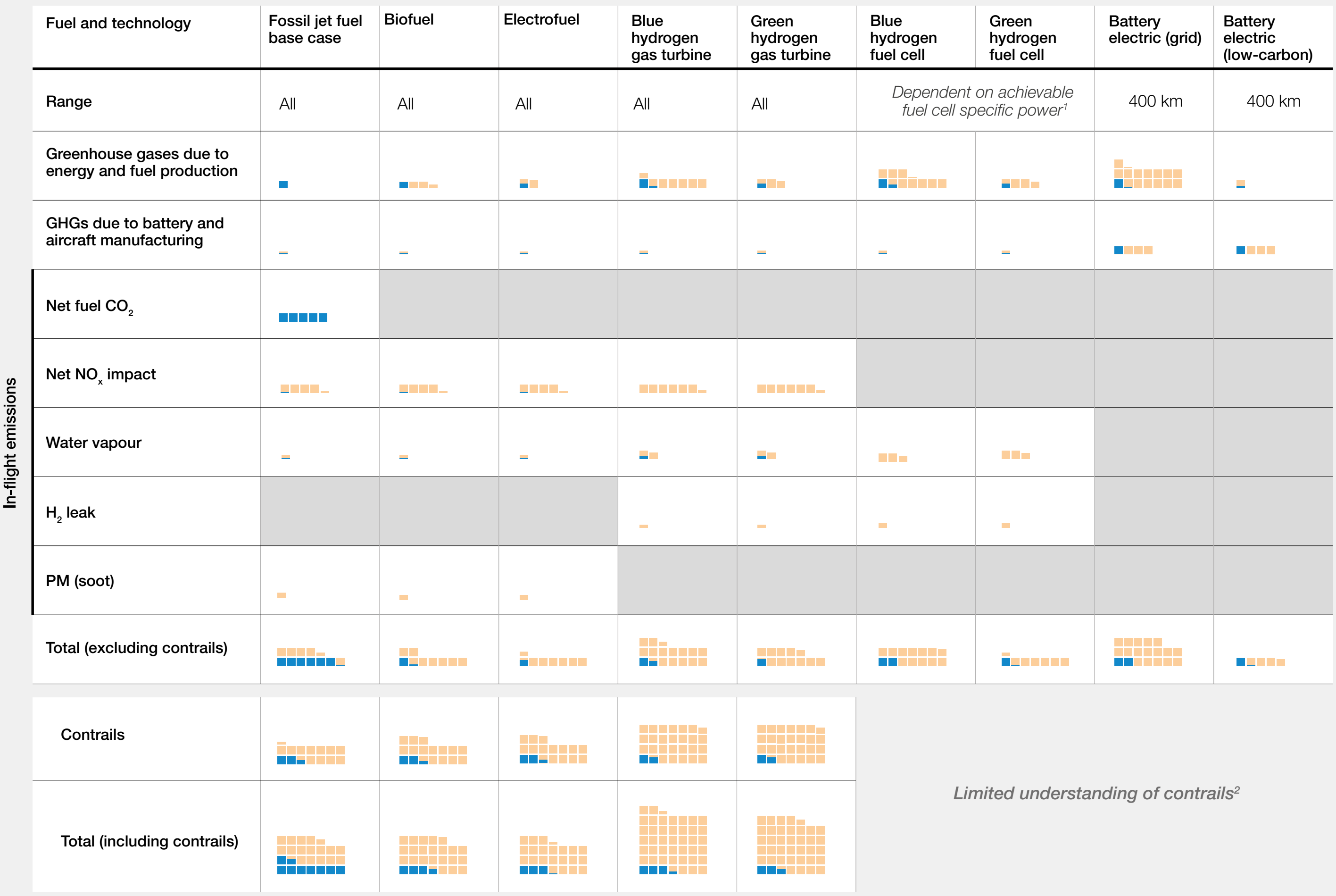
SAFs are produced from non-fossil sources but have properties almost identical to conventional jet fuel. These fuels still result in CO_2 being emitted from an aircraft; however, they result in reduced life cycle CO_2 emissions as they are produced by recycling carbon or using carbon that would otherwise have been released into the atmosphere. Unless specified, traditional kerosene-based jet fuels and SAFs are both referred to as jet fuel in this report.

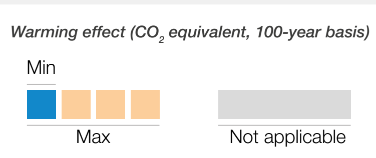
Two main types of SAF exist: biofuels and electrofuels.

- Biofuels are already used in aviation. They are primarily produced from biological sources and can lead to life cycle emissions reductions of up to approximately 80%. However, the biological sources are either limited in supply or require a large land area, which has implications for biodiversity and displacement of food crops, further limiting their supply.
- Electrofuels are produced using renewable electricity to decompose the water molecule into oxygen and hydrogen and combine the latter with carbon captured from the atmosphere, using the Fischer-Tropsch process. Theoretically, this can lead to life cycle emissions reductions of 100%. They have the advantage of using less land in their production than biofuels; however, their cost will be much higher, and the technology required to capture carbon from the atmosphere has not yet been demonstrated at scale.

While the primary benefit of SAFs is reducing CO_2 emissions over the fuel's life cycle, the chemical make-up of some types of SAF could potentially generate other climate benefits due to reduced soot emissions and contrail impacts compared to jet fuel.

FIGURE 1 | Total climate impact of conventional and alternative propulsion technologies





[1] As discussed in the report, fuel cell aircraft have the technical capability to fly mid-range and even beyond, but whether in practice this will be achieved will depend on the achievable fuel cell specific power.

[2] Battery-electric aircraft do not produce contrails, but neither do jet fuel aircraft flying the same route (at low altitudes), to which they are referenced. Contrails could be avoided on fuel cell aircraft through good water management but, if not managed, contrail formation is not well-understood at the moment.

Source: Aviation Impact Accelerator

Using the AIA's model, Target True Zero has analysed the total climate impact of different propulsion technologies that could exist in 2035. By that point, hydrogen-powered aircraft and more advanced types of SAFs could be available. Figure 1 shows a systematic assessment of the total climate impact, represented as CO_2 equivalent impacts generated by a single economy class passenger per km. To compare the climate impact of the different types of emissions, their impact has been averaged over a 100-year period, as the climate impacts associated with them occur on different time scales.

The purpose of this analysis is to present a comparison of the environmental impact of the different decarbonization options that exist based on the latest climate science and an understanding of future technologies and energy systems. There are still significant uncertainties associated with analysis – due to areas where greater scientific clarity is needed or where future decisions on fuel or energy production or aircraft design and operation are not yet known. To provide a comprehensive analysis, Figure 1 presents the best- and worst-case scenarios – both the minimum and maximum potential climate impact associated with each.

As noted above, because there is particularly high uncertainty around the climate impact of contrails for different propulsion types and because it may be possible to avoid these impacts altogether with operational changes, two totals are provided – with and without contrail impacts. Contrail avoidance by route and altitude changes is desirable when using fuels with minimal climate impact. The additional fuel penalty represents a relatively negligible climate impact compared to the contrails avoided.

Presenting the information as shown in Figure 1 allows future decision-makers to understand the opportunity that each of these technology options present for reducing climate impacts but also informs them about potential risks associated with each that will need to be addressed if the desired impact is to be achieved. It is important to note that further scientific understanding – especially about non-CO_2 emissions during flight – is expected to reduce the uncertainty about how different propulsion options will perform. However, realizing the best-case scenario will require decisions with tangible economic consequences – such as investing in cleaner energy infrastructure, operating aircraft in certain ways, or incorporating advanced aircraft design features to manage emissions.

From this analysis, some key observations can be made about the three alternative propulsion technologies being considered in this report:

Battery-electric:

- Battery-powered aircraft would eliminate CO_2 and all other in-flight emissions. It should be noted that for the types of very short routes where these would most likely be used, the altitude they fly at means contrails are not expected to be a significant issue for aircraft using jet fuel. Even in larger aircraft on these short routes, the proportion of the aircraft's flight at cruise altitudes where contrail formation is of concern is very low.

- In a best-case scenario, where fully renewable energy was used to charge the batteries, the full life cycle climate impact of producing and using the electricity would be minimal. However, aircraft operations limit the times when "in situ" battery charging occurs and would likely require charging from the grid. Electrical grids in many parts of the world will not be zero-emission by 2035, and this could result in a life cycle impact that is potentially greater than the use of SAF or even traditional jet fuel.

- Battery manufacture is currently associated with a major climate impact. This could be a significant cause of emissions over the life cycle

“ Electrical grids in many parts of the world will not be zero-emission by 2035, and this could result in a life cycle impact that is potentially greater than the use of SAF or even traditional jet fuel.

For hydrogen fuel cell electric and hydrogen combustion gas turbine aircraft, the life cycle climate impact of hydrogen fuel is highly dependent on the method of hydrogen production.

of a battery-electric aircraft because the batteries would need to be replaced somewhere between every few hundred and every few thousand flights. The climate impact, therefore, depends on the processes used to manufacture the batteries, how often the batteries are replaced and whether, once removed, the batteries have a secondary use in another industry.

Hydrogen fuel cell electric:

– Like fully battery-electric aircraft, fuel cell aircraft have the advantage of no in-flight CO_2, NO_x or soot emissions, but could still release water vapour into the atmosphere. Certain design decisions and the low temperatures at which fuel cells operate could allow the potential to condense any water vapour into a liquid in the exhaust. This would reduce these effects but require a more complicated design, which would be more costly to operate and potentially use more fuel due to additional drag.

– Uncertainty about how water vapour is dealt with on fuel cell aircraft makes it especially difficult to assess their full climate impact due to its effect on contrail formation. If water was to remain in vapour form, high uncertainty about the climate impact of hydrogen contrails means there is a chance the impact could be greater than contrails from jet fuel aircraft. If the water is managed and condensed into liquid form, it could be possible to eliminate these impacts entirely.

Hydrogen combustion:

– Hydrogen combustion would eliminate CO_2 and soot emissions in-flight but would still produce NO_x emissions, resulting in increased water vapour compared to jet fuel.

– Assessing the total climate impact of hydrogen combustion aircraft is especially difficult due to the high uncertainty about the climate impact of hydrogen contrails. While the increased water vapour means contrails would be more likely to form, it is not certain whether their different composition (e.g. no particulate formation) would result in a greater or lesser climate impact. There are currently no experimental measurements of contrails formed by hydrogen aircraft, although some studies are planned for the middle of the decade. Even if the impact of hydrogen contrails were greater than those produced from flying on jet fuel, there remains the possibility that changes to aircraft operations could be used to reduce or eliminate contrail formation from both hydrogen and traditional jet fuel aircraft.

– This uncertainty in contrail impact of hydrogen combustion aircraft also applies to SAFs, albeit to a much lesser degree. Due to their precise chemical composition (low aromatic content), SAFs generally produce slightly more water than fossil jet fuel but potentially produce less soot. Evidence about contrails from SAFs will likely be established more quickly than hydrogen due to earlier flight trials of using 100% SAF and their use in blends.

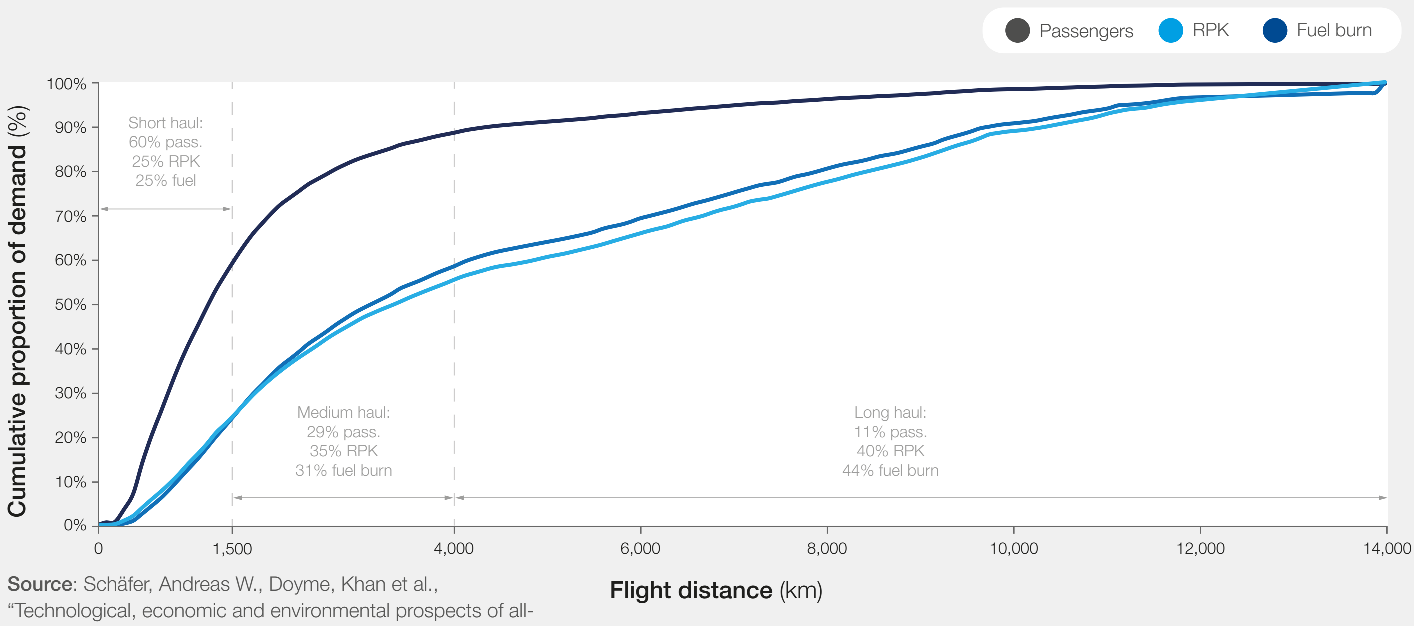
For hydrogen fuel cell electric and hydrogen combustion gas turbine aircraft, the life cycle climate impact of hydrogen fuel is highly dependent on the method of hydrogen production. In the worst-case scenario, "blue" hydrogen, produced using natural gas combined with carbon capture, could have a similar climate impact as the in-flight CO_2 that it eliminates. This is because not all the CO_2 is captured, and the remainder is emitted into the environment, along with any methane leaks. Using "green" hydrogen, produced by electrolysis using renewable or low-carbon electricity, would remove this climate impact.

While there remains much uncertainty about the total climate impact of alternative propulsion technologies, these findings demonstrate that they present an opportunity to transition to a more sustainable future aviation system. A priority for industry and governments in the coming years should be working to reduce the current scientific uncertainty, as well as taking decisions now so that the full potential of these technologies can be realized.

1.2 Applications of alternative propulsion technologies

FIGURE 2

Cumulative proportion of scheduled commercial passengers (pass.), revenue passenger kilometres (RPK) and fuel burn as a function of flight distance. Note: fuel burn is comparable to CO_2 in-flight



Source: Schäfer, Andreas W., Doyme, Khan et al., "Technological, economic and environmental prospects of all-electric aircraft", Nature Energy. Vol. 4, 2019, pp. 160-166

Batteries and hydrogen are types of energy carriers – a fuel or system that contains energy that can be converted to some other form – as is conventional jet fuel. Alternatives to jet fuel have long been explored. Yet, the transition away from hydrocarbon fuels for aviation has lagged other sectors due to energy carrier requirements for aviation, which are much higher than for ground-based applications such as automobiles. This is because the energy in the energy carrier must overcome the drag of an aircraft to propel it forward. The drag of an aircraft is proportional to its lift, and in level flight, this must balance the weight of the aircraft. A heavy energy carrier produces a high aircraft drag and energy requirement. This in turn increases the weight of the energy carrier. As a result, energy carriers in aviation must be very light.

Two determinants of how suitable an energy carrier is for aviation are its gravimetric and volumetric energy density:

– **Gravimetric energy density:** This is how much energy there is within a given weight of an energy carrier. A high gravimetric energy density means that the aircraft is light and therefore has a low energy requirement for a given flight. A low value means that the aircraft is heavy and has a high energy requirement for the same flight.

– **Volumetric energy density**: This is how much energy can be stored within a given volume. A high volumetric energy density means the space required to store the energy within the aircraft is small. A low value means that the aircraft's size must increase to hold the same amount of energy, which increases the aircraft's drag, weight and cost.

While both measures are important, gravimetric energy density has the most significant impact on aircraft capability. As the range of an aircraft increases, the total energy that must be stored in the aircraft rises both in absolute terms and as a proportion of the aircraft's total weight. For example, for a traditional aircraft, on a short-haul flight, about 15% of the plane's mass at take-off is fuel, whereas, for long-haul flights, this rises to about 40%.[8] In simple terms, gravimetric energy density can be seen as the factor determining the aircraft's range. The effect of volumetric energy density is more subtle, and to understand this correctly, an aircraft design must be undertaken. This will be discussed in more detail later in the report.

The importance of designing an aircraft with appropriate range can be seen when the profile of aviation emissions across the whole sector is considered. Figure 2 shows the fraction of passengers, RPK and total fuel burnt from short-, medium- and long-haul aircraft. While only 40% of passengers fly medium- or long-haul, they are responsible for 75% of the fuel burn. This means that most of the climate impact of aviation comes from medium and long-haul routes. Solutions that can be applied to these market segments will deliver the most significant climate benefits.

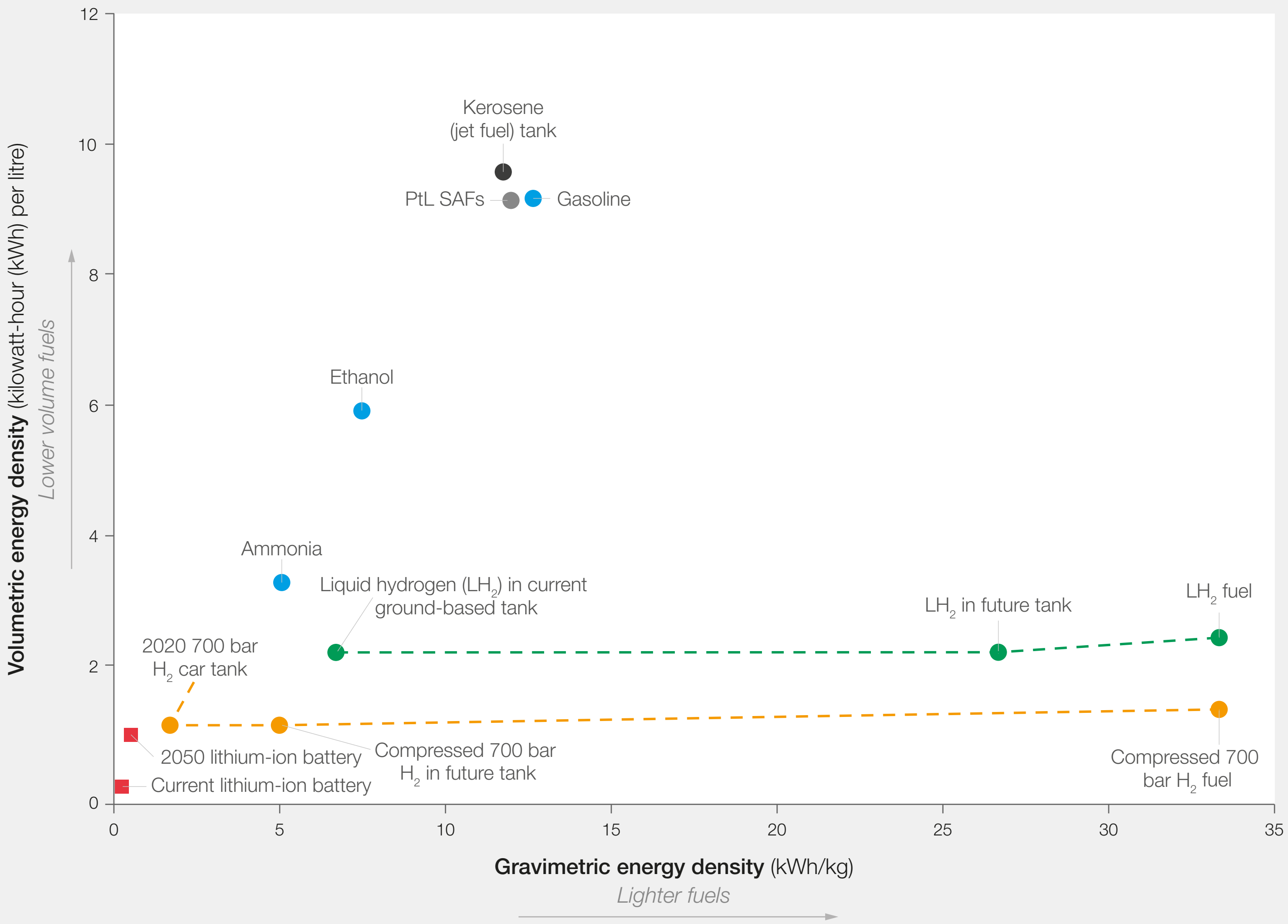
“For a traditional aircraft, on a short-haul flight, about 15% of the plane's mass at take-off is fuel, whereas, for long-haul flights, this rises to about 40%.

Figure 3 shows the gravimetric and volumetric energy density of various energy carriers, including jet fuel, SAF, lithium-ion batteries and different forms of hydrogen. As SAFs have properties almost identical to traditional jet fuel, their gravimetric and volumetric energy densities are very similar, and the range of an aircraft using SAF instead of traditional jet fuel is not impacted. Both batteries and hydrogen have energy densities that are very different from jet fuel, meaning there are different considerations if used for aviation.

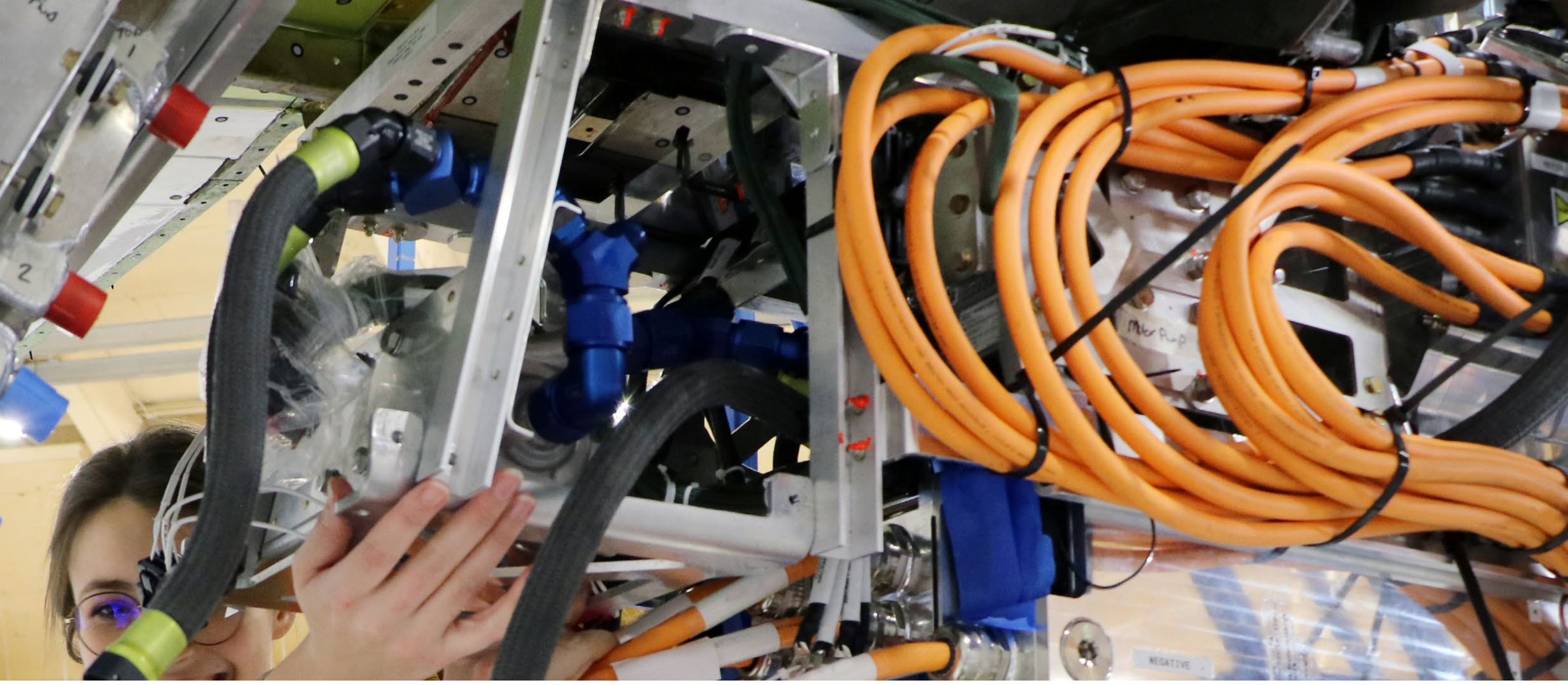
– Existing lithium-ion batteries can be seen to have gravimetric energy densities, which are around fifty times lower than jet fuel. This difference will remain significant even with expected improvements in battery technology. Their low gravimetric energy means battery-powered aircraft are limited to short-haul, though the exact range is the subject of intense debate. Breakthroughs arising from radically new battery chemistries may significantly increase the range of battery-electric aircraft in the future. It is, however, impossible to predict when or if these might become available or the improvements they would deliver.

– The situation with hydrogen is more complicated. The volumetric energy density of liquid hydrogen is only around a quarter of that of jet fuel. This will mean an increase in the size of the aircraft's fuselage (where the liquid hydrogen must be stored), with a consequent increase in the aircraft's drag, weight and cost. Hydrogen benefits from a gravimetric energy density three times higher than jet fuel. While existing methods of storing it mean that the gravimetric energy density of the fuel and tank is currently lower than jet fuel, expected advances in lightweight cryogenic tanks could mean liquid hydrogen – which doesn't require the heavy, pressurized tanks that gaseous hydrogen does – could achieve a gravimetric energy density that is over twice that of jet fuel. Given that gravimetric energy density is a more important factor for aviation, liquid hydrogen fuel offers significant potential for powering long-range aircraft if it can be designed for the liquid hydrogen's low volumetric energy density.

FIGURE 3 **Volumetric and gravimetric energy density of a selection of hydrocarbons and batteries, as well as liquid and compressed hydrogen stored in different tanks**



Source: Aviation Impact Accelerator



> “ **Using liquid hydrogen as a fuel will allow new types of jet engine to be designed, which could be significantly more efficient than current jet engines.**

While the energy densities of hydrogen and current batteries are well understood, competing views remain about the capabilities these would provide at the aircraft level. To build consensus on this topic, the AIA has undertaken extensive modelling to understand what capabilities aircraft using these energy carriers could achieve with the technologies that will be available in the near future. 2035 has been chosen as a reference point for this analysis, as it would allow the maturation of critical technologies. It represents a realistic time frame for designing, certifying and commercializing an aircraft using novel propulsion systems. Based on an assessment of the underlying technologies, aircraft employing these different propulsion technologies could achieve the following in this period:

- **Battery-electric aircraft**: The maximum operating range of lithium-ion battery-electric aircraft by 2035 is around 400 km, rising to 600 km in 2050. These figures are largely independent of the number of passengers an aircraft would carry. While the economics of existing aircraft means the number of passengers usually increases with route length, larger planes sometimes carry a high number of passengers short distances even if these are not the routes they are optimized to operate. It is possible that the economics of electric aircraft could support very different business models and serve shorter routes with high demand using large aircraft. Considering Figure 2, aircraft powered using lithium-ion batteries have the potential to displace up to 5% of the current fossil fuel burn of the aviation sector. Extending the range of these aircraft beyond this limit would require the use of breakthrough battery technologies, the development and commercialization of which are extremely difficult to forecast.

- **Hydrogen fuel cell aircraft:** This technology will allow aircraft to be designed for a range of around 2,000 km by 2030. If efficient cooling methodologies for larger fuel cell systems can be developed, that range could reach 4,000 km by 2035. Hydrogen fuel cell aircraft, therefore, have the potential to replace between 30% and 50% of the current fossil fuel burn in the aviation sector.

- **Hydrogen combustion jet aircraft:** The take-off weight of the longest-range aircraft operating on liquid hydrogen is likely to be significantly lighter than the weight of an equivalent range of a traditional aircraft using jet fuel. In addition, using liquid hydrogen as a fuel will allow new types of jet engine to be designed, which could be significantly more efficient than current jet engines. This means that by 2035, hydrogen aircraft may be able to operate over the same distances as current jet-powered aircraft. This offers the potential to replace current jet fuel-powered aircraft at any range and means SAFs are not the only viable option for decarbonizing the longest-range flights.

The above findings are based on the assumption that key technological developments will enable such future aircraft. This report is not attempting to forecast the rate at which these technologies, once developed, will enter the fleet. Other factors that will determine this include the economic viability of producing such aircraft, the total cost of ownership and operation compared to alternatives, and how policy or regulations might incentivize or require adopting technologies with reduced climate impact. While this report is focused only on the options these technologies will present, future work of Target True Zero will explore these issues in more detail.

1.3 Unlocking alternative propulsion

The above findings show that battery and hydrogen-powered aviation provide significant opportunities for addressing the climate impact of aviation and help to establish the evidence about what capabilities these aircraft could deliver by the middle of the next decade. These findings demonstrate what could be possible in this timeframe but are not assured. To ensure that alternative propulsion technologies can be deployed in a timely and sustainable manner to reduce the climate impact of aviation, Target True Zero has identified eight technological unlocks that will be needed if the opportunities of alternative propulsion are to be realized. The first three unlocks focus on reducing the climate impact of energy and battery production to ensure that in-flight emissions savings are not replaced by emissions elsewhere. The following four unlocks will help extend the performance of alternative propulsion aircraft by maximizing their range and efficiency, thereby improving their potential as alternatives to conventional jet fuel. The final unlock concerns increasing the knowledge of contrails, with the aim to avoid their climate impact.

FIGURE 4 **Technological unlocks that will contribute to reaching true-zero flight**

- **Technology unlock 1** Ensuring aviation batteries are charged with renewable energy
- **Technology unlock 2** Accelerating the introduction of green hydrogen
- **Technology unlock 3** Improving battery life cycles and management for aviation
- **Technology unlock 4** Improving battery-electric aircraft energy density
- **Technology unlock 5** Developing lighter fuel cell systems
- **Technology unlock 6** Developing lighter storage tanks for liquid hydrogen
- **Technology unlock 7** Redesigning aircraft for optimized hydrogen performance
- **Technology unlock 8** Contrail research and mitigation

Other unlocks

The technological unlocks above will be essential if the potential of battery and hydrogen-powered aviation is to be realized. These will not be sufficient on their own. There are also obstacles related to industry dynamics and supply chains, infrastructure, and policy and regulation that will need to be addressed if these technologies are ever to be deployed at scale within the aviation system. Target True Zero will work to address the critical questions of these other aspects to ensure that both industry and government decision-makers can make informed decisions to ensure alternative propulsion technologies play their full part in addressing the climate impact of aviation.

2 Technology unlocks

In order to move towards an aviation system with a true zero climate impact, eight key unlocks need to be realized.

2.1 Technology unlock 1

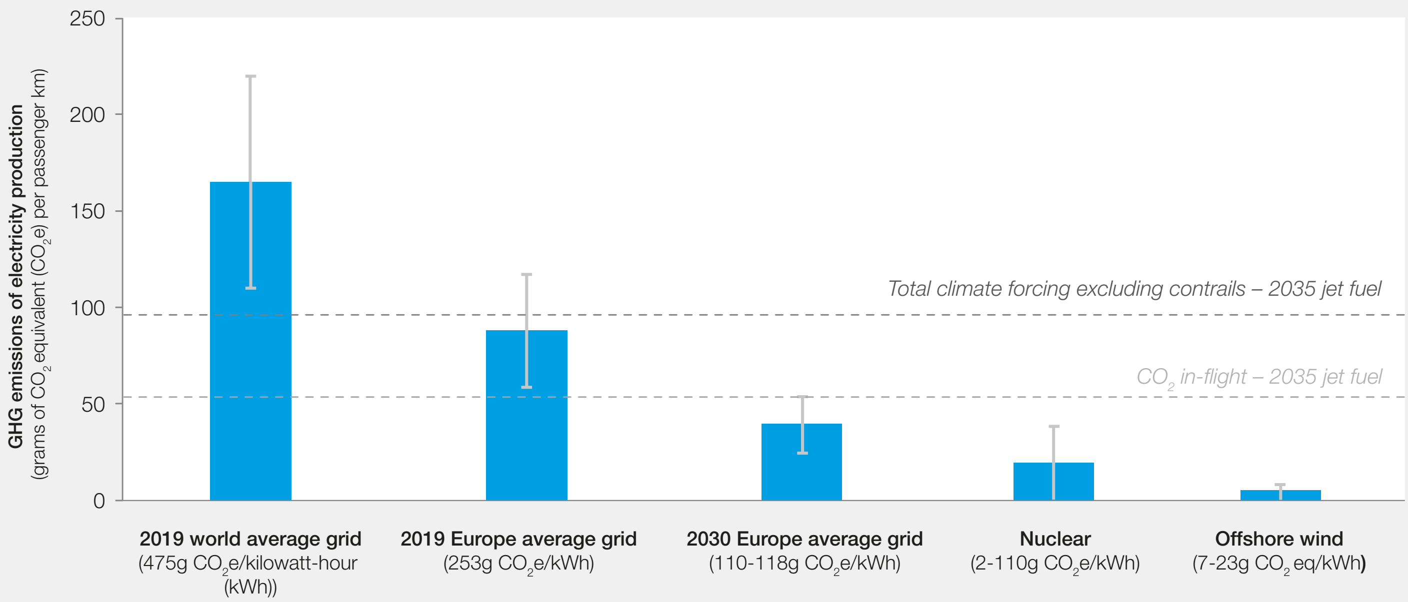
Ensuring aviation batteries are charged with renewable energy

A significant factor determining the economics of operating an aircraft is how heavily it can be used – and how quick the turnaround time is between landing and taking off again. For battery-electric aircraft, batteries must be recharged as soon as possible after landing. This requirement makes battery-electric aircraft unsuitable for direct connection to renewable electricity sources due to their intermittency. It is therefore likely that battery-electric aircraft would be charged directly from national or regional electricity grids, which in many areas of the world will remain partly powered by fossil fuels for many years to come.

Figure 5 shows the greenhouse gas (GHG) emissions caused by the electricity production of different methods for charging battery-electric aircraft. It shows that if battery-electric aircraft were charged from a world or European average grid today, switching from jet fuel to battery-electric aircraft would increase GHG emissions.

By 2030 it is shown that the advantage of switching from jet fuel aircraft to battery-electric aircraft in Europe would only result in around a 30% to 50% reduction in GHG emissions. This compares to more than an 85% reduction if fully renewable electricity is used. The opportunity presented by battery-electric aircraft for reducing aviation emissions depends on finding ways to ensure that they will be charged by renewable or nuclear electricity.

FIGURE 5 **GHG emissions in electricity production required to charge electric aircraft**



Source: Aviation Impact Accelerator

Two options are available to avoid charging battery-electric aircraft directly from the grid. The first option is to ensure that airports have appropriate capabilities for preventing the need to charge batteries directly from the grid when renewable sources are not available. This could involve having ample storage so that renewable energy produced during energy supply peaks could be used when supply is low or by using low-carbon electricity options such as nuclear or hydro, which are less intermittent than solar or wind power. The second option is to decouple the need for batteries to be charged between landing and take-off. Most current designs for battery-electric aircraft have fixed batteries, which are usually simpler and reduce aircraft weight. If batteries could be swapped in and out of aircraft, that would enable batteries to be charged off-plane using renewable electricity while also allowing a degree of flexibility to charge during energy supply peaks. This solution would also enable batteries to be charged at a slower rate, which is more efficient and preserves battery life. Additionally, swapping batteries could allow aircraft to load only the batteries they need for a particular mission, which is more energy-efficient and allows older batteries to be used for shorter missions, extending their lifetime.

2.2 Technology unlock 2
Accelerating the introduction of green hydrogen

Clean hydrogen can be produced in two major ways, as shown in Figure 6. Blue hydrogen is created using fossil fuel (natural gas) and then uses carbon-capture technology to store the CO_2, which is released as a by-product. Green hydrogen is made by converting water into hydrogen and oxygen in a process called electrolysis, powered by renewable electricity.

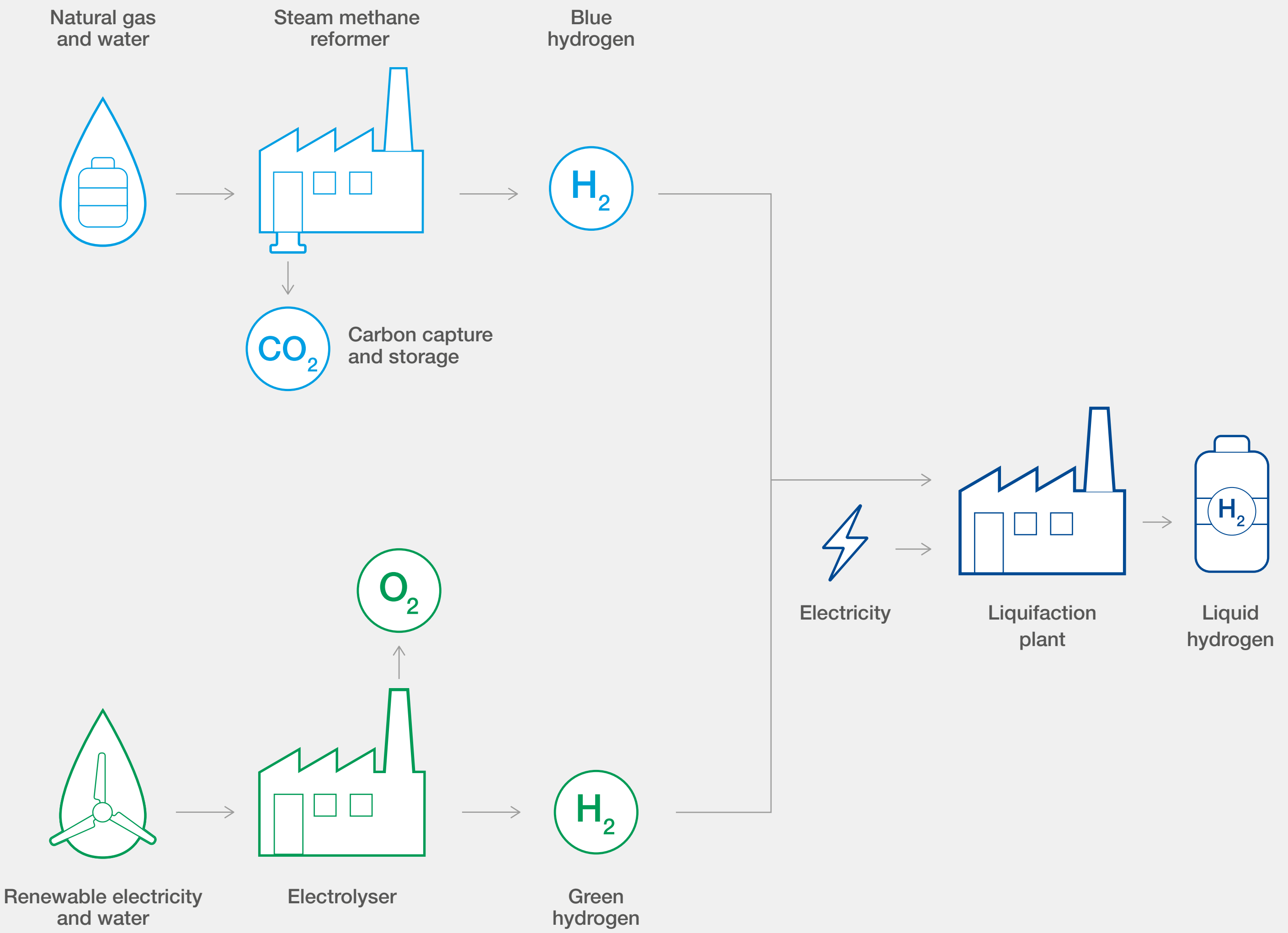
The route of hydrogen production can significantly influence the total climate impact of using hydrogen for aviation. To illustrate this, the climate impact of the on-ground fuel production and distribution of hydrogen, for a flight from New York to London in 2035 is shown in Figure 7. For simplicity, due to the uncertainty – particularly concerning contrails – the climate impact of non-CO_2 effects in-flight has been removed.

Both blue and green hydrogen eliminate in-flight CO_2 emissions for the hydrogen-powered aircraft.

However, the production of blue hydrogen has the potential to result in an overall climate impact similar in scale to the fossil jet fuel-powered aircraft. This is because the production of blue hydrogen can result in CO_2 emissions that are not properly captured and methane that is leaked into the atmosphere – offsetting the CO_2 savings during flight. Using green hydrogen produced using renewable electricity has no such climate impact.

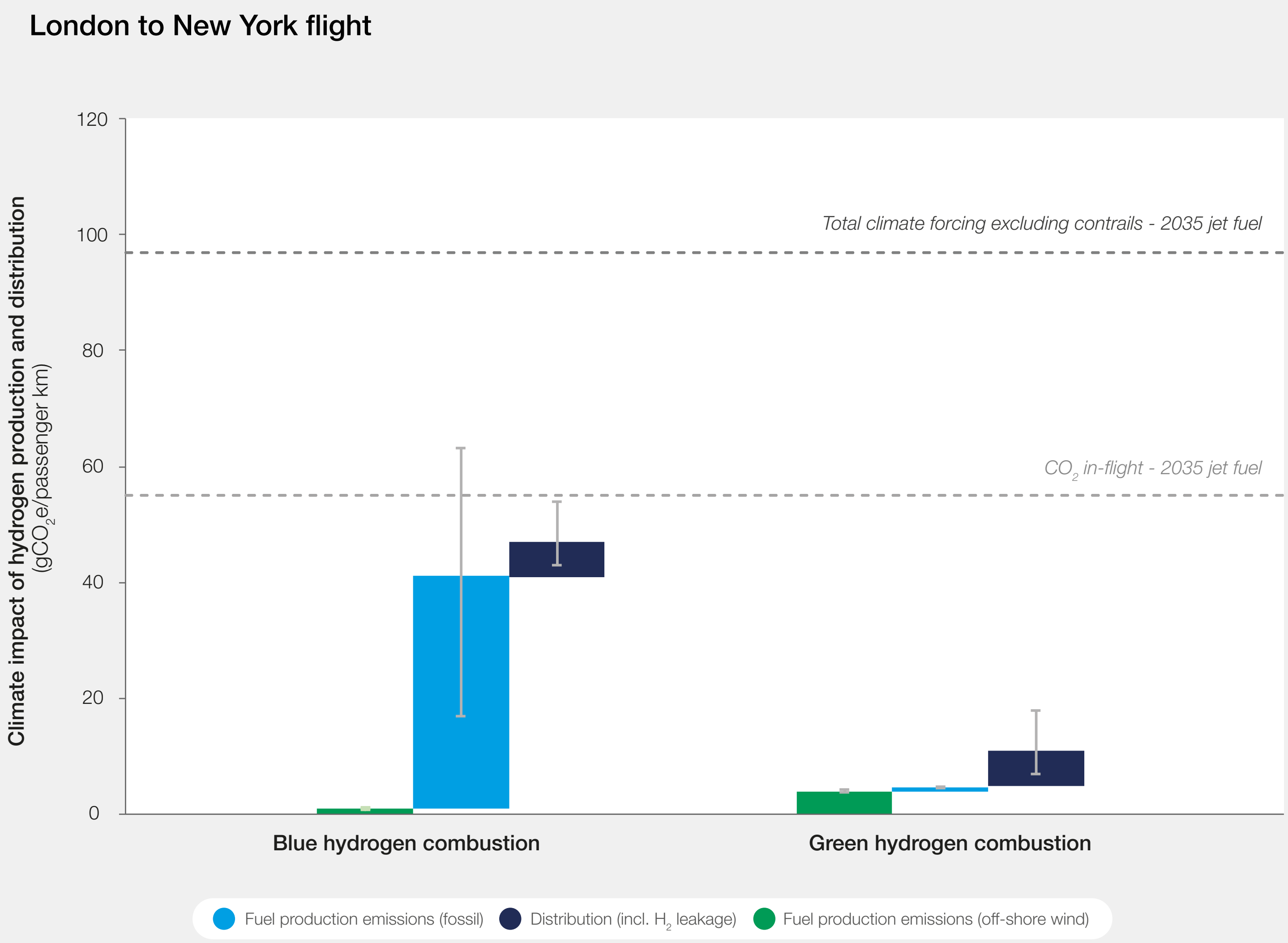
To ensure hydrogen aircraft deliver the intended climate benefits, it will be necessary to use green or blue hydrogen that conforms to the highest environmental standards. Given the risk that blue hydrogen may not result in any level of climate improvement compared to jet fuel, steps should be taken to ensure a sufficient supply of green hydrogen by 2035, when the first medium- or long-haul hydrogen aircraft could enter the market.

FIGURE 6 **Production of blue and green liquid hydrogen**



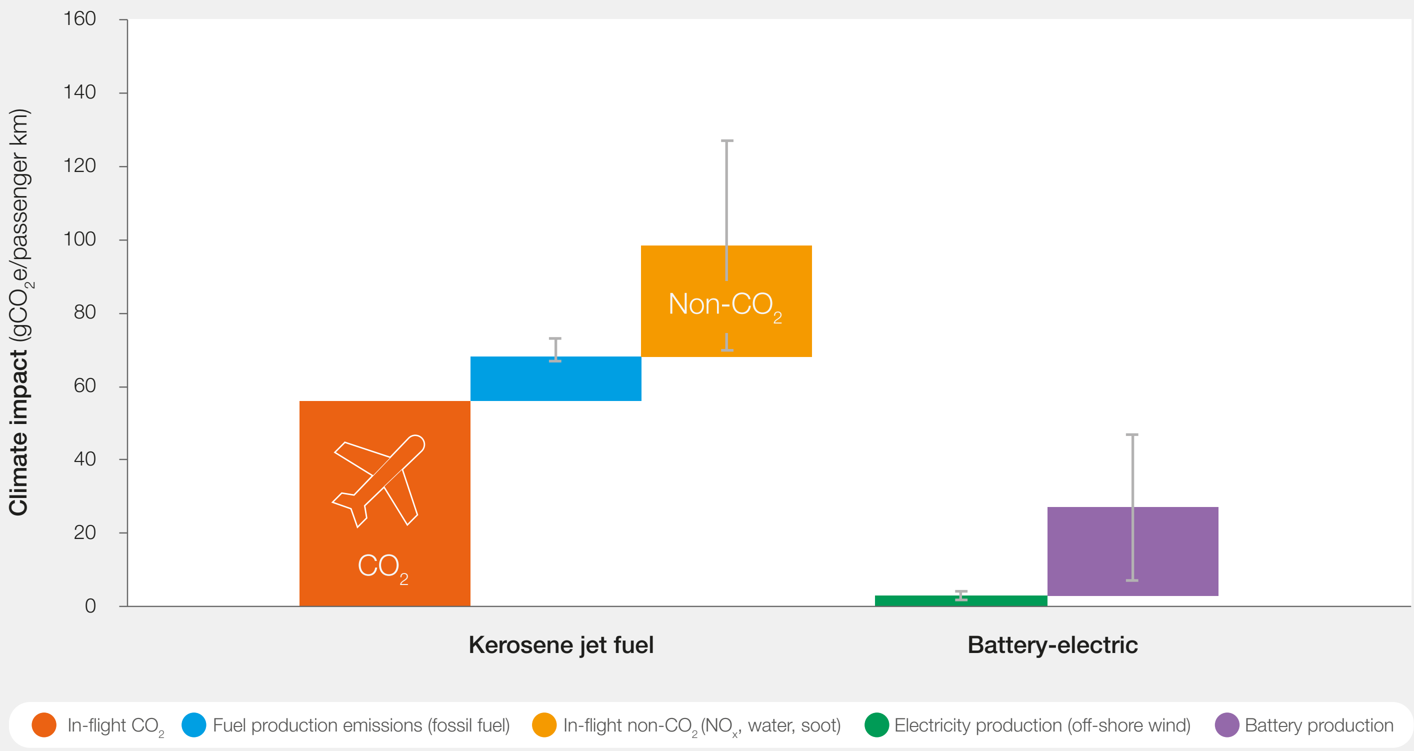
Source: Aviation Impact Accelerator

FIGURE 7 | **Climate impact of hydrogen production and distribution**



Source: Aviation Impact Accelerator

FIGURE 8 | **Climate impact of a battery-electric flight**



Source: Aviation Impact Accelerator

2.3 Technology unlock 3

Improving battery life cycles and management for aviation

Battery capacity degrades with use. Battery-electric aircraft would therefore require their batteries to be replaced, somewhere between every 500 to 10,000 charging cycles,[9,10] which could be as often as every few months. This has the potential to amount to a significant climate impact over the lifespan of the aircraft.

Figure 8 shows the climate impact of a battery-electric aircraft per passenger per km flown compared to an equivalent fossil fuel-powered aircraft. The climate impact of battery production could be up to 75% of the climate impact of the in-flight CO_2 of the equivalent jet fuel aircraft if the batteries are replaced every 500 cycles. This impact can be reduced by making the production of new batteries cleaner, finding ways to extend the number of flights before the batteries must be replaced, or by finding a secondary use or efficiently recycling the batteries that have been removed from the aircraft.

Several methods can be employed to reduce the impact of battery production. The first is to reduce the emissions associated directly with battery production by switching to cleaner methods of raw material extraction and production and maximizing the use of recycled materials (including used batteries) in the production of new batteries. A second way is to optimize the number of cycles the batteries can complete before needing to be replaced. This can be achieved by avoiding situations known to cause battery degradation – such as charging or discharging too quickly or running them down to 0% charge – or by battery swapping, which would allow slower rates of battery charging and the use of older batteries on shorter missions. In addition, reducing the range that battery-electric aircraft fly with a given quantity of batteries, either during service or by design, allows batteries to degrade more before they have to be replaced.

Finally, after the performance of batteries drops below a certain threshold, using aviation batteries for ground-based applications, such as grid storage where the gravimetric energy density of batteries is much less important than in aviation, would prolong their useful life and reduce the impact of battery production elsewhere in the economy.

“ Reducing the range that battery-electric aircraft fly with a given quantity of batteries, either during service or by design, allows batteries to degrade more before they have to be replaced.

2.4 Technology unlock 4
Improving battery-electric aircraft energy density

While the range of battery-electric aircraft is limited due to the energy density of existing batteries, finding ways to maximize this will allow an increased number of routes for which they are a viable alternative to other aviation technologies. Extending the range of battery-electric aircraft can be achieved by increasing the aircraft's energy density, i.e. the useable energy stored in the batteries divided by the aircraft's total weight. This can be done by increasing the specific energy of the batteries or by reducing the overall structural weight of the aircraft.

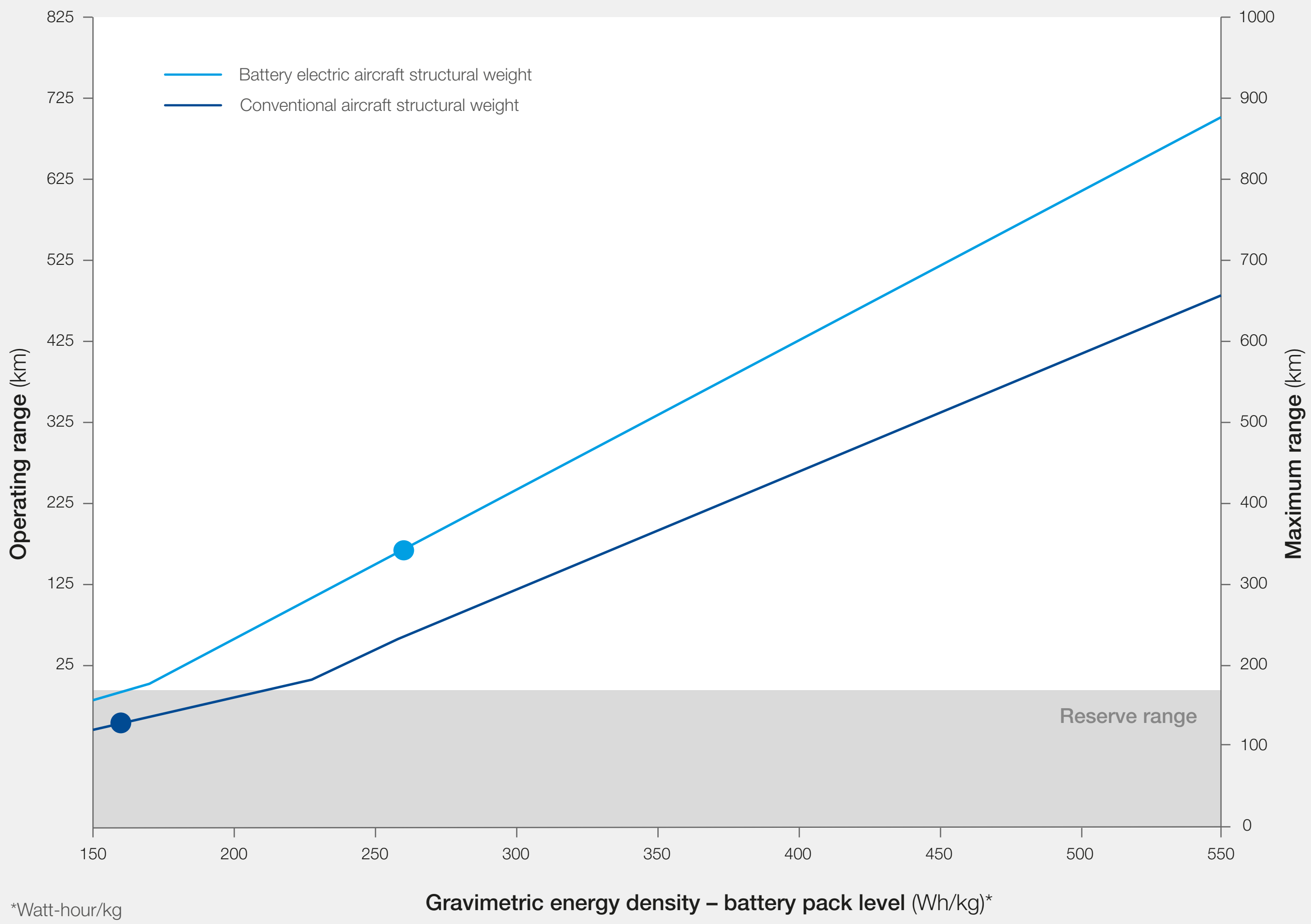
Figure 9 shows how aircraft structural weight and battery gravimetric energy density influence the operational range (incorporating a reserve range of 175 km for safety) of battery-electric aircraft. In this figure, the battery gravimetric energy density is defined at the pack level; the weight of the battery includes the weight of the individual battery cells, the interconnects and the packaging.

The dark blue line represents a conservative scenario where the aircraft's structural weight is 55% of the total weight. This is representative of the structural weights used in aircraft designs today. The dot is fixed on the line by the gravimetric energy density of batteries certified to be used in aviation today.

The light blue line represents an optimistic scenario where the aircraft's structural weight is 45% of the total weight. This is representative of the structural weights the new entrant battery-electric aviation companies aim to achieve. The dot is fixed on the line by the gravimetric energy density of batteries, which the new entrant aims to achieve.

Whether the conservative or optimistic scenarios are used for the underlying assumptions, Figure 9 shows that the operating range of lithium-ion battery-electric aircraft available in the next few years varies anywhere from 0 (once the necessary reserve range is factored in) to about 150 km.

FIGURE 9 **Maximum and operating ranges of battery-electric aircraft**



*Watt-hour/kg

Source: Aviation Impact Accelerator

Though reducing structural weight is essential for any aircraft, Figure 9 illustrates how for battery-electric aircraft, it is a critical requirement for increasing operating range and the capability of batteries. Ultimately, it is the total energy density of the entire battery-electric aircraft that matters.

Current forecasts for the gravimetric energy density of lithium-ion batteries at pack level in 2035 is 240-370 watt-hours per kilogram (Wh/kg); in 2050 it is 390-500 Wh/kg. Figure 9 shows that, using optimistic assumptions on both aircraft structural weight and the highest possible gravimetric energy densities of lithium-ion batteries in each time frame, there is opportunity to achieve operating ranges for battery-electric aircraft up to 400 km by 2035 and 600 km by 2050. For context, a 600 km range would make battery-electric aircraft viable for routes that currently make up 5% of the industry's fuel burn.

Further increases in the operating range of battery-electric aircraft will require the use of different battery chemistries. While it is impossible to predict when such a breakthrough will occur, two promising radical battery technologies are aluminium-air and lithium-air. Both are currently still at the fundamental stage of research. If a lithium-air battery pack was commercialized at 1,000 Wh/kg (just 10% of its maximum theoretical gravimetric energy density), it could power an aircraft with an operating range of around 1,500 km, i.e. all short-haul flights. Such battery chemistries are still in very early stages of development, however. If they are proven in small-scale tests, it will take several years to commercialize a stable, safe product.

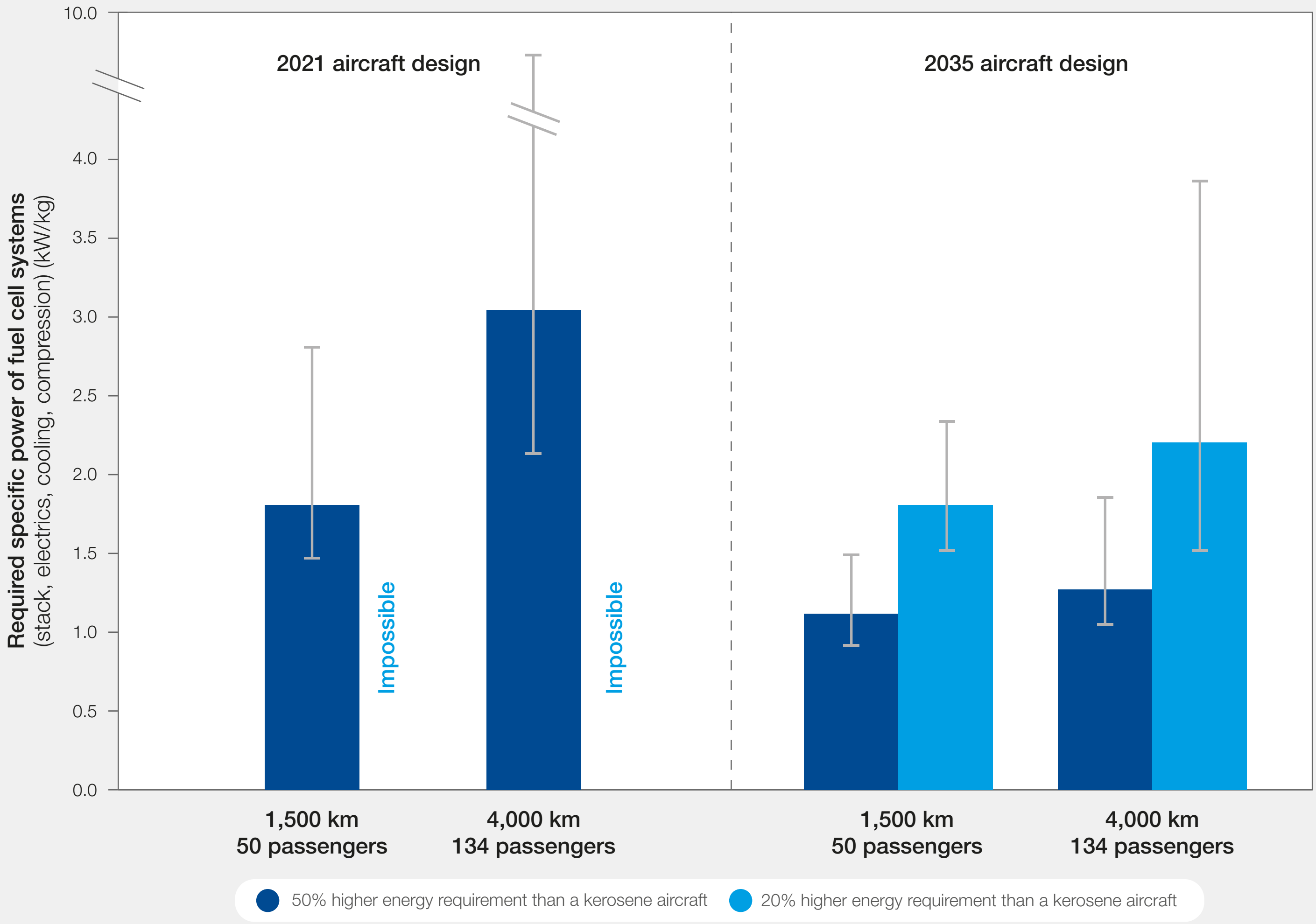
2.5 Technology unlock 5
Developing lighter fuel cell systems

Unlike battery-electric aircraft, which have an operating range limited by the low gravimetric energy density of batteries, fuel cell aircraft use hydrogen as an energy carrier and therefore have the potential to operate over much longer ranges. The major attraction of fuel cell aircraft over hydrogen gas turbine aircraft is their potentially extremely low total climate impact. The low temperature and pressure at which they operate mean that emissions such as NO_x and soot are eliminated. In addition, the low exhaust temperature offers the possibility of condensing out the water from the exhaust and then intermittently exhausting it in a way that avoids the climate impacts of water vapour and contrail formation.

The fraction of the aviation sector's total fuel burn displaced by fuel cell aircraft depends on the aircraft's range. The operating range of fuel cell aircraft is limited by the weight of the fuel cell system (stack, electronics, cooling, compression systems), which is higher than the weight of a gas turbine of the equivalent power. The weight of the fuel cell is set by the maximum power requirement during aircraft take-off and climb, which is significantly higher than the requirement in cruise. The operating range of a fuel cell aircraft is therefore determined by the specific power of the fuel cell system.

The effect of the specific power of the fuel cell system on the operating range of fuel cell aircraft using aviation technologies from 2021 and 2035 is shown in Figure 10. For each time frame, two aircraft have been designed, the first operating at the upper range limit of the short-haul sector (1,500 km) and the second at the upper limit of the medium-haul sector (4,000 km). Due to the weight of fuel cell aircraft being higher than that of a jet fuel aircraft operating at the same range and capacity, the energy required per passenger-kilometre must be higher. The dark and light blue bars represent aircraft that require 50% and 20% more energy per passenger-kilometre than the equivalent jet fuel-powered aircraft.

FIGURE 10 | **Required specific power of a fuel cell system**



Source: Aviation Impact Accelerator

The left-hand side of Figure 10 shows that using today's aerospace technologies, it is impossible to design a fuel cell aircraft with an energy per passenger-kilometre, which is 20% higher than the equivalent jet fuel-powered aircraft. Currently, fuel cell systems with a specific power of 1.5-2.0 kW/kg can be constructed. With such fuel cells, if an energy per passenger-kilometre 50% higher than the equivalent jet fuel-powered aircraft is accepted, the maximum operating range of a fuel cell aircraft is around 1,500 km.

The right-hand side of Figure 10 shows a dramatically different picture. If aerospace technologies, such as aircraft lift-to-drag ratio, or the weight of the hydrogen tank, are set to values that the industry considers possible in 2035, then it is possible to design a fuel cell aircraft with an operating range of 4,000 km with an energy per passenger-kilometre that is only 20% higher than the equivalent jet fuel-powered aircraft. The reason for this dramatic change is that the improvement in aircraft technologies reduces the aircraft weight, which counteracts the high weight of the fuel cell system. This effect is highly non-linear, with relatively small technological improvements resulting in a substantial increase in range.

This non-linear behaviour also means that any weight savings in the fuel cell system can significantly increase the range of fuel cell aircraft. A fuel cell system includes not only the fuel cell stack but also its casing, electronics, control, cooling and air compression systems. Up to 60% of the weight corresponds to the cooling system required to deal with the high levels of heat the fuel cells generate - especially during take-off. The development of high-temperature proton-exchange membrane (HTPEM) fuel cells – in contrast to low-temperature proton-exchange membrane (LTPEM) fuel cells that are standard in transport applications today – would enable fuel cells to operate at higher temperatures and may offer a way to achieve substantial weight reductions by allowing the heavier water cooling systems to be replaced by a much lighter air cooling system. However, such cooling systems have not yet been practically demonstrated. They are particularly challenging to design for take-off conditions, where the fuel cell operates at maximum power; high heat levels are generated, but the aircraft's airspeed is low, so air cooling is exceptionally challenging.

“ The development of high-temperature proton-exchange membrane fuel cells would enable fuel cells to operate at higher temperatures and may offer a way to achieve substantial weight reductions.

2.6

Technology unlock 6
Developing lighter storage tanks for liquid hydrogen

While hydrogen is very light, the current method of storing it using existing tanks makes it heavier than the jet fuel it would replace.

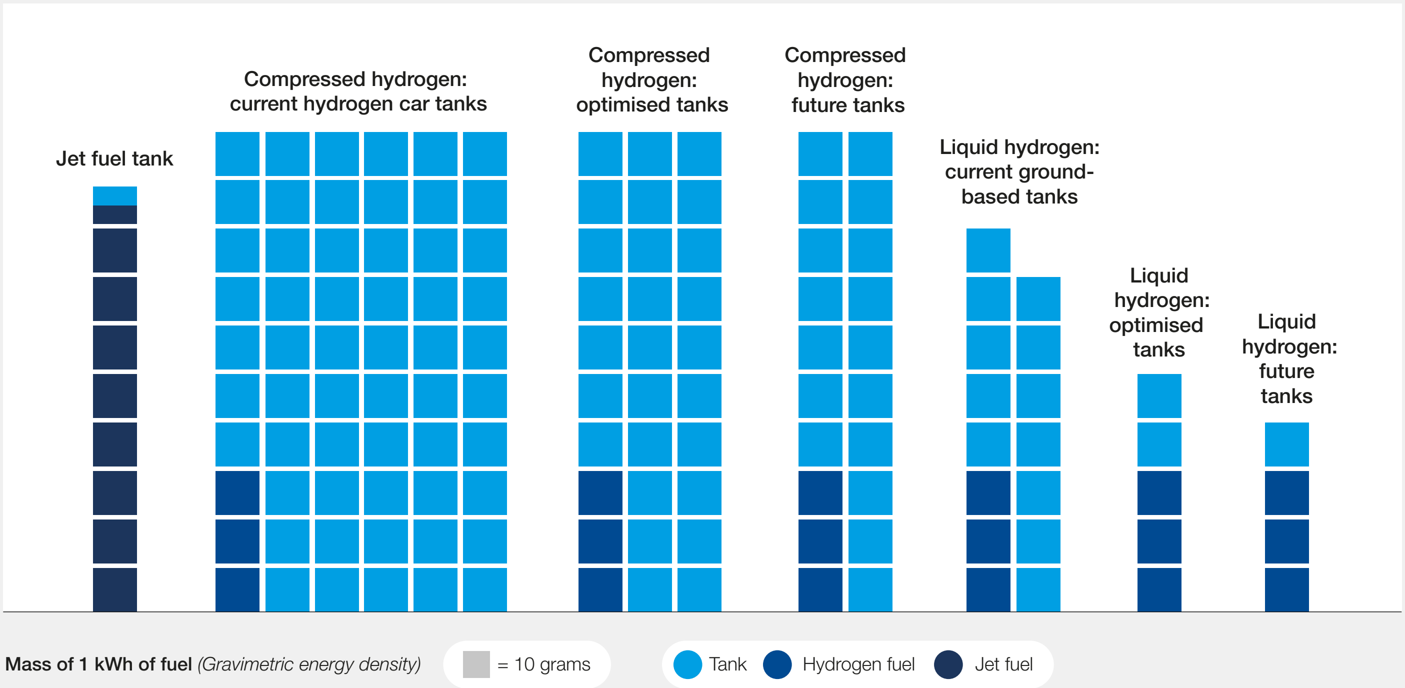
The total weight of fuel an aircraft carries increases as the range increases. The range of the aircraft is therefore primarily determined by the combined weight of the fuel and the fuel tank required to store it. While hydrogen is very light, the current method of storing it using existing tanks makes it heavier than the jet fuel it would replace. Reducing the weight of hydrogen tanks will therefore be important in maximizing the range of hydrogen aircraft – especially if they are to break into longer-haul routes where the weight of the fuel and fuel tank represents a more significant portion of the aircraft's overall weight.

The weight of hydrogen fuel tanks depends on whether the hydrogen is stored on the aircraft as a compressed gas at high pressure or as a liquid at very low temperatures. Figure 11 shows the mass required to store 1 kilowatt hour (kWh) of energy using jet fuel, compressed gaseous hydrogen and liquid hydrogen. Though the hydrogen in each case has the same weight, the weight of the hydrogen tank varies considerably. Storing compressed hydrogen at 700 bar requires incredibly heavy tanks.

The tanks used in current compressed hydrogen cars make up the vast majority of the total weight of the tank and fuel – about 95% – which could be reduced to 85% in the future with the development of new technologies.[11] Storing hydrogen as a liquid at temperatures below -250°C means it can be stored at much lower pressure, requiring much lighter tanks. Currently, ground hydrogen tanks storing liquid hydrogen make up about 80% of the total weight of the tank and fuel. Optimizing current technologies could reduce this to 40%, while developing new technologies could get this to 25% or lower. This would mean that the combined weight of the tank and fuel for liquid hydrogen could be half that of jet fuel.[12] It should be noted that these high gravimetric efficiencies depend on the tank size and shape; the tank must be large and either spherical or cylindrical with dome end caps. This indicates that the liquid hydrogen cannot be located in the wings – as jet fuel is – but must be located within the aircraft's fuselage.

Currently, hydrogen is mostly used in applications where weight is not as important a factor as for aviation. Compressed hydrogen is generally favoured for these applications due to its lower costs and ease of storage. Most industrial research and development is focused on improvements for compressed hydrogen storage. As a result, the aviation industry would need to spearhead efforts to focus on reduced weight for liquid hydrogen tanks and other improvements that would be required to support the physical and environmental demands associated with flight.

FIGURE 11 **Mass of 1 kWh of hydrogen and kerosene-based jet fuel and various tank options for their storage**



Source: Aviation Impact Accelerator

2.7 Technology unlock 7

Redesigning aircraft for optimized hydrogen performance

The location of hydrogen tanks is a critical factor when designing hydrogen aircraft as this will determine their size and shape, significantly impacting their weight.

Current aircraft are optimized to use jet fuel. Liquid hydrogen fuel places very different constraints on the design of an aircraft. The size of hydrogen tanks (four times larger than those for jet fuel), due to their lower volumetric energy density and their typical shape (spherical or cylindrical with domed ends), means that, unlike jet fuel aircraft, hydrogen fuel cannot be stored in the wings. The result is that when hydrogen tanks are retrofitted into an existing aircraft designed to use jet fuel, the space available for passengers is reduced. This reduction in the number of passengers results in a rise in the energy requirement per passenger. If aircraft are designed from scratch for liquid hydrogen fuel – using what is known as a clean-sheet aircraft design – this rise in the energy requirement per passenger does not occur.

To understand this, consider the example of a flight from London to New York, showtn in Figure 12. The figure shows a comparison of the energy required per passenger per km of several jet fuel and hydrogen gas turbine aircraft in 2021 and 2035. Each bar is broken down into the energy used to produce the fuel (including liquefaction for hydrogen) and transport it, and the energy used in-flight.

- The first two bars on the left-hand side of Figure 12 show kerosene aircraft today and in 2035. This indicates that the technological improvement up to 2035 will result in around a 25% reduction in energy requirements. The first hydrogen aircraft (middle bar) is the aircraft designed to use jet fuel in 2035, but it has been retrofitted with hydrogen tanks and fuel system. This displaces 40% of the passengers, increasing the energy required per passenger per km by around 33%.

- The penultimate bar in Figure 12 shows the effect of redesigning an aircraft to use hydrogen as a fuel, i.e. a clean-sheet design. Doing this increases the fuselage size, increasing the aircraft's drag and weight. However, the combined weight of the hydrogen tank and fuel remains substantially lighter than for a jet fuel aircraft, even when the extra structural mass required to support the tank in the airframe is included. Comparing the jet fuel aircraft and clean-sheet design of a hydrogen aircraft in 2035, within the uncertainty bands, the energy requirement per passenger in-flight of jet fuel and hydrogen aircraft are very similar.

- The last bar in Figure 12 shows the effect of redesigning the aircraft and the jet engines for a liquid hydrogen fuel. Cooling and liquefaction of hydrogen on the ground require a work input. It is then possible to extract this extra work potential from the liquid hydrogen in-flight. By redesigning the jet engine to extract all, or part, of this work, it is possible to increase the thermal efficiency of the core of a jet engine by 20%. The result is that in 2035 a hydrogen aircraft may require 25% less energy per passenger per km in-flight than a jet-fuelled aircraft.

- As hydrogen is lighter than jet fuel, even when the weight of the tank is considered, the relative energy benefits of optimizing for hydrogen get better as the range of the aircraft is increased. This means that hydrogen aircraft can operate over the same distances as jet fuel aircraft and are better suited to longer ranges in many ways. This offers the potential to replace current jet fuel-powered aircraft at any range and means SAFs are not the only viable option for decarbonizing the longest-range flights.

- It should be noted that the location of hydrogen tanks is a critical factor when designing hydrogen aircraft as this will determine their size and shape, significantly impacting their weight. This analysis assumes a design with two hydrogen tanks, one in the front of the aircraft's fuselage and one in the rear.

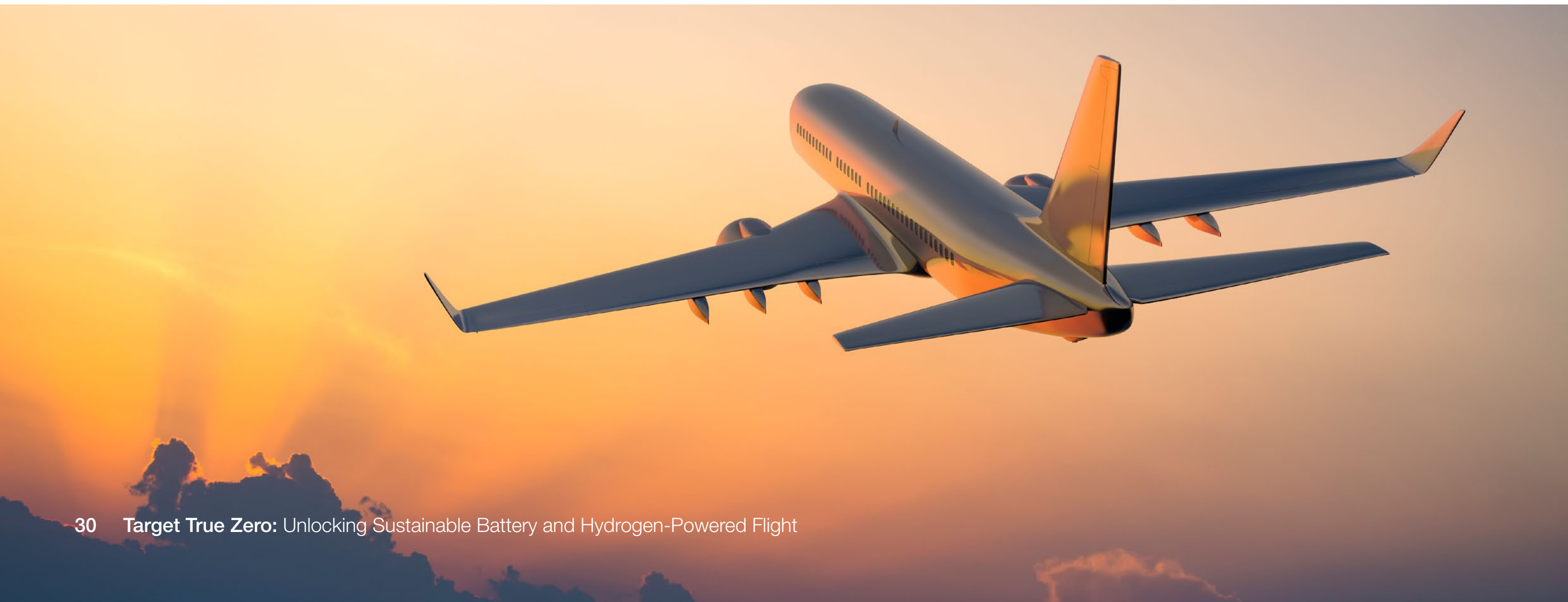
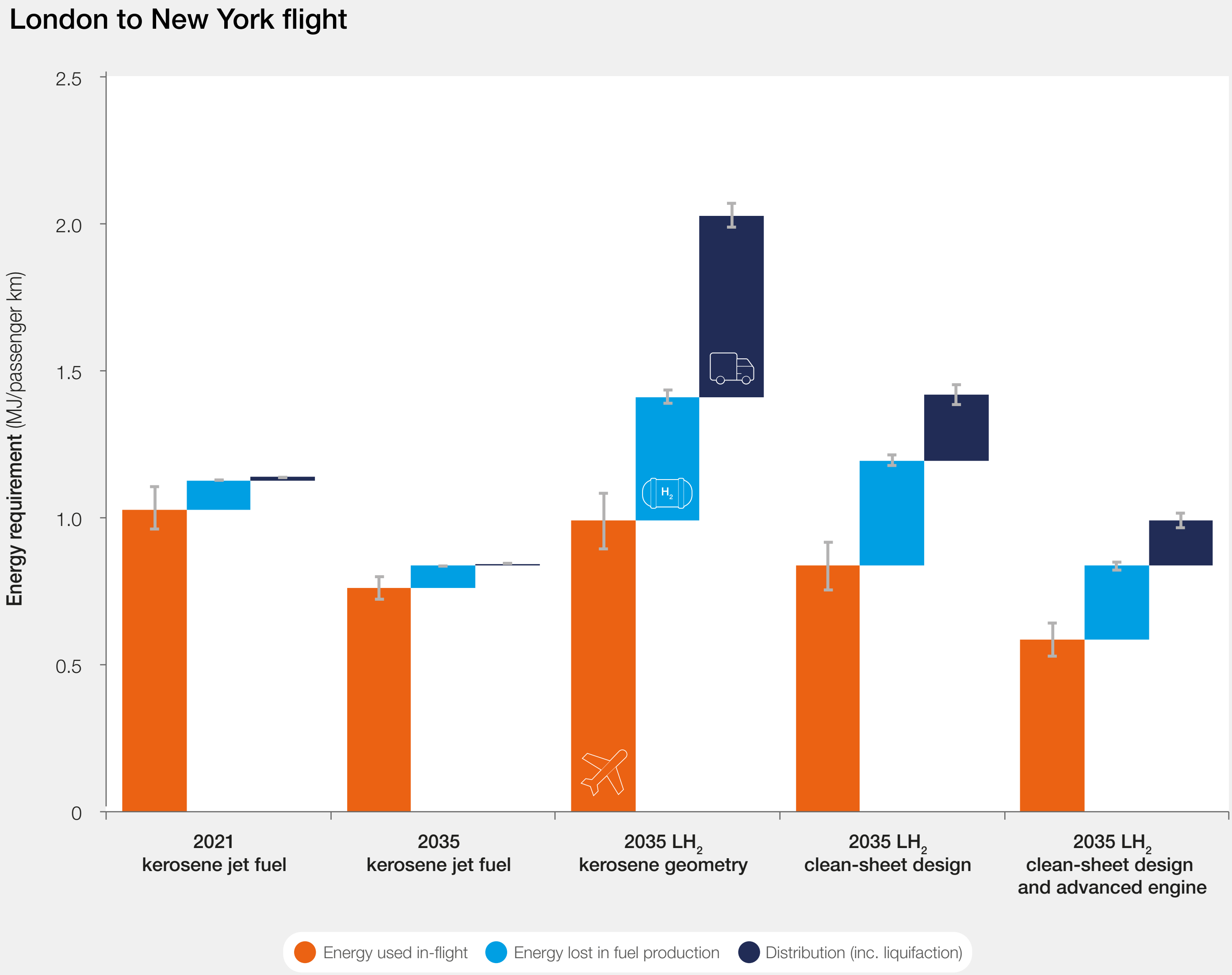


FIGURE 12 | **Energy requirement of jet fuel and hydrogen aircraft**



Source: Aviation Impact Accelerator

2.8 | Technology unlock 8 Contrail research and mitigation

The climate impact of contrails is a major source of overall uncertainty about the total climate impacts of hydrogen-powered aviation compared to other propulsion technologies. Contrails are line-shaped clouds that form behind aircraft due to water vapour and aerosol particles released from aircraft that can form ice crystals in cold and relatively humid atmospheric conditions. In certain conditions, they can spread and evolve into cirrus clouds that are understood to have a significant net warming impact on the climate. Individual cloud formations can have a warming or cooling effect depending on the time of day and where they form. Despite many decades of research into contrails, their full climate impact is unknown.

Compared to contrails from jet fuel aircraft, little research and no in-flight observation has been conducted into how the introduction of hydrogen fuel affects contrail formation. It is known, however, that there will be differences between contrails from hydrogen fuel cell-powered aircraft and those from hydrogen combustion aircraft:

– For fuel cell aircraft, water vapour will be released at comparatively low temperatures, which offers the potential to condense out the water in the exhaust. This would likely prevent the possibility of contrail formation. Additionally, the electric power train in a hydrogen fuel cell aircraft offers the potential to switch to battery

> Research has shown that hydrogen contrails could form at lower altitudes, cover greater geographical areas, and be thicker and longer than those produced by burning jet fuel.

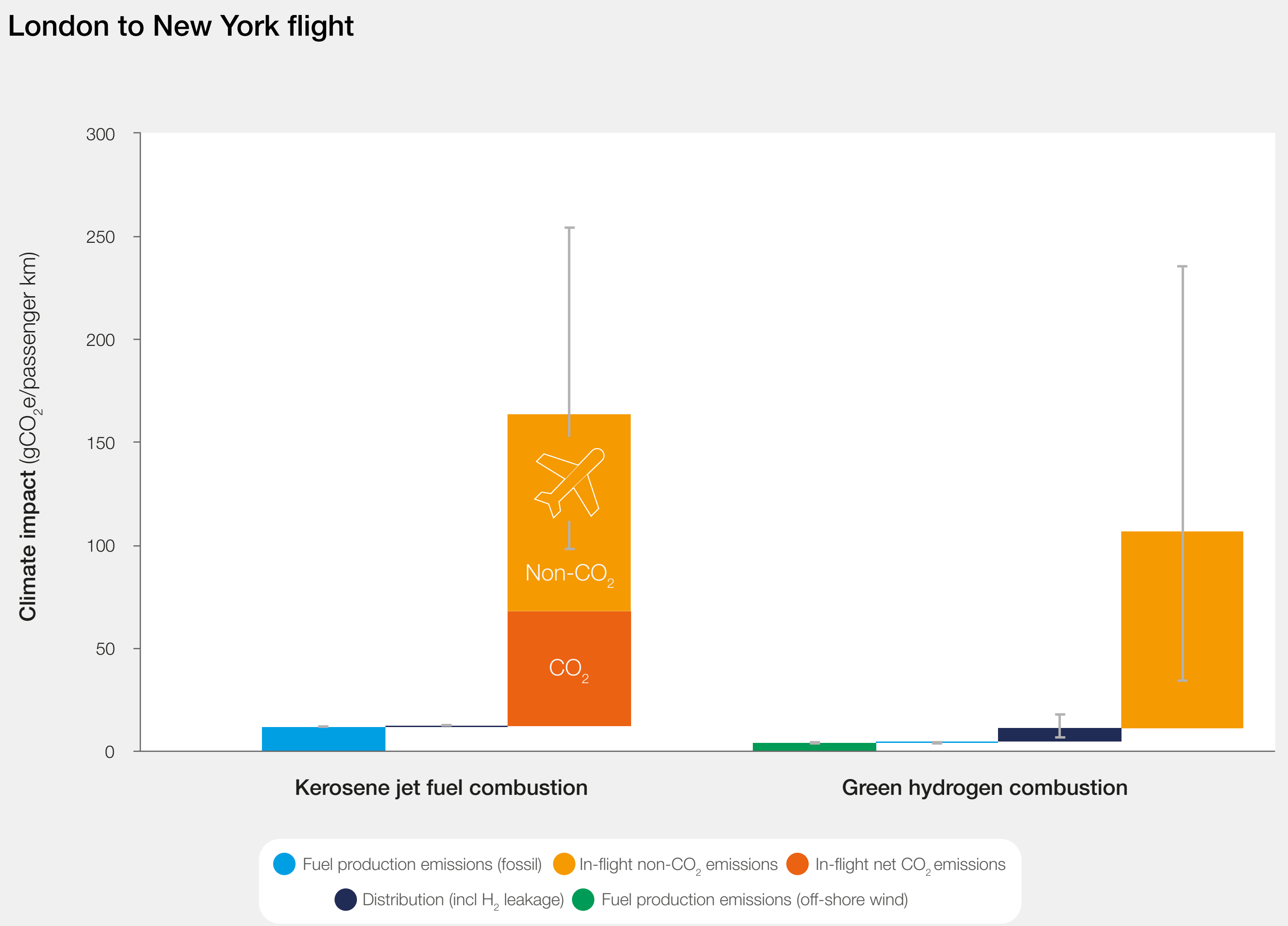
power, preventing water vapour emissions in areas where the risk of contrail formation is high.

– Hydrogen-fuelled aircraft would emit more than double the amount of water vapour emitted by jet fuel aircraft,[13] but the characteristics of the ice crystals that would be formed and the impact of these contrails are unknown. Research has shown that hydrogen contrails could form at lower altitudes, cover greater geographical areas and be thicker and longer than those produced by burning jet fuel.[14,15] This does not necessarily mean their climate impact would be greater, as the ice crystals are likely to be fewer in number, larger and have a shorter lifespan, resulting in a reduced heating effect.

Figure 13 illustrates the uncertainty of the climate impact of contrails for different technologies. It shows the total climate impact of a jet fuel and a green hydrogen combustion aircraft flying between London and New York in 2035 – these are the same flights as shown previously in Figure 7 but now include all climate impacts. For both types of aircraft, the non-CO_2 impacts – of which contrails are the major contributor – are believed to make up most of the climate impact, but the exact level is uncertain. For the jet fuel-powered flight, the range of non-CO_2 effects is between 50% and 300% of the total combined climate impact of in-flight CO_2 and on-ground effects. For the hydrogen-powered flight, the uncertainty range is even higher due to the lack of observable measurements.

Further research, including direct measurement of contrails from hydrogen aircraft, is urgently needed to reduce the uncertainty about the climate impact of contrails. This should be complemented by research into how the composition of SAFs in traditional aircraft affects their formation. Findings from such research can help inform future strategies for mitigating the impact of contrails through contrail avoidance strategies, such as changing the time, route or altitude of a flight to avoid regions of the atmosphere where they form. Such research may provide comparatively quick and easy ways to eliminate a significant contributor to aviation's overall climate and inform future decisions on the design of hydrogen aircraft. This should therefore be pursued as a priority.

FIGURE 13 **Climate impact of a London to New York flight on jet-fuelled and green hydrogen-fuelled aircraft in 2035**



Source: Aviation Impact Accelerator

Conclusion

Building greater resilience is a strategic long-term investment for business, the global economy and society.

Alternative propulsion technologies hold significant potential for addressing the climate impacts of aviation. This report has shown that not only can these technologies eliminate CO_2 impacts during flight – but they offer an opportunity to reduce the total climate impact of aviation. Furthermore, this report has shown that SAFs are not the only option for decarbonizing the sector. Alternative propulsion options exist and could begin to replace jet fuel aircraft for any range by 2035 if the proper technology development occurs.

This report has also shown that the opportunities offered by alternative propulsion will not be realized automatically. If the right measures are not taken, aircraft using alternative propulsion might not be viable options for the aviation industry – at least in the time needed if they are to help meet its net-zero goals – or could be deployed without appropriate safeguards preventing them from offering meaningful climate benefits.

To ensure that alternative propulsion can be deployed sustainably and at scale, decision-makers in industry and government must ensure that delivering zero-carbon flight does not come at the expense of climate-impacting emissions associated with energy, fuel or battery production. This will require investment in infrastructure and careful choices about how alternative propulsion aircraft are designed and operated.

Technological advances will also be needed for alternative propulsion to play a significant role in reducing the climate impact of the sector. Maximizing the range of these aircraft will require better batteries or structural weight savings for battery-electric aircraft, higher power fuel cell systems for hydrogen fuel cell electric aircraft and the development of lighter cryogenic tanks for both types of hydrogen-powered aircraft. Additionally, clean-sheet designs to optimize both the aircraft and the jet engine design for liquid hydrogen as a fuel will be essential if it is to be a viable alternative for the longest-range flights.

Finally, further work is needed to increase understanding where there is currently high uncertainty, notably with the impact of contrails and ways of mitigating them, to determine the suitability of hydrogen-powered aircraft for addressing the sector's climate impact.

The findings in this report provide a strong rationale for continued work to understand how the development of battery-electric, hydrogen fuel cell electric and hydrogen combustion aircraft can be accelerated and how these aircraft can be deployed at scale across the aviation industry. Achieving these outcomes will require further work to understand the role these technologies will play alongside solutions such as SAF and sustained collaboration between governments, the aviation industry and other enabling sectors. The unlocks identified in this paper represent important areas that must be addressed if the potential of alternative propulsion is to be realized. Yet, more work is needed to determine the infrastructure changes, policy and regulatory frameworks, and industry adaptation that will be required. The Target True Zero coalition will provide a platform for future efforts of key players to address these challenges and help deliver a sustainable aviation sector compatible with global efforts to address climate change.

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