REALISING ZERO-CARBON EMISSION FLIGHT

Primary Energy Source Comparison and Selection

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ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK Government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements, and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

The outputs from FlyZero will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

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FOREWORD

Led by the Aerospace Technology Institute and backed by the UK Government, FlyZero is a one-of-a-kind research project aiming to realise zero-carbon emission commercial aviation by the end of the decade.

This intensive 12-month strategic research programme is bringing experts together from across the UK to conduct a detailed and holistic study of the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

Crucially, FlyZero is undertaking an independent and impartial assessment of the advanced technologies which are most likely to have the largest positive impact on reducing carbon emissions in commercial aviation helping to meet climate change commitments, including net zero by 2050, while being economically viable by meeting competitive cost and operational requirements.

As this paper outlines, some of the primary energy sources being investigated by FlyZero are expected to have limited mass transit application as part of the future of commercial air travel, unless unexpected ground-breaking advances are made in their capability.

Nevertheless, their development remains vital to delivering zero-carbon solutions for other parts of the transport market while also harbouring the potential to provide auxiliary power for the aircraft of the future more efficiently.

These challenges present a unique opportunity for UK industry to unlock the potential of advanced technologies protecting our planet and securing valuable market share in the process.

Chris Gear, Project Director.

“In doing so, our first paper also outlines some of the challenges we must overcome to make zero-carbon emission commercial aviation a reality by 2030”

EXECUTIVE SUMMARY

This paper provides a high-level, fundamentals-based comparison of zero-carbon emission energy sources; namely hydrogen, ammonia, and batteries, both in terms of their ability to service the aircraft market (range and payload) and also their wider environmental effects. To make a significant impact on carbon dioxide (CO_2) emissions, zero-carbon technology must be scaled up beyond sub-regional and regional aircraft to larger aircraft sizes capable of mass transport. As FlyZero is dedicated to creating a zero-carbon emission future for aviation, low and net zero-carbon solutions such as Sustainable Aviation Fuel are not in scope but will be considered as reference points of comparison as the programme progresses.

> “In summary, it is concluded that hydrogen fuel, stored in liquid state, offers the best opportunity to service the majority of the aircraft market.”

While batteries present a very attractive option in terms of emissions, their low specific energy (energy per unit mass) makes a pure battery powered solution suitable only for short-range aircraft market applications. Gaseous hydrogen offers reduced complexity and a quicker route to market compared to liquid hydrogen, however, its respective storage tank mass again limits its use to short-range aircraft. Ammonia, has a more promising payload / range capability compared to batteries and gaseous hydrogen and industry is actively pursuing ammonia lightweight cracking technology (converting ammonia into hydrogen and nitrogen) in order to realise ammonia's payload / range potential. While ammonia offers a potential nearer term solution in terms of fuel production infrastructure compared to liquid hydrogen, its payload / range capability falls short of achieving the mass transport objective of FlyZero. In addition, the environmental hazard ammonia presents would need to be addressed.

To realise the full potential of liquid hydrogen as a zero-carbon emission aviation fuel, industry will need to overcome many challenges, with the aim to equal or better the current range and payload capability of kerosene.

The challenges of realising liquid hydrogen include, but are not limited to; the storage and distribution of a cryogenic fuel onboard an aircraft, developing sustainable technologies for stable and reliable hydrogen combustion in gas turbines, efficient energy conversion and thermal management of hydrogen fuel cells and hybrids thereof, minimising the generation of other climate impacts i.e. NO_x and contrails, minimising the impact on aircraft structural mass and drag, and developing a sustainable hydrogen fuel production infrastructure.

These will be the subject for future FlyZero outputs, which will include papers and roadmaps.

01. SCOPE

This paper begins by outlining the aircraft market sectors that FlyZero is targeting, both in terms of carbon emissions and commercial value (**Section 3**). The zero-carbon emission energy sources are subsequently compared by their direct and indirect mass impacts on achievable aircraft range and payload, namely; the direct impact of fuel specific energy (**Section 4**), the indirect impact of the respective fuel tank mass (Section 5), and considerations of the indirect impact of respective fuel distribution system mass from tank to powerplant (**Section 6**). Note, neither the powerplant mass (i.e. post cracking in the case of ammonia), nor the aircraft mass or performance is factored as a differentiator in the down selection of the fuels. The energy sources are finally compared in terms of their wider environmental effects (**Section 7**), with a summary of the papers' conclusions provided in (**Section 8**).

02. AIRCRAFT MARKET

To make a significant impact on carbon dioxide (CO_2) emissions, zero-carbon technology must be scaled up beyond sub-regional and regional aircraft to larger aircraft sizes capable of mass transport. **Figure 1** shows that narrowbody and widebody aircraft markets account for the majority of CO_2 emissions.

FlyZero will target the regional (up to 1000nm, with an average sector distance of 350 nm) and narrowbody markets (up to 2400 nm, with an average sector distance of 800 nm), see **Figure 2**, where regional will likely be the first viable commercial aircraft, and an opportunity to de-risk technology for a following narrowbody zero emission airliner. FlyZero will also evaluate zero-carbon technology for enabling midsize aircraft (beyond 3000nm) as part of our efforts to push the boundaries of the technologies to maximise carbon emission reductions.

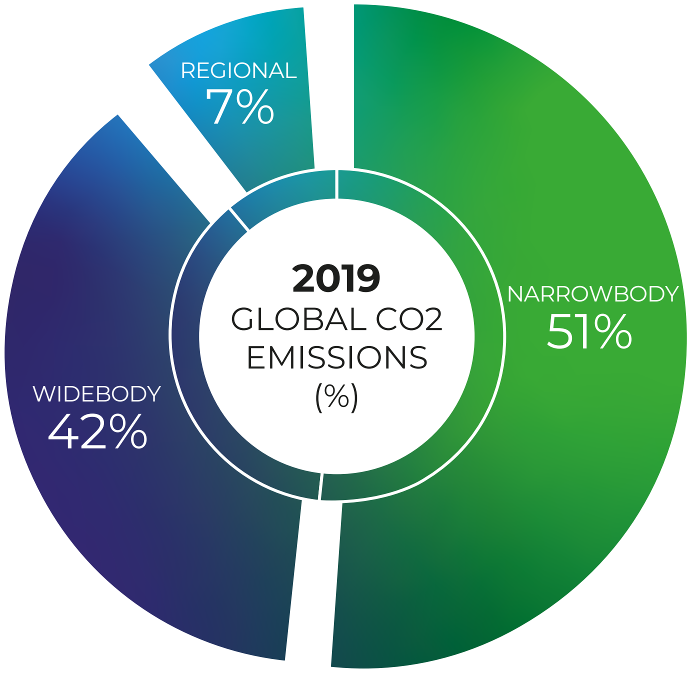


Figure 1 – 2019 global aviation CO_2 emissions (ICCT 2020 [1])

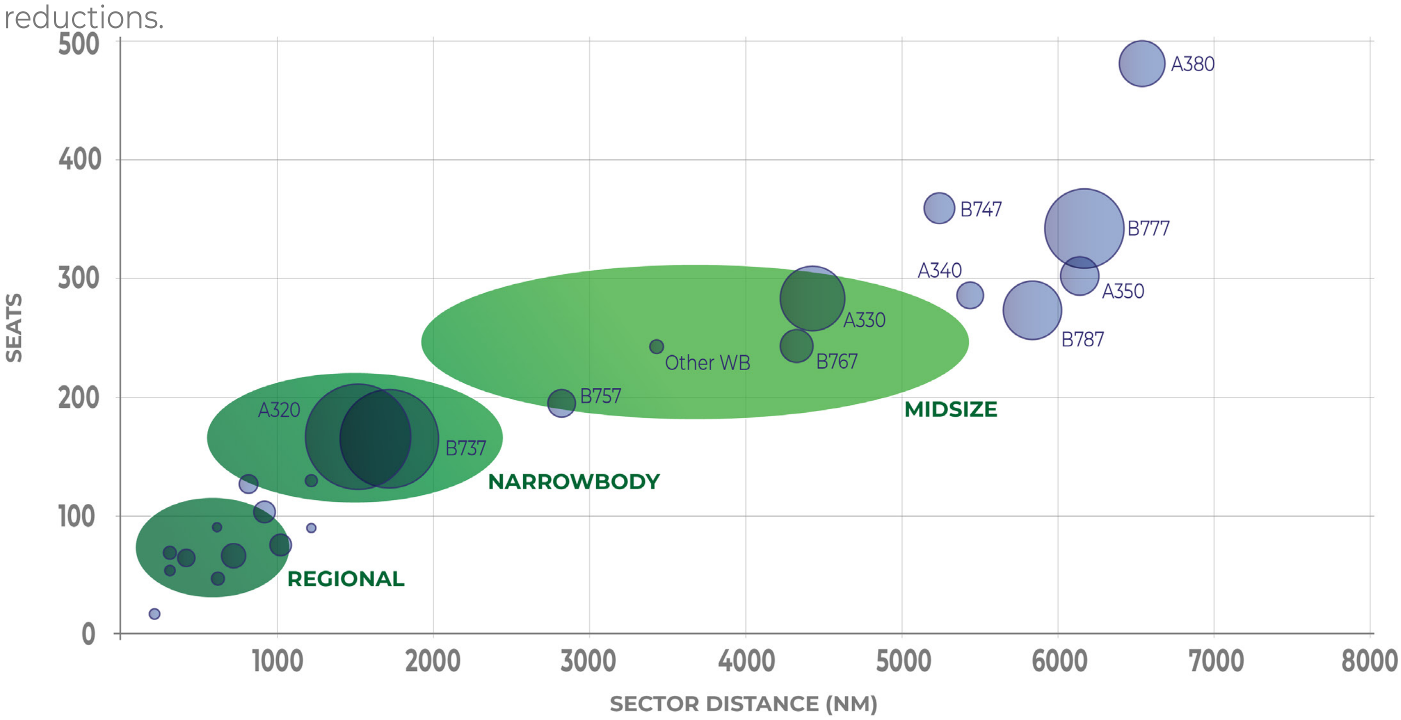


Figure 2 – Market Opportunities for future zero-carbon emissions aircraft. Source: FlyZero

03. IMPACT OF FUEL SPECIFIC ENERGY ON AIRCRAFT AND PAYLOAD

The zero-carbon energy sources are firstly compared purely by the impact of their specific energy on aircraft range and payload. For reference, Table 1 provides the specific energy of the different zero-carbon emission energy sources considered, where kerosene is quoted for comparison. Here, the lower heating value for hydrogen is given and the 2 MJ/kg quoted for batteries (~0.55 kWh/kg) is assumed to be that possible within the 2030 timeframe.

Paramount	Nomenclature	Units	Hydrogen	Kerosene	Ammonia	Battery
Specific Energy	Δh_{fuel} for fluids $E_{battery}$	MJ/kg	~120	~43	~18	~2

Table 1. Specific energy for zero-carbon emission energy sources with the carbon-based fuel kerosene included as a comparison.

Hydrogen has approximately three times the available energy content per kg of fuel carried on board the aircraft compared to kerosene, approximately six times that of ammonia and approximately sixty times that compared to a battery. The direct impact of fuel specific energy on achievable aircraft range is plotted in **Figure 3** for each fuel. Here, each respective coloured line defines the amount of fuel (as a percentage of aircraft mass) required to take an aircraft a certain range. On average, approximately 20% of an aircraft's take-off mass is fuel, leaving approximately 25% for payload (passengers) and approximately 55% for the aircraft 'dry mass' i.e., everything else (aircraft structure, propulsion system powerplant, auxiliary systems etc). The yellow dashed line drawn in **Figure 3** highlights the range each respective fuel can achieve for 20% fuel loading on aircraft: ~200 nm for batteries, ~870 nm for ammonia, ~2160 nm for kerosene and ~ 6100 nm (off the chart) for hydrogen and demonstrates that the aircraft range increases approximately proportionally to the fuel specific energy.

Where each fuel line extends up to and intersects the red dashed line, this highlights the maximum range achievable at the expense of zero payload mass i.e., where ~45 % of the aircraft mass is fuel. As can be seen, for a purely battery powered aircraft in this case, the maximum range at the expense of zero payload is approximately 450 nm. Purely battery powered aircraft are therefore deemed only suitable for short-range aircraft applications.

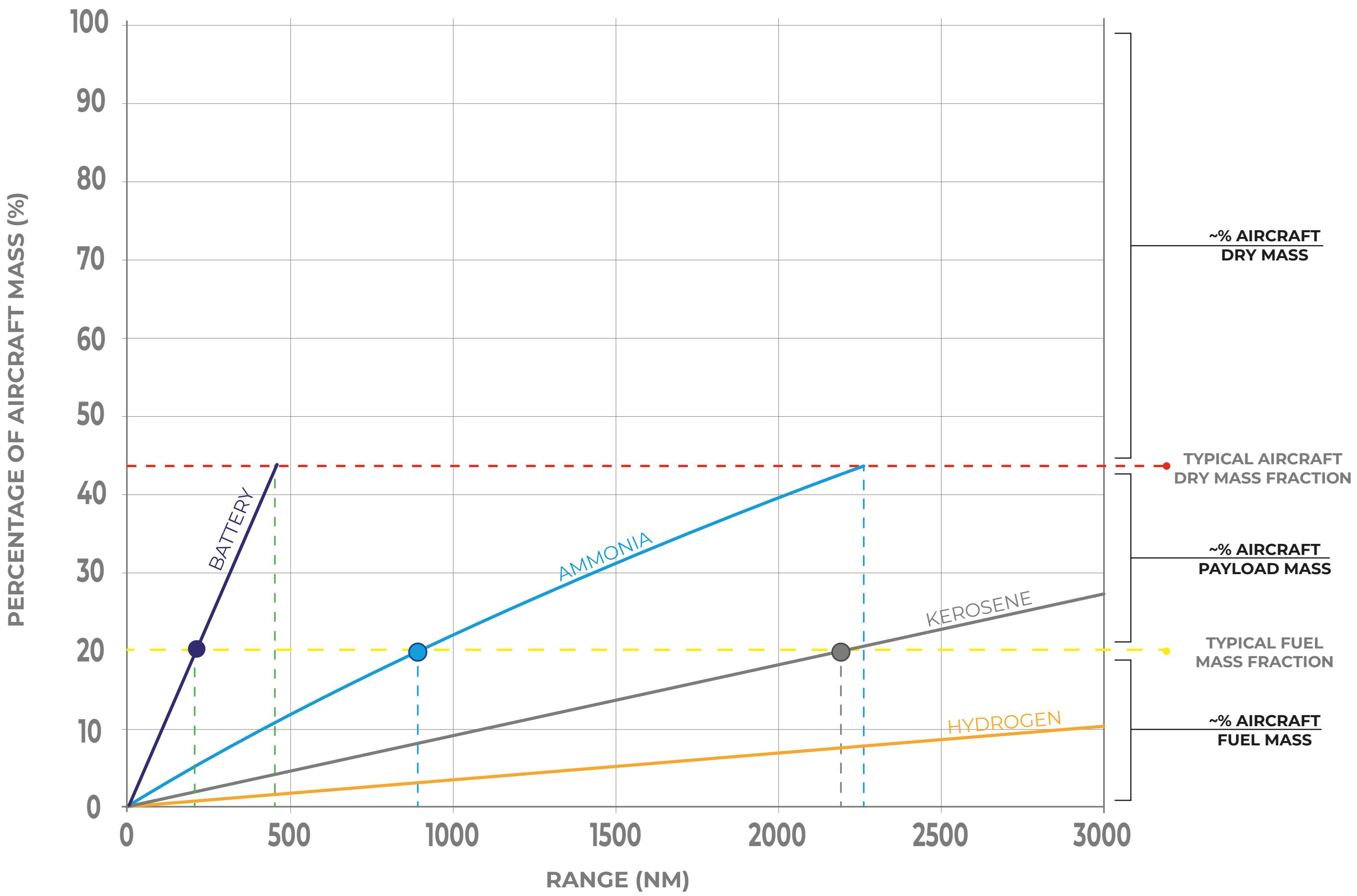


Figure 3 – Fuel and payload mass fractions vs aircraft range in nautical miles (nm) [1]

[1] *Note, these trends are a direct plot of the Breguet range equations 1, 2 and 3 provided in the Appendix, and assume a constant aircraft Lift to Drag ratio (L/D) = 12, an overall powerplant efficiency (η) = 0.36 for all fluid fuels and an η = 0.76 for a pure battery powerplant.*

04. IMPACT OF FUEL STORAGE MASS ON AIRCRAFT AND PAYLOAD

Section 4 considers only the specific energy impact of different zero-carbon emission fuels, however, how the fuel is stored can have a large impact on tank mass and therefore on available payload margin or range. The battery payload and range capability plotted in **Figure 3** in this case remains unchanged since its 'storage mass' is integral to that plotted.

Table 2 outlines the normal storage conditions considered for hydrogen and ammonia, with kerosene provided for comparison. Also provided in the table is an assumed number for the respective storage tank gravimetric efficiency i.e. the relative weight of the tank to the fuel (**Equation 4** in Appendix) and is a function of fuel type and storage conditions. Note, the gravimetric efficiencies given are based on FlyZero's current understanding and will be iterated as the tankage design matures over the course of the project.

Heading	*Paramount*	*Units*	*Hydrogen*		*Kerosene*	*Ammonia*
Normal Storage Conditions	*State*	-	*Liquid (Cryogenic)*	*Gas*	*Liquid*	*Liquid*
	Temperature	*K (˚C)*	*20 K (-253°C)*	*298 K (25°C)*	*298 K (25°C)*	*240 K (-33°C)*
	Pressure	*bar*	*1.5*	*700*	*1*	*1*
	Density	*kg/m^3*	*71*	*39*	*804*	*682*
Specific Energy	*Gravimetric Efficiency*	*%*	*60*	*10*	*98*	*95*

Table 2 – Normal storage conditions and assumed tank gravimetric efficiencies for zero-carbon emission energy sources, with the carbon-based fuel kerosene included as a comparison.

Hydrogen is typically stored as a liquid or a gas. Slush and supercritical states are also being evaluated as part of ongoing trade studies, but for simplicity only liquid and gaseous states are compared here. As a liquid, hydrogen is loaded into the tank at cryogenic temperatures of approximately 20 K and pressurised at slightly greater than atmospheric pressure (approximately 1.5 bar), to ensure no air leakage into the tank to ensure no air leakage into the tank and to provide sufficient net positive suction head for the fuel boost pump. The liquid hydrogen tank must be well insulated to both minimise heat soak into the tank, and therefore hydrogen boil-off, as well as ensuring that the tank surface temperature remains above surface frost or air liquefaction temperatures which would present an onboard safety hazard. Note that the most efficient storage tank shape for liquid hydrogen for minimising heat soak is a sphere (minimal surface area to volume), and therefore liquid hydrogen would be stored in separate tanks outside of the aircraft wings. In addition, although the required mass of the hydrogen fuel is approximately three times less than kerosene for a given aircraft range, the storage volume is approximately four times more due to its significantly lower density. The need for separate storage tanks (i.e. not making use of the wing structure), the larger relative tank volume and the need for tank insulation result in a tank gravimetric efficiency of approximately 60% compared to that of 98% for kerosene. Here 60% is given as conservative assumption based on the sizing methods used in Brewer **[2]**. The resultant negative impact on payload and range for the storage of hydrogen as a liquid cryogen is shown by the large green dashed line in **Figure 4**, but still shows margin above kerosene. The margin above kerosene could be absorbed by the additional complexity of the cryogenic fuel management system and is discussed further in **Section 6**.

To remove the need for insulation, as well as the complexity of a cryogenic fuel management system, hydrogen could be stored as a gas. In order not to occupy the entire volume of the aircraft, gaseous hydrogen would need to be compressed and stored at high pressures (a density of 39 kg/m^3 is achievable for 700 bar storage). This presents a much greater impact on storage mass however than liquid hydrogen, because of the greater tank wall thickness required to contain the pressure. This reduces the tank gravimetric efficiency to approximately 10% (approximate industry standard). The negative impact on payload and range is shown in **Figure 4** by the small, dotted orange line, showing that gaseous hydrogen can achieve a range of ~ 550 nm for 20% fuel + tank mass (retaining 25% payload mass), and achieve a maximum range of ~1200 nm range at the expense of zero payload. Gaseous hydrogen fuelled aircraft are therefore deemed only suitable for short range applications. In this simplistic analysis, gaseous hydrogen is still seen to have a more promising payload and range capability compared to purely battery powered aircraft, however, the mass of the powerplant and overall impact on aircraft performance and mass would need to be factored to make a true comparison of the two.

Ammonia can be stored as a liquid, and at atmospheric pressure the boiling point of ammonia is -33 °C. As the storage temperature is higher than liquid hydrogen, and the latent heat of vaporisation is higher, the insulation weight for an ammonia tank will not be as significant. In addition, it may be possible to store ammonia within the aircraft wings and therefore the tank gravimetric efficiency provided for ammonia is only marginally less than that of kerosene, given the addition of insulation and greater storage volume. The impact of the ammonia tank gravimetric efficiency on payload and range is indicated by the blue dashed line in **Figure 4**.

For reference, illustrated examples of the relative tank volumes for liquid hydrogen, gaseous hydrogen at 700 bar, ammonia and kerosene are shown in **Figure 5** for an ATR72 and an A320 for a given mission for each aircraft.

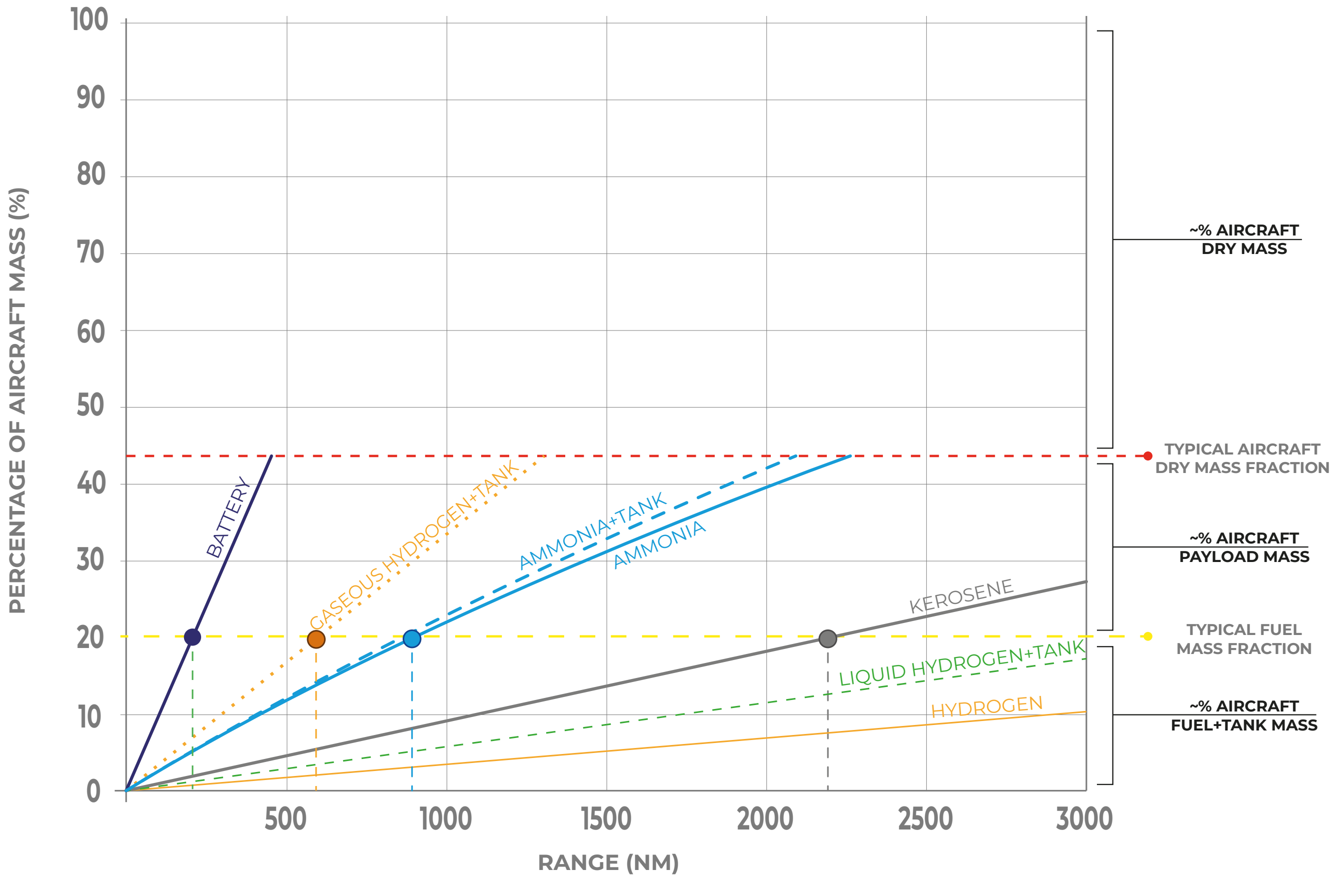


Figure 4 – Fuel + tank storage mass and payload mass fractions vs aircraft range in nautical miles (nm)[2] *.*

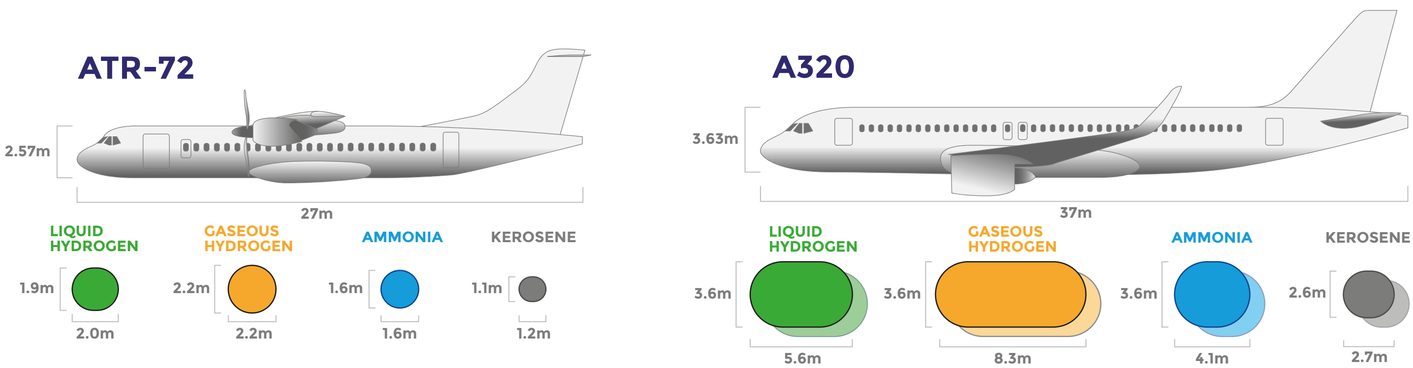


Figure 5 – Relative tank size for different zero-carbon emission fuels, with kerosene provided for comparison. Here x 2 tanks are required for the storage of each fuel illustrated for the A320.

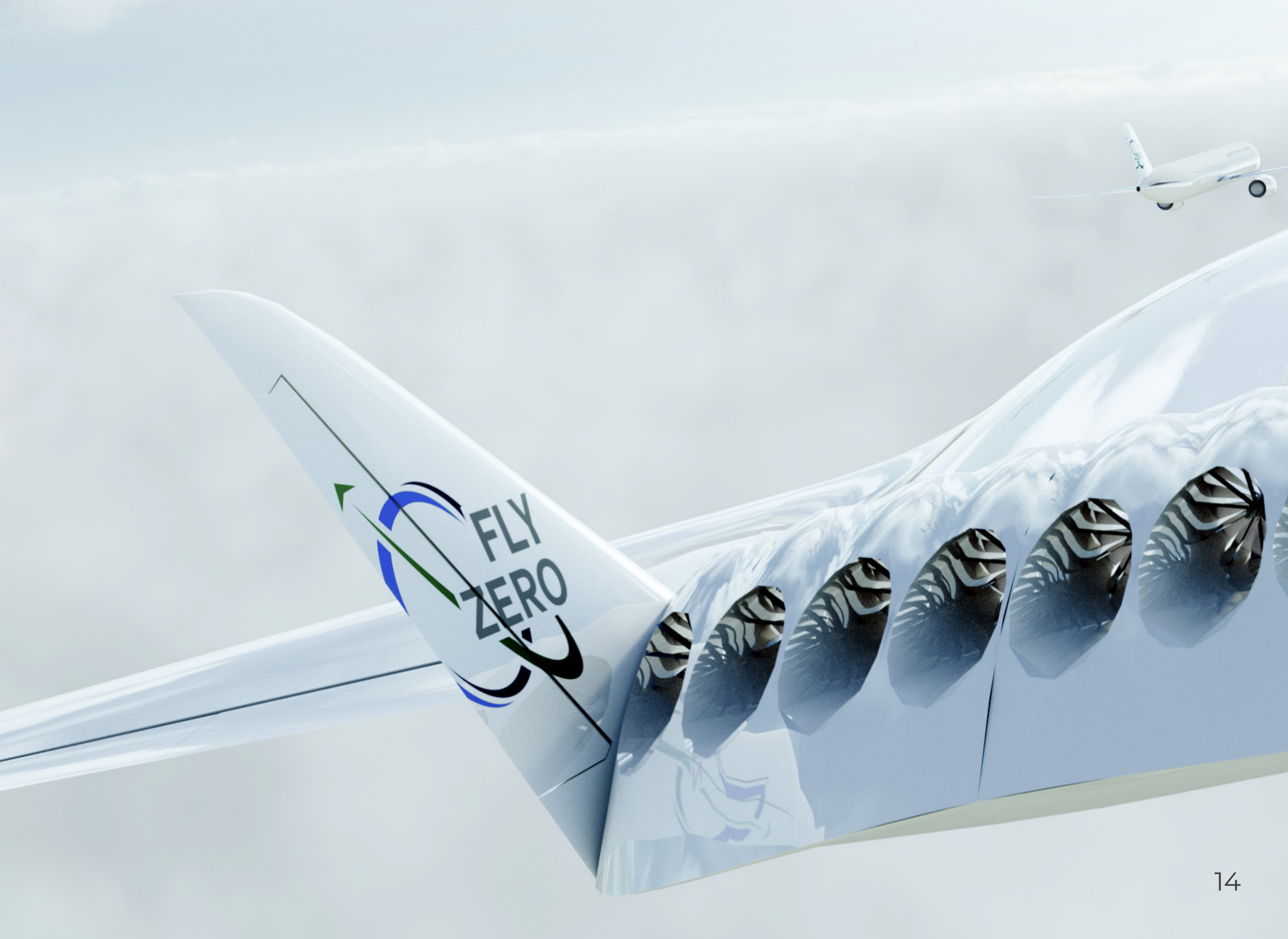
[2] *Note, these trends are a direct plot of the Breguet range equations 1, 2 and 3 provided in the Appendix, and assume a constant aircraft Lift to Drag ratio (L/D) = 12, an overall powerplant efficiency (η) = 0.36 for all fluid fuels and an η = 0.76 for a pure battery powerplant.*

05. IMPACT OF FUEL DISTRIBUTION SYSTEM MASS ON AIRCRAFT RANGE AND PAYLOAD

Figure 4 highlights that pure battery and gaseous hydrogen fuelled aircraft are limited to short range markets. Ammonia is shown to have a more promising payload / range capability than batteries and gaseous hydrogen, with liquid hydrogen shown to have the potential to realise the full mass transport objectives of FlyZero. In order for ammonia and liquid hydrogen to realise their respective payload / range trends shown **Figure 4**, the mass of the fuel management system i.e., from tank to powerplant, will need to be minimised.

Both fuel cell and gas turbine powerplants can be considered for use with ammonia and hydrogen fuel. In the case of liquid hydrogen, the hydrogen fuel management system will require the functionality to deliver the fuel from the tank to the powerplant, perform tank pressurisation, tank re-fuelling, and a means to manage hydrogen boil-off. In the case of delivering fuel to the powerplant, for fuel cells, hydrogen will need to be delivered at low pressures (~1-2 bar) and in gaseous form at room temperature. For a fuel cell therefore, the liquid hydrogen will be pumped as a liquid from the tank to a low pressure and passed through a heat exchanger to vaporise the fuel and warm it to ~ 300 K. For the gas turbine fuel delivery system, the liquid hydrogen from the tank will need to be pumped to much higher pressures and subsequently heated prior to entry to the combustion chamber (delivering fuel into the combustor in a supercritical state). The degree of hydrogen heating is major part of FlyZero project studies and is dependent on combustion chamber requirements and performance optimisation of the gas turbine engine. For both fuel cells and gas turbines, all surfaces will require insulation to minimise boil-off and to protect against surface frost or air liquefaction, which would pose a safety hazard. The liquid hydrogen fuel delivery system is a major part of the design activity for FlyZero and presents new challenges and opportunities for the industry to enable low mass and long-life cryogenic fuel management technologies. The payload and range margin of liquid hydrogen above kerosene shown in **Figure 4** could be absorbed by the additional complexity of the cryogenic fuel management system; the challenge to industry will therefore be to optimise the mass of these new cryogenic technologies to equal or better the current range and payload capability of kerosene.

In the case of an aircraft carrying ammonia fuel, the complexity of managing the ammonia itself is reduced compared to liquid hydrogen as it is storable at much higher temperatures (-33˚C compared to -253˚C). However, additional complexity results from the need to 'crack' ammonia (where ammonia is decomposed towards hydrogen and nitrogen) to some degree before it can be used to power a gas turbine or a fuel cell. For a fuel cell with onboard ammonia storage, the ammonia will first need to be 100 % cracked and delivered to the fuel cell at very high purity levels. For a gas turbine, some cracking (nominally 30% of pure ammonia cracked into hydrogen and delivered alongside to the combustion chamber) is required to improve upon pure ammonia's poor combustion characteristics. The requirement for cracking presents both a mass and operational challenge and industry is actively pursuing the development of lightweight cracking technology to realise the payload / range potential of ammonia.



06. SUSTAINABILITY CONSIDERATIONS

While batteries, hydrogen and ammonia avoid in-flight carbon dioxide emissions, there are other environmental impacts related to fuel use, including:

- Non-CO_2 impacts on climate change
  - Persistent contrail formation
  - Nitrogen oxides (NO_x) as indirect greenhouse gas (GHG)
  - Water vapour as greenhouse gas
  - Hydrogen as indirect greenhouse gas, from leakage/boil-off/unburnt fuel
- Local air quality emissions
- Renewable electricity demand

We are seeking to evaluate these according to the best available science, although uncertainty remains high, especially around the environmental impact of contrails. Aircraft noise is also being considered in the next phases of the FlyZero study, but it is not considered a differentiator for the down select of the primary energy source.

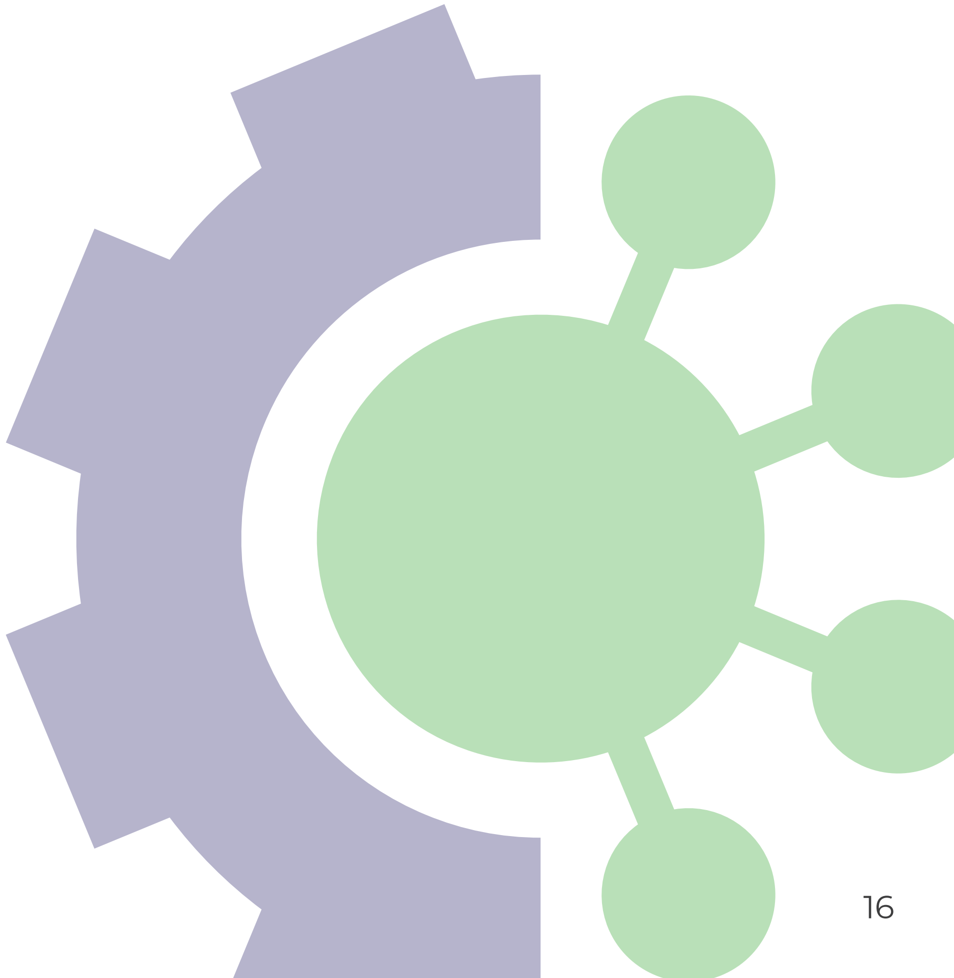
06.1 BATTERY ELECTRIC

Battery electric is by far the best “fuel” from a sustainability perspective, as it produces no in-flight emissions or local air quality impact.

Also, the renewable electricity demand per unit of propulsive power is much less than for hydrogen since there is no hydrogen production and liquefaction process. The mass of batteries limit applications to relatively short range as noted in (**Section 4**), but from a sustainability perspective it is a priority to push technology to improve the range / payload and therefore the market uptake of battery electric aircraft as well as hydrogen / battery electric hybrids.

Sourcing of raw materials and end-of-life considerations for battery materials are challenging. This is being addressed extensively, primarily for the automotive context, in particular by the Faraday Institute and its partner organisations (20 universities and 50 businesses), [3]. The cobalt supply chain is of particular concern due to geopolitical issues in Democratic Republic of Congo, [4] where the majority of supply is from.

Recycling processes have been developed to recover cobalt, lithium and nickel from batteries, and are being commercialised globally. Volumes of end-of-life batteries are still relatively small, but by the late 2020s tens of thousands of tonnes of material will require processing, with the expectation that a strong recycling supply chain will be established, [5].



06.2 HYDROGEN

The extra water emissions from hydrogen in gas turbine combustion and in fuel cells will form more contrails than traditional kerosene aircraft, but these are likely to be optically thinner and less persistent due to the absence of particulate matter in the exhaust, **[6]**. There is very little prior literature in this area, and while some academics expect that the overall climate impact from contrails will be less than that for kerosene, there is, as yet, no published data, simulated or measured, to verify this.

The FlyZero team is working with leading climate scientists at the University of Leeds to develop global climate impact models for hydrogen aircraft, which will add to the knowledge, but future research will be needed to improve climate models to predict contrail impacts.

Contrails are less of a concern for regional aircraft flying at lower altitudes, as they will only persist in ice supersaturated regions (ISSRs) which more commonly occur at higher altitudes, near the tropopause. For higher altitude flights, there is potential to reduce contrail impact by navigational avoidance of ISSRs, without the risk of emitting extra CO_2 as would be the case with kerosene flights.

NOx from hydrogen combustion is expected to be significantly lower than kerosene aircraft, resulting in reduced effect both on climate and local air quality. There are no NOx emissions from fuel cells. The direct climate impacts of water vapour and hydrogen are relatively small in comparison to other effects. Water emissions in the stratosphere should be avoided due to warming effects and can be achieved through current flight altitude for commercial aviation.

Hydrogen itself has indirect greenhouse gas effects if leaked to the environment, so good practice will minimise or eliminate any venting of hydrogen, except in emergency situations for safety reasons. This is an issue that needs to be addressed by the hydrogen production supply chain, but volumes would be small, and the impact is less than, for example, emissions from leakage of natural gas, **[7]**.

06.3 AMMONIA

Ammonia is both toxic and corrosive. Contrail impacts have not been assessed, but may be similar to those for hydrogen above, slightly increased due to higher water vapour emissions (12% higher for pure ammonia, or less if blended with hydrogen).

NOx would be significantly increased compared to hydrogen, because there is nitrogen in the ammonia, in addition to the nitrogen from the air. This would result in increased effect on both climate warming and local air quality. As noted above for hydrogen, the direct climate impact of water vapour in the stratosphere is small.

Any leakage of ammonia is toxic to humans and aquatic organisms, with human exposure limits varying globally, typically a short-term exposure limit of 35 ppm for 15 minutes, [8].

If ammonia were combusted directly, significant amounts are likely to be released unburnt on the ground, which is deemed unacceptable. However if some ammonia is cracked into hydrogen, as described in (**Section 6**) to improve the combustion characteristics, this would reduce any unburnt ammonia to well within acceptable thresholds. Any leaked or unburnt ammonia in flight will be very short-lived in the atmosphere as it is highly reactive, and in any case, quantities would be small.

07. CONCLUSION

A high-level, fundamentals-based comparison of zero-carbon emission energy sources on aircraft payload and range capability has been conducted. Although the analysis conducted is simplistic, making no differentiation of potential variation in aircraft performance and dry mass with respect to each fuel, this is considered second order with respect to the impact of fuel specific energy and fuel storage mass, and has allowed the down-selection of a primary fuel.

To make a significant impact on carbon dioxide (CO_2) emissions, zero-carbon technology must be scaled up beyond sub-regional and regional aircraft to larger aircraft sizes capable of mass transport. It is shown that liquid hydrogen fuel has the potential to service the majority of the aircraft market.

Section 4 compared the direct impact of fuel specific energy on aircraft payload and range capability. While batteries present a very attractive option in terms of emissions, here it is clearly demonstrated that, due to the very low specific energy of batteries, a purely battery powered aircraft is suitable for only short-range applications and therefore out of scope for FlyZero. The opportunity to use batteries as part of a hybrid solution or auxiliary system is however still very much part of FlyZero's continued analysis.

Section 5 subsequently factored in the additional mass of the tankage, illustrating that storing hydrogen in gaseous form (attractive for simplicity and a quicker route to market point of view compared to liquid hydrogen), at high pressures, significantly impacts the payload and range capability of hydrogen and limits gaseous hydrogen aircraft to short range applications also. To make a true comparison of the payload and range capability of gaseous hydrogen and a purely battery powered aircraft, the mass of the powerplant and overall aircraft mass and performance would need to be evaluated.

Section 6 discussed the additional complexities, and therefore the potential mass impact on payload / range, of the fuel management systems of both ammonia and liquid hydrogen. In the case of ammonia, industry is actively pursuing the development of lightweight cracking system technologies in order to realise the payload / range potential of ammonia. The additional environmental concerns of ammonia in terms of toxicity and NOx production would be major barriers to widespread use.

Hydrogen has clear potential to power aircraft up to narrowbody size and FlyZero is assessing the potential for it to be scaled up to midsize aircraft. To realise the full potential of liquid hydrogen as a zero-carbon emission aviation fuel, industry will need to overcome many challenges, with the aim to equal or better the current range and payload capability of kerosene. The challenges of realising liquid hydrogen include, but are not limited to; the storage and distribution of a cryogenic fuel onboard an aircraft, developing sustainable technologies for stable and reliable hydrogen combustion in gas turbines, efficient energy conversion and thermal management of hydrogen fuel cells and hybrids thereof, minimising the generation of other climate impacts i.e., NOx and contrails, minimising the impact on aircraft structural mass and drag, and developing a sustainable hydrogen fuel production infrastructure.

These will be the subject for future FlyZero outputs, which will include papers and roadmaps, outlining key enabling technology and infrastructure to allow a viable concept to be brought to market and competitively operated.

Figure 6 provides a summary comparison of the zero-carbon emission energy sources considered, with an initial comparison of hydrogen fuel cell to hydrogen gas turbine powerplants included.

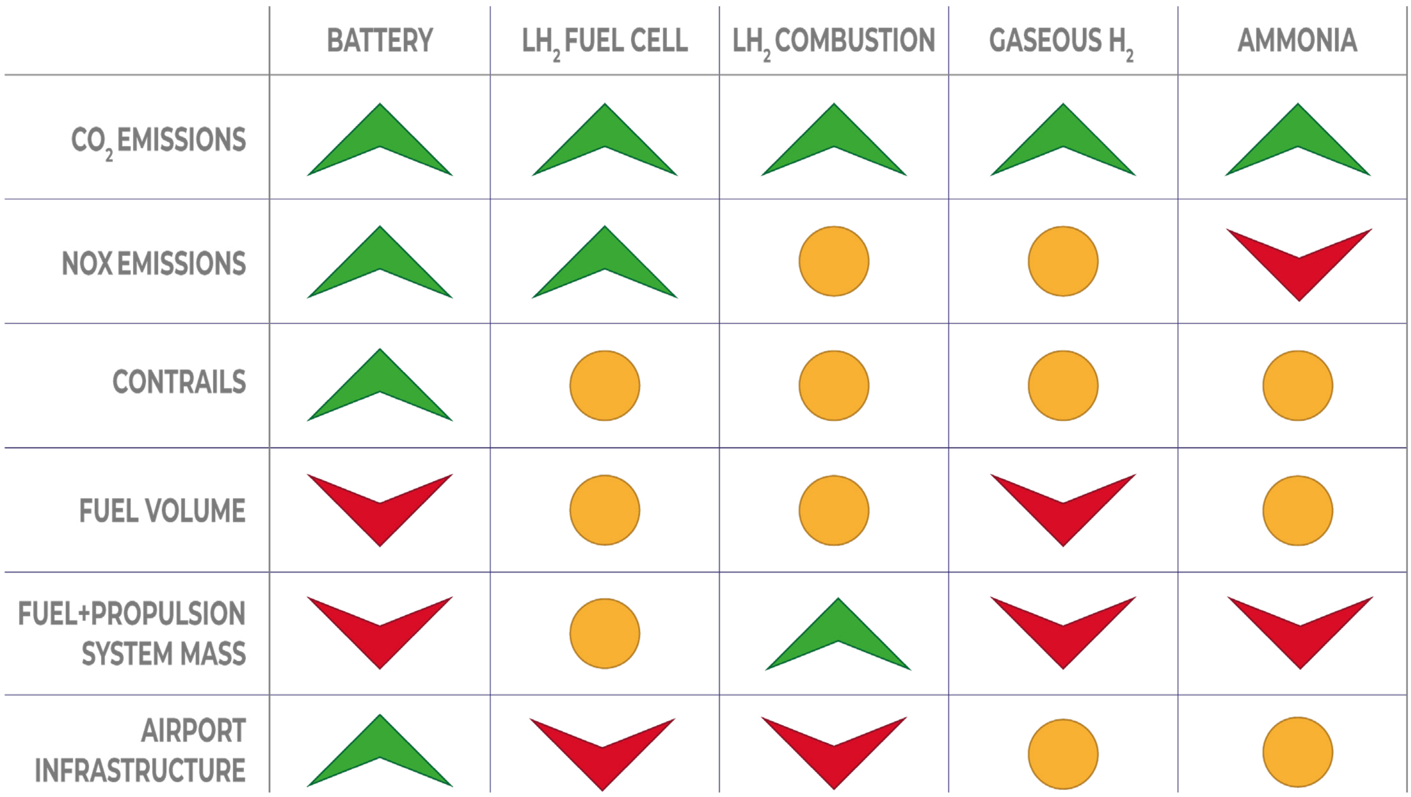


Figure 6 – Zero-carbon emission aviation fuels, initial assessments for FlyZero scope focus market.

In summary, this paper has explained the logic for selecting liquid hydrogen as the primary energy fuel source to enable zero-carbon emissions flight for larger aircraft. The FlyZero team will now focus on the modelling of concepts embodying this as a primary fuel source, with the aim of building confidence in safe and commercially competitive zero-carbon emissions aircraft.

This work will underpin a specific call for action for the aerospace industry and for investment in the UK to accelerate the development of aircraft technologies critical to the realisation of truly sustainable and affordable mass air travel.

FlyZero will also identify the requirements for fuel production and distribution and the challenges around airport operations – requirements that can inform future complementary investment into the infrastructure needed to enable zero-carbon emissions flight.

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09. APPENDIX A

11.1 EQUATIONS

The classic Breguet Range equation for aircraft whose fuel mass depletes during the course of the flight is provided in **Equation 1**:

$$S = \left(\frac{\Delta h_{fuel}}{g}\eta\right)\left(\frac{L}{D}\right)ln\left(\frac{1}{1-\frac{m_{fuel}}{m_{TO}}}\right)$$

Equation 1

Equation 2 provides the equivalent Breguet Range relation for fixed mass energy sources i.e. battery powered aircraft:

$$S = \left(\frac{E_{battery}}{g}\eta\right)\left(\frac{L}{D}\right)\left(\frac{m_{battery}}{m_{TO}}\right)$$

Equation 2

Equation 3 simply shows that the total mass of the aircraft is composed of the 'dry mass' i.e. structure and engines etc, its passengers i.e. payload, and the fuel (in this case either fluid fuel or batteries).

$$1 = \frac{m_{dry}}{m_{TO}} + \frac{m_{payload}}{m_{TO}} + \frac{m_{fuel\ or\ battery}}{m_{TO}}$$

Equation 3

Equation 4 provides the relation for tank gravimetric efficiency.

$$\eta_{grav} = \frac{m_{fuel}}{m_{fuel} + m_{tank}}$$

Equation 4

Δh_{fuel} = Fuel Specific Energy

$E_{battery}$ = Battery Energy Density

11.2 NOMENCLARURE

η = Overall Efficiency

η_{grav} = Tank Gravimetric Efficiency

D = Drag

g = gravity

L = Lift

$m_{battery}$ = Battery mass

m_{dry} = Aircraft dry mass i.e.minus payload and energy source

m_{fuel} = Fuel mass

$m_{payload}$ = Payload Mass

m_{tank} = Tank Mass

m_{TO} = Aircraft Take Off mass

S = Range

REALISING ZERO-CARBON EMISSION FLIGHT

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