ZERO-CARBON EMISSION AIRCRAFT CONCEPTS

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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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.

This report forms part of a suite of FlyZero outputs which 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.

To discover more and download the FlyZero reports, visit **ati.org.uk**

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The FlyZero project has developed three aircraft concepts to illustrate the potential for zero-carbon aircraft using liquid hydrogen as a fuel, based on the projections reported in the FlyZero technology roadmaps.

The three concepts sit in the regional, narrowbody and midsize market segments and show that hydrogen aircraft can be competitive on a mission energy basis with a sustainable aviation fuel (SAF) powered aircraft using consistent 2030 technology. The FlyZero studies showed that hydrogen aircraft have the potential to address 100% of short-haul and 93% of existing scheduled long-haul flights. The midsize concept could provide global connectivity with two flights and one stop. The aircraft level design trades when using hydrogen fuel have been demonstrated to be fundamentally different to a kerosene aircraft, primarily due to the high specific energy of hydrogen, meaning much less hydrogen by weight is required in comparison with kerosene. This may drive different technology priorities. Hydrogen aircraft will require more integration than kerosene aircraft between the propulsion system and the airframe as the fuel phase change from liquid to gas and associated energy management are novel challenges for commercial aircraft design.

Significant technical, safety and operational challenges remain which must be characterised and solved before a hydrogen powered aircraft could achieve certification and enter commercial service, but the FlyZero analysis has shown sufficient promise that further hydrogen technology research should be pursued. Considerable uncertainty exists around certification standards and some sustainability aspects such as contrails; further work to understand these areas should be undertaken in parallel.

The design of hydrogen aircraft is inherently more integrated than for kerosene or SAF and this reinforces the need for the ATI strategic objective to maintain and develop independent whole aircraft analysis capability within the UK. The FlyZero concepts will continue to be updated by the ATI as hydrogen knowledge and technologies develop. The concepts are a critical part of the overall understanding as they are required input data for climate models to predict the overall environmental impact of a switch to hydrogen aviation.

01. INTRODUCTION

This report provides an overview of the three zero-carbon tailpipe emission aircraft concepts developed by the FlyZero project. Each concept represents a possible aircraft configuration, but the ATI is not an aircraft manufacturer and the concepts are not intended for production.

The overall objective for the FlyZero concept aircraft is to help understand and to demonstrate the potential of the proposed technologies for zero-carbon emission flight and to act as a catalyst to identify the critical elements which need further work to better understand the potential of a zero-carbon aircraft.

The FlyZero project team assessed the feasibility of all zero-carbon energy sources, concluding that green liquid hydrogen is the most promising zero-carbon fuel for large commercial aircraft [1]. The project subsequently identified 13 technology 'bricks' fundamental to realising hydrogen fuelled aviation. Six 'hydrogen aircraft' bricks are revolutionary aerospace technologies fundamental to realising liquid hydrogen fuelled aircraft. Seven 'cross-cutting' bricks are critical to ensuring that hydrogen aircraft are commercially and operationally enabled and deliver tangible sustainability improvements [2]. The projections from the technology research were used directly in the design of the concepts and an iterative design loop was completed multiple times during the project. The concepts therefore illustrate what could be achieved by an aircraft if the technology levels identified in each of the roadmaps are realised.

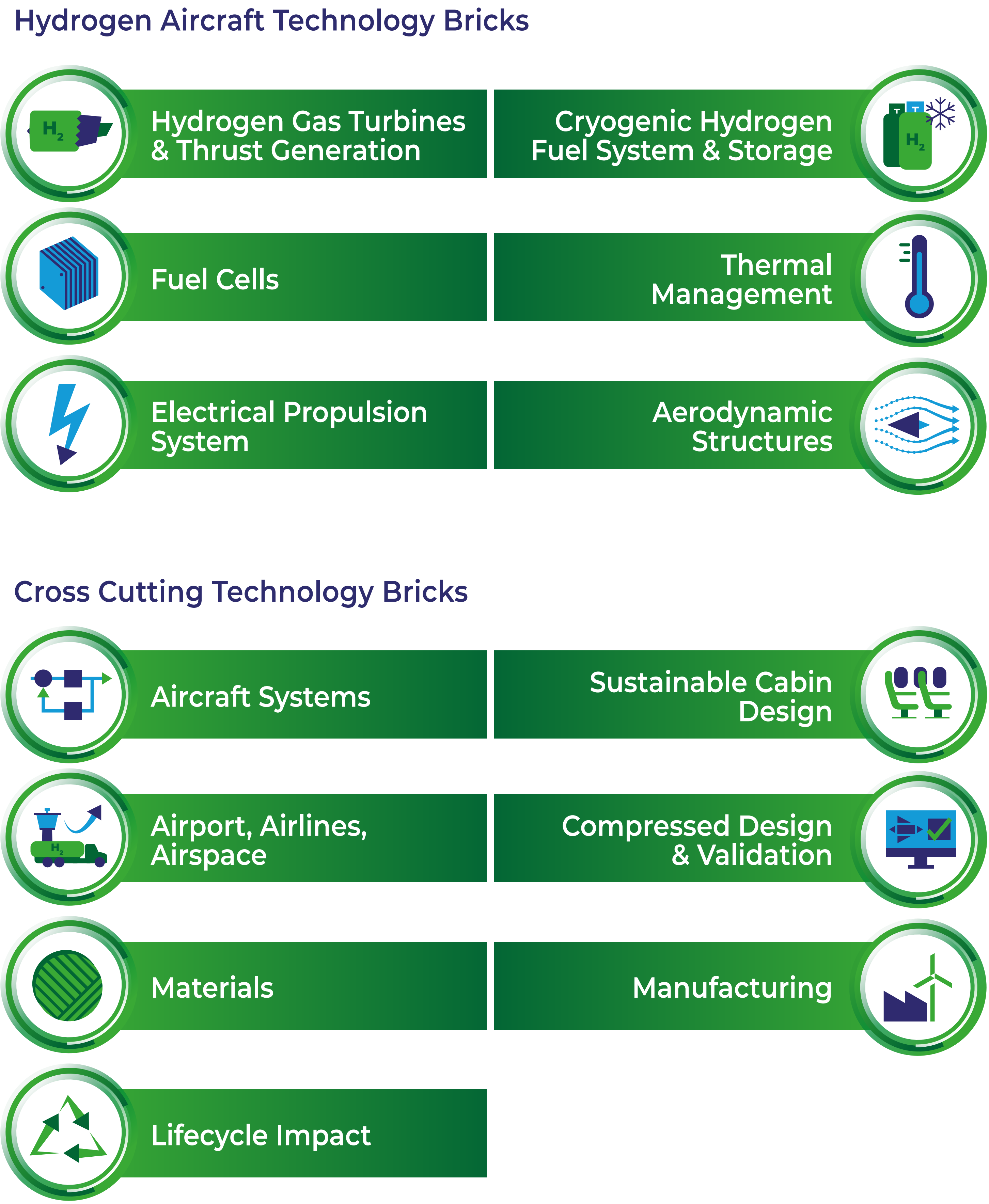


Figure 1 – FlyZero technology bricks

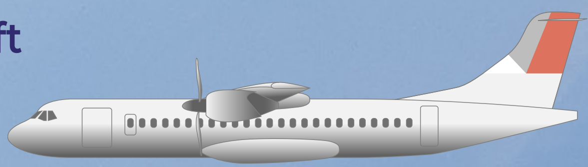
The design requirements for each concept were initially based on the in-service aircraft used as a reference. These were then adapted and refined as our understanding improved. The concept data are shown in comparison to these reference aircraft, which were modelled as the starting point for the concept analysis. FlyZero did not undertake direct research into sustainable aviation fuel (SAF), but baseline aircraft using 2030 technology and using SAF as a fuel have been created and optimised using the same technology level as the concepts to act as a direct comparison to the zero-carbon designs.

FlyZero Aircraft Definitions	
Reference Aircraft	*The reference aircraft are existing, in-service aircraft comparable to the relevant concept. They were used as the starting point for the analysis to allow a level of model validation and to provide the basis for any technology improvements included in the baseline or concept aircraft.*
Baseline Aircraft	*The baseline aircraft are a 'clean sheet' sustainable aviation fuel design with 2030 technology. The payload and range have been matched to the concept aircraft, but other parameters have been optimised independently. The primary purpose of these aircraft is to provide a direct comparison with the zero-carbon concept aircraft.*
Concept Aircraft	*The concept aircraft are the zero-carbon emissions hydrogen-powered aircraft designed by the FlyZero team.*

Table 1 – FlyZero aircraft definitions

Regional Reference Aircraft

ATR 72-600



Narrowbody Reference Aircraft

Airbus A320neo

Midsize Reference Aircraft

Boeing 767-200ER

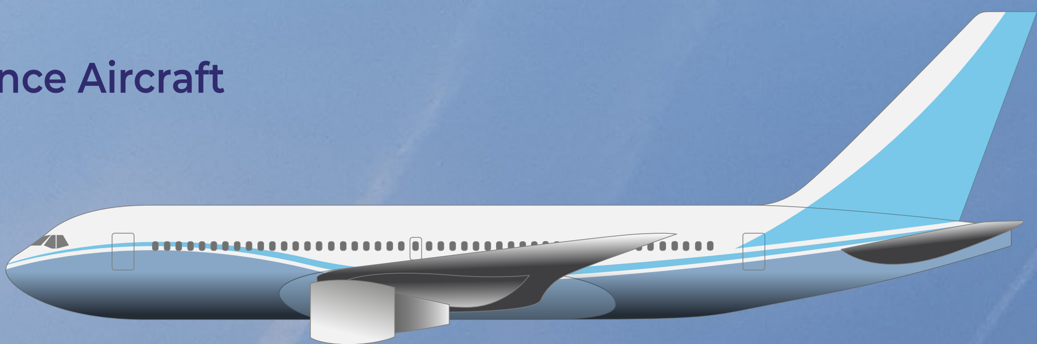


Figure 2 – FlyZero reference aircraft

The concepts were aligned to market sectors and each had specific objectives, in addition to a shared objective to highlight UK technology opportunities:

Regional: demonstrate the feasibility of a fuel cell aircraft. The aircraft performance and cost relative to a kerosene or SAF powered aircraft was a critical factor. The integration of the fuel cell system was also a key challenge to be assessed.

Narrowbody: explore the opportunity for hydrogen to replace carbon-based fuels in the largest and most competitive sector of commercial aviation. Key drivers for this market segment include turnaround time, aircraft utilisation and flexibility.

Midsize: assess the potential for hydrogen to address longer haul routes which have traditionally been served by larger twin-aisle aircraft. The generally accepted view at the start of FlyZero was that hydrogen aircraft could not support this market segment and long-haul flights could only be made sustainable through the use of SAF, however the FlyZero initial analysis suggested a larger aircraft flying longer range was feasible, so a concept was created to allow further analysis.

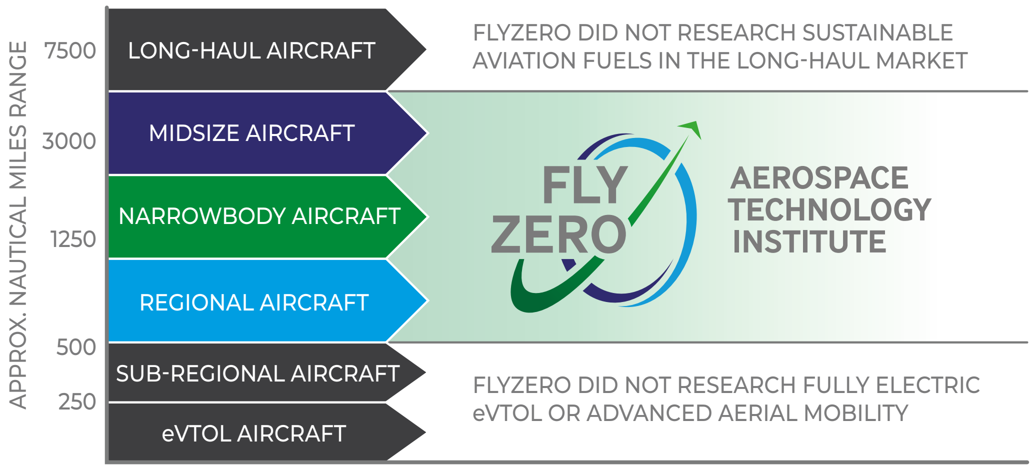


Figure 3 – FlyZero research scope

The zero-carbon concept models developed within the FlyZero project have expanded the ATI's independent capability for whole aircraft modelling. This enhances the ATI's ability to act as a virtual airframer to help the UK aviation industry understand sustainable aviation technologies, and provide objective expertise to the UK government. The ATI has a strategic objective to advance whole aircraft modelling capability in the UK as this is a critical element in understanding the impact of new technologies at aircraft level. It is not enough to consider the component or system technology in isolation, it must be considered in the wider context of the overall aircraft. It is recognised that the requirements and technology understanding will continue to evolve, and the ATI will reassess the concept designs in the future when required.

The aircraft concepts presented in this report have been used to support a sustainability assessment, operational impact analysis, market competitiveness evaluation and studies into the required energy infrastructure.

02. SCOUTS

In the early stages of the project, it was important to allow creative freedom for the team to innovate zero-carbon aircraft configurations based on the different technology bricks being developed. A list of key questions was created to guide the team, which was continually updated throughout the literature review and ideas generation activities. The output of the idea generation task was 27 different aircraft configurations which were named Scouts. The relative performance of these Scouts was explored through high-level analysis to provide an initial assessment in a short timescale.

The Scouts were then scored in various categories by the functional teams against a comprehensive matrix to select the most appropriate design features to satisfy the objectives of the FlyZero project. This system was independently audited to check for bias and allowed the whole team to influence the selection of features for the three initial FlyZero concept aircraft. The scoring process culminated in a review where each FlyZero sub-team (airframe, propulsion, aircraft integration, commercial, sustainability, industrial strategy, and safety) presented their recommendations for the initial concept aircraft. The aircraft integration team and chief engineers then made the final decision for the initial concepts in the regional, narrowbody and midsize market segments to be taken forward for further analysis.

As the concept iteration progressed, the team were challenged to continually review the decisions made at this stage, to ensure that alternative configurations or features considered within the Scouts could be reintroduced in later concept iterations if shown to be optimum.

03. REGIONAL CONCEPT

An aircraft in the regional market segment is considered by many to be the most likely initial entry point of a hydrogen aircraft. While the sector only contributes around 7% of global aviation emissions, regional aircraft generally have higher emissions per passenger mile flown so it is important this sector is not overlooked. The FlyZero reference aircraft for the regional market sector is the ATR72-600.

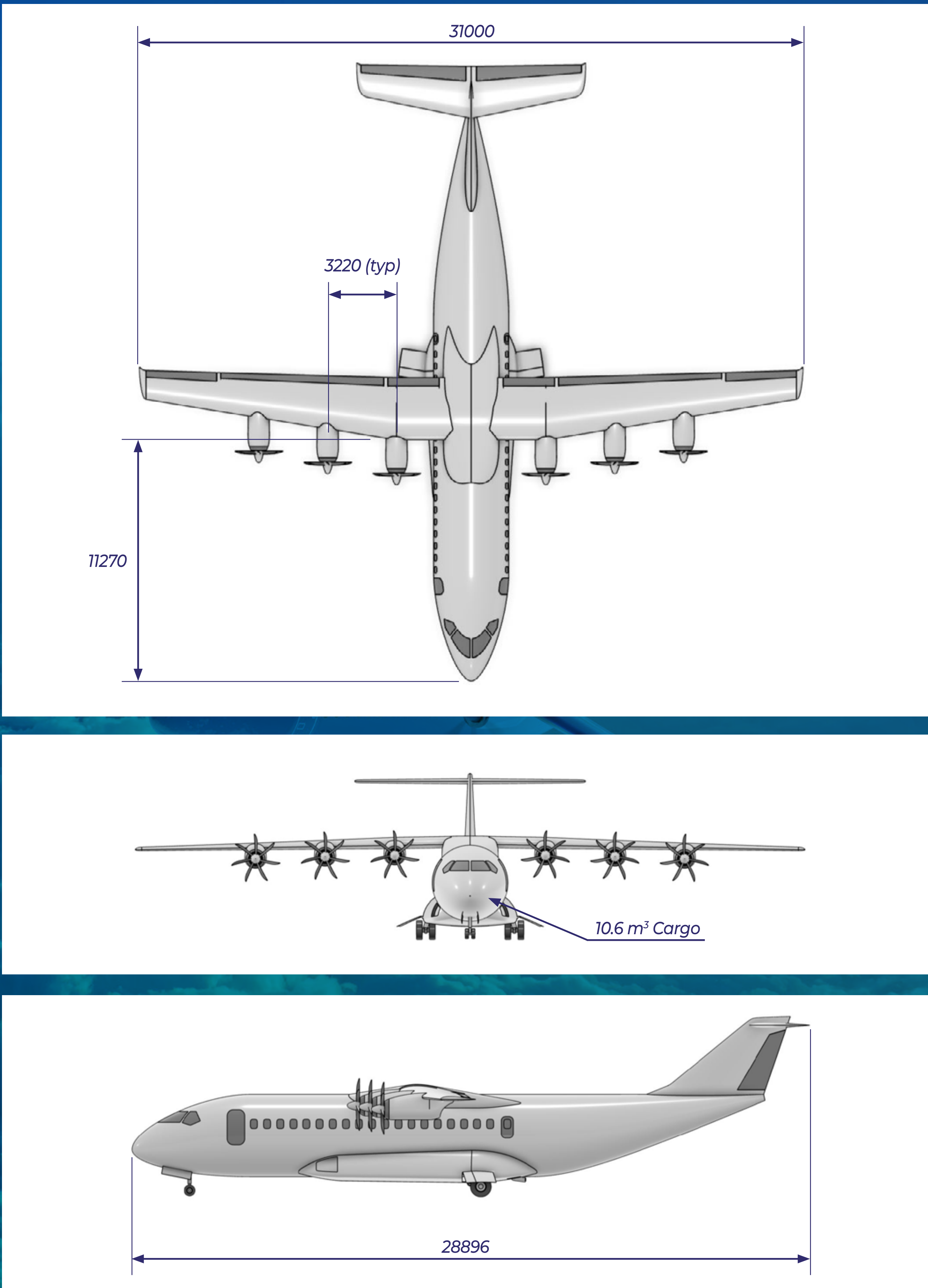


Figure 4 – Regional concept 3-view, measurements in mm (source: FlyZero)

The requirements for the regional concept were set at 800 nautical miles (nmi) range and 325 knots (kts) cruise speed. The concept range and payload requirements considerably exceed the capability of the reference aircraft with the aim of bridging the regional turboprop and jet markets, though the cruise speed is within the capability of existing turboprops such as the Q400. **Figure 5** below shows the concept market positioning. The design range of 800 nmi would allow a fleet to cover 87% of the available seat nautical miles (ASNMs) and the 75 seat concept sits just under the maximum seat popularity of 80 seats. This seat limit was intentionally applied to fall within the US scope clause limit of 76 seats (a key passenger limit for the US market which is also the largest regional market).

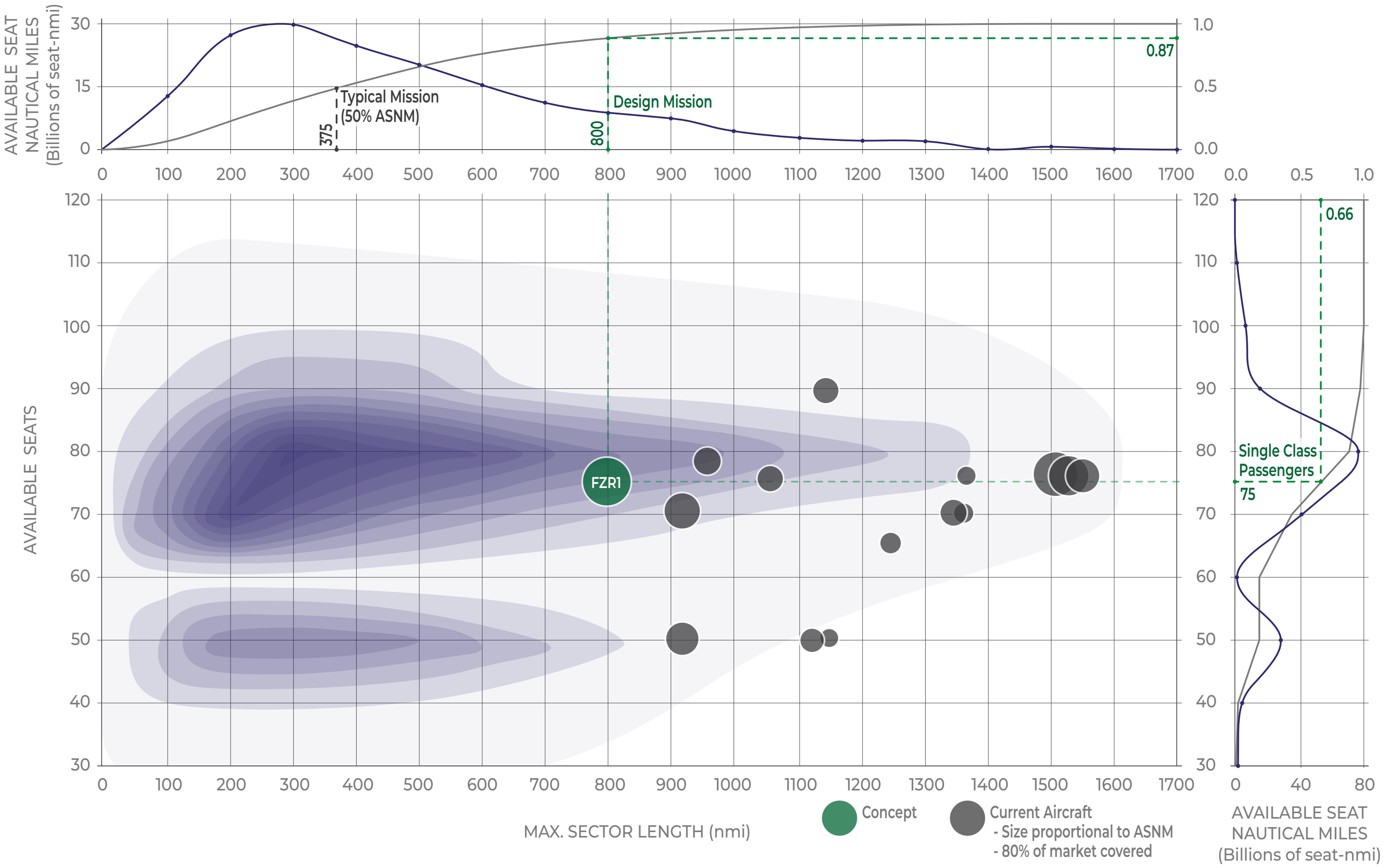


Figure 5 – Regional market joint available seat range density plot (source: Cirium SRS Analyzer Data 2019 and FlyZero analysis)

The joint available seat range density plot is designed to compare annual global sector revenue capability (approximated as available seat nautical miles (ASNMs)) against the operational capability of the current fleet and FlyZero concept positioning. Centrally, a heatmap of the ASNMs for all 2019 commercial flights in the relevant market sector is overlaid with the concept and current fleet capability bubbles. The current fleet capability is approximated by grouping aircraft variants with their available seats into seat group buckets. The most popular variants accumulating 80% of the market share are plotted as seat average vs max sector length flown and sized proportionally to total ASNMs. Joint plots integrating ASNMs across sector and seat ranges are aligned above and to the right respectively. A normalised cumulative sum (in grey) for both joint plots allows either available seat or sector length targets to be cross referenced against the corresponding relative market coverage.

The FlyZero regional concept is very similar in size to the baseline and reference aircraft and therefore is considered comparable from an air traffic management perspective; in particular, it conforms with the same wake turbulence and approach categories. It also sits within the same categories for ICAO aerodrome reference codes (e.g. wing span limits and reference field lengths).

A fuel cell's main advantages over other propulsion systems for large commercial aircraft are that it only emits water and eliminates all other exhaust emissions (CO_2, NO_x, particulates). The following illustrates the features and technology bricks that have been incorporated into the regional concept design as well as some of the key learning points.

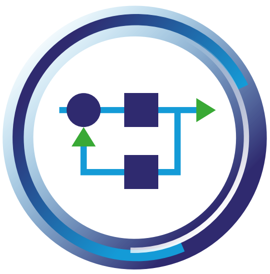
Fuel Cell Aircraft Size

The FlyZero analysis has shown a fuel cell system coupled with an electric powertrain driving propellers is feasible in this size class, based on the FlyZero technology projections in the 2026 timeframe [3]. The FlyZero concept uses around 10% more energy than the baseline aircraft. For a given power density it is likely that a fuel cell system would become more competitive as aircraft size decreases because gas turbines become less efficient as they decrease in size, while a fuel cell system is inherently modular and therefore the system efficiency does not reduce.

Fuel Cell System Sizing

The take-off power requirement, driven by the field length target, was the sizing case for the fuel cell system with the system weight sensitive to the peak power demand. The concept performance is responsive to changes in the power density of the fuel cell system, so if the roadmap future technology improvements are realised the fuel cell option would become more attractive. Fuel cell operating efficiency also improves significantly as the power demand is reduced relative to peak power. Up to a point, the weight penalty for over-sizing the fuel cell stack is offset by the reduced weight of the thermal management system and reduced fuel consumption. Therefore, the system take-off power to cruise power ratio will differ from a normal combustion aircraft and the key to this is understanding how to manage transient heat loads at the extremes of the operating envelope.

Fuel Cell System Integration



The fuel cells are located under the rear cabin floor in an unpressurised zone. Even with the increased fuselage diameter, extension of the landing gear fairings was required to accommodate all the system elements (fuel cells, thermal management, air and water management systems). The fuel cells were originally housed behind the cabin but were moved forward for space, weight and balance reasons.

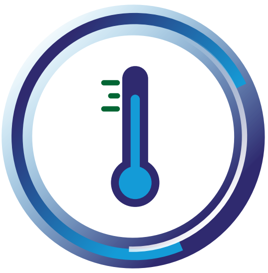
Fuselage Diameter

The fuselage diameter of the concept has been increased relative to the reference and baseline aircraft as it makes the hydrogen storage more efficient. Even with this increase, the regional concept uses vacuum-insulated tanks as the surface-area-to-volume ratio meant that the required thickness of foam insulation became difficult to accommodate, particularly for the aft tank.

Distributed Propulsion

The concept features six electric propulsor units driving propellers. This configuration minimises the impact of the one engine failure case during take-off and initial climb to avoid it becoming the system sizing case. No credit was taken for enhanced wing lift coefficient as a result of the propeller slipstream, despite it covering a significant portion of the wingspan. While powered lift may provide a benefit for take-off, the commercial benefits are not clear, and it can also create challenges with approach and landing performance if high thrust is needed to generate maximum lift.

Thermal Management System



The propulsor unit nacelles incorporate the heat exchangers for the electrical and the fuel cell thermal management systems. The thermal management system is a key weight driver due to the exhaust temperature of around 80°C that is produced by low-temperature fuel cells.

Water Management

The water produced in the exhaust of a fuel cell is a mixture of liquid water and water vapour. Following consultation with airport operators it was decided that liquid water emissions were not acceptable on a runway due to the potential for reduced runway friction, and the creation of precipitation during initial climb. A water storage system was therefore incorporated into the concept aircraft for these flight phases which will retain the water produced by the fuel cells on-board the aircraft. The water could be exhausted at another point in the flight or potentially used for other applications within the aircraft.

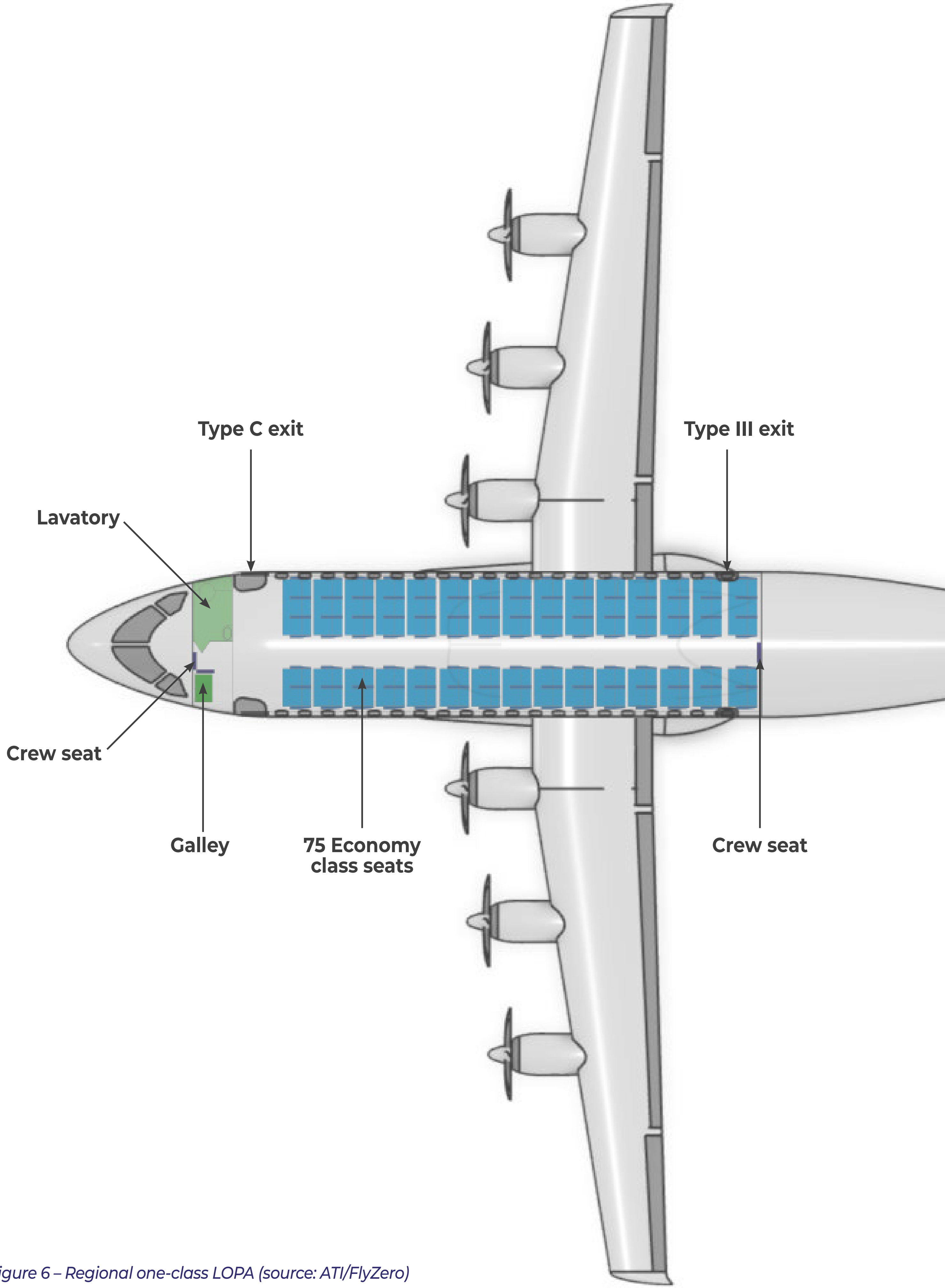


Figure 6 – Regional one-class LOPA (source: ATI/FlyZero)

Figure 7 – Regional concept transparent view (source: FlyZero)

Figure 8 – Regional concept cabin view (source: FlyZero)

Regional Aircraft Geometric Data		*Reference ATR72-600*	*Baseline ATR72-2030*	*Concept FZR-1E*
Fuel Type		*Jet A-1*	*SAF*	*LH_2*
Overall Aircraft Length (m)		*27.2*	*28.5*	*28.0*
Fuselage	*Length (m)*	*27.2*	*27.2*	*27.0*
	Diameter (m)	*2.8*	*2.8*	*3.5*
Wing	*Aspect Ratio (-)*	*12*	*14*	*14*
	Quarter-Chord Sweep (deg)	*1.6*	*1.8*	*7.0*
	Thickness Root/Tip (%)	*18/13*	*18/13*	*18/12*
	Span (m)	*27.1*	*31.3*	*31.0*
	Area (m^2)	*61.0*	*70.0*	*70.8*
	Loading (kg/m^2)	*374*	*368*	*407*
Propulsors	*No. of Propulsors*	*2*	*2*	*6*
	Propeller Diameter (m)	*3.9*	*4.0*	*2.3*
	Nacelle Diameter (m)	*1.1*	*1.2*	*0.96*
Empennage	*Vertical Area (m^2)*	*12.5*	*13.6*	*11.0*
	Horizontal Area (m^2)	*11.6*	*11.9*	*20.2*
	Horizontal Span (m)	*7.3*	*7.4*	*10.7*

Table 2 – Regional reference, baseline, and concept geometric comparison (source: ATI/FlyZero)

Regional Aircraft Performance Data		*Reference ATR72-600*	*Baseline ATR72-2030*	*Concept FZR-1E*
Fuel Type		*Jet A-1*	*SAF*	*LH_2*
Normal Take-off	*Aircraft Sea Level Shaft Power (kW)*	*3,692*	*4,235*	*4,400*
	Aircraft Power to Weight (kW/kg)	*0.162*	*0.164*	*0.153*
	Field Length (m)	*1,240*	*1,201*	*1,387*
Start of Cruise	*Aircraft Propulsive Power (kW)*	*1,796*	*2,684*	*3,115*
	Lift to Drag Ratio (-)	*16.8*	*15.5*	*15.1*
	Speed (ktas)	*266*	*325*	*325*
	Altitude (ft)	*25,000*	*25,000*	*25,000*
	SFC (kg/s/N) x 10^{-6}	*13.3*	*12.4*	*4.6*
	EPSFC (kg/kWhe)	*0.350*	*0.267*	*0.100*
Landing	*Approach Speed (keas)*	*111*	*109*	*114*
	Field Length (m)	*1,252*	*1,205*	*1,331*

Table 3 – Regional reference, baseline, and concept performance comparison (source: ATI/FlyZero)

Regional Aircraft Mission Data		Reference ATR72-600	Baseline ATR72-2030	Concept FZR-1E
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	72 @ 30”	75 @ 30”	75 @ 30”
	Cargo (kg)	0	0	0
	Total Payload (kg)	7,200	7,875	7,875
Max. Take-Off Weight (MTOW) (tonnes)		22.8	25.8	28.8
Operating Empty Weight (tonnes)		13.5	15.0	19.8
Design Mission	Range (nmi)	448	800	800
	Total Mission Fuel Mass inc. reserves (kg)	2,156	2,954	1,158
	Block Time (hrs)	2.1	3.0	2.9
	Block Fuel Mass (kg)	1,381	2,115	877
	Block Fuel Energy (MJ)	59,383	97,308	105,287
	Energy Intensity (MJ/ASNM)	1.84	1.62	1.75
Typical Mission	Range (nmi)	375	375	375
	Total Mission Fuel Mass inc. reserves (kg)	1,974	1,959	730
	Block Time (hrs)	1.9	1.6	1.6
	Block Fuel Mass (kg)	1,208	1,168	470
	Block Fuel Energy (MJ)	51,951	53,708	56,436
	Energy Intensity (MJ/ASNM)	1.92	1.91	2.01

Table 4 – Regional reference, baseline, and concept mission comparison (source: ATI/FlyZero)

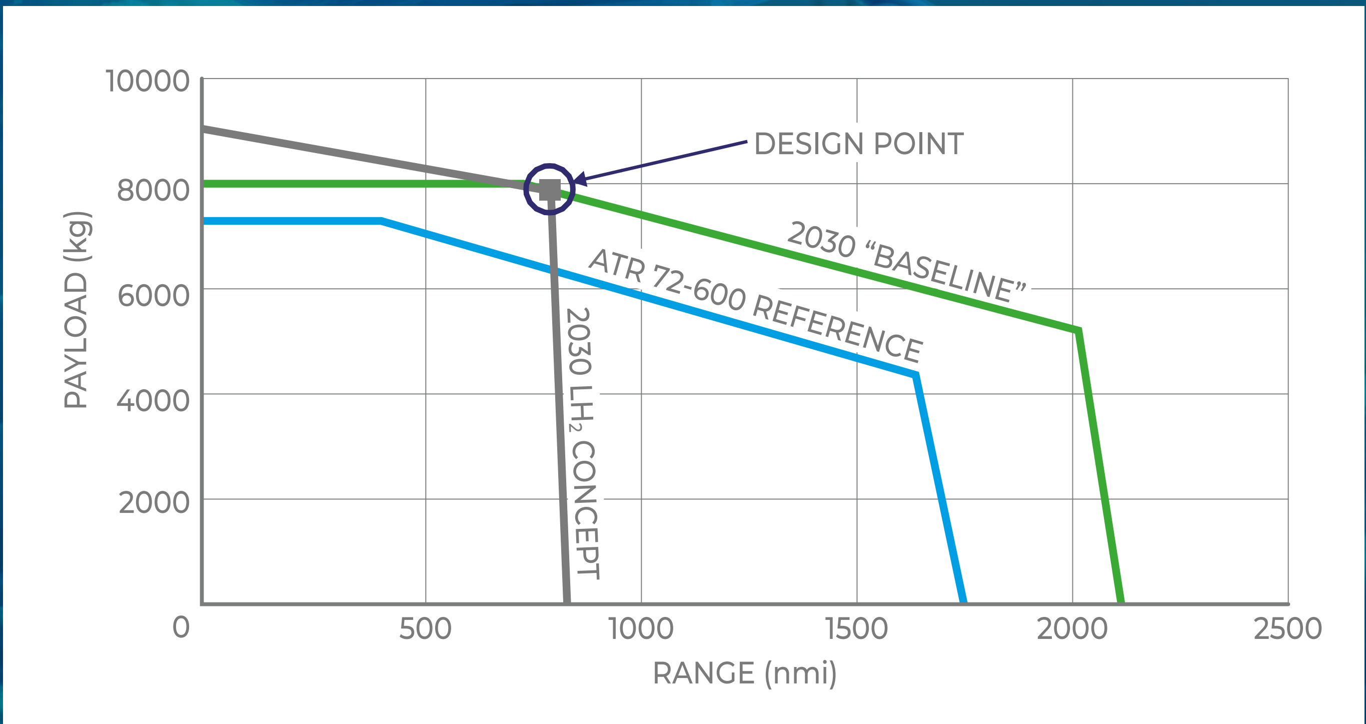


Figure 9 – Regional concept payload/range (source: FlyZero)

04. NARROWBODY CONCEPT

The narrowbody market segment is anticipated to account for 67% of new commercial aircraft acquisitions between 2030 and 2050 based on FlyZero analysis. However, this makes it unlikely that a narrowbody would be the entry point for a zero-carbon hydrogen aircraft due to the level of commercial risk this would entail.

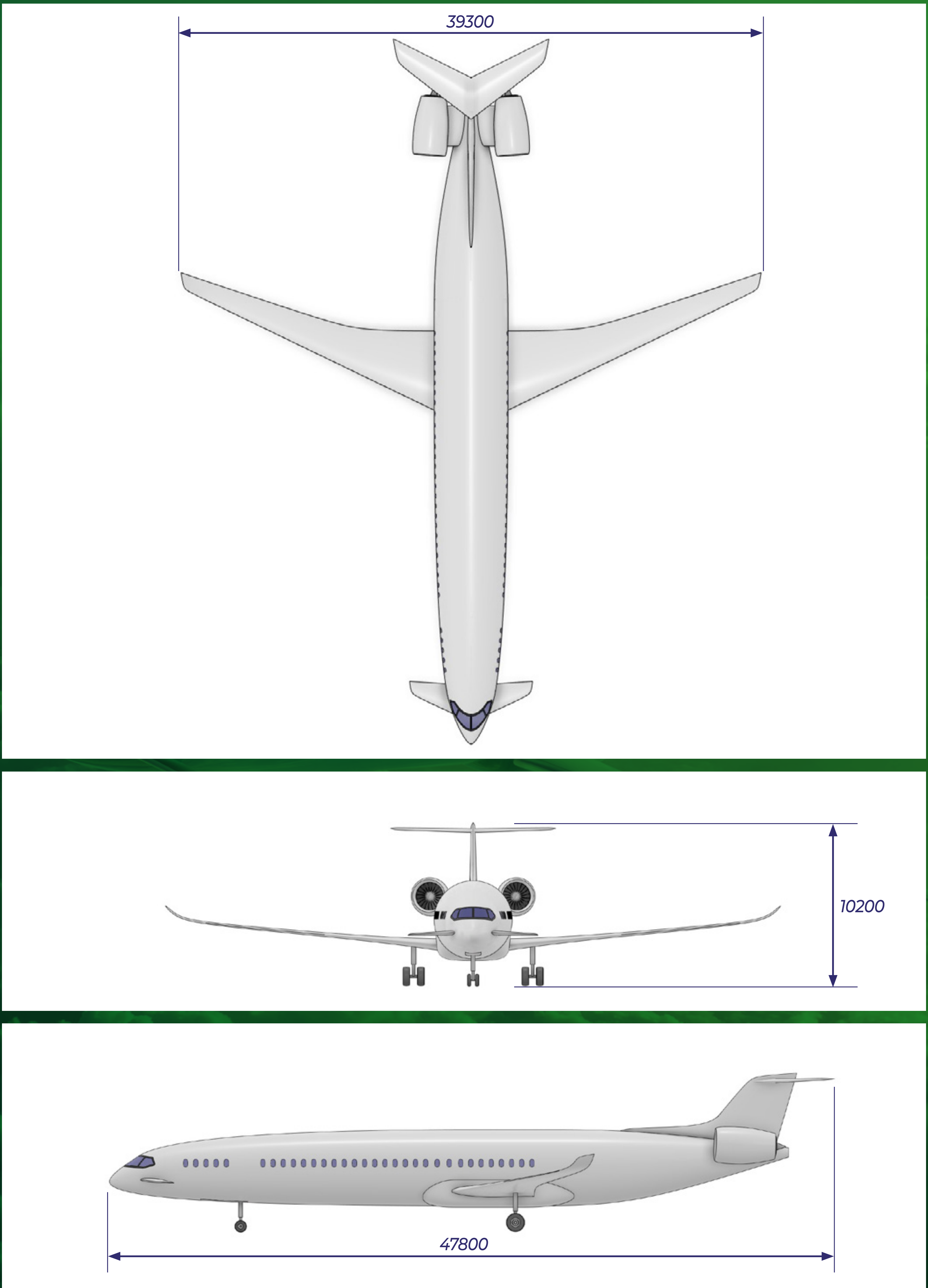


Figure 10 – Narrowbody concept 3-view, measurements in mm. (source: FlyZero)

Due to the size and commercial importance of this market segment, in combination with feedback from airlines, the concept aircraft requirements were initially specified to be similar to the reference aircraft, the A320neo. The range was set at 2400 nmi which is the maximum payload and maximum fuel point for the reference aircraft. **Figure 11** below shows this range covers 99% of the ASNMs with an aircraft also meeting the maximum seat popularity of 180 seats. Crucially, with the 50% mission at 850 nmi, this design range would allow concurrent network and liquid hydrogen infrastructure growth enabled by return flights without refuelling (tankering). The cruise speed and altitude were set to match the reference aircraft.

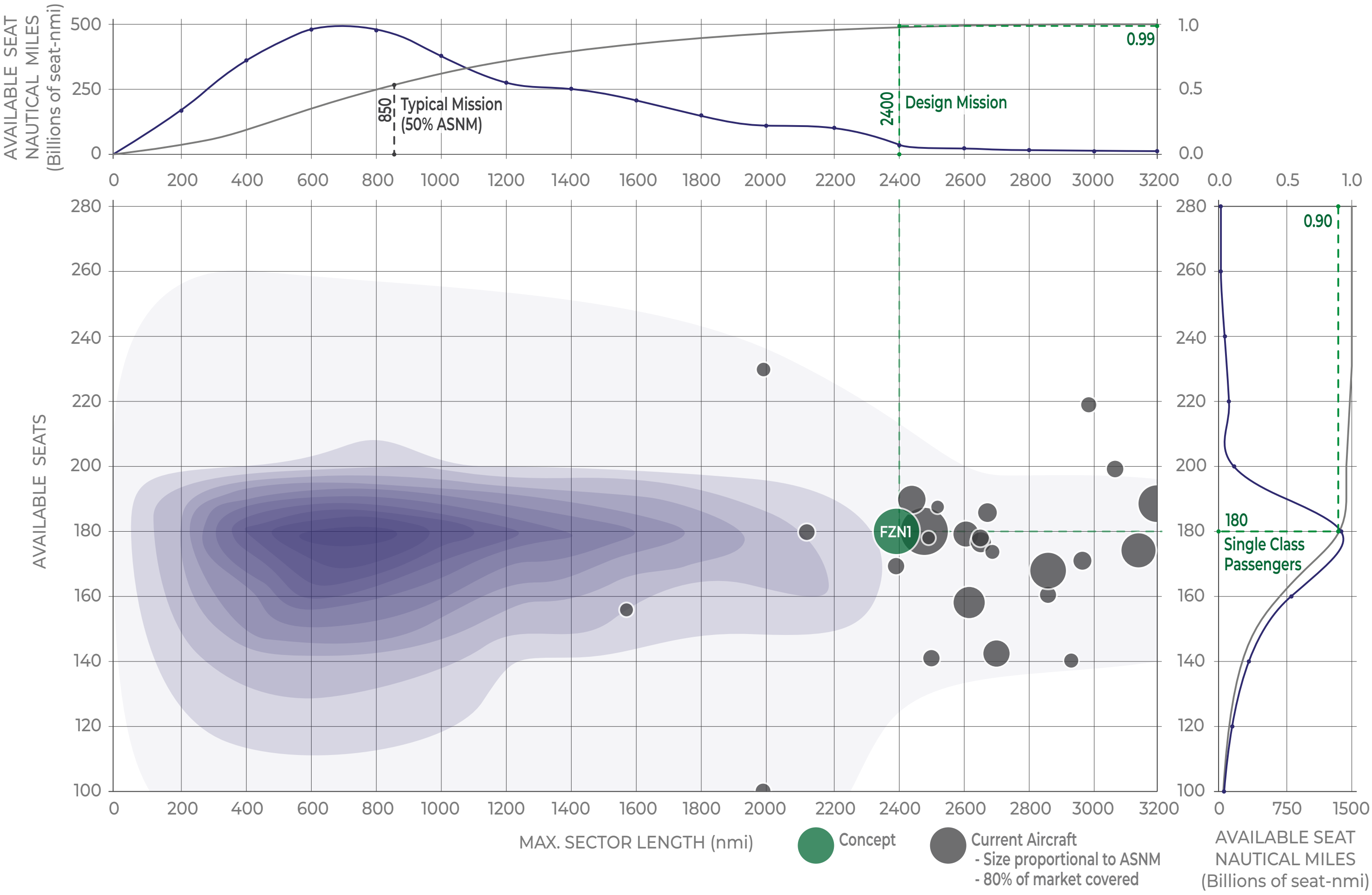


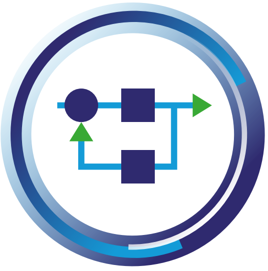
Figure 11 – Narrowbody market joint available seat range density plot (source: Cirium SRS Analyzer Data 2019 and FlyZero analysis)

The joint available seat range density plot is designed to compare annual global sector revenue capability (approximated as available seat nautical miles (ASNMs)) against the operational capability of the current fleet and FlyZero concept positioning. Centrally, a heatmap of the ASNMs for all 2019 commercial flights in the relevant market sector is overlaid with the concept and current fleet capability bubbles. The current fleet capability is approximated by grouping aircraft variants with their available seats into seat group buckets. The most popular variants accumulating 80% of the market share are plotted as seat average vs max sector length flown and sized proportionally to total ASNMs. Joint plots integrating ASNMs across sector and seat ranges are aligned above and to the right respectively. A normalised cumulative sum (in grey) for both joint plots allows either available seat or sector length targets to be cross referenced against the corresponding relative market coverage.

The FlyZero narrowbody concept is very similar in size to the baseline and reference aircraft and therefore it is considered comparable from an air traffic management perspective as it would sit in the same wake turbulence and approach categories. It also sits in the same categories for ICAO aerodrome reference codes. The FlyZero narrowbody concept uses around 4% less energy compared to the baseline aircraft for the design mission.

At this size of aircraft, the overall power required favours the high power density of a gas turbine. The following illustrates the features and technology bricks that have been incorporated into the narrowbody concept design as well as some of the key learning points.

Propulsion and Fuel System Location



The narrowbody concept investigates the option to locate the propulsion and fuel systems at the rear of the aircraft. This includes the two liquid hydrogen tanks, fuel system, and gas turbines. This architecture necessitates a T-tail and keeps all the hydrogen fuel lines behind the cabin in a more compact system layout than locating the engines under the wing; it minimises fuel pipe length and the number of aircraft zones containing hydrogen, as hydrogen leakage is a known risk. FlyZero research also concluded this layout enables a reduction in overall aircraft noise.

The chosen concept architecture creates centre of gravity (CG) issues because of the distance that the CG moves during different flight and loading conditions. A canard has therefore been added at the front of the fuselage to address this issue. One solution to the CG challenge would be to mount the engines under the wings, though the narrowbody concept was specifically defined to explore rear-mounted engines and what benefits and challenges this would bring. FlyZero analysis of an alternative narrowbody concept architecture with the engines positioned under the wing showed similar performance.

Three-Lifting-Surface Configuration

The three-lifting-surface (3LS) configuration was introduced in conjunction with the propulsion and fuel system architecture described above to address the CG movement issue. The canard provides improved longitudinal trim authority, allowing a wider CG range and improved pitch authority for rotation. It can also be used in combination with the tailplane to minimise aircraft trim drag through the wide range of CG changes in flight. With the 3LS configuration and an active stability system this aircraft architecture appears feasible, but further research is required to validate this.

Dry Wing

The wings are dry (they do not contain any fuel) with the fuel stored in the fuselage, and this offers a potential performance benefit as the structure can be optimised for wing bending moment and aeroelastic purposes. The flap mechanisms can be located within the wing structure rather than requiring external fairings. There is also an opportunity to relocate some systems within the wing, though this has not been investigated by FlyZero.

Folding Wing Tips

The concept analysis showed the optimum wing configuration slightly exceeded the span limit for the ICAO category of the reference aircraft. Folding wingtips were therefore introduced to bring the wingspan within the code C limit. Folding wingtips have been demonstrated on the Boeing 777X, but further work is required to develop a lightweight, low-cost, and certifiable solution for a narrowbody aircraft.

Fuel Tankering

Fuel tankering is the practice of carrying more fuel than needed for a specific flight to reduce or avoid refuelling at the destination airport. The performance and environmental penalty for carrying more fuel than necessary can be significant and jet fuel is relatively heavy when compared to hydrogen for the same energy value. FlyZero analysis shows that an A320neo would pay a 6.3% fuel consumption penalty on the outbound leg of a 1000 nmi round trip for carrying the required return fuel, whereas the narrowbody concept aircraft would only incur a 1.3% penalty and not emit any additional CO_2. This may be significant for the early stages of hydrogen operation when fuel infrastructure is limited.

Engine Diameter

On a hydrogen aircraft a lighter, smaller diameter engine reduces aircraft fuel burn even though the engine specific fuel consumption (SFC) is worse. This effect was first identified during a midsize concept trade study and therefore is covered in more detail in that section, but the principle reads across to the narrowbody concept. Smaller diameter engines are also helpful for the narrowbody concept engine position at the rear of the aircraft.

Laminar Flow Fuselage

Typically, a narrowbody jet would have a constant section fuselage, however it was decided to illustrate an alternative approach on the narrowbody concept. As it would be beneficial for the fuselage to be wider at the rear where the fuel tanks are located, the cross-section was made variable to encourage natural laminar flow with the aim of reducing drag. This idea is similarly examined in the NASA report CR3970 'Design of Fuselage Shapes for Natural Laminar Flow' [4]. For the other FlyZero concepts the chosen solution was to maintain a constant section with an increased diameter to mitigate the volume challenge presented by liquid hydrogen.

The fuselage typically contributes 25% of overall aircraft drag, and while this fuselage configuration would require further validation to demonstrate and quantify the benefit, it has been included to illustrate that all areas of the aircraft need to be considered for performance improvements as part of the overall effort to de-carbonise aviation. An additional benefit of this fuselage shape is it allows a novel cabin configuration which is shown in the layout of passenger accommodation (LOPA) diagram below.

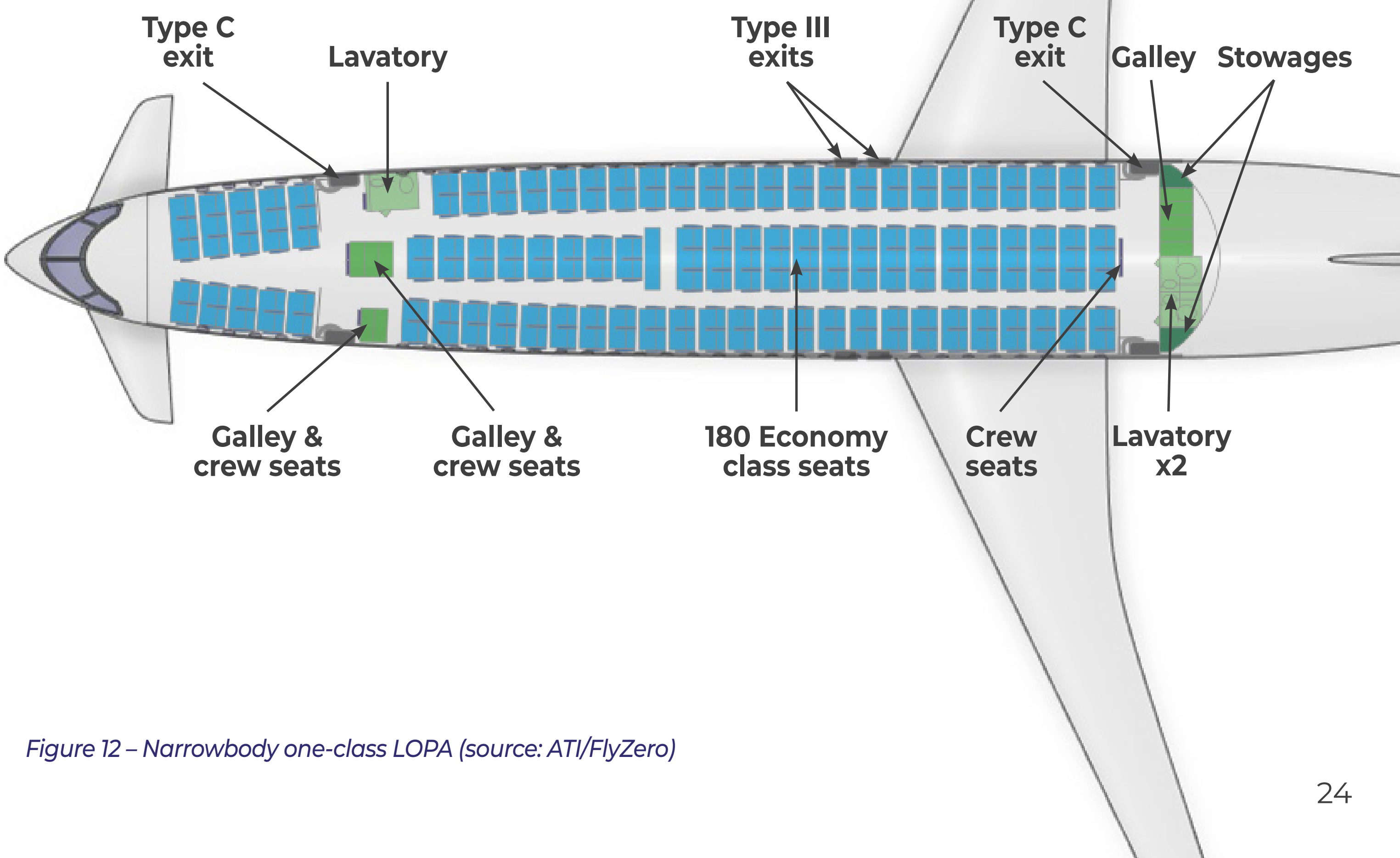


Figure 12 – Narrowbody one-class LOPA (source: ATI/FlyZero)

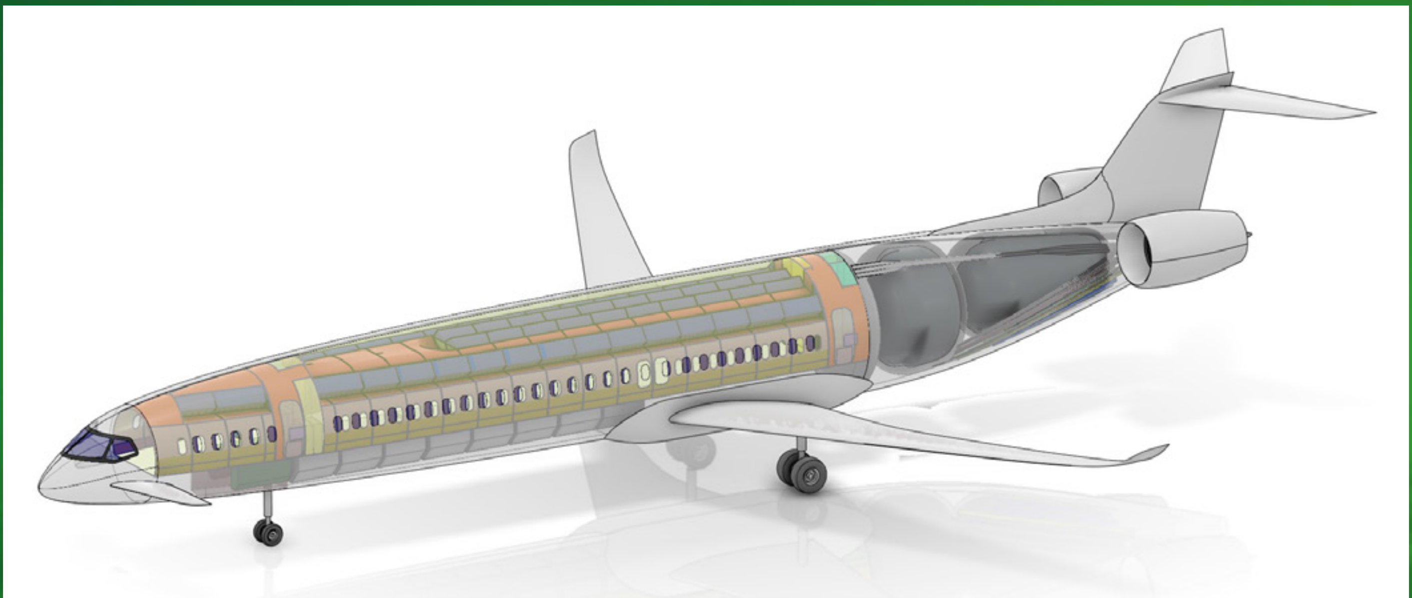


Figure 13 – Narrowbody concept transparent view (source: FlyZero)

Figure 14 – Business class narrowbody concept cabin view. (source: FlyZero)

Figure 15 – Economy class narrowbody concept cabin view. (source: FlyZero)

Figure 16 – Narrowbody concept entryway (source: FlyZero)

Narrowbody Aircraft Geometric Data		Reference A320neo	Baseline A320-2030	Concept FZN-1E
Fuel Type		Jet A-1	SAF	LH_2
Overall Aircraft Length (m)		37.6	37.6	44.8
Fuselage	Length (m)	37.6	37.6	44.8
	Diameter (m)	4.050	4.050	5 (max)
Wing	Aspect Ratio (-)	10	13	13
	Quarter-Chord Sweep (deg)	25.0	24.0	24.0
	Thickness Root/Tip (%)	15/11	15/11	14/10.5
	Span (m)	35.8	38.8	39.3
	Area (m^2)	128	116	119
	Loading (kg/m^2)	617	608	594
Propulsors	Fan Diameter (in.)	78.0	83.2	70.5
	Bypass Ratio (-)	11	11	13
	Nacelle Diameter (m)	2.7	2.9	2.4
Empennage	Vertical Area (m^2)	21.5	21.8	22.4
	Horizontal Area (m^2)	31.0	22.2	22.7
	Horizontal Span (m)	12.5	10.5	10.6
	Hotizontal Aspect Ratio (-)	5.0	5.0	5.0

Table 5 – Narrowbody reference, baseline, and concept geometric comparison (source: ATI/FlyZero)

Narrowbody Aircraft Performance Data		Reference A320neo	Baseline A320-2030	Concept FZN-1E
Fuel Type		Jet A-1	SAF	LH_2
Take-off	ISA Sea Level Static Thrust (kN)	120.6	105.9	105.5
	Field Length (m)	1,951	2,000	1,998
Start of Cruise	Thrust (kN)	21.1	17.2	17.5
	Lift to Drag Ratio (-)	17.9	19.7	19.6
	Speed (ktas)	450	450	450
	Altitude (ft)	35,000	35,000	35,000
	SFC (kg/s/N) x 10^{-6}	14.7	12.6	4.7
Landing	Approach Speed (keas)	131	133	137
	Field Length (m)	1,931	1,804	1,904

Table 6 – Narrowbody reference, baseline, and concept performance comparison (source: ATI/FlyZero)

Narrowbody Aircraft Mission Data		Reference A320neo	Baseline A320-2030	Concept FZN-1E
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	180 @ 32”	180 @ 32”	180 @ 32”
	Cargo (kg)	-	-	-
	Total Payload (kg)	19,400	18,795	18,795
Max. Take-Off Weight (MTOW) (tonnes)		79.0	70.6	70.7
Operating Empty Weight (tonnes)		44.9	41.5	48.0
Design Mission	Range (nmi)	2,495	2,400	2,400
	Total Mission Fuel Mass inc. reserves (kg)	14,753	10,312	3,903
	Block Time (hrs)	6.0	5.8	5.8
	Block Fuel Mass (kg)	12,184	8,439	3,283
	Block Fuel Energy (MJ)	523,912	388,194	374,262
	Energy Intensity (MJ/ASNM)	1.13	0.899	0.866
Typical Mission	Range (nmi)	850	850	850
	Total Mission Fuel Mass inc. reserves (kg)	6,638	4,902	1,800
	Block Time (hrs)	2.4	2.4	2.4
	Block Fuel Mass (kg)	4,306	3,187	1,241
	Block Fuel Energy (MJ)	185,158	146,602	141,747
	Energy Intensity (MJ/ASNM)	1.17	0.96	0.92

Table 7 – Narrowbody reference, baseline, and concept mission comparison (source: ATI/FlyZero)

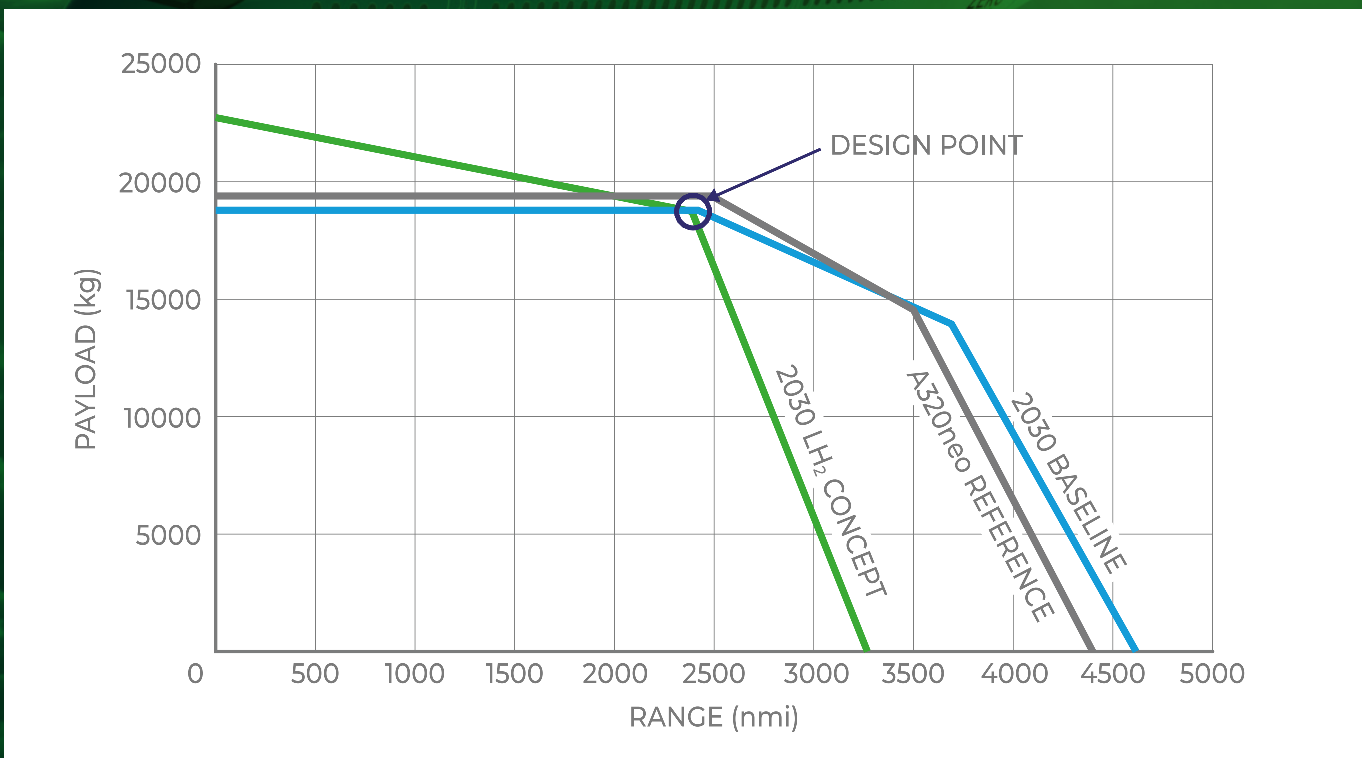


Figure 17 – Narrowbody concept payload/range (source: FlyZero)

05. MIDSIZE CONCEPT

The widebody market segment is the second largest source of aviation emissions, though the emissions per aircraft are higher than narrowbodies. It is possible that a hydrogen aircraft could enter this market segment first, despite relatively higher development costs than a smaller aircraft. This is because an initial hydrogen widebody aircraft route network would cover a relatively small number of major airports. Therefore, the hydrogen infrastructure requirements may be easier to manage at initial entry into service. It is also worth noting that the first Airbus aircraft was a widebody.

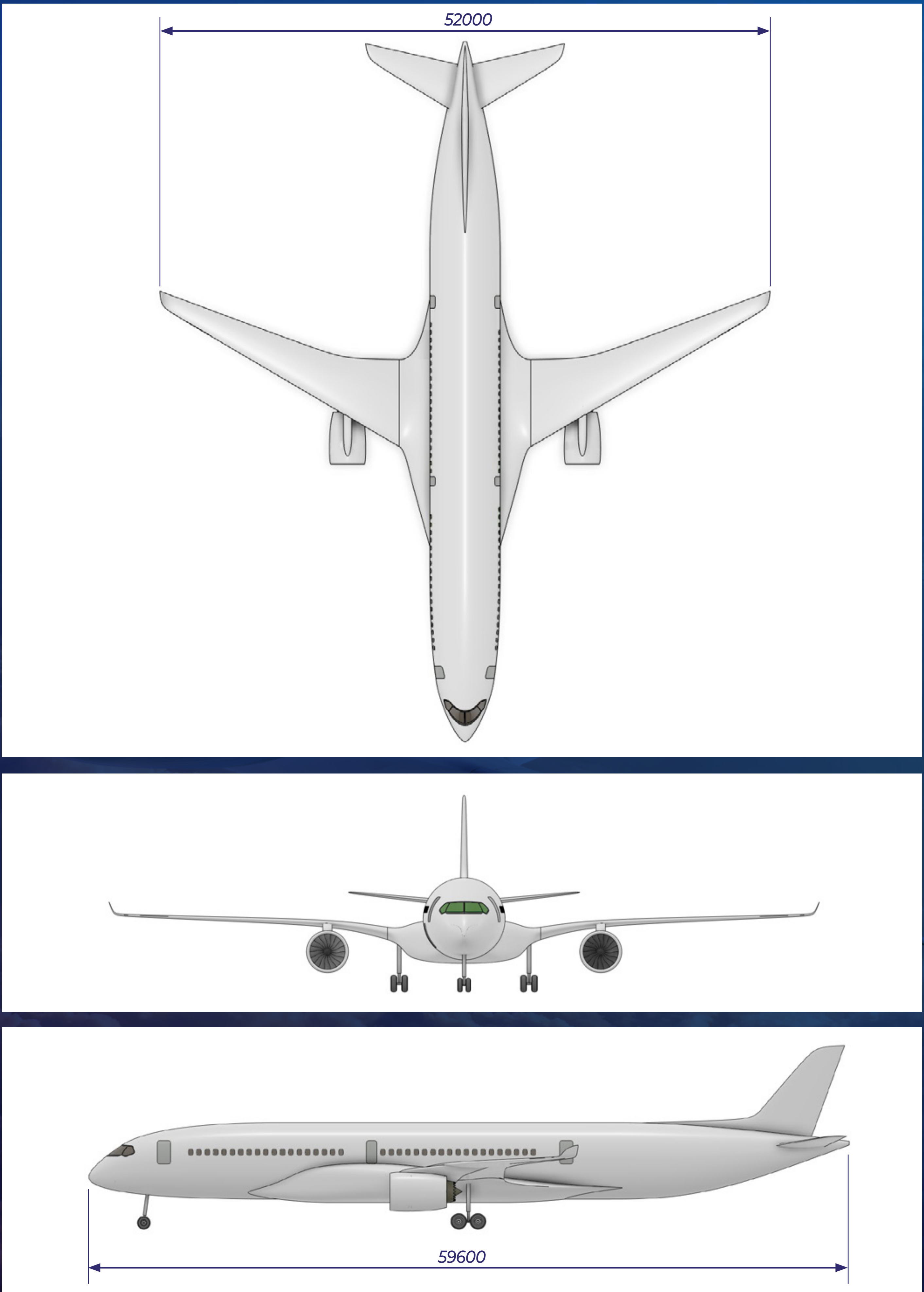


Figure 18 – Midsize concept 3-view, measurements in mm (source: FlyZero)

During the Scout analysis task, initial results showed that a hydrogen aircraft using gas turbines could be competitive at higher passenger numbers and longer ranges than the narrowbody. Further analysis supported this conclusion, and the result is the concept shown. A benefit of the midsize configuration is that it would allow an aircraft to be introduced more harmoniously into the "middle of the market" currently served by older aircraft designs or larger aircraft operating below their design points. The design range was set at 5750 nmi, based on a target operational range of 5250 nmi, to enable flights to all major global destinations with two flights and one stop. Cruise speed and altitude were initially set to match the reference aircraft, which was the 767-200ER. **Figure 19** below shows that this market segment does not have the same concentration as the regional and narrowbody sectors. The midsize concept could service 83% of the ASNMs with an aircraft also meeting the maximum seat popularity of 280 seats, though it is likely this number of passengers is provided with multi-class layouts (rather than a single-class layout) in existing aircraft.

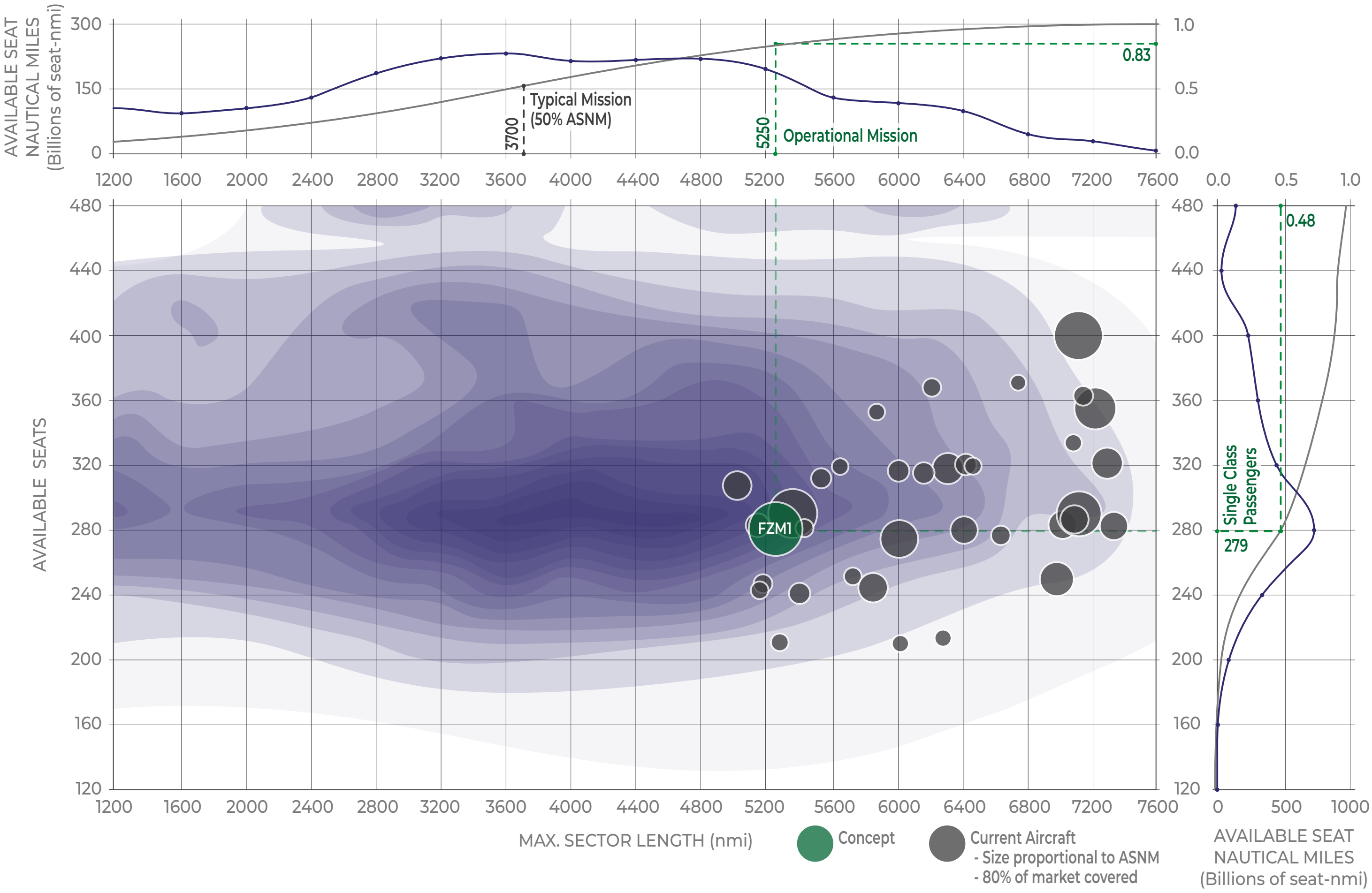


Figure 19 – Midsize market joint available seat range density plot (source: Cirium SRS Analyzer Data 2019 and FlyZero analysis)

The joint available seat range density plot is designed to compare annual global sector revenue capability (approximated as available seat nautical miles (ASNMs)) against the operational capability of the current fleet and FlyZero concept positioning. Centrally, a heatmap of the ASNMs for all 2019 commercial flights in the relevant market sector is overlaid with the concept and current fleet capability bubbles. The current fleet capability is approximated by grouping aircraft variants with their available seats into seat group buckets. The most popular variants accumulating 80% of the market share are plotted as seat average vs max sector length flown and sized proportionally to total ASNMs. Joint plots integrating ASNMs across sector and seat ranges are aligned above and to the right respectively. A normalised cumulative sum (in grey) for both joint plots allows either available seat or sector length targets to be cross referenced against the corresponding relative market coverage.

The FlyZero midsize concept is very similar in size to the baseline and reference aircraft and therefore it is considered comparable from an air traffic management perspective as it would sit in the same wake turbulence categories. It also sits in the same categories for ICAO aerodrome reference codes. The midsize data tables show that the FlyZero concept is competitive with the baseline aircraft from an energy intensity perspective. The following illustrates the features and technology bricks that have been incorporated into the midsize concept design as well as some of the key learning points.

Hydrogen Storage and Aircraft Architecture

When designing for longer ranges, the location of the hydrogen storage is a key driver of aircraft architecture. FlyZero design principles required the storage location to be outside of gas turbine uncontained engine rotor failure zones, wheel and tyre debris arcs, and also account for impact from tail strikes, bird strikes, belly landings and general crashworthiness. It also needs to allow sufficient control of longitudinal trim and stability during all flight phases. For the midsize concept, the engines have been placed under the wings and 'delta' tanks have been added in an unpressurised zone in front of the wing to ensure weight and balance stay within reasonable limits. This configuration also takes current regulations and operational constraints into consideration. As an example, the hydrogen exclusion zones when refuelling a large hydrogen tank located at the front of the aircraft could prevent the pilots being on the flight deck doing pre-flight checks. Future changes to design requirements, regulatory or operational constraints could change the optimum aircraft configuration.

Engine Diameter

During the midsize concept analysis, it was noticed that for the same thrust requirement, a smaller diameter gas turbine led to a lower mission fuel burn, even though the specific fuel consumption (SFC) of the smaller gas turbine is worse. This is different to how engine size trades for a kerosene aircraft. The reason for this is that kerosene or SAF is relatively heavy compared to hydrogen as a fuel, and therefore an increase in engine efficiency or SFC gives a significant fuel mass reduction at the aircraft level, which outweighs any increase in engine weight from increasing the engine diameter. With hydrogen the reduction in fuel mass is relatively small so a smaller, lighter engine is the better option overall. FlyZero noise analysis suggests it is possible to achieve lower levels of noise for a hydrogen aircraft than the project noise requirements, which are more stringent than the current regulations. Further work is needed to better understand how the noise characteristics of a hydrogen aircraft differ from a kerosene aircraft.

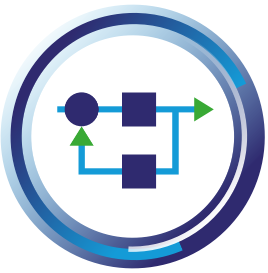
Fuselage Diameter

The midsize concept has a large liquid hydrogen tank in the rear of the fuselage, in addition to the two delta tanks ahead of the wing. Hydrogen storage becomes more weight and volume efficient as the tank diameter increases, which then requires the fuselage diameter to increase. This has the benefit of reducing the overall aircraft length, at the expense of increased drag. The alternative is to increase the fuselage length at the same diameter, but in practice there is a limit to the maximum aircraft length for design and operational reasons. Relative to kerosene, the net effect of this for a hydrogen aircraft is to reduce the aircraft size where the transition to a widebody configuration makes sense. As a result, the midsize concept has a fuselage diameter comparable to that of large twin-aisle aircraft like the A350 or 777X, which is significantly larger than the reference and baseline aircraft.

Dry Wing

Trade studies on the midsize concept wingspan and cruise altitude showed that any efficiency benefits of cruising at a higher altitude enabled with a larger wingspan were cancelled out by the additional structural wing weight. This drove the final wingspan of the midsize concept to be within the criteria for the same ICAO category as the reference aircraft, so folding wingtips were not required. This trade is different to a kerosene aircraft as, like the gas turbine example above, the fundamental trade for efficiency and performance vs weight changes for a hydrogen aircraft due to the difference in the weight of the fuel. As with the narrowbody concept, the dry wing enables novel design options such as aeroelastically optimised structures and integrated flap mechanisms which create new opportunities to realise aerodynamic performance benefits.

Fuel System Integration



To ensure that all hydrogen systems are located in unpressurised zones, the trailing edge of the wing root was extended to provide suitable space for routing the fuel pipes from the rear hydrogen tank to the forward delta tanks and engines outside of the pressure vessel. This requires long liquid hydrogen fuel lines which introduce design challenges and attendant potential risks. Further work is required in this area.

Fuel Tankering

As discussed in the narrowbody section, fuel tankering with a hydrogen aircraft carries a lower performance penalty for the outbound flight than it would with a kerosene or SAF aircraft. This could be utilised in early service to enable return flights without refuelling to reduce the requirement for hydrogen infrastructure.

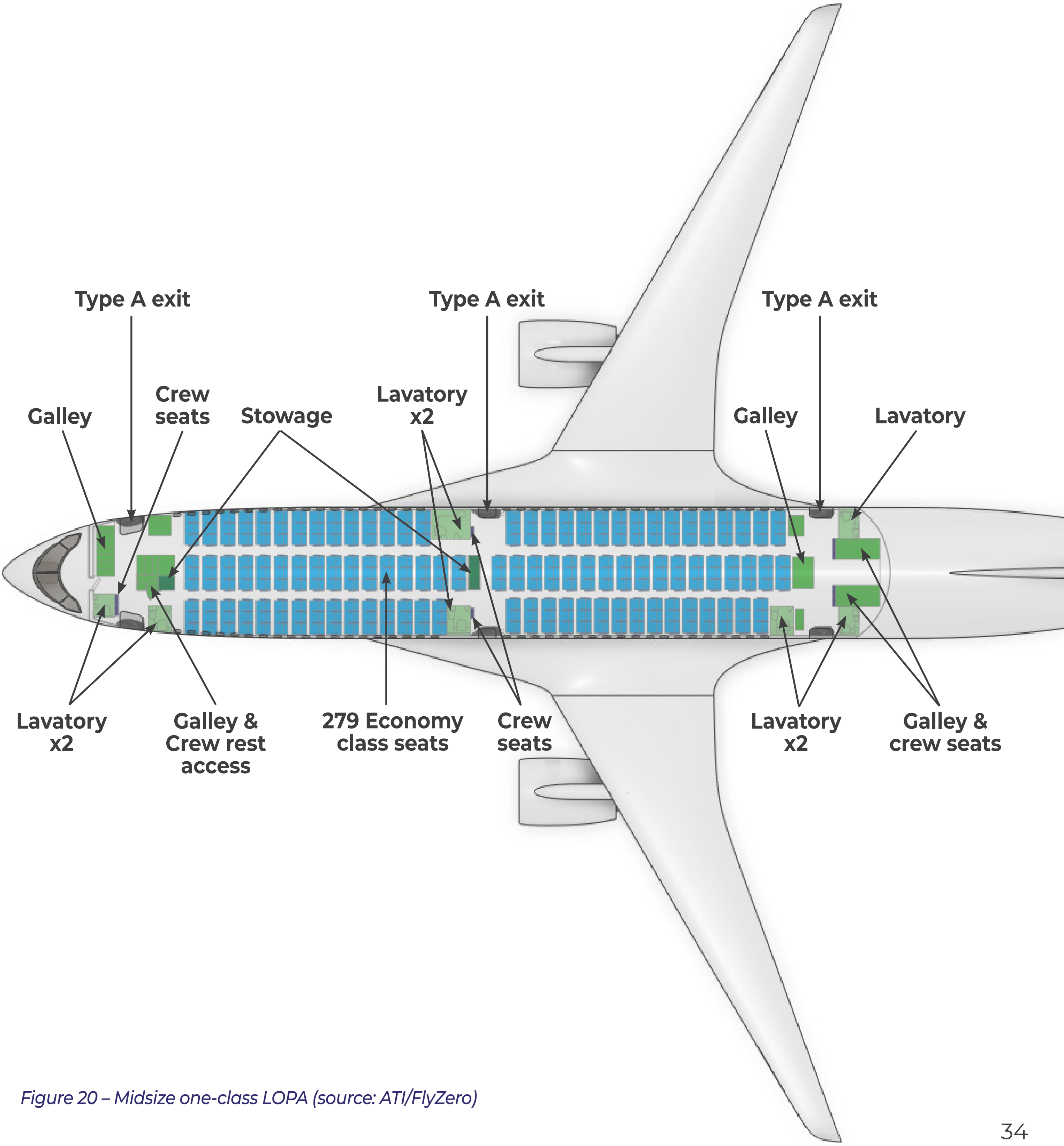


Figure 20 – Midsize one-class LOPA (source: ATI/FlyZero)

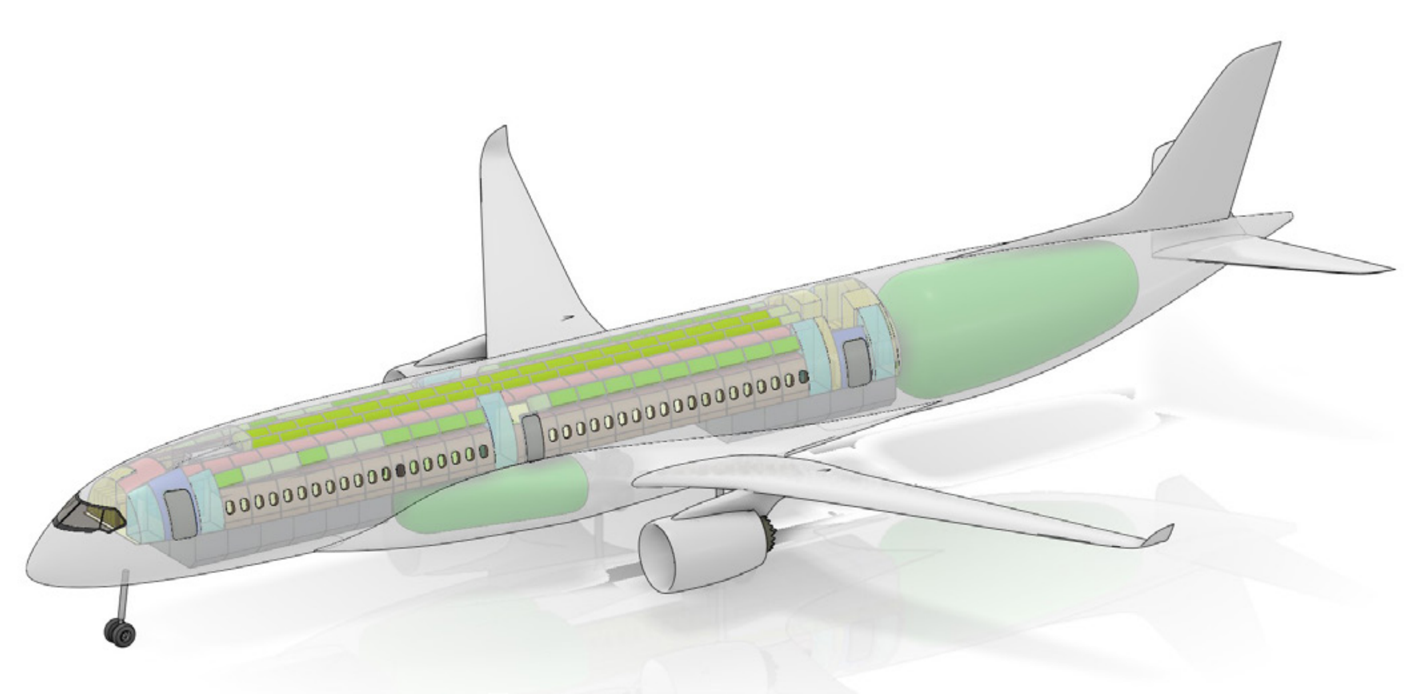


Figure 21 – Midsize concept transparent view (source: FlyZero)

Figure 22 – Business class midsize concept cabin view (source: FlyZero)

Figure 23 – Premium Economy class midsize concept cabin view (source: FlyZero)

Midsize Aircraft Geometric Data		Reference B767-200ER	Baseline B767-2030	Concept FZM-1G
Fuel Type		Jet A-1	SAF	LH_2
Overall Aircraft Length (m)		48.5	51.7	59.6
Fuselage	Length (m)	47.2	51.7	59.6
	Diameter (m)	5.030	5.040	6.000
Wing	Aspect Ratio (-)	8.0	10.0	10.7
	Quarter-Chord Sweep (deg)	31.5	29.0	28.0
	Thickness Root/Tip (%)	14.6/10.3	17/10	15/10
	Span (m)	47.6	52.0	52.0
	Area (m^2)	283.3	254.8	244.7
	Loading (kg/m^2)	632.5	667.5	616.1
Propulsors	Fan Diameter (in.)	93	106.0	101.9
	Bypass Ratio (-)	5	~15	~13
	Nacelle Diameter (m)	2.68	3.35	3.05
Empennage	Vertical Area (m^2)	46.1	32.7	28.8
	Horizontal Area (m^2)	77.7	55.7	48.5
	Horizontal Span (m)	18.6	18.3	17.0
	Hotizontal Aspect Ratio (-)	4.5	6.0	5.9

Table 8 – Midsize reference, baseline, and concept geometric comparison (source: ATI/FlyZero)

Midsize Aircraft Performance Data		Reference B767-200ER	Baseline B767-2030	Concept FZM-1G
Fuel Type		Jet A-1	SAF	LH_2
Normal Take-off	ISA Sea Level Static Thrust (kN)	270.5	235.8	224.6
	Field Length (m)	2,670	3,057	2,438
Start of Cruise	Thrust (kN)	45.1	37.1	43.9
	Lift to Drag Ratio (-)	19.1	22.1	19.9
	Speed (ktas)	459	477	473
	Altitude (ft)	31,000	33,000	35,000
	SFC (kg/s/N) x 10^{-6}	16.80	15.87	4.85
Landing at MLW	Approach Speed (keas)	135	145	145
	Field Length (m)	1,856	2,146	2,146

Table 9 – Midsize reference, baseline, and concept performance comparison (source: ATI/FlyZero)

Midsize Aircraft Mission Data		Reference B767-200ER	Baseline B767-2030	Concept FZM-1G
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	242 @ 32”	279 @ 32”	279 @ 32”
	Cargo (kg)	10,190	0	0
	Total Payload (kg)	35,600	29,250	29,250
Max. Take-Off Weight (MTOW) (tonnes)		179.2	170.0	150.8
Operating Empty Weight (tonnes)		82.4	96.5	104.8
Design Mission	Range (nmi)	5,273	5,750	5,750
	Total Mission Fuel Mass inc. reserves (kg)	61,440	44,375	16,743
	Block Time (hrs)	11.9	12.5	12.7
	Block Fuel Mass (kg)	54,910	40,383	15,151
	Block Fuel Energy (MJ)	2,361,130	1,857,613	1,727,214
	Energy Intensity (MJ/ASNM)	1.69	1.16	1.08
Typical Mission	Range (nmi)	3,700	3,700	3,700
	Total Mission Fuel Mass inc. reserves (kg)	42,085	28,672	11,104
	Block Time (hrs)	8.5	8.4	8.4
	Block Fuel Mass (kg)	36,190	25,138	9,677
	Block Fuel Energy (MJ)	1,556,170	1,156,348	1,103,178
	Energy Intensity (MJ/ASNM)	1.74	1.12	1.07

Table 10 – Midsize reference, baseline, and concept mission comparison (source: ATI/FlyZero)

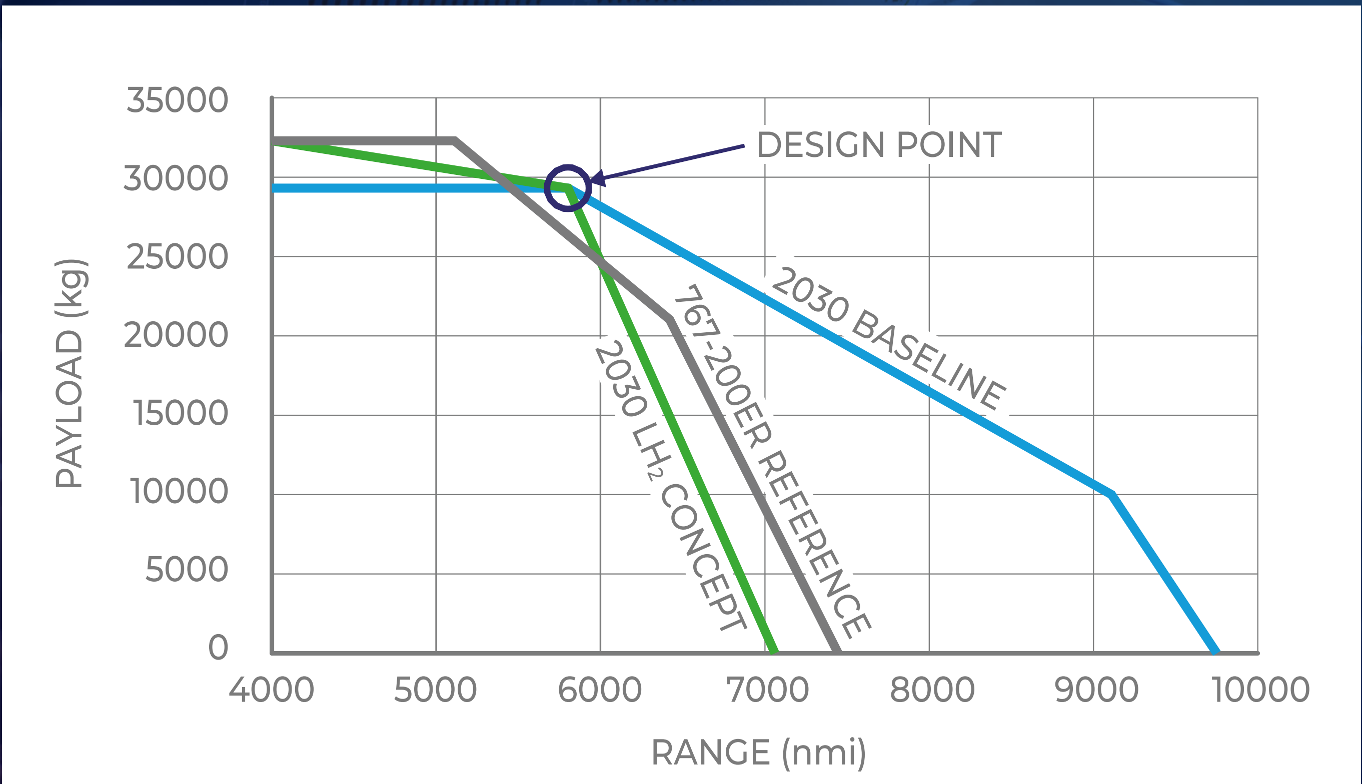


Figure 24 – Midsize concept payload/range (source: FlyZero)

06. CONCLUSIONS AND NEXT STEPS

The FlyZero concepts illustrate possible designs for hydrogen powered zero-carbon tailpipe emission aircraft in three market segments. The project research concluded that hydrogen aircraft have the potential to address 100% of short-haul and 93% of long-haul scheduled flights competitively with a SAF powered aircraft at the same technology levels.

The aircraft level design trades when using hydrogen fuel have been shown to be fundamentally different to a kerosene aircraft, primarily due to the low weight of hydrogen. This may drive different technology priorities for a hydrogen aircraft, and hydrogen aircraft will require more integration than kerosene aircraft between the propulsion system and the airframe as there is a significant energy management challenge with liquid hydrogen fuel that does not exist for kerosene or SAF aircraft.

The location of the hydrogen storage dominates the choice of aircraft architecture. The diameter of the liquid hydrogen tanks significantly affects their internal volume and gravimetric efficiency which means a tube and wing aircraft design with an increased fuselage cross-section is an efficient solution.

The concepts were constructed using the FlyZero technology projections. It is important to recognise that, despite the best efforts of the project team, considerable uncertainty remains in many areas due to the fundamental changes introduced by going to a cryogenic hydrogen system. The concept data shown in this report is sensitive to changes in key areas such as hydrogen storage efficiency. It is likely the configuration and performance of hydrogen aircraft will change significantly as research continues and technology understanding matures. It is therefore important that the FlyZero concepts continue to be updated by the ATI. The concepts are a critical part of the overall understanding of the potential impact of hydrogen aircraft. The updated concept aircraft can be used to revise market projections and then to calculate overall environmental impact.

Safety is a key consideration. The design of the concepts considered current regulations and operational safety principles. Many of the existing certification specifications can be read across to hydrogen aircraft, however, there are some key areas where no regulations are currently defined. FlyZero worked with the UK Civil Aviation Authority (CAA) to assess novel areas where the existing regulations were not applicable or suitable. The concept architecture was driven by FlyZero requirements and design principles guided by the objective to deliver a solution at least as safe as existing aircraft and informed by the work with the CAA. However, there are areas where the fundamental behaviour of cryogenic hydrogen is not well understood and it is possible the FlyZero designs incorporate features which may not be acceptable to future safety standards when they are defined. Substantial further work is needed in this area and global collaboration on safety standards will be required.

There are significant technology challenges which must be characterised and solved before a hydrogen powered aircraft could achieve certification and enter service. The following research areas are considered a priority in the short term:

- Fundamental LH_2 behaviour and materials compatibility data
- Liquid hydrogen storage
- Cryogenic fluid pumps
- Hydrogen combustion systems
- Fuel cells and associated thermal management
- Aircraft integration of cryogenic hydrogen fuel systems

There are also several other critical areas which need to be better understood in parallel, including green hydrogen production and infrastructure, and the climate change impact of contrails, which affects all aircraft. These examples have been studied by FlyZero and are covered in other reports.

The FlyZero analysis has shown sufficient promise that research into hydrogen aircraft should be pursued and accelerated. However, the overall challenge for aviation is to achieve net-zero carbon emissions by 2050; hydrogen will not be able to deliver this on its own. Limited quantities of low carbon impact bio-derived SAF are available now and there are schemes underway to rapidly increase global production. Further parallel investment is required in bio-derived and synthetic SAF to accelerate progress, in addition to the proposed research into hydrogen. Each of these options have advantages and disadvantages and it is too soon to choose one over the other; there is no silver bullet to solve the challenge of de-carbonising aviation.

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ZERO-CARBON EMISSION AIRCRAFT CONCEPTS

FLY ZERO

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