MARKET FORECASTS & STRATEGY

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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Market Forecasts

Air travel connects the world and enables affordable mass transportation between continents. It allows people to re-unite with friends and families, experience new cultures, and do business globally.

The Covid-19 pandemic has had a profound impact on aviation since March 2020. It is the deepest and most prolonged disruption to air travel in the post war era, but experience of previous crises indicates that the need for air travel is resilient, and that passenger demand recovers.

This crisis may be different, however, and there are risks that dislocations caused by Covid-19 combined with growing concerns about climate change could have lasting effects, long after the direct impacts of the pandemic have subsided:

- Has the pandemic nudged societies into different ways of working, requiring less business travel?
- Will the damage to the airline industry lead to loss of competition and more expensive air travel?
- Will pandemic restrictions lead to long-term impediments to international air travel, curtailing demand?
- Will environmental concerns and "flight shaming" reduce passenger demand?
- Will government climate change commitments lead to higher carbon pricing and policies to dampen aviation growth?

Under the FlyZero baseline forecasts, we expect passenger demand to recover in line with the post-pandemic economic recovery by the mid-2020s. Traffic grows at an average rate of 3.2% per annum to 2050, reaching 22.9 trillion revenue passenger kilometres (RPKs).

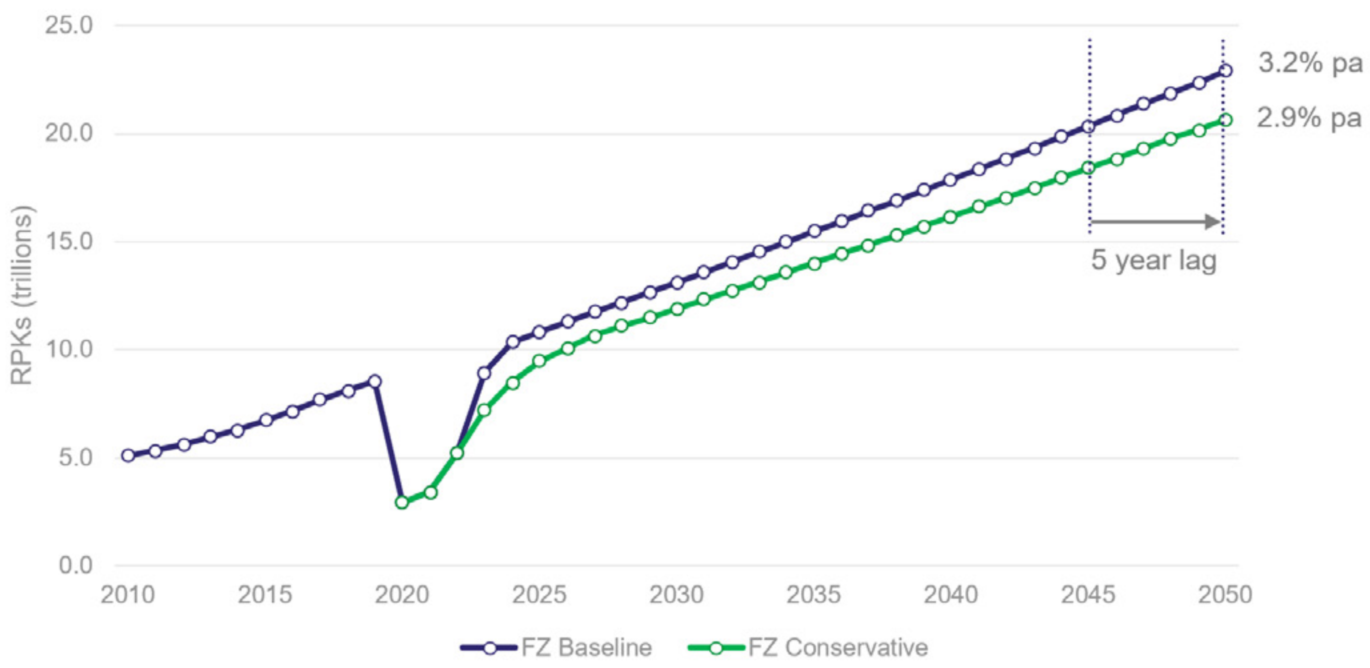


Figure 1 – FlyZero Global Forecast Scenarios (Source © FlyZero analysis)

Our conservative forecast scenario takes account of incomplete post-pandemic traffic recovery due to shifts in passenger behaviour and increased surface mode competition. It is about 10% lower than the baseline at 20.7 trillion RPKs in 2050. The conservative scenario lags the baseline growth trajectory by about five years – the growth in demand still occurs, but in a later year.

Like all forms of mass transport, air travel is currently dependent on fossil fuels that emit greenhouse gases. The aviation industry has made year-on-year investments in cleaner, more efficient aircraft and driven operational efficiencies that have reduced per-passenger fuel consumption and carbon emissions by 56% since 1990 [1]. Despite these efficiency improvements, strong traffic growth over the past 30 years means that aviation's CO_2 emissions have doubled in absolute terms to 920 Mt in 2019 [2], and are equivalent to 2.5% of total global CO_2 emissions [3].

If air travel is to continue to grow in a sustainable way, aviation must find innovative ways to truly decarbonise and reduce its impacts on the environment. Without the development of zero carbon emissions aircraft, aviation's annual atmospheric CO_2 emissions are projected to grow to 1,540 Mt (+67%) by 2050, and to 1,850 Mt (+100%) by 2070 (see **section 2.3**).

Enabling the continued growth of aviation is a matter of global equity – around 75% of air passenger growth over the next 30 years will be to, from or within developing countries [4]. Aviation supports the economic development of poorer countries by enabling inward investment, promoting travel and tourism [5] and facilitating migration and remittance incomes [6].

Figure 2 – FlyZero Global Forecast Summary: Average annual growth rates (Source © FlyZero analysis; baseline demand)

Fleet Forecasts

The FlyZero Global Fleet Forecast model translates projections of passenger demand into future fleet requirements by market segment. The market segments are defined based on a combination of aircraft size and sector distance, as shown in the table below:

Category	*Description*	*Typical Examples*
Subregional	*9 - 19 seat turboprops*	*Cessna Caravan, Beach 1900, DeHavilland Twin Otter, Dornier 228*
Regional	*20 - 120 seat turboprops or regional jets*	*ATR, Dash 8, CRJ, E170/190*
Narrowbody	*120 - 220 seat narrowbody aircraft, up to 2,400 nmi sector distance*	*A220, A320, B737*
Midsize	*Narrowbody aircraft over 2,400 nmi sector;* *200-300 seat widebody aircraft, less than 5,250 nmi sector distance*	*A321XLR, B757, B767, A330*
Widebody	*Over 300 seats or over 5,250 nmi sector distance*	*A350, B787, B777*

Table 1 – Aircraft Market Segments.

As aviation recovers from the current downturn, growing passenger demand will drive the need for more aircraft globally. The in-service fleet is expected to more than double from its 2019 pre-pandemic level of 29,900 aircraft to 69,090 aircraft by 2050, an average growth rate of 2.7% per year. The demand for new aircraft to fund fleet growth and replace retiring aircraft averages about 2,600 aircraft per year during the 2030s, rising to 3,000 aircraft per year in the 2040s.

Fleet Forecast **Delivery Forecast**

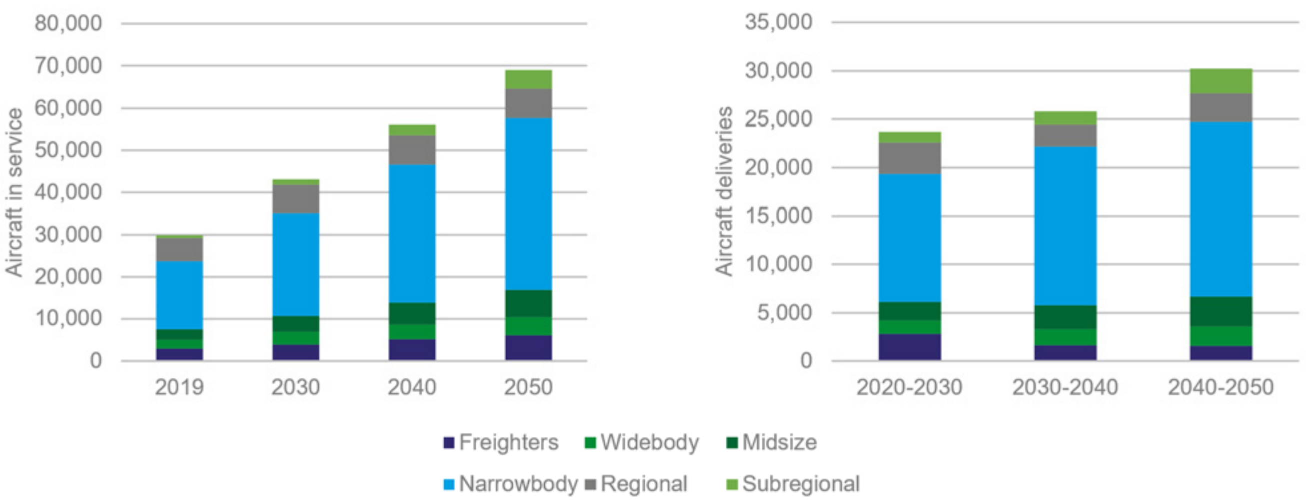


*Figure 3 – FlyZero Global Fleet Forecasts (Source © FlyZero analysis; baseline demand scenario. * Freighter deliveries include conversions of passenger aircraft.)*

Market Opportunity

FlyZero's objective is to identify ways to decarbonise aviation through the development of true zero carbon emissions (ZE) aircraft by the early 2030s. The FlyZero aircraft concepts are intended to demonstrate the technical feasibility and commercial viability of ZE aircraft in each market segment.

Each FlyZero concept represents an archetype of a class of aircraft, with scope to stretch or shrink around this concept design point, in the same way that the A320 can be considered representative of the narrowbody class of aircraft.

The figures below summarise the overall aircraft market opportunity between 2030 – 2050 by segment. The narrowbody segment is the most commercially important aircraft market, and a ZE narrowbody aircraft would deliver the greatest atmospheric CO_2 emissions abatement. However, the commercial importance of this segment means that introducing novel ZE hydrogen technology into the narrowbody market first is a high risk strategy for both aircraft manufacturers and airlines.

The FlyZero market strategy seeks to mitigate these risks by introducing a ZE aircraft first into either the regional or midsize markets, as a pathway to develop and prove ZE technologies before the development of a ZE narrowbody aircraft. These are the **Midsize First** or **Regional First** strategies.

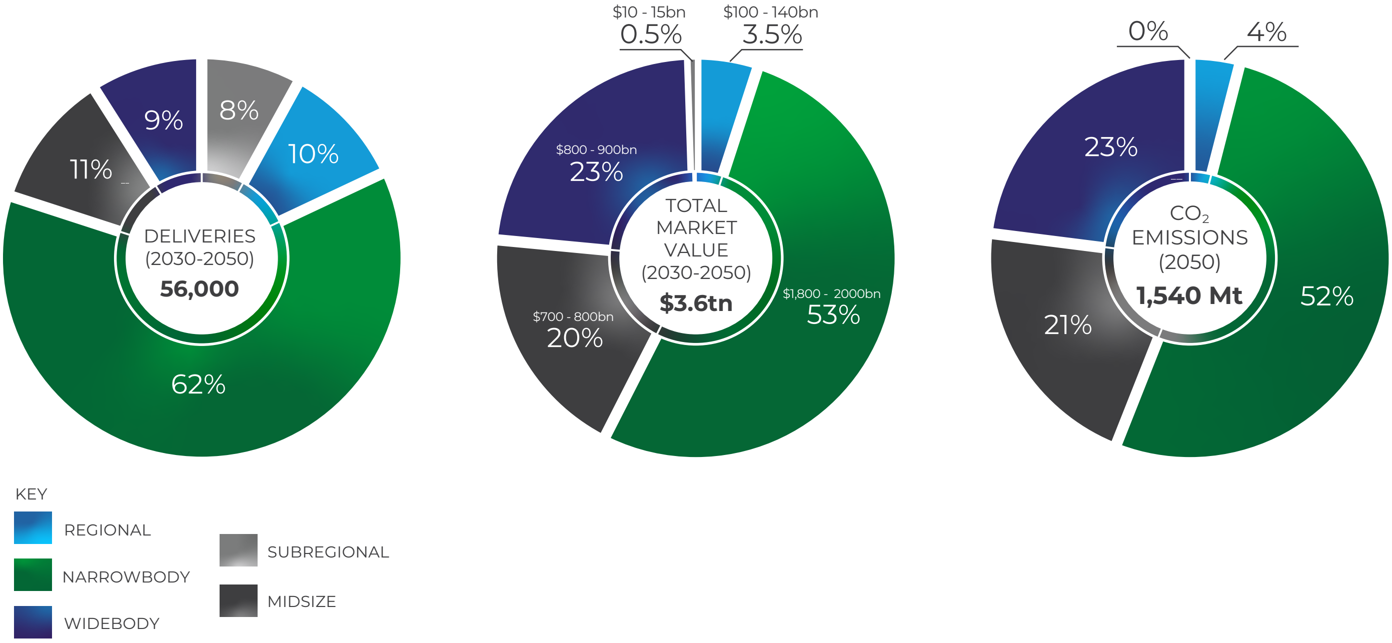


Figure 4 – Market Opportunities – 2030 to 2050 (Source © FlyZero analysis; baseline demand scenario – Values in constant 2022 prices)

The commercial positioning of the FlyZero concepts can be summarised as:

- **FlyZero Regional (FZR)** – fast turboprop-equivalent hydrogen fuel cell aircraft, competitive with both conventional turboprop and regional jet aircraft.
- **FlyZero Narrowbody (FZN)** – targeted at the heart of the narrowbody aircraft market, matching the A320neo for passenger capacity and range with a full payload.
- **FlyZero Midsize (FZM)** – midsize aircraft offering zero carbon emission intercontinental flight with one stop global connectivity.

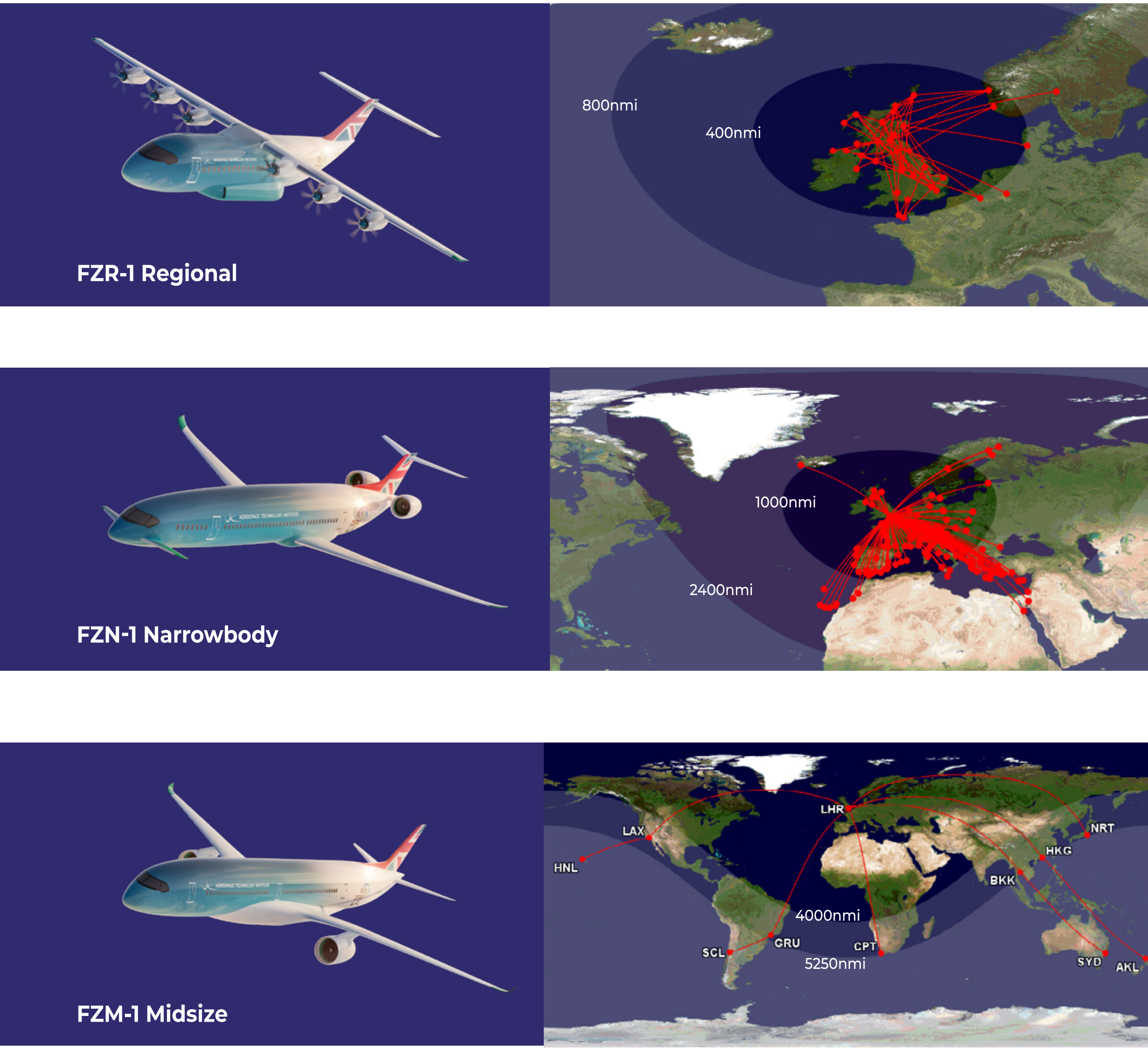


Figure 5 – FlyZero Concepts, maps generated by the Great Circle Mapper (www.gcmap.com) (copyright © Karl L. Swartz).)

Concept Competitiveness

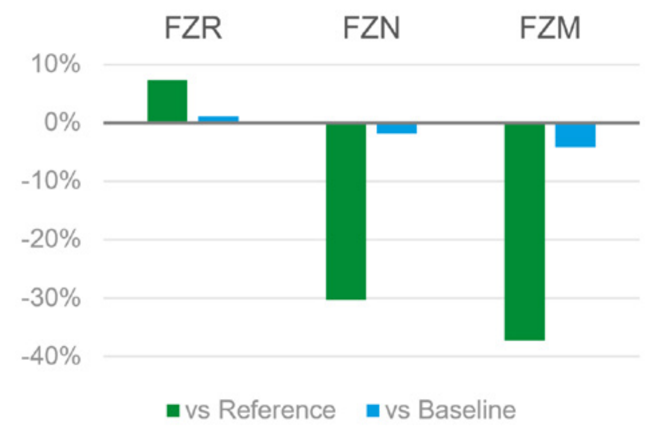
The commercial success and market penetration of future ZE aircraft is driven by their cost competitiveness, measured against conventional kerosene or sustainable aviation fuel (SAF) burning aircraft types.

The FZN and FZM concepts, with hydrogen combustion turbofan propulsion, are over 30% more energy efficient than existing conventional aircraft. The light weight of the hydrogen fuel contributes to the FZN and FZM concepts also having an energy advantage over newly designed conventional aircraft – the FZN is 2% better than a new narrowbody aircraft (NNA) and the FZM is 5% better than a new midsize aircraft (NMA). The hydrogen advantage is greater for the longer range FZM concept, where the weight benefit of hydrogen on block fuel energy is greater.

The FZR regional aircraft, with hydrogen fuel cell and electric motor / propeller propulsion, uses 7% more energy than an ATR-72 reference aircraft. This extra energy is partly due to the FZR's higher performance – faster cruise speed and longer range. Compared with a new regional aircraft (NRA), with comparable speed and range, the FZR is very slightly less energy efficient (+1%) due to the FZR's fuel cell mass and higher aircraft weight.

All ZE aircraft concepts have a direct operating cost (DOC) advantage over the conventional aircraft. The DOC advantage arises from lower fuel costs – a combination of greater energy efficiency and the expected lower cost of hydrogen per unit energy (when compared with taxed kerosene or SAF blends) from the mid-2030s. However, the ZE aircraft are expected to have slightly higher aircraft ownership and maintenance cost components.

Energy per ASK



DOC per RPK

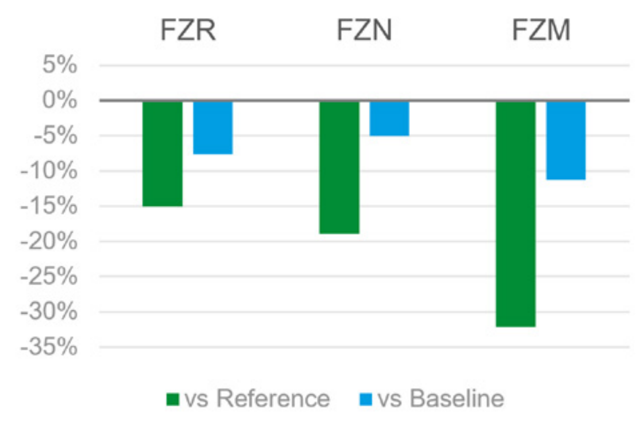


Figure 6 – FlyZero Concept Cost Competitiveness (Source © FlyZero analysis – Reference aircraft are: ATR-72 (Regional), A320neo (Narrowbody), B767-200 (Midsize); Baseline aircraft are hypothetical clean-sheet new aircraft designs representing 2030s technology: NRA (new regional aircraft), NNA (new narrowbody aircraft), NMA (new midsize aircraft); DOC per RPK comparisons are based on 2050 projected fuel costs.)

Market Penetration Scenarios

The FlyZero market model examines four scenarios following the Midsize First or Regional First strategies, with High Ambition or Unaccelerated entry into service dates. These scenarios are described below.

Midsize First Strategy

Midsize First – High Ambition (Accelerated) scenario achieves the most rapid transition towards ZE aircraft in service and abatement of CO_2 emissions – with ZE aircraft making up 50% of the global fleet and abating 45% of atmospheric CO_2 emissions by 2050.

The Midsize First strategy minimises the early-years infrastructure challenges, as a relatively small number of larger hub airports require hydrogen refuelling capability to provide a "minimum viable" airline network for intercontinental flights.

The FlyZero commercial analysis indicates that a ZE midsize aircraft will enjoy a significant operating cost advantage by the early 2030s. This cost advantage underpins the projected rate of ZE aircraft uptake by airlines.

Another advantage of the Midsize First strategy is that the FZM aircraft has similar hydrogen combustion turbofan technology to the FZN narrowbody concept, so the midsize aircraft more effectively de-risks a ZE narrowbody aircraft development.

Regional First Strategy

Regional First – High Ambition (Accelerated) scenario achieves the second most rapid transition towards ZE aircraft in service and abatement of CO_2 emissions – with ZE aircraft making up 45% of the global fleet and abating 31% of atmospheric CO_2 emissions by 2050.

The Regional First scenarios are more complex in terms of early-years infrastructure challenges, as many small regional airports will require hydrogen refuelling capability in order to provide airlines with a minimum viable route network.

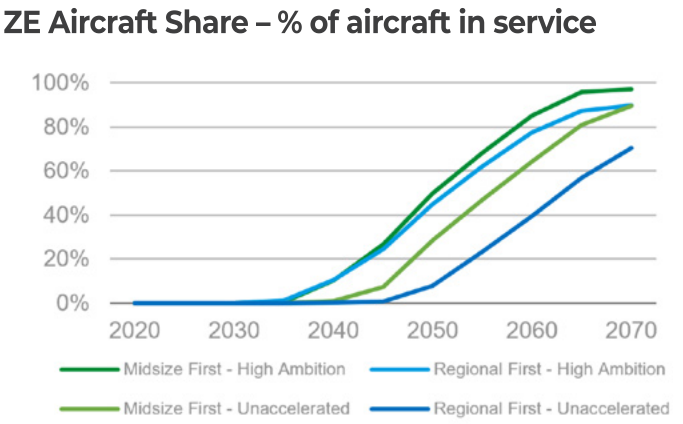
Another disadvantage of the Regional First strategy is that a ZE regional aircraft based on fuel cell technology does not de-risk the development of hydrogen combustion turbofan aircraft technology, which is necessary for the development of larger ZE narrowbody and midsize aircraft. Regional aircraft only represent 4% of atmospheric CO_2 emissions in 2050, so decarbonising the narrowbody and longer-haul markets is necessary to achieve true zero carbon emission aviation.

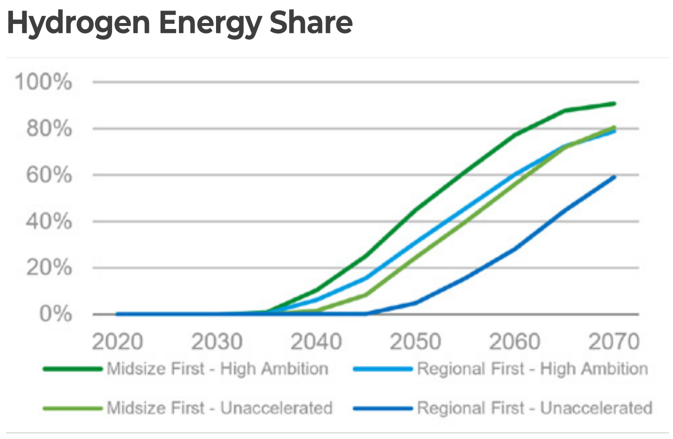
The FlyZero commercial analysis (**section 4**) indicates that the FZR fuel cell aircraft has more marginal operating cost benefits compared with conventional kerosene / SAF competitor aircraft than the narrowbody and midsize designs. The relatively heavy fuel cell aircraft is not more energy efficient than comparable conventional aircraft, so it is reliant on hydrogen fuel costs dropping below kerosene / SAF prices (on a per unit energy basis) to have a competitive advantage. This relative cost competitiveness means that government support and incentives may be required to encourage airlines to switch to ZE regional aircraft in the early years, perhaps through government subsidies provided on "public service obligation" routes.

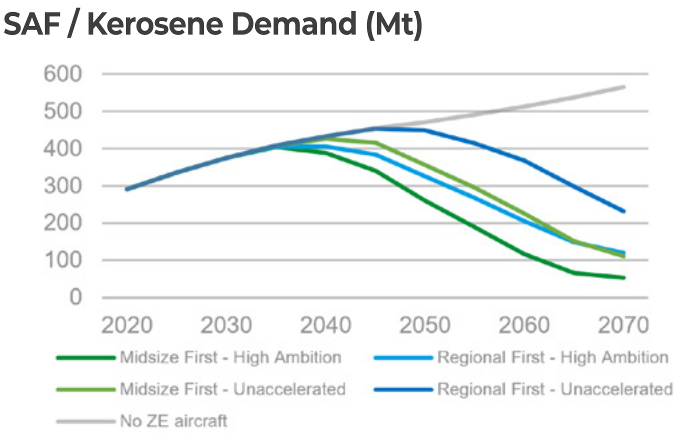
Comparisons between the different scenarios are provided in the table and figures below.

	Midsize First		Regional First	
High Ambition (Accelerated)	*Number of ZE aircraft*	*29,200*	*Number of ZE aircraft*	*26,300*
	Value	*$2 trillion*	*Value*	*$1.5 trillion*
	CO_2 Abated	*45%*	*CO_2 Abated*	*31%*
Unaccelerated	*Number of ZE aircraft*	*16,600*	*Number of ZE aircraft*	*4,600*
	Value	*$1.1 trillion*	*Value*	*$240 billion*
	CO_2 Abated	*24%*	*CO_2 Abated*	*5%*

Table 2 – Market Penetration Scenario Comparison – 2050 (Source © FlyZero analysis – Number of aircraft and values is cumulative to 2050; CO_2 abated is percent of the projected 2050 annual atmospheric emissions abated by ZE aircraftuse).







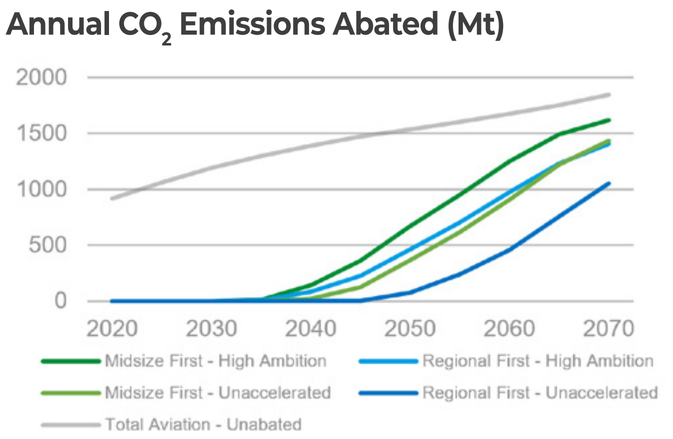


Figure 7 – Market Penetration Scenario Comparisons.

01. MARKET FORECASTS

01.1 DEMAND DRIVERS

Air travel connects the world and enables affordable mass transportation between continents. It allows people to re-unite with friends and families, experience new cultures, and do business globally.

The long-term trend is increasing passenger demand as incomes grow and air travel becomes more affordable. As more people enter the global middle class, air travel becomes a higher priority expenditure – currently half of the world's population is considered "middle class" and this is expected to grow to 67% by 2030 [7].

At the same time, the cost of air travel is decreasing due to airlines' investment in new, more efficient aircraft, the growth of low cost carriers (LCCs), and operational improvements such as greater aircraft utilisation, higher passenger load factors and more efficient air traffic management. Average airfares have decreased by more than 50% in real terms since 2008 (see **Section 1.4**, **Figure 16b**).

Like all forms of mass transport, air travel is currently dependent on fossil fuels that emit greenhouse gases. The aviation industry has made year-on-year investments in cleaner, more efficient aircraft and driven operational efficiencies that have reduced per-passenger fuel consumption and carbon emissions by 56% since 1990 [1]. Despite these efficiency improvements, strong traffic growth over the past 30 years means that aviation's CO_2 emissions have doubled in absolute terms to 920 Mt in 2019 [2], and are equivalent to 2.5% of total global CO_2 emissions [3].

If air travel is to continue to grow in a sustainable way, aviation must find innovative ways to truly decarbonise and reduce its impacts on the environment. Without the development of zero carbon emissions aircraft, aviation's annual atmospheric CO_2 emissions are projected to grow to 1,540 Mt (+67%) by 2050, and to 1,850 Mt (+100%) by 2070 (see **Section 2.3**).

Enabling the continued growth of aviation is a matter of global equity – around 75% of air passenger growth over the next 30 years will be to, from or within developing countries [4]. Aviation supports the economic development of poorer countries by enabling inward investment, promoting travel and tourism [5] and facilitating migration and remittance incomes [6].

Pandemic Recovery

The Covid-19 pandemic has had a profound impact on aviation since March 2020. It is the deepest and most prolonged disruption to air travel in the post war era, but experience of previous crises indicates that the need for air travel is resilient, and that passenger demand recovers.

This crisis may be different, however, and there are risks that dislocations caused by Covid-19 combined with growing concerns about climate change could have lasting effects, long after the direct impacts of the pandemic have subsided:

- Has the pandemic nudged societies into different ways of working, requiring less business travel?
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- Will pandemic restrictions lead to long-term impediments to international air travel, curtailing demand?
- Will environmental concerns and "flight shaming" reduce passenger demand?
- Will government climate change commitments lead to higher carbon pricing and policies to dampen aviation growth?

This study is concerned with long-term trends in air travel from 2030 onwards. Short-term uncertainty and different paths to recovery over the next five years or so are less important. Our forecasts focus on the econometric fundamentals that drive growth in air travel demand and on the downside factors that need to be considered.

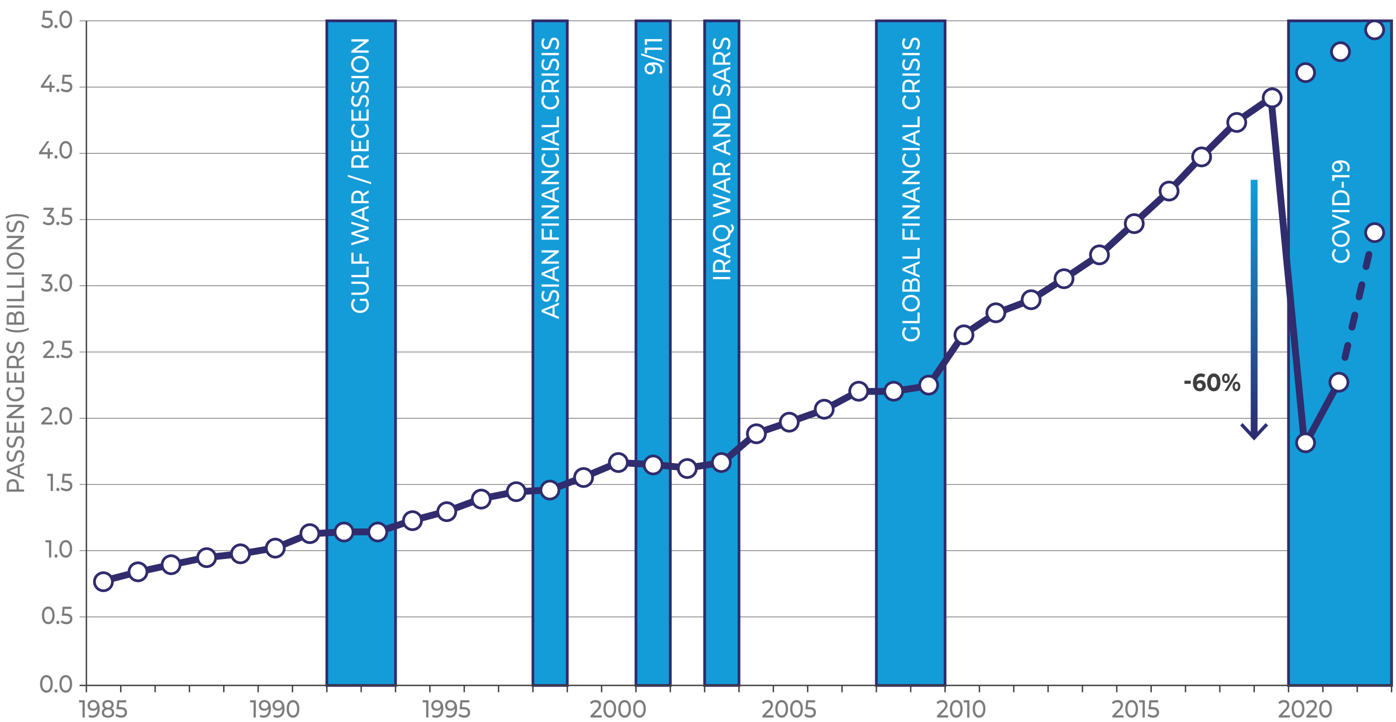


Figure 8 – World Air Travel Passengers (Source © FlyZero analysis – Data from World Bank)

01.2 WORLD REGIONS

The FlyZero global market forecast examines air travel flows within and between twelve geographical world regions, as illustrated below:

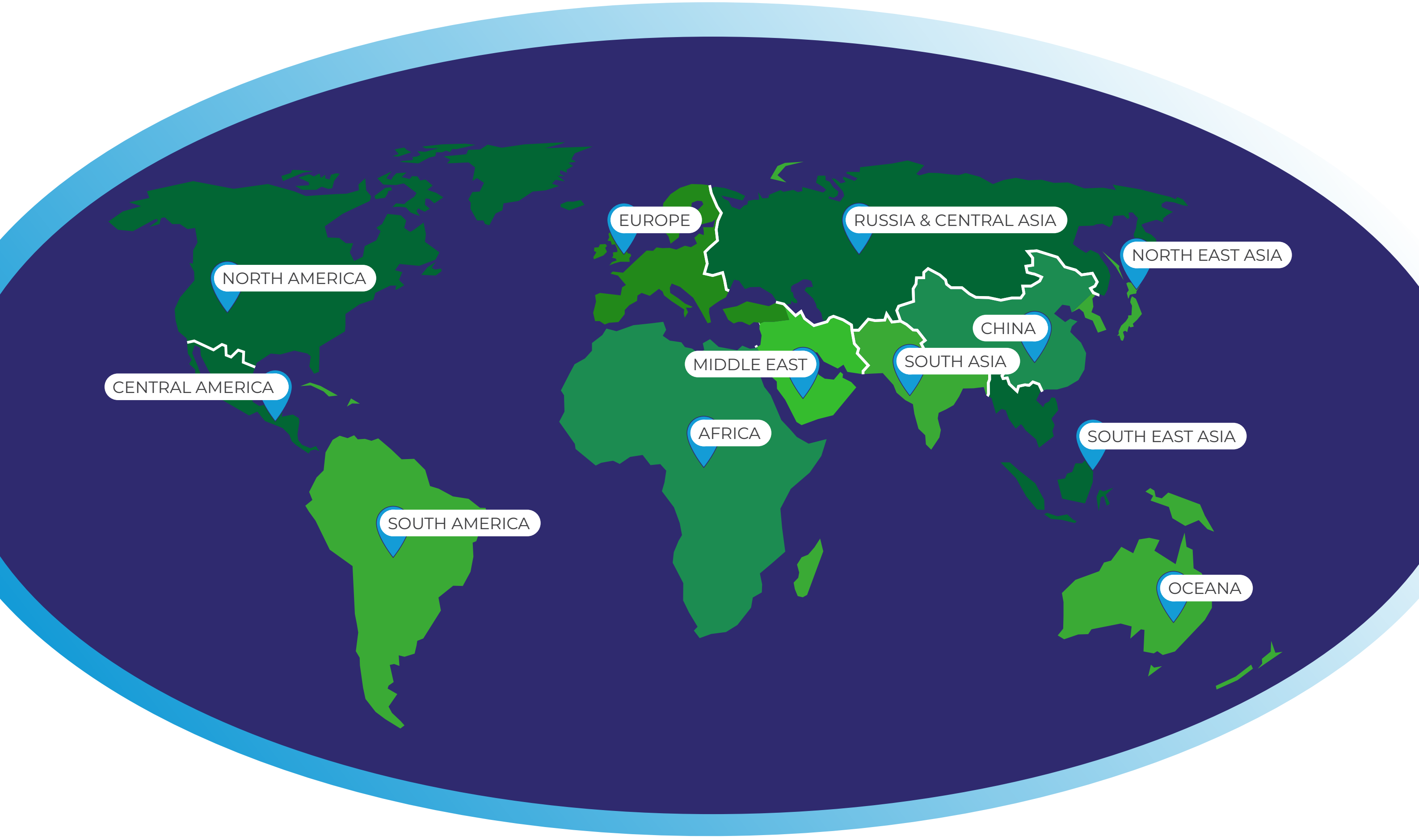


Figure 9 – World Market Regions.

The largest flows are intra-regional within North America, Europe, and China. The busiest intercontinental flows (between regions) are Europe – North America, Europe – Middle East, and Oceana – Southeast Asia, as shown in **Figure 10** below.

Global traffic growth, measured in revenue passenger kilometres (RPKs), averaged 6.1% per annum during the last decade (2009 -2019), almost twice the rate of growth in world gross domestic product (GDP) at 3.1% per annum. The fastest growing regions were China (+10.7% pa), South Asia (+8.9% pa), Russia & Central Asia (+8.8% pa), the Middle East (+8.8% pa), and Southeast Asia (8.5% pa).

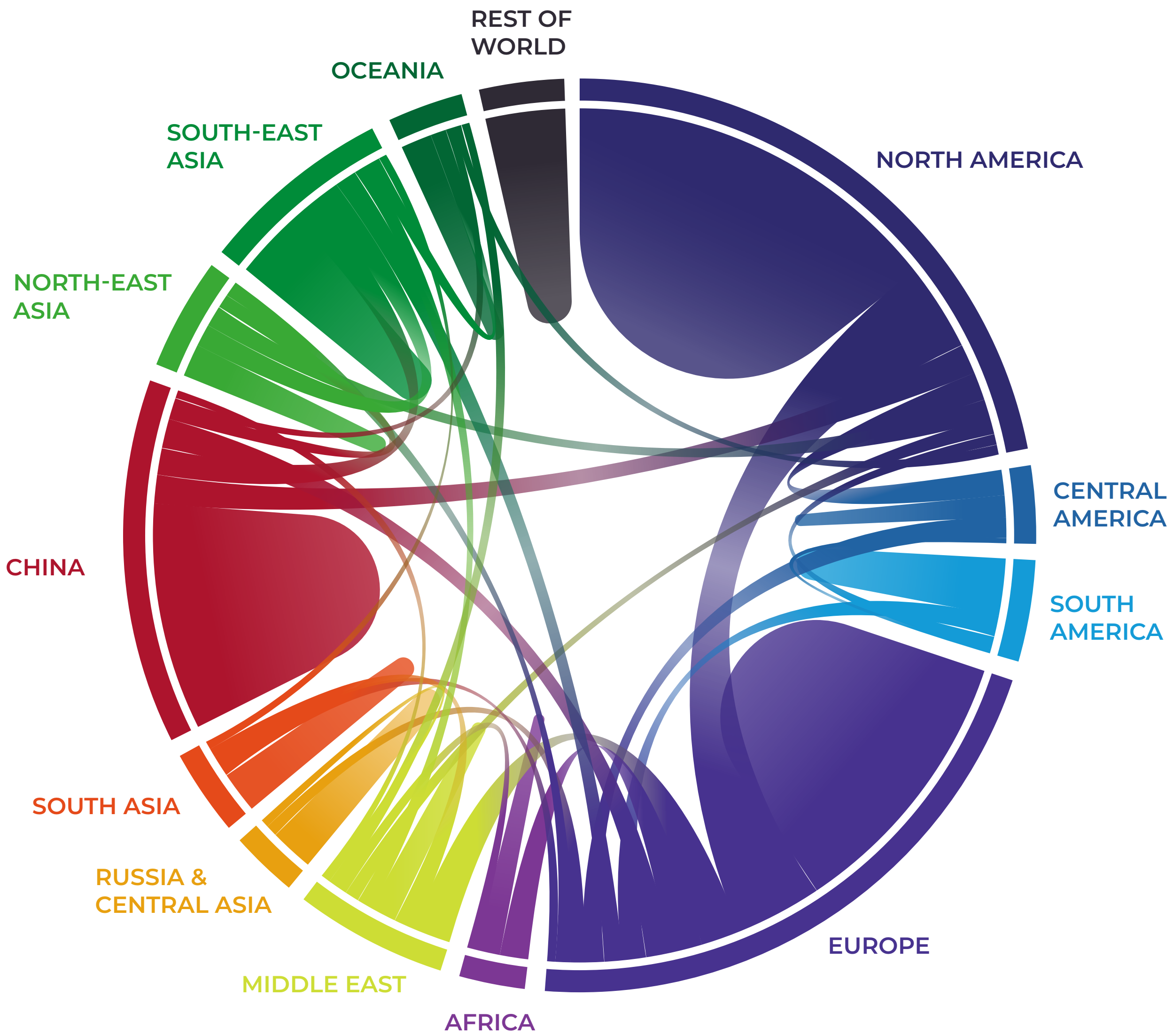


Figure 10 – Air Traffic Flows Between World Regions (source © FlyZero analysis; 2019 flow share by Revenue Passenger Kilometres, MIDT data)

FlyZero has developed econometric forecasts for 41 market pairs (including the within-region markets). These 41 market pairs represent 97% of global traffic – the remaining flows are modelled in aggregate as a 'Rest of the World' market.

The econometric regression model has high correlation coefficients (R-squared values) between the explanatory variable (GDP) and dependent variable (RPKs). Most of the markets, accounting for 92% of total traffic, have very high correlation coefficients of at least 0.9, and all market flows have an R-squared value over 0.8. This indicates that the market model provides a sound basis for future projections.

	1.0 NORTH AMERICA	2.1 CENTRAL AMERICA	2.2 SOUTH AMERICA	3.0 EUROPE	4.0 AFRICA	5.0 MIDDLE EAST	6.0 RUSSIA & CENTRAL ASIA	7.1 SOUTH ASIA	7.2 CHINA	7.3 NORTH EAST ASIA	7.4 SOUTH EAST ASIA	7.5 OCEANA
1.0 NORTH AMERICA	97%	99%	95%	98%		94%			98%	93%		97%
2.1 CENTRAL AMERICA		97%	97%	93%								
2.2 SOUTH AMERICA			83%	92%								
3.0 EUROPE				99%	82%	98%	89%	95%	94%	85%	93%	
4.0 AFRICA					95%	99%						
5.0 MIDDLE EAST						92%	90%	99%	98%		99%	97%
6.0 RUSSIA & CENTRAL ASIA							91%					
7.1 SOUTH ASIA								95%			98%	
7.2 CHINA									99%	95%	97%	94%
7.3 NORTH EAST ASIA										87%	97%	
7.4 SOUTH EAST ASIA											98%	98%
7.5 OCEANA												96%

Figure 11 – Traffic Flow Regression Matrix (Source © FlyZero analysis; baseline demand scenario. Percentage values are the market flow regression correlation coefficients (R-squared values)

01.3 ECONOMICS AND DEMOGRAPHICS

01.3.1 COVID-19 RECESSION AND RECOVERY

The Covid-19 pandemic resulted in a sharp contraction of the world's economies in 2020 due to widespread lockdowns and travel restrictions as governments attempted to control the spread of the virus.

Figure 12 shows global GDP forecasts and how they have evolved during the pandemic. Initial expectations of the International Monetary Fund (IMF) in October 2020 were for a deep recession with prolonged recovery [8], such that global growth still lagged 5% below pre-crisis expectations by 2024.

More recently, the IMF has upgraded its medium-term economic outlook, and the latest GDP forecasts produced by Oxford Economics (OE) expect almost full recovery to within 1% of pre-pandemic expectations. By 2025, the global economy is expected to be 17% larger than in 2019.

The economic downturn has been softened and recovery bolstered by government policy support and stimulus packages, at least in developed countries. These relatively optimistic medium-term growth forecasts mask significant short-term uncertainty and downside risks due to emerging Covid-19 variants, unequal vaccine distribution globally, supply chain disruption, and inflationary pressures [8].

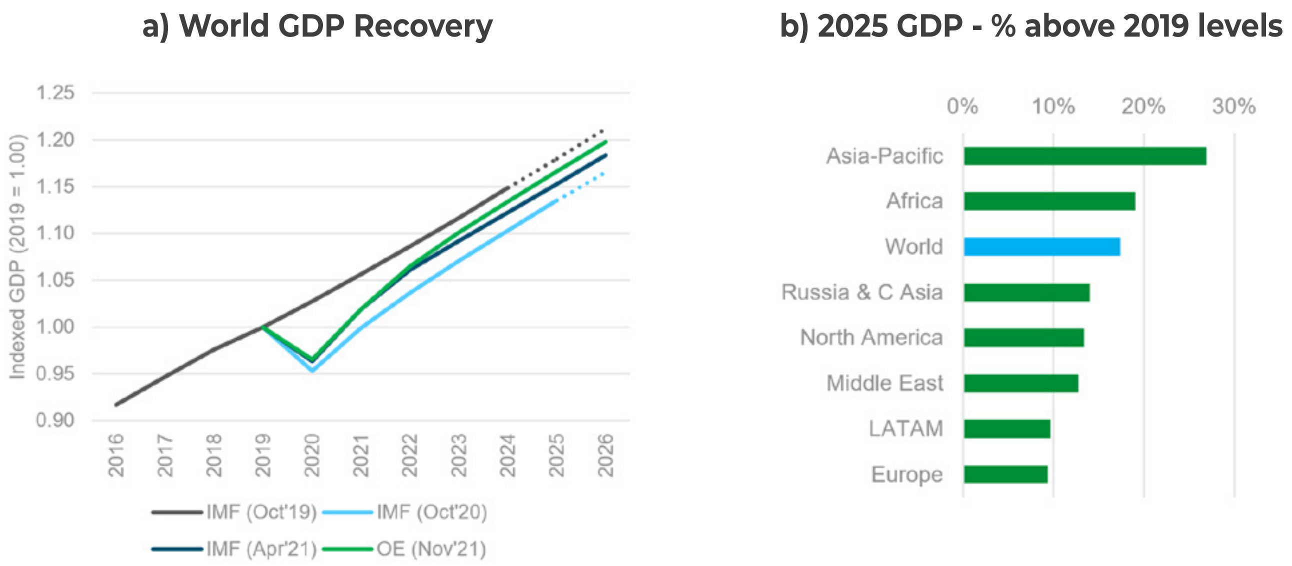


Figure 12 – Post Covid-19 Economic Recovery.

Source © International Monetary Fund; Oxford Economics.

01.3.2 LONG-TERM ECONOMIC GROWTH

Global GDP is expected to double in real terms by 2050, growing at an average rate of 2.3% a year from 2019 to 2050. After an initial post-pandemic recovery phase with bounce-back growth rates over 5%, annual growth is expected to stabilise at 3.0% by 2024 and taper to 1.7% by 2050 [9].

A key driver of long-term economic growth forecasts is population change and trends in productivity improvement. The world's population is expected to stabilise at around 10 billion people by 2060, up from 7.7 billion people today. Population growth is already largely stable in developed countries **[10]**.

China is experiencing the most rapid demographic change, as its population distribution ages rapidly. Since 1970, China's population of over 65-year-olds has tripled from less than 4% to 12%, while the proportion of under 18s has decreased from 47% to just 21%, on par with developed countries. This demographic shift in China corresponds to a marked slowing of economic growth expectations – from an average of 8.4% per annum during 2000-2019 to a forecast 3.8% per annum during the period 2019-2040.

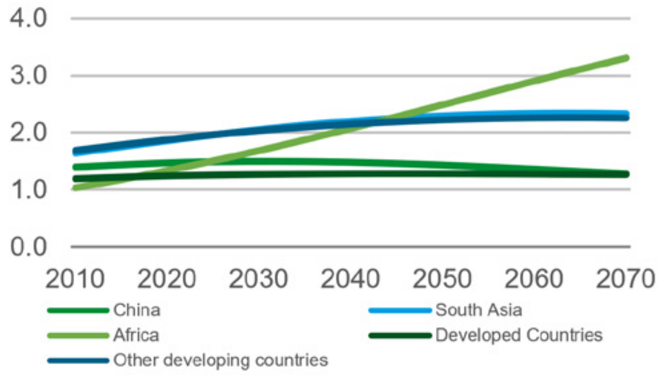
The fastest growing region in the next 30 years (to 2050) is South Asia, driven by India's economic development. GDP is forecast to grow at 5.1% per annum and GDP-per-capita at 4.3% per annum. Southeast Asia is also expected to grow strongly, with GDP growing at 3.5% per annum and GDP-per-capita at 2.9% per annum.

In contrast to the global trend of flattening population growth, Africa's population is forecast to grow continuously – from 1.3 billion today to 3.3 billion people by 2070 (see **Figure 13b** below). Africa would then make up one-third of the world's population. High population growth is combined with relatively weak economic growth of 2.9% per annum to 2050, so that GDP-per-capita grows more slowly in Africa than in any other region at just 0.8% per annum. The global average growth in GDP-per-capita is 1.5% per annum to 2050.

a) GDP Annual Growth - World Average

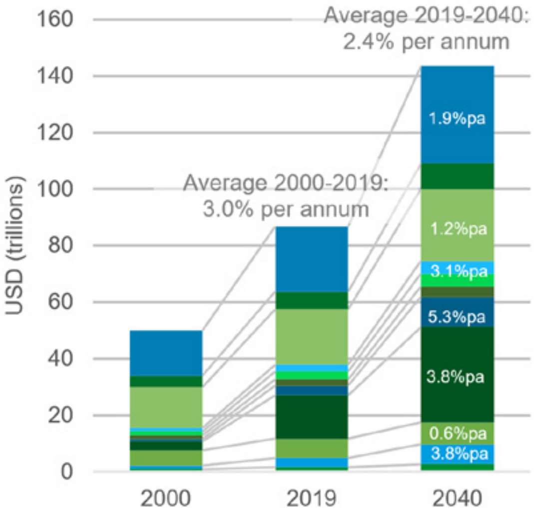
Source © Oxford Economics; real percent change.

b) Population Forecast (billions)



Source © UN World Population (August 2019).

c) GDP by Region

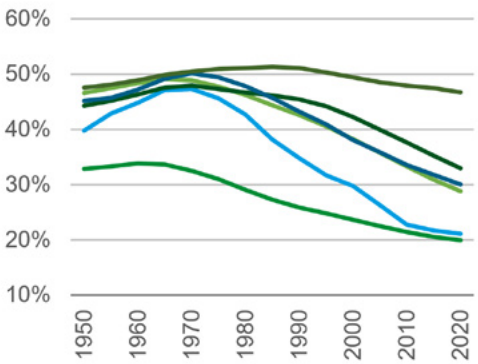


GDP Shares

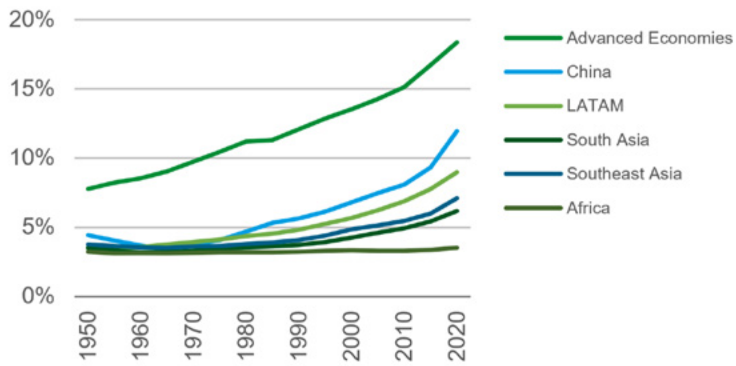
	2000	2019	2040	2060
1.0 North America	31.9%	26.7%	24.1%	23.7%
2.0 LATAM	8.2%	7.1%	6.2%	5.7%
3.0 Europe	29.0%	22.5%	17.7%	15.4%
4.0 Africa	2.3%	2.8%	3.2%	3.6%
5.0 Middle East	2.9%	3.2%	3.2%	3.1%
6.0 Russia & C Asia	2.3%	2.7%	2.6%	2.7%
7.1 South Asia	1.9%	3.8%	7.4%	10.3%
7.2 China	6.6%	17.7%	23.5%	24.1%
7.3 NE Asia	10.6%	7.8%	5.4%	3.9%
7.4 SE Asia	2.5%	3.7%	4.9%	5.8%
7.5 Oceana	1.9%	1.9%	1.9%	1.8%

Source © Oxford Economics.

d) Population - % under 18



e) Population - % over 65



Source © World Bank.

Figure 13 – Economic and Demographic Statistics.

Growth in personal income and the developing middle class is a key driver of air travel demand. As more people enter the global middle class, travel becomes a higher priority expenditure: currently half of the world's population are considered "middle class" and this is expected to grow to 67% by 2030 [3].

Propensity to travel (annual trips per capita) increases in line with per capita income, as illustrated in **Figure 14** below. **Figure 15** plots the historic trends in trips-per-capita over the past 10 years, and our forecast to 2050, showing how traffic growth correlates with income.

Enabling continued aviation growth, in an environmentally sustainable way, is a matter of global equity. Around 75% of air passenger growth over the next 30 years will be to, from or within developing countries [5]. Aviation supports the development of poorer countries by enabling inward investment, promoting travel and tourism [6] and facilitating migration and remittance incomes [7].

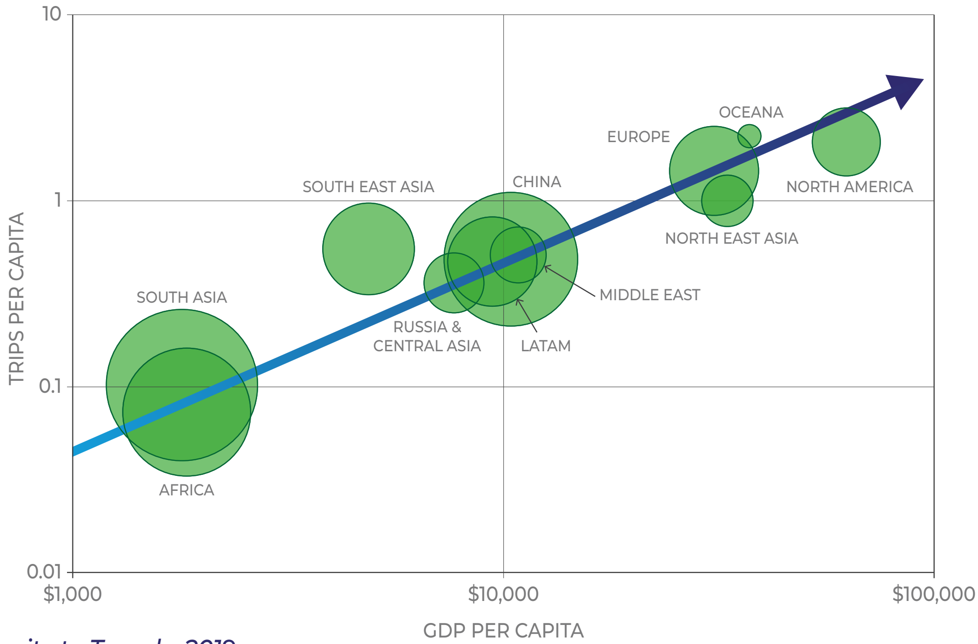


Figure 14 – Propensity to Travel – 2019.

Source © FlyZero analysis; UN World Population (August 2019), MIDT data – Bubble size is region population. Log-log axis.

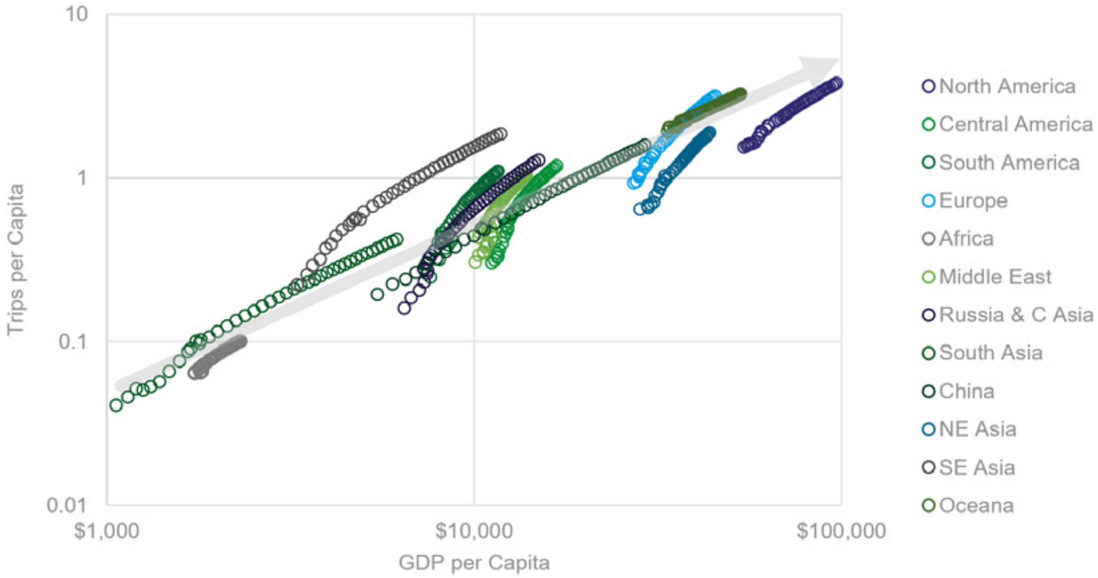


Figure 15 – Trips per Capita Trends (2009 – 2050).

Source © FlyZero analysis; UN World Population (August 2019), MIDT data, Oxford Economics GDP forecast (November 2021).

01.4 AIR TRAVEL COSTS AND EFFICIENCY

The aerospace and air transport industry has a strong track record of driving fuel efficiency and cost savings. Since 1990, fuel efficiency and CO_2 emissions per revenue passenger kilometre (RPK) have reduced by 56%, an average improvement of 2.8% per annum **[2]**.

These efficiency improvements are a result of a combination of:

Investment in new, more fuel efficient aircraft

- More efficient engines, better aerodynamics, and use of lighter weight materials

Fleet evolution and optimisation

- Shorthaul shift from small regional aircraft to larger narrowbody aircraft with better per-seat efficiencies
- Longhaul shift from four-engine aircraft to more efficient modern twinjets

Higher seat density

- New slimline seats allowing reduced seat pitch with the same legroom
- Market share shift to low cost carriers (LCCs) with higher seat densities
- Seat densification by legacy airlines, particularly in shorthaul markets

Increased passenger load factors

- Better airline inventory and yield management
- Market share shift to high load factor LCCs

Air traffic management improvements

- Airspace modernisation and improvements
- More direct routings and performance-based navigation
- Continuous descent approach and continuous climb operations

The past 10 years has seen a step-change in aircraft efficiency. New efficient twin-engine longhaul aircraft (B787 and A350) are replacing less efficient four-engine and older twin-engine types. The shorthaul sector has seen new geared turbofan aircraft enter service on the A220, A320neo, B737 MAX, and Embraer E-Jet E2 family.

In 2019, about 13% of the global fleet was made up of these latest generation aircraft [10]. This retirement/replacement cycle will be largely complete by 2040, after which further aircraft efficiency improvements are reliant on the development of a further generation of new aircraft technology. Efficiency improvements due to higher seat densities and load factors have a natural upper bound, and air traffic management system efficiencies can be offset by additional airspace congestion due to traffic growth. Therefore, the rate of efficiency improvements will slow in the longer term.

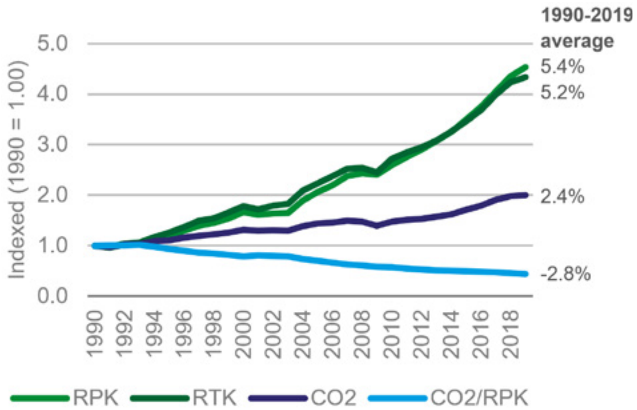
Overall, the FlyZero forecasts assume continued efficiency improvements that reduce the CO_2 intensity of conventional aircraft (measured in "grams CO_2 per RPK") by 1.5% per annum during the period 2019-2050, tapering to 1% per annum in the long-term. The 1.5% is made up of approximately 1.0% due to aircraft efficiency improvements and fleet renewal, 0.4% due to operational efficiencies, and 0.1% due to changes in aircraft mix (mainly changes from regional aircraft to larger types with better per-seat efficiencies).

This 1.5% per annum efficiency factor is slightly higher than estimates by the Air Transport Action Group (ATAG) [11] and is in line with the UK Department for Transport's "Continuation of Current Trends" scenario of 1.5% per annum to 2050 [12].

These efficiency improvements, combined with increased airline competition and the growth of LCCs, have reduced the cost of air travel. Average airfares have decreased by more than 50% in real terms since 2008 [4]. Decreasing real-terms airfares help to support growth in passenger demand.

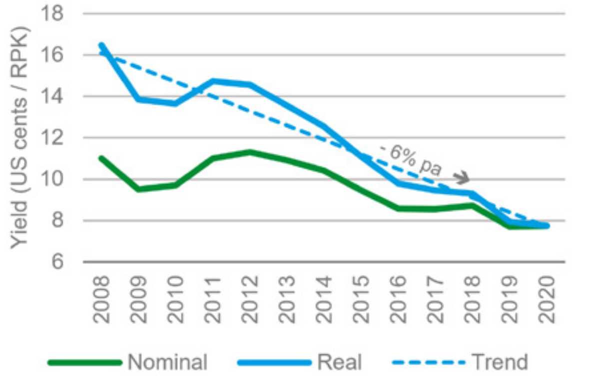
Fuel prices are a key driver of airline costs, averaging 23.5% of airline costs in 2019 [13]. Aviation fuel prices, linked to oil prices, are highly volatile – between 2008 and 2019 they varied from $300 to $1280 per tonne, and briefly dropped to around $200 per tonne in April 2020 due to the Covid-19 pandemic [14].

a) Aviation Efficiency Improvements



Source © ATAG, IATA Economics [1].

b) Average Airfares

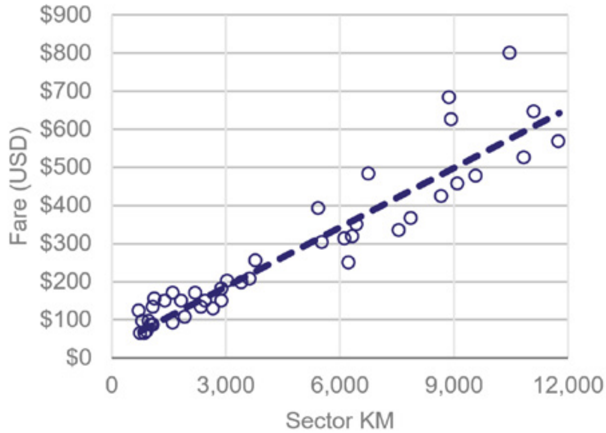


Source © FlyZero analysis, MIDT airfare data, IMF inflation rates. Real prices in 2020 USD.

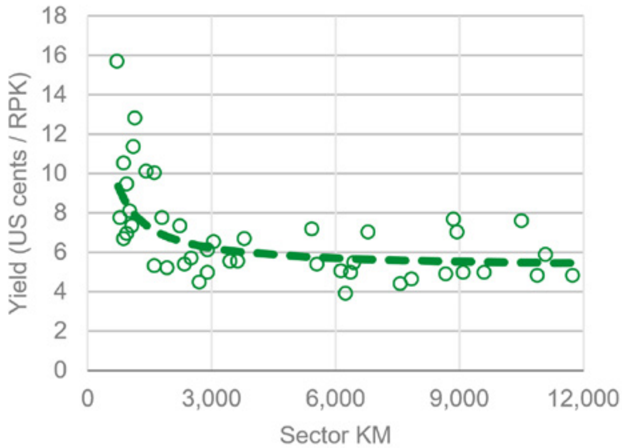
c) Aviation Fuel Price History

Source © US EIA [16]; nominal prices.

d) Airfare v Sector KM



e) Yield versus Sector KM



Source © FlyZero analysis based on MIDT airfare data (2019 data).

Figure 16 – Aviation Efficiency, Airfares and Fuel Price.

01.5 SHIFTS IN PASSENGER DEMAND

The underlying long-term trends driving growth in air travel demand – economics, demographics, costs and efficiencies – are subject to behaviour changes and demand shifts. This is particularly true as the world recovers from the Covid-19 pandemic and climate change issues become more important to consumers and the travelling public.

The FlyZero **baseline forecast** represents continuation of pre-pandemic trends, driven by econometric fundamentals in the medium and long term (from 2024, after pandemic travel restrictions are assumed to cease). The baseline forecast takes account of the pandemic induced economic downturn, but not lasting behavioural changes.

As a sensitivity, we also consider a **conservative forecast** scenario that assesses the impact of long-term behaviour shifts post Covid-19 and increased competition from surface modes of transportation, particularly high speed rail (HSR).

01.5.1 JOURNEY PURPOSE AND RESILIENCE

Leisure Travel

Passengers may travel for business or for leisure. Leisure air travel represents about 80% of passengers [15] and is a broad category encompassing many individual reasons for travel. Typically, about half of leisure passengers are travelling for tourism and holidays, while the remainder are visiting friends and relatives (VFR), migrant workers, students, medical tourists and other non-business travellers [16].

This type of travel has few substitutes and limited competition from other modes of transport, so it is expected to be quite resilient once the Covid-19 pandemic has subsided and travel restrictions are lifted.

There may be some lasting impacts and changes in leisure passenger demand as the air travel sector recovers from Covid-19, including passenger behaviour changes due to climate change concerns. The FlyZero conservative scenario assumes a “95% recovery” – that leisure travel will recover to a level 5% below the baseline forecast due to long-term scarring and behaviour change.

Business Travel

The full recovery of business air travel post-pandemic is more uncertain due to a combination of:

- A step-change in business' use of remote meeting technology due to forced adoption of working-from-home during the pandemic
- Cost saving opportunities, where companies have found ways to do business with less travel
- Environmental targets, where companies have made commitments to reduce their carbon footprints

Offsetting these downside factors is the renewed value, post-pandemic, that people and businesses place on face-to-face interaction and the competitive pressures on companies to keep traveling in order to win and retain business.

There are many reasons for business travel, some of which are more easily substituted than others. A UK Department for Transport survey in 2018 (see **Figure 17** below) [19] found that the most common reason for business air travel was to attend a meeting (58%), but that almost half of these were internal company meetings. Internal meetings may be more substitutable by remote meeting technology than external meetings with customers and suppliers.

Business travel is dominated by professional services (IT, financial services, scientific, technical and education industries) and the manufacturing industry. Travel is also highly concentrated on some high frequency travellers – 85% of business travellers fly multiple times per year, but 31% fly more than monthly [19].

There is evidence that many companies do not plan to resume business travel at pre-pandemic levels, taking advantage of the shift towards online meetings to reduce costs and greenhouse gas emissions. Estimates of 20-30% less business air travel than pre-pandemic baselines have been reported by several large corporations [20].

Overall, the FlyZero conservative scenario assumes a "75% recovery" – that business travel recovers to a level 25% below the baseline forecast. Given that business travel represents about 20% of total air passengers, this is a 5% overall traffic reduction compared with the baseline forecast. In revenue terms for airlines, the impact of fewer business travellers is much higher and, if this shift were to transpire, would require significant changes in airline business models.

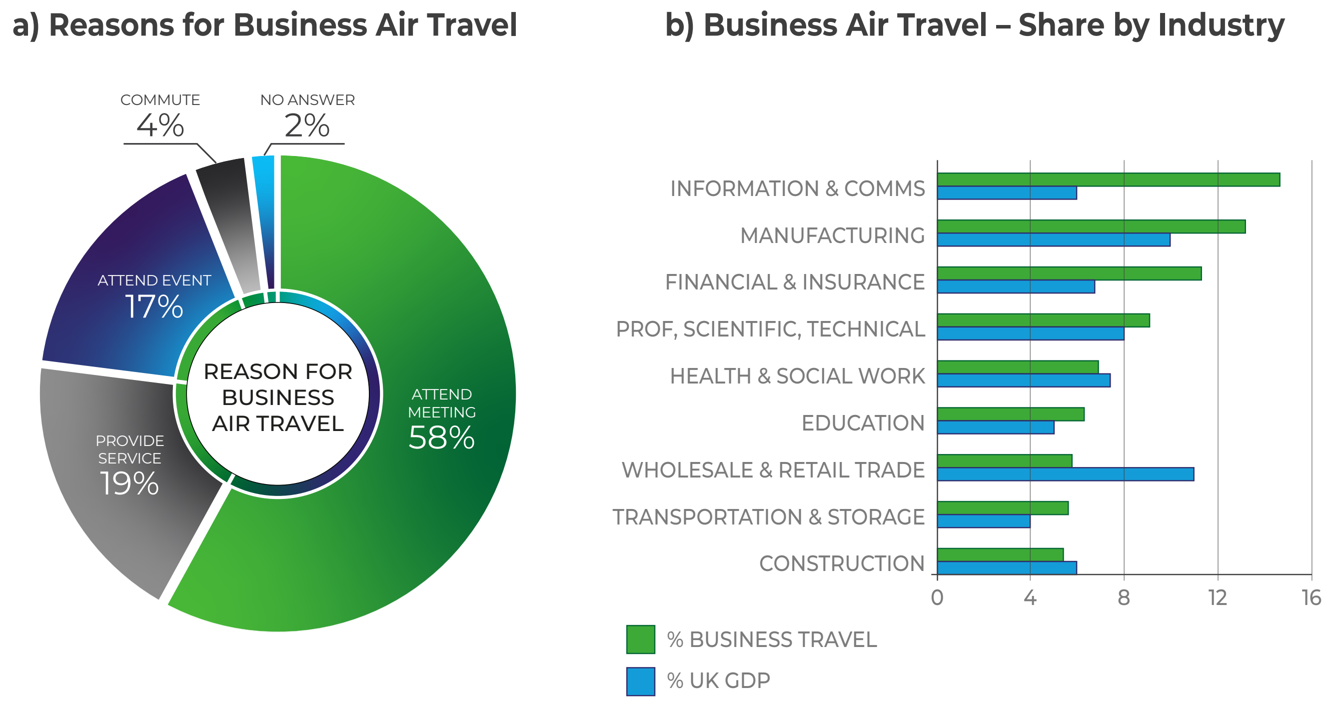


Figure 17 – Reasons for Business Travel – 2018.
Source © DFT Dynamic surveying for Aviation (2018).

01.5.2 SURFACE MODE COMPETITION

Air travel is one component of a mass public transportation system that includes road, rail and sea modes of travel. The different travel modes are largely complementary and are optimised for different travel distances and route densities. Air travel is best suited to longer distances or where geography (eg, water or mountains) makes surface journey times prohibitively long.

For inter-city travel, the main competitor for air travel is high speed rail (HSR). HSR routes require high density traffic flows, whereas aviation can link thinner routes more cost effectively.

Electrified rail services generally have lower per-passenger-kilometre CO_2 emissions than aviation, so greater use of rail modes is an important way to decarbonise the overall transportation system, particularly in advance of zero carbon emissions aircraft becoming available.

Impact of HSR on Air Travel Demand

FlyZero's assessment of the impact of HSR on air travel demand is based on analysis of the rail and air modes (see **Figure 18** below) and a study undertaken by Mott MacDonald **[21]**.

The analyses indicate:

- **North America** – 3-8% of intra North American air traffic could move to HSR by 2050 with planned rail developments, principally on trunk routes in the east and west coast regions. The FlyZero conservative scenario assumes a mid value of 5.5%, or around 75 million annual passengers by 2050.
- **Europe** – up to 14% of passengers (over 200m passengers by 2050) could switch to rail modes through the development of new lines, better connectivity between EU countries and streamlined international rail ticketing.
- **Northeast Asia** – Already around 50% of domestic travel uses HSR in this region. New HSR routes under construction in Japan are expected to capture an additional 13 million domestic air passengers per year by 2050.
- **China** – China has rapidly expanded its HSR network in recent years. It has 68% of the world's HSR line-kilometres and 66% of lines under construction. Because domestic air and HSR travel have developed in parallel over the past 20 years, this HSR development trend is already incorporated into our baseline forecasts and further adjustments are not required.
- **Other Regions** – There is little development or trend towards HSR in other world regions, so no adjustments to the air travel demand forecasts are required.

Overall, increased use of rail could result in about 300 million fewer annual air passengers by 2050 than in our baseline forecast, around 200 million of which are in Europe. This represents about 6% of intra-regional passenger volumes, but only 0.8% of global passenger-kilometres carried due to the shorter sectors impacted by HSR competition (typically 300 - 800 km distance).

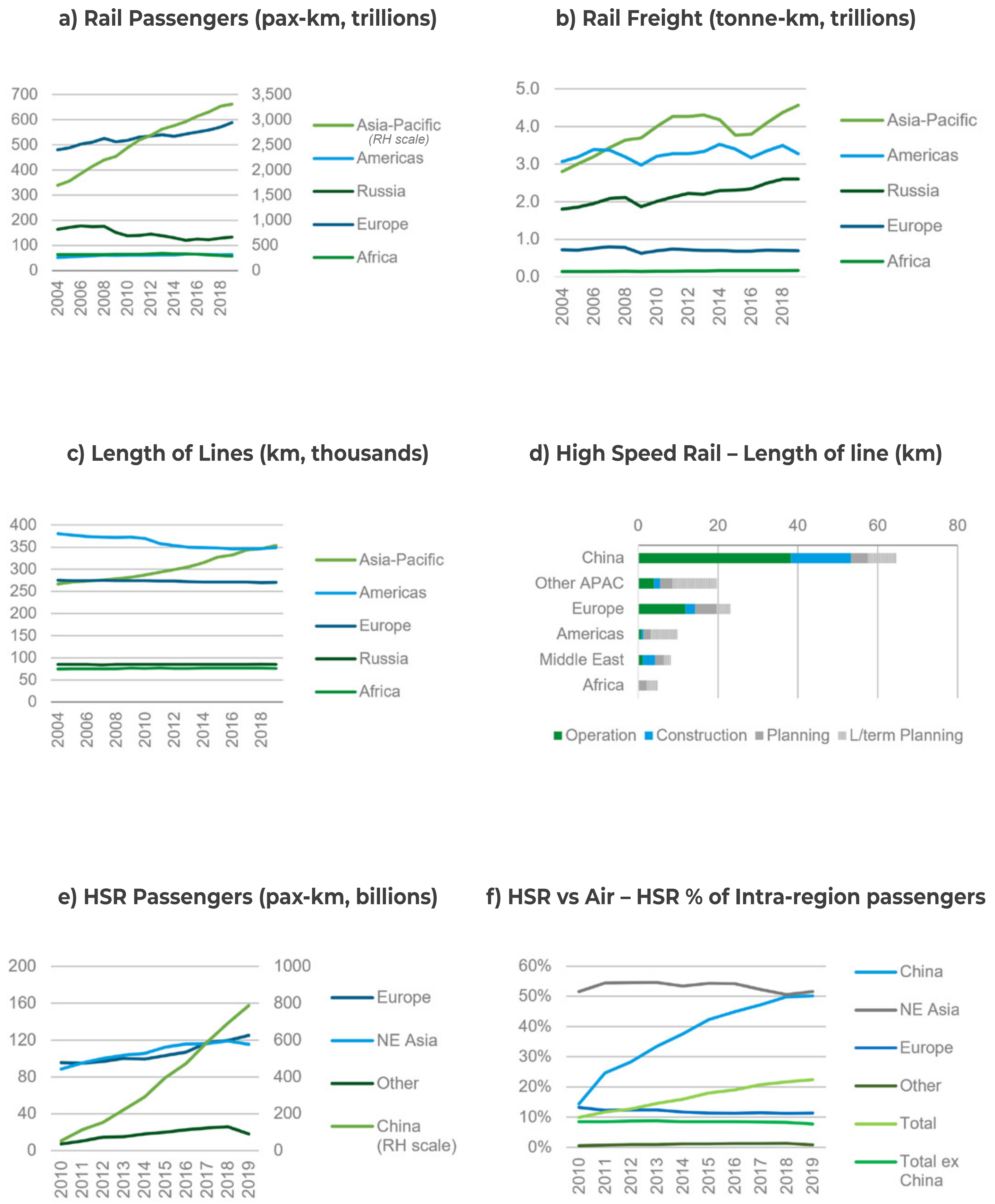


Figure 18 – Global Rail Statistics.

Source © UIC Rail Statistics [19] – MIDT air passenger data, FlyZero analysis.

01.6
DEMAND FORECAST SUMMARY

The FlyZero baseline forecast projects growth at an average of 3.2% per annum to 2050, reaching 22.9 trillion RPKs.

Our conservative scenario, taking account of incomplete post-pandemic traffic recovery and increased surface mode competition, is about 10% lower at 20.7 trillion RPKs. The conservative scenario lags the baseline growth trajectory by about 5 years – the growth in demand still occurs, but in a later year.

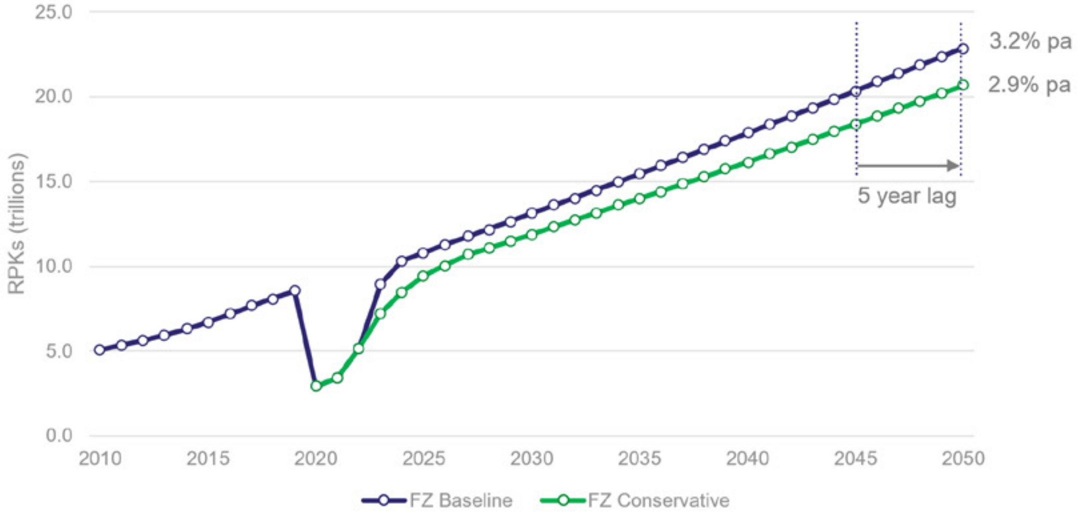


Figure 19 – Demand Forecast Sensitivities. Source © FlyZero analysis.

Market			< Actual	Forecast >						Average growth %		
										2019	2019	2050
	2010	2015	2019	2025	2030	2040	2050	2060	2070	2040	2050	2070
1.0 North America	1,430	1,700	2,030	2,420	2,750	3,540	4,420	5,420	6,560	2.7%	2.5%	2.0%
2.1 Central America	140	190	250	310	380	530	690	870	1,070	3.6%	3.3%	2.2%
2.2 South America	210	300	340	410	520	710	890	1,080	1,290	3.6%	3.1%	1.9%
3.0 Europe	1,270	1,570	1,950	2,390	2,760	3,510	4,360	5,310	6,380	2.8%	2.6%	1.9%
4.0 Africa	170	180	230	290	370	530	720	930	1,180	4.1%	3.8%	2.5%
5.0 Middle East	250	400	510	680	870	1,260	1,660	2,100	2,620	4.4%	3.9%	2.3%
6.0 Russia & C Asia	110	170	220	280	350	500	700	920	1,200	4.0%	3.8%	2.7%
7.1 South Asia	140	200	290	400	560	930	1,350	1,850	2,520	5.8%	5.1%	3.2%
7.2 China	500	820	1,190	1,660	2,090	2,920	3,710	4,480	5,390	4.4%	3.7%	1.9%
7.3 NE Asia	230	300	370	440	500	600	700	790	900	2.4%	2.1%	1.3%
7.4 SE Asia	320	480	640	880	1,150	1,700	2,280	2,930	3,730	4.8%	4.2%	2.5%
7.5 Oceana	170	210	250	320	380	510	630	770	930	3.4%	3.0%	1.9%
8.0 Rest of World	160	200	280	360	440	610	780	980	1,220	3.7%	3.4%	2.2%
Baseline	5,090	6,720	8,540	10,830	13,120	17,860	22,880	28,440	34,990	3.6%	3.2%	2.1%
Conservative	5,090	6,720	8,540	9,470	11,900	16,160	20,660	25,680	31,600	3.1%	2.9%	2.1%

Table 3 – Market Forecast Summary – RPKs (billion). Source © FlyZero analysis; MIDT data.

Forecast Benchmarking

The FZ Baseline forecast matches the latest Airbus [11] and Boeing [23] global market forecasts closely in 2030, but our FlyZero forecast tapers more with market maturity in the longer term (forecasting average growth to 2040 of 3.6% per annum, compared with 3.9% and 4.0% for Airbus and Boeing respectively).

The FZ Conservative forecast tracks 9-10% lower than the Baseline forecast, and is comparable to the latest forecast update from Oxford Economics / IATA of November 2021 [9].

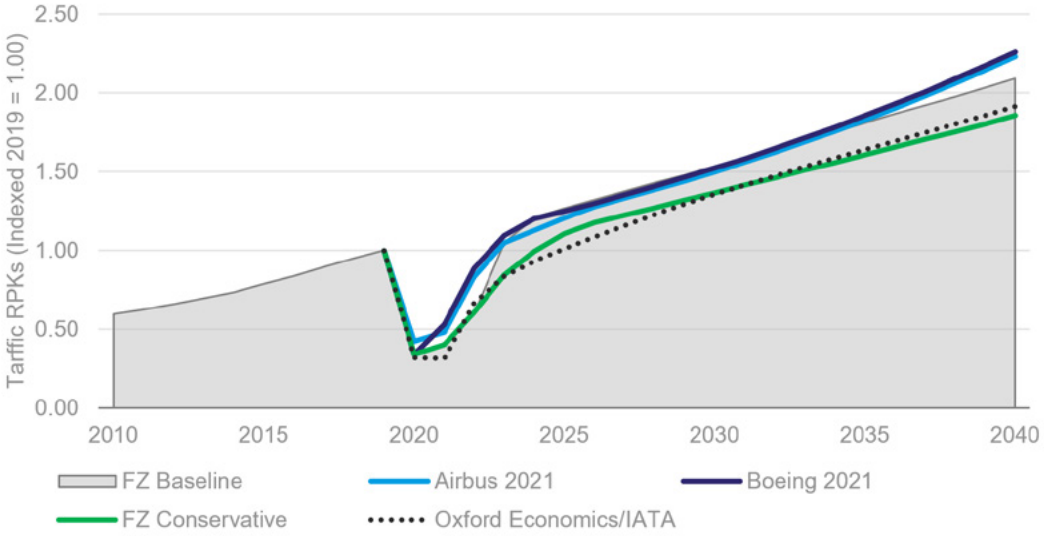


Figure 20 – Forecast Comparisons.
Source © FlyZero analysis; Boeing CMO 2021, Airbus GMF 2021, Oxford Economics/IATA (Nov 2021).

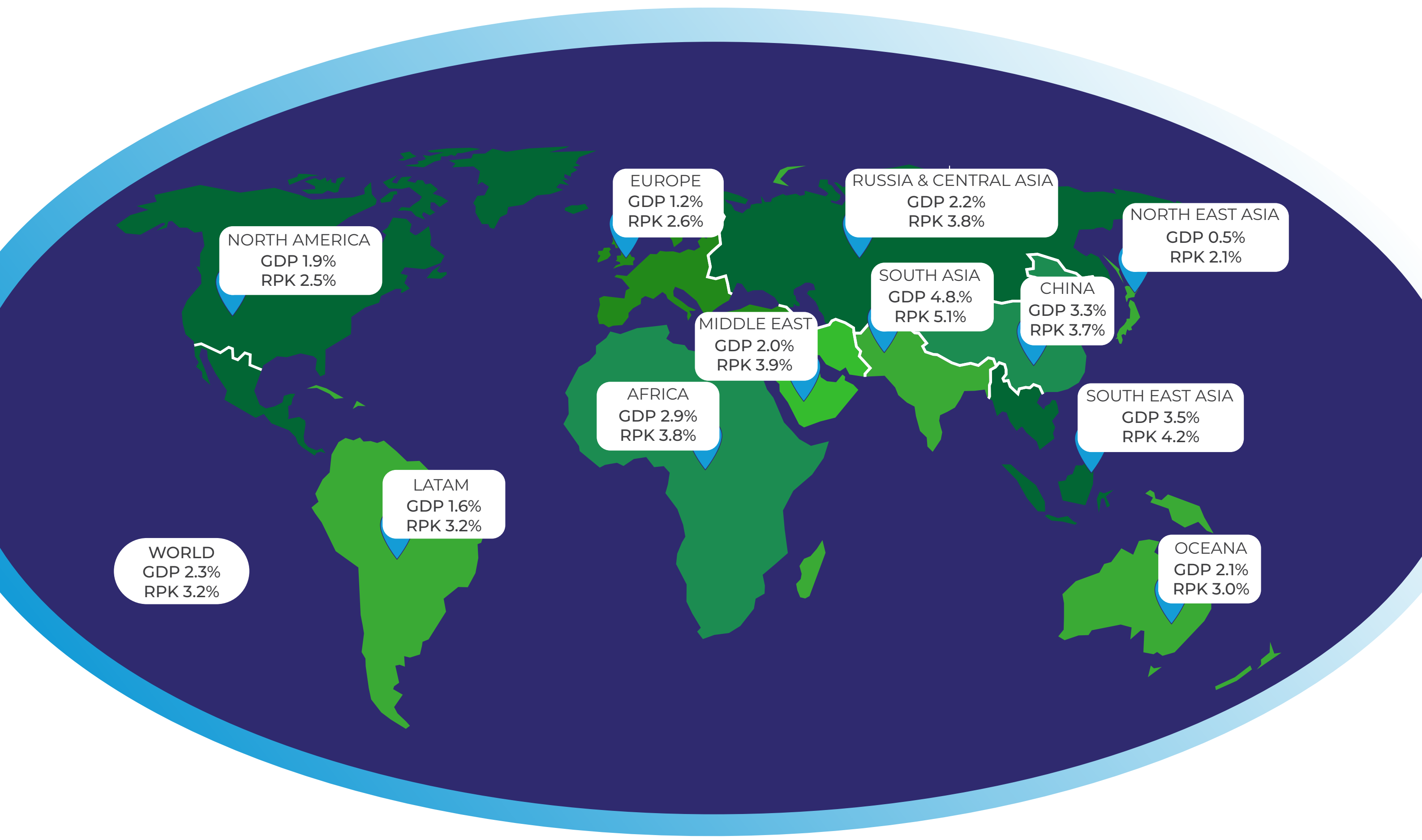


Figure 21 – Global Forecast Summary – 2019 to 2050 average annual growth rates.
Source © Oxford Economics GDP forecast, FlyZero baseline forecast.

02. FLEET FORECASTS

02.1 MARKET SEGMENTS

The FlyZero Global Fleet Forecast model translates projections of passenger demand into future fleet requirements by market segment.

The market segments are defined based on a combination of aircraft size and sector distance, as shown in the table below. Figure 22 shows the general relationship between sector distance and aircraft size, and how current aircraft types cluster into the different market segments.

Category	*Description*	*Typical Examples*
Subregional	*9 - 19 seats*	*Cessna Caravan, Beach 1900, DeHavilland Twin Otter, Dornier 228*
Regional	*20 - 120 seat turboprops or regional jets*	*ATR, Dash 8, CRJ, E170/190*
Narrowbody	*120 - 220 seat narrowbody aircraft, up to 2,400 nmi sector distance*	*A220, A320, B737*
Midsize	*Narrowbody sectors over 2,400 nmi;* *200-300 seat widebody aircraft, less than 5,250 nmi sector distance*	*A321XLR, B757, B767, A330*
Widebody	*Over 300 seats or over 5,250 nmi sector distance*	*A350, B787, B777*

Table 4 – Aircraft Market Segments.

Subregional

The subregional aircraft segment is defined as aircraft with less than 20 seats. The subregional fleet is now quite old, with an average age of 29 years, and its share of the market has been in steady decline due to trends towards larger aircraft with better per-seat operating economics. The development of electric aviation has the potential to reverse this trend, with new subregional electric aircraft offering zero emissions flight with competitive operating economics on short routes, up to about 200 nmi distance [24].

The subregional segment is outside of the scope of the FlyZero project's concept designs, but changes in the subregional share of the market is considered in our fleet forecast, as it affects demand for regional aircraft in the 20-120 seat range. Our assessment is that subregional electric aircraft may capture an increased share of the combined subregional/regional market – subregional aircraft could capture 25% of the market on routes up to 200 nmi range, or about 10% of the total subregional/regional market.

The FlyZero Global Fleet Forecast is focussed on demand for inter-city and regional air travel. Therefore, the potential development of short-range urban air mobility (UAM) aircraft concepts is not considered.

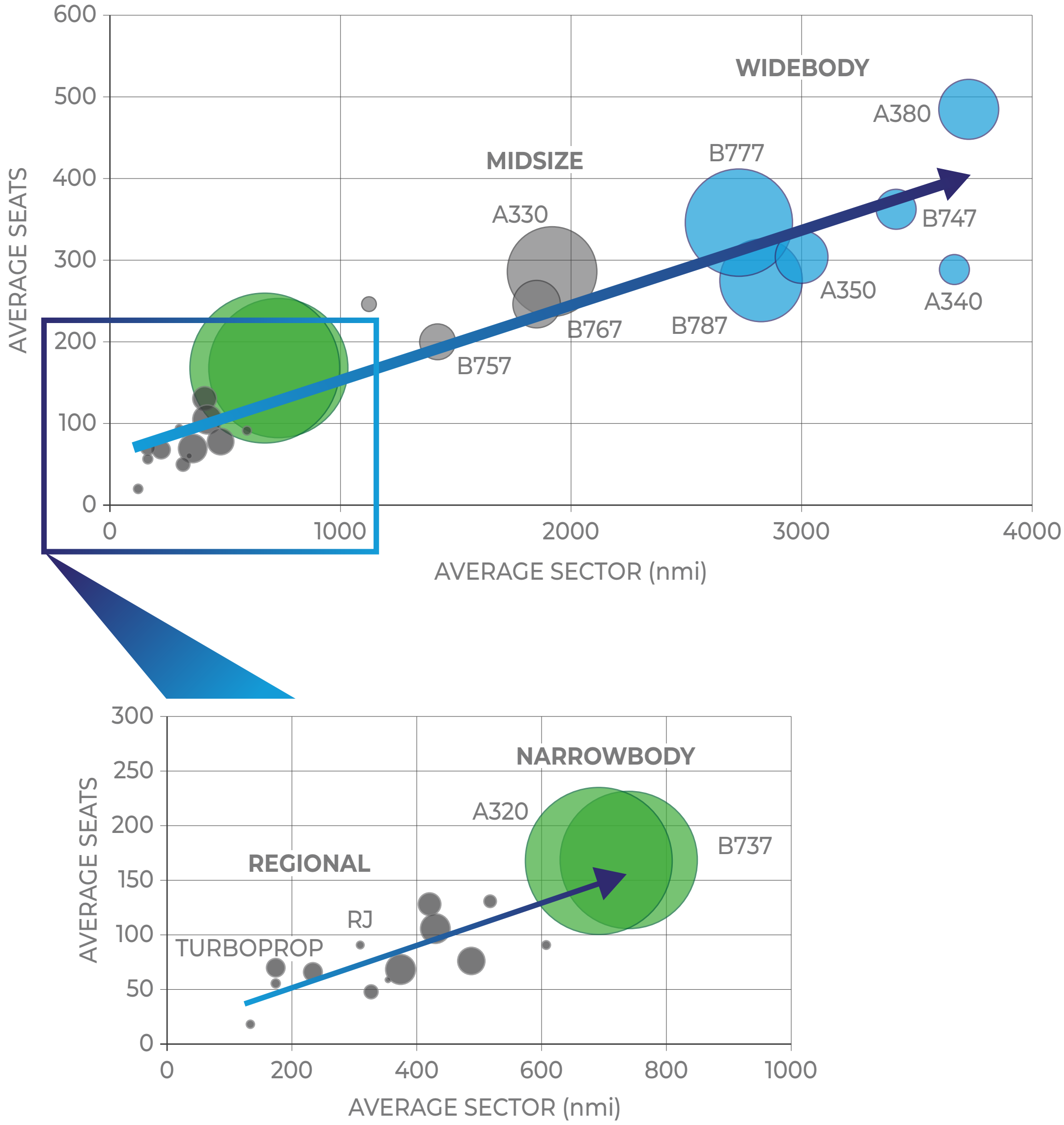


Figure 22 – Aircraft Markets – relationship between aircraft size and sector distance.

Source © FlyZero analysis; SRS Analyzer schedule data (2019). Bubble size is proportional to share of available-seat-kilometres (ASKs).

Regional

The regional aircraft segment (20-120 seats) is highly fragmented between turboprop and regional jet types. It has been in relative decline in recent years – the share of flights operated by regional aircraft declined from 32% to 25% between 2004 and 2019. Regional aircraft make up 21% of the current fleet, but only 10% of expected new aircraft deliveries to 2050. The regional segment is exposed to competition and substitution from electric subregional aircraft at the lower end, narrowbody aircraft at the upper end, and increased surface mode competition (eg, high speed rail) in some markets. Regional aircraft are currently responsible for about 7% of aviation's CO_2 emissions, and this share is expected to fall to around 4% by 2050 due to dilution of the regional aircraft market share.

Narrowbody

The shorthaul market is dominated by narrowbody aircraft with 120-220 seats, operating 93% of shorthaul capacity (as a share of available-seat-kilometres). Narrowbody aircraft represent 60% of the total passenger aircraft fleet and operated 64% of flights in 2019, an increase from 52% in 2004. This increasing share of the narrowbody segment is expected to continue, driven by shorthaul market growth trends and up-gauging of regional aircraft types. Narrowbody aircraft are expected to make up 65% of passenger aircraft deliveries to 2050 and over 50% of the aircraft market by value. Narrowbody aircraft are currently responsible for about 49% of aviation's CO_2 emissions, so decarbonising the narrowbody segment is key to meeting aviation's environmental objectives.

Midsize

There is a midsize aircraft segment between the shorthaul narrowbody and ultra-long range widebody segments. Historically this segment was served by aircraft such as the A300/310, A330 and B757/B767, and most recently by the extended range A321XLR. Only the A330neo and A321XLR are in current production as passenger aircraft.

FlyZero identified the opportunity to develop a midsize zero carbon emissions (ZE) aircraft concept with an operational range of 5,250 nmi, capable of intercontinental operations and providing one stop global connectivity.

The FlyZero Global Fleet Forecast defines the midsize market segment as:

- Narrowbody sectors over 2,400 nmi distance (0.5% of narrowbody flights in 2019)
- Widebody aircraft with 200-300 seats operating sectors less than 5,250 nmi distance (55% of widebody flights in 2019)

In 2019, 5% of flights operated were in this midsize segment, and these were responsible for about 19% of aviation's CO_2 emissions.

Widebody

The long range widebody aircraft segment includes the latest generation widebody twin-engine aircraft (A350, B787, B777X) with ultra-long ranges of 7,300-8,700 nmi. These aircraft offer superior operating economics and are replacing the remaining four-engine aircraft types (A340, A380, B747), which have now ceased production.

Large aircraft operating long distances are high emitters of CO_2 – widebody aircraft currently operate 4% of flights but emit 25% of aviation's total CO_2.

The table and figure below summarise characteristics of the baseline passenger aircraft fleet. This reflects the global fleet and scheduled use of aircraft in 2019, before the impacts of the Covid-19 pandemic. In addition to the 26,860 passenger aircraft, there was a fleet of 3,040 freighter aircraft, giving a total fleet of 29,900 aircraft at the end of 2019.

Class	2019 Fleet	Fleet (%)	Flights (%)	ASK (%)	CO_2 (%)	Ave Seats per flights	Ave Sector (nmi)	Ave Block time (h)	Sectors per day	Utilisation (BH/day)
Subregional	620	2.3%	3.3%	0.02%	0%	13	87	0.7	5.3	3.8
Regional	5,630	21%	24%	4%	7%	71	356	1.5	4.6	6.7
Turboprop	2,105	8%	9%	1%		63	196	1.1	4.6	5.3
Regional Jet	3,525	13%	15%	3%		76	411	1.7	4.5	7.6
Narrowbody	16,190	60%	64%	51%	49%	167	711	2.4	4.1	9.7
Midsize	2,490	9%	5%	19%	19%	258	2,297	5.8	2.0	11.5
Widebody	1,930	7%	4%	25%	25%	356	2,806	7.0	2.0	13.7
Total	26,860	100%	100%	100%	100%	150	750	2.4	3.9	9.4

Table 5 – Fleet Characteristics – 2019.

Source © Cirium Fleet Database (as at 31 Dec 2019), SRS Analyzer schedules (2019), FlyZero analysis. Based on commercial passenger aircraft fleet (excluding freighters) as at 31 Dec 2019. Sectors per day and Utilisation averaged over 365 days.

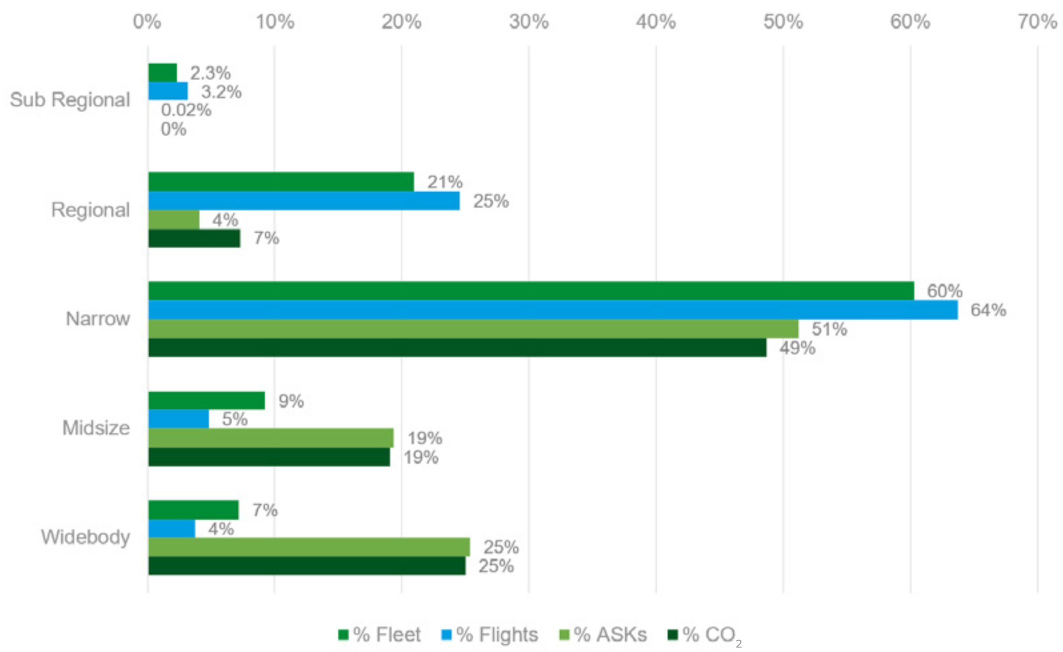
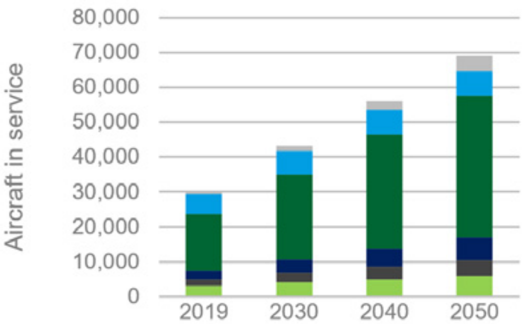


Figure 23 – Fleet Shares (2019). *Source © Cirium Fleet Database, SRS Analyzer schedules (2019), ICCT (October 2020), FlyZero analysis. % passenger fleet / operations.*

02.2 FUTURE FLEET FORECAST

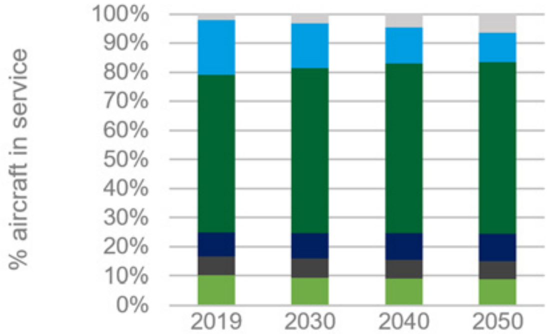
The figures below summarise the FlyZero Global Fleet Forecast, aligned with the FlyZero baseline passenger demand scenario:

a) Fleet Forecast



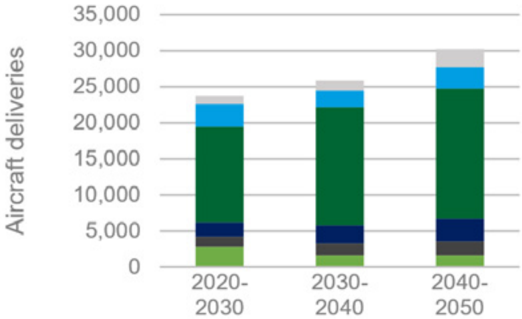
	2019	2030	2040	2050
Total	29,900	43,130	56,070	69,090
Subregional	620	1,330	2,530	4,460
Regional	5,630	6,690	7,040	6,910
Narrowbody	16,190	24,460	32,720	40,820
Midsize	2,490	3,810	5,160	6,520
Widebody	1,930	2,800	3,600	4,310
Freighters	3,040	4,040	5,030	6,070

b) Fleet Share Forecast



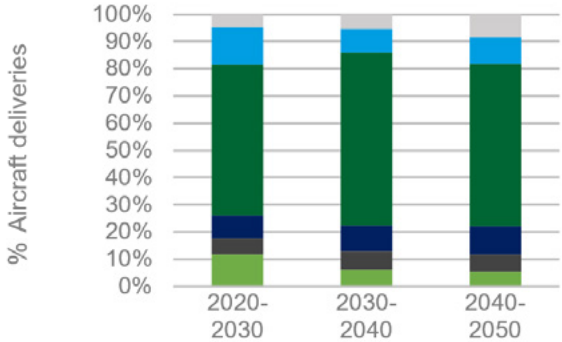
	2019	2030	2040	2050
Subregional	2%	3%	5%	6%
Regional	19%	16%	13%	10%
Narrowbody	54%	57%	58%	59%
Midsize	8%	9%	9%	9%
Widebody	6%	6%	6%	6%
Freighters	10%	9%	9%	9%

c) Delivery Forecast



	2020-2030	2030-2040	2040-2050
Total	23,740	25,790	30,220
Subregional	1,130	1,350	2,540
Regional	3,230	2,250	2,950
Narrowbody	13,220	16,400	18,040
Midsize	1,960	2,480	3,100
Widebody	1,370	1,670	1,990
Freighters *	2,830	1,630	1,600

d) Delivery Shares



	2020-2030	2030-2040	2040-2050
Subregional	5%	5%	8%
Regional	14%	9%	10%
Narrowbody	56%	64%	60%
Midsize	8%	10%	10%
Widebody	6%	6%	7%
Freighters *	12%	6%	5%

Figure 24 – FlyZero Global Fleet Forecast (source © FlyZero analysis).

** Freighter deliveries include conversions of passenger aircraft.*

02.3
BASELINE CO_2 EMISSIONS FORECAST

Global aviation emitted 920 Mt of CO_2 into the atmosphere in 2019 [2]. Without efficiency improvements, this would grow to 2,470 Mt by 2050.

Aircraft and operational efficiency improvements (described in **Section 1.4** above) are expected to reduce aviation's carbon intensity (measured in "grams CO_2 per RPK") by 1.5% per annum, or by 38% in aggregate by 2050.

With these efficiency improvements, the baseline forecast of aviation's annual atmospheric CO_2 emissions ("tail pipe" emissions) grows to 1,540 Mt by 2050 and 1,850 Mt by 2070 (+67% and +100% respectively compared with 2019 emissions).

Section 5 of this report presents the FlyZero scenarios for the market penetration of zero carbon emissions (ZE) aircraft technology and the potential abatement of these CO_2 tailpipe emissions.

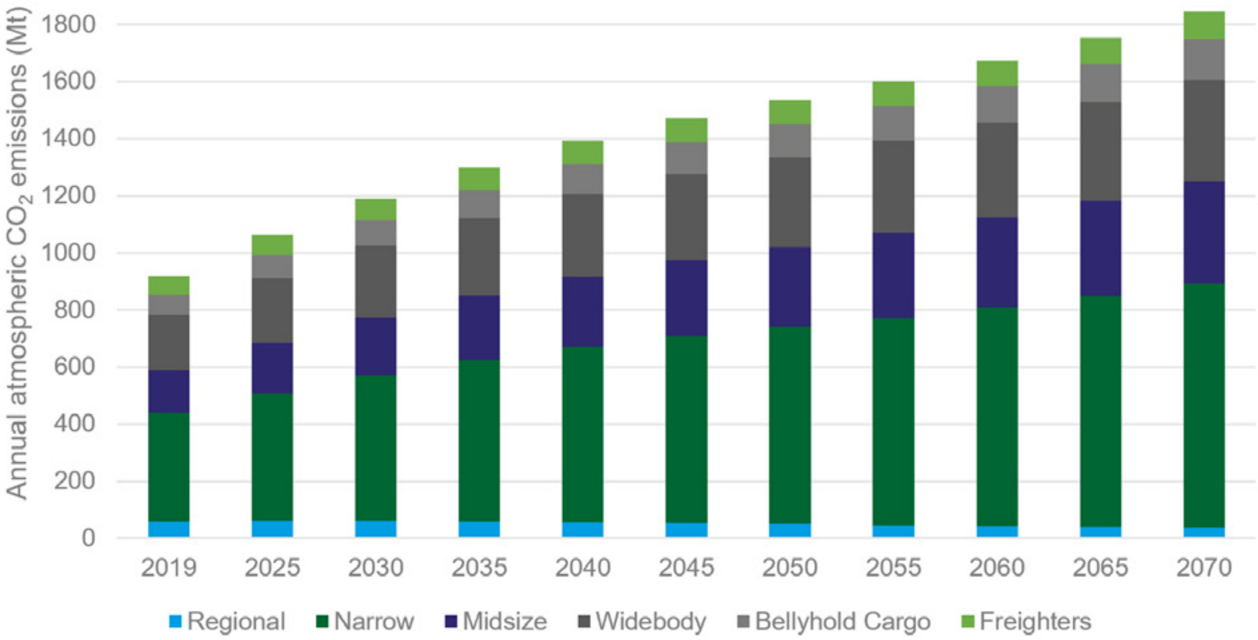


Figure 25 – Baseline Atmospheric CO_2 Emissions – No zero carbon emission aircraft.

Source © FlyZero analysis.

03. MARKET OPPORTUNITY

03.1 MARKET STRATEGY

FlyZero's objective is to identify ways to decarbonise aviation through the development of true zero carbon emissions (ZE) aircraft by the early 2030s. The FlyZero aircraft concepts are intended to demonstrate the technical feasibility and commercial viability of ZE aircraft in each market segment.

Early in the FlyZero project, a number of high-level "scout" aircraft concepts were developed to explore the technical capabilities and feasibility of different ZE aircraft configurations. The most promising configurations were developed in detail as FlyZero "concept" aircraft.

The commercial positioning of the FlyZero concepts can be summarised as:

- **FlyZero Regional (FZR)** – fast turboprop-equivalent hydrogen fuel cell aircraft, competitive with both conventional turboprop and regional jet aircraft
- **FlyZero Narrowbody (FZN)** – targeted at the heart of the narrowbody aircraft market, matching the A320neo for passenger capacity and range with a full payload
- **FlyZero Midsize (FZM)** – midsize aircraft offering zero carbon emission intercontinental flight with one stop global connectivity

Each FlyZero concept represents an archetype of a class of aircraft, with scope to stretch or shrink around this concept design point, in the same way that the A320 can be considered representative of the narrowbody class of aircraft.

The narrowbody aircraft segment is the largest, both in terms of its share of aviation CO_2 emissions and its value. Narrowbody aircraft sales are expected to represent over 50% of the total aircraft market by value during the period up to 2050. The commercial importance of this segment means that introducing novel ZE hydrogen technology into the narrowbody segment first is a high risk strategy for both aircraft manufacturers and airlines.

The FlyZero market strategy seeks to mitigate these risks by launching a ZE aircraft into either the regional or midsize market segments first, as a pathway to develop and prove ZE technologies before the development of a ZE narrowbody aircraft. These are the **Midsize First** or **Regional First** strategies, discussed further in **section 5**.

The table below summarises the three FlyZero concept aircraft specifications:

	FZR	FZN	FZM
Market Segment	Regional	Narrowbody	Midsize
Power System	LH_2 Fuel Cell 6x Propeller	LH_2 Combustion 2x Turbofan	LH_2 Combustion 2x Turbofan
Range	800 nmi	2,400 nmi ESAD 2,200 nmi typical	5,750 nmi ESAD 5,250 nmi typical
Cruise Speed	325 kts	0.78M	0.82M
Cruise Altitude	FL250	FL350	FL350 - 380
Number of seats	75 (1 class)	180 (1 class)	201 (3 class) 279 (1 class)
Payload Based on 105 kg/pax allowance, including baggage [22]	7.9 tonne	18.8 tonne	29.3 tonne (8.2 tonne cargo payload available in 201-seat config)
Cargo Capacity	10.6 m^3	37.5 m^3 7 x LD3-45W	107.3m^3 22 x LD3
Aircraft Weights			
Max Takeoff Weight (MTOW) Operating Empty Weight (OEW)	28.8 tonne 19.8 tonne	70.7 tonne 48.0 tonne	150.8 tonne 104.8 tonne
Fuel Capacity	16.2 m^3	55.3m^3	235.8m^3
Aircraft Dimensions			
Length Wingspan ICAO Code	28.0 m 31.0 m Code C	47.8 m 39.3 m (35.8 m folded) Code C (folded)	59.6 m 52.0 m Code E
Runway Length			
Takeoff (MTOW, SL, ISA) Landing (MLW, SL, ISA)	1,330 m 1,390 m	2,000 m 1,905 m	2,440 m 2,150 m
Approach Speed	114 kts	137 kts	145 kts
ICAO Approach Category Wake Vortex Category	Cat B Small	Cat C Medium	Cat D Heavy

Table 6 – FlyZero Concepts Specification.

03.2 REGIONAL CONCEPT

The FlyZero regional concept (FZR) is designed to demonstrate the capabilities of a zero carbon emissions hydrogen fuel cell aircraft, with a distributed electric motor/propeller powertrain. The concept is positioned as a fast turboprop-equivalent aircraft, capable of offering a ZE alternative for both conventional turboprops and regional jets.

The FZR concept has 75 seats in a single-class configuration, equivalent to the ATR-72, Dash 8 Q400, Embraer E170, and Bombardier CRJ700 types.

Figure 26 – FlyZero FZR-1 Regional Concept.
Source © ATI.

There is a trade-off between cruise speed and range for a regional aircraft. A 325kt cruise speed (equivalent to a fast turboprop) allows the operation of an 800 nmi sector within a 180 minute block time. A range of 800 nmi caters for 99.9% of turboprop routes and about 90% of the regional jet market.

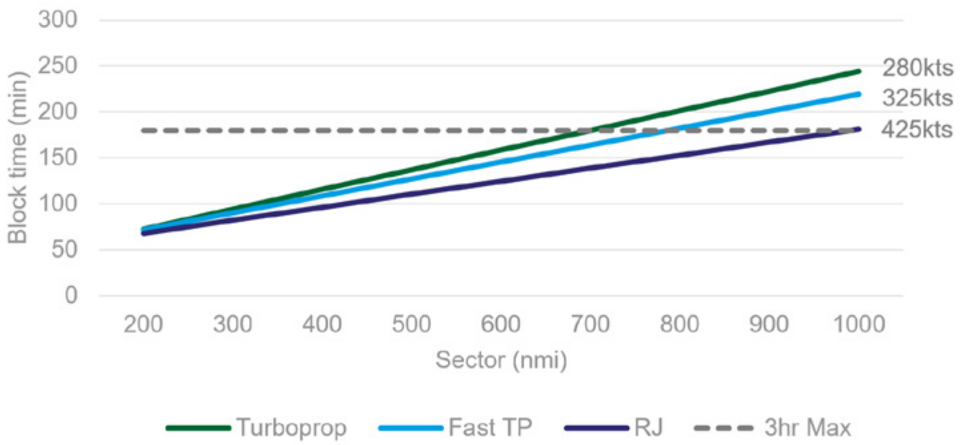


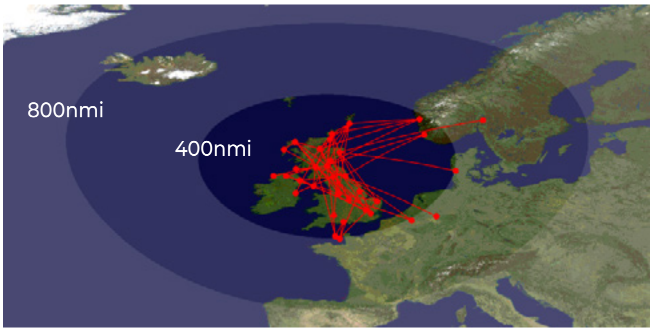
Figure 27 – Regional Aircraft – Range versus Cruise Speed.

Range Plots

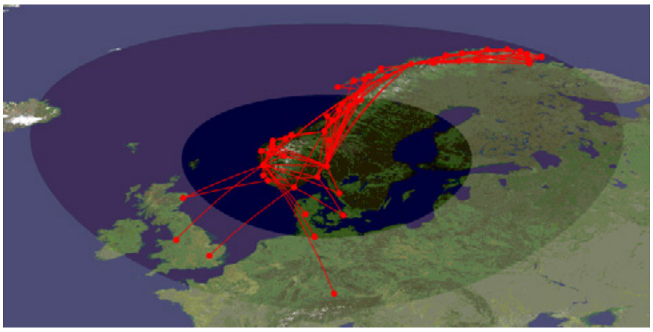
The plots below show the FZR range capability for regional airline networks, based on typical airline networks and airports with an 800 nmi range. Tankering return sector fuel for sectors under 400 nmi is also feasible with the FZR concept. A 400 nmi tankering range covers 90% of turboprop routes and 70% of the overall regional market.

Regional airline networks are very fragmented, serving a large number of smaller airports at relatively low flight frequency. This makes roll-out of hydrogen fuelled ZE aircraft more complex, as it requires hydrogen capability at a large number of airports (many quite small) to provide a minimum-viable airline network.

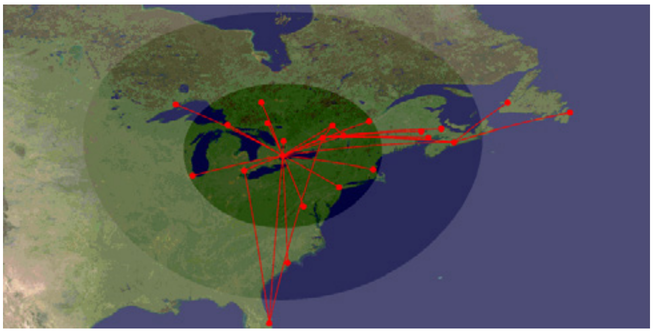
a) Loganair – United Kingdom



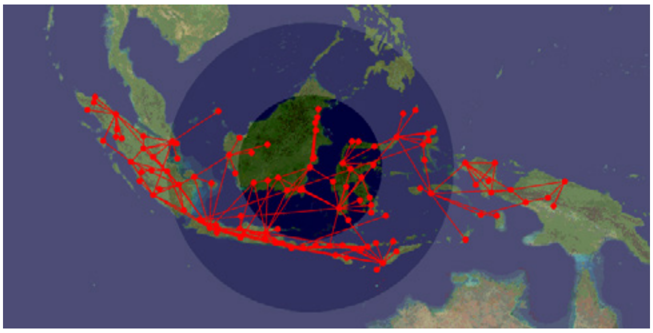
b) Wideroe – Norway



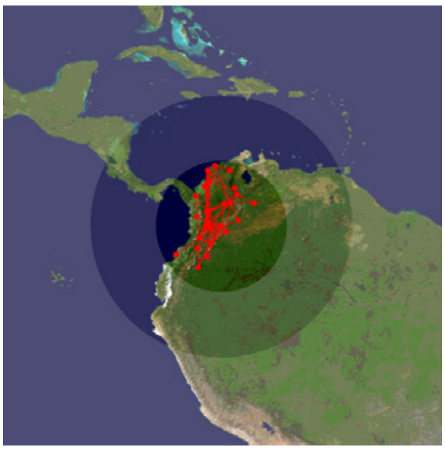
c) Porter Airlines – Toronto



d) Wings Air – Indonesia



e) EasyFly – Colombia



f) SAA Express – South Africa

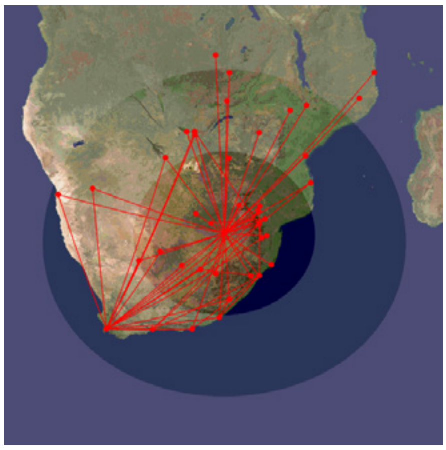


Figure 28 – FZR Regional Concept – Example Range Plots.

Source © SRS Analyzer (2019 schedules); Maps generated by the Great Circle Mapper (www.gcmap.com) - (copyright © Karl L. Swartz).

03.3 NARROWBODY CONCEPT

The FlyZero narrowbody concept (FZN) is designed to compete directly with the Airbus A320neo and Boeing 737-8 MAX aircraft at the heart of the narrowbody market.

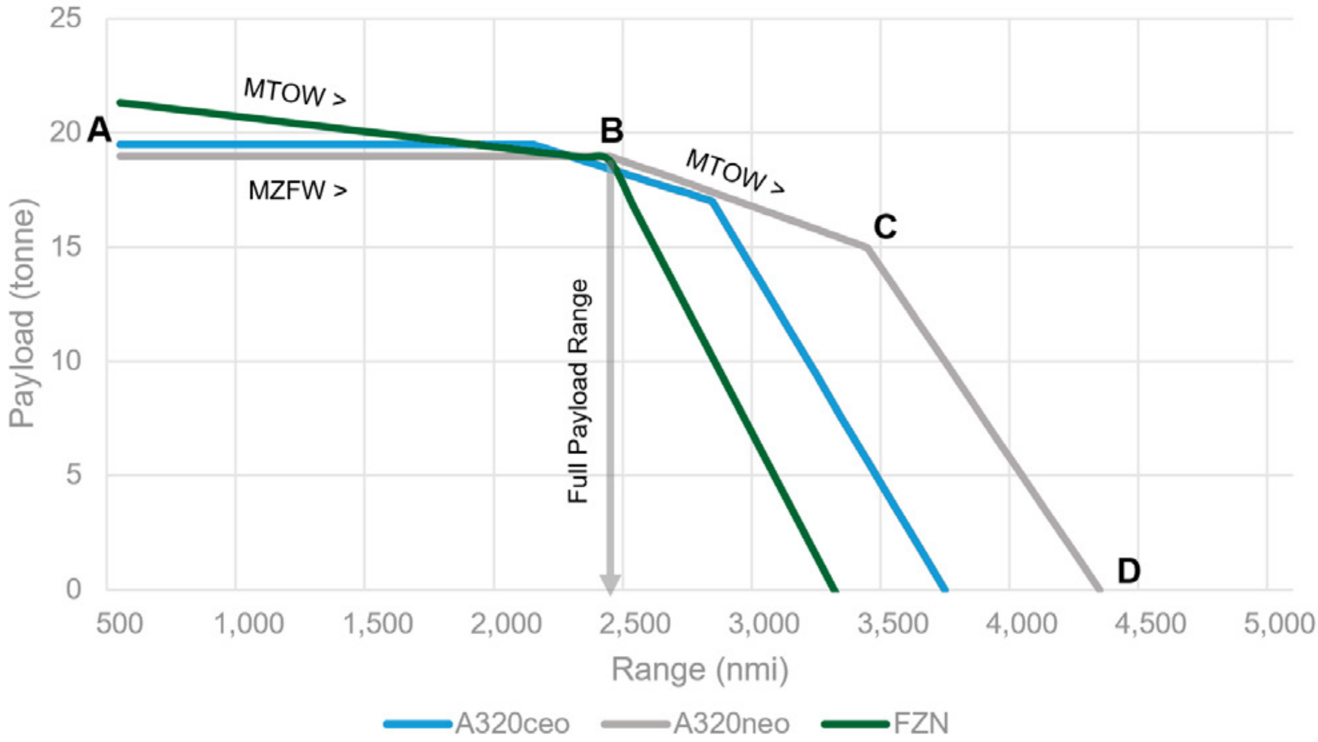
The FZN concept can operate with a full 180-passenger payload over a 2,400 nmi range. This range matches the A320neo and is about 10% longer than the full payload range of the older A320ceo.

Figure 29 – FlyZero FZN-1 Narrowbody Concept.
Source © ATI.

A characteristic of conventional kerosene aircraft is that they tend to have excess fuel tank volumetric capacity, so that the aircraft is constrained by its Maximum Takeoff Weight (MTOW) when carrying a maximum payload – it cannot operate both with a maximum payload and with full fuel tanks. The aircraft's range with full payload occurs at point B in the payload-range diagram below **(Figure 30)**. A kerosene aircraft can only fly further with a payload penalty, trading commercial payload for additional fuel up to the volumetric limit of the fuel tank (point C).

For a hydrogen aircraft, fuel tank volume is the critical constraint and there is a greater penalty for providing an oversized fuel tank than for a kerosene aircraft. Since liquid hydrogen is much lighter than kerosene, it is optimal to design for a MTOW that accommodates full fuel tanks at maximum commercial payload.

The FZN concept is sized to match the A320neo's maximum payload range of 2,400nmi (point B in the payload-range diagram). An A320neo can fly up to 3,400 nmi, but only with a payload penalty (point C). However, given the lost revenue associated with payload restrictions, airlines rarely operate further than the aircraft's maximum payload range – only 0.5% of narrowbody flights operated on sectors over 2,400 nmi in 2019.



A: Maximum Zero Fuel Weight (MFZW)
B: MTOW with full payload
C: MTOW with full fuel tanks
D: Maximum ferry range, no payload
Ranges include reserves and contingency fuel

Figure 30 – Payload-Range Diagram.

Fuel Tankering

Another favourable characteristic of light weight hydrogen fuel is that it opens up the opportunity for airlines to "tanker" fuel with little penalty – to carry sufficient fuel on the outbound sector for the return flight without refuelling.

If an A320neo were to operate at 1,000 nmi sector while tankering the return-trip fuel, it would burn an additional 315 kg of fuel (+6.3%) and emit about 1 tonne of additional CO_2 into the atmosphere, due to the energy required to carry the extra weight of the tankered fuel. The FZN hydrogen aircraft requires only an additional 19 kg of fuel (+1.3%) to tanker a 1,000 nmi sector return-trip fuel, and has no carbon emissions.

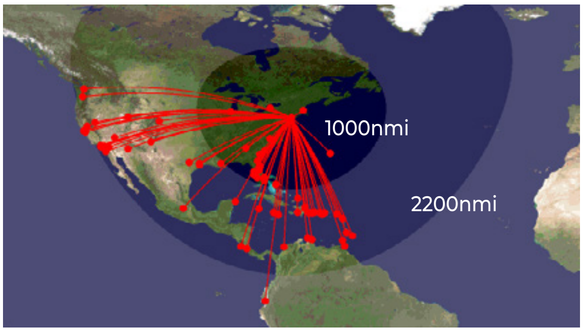
The benefits of hydrogen fuel tankering are:

- Fewer hydrogen-capable airports required for a commercially viable airline route network, particularly in the early days of zero carbon emissions flying
- Quicker outstation turnarounds (without refuelling), minimising the impact of any extended hydrogen refuelling times on overall aircraft utilisation

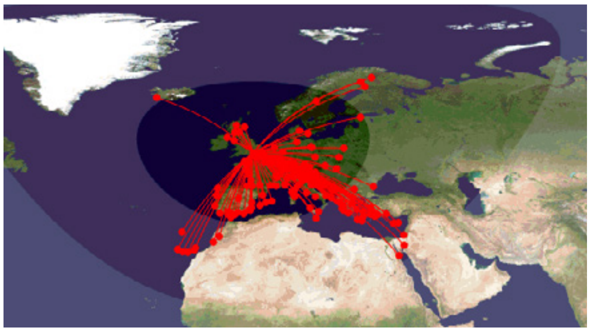
Range Plots

The range plots in **Figure 31** below show the FZN range capability for typical narrowbody route networks, based on example airlines and airports. The 1,000 nmi tankering range caters for 80% of all narrowbody flights, and the 2,200 nmi operational range (taking account of indirect flight routings and typical en route winds) covers 99% of the narrowbody market.

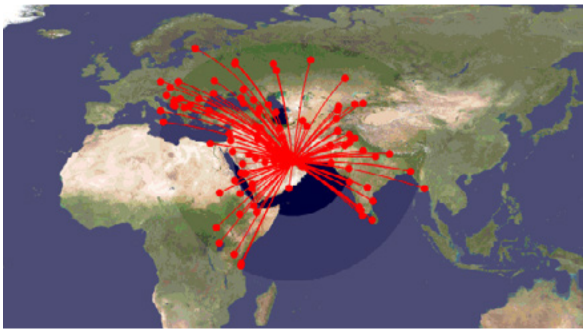
a) JetBlue – New York JFK



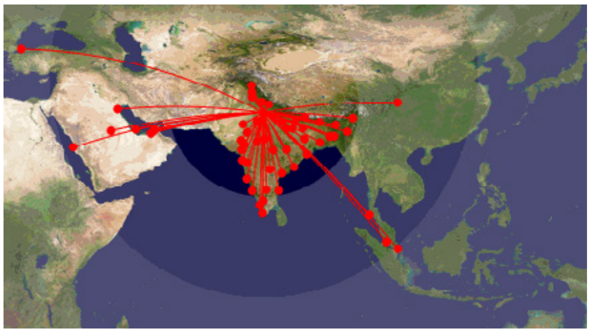
b) easyJet – London Gatwick



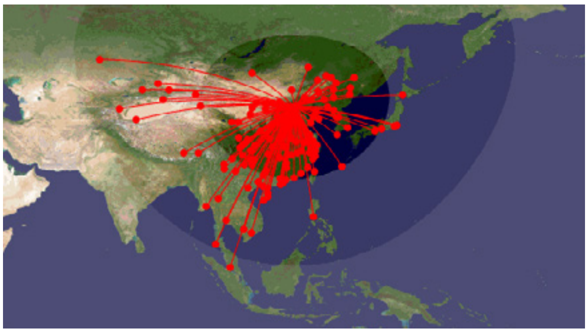
c) FlyDubai – Dubai DXB



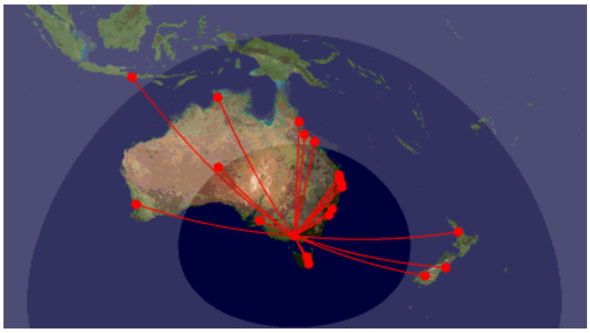
d) Indigo - Delhi



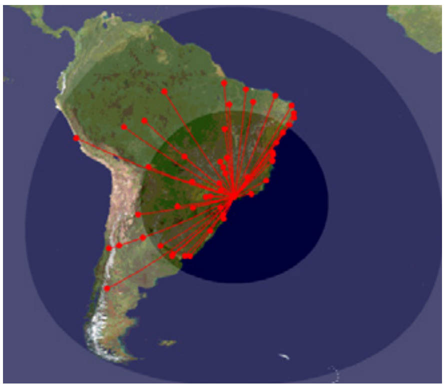
e) Air China – Beijing



f) JetStar – Melbourne



g) LATAM – Sao Paulo



h) Ethiopian Airlines – Addis Ababa

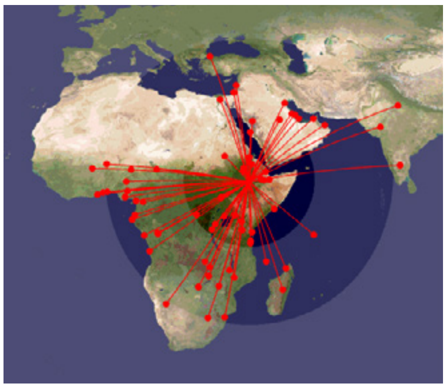


Figure 31 – FZN Narrowbody Concept – Example Range Plots.

Source © SRS Analyzer (2019 schedules); Maps generated by the Great Circle Mapper (www.gcmap.com) - (copyright © Karl L. Swartz).

03.4
MIDSIZE CONCEPT

The FlyZero midsize concept (FZM) is designed to demonstrate the ability for a zero carbon emission hydrogen aircraft to operate intercontinental longhaul sectors and to offer one stop global connectivity.

The FZM concept does not require a radical new aircraft layout, like a blended-wing body (BWB). It is a broadly conventional tube-and-wing layout that is compatible with existing airport infrastructure.

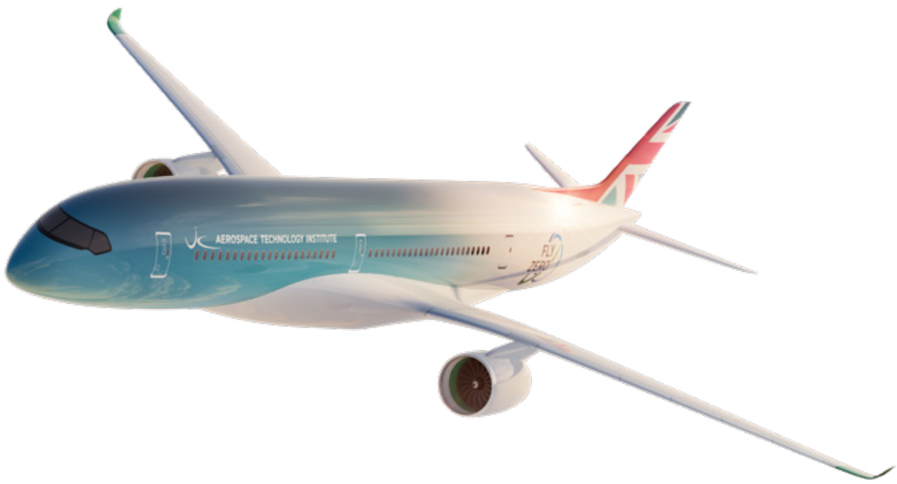


Figure 32 – FlyZero FZM-1 Midsize Concept.
Source © ATI.

The FZM concept is designed with a maximum full payload range of 5,750 nmi (assuming zero wind, but allowing for contingency and reserve fuel). This range allows the aircraft to operate scheduled sectors up to 5,250 nmi, allowing for indirect flight routings and typical en route winds.

A 5,250 nmi practical range delivers one stop global connectivity – the aircraft can fly between almost any two points in the world with one stop. From London the FZM could fly direct to most major destinations (as shown in **Figure 33** below), and could reach points in Australia or New Zealand with a single connection in Asia.

In practice, this range is competitive with ultra-long range widebody aircraft like the B787 and A350 on all but a small number of routes – 84% of widebody flights are within 5,250 nmi range. Therefore, there is scope for a ZE midsize aircraft to attract market share from carbon-emitting aircraft in the widebody segment.

Figure 33 – FZM Midsize Range Map from London.

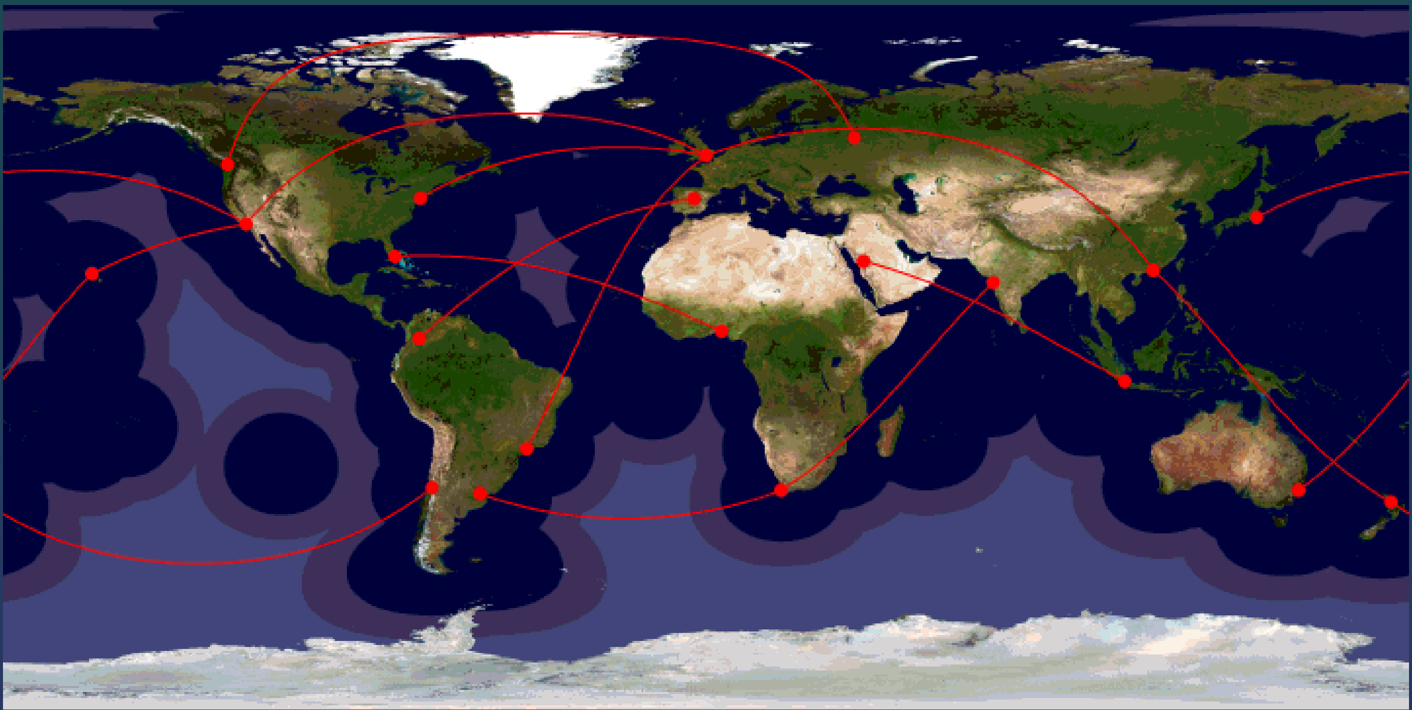
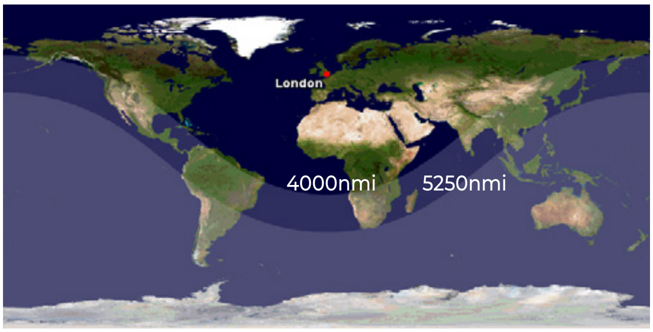


Figure 34 – FZM Example Routes (within 5,250 nmi operational range).
Shading shows ETOPS 120 min and 180 min exclusion zones.

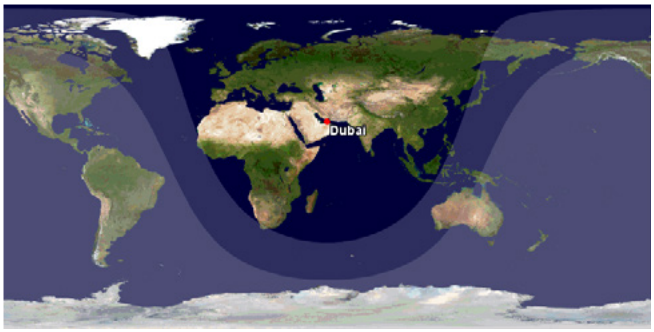
Maps generated by the Great Circle Mapper (www.gcmap.com) - (copyright © Karl L. Swartz).

The range plots below show the FZM midsize concept's practical range capabilities from major hub airports worldwide.

a) London

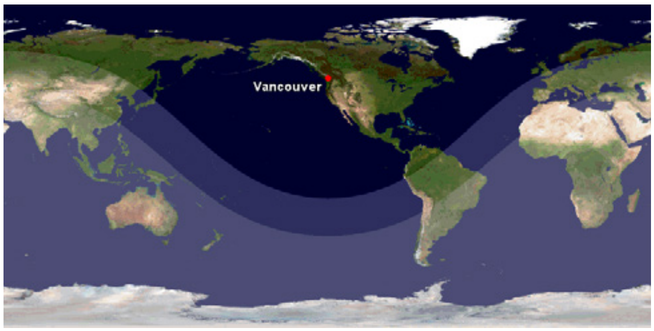


b) Dubai

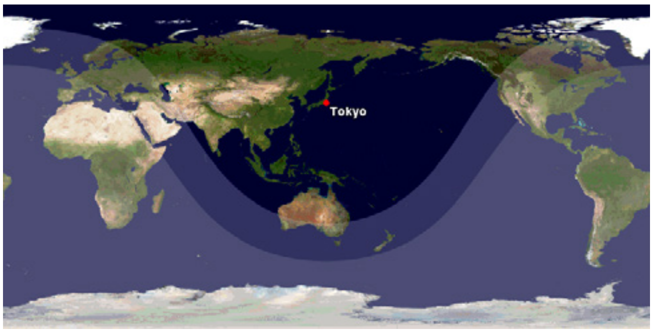


c) New York

d) Vancouver



e) Tokyo



f) Hong Kong

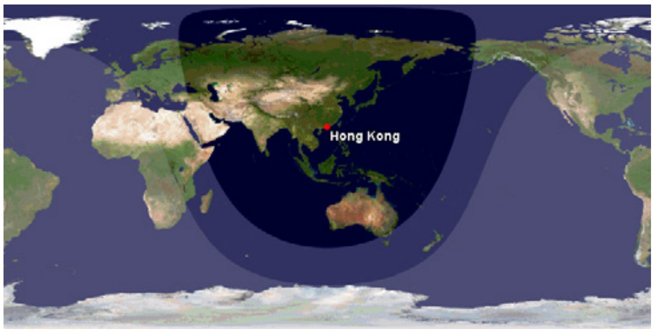


Figure 35 – FZM Midsize Concept – Example Range Plots.

Maps generated by the Great Circle Mapper (www.gcmap.com) - (copyright © Karl L. Swartz).

The charts below show the percentage distribution of flights by sector distance (in nautical miles) for each market segment, based on 2019 airline schedules.

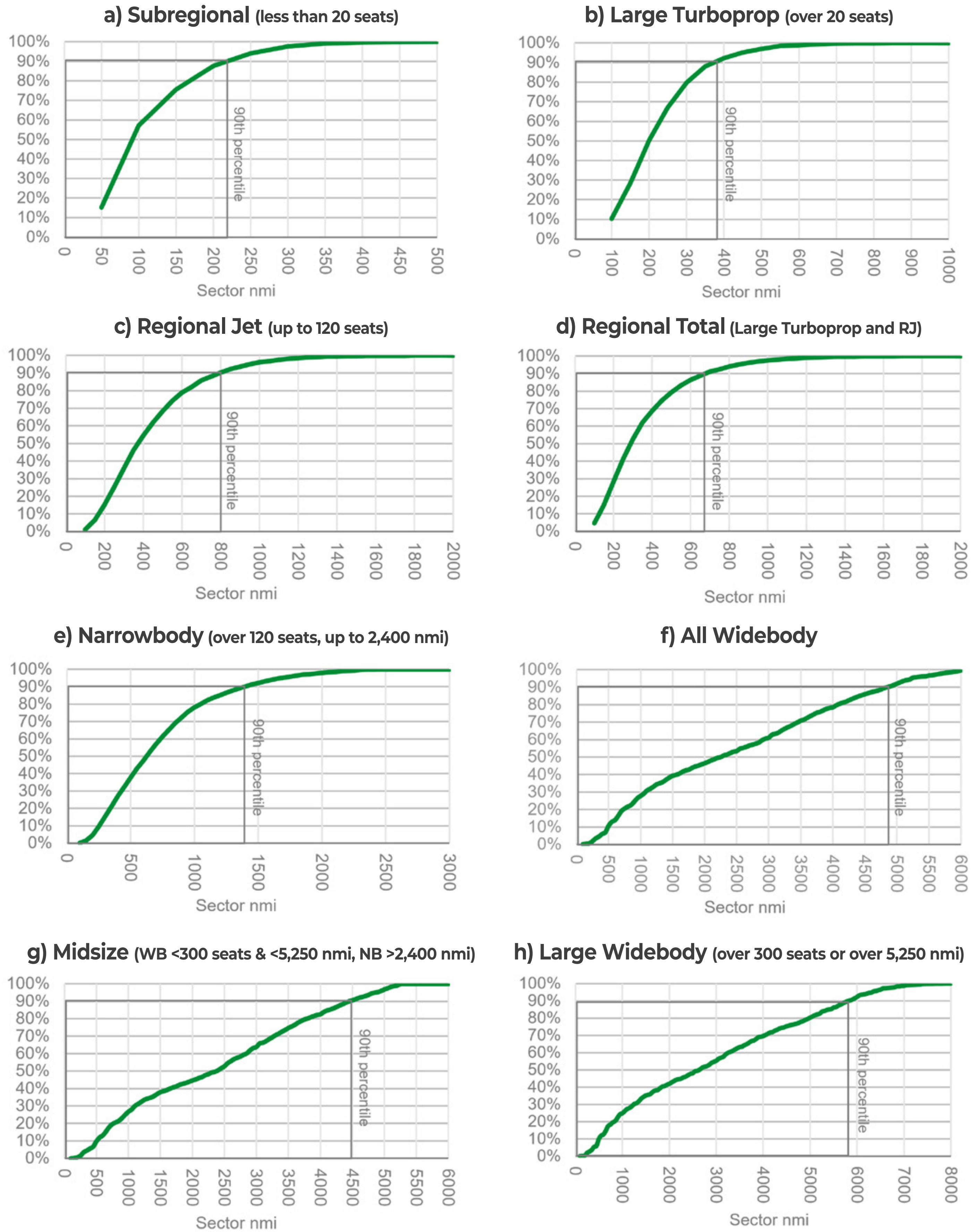


Figure 36 – Sector Distance: Cumulative Distribution by Number of Flights.

Source © FlyZero analysis of SRS Analyzer schedule data (2019). Sector distance in nautical miles.

04. CONCEPT COMPETITIVENESS

04.1 COST COMPETITIVENESS

The commercial success and market penetration of future ZE aircraft will be driven by their cost competitiveness in the market, measured against conventional kerosene / SAF burning aircraft types.

The **reference** aircraft is the closest existing competitor aircraft in each market segment.

The **baseline** aircraft is hypothetical clean-sheet design representing the extent to which conventional kerosene-burning aircraft technology might be improved by the 2030s. As clean-sheet designs, the baseline aircraft represent a larger technology step than might be expected with derivative aircraft developments, such as a next generation development of the A320neo.

Market Segment	*FZ Concept*	*Reference*	*Baseline*
Regional	*FZR*	*ATR-72*	*New Regional (NRA)*
Narrowbody	*FZN*	*A320neo*	*New Narrowbody (NNA)*
Midsize	*FZM*	*B767-200*	*New Midsize (NMA)*

Table 7 – Concept, Reference and Baseline Aircraft.

Commercial Comparisons

The FlyZero project developed its aircraft concept designs using the *Pacelab APD* preliminary aircraft design platform. The commercial analysis used the integrated *Pacelab Mission Suite* software to assess the aircraft economic performance on representative routes.

The key commercial parameters are:

- Block fuel energy per-sector and per available-seat-km (ASK)
- Trip fuel costs
- Trip cash operating costs (COC) – operating costs excluding aircraft ownership cost
- Direct operating costs (DOC) per-sector and per revenue-passenger-km (RPK)

Fuel Costs

The cost of aviation fuel is a key variable when comparing liquid hydrogen ZE aircraft with conventional aircraft burning fossil fuel kerosene or a blend of sustainable aviation fuels (SAFs).

The fuel cost assumptions used in our commercial analysis are shown in **Figure 37** below. These cost projections are intended to be central values, used to illustrate the relative cost competitiveness of zero carbon emissions aircraft, compared with conventional aircraft using kerosene or SAF. The costs of fossil fuel kerosene (Jet A1) are based on a constant $0.70 per kg base price in all years, plus a rising cost of carbon in future years **[26]**. SAF blend costs are based on the blended cost of kerosene and different types of SAF, with carbon prices applied to the residual carbon in the blend. The share of SAF versus kerosene in the blend increases over time. The hydrogen costs are based on projections of the costs of green hydrogen **[27, p.39]** plus the costs of liquification (related to renewable energy input costs).

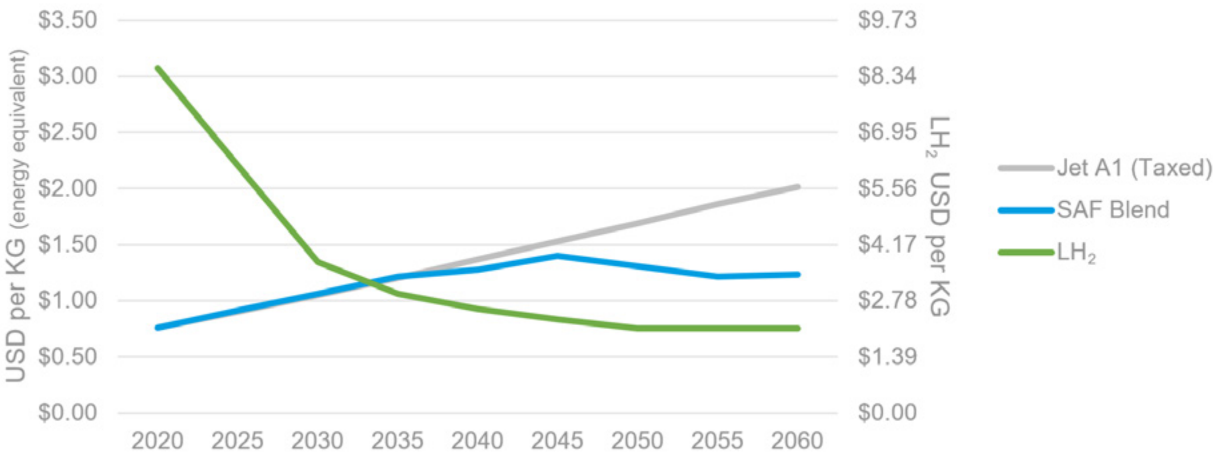


Figure 37 – Costs of Aviation Fuel.

Source © FlyZero analysis. Based on:

– The price of Jet A1 fossil fuel kerosene assumes a constant underlying fuel price of $0.70 per kg, with future carbon prices applied following the UK Government's Green Book guidance [26].

– SAF costs are based on the Air Transport Action Group (ATAG) Waypoint 2050 report [12] and supporting analysis by ICF [27].

– Green hydrogen costs are derived from information published by ATAG [12], the World Economic Forum [28], and analysis undertaken by ARUP for the FlyZero project [29].

Airport and Air Navigation Charges

Airport infrastructure investment is usually recovered through general airport charges levied on all airport users. This was the approach typically adopted to recover airport investments to accommodate the Airbus A380, for example. Therefore, we assume that the hydrogen fuel infrastructure investment is reimbursed through general airport charges. Conversely, we do not assume that operators of ZE aircraft will benefit from reduced airport charges or environmental incentives, or benefit from enhanced priority in the allocation of airport slots. Therefore, on balance, we apply common airport charges (varying only by aircraft MTOW) to both ZE and conventional aircraft in our commercial analyses – airport charges are not a distinguishing factor in assessing the cost competitiveness of ZE and conventional aircraft.

Air navigation charges are based on the Eurocontrol formula, where charges are related to distance flown and the square root of the aircraft's maximum takeoff weight (MTOW). The air navigation charges for ZE and conventional aircraft only differ to the extent that MTOWs are different. Charges for aerodrome air traffic services are included in the landing fee component of airport charges.

Crew costs

Within each market segment, the reference, baseline and FlyZero concept aircraft have the same number of pilots and cabin crew, so crew costs are common across types.

Ownership and Maintenance Costs

The table below shows the differences in aircraft ownership and maintenance costs for the baseline and concept aircraft, compared with the current technology reference aircraft (the ATR-72, A320neo and B767-200, as described above).

The new design conventional baseline aircraft (NRA, NNA, NMA) are expected to have comparable ownership costs to the current reference aircraft. Ownership costs of the FlyZero concepts (FZR, FZN, FZM) are higher due to the additional systems and technology associated with the liquid hydrogen fuel and propulsion systems, and the additional aircraft structure necessary to accommodate the larger liquid hydrogen tanks.

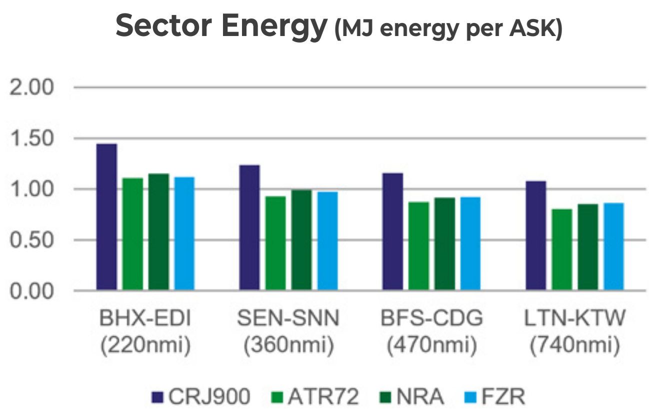
Maintenance cost improvements of around 10% are expected for the new design conventional baseline aircraft, taking advantage of latest technologies. The FlyZero concepts have additional fuel system maintenance costs. The FZR concept is expected to have lower overall maintenance costs due to use of electric motors instead of gas turbine engines.

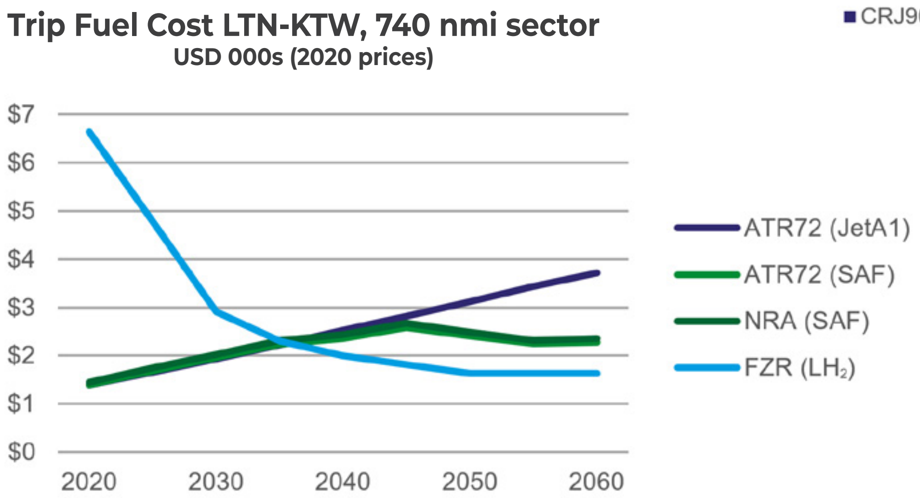
Market Segment		*Ownership*	*Maintenance*
Regional	*NRA baseline*	*0%*	*-10%*
	FZR concept	*+20%*	*-29%*
Narrowbody	*NNA baseline*	*0%*	*-10%*
	FZN concept	*+13%*	*+3%*
Midsize	*NMA baseline*	*0%*	*-10%*
	FZM concept	*+8%*	*+3%*

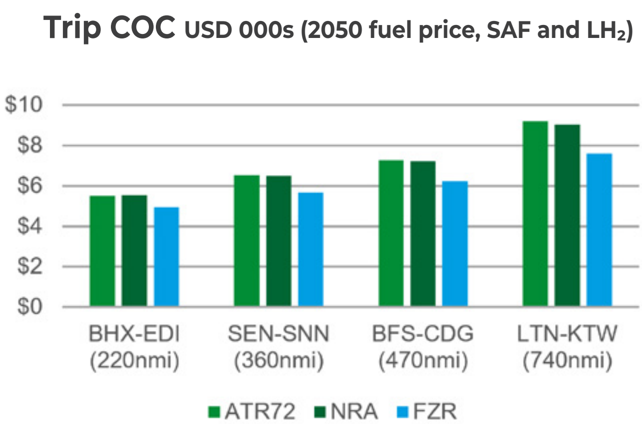
Table 8 – Ownership and Maintenance costs – compared with reference aircraft.
Source © FlyZero analysis.

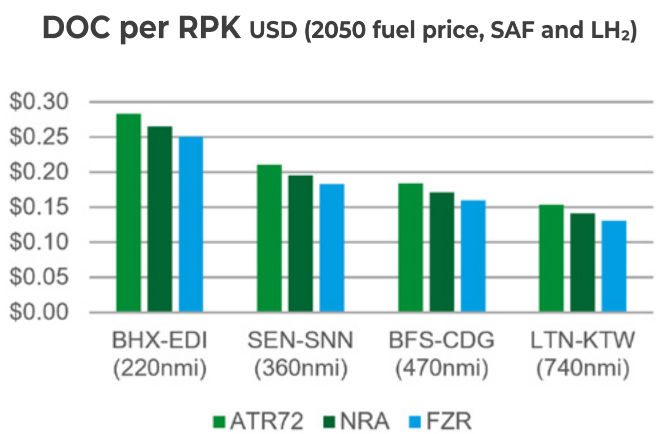
04.2 REGIONAL CONCEPT COMPETITIVENESS

- FZR concept uses **20% less energy per ASK** than a regional jet, but **7% more** than an ATR-72 turboprop, and **1% more energy per ASK** than a new clean-sheet design turboprop aircraft (NRA).
- Hydrogen trip fuel costs are expected to be cheaper than a comparable SAF-burning regional aircraft or an NRA by the mid-2030s.
- FZR has lower Cash Operating Costs per sector: **17% less than an ATR-72** and **16% less than an NRA.**
- DOCs per RPK are also less for the hydrogen aircraft: **15% less than an ATR-72** and **8% less than an NRA.**







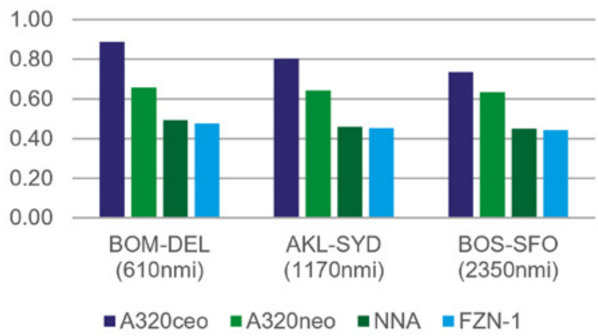


Source © FlyZero analysis.

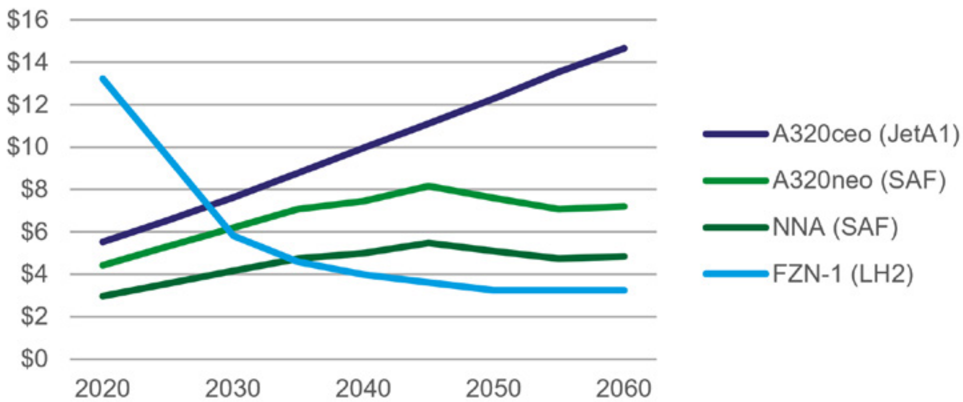
04.3
NARROWBODY CONCEPT COMPETITIVENESS

- FZN concept uses **30% less energy per ASK than an A320neo**, and **2% less energy** than a new clean-sheet design conventional aircraft (NNA).
- Hydrogen trip fuel costs are expected to be cheaper than a SAF-burning A320neo by 2030, and cheaper than an NNA by the mid-2030s.
- FZN has lower Cash Operating Costs per sector: **28% less than an A320neo** and **13% less than an NNA.**
- DOCs per RPK are also less for the FZN: **19% less than an A320neo** and **5% less than an NNA.**

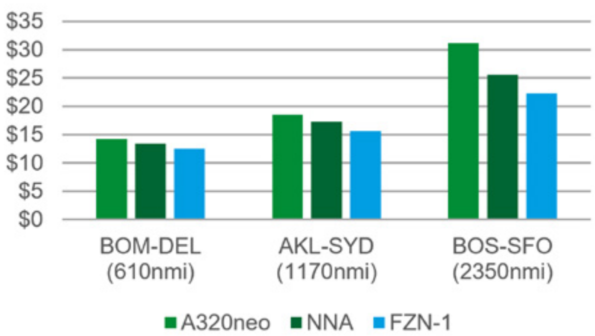
Sector Energy (MJ energy per ASK)



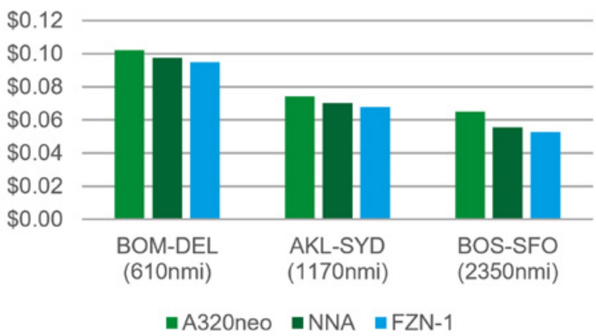
Trip Fuel Cost AKL-SYD, 1,170 nmi sector
USD 000s (2020 prices)



Trip COC USD 000s (2050 fuel price, SAF and LH_2)



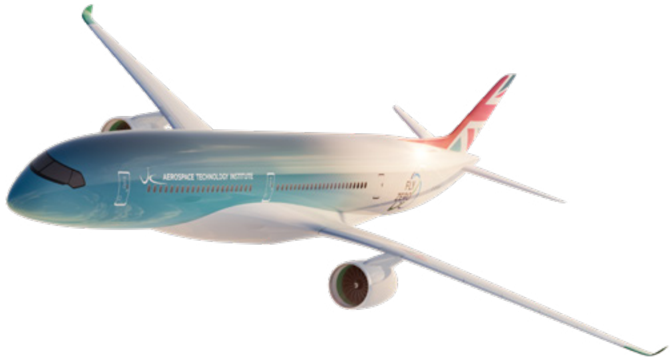
DOC per RPK USD (2050 fuel price, SAF and LH_2)



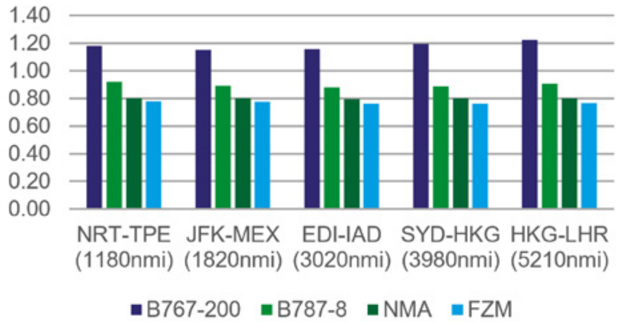
Source © FlyZero analysis.

04.4
MIDSIZE CONCEPT COMPETITIVENESS

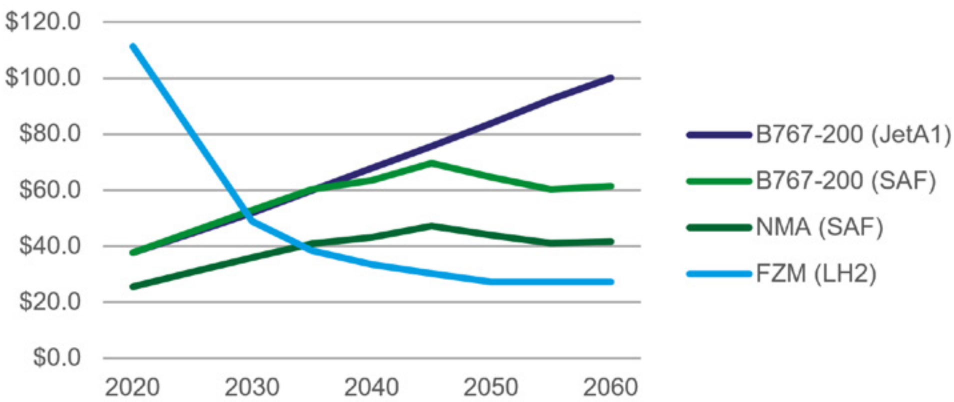
- FZM concept uses **37% less energy per ASK than a B767.** Compared with the larger B787-8, sector energy is 33% less and energy per ASK is still 15% less. The FZM uses **4% less energy** than an equivalent kerosene burning new midsize aircraft (NMA).
- Hydrogen trip fuel costs are expected to be cheaper than a comparable SAF-burning widebody by 2030, and cheaper than a NMA by the mid-2030s.
- FZM has lower Cash Operating Costs per sector: **36% less than an B767-200** and **20% less than an NMA.**
- DOCs per RPK are also less for the FZM: **32% less than a B767-200** and **11% less than an NMA.**



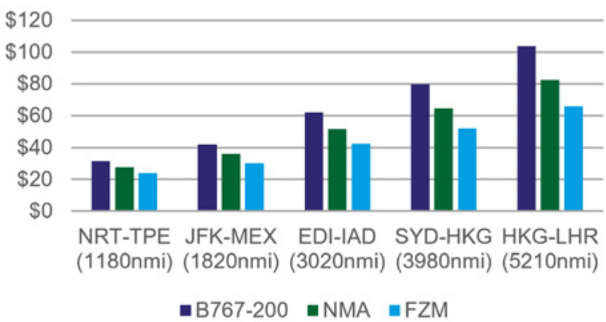
Sector Energy **(MJ energy per ASK)**



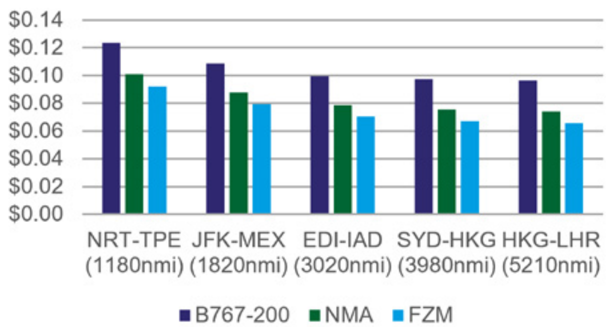
Trip Fuel Cost LHR-HKG, 5,210 nmi sector
USD 000s (2020 prices)



Trip COC **USD 000s (2050 fuel price, SAF and LH_2)**



DOC per RPK **USD (2050 fuel price, SAF and LH_2)**



Source © FlyZero analysis.

04.5 COMPETITIVENESS CONCLUSIONS

Energy Efficiency

The FZN and FZM concepts, with hydrogen combustion turbofan propulsion, are over 30% more energy efficient than existing conventional aircraft. The light weight of the hydrogen fuel contributes to the FZN and FZM concepts also having an energy advantage over newly designed conventional aircraft – the FZN is 2% better than the NNA and the FZM is 5% better than the NMA. The hydrogen advantage is greater for the longer range FZM concept, where the weight benefit of hydrogen on block fuel energy is greater.

The NNA and NMA baseline aircraft are hypothetical clean-sheet designs representing the extent to which conventional kerosene-burning aircraft technology might be improved by the 2030s. They represent an energy efficiency improvement of about 30% over todays' comparable aircraft. This is more than the 15-20% efficiency improvement typically seen between aircraft generations in practice. The baseline aircraft, therefore, represent a challenging target for the hydrogen aircraft concepts to outperform.

The FZR regional aircraft, with hydrogen fuel cell and electric motor / propeller propulsion, uses 7% more energy than an ATR-72 reference aircraft. This extra energy is partly due to the FZR's higher performance – faster cruise speed and longer range. Compared with the NRA baseline turboprop aircraft, with comparable speed and range, the FZR is very slightly less energy efficient (+1%) due to the FZR's fuel cell mass and higher aircraft weight.

Direct Operating Costs

All concepts have a direct operating cost (DOC) advantage over the reference or baseline conventional aircraft. The DOC advantage arises from the lower fuel costs – a combination of greater energy efficiency and the lower cost of hydrogen from the mid-2030s than taxed kerosene or SAF blends. Offsetting the hydrogen fuel cost savings, the FlyZero concepts have higher aircraft ownership and maintenance costs than the baseline aircraft.

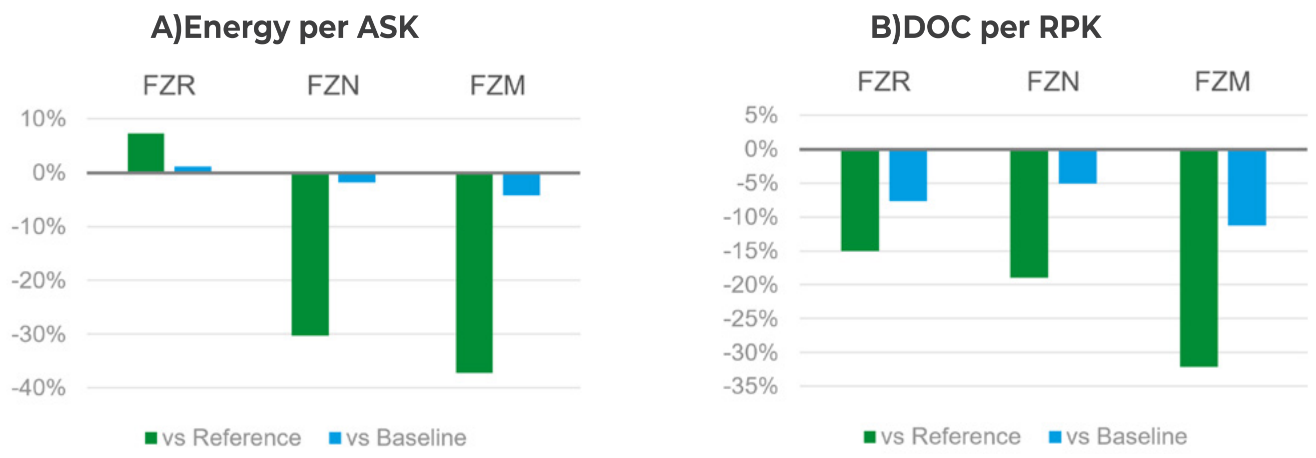


Figure 38 – FZ Concept Energy and Cost Comparison.

Reference aircraft are: ATR-72 (regional), A320neo (narrowbody), B767-200 (midsize); Baseline aircraft are hypothetical clean-sheet new aircraft designs representing 2030s technology: NRA, NNA, NMA; DOC per RPK comparisons are based on 2050 projected fuel costs.

05. MARKET PENETRATION SCENARIOS

The FlyZero concept competitiveness analysis (Section 4) shows that, by the mid-2030s, hydrogen powered aircraft are likely to have significant direct operating cost (DOC) advantages over conventional aircraft fuelled by taxed kerosene or SAF blends.

These DOC advantages will make hydrogen ZE aircraft the preferred option for airlines on both economic and environmental grounds. These economic and environmental drivers are expected to encourage the timely investment in the airport and fuel supply infrastructure necessary to support a transition towards liquid hydrogen powered ZE aircraft.

We modelled potential ZE aircraft market penetration based on the **Midsize First** and **Regional First** strategies described in **section 3.1**.

For each strategy, we assess a **high ambition** case representing coordinated efforts and investment to accelerate the development of zero carbon emissions aviation, and an **unaccelerated** case. This results in the four market penetration scenarios described in the table below. The numbers of aircraft in service and the projected share of global fuel demand for each scenario are shown in the **Figure 39** below.

	Scenario 1 *Midsize First - High Ambition (Accelerated)*	*Scenario 2* *Regional First - High Ambition (Accelerated)*	*Scenario 3* *Midsize First - Unaccelerated*	*Scenario 4* *Regional First - Unaccelerated*
Subregional	***2027 Entry in Service*** *9-19 seat eCTOL*	***2027 Entry in Service*** *9-19 seat eCTOL*	***2027 Entry in Service*** *9-19 seat eCTOL*	***2027 Entry in Service*** *9-19 seat eCTOL*
Regional (FZR)	***2042 Entry in Service*** *Conventional NTP EIS in ~2027* *ZE version 15 years later*	***2033 Entry in Service*** *Accelerated FZR market entry* *Proves tech for early FZN launch*	***2042 Entry in Service*** *As Scenario 1* *Conventional NTP EIS in ~2027* *ZE version 15 years later*	***2035 Entry in Service*** *Unaccelerated FZR market entry* *Limited turboprop-style performance only captures 25% of the regional market*
Narrowbody (FZN)	***2037 Entry in Service*** *EIS accelerated by FZM tech proving* *No conventional NNA launched*	***2037 Entry in Service*** *EIS accelerated by FZR tech proving* *No conventional NNA launched*	***2042-2047 Entry in Service*** *OEM #1 launches FZN in 2042 (+7 years after FZM)* *OEM #2 launches a conventional NNA ~2032, with ZE version 15 years later*	***2047-2049 Entry in Service*** *Both OEMs launch conventional NNAs in early 2030s* *FZNs launched 15 years later*
Midsize (FZM)	***2033 Entry in Service*** *Accelerated FZM market entry* *Proves tech for early FZN launch*	***2044 Entry in Service*** *Follows FZN after 7 years*	***2035 Entry in Service*** *Unaccelerated FZM market entry* *Proves tech for FZN launch*	***2055-2057 Entry in Service*** *Follows FZN after 8 years*
Widebody	***2038 Entry in Service*** *FZM stretch after 5 years; gradual ZE penetration into addressable market*	***2049 Entry in Service*** *FZM stretch after 5 years; gradual ZE penetration into addressable market*	***2050 Entry in Service*** *Slower widebody market transition than Scenario 1*	***2060 Entry in Service*** *FZM stretch after 5 years; gradual ZE penetration into addressable market*

Table 9 – Market Penetration Scenarios.

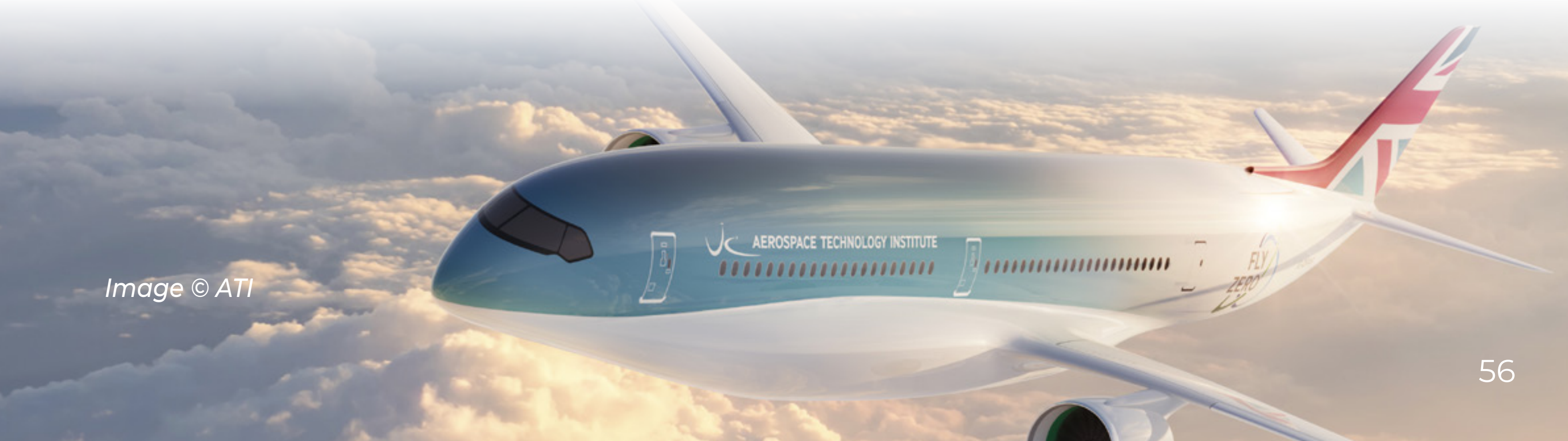
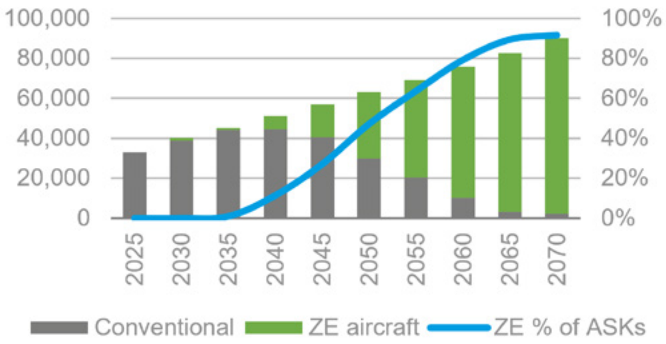


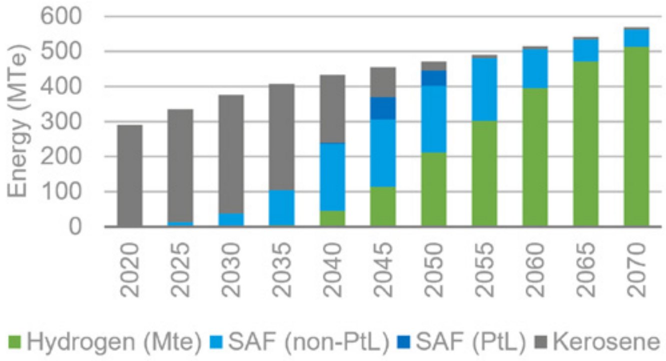
Image © ATI

Scenario 1: Midsize First – High Ambition (Accelerated)

a) Number of Aircraft in Service

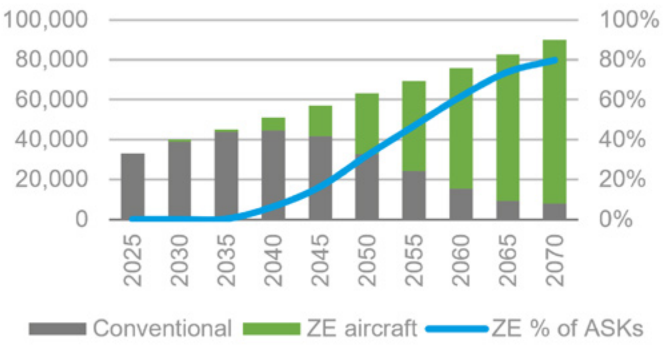


b) Global Energy Used by Fuel Type

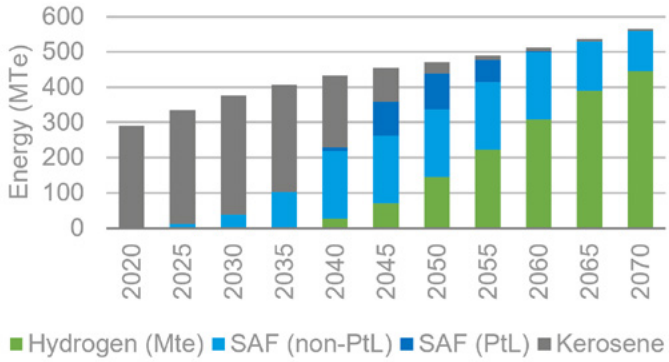


Scenario 2: Regional First – High Ambition (Accelerated)

a) Number of Aircraft in Service

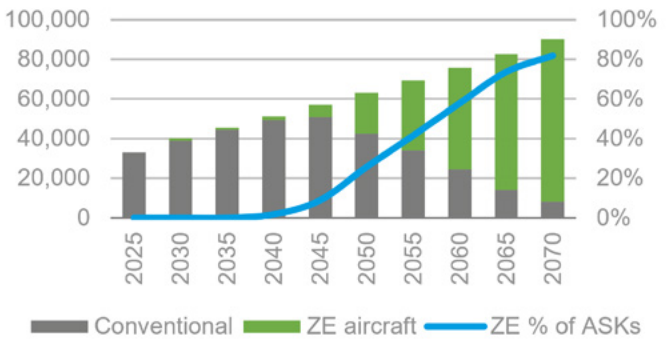


b) Global Energy Used by Fuel Type

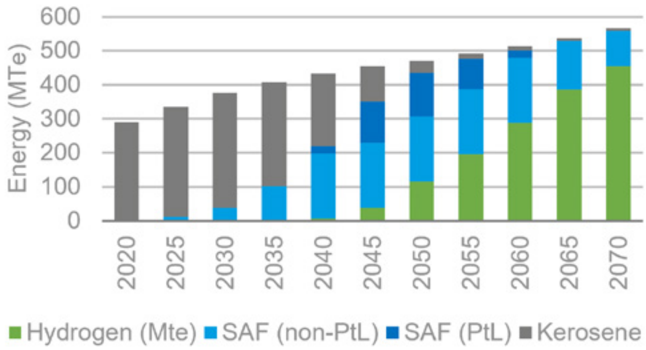


Scenario 3: Midsize First – Unaccelerated

a) Number of Aircraft in Service

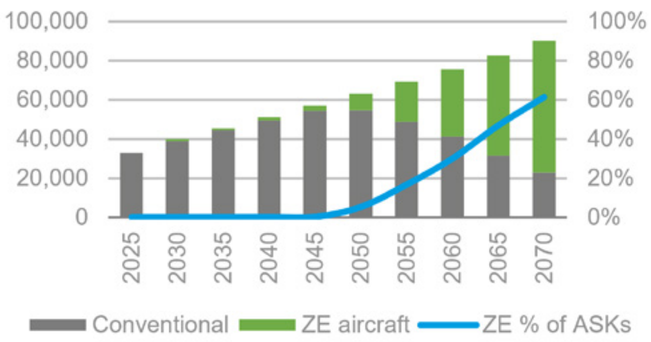


b) Global Energy Used by Fuel Type



Scenario 4: Regional First – Unaccelerated

a) Number of Aircraft in Service



b) Global Energy Used by Fuel Type

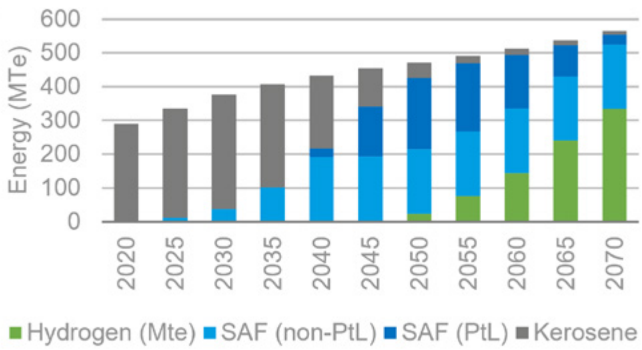


Figure 39 – Market Penetration Scenarios. Source © FlyZero analysis.

05.1 SCENARIO COMPARISONS

Midsize First Strategy

Midsize First – High Ambition (Accelerated) (scenario 1) achieves the most rapid transition towards zero carbon emissions aircraft in service and abatement of aviation's atmospheric CO_2 emissions – with ZE aircraft making up 50% of the global fleet and abating 45% of atmospheric CO_2 emissions by 2050.

The Midsize First strategy minimises the early-years infrastructure challenges, as a relatively small number of larger hub airports require hydrogen refuelling capability to provide a "minimum viable" airline network for intercontinental flights.

The FlyZero commercial analysis indicates that a ZE midsize aircraft will enjoy a significant operating cost advantage by the early 2030s. This cost advantage underpins the projected rate of ZE aircraft uptake by airlines.

Another advantage of the Midsize First strategy is that the FZM aircraft has similar hydrogen combustion turbofan technology to the FZN narrowbody concept, so the midsize aircraft more effectively de-risks a ZE narrowbody aircraft development.

Projected ZE aircraft deliveries and values up to 2050 are:

- Regional – 2,340 aircraft ($45-55 billion)
- Narrowbody – 21,800 aircraft ($1200-1400 billion)
- Midsize – 5,040 aircraft ($600-700 billion)
- Total – 29,200 ($1900-2100 billion)

Midsize First – Unaccelerated (scenario 3), with later entry in service (EIS) dates for the ZE midsize and narrowbody aircraft achieves a somewhat slower transition – ZE aircraft make up 28% of the global fleet and abate 24% of atmospheric CO_2 emissions by 2050.

Projected ZE aircraft deliveries and values up to 2050 are:

- Regional – 2,350 aircraft ($45-55 billion)
- Narrowbody – 11,100 aircraft ($600-700 billion)
- Midsize – 3,200 aircraft ($400-500 billion)
- Total – 16,600 ($1050-1250 billion)

Regional First Strategy

Regional First – High Ambition (Accelerated) (scenario 2) achieves the second most rapid transition towards zero carbon emissions aircraft in service and abatement of aviation's atmospheric CO_2 emissions – with ZE aircraft making up 45% of the global fleet and abating 31% of atmospheric CO_2 emissions by 2050.

The Regional First scenarios are more complex in terms of early-years infrastructure challenges, as many small regional airports will require hydrogen refuelling capability in order to provide airlines with a "minimum viable" route network.

Another disadvantage of the Regional First strategy is that the FZR regional aircraft, based on fuel cell technology, does not de-risk the development of hydrogen combustion turbofan aircraft technology, which is necessary for the development ZE narrowbody and midsize aircraft. Regional aircraft only represent 4% of atmospheric CO_2 emissions in 2050, so decarbonising the narrowbody and longer-haul markets is necessary to achieve true zero carbon emission aviation.

The FlyZero commercial analysis (**section 4**) indicates that the FZR fuel cell aircraft has more marginal operating cost benefits compared with conventional kerosene/SAF competitors than the FZN narrowbody and FZM midsize designs. A relatively heavy fuel cell aircraft is not more energy efficient than comparable conventional aircraft, so it is reliant on hydrogen fuel costs dropping below kerosene/SAF prices (on a per unit energy basis) to have a competitive advantage. This relative cost competitiveness means that government support and incentives may be required to encourage airlines to switch to ZE regional aircraft in the early years, perhaps through government subsidies provided on "public service obligation" routes.

Projected ZE aircraft deliveries and values to 2050 are:

- Regional – 4,500 aircraft ($90-110 billion)
- Narrowbody – 20,700 aircraft ($1050-1250 billion)
- Midsize – 1,080 aircraft ($130-150 billion)
- Total – 26,300 ($1400-1600 billion)

Regional First – Unaccelerated (scenario 4), with later entry in service (EIS) achieves the slowest ZE transition – ZE aircraft make up just 8% of the global fleet and abate 5% of atmospheric CO_2 emissions by 2050.

Projected ZE aircraft deliveries and values to 2050 are:

- Regional – 870 aircraft ($18-22 billion)
- Narrowbody – 3,700 aircraft ($210-230 billion)
- Midsize –0 aircraft ($0 billion)
- Total – 4,570 ($230-250 billion)

Comparisons between the different scenarios are provided in Figure 40 below.

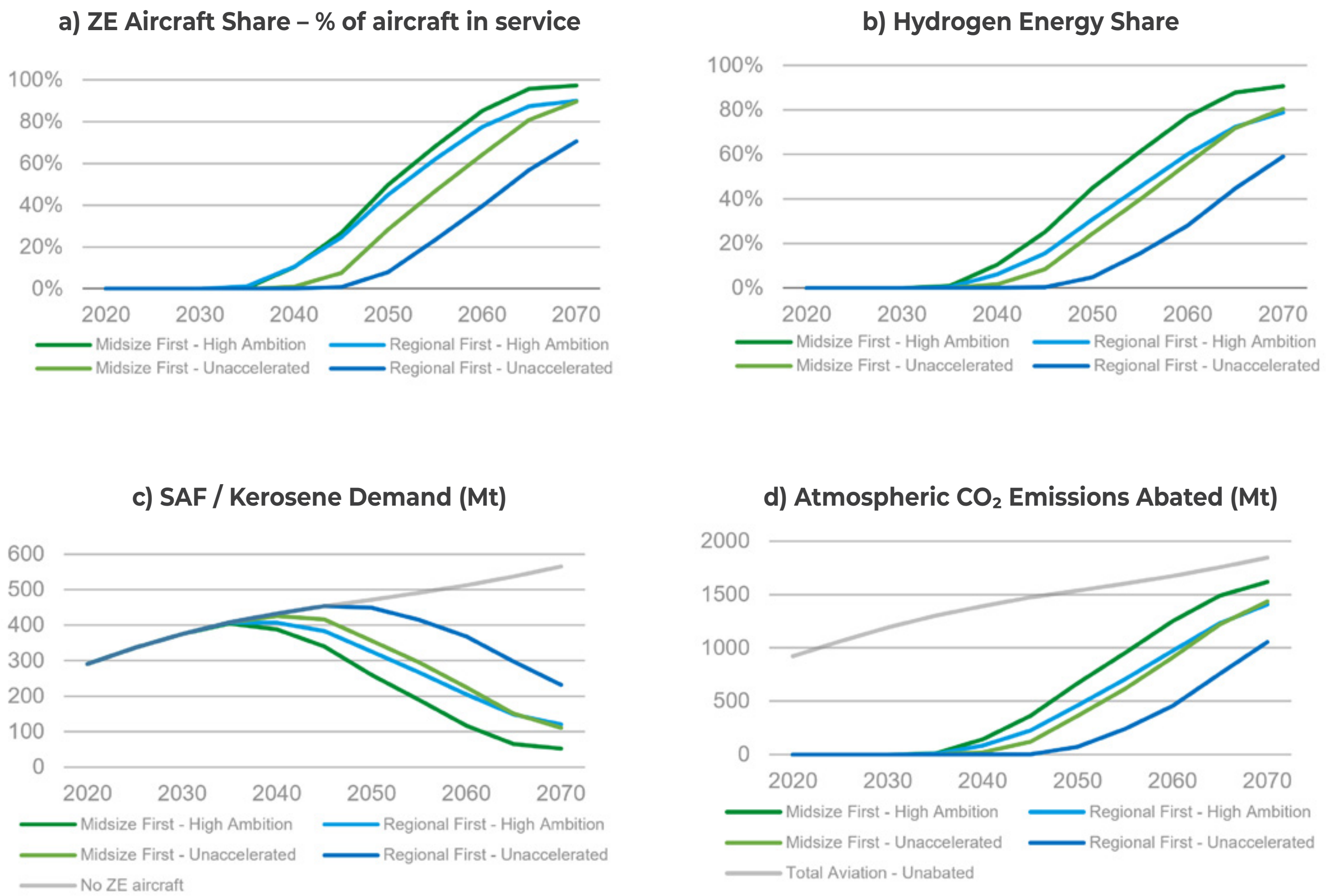


Figure 40 – Scenario Comparisons.
Source © FlyZero analysis.

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06.1 LIST OF ABBREVIATIONS

ACI	*Airports Council International*
ASK	*Available Seat Kilometres*
ATI	*Aerospace Technology Institute*
CAA	*Uk Civil Aviation Authority*
CO_2	*Carbon Dioxide*
DfT	*Uk Department for Trtansport*
eCTOL	*Electric Conventional Takeoff and Landing*
EIS	*Entry in Service*
ESAD	*Equivalent Still Air Distance*
eSTOL	*Electric Short Takeoff and Landing*
ETOPS	*Extended range Twin-engine Operational Performance Standards*
eVTOL	*Electric Vertical Takeoff and Landing*
FL	*Flight level (100 foot increments), eg, FL250 = 25,000 ft*
FZ	*FlyZero*
FZM	*FlyZero Midsize concept*
FZN	*FlyZero Narrowbody concept*
FZR	*FlyZero Regional concept*
GDP	*Gross Domestic Product*
HSR	*High Speed Rail*
IATA	*International Air Transport Association*
ICAO	*International Civil Aviation Organization*
IMF	*International Monetary Fund*
ISA	*International Standard Atmosphere*
LH_2	*Liquid Hydrogen*
MJ	*Mega Joule*
MLW	*Maximum Landing Weight*
Mt	*Mega Tonne*
Mte	*Mega Tonne equivalent, Conveting LH2 into equivalent energy content mass of kerosene*
MTOW	*Maximum Takeoff Weight*
NMA	*New Midsize Aircraft - 2030 baseline conventional midsize aircraft*
nmi	*Nautical miles*
NNA	*New Narrowbody Aircraft - 2030 baseline conventional narrowbody aircraft*
NRA	*New Regional Aircraft - 2030 baseline conventional regional aircraft*
NTP	*New Turboprop, a hypothetical new conventional turboprop development*
OE	*Oxford Economics*
OEM	*Original Equipment Manufacturer*
pa	*Per Annum*
RPK	*Revenue Passenger Kilometre*
SAF	*Sustainable Aviation Fuel*
SL	*Sea Level*
UN	*United Nation*
UAM	*Urban Air Mobility*
VFR	*Visiting Friends and Relatives*
ZE	*Zero carbon emissions aircraft*

06.2
TABLE OF FIGURES

MARKET FORECASTS & STRATEGY

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE