REPORT

The potential impact of hybrid propulsion on aviation

By Oscar Watkins, Associate – Aviation, Travel and Tourism, ICF

1. Executive summary

The establishment of net-zero targets within aviation, aiming to bring the sector to net zero by 2050, has led to the publication of various pathways that trade bodies and organisations anticipate being the route to achieve these targets. One segment of these roadmaps is novel propulsion technology, which includes battery electric, hydrogen, and hybrid propulsion. The contribution of these technologies towards achieving net zero lacks consensus and their contributions are often consolidated and combined with other anticipated efficiency technologies to be introduced to aviation.

This is especially the case for hybrid electric aviation; no mainstream net-zero pathway publication has yet investigated its impact in isolation. Given the potential emissions that can be mitigated by hybrid aviation, ICF, with input from Heart Aerospace—a hybrid aircraft Original Equipment Manufacturer (OEM) looking to bring a 30-seater hybrid aircraft to market in 2029—analysed and calculated an independent assessment of the potential market size and emission reduction impact of hybrid electric aircraft.

Using information provided by Heart Aerospace on range and capacity capabilities, ICF applied this to a forecast based on the historical growth data of flights and routes, the aircraft currently serving them, and the current ratio of aircraft to routes. ICF also estimated the potential size of the hybrid aircraft market for existing operations. This was combined with an estimate on the number of new routes that could be opened up by the increased operating economics of hybrid aircraft using NASA research. The combination of these analyses led to an **estimate of demand for over 18,200 hybrid aircraft by 2050.**

The impact on emissions was also estimated through the same filtering of routes and frequencies and applying the calculated emissions emitted by current aircraft to give a total emissions forecast estimate, which was combined with the estimated emissions contributed by the addition of hybrid aircraft to the market. The calculated emission reduction potential of hybrid aircraft was then applied to this to determine the potential feasible impact on emissions by hybrid aircraft.

With limited OEMs present in the hybrid space—with leading aircraft OEMs having refocused their efforts on hydrogen and battery electric—and demand exceeding supply in 100% and 50% market share scenarios, the market for hybrid aircraft is unlikely to be satisfied by Heart and a small number of additional OEMs in the years following the introduction of hybrid aircraft and resemble a concentrated market.

As such, this report shows that there is a market for hybrid aviation, and the impact could contribute a material reduction in global aviation emissions. To date, the focus of governments, policymakers, and private capital has been on Sustainable Aviation Fuel (SAF). Whilst this must continue, ICF believes that the route to net zero in aviation is not centred around a single decarbonisation activity, but rather, the combination of multiple decarbonisation activities operating together and in unison. In light of these findings, it is ICF's view that hybrid aviation warrants levels of attention and investment observed in, and in conjunction with, other decarbonisation activities to meaningfully contribute to the aviation sector's efforts in achieving net zero.

ICF calculated that hybrid aviation had the potential to mitigate up to **9%** of global emissions with an unconstrained supply of hybrid aircraft. The application of Heart's production estimates and several market share scenarios suggested that hybrid aircraft could reduce global aviation emissions by **5%**.

2. International sustainability goals

The global push towards reducing greenhouse gas emissions has led to targets on local to global levels. The majority of these commitments were established to reduce carbon emissions to net zero by the year 2050. On an international scale, these Net Zero Targets, as they are known, have been introduced by various organisations across the world concerned with sustainability and the environment as a means of setting goals to meet the required levels of decarbonisation.

As one of the seven hard-to-abate sectors, accounting for 2.5% of global energy related CO_2 emissions in 2023, aviation is no exception. Airlines, airports, governments, and trade groups have all been proactive at implementing net-zero targets to aviation as reducing emissions is a key step towards a sustainable, non-demand regulated future. Some notable international organisations and targets include:

Organisation	Name	Target
United Nations Framework Convention on Climate Change (UNFCCC)	Paris agreement	To limit global average temperatures to well below 2°C above preindustrial levels
European Union (EU)	Destination 2025	To reduce CO_2 emissions of EU flights by 45% in 2030 and achieve net zero by 2050
International Civil Aviation Organization (ICAO)	Long-Term Aspirational Goal (LTAG)	International aviation to achieve net zero carbon emission by 2050
International Air Transport Association (IATA)	Fly Net Zero	Commitment by airlines to achieve net-zero carbon emissions from the operations by 2050
Air Transport Action Group (ATAG)	Waypoint 2050	Long term strategy to achieve net-zero by 2050
International Council on Clean Transport (ICCT)	Vision 2050	Analysis of the technologies and policies needed to achieve net-zero by 2050

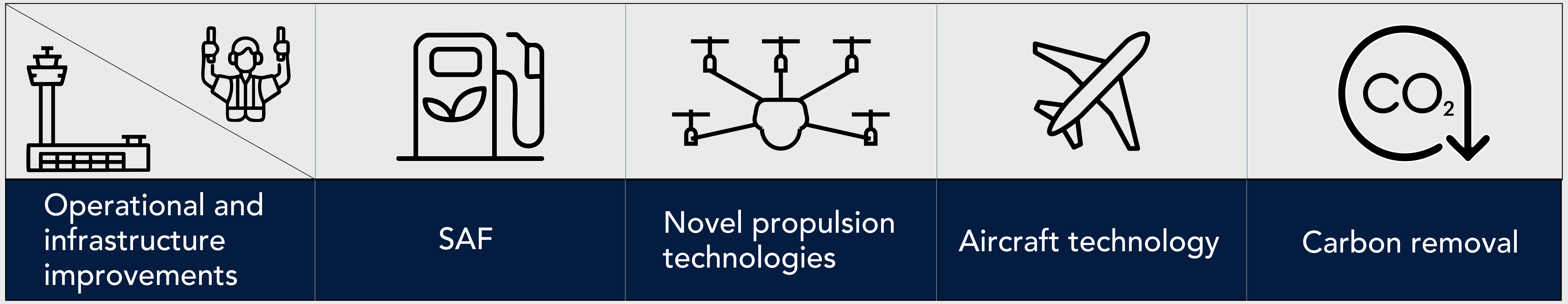
2.1 Net-zero pathways

To achieve these decarbonisation targets, organisations have published net-zero roadmaps that model the plans and strategies required to reduce carbon emissions. They produce detailed methodologies and targets for the aviation industry through policy changes, technological advancements, and behavioural changes that create a roadmap for the sector to accomplish its decarbonisation objectives.

Through the examination of multiple pathways, aviation roadmaps commonly explore several decarbonising activities with significant contributions to reducing carbon emissions.

It is the view of ICF that no single activity can function in isolation and that the different decarbonising activities are all interconnected and interdependent to allow for the sector to collectively achieve net zero. For example, the use of novel propulsion on routes within the range of zero or reduced emission emitting aircraft allows for the use of SAF on routes beyond the range capabilities of these aircraft. As such, all activities need to be considered in conjunction with each other and to decide to only focus efforts and investment in only one activity would result in the overall failure of efforts to achieve industrywide net zero.

Figure 1: The five main decarbonising activities within aviation

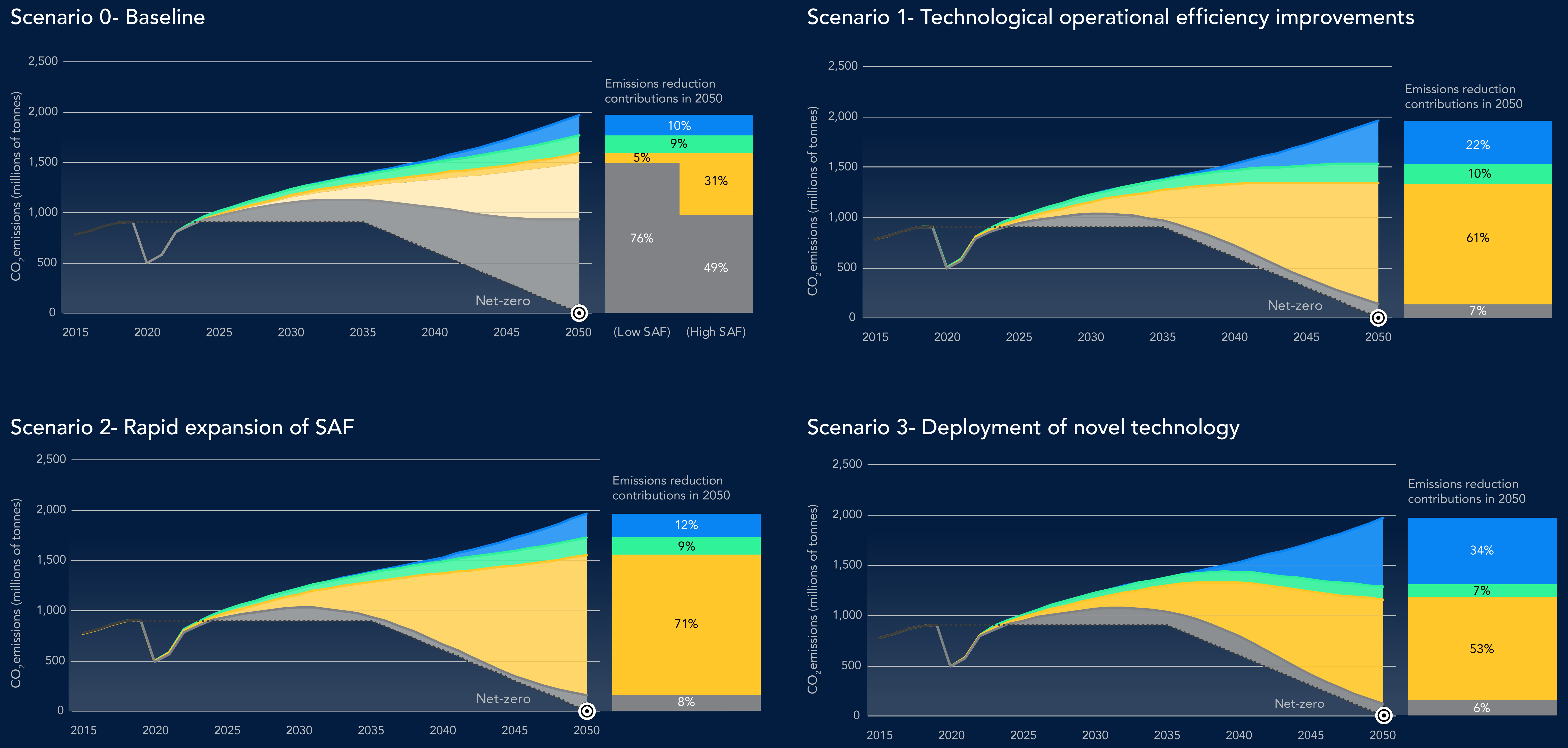


Source: ICF analysis

Within aviation, there are several industry recognised organisations with published net-zero pathways that are widely accepted. One example that illustrates a net zero pathway is the 2nd edition of Air Transport Action Group's (ATAG) Waypoint 2050 report, published in September 2021[1]. The report collaborates with experts across the aviation value chain to present several pathways to reduce CO_2 emissions to net zero by 2050. The report explores the effects of traffic forecasts, technological advancements, operational and infrastructure improvements, SAF, and carbon offsetting towards decarbonisation.

The report plots a baseline and explores three scenarios where one of or a selection of variables is prioritised as ATAG argue that there are constraints and trade-offs where not all the variables can be maximised to their fullest potential.

Figure 2: ATAG net zero pathway scenarios



- T Technology
- O Operations and infrastructure (Including efficiency improvements from load factor)
- F Sustainable aviation fuel
- M Market-based measure

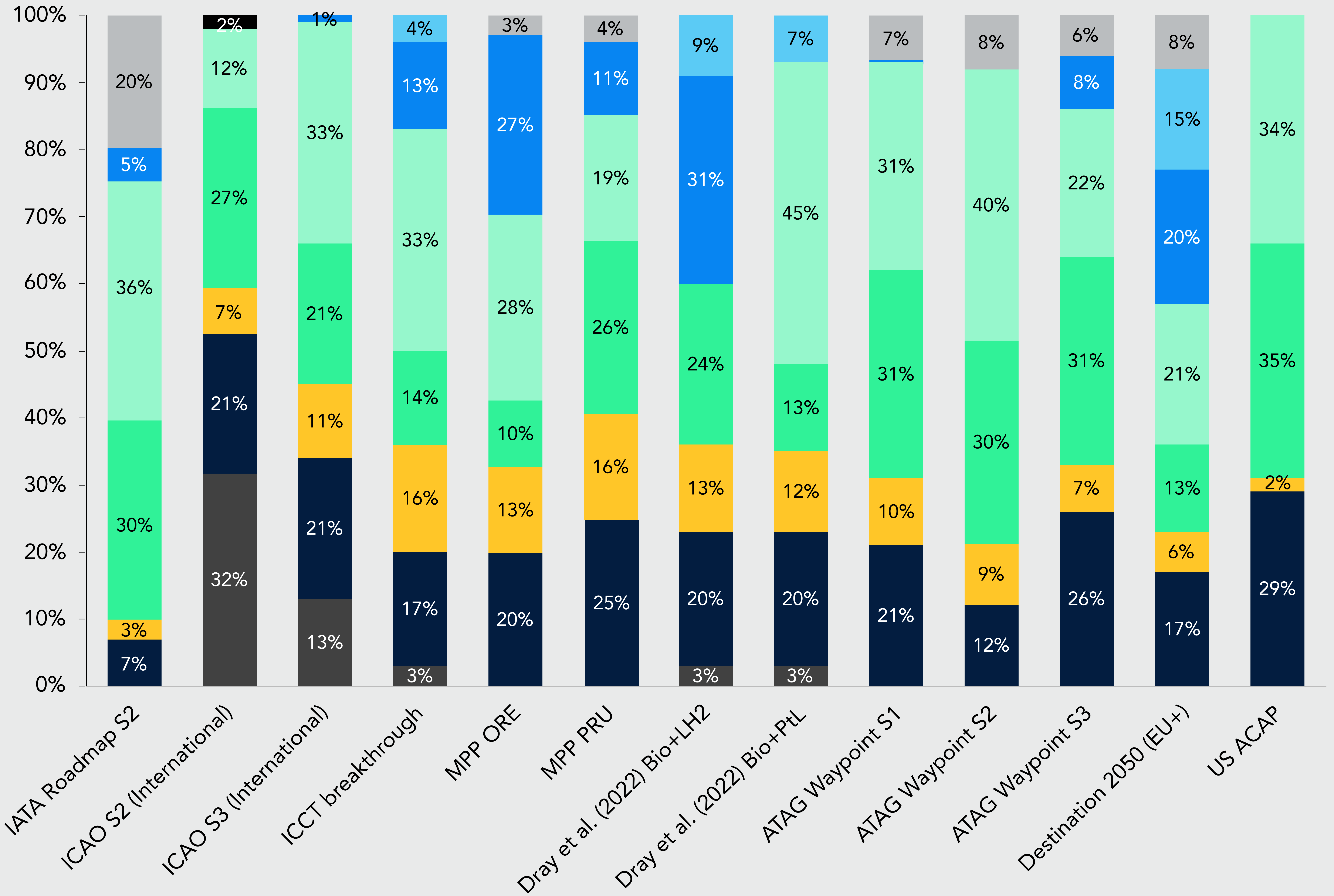
Source: ATAG Waypoint 2050 2nd Edition

[1] An updated report is expected to be released and so the included information was the latest available and accurate information at the time of publication

The IATA Aviation Net-Zero CO_2 Transition Pathways Comparative Review is another source that consolidates the leading net-zero pathways from a range of organisations. The report allows for easy comparison of the different approaches and emphases.

As the figure shows, the estimated emission reduction by novel propulsion ranges from **1%-31%**[2] by **2050**. With such a spread of anticipated emission reduction that novel propulsion can contribute, as well as no scenario that deals with the impact of hybrid aviation in isolation, there is value in estimating the impact on carbon emissions that can be directly attributed to hybrid aviation.

Figure 3: Emission reduction potential by decarbonisation activity



Source: IATA Aviation Net-Zero CO_2 Transition Pathways Comparative Review

[2] The impact of novel propulsion technologies is sometimes combined with technological advancements and so where it is not directly referenced may not mean that there is no emission reduction attributed to novel propulsion in net zero pathways.

3. Novel propulsion technologies

Novel propulsion technologies, of which hybrid aviation is a part, are aircraft that produce little to zero emission from aircraft operations. These types of aircraft are currently in the development phase with players across the world in the process of certifying clean sheet aircraft that they plan to bring to market at the end of this decade into the early 2030s.

The development and widespread deployment of alternative propulsion systems for aircraft offers emission reduction in two areas: 1. when used in place of existing conventionally powered aircraft, and 2. an alternative zero/reduced emission travel option on new routes that previously weren't financially viable.

While battery electric and hydrogen propulsion are the most well-known forms of novel propulsion and have received the most investment (with battery electric aviation, especially in the eVTOL sector, being the furthest along the development timeline), hybrid propulsion is a growing technology within the fixed wing regional aircraft sector. Having lagged comparatively in terms of recognition and interest in analysis, investment, and global players, the use of hybrid in aviation is beginning to receive greater interest and shows promise as a viable alternative novel propulsion technology.

Another consideration of novel propulsion technologies and a growing area of research is the impact on non-CO_2 emissions, including contrails, the warming impact of which is still being investigated. However, regardless of their ultimate impact, novel propulsion technologies can mitigate these impacts offering greater environmental benefit beyond CO_2 emissions.

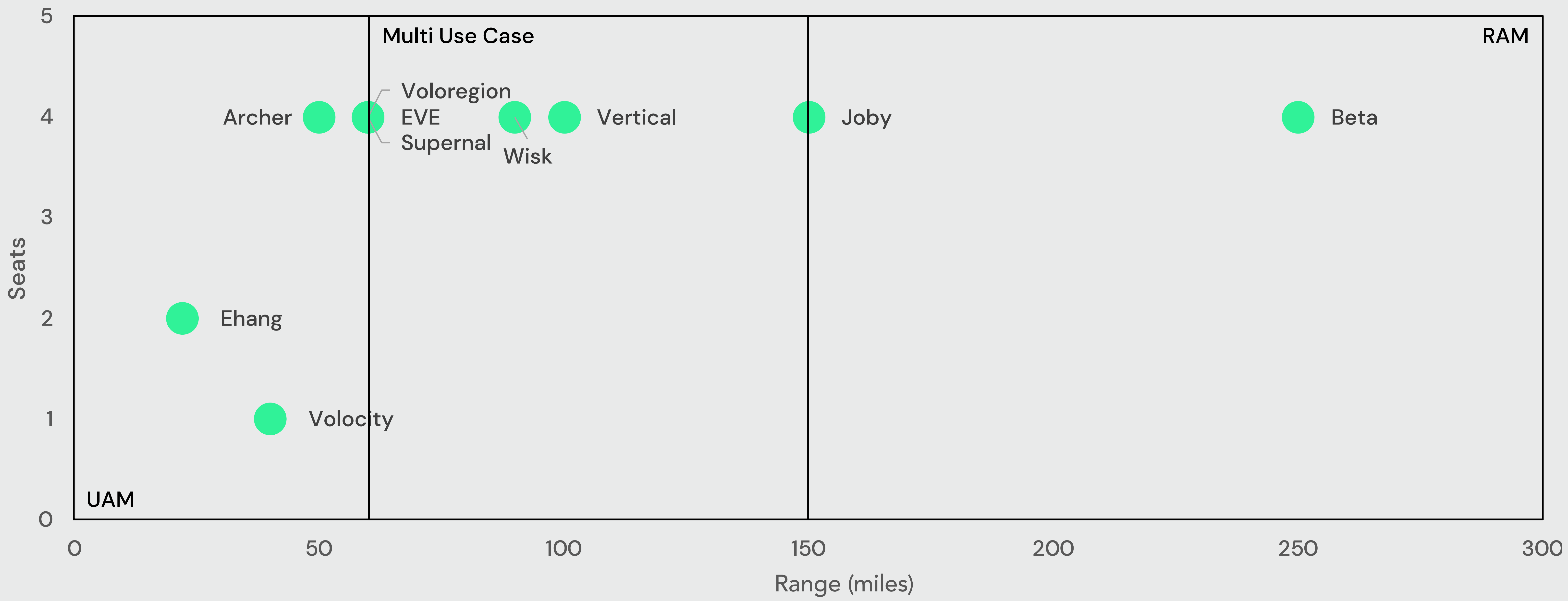
3.1 Battery electric aircraft

Battery electric aviation refers to the use of batteries to power electric propulsion systems on aircraft, eliminating the need for traditional fossil fuels. Though this technology can be implemented on fixed wing aircraft, it is more commonly seen in the application of battery electric propulsion on eVTOLs (electric vertical take-off and landing) aircraft.

These aircraft, and battery electric aviation in general, are limited in range and capacity capabilities due to the current technological limitations of batteries. The predominant proposed use cases for these aircraft are Urban Air Mobility (UAM), short and frequent missions moving people around and in and out of population centres, and Regional Air Mobility (RAM), longer missions between population centres.

While battery technology is steadily improving, it is unlikely that aircraft larger than six seats performing missions longer than ~250 miles we be commonplace for the foreseeable future. However, as battery technology does develop, the range capabilities of battery electric aircraft may grow to exceed these limits.

Figure 4: Range and passenger capabilities of leading eVTOLs



Source: ICF analysis

3.2 Hydrogen powered aircraft

Hydrogen is a carbon-free fuel that can provide propulsion in two ways:

1. **Hydrogen combustion**
   Hydrogen is used as a replacement for jet fuel in internal combustion jet engines. Hydrogen has different combustion characteristics than conventional jet fuel when burnt in air, leaving water vapour and NOx as by products, but eliminates CO_2 emissions.

2. **Fuel cells**
   Liquid or gaseous hydrogen is combined with oxygen in air to generate electricity in hydrogen fuel cells and this electricity powers electric motors.

Hydrogen aircraft depending upon system and size, impact the climate **70%-90%** less than traditional aircraft, however, being a gas at atmospheric temperature and pressure, hydrogen weighs 3x less than jet fuel but occupies much more volume, 4x more even in liquid form[3]. As a result, to utilise hydrogen as a power source requires fundamental alternations to both aircraft and ground infrastructure. Therefore, although the introduction of the first commercial hydrogen powered aircraft is publicised to be late 2020s to early/mid 2030s, the required infrastructure to support hydrogen suggests that it would be difficult to scale at pace.

Furthermore, the dominant current methods of hydrogen production are energy intensive and therefore carbon intensive given levels of grid power that is fossil fuel based. Until an abundance of green power is available for hydrogen production, hydrogen powered aircraft are potentially likely to remain more carbon intensive than conventionally powered aircraft on a fuel lifecycle basis.

3.3 Hybrid electric aircraft

Hybrid propulsion combines conventional propulsion methods with electric propulsion systems, which optimises overall energy efficiency and reduces fuel consumption. This allows for larger aircraft to utilise electric propulsion while overcoming the issues of limited range and capacity of fully electric aircraft. Similarly with battery electric, as battery technology does develop, the range capabilities of hybrid electric aircraft will grow. This system also increases redundancy through the presence of dual power sources as well as overcomes issues related to mandatory fuel reserves present with other novel propulsion technologies through having the ability to carry reserve fuel.

ICF estimate that Hybrid aircraft will be able to produce on average between **60%-80%** less CO_2 and as well as offering improved capabilities versus fully electric, means that their use case is more similarly aligned to that of conventional short haul, regional aviation. Coupled with lower emissions compared to conventional aircraft makes hybrid propulsion an attractive proposition for aircraft operators. Furthermore, though hybrid aircraft are comparatively further behind electric aviation on their development curve, they're expected to enter service in the late 2020s.

3.3.1 Hybrid electric propulsion engine architecture

In a hybrid configuration, an aircraft can use multiple energy sources in flight, either in tandem or alternately. Hybrid propulsion covers multiple means of combining electric power sources with conventional thermal engines, the most prominent are serial, parallel and independent (also referred to as partial).

[3] For the same energy output

3.3.2 Serial

In a serial hybrid system, the propeller is typically driven by the electric motor. The electrical power to drive the motor is provided by the battery which is recharged by an electric generator connected to the conventional thermal engine. The battery pack is typically drained during peak demand periods and is recharged by the generator when the vehicle is operating at constant speeds. The generator may also be capable of powering the electric motor in some instances.

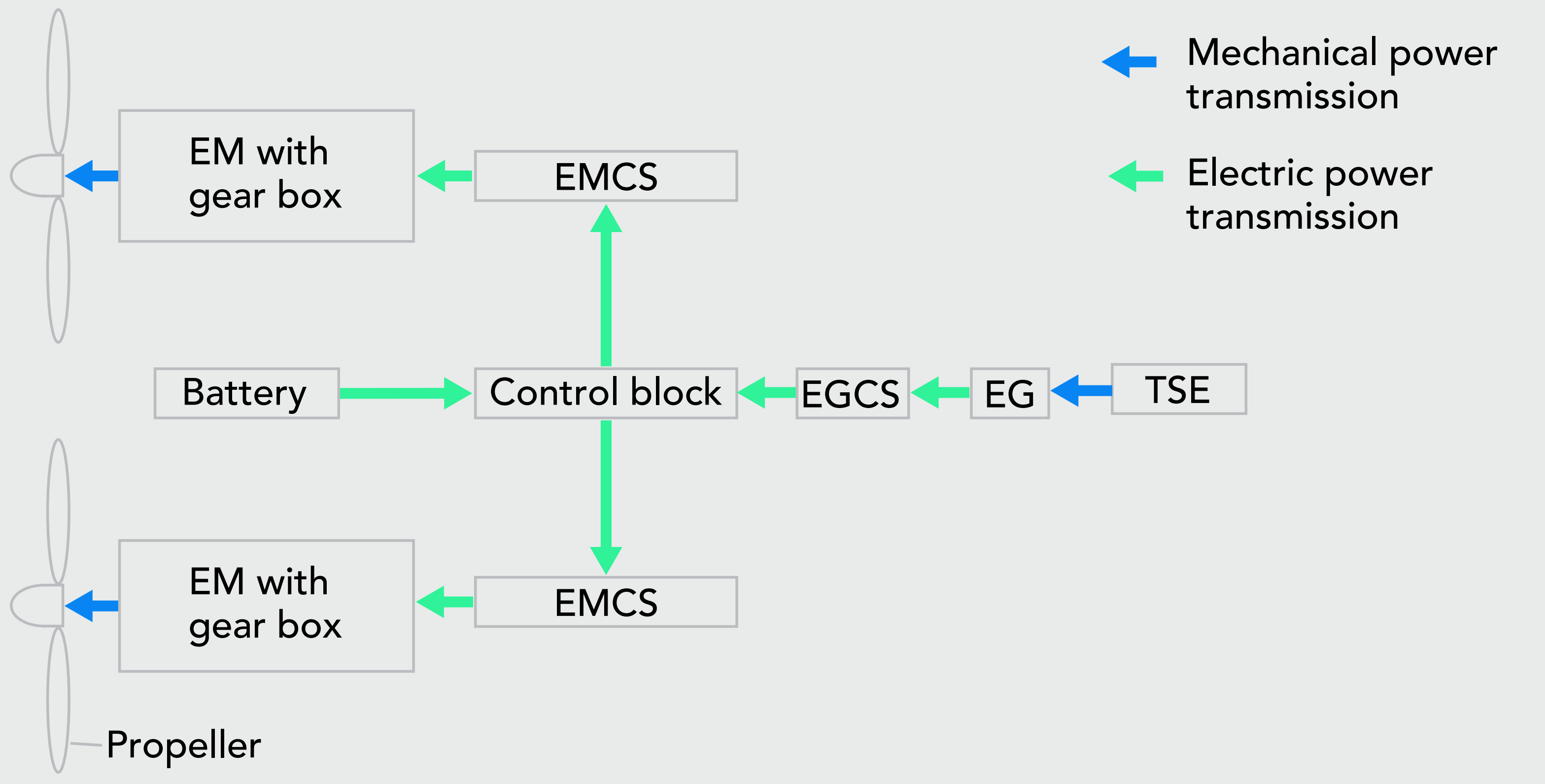
3.3.3 Parallel

In parallel systems, the propeller can be powered by both an electric motor, powered by batteries, and by the conventional thermal engine. Propulsion can be driven by both power sources independently, or together. Electrical energy produced during the flight can also be stored in batteries allowing for extended range.

3.3.4 Independent hybrid

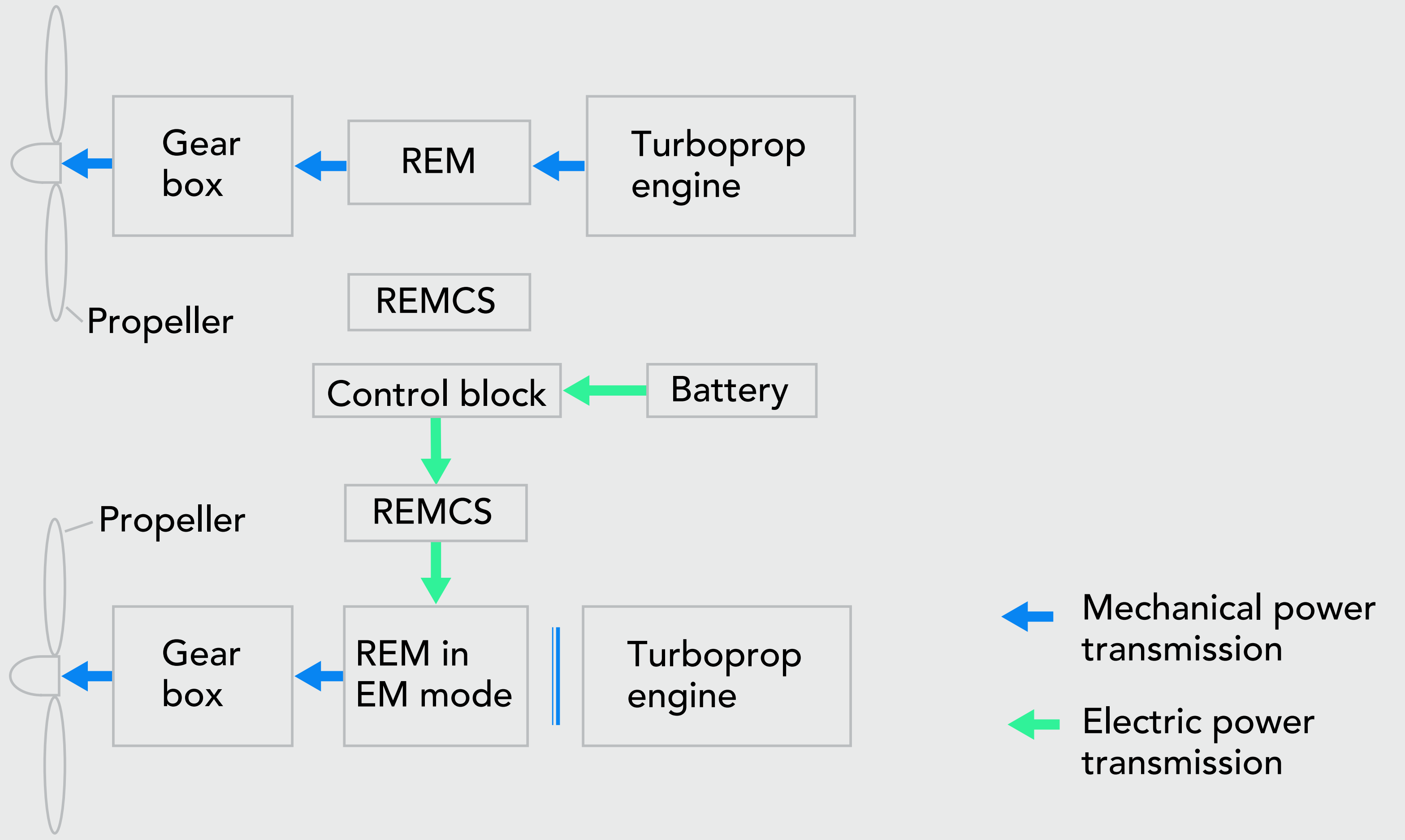
In an independent hybrid system, one or more propulsors are driven directly by a conventional thermal engine while additional propulsors are exclusively driven by electrical motors, which can be powered by a battery or a turbine-driven generator which is independent of the conventional thermal engine. In an independent system, the electrical and conventional thermal engine system can be run simultaneously or with one of the powertrains shut down. This means a partial hybrid aircraft can fly conventionally under hybrid power or fully electric.

Figure 5: Serial hybrid system



TSE- Turboshaft engine EG- Electric generator EGCS- Electric generator control system
EM- Electric motor EMCS- Electric motor control system

Figure 6: Parallel hybrid system



REM- Reversible electric machine REMCS- Reversible electric machine control system
EM- Electric motor

Source: CIAM

3.4 Challenges of key emission reduction methods

All methods used to reduce emissions including SAF, H_2 or battery electric propulsion systems carry limitations and drawbacks such as current costs, lack of scalability, and shortfall in present technology.

3.4.1 SAF

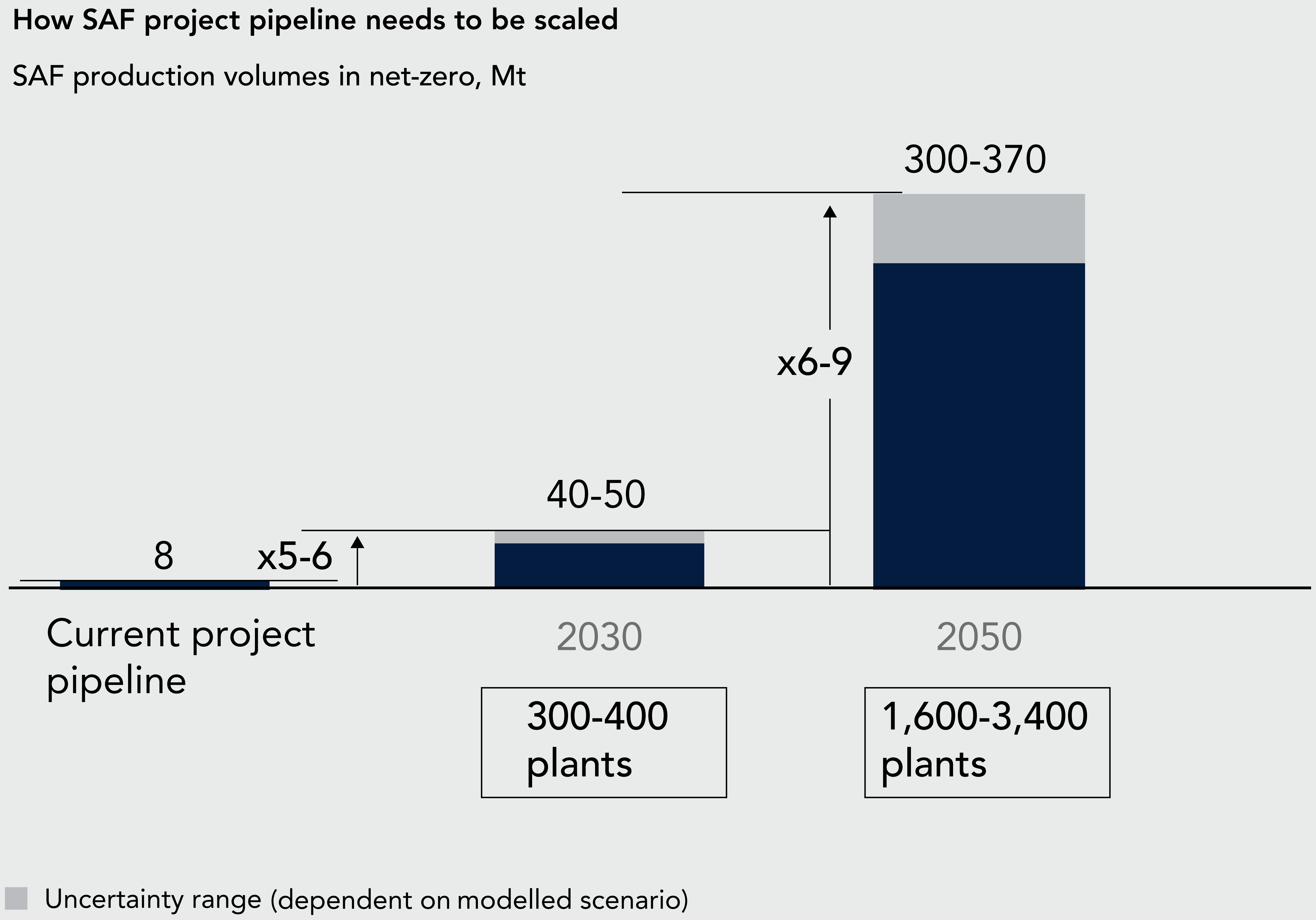
3.4.1.1 Cost

The cost of SAF is currently 3x-4x that of conventional Jet A1. It is expected to continue to rise until 2038, according to the IEA Net Zero Pathway, due to limited feedstock for certain types of SAF and the massive scaling up of production required to increase the competitiveness of sustainable fuel alternatives. SAF therefore faces a challenge to be a commercially viable sustainable alternative despite its energetic practicality.

3.4.1.2 Scalability

In order to be able to scale global SAF production in the 2030s to reach net zero by 2050, between 300–400 new production plants and associated upstream infrastructure need to be constructed by 2030, and 1600-3400 plants by 2050. To accomplish this would require significant amounts of construction and investment that is yet to materialise.

Figure 7: SAF production facility requirements



Source: MPP

3.4.1.3 Availability

As with the issue of scalability, the lack of production of SAF presents the potential for a shortage of supply and sustained high market prices, with SAF likely to be prioritised for long haul flights where there are limited sustainable alternatives with the energy capacity available capable of achieving the mission lengths required. As such, regional and short haul aviation is particularly at risk of facing a shortage of SAF in the future. However, these flights are the best mission lengths to benefit from alternative propulsion and energy solutions such as hydrogen and electric propulsion.

3.4.2 H_2 propulsion

3.4.2.1 Procurement of green hydrogen

In order for hydrogen to be fully sustainable at use, it must come from renewable production upstream. This is known as green hydrogen.

Currently, only around 0.1% of the global supply of hydrogen is green with the majority of hydrogen being black (coal), grey (natural gas), or brown (lignite). All processes that release significant emissions and as already discussed, are energy intensive.

3.4.2.2 Aircraft design

The cost of hydrogen powered aircraft is expected to be higher than for conventional aircraft as the LH_2 tank needs to be integrated in the fuselage. Increasing the complexity of the fuel distribution, propulsion, and increasing the aircraft's size. Furthermore, integrating LH_2 tanks is not compatible with present aircraft design meaning completely new aircraft systems would need to be developed.

Figure 8: H2 production key

Colour	Fuel	Process	Products
Brown/Black	Coal	Steam reforming or gasification	$H_2 + CO_2$ (released)
White	N/A	Naturally occurring	H_2
Grey	Natural Gas	Steam reforming	$H_2 + CO_2$ (released)
Blue	Natural Gas	Steam reforming	$H_2 + CO_2$ (% captured and stored)
Turquoise	Natural Gas	Pyrolysis	$H_2 + C$ (solid)
Red	Nuclear Power	Catalytic splitting	$H_2 + O_2$
Purple/Pink	Nuclear Power	Electrolysis	$H_2 + O_2$
Yellow	Solar Power	Electrolysis	$H_2 + O_2$
Green	Renewable Electricity	Electrolysis	$H_2 + O_2$

Source: Sustainable Northern Ireland

3.4.2.3 Refuelling infrastructure

Hydrogen, unlike SAF, is not a drop-in substitute for Jet A1. H_2 needs to be compressed or liquified and requires specialist storage facilities at airports, separate to jet fuel tanks. As such, significant ground infrastructure is required to provide hydrogen at airports that may cost as much as five times the cost of conventional hydrant systems according to research published by EU Clean Aviation.

3.4.2.4 Certification

As white sheet aircraft capable of deploying hydrogen will need to be developed, certification of a novel propulsion system—as well as brand new aircraft design—will be a costly and lengthy process.

3.4.3 Challenges with battery electric propulsion

3.4.3.1 Certification

As with H_2 powered aircraft, electric aircraft are white sheet designs with novel propulsion methods and so achieving certification will be expensive and time consuming, albeit to a lesser extent than hydrogen with the technologies having already been demonstrated in other industries and general aviation.

3.4.3.2 Battery capabilities

The issues surrounding the gravimetric density of batteries (energy storage by mass) and volumetric energy density of batteries are well documented and significantly limit the range and capacity capabilities of electric aircraft. However, as already raised, as battery technology develops, the range capabilities of battery electric aircraft may grow to alleviate these challenges.

Other issues such as degradation (of battery capacity and power fade) and fast charging capabilities means that batteries will need to be replaced frequently and must be able to charge rapidly. Two requirements that the operating cost and feasibility of, respectively, are yet to be confirmed. That being said, research released in 2024 by Geotab showed that degradation in EV batteries had Improved by over 20% compared to five years ago, and breakthroughs in research on Li-ion battery design and extreme fast charging (XFC) suggest that the technology is progressing.

3.4.3.3 Charging infrastructure

While technology behind high powered, rapid chargers that will be required for electric aviation is developing quickly thanks in part to the development and adoption of high-power chargers in the EV and trucking industries, they are still in their infancy and remain expensive. The challenges that surround developing these chargers will need to be resolved in line with the introduction of electric powered aircraft or they could delay the arrival of this industry.

The electrical infrastructure to supply these chargers will also need to be built and paid for and will require work both on airport and in grid infrastructure. While this is less of a challenge, this similarly needs to be addressed before the intended initiation of electric aviation operations.

4. Heart Aerospace ES-30

The ES-30 from Heart Aerospace is a hybrid electric aircraft designed for region travel with a capacity of 30 pax with luggage. It aims to provide (at entry into service) a range of 200km fully electric and 800km hybrid through two inboard electric motors and two outboard turboprop engines.

It is the first hybrid aircraft the manufacturer plans to develop and release with three further aircraft designs planned for release in 2035 and 2040s that will offer both greater capacity and range.

Its independent hybrid electric engine most closely resembles a partial hybrid system as the electric and thermal systems are not directly linked. The ES-30's battery pack is predominantly charged as a plug-in hybrid but is capable of some regenerative charging through the electric propellers when feathered in flight.

This design means the ES-30 can emit significantly less CO_2 than conventional aircraft on greater range and capacity missions compared to eVTOLs and other fully electric aircraft utilising its hybrid capability.

The ES-30 features 3 modes of operation:

4.1 All electric

Here the electric drivetrain is engaged, and the turboprops are feathered. This allows for short fully electric flights and zero carbon emissions missions.

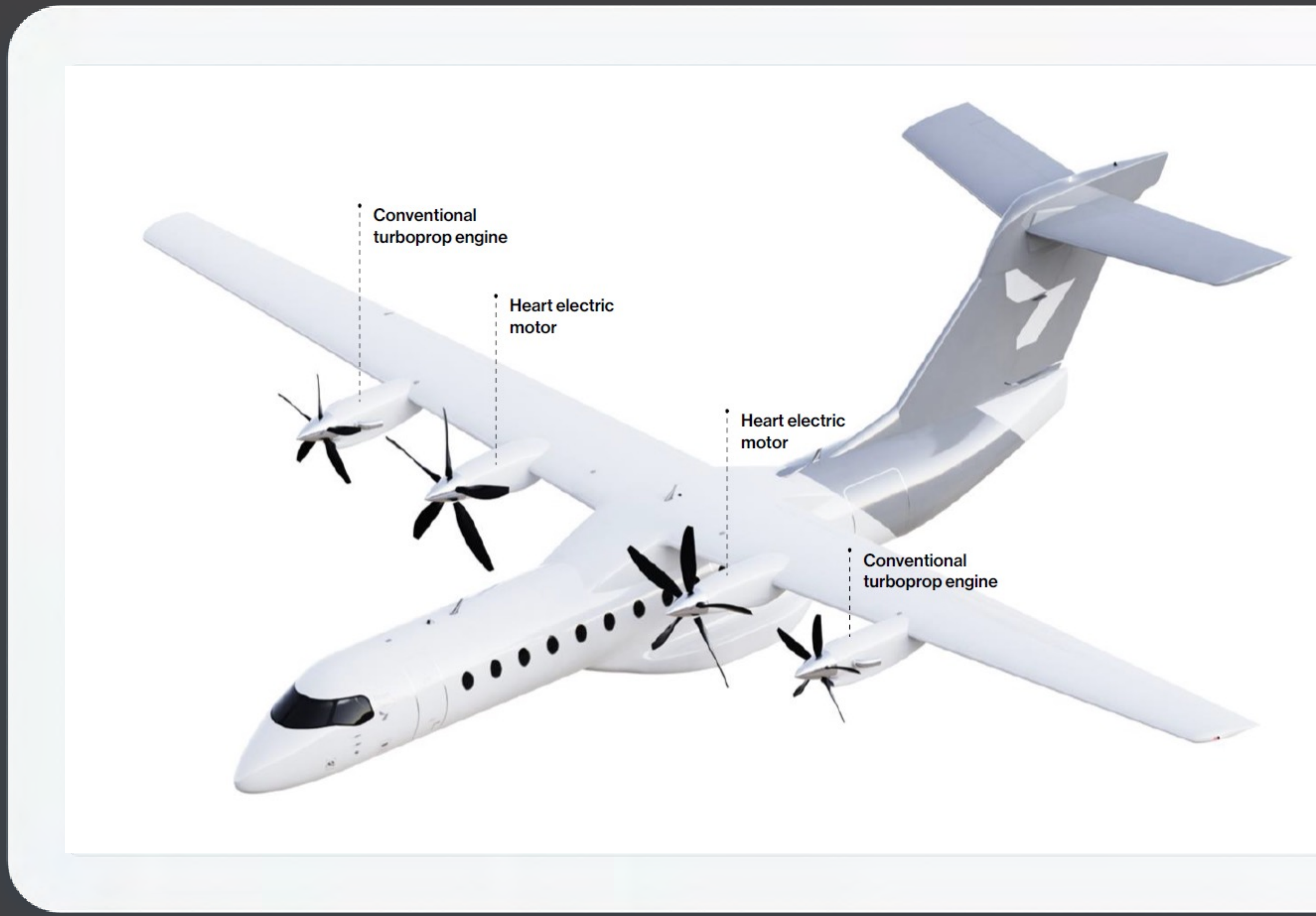
4.2 Hybrid range extension

Here the turboprops are engaged, and the electric drivetrain is shut down once the batteries have been depleted. This gives the plane has significantly more range and flight time than a fully electric operation.

4.3 Short take-off/Missed approach

The electric drivetrain and turboprops can both be fully engaged periods of peak power requirement including take-off, climb and missed approaches.

Figure 9: Heart ES-30 aircraft and propulsion system layout



Source: Heart Aerospace

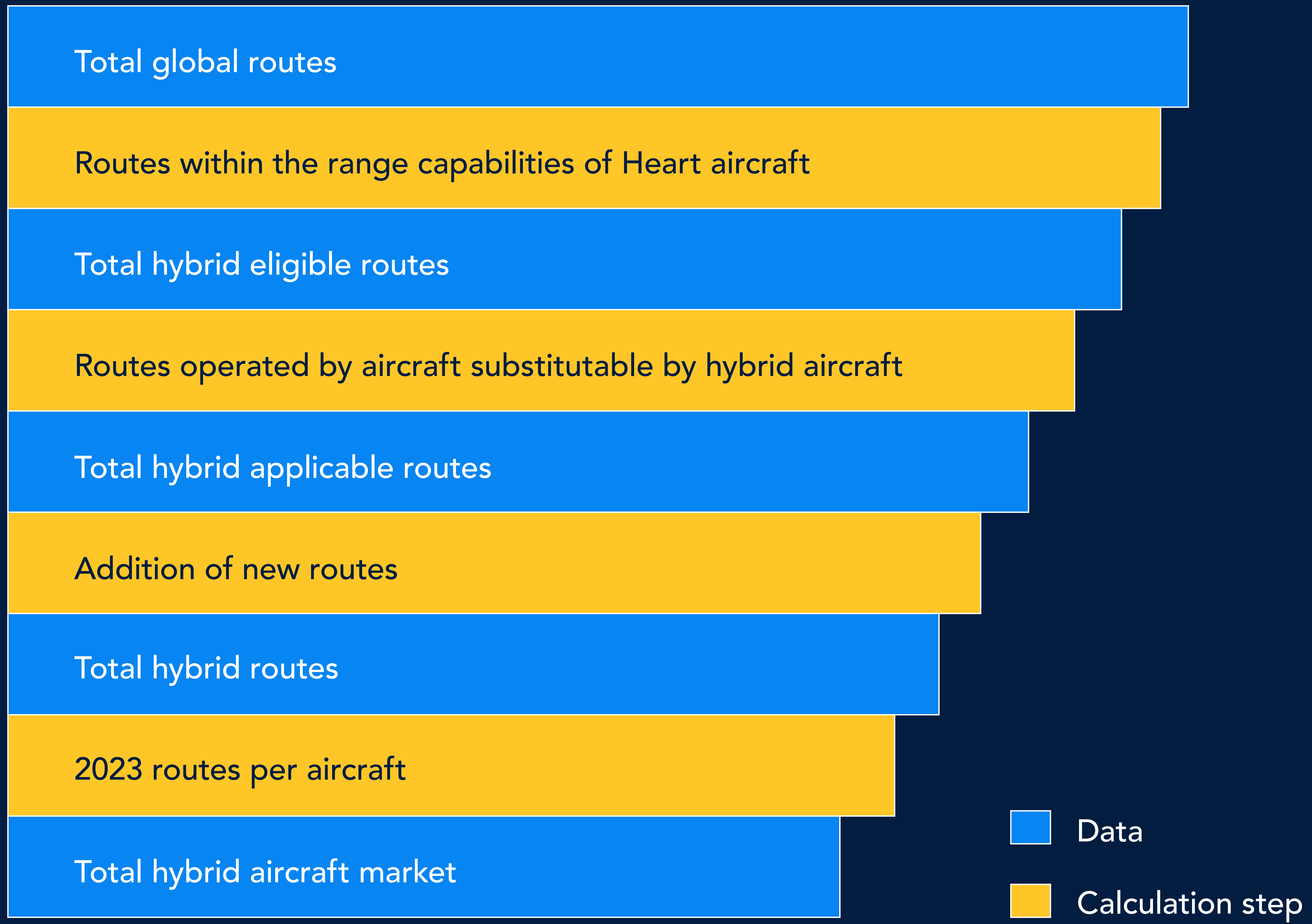
5. Addressable market of the hybrid aircraft

To determine the potential global market size for hybrid aircraft, the range capabilities of Heart's aircraft and their publicised entry into service dates were considered along with the route networks of existing aircraft to establish the total routes and frequencies that Heart aircraft could feasibly operate. From this, the number of hybrid aircraft required to operate the applicable routes was then calculated.

The potential new route opportunities created by the improved operating economics of hybrid aircraft were also assessed to estimate the number of aircraft that would be required to serve newly created markets.

The methodology for this forecast that will be expanded upon in more detail through this section of the report is illustrated.

Figure 9: Heart ES-30 aircraft and propulsion system layout



Source: ICF

5.1 Hybrid eligible routes

We counted all routes within the range capabilities of Heart's aircraft (800km at the ES-30's introduction in 2029 to 1500km from 2041 as a result of larger hybrid aircraft with longer ranges that Heart plans on introducing to the market after the ES-30) regardless of the aircraft currently operating on them, split by region, from OAG's data and expanded to 2050 using the route growth CAGR observed between 2013 and 2023 for each region[4]. The 2023 routes per aircraft were calculated for turboprop and regional jet aircraft and applied to the number of hybrid eligible routes to reach the number of hybrid aircraft required to service the identified routes each year.

The outcome was a growing requirement until 2041 when there is an increase in the number of hybrid capable routes as the range of hybrid aircraft increases to 1,500km with the introduction of newer aircraft capable of longer missions, **creating a market for over 27,200 hybrid aircraft in 2050**. Applying a 50% increase and decrease to the routes growth rate led to scenarios with an increasing separation that peaked at 44% and -29%, respectively, at the end of the time series.

Figure 11: Number of hybrid aircraft required to fulfil all hybrid capable routes in each year

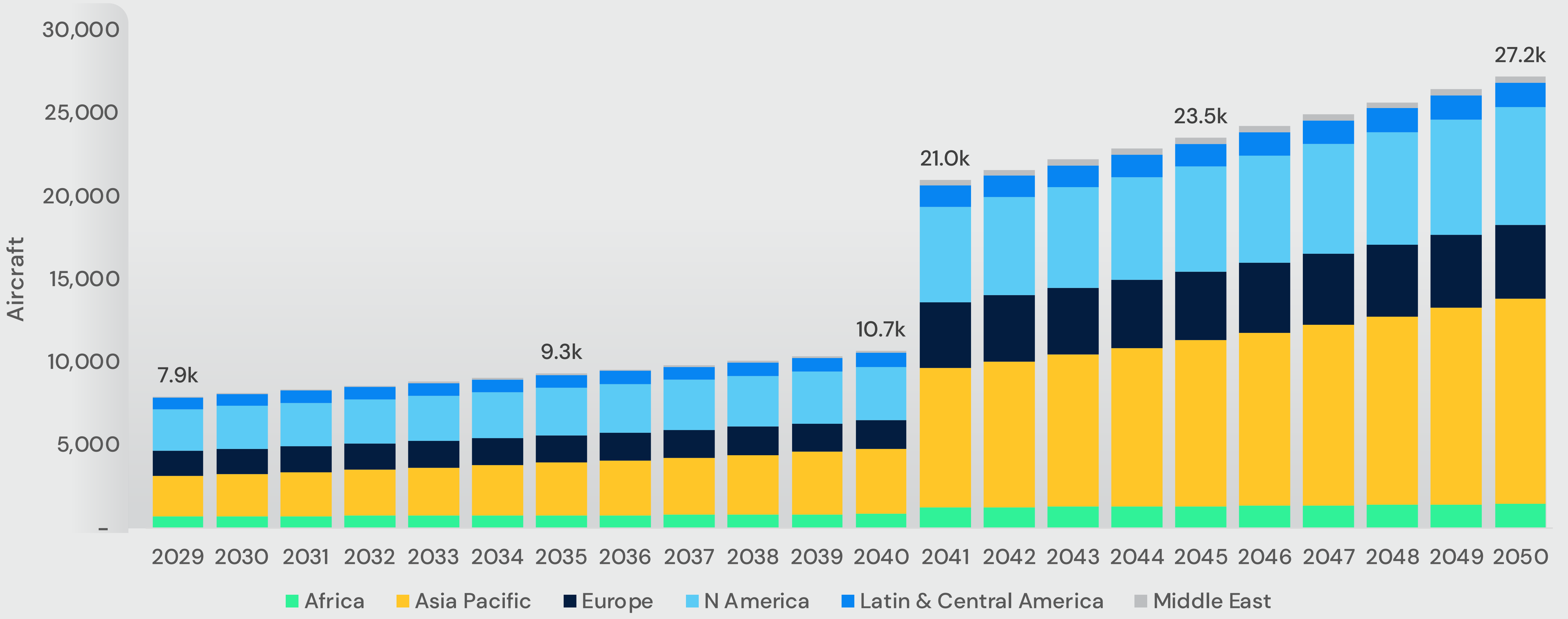
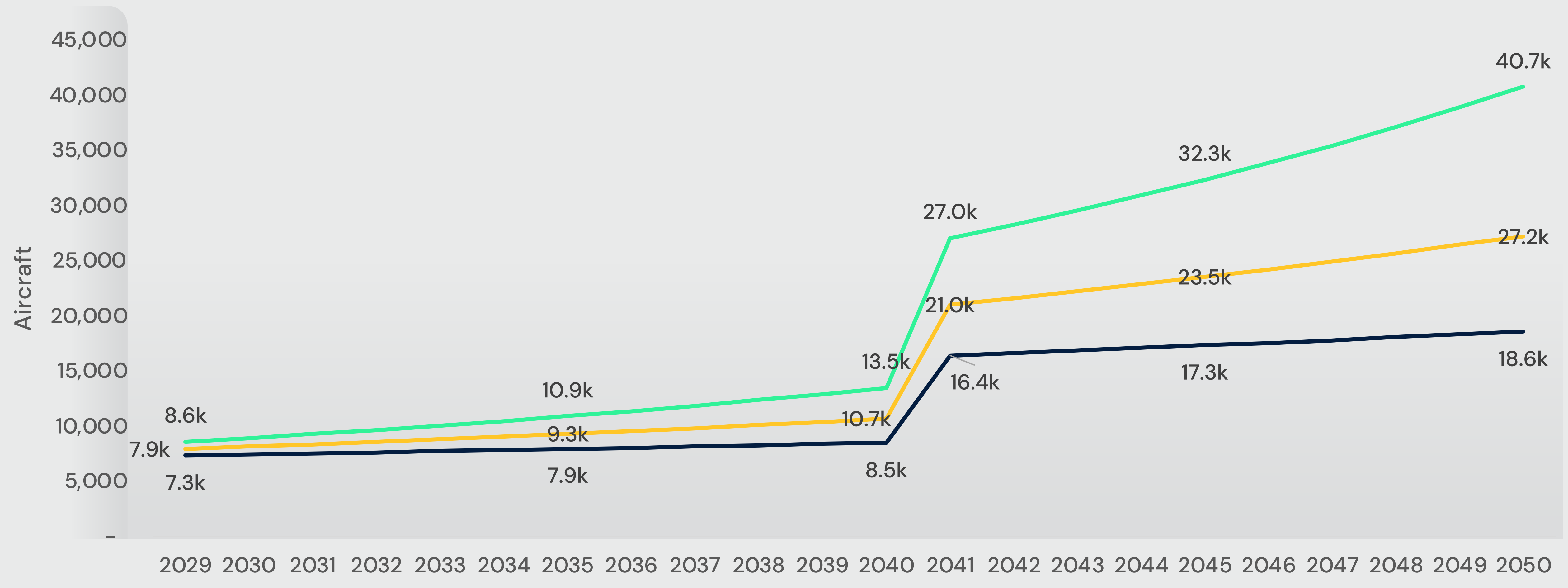


Figure 12: Number of hybrid aircraft required to fulfil all hybrid capable routes in each year



Source: OAG, ICF analysis

[4] 2.3% globally

5.2 Hybrid applicable routes

The total eligible routes, based solely on distance, were then filtered to only include missions completed by turbojet and regional jet aircraft—and then again by the capacity of the currently operated aircraft aligning with Heart aircraft such that they could be utilised on those flights without constricting capacity.

The increases observed in 2035, 2041, and 2046 are as a result of the introduction of larger aircraft as battery and weight improvements are made. The hybrid eligible routes determined represent 14% of all routes within range of hybrid aircraft till 2035, 22% between 2035 and 2040, 24% between 2041 and 2045, and 43% from 2046 to 2050.

The total market for hybrid aircraft in this scenario was calculated to be 11,600 aircraft in 2050. Applying a 50% increase and decrease to the route growth rate led to the following three scenarios, indicating an increasing separation between the high and low scenarios, reaching at 46% and -30% in 2050 respectively.

Figure 13: Annual aircraft required to fulfil all hybrid replaceable routes

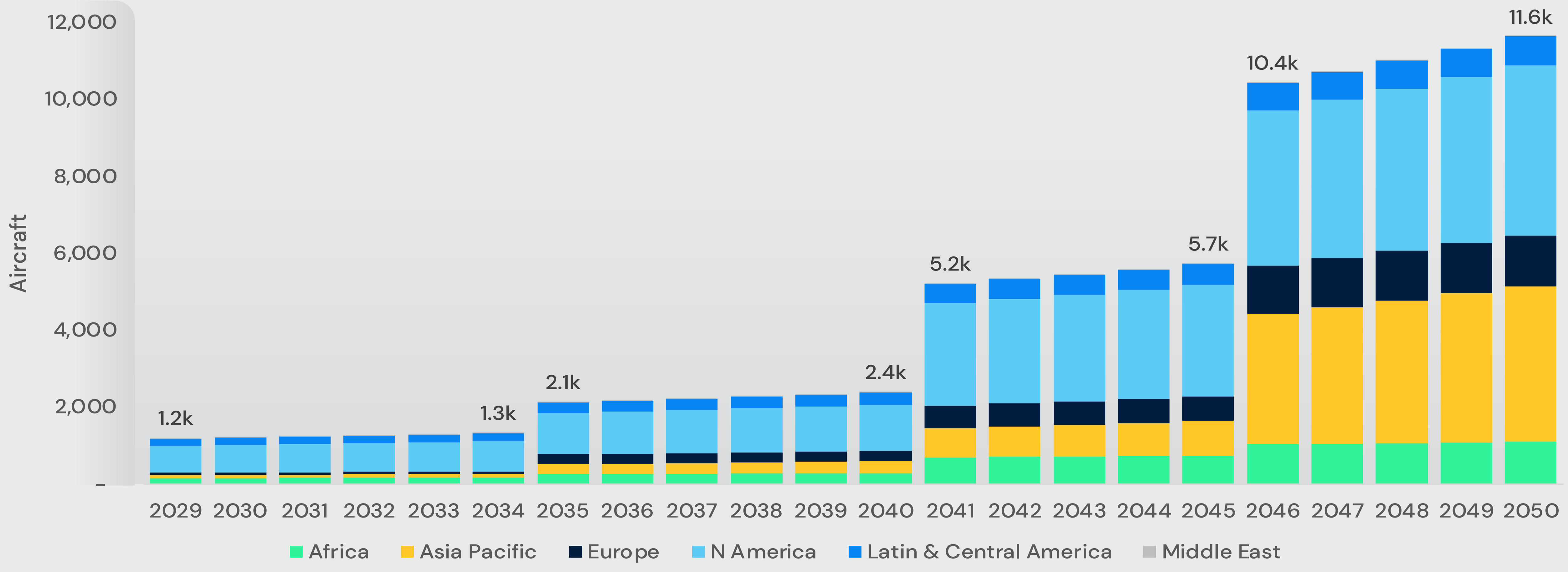
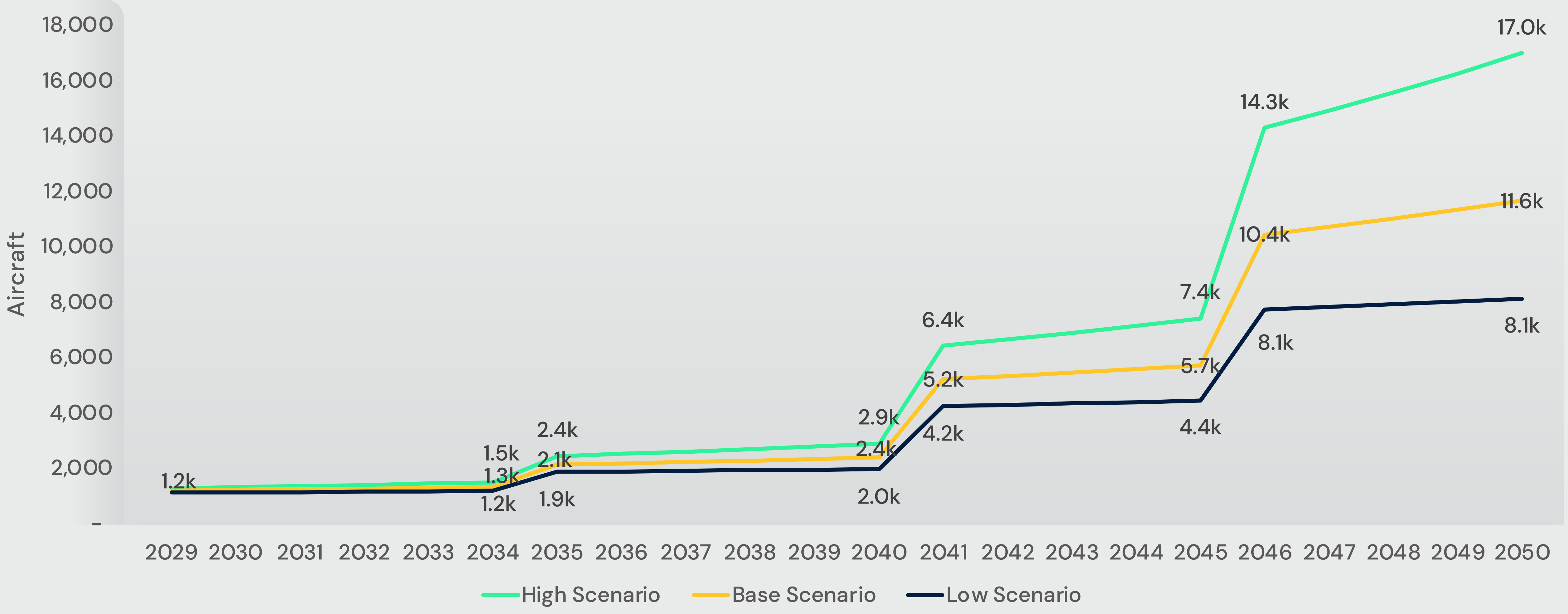


Figure 14: Annual aircraft required to fulfil all hybrid replaceable routes



Source: OAG, ICF analysis

5.3 New routes

Hybrid aircraft like the ES-30 will also open new route opportunities through greater route economics than currently achievable with existing conventional aircraft. Analysis completed by NASA predicts that a 50% decrease in operating cost could lead to between 3,600 and 4,500 new routes in the U.S. for aircraft with the capacity of the ES-30[5]. The cost reduction assumptions of the study also align with the estimated direct operating cost performance improvement projected by the ES-30.

Using these approximations, the proportion of the number of feasible new routes compared to number of existing routes in the U.S. was calculated and applied across the number of routes in other regions to reach an estimate for the number of new feasible routes globally.

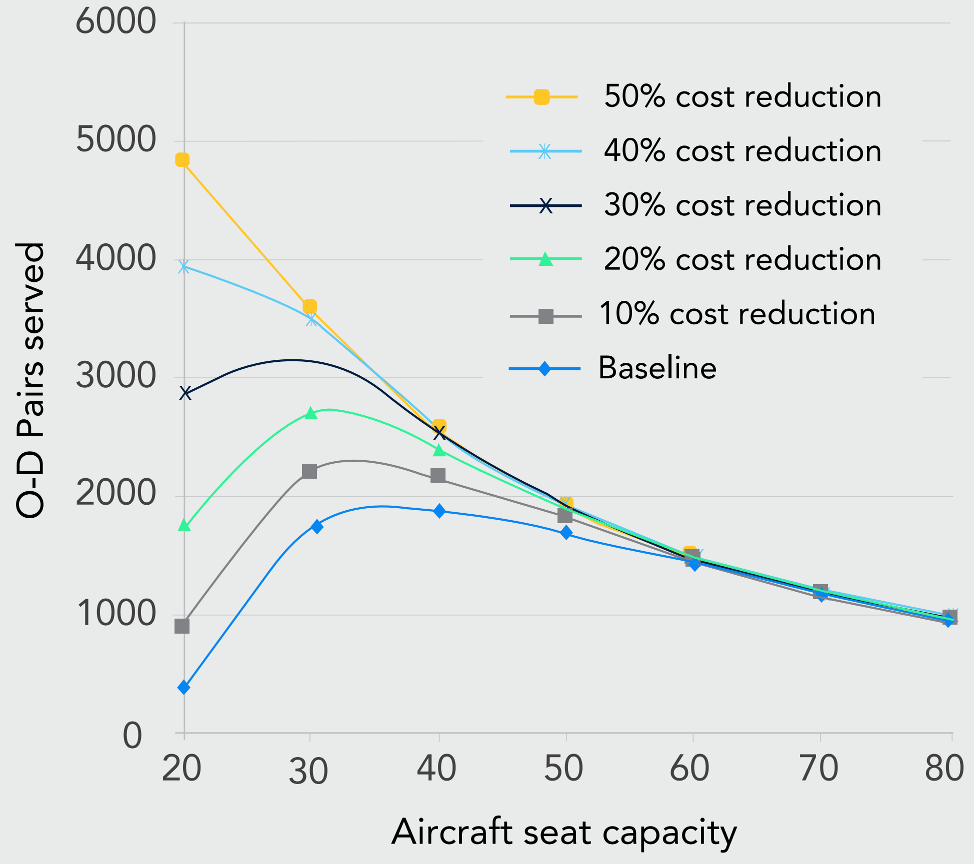
Using the same route to aircraft ratio used to estimate aircraft demand on existing routes, ICF estimates that the NASA analysis implies a potential market for over **6,500 additional hybrid regional aircraft**.

5.4 Total aircraft

Combining the hybrid aircraft required to service all applicable existing routes and feasible new routes provides the total hybrid aircraft market from entry into service until 2050.

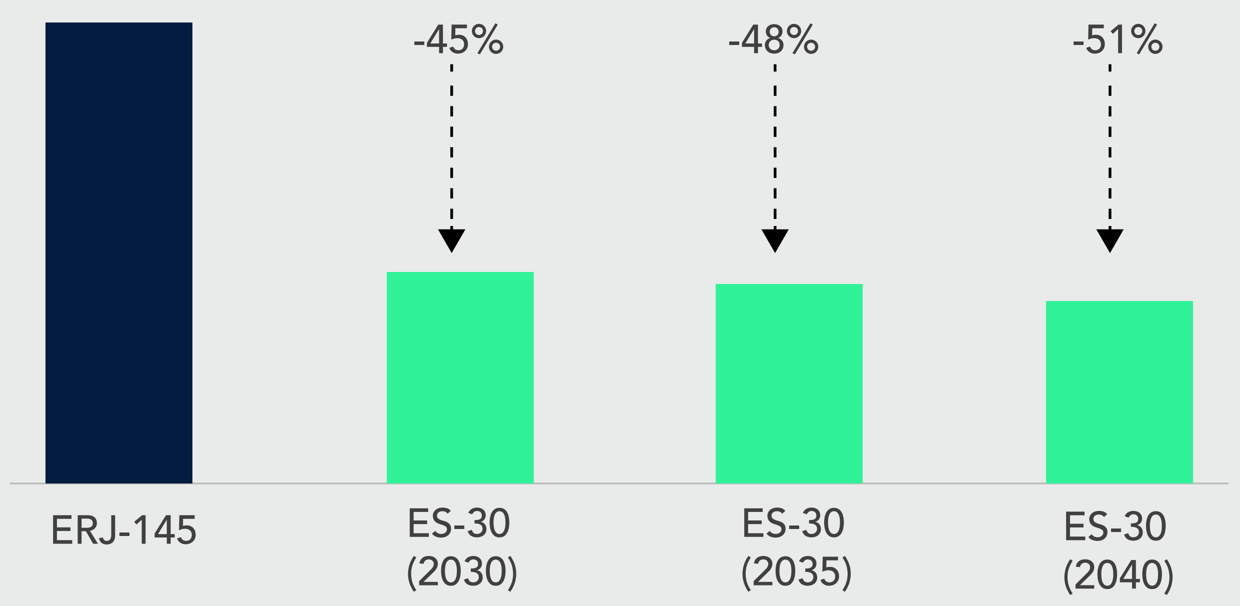
[5] 25-30 pax

Figure 15: Number of short-haul o-d pairs served vs. seat capacity for different levels of cost reduction



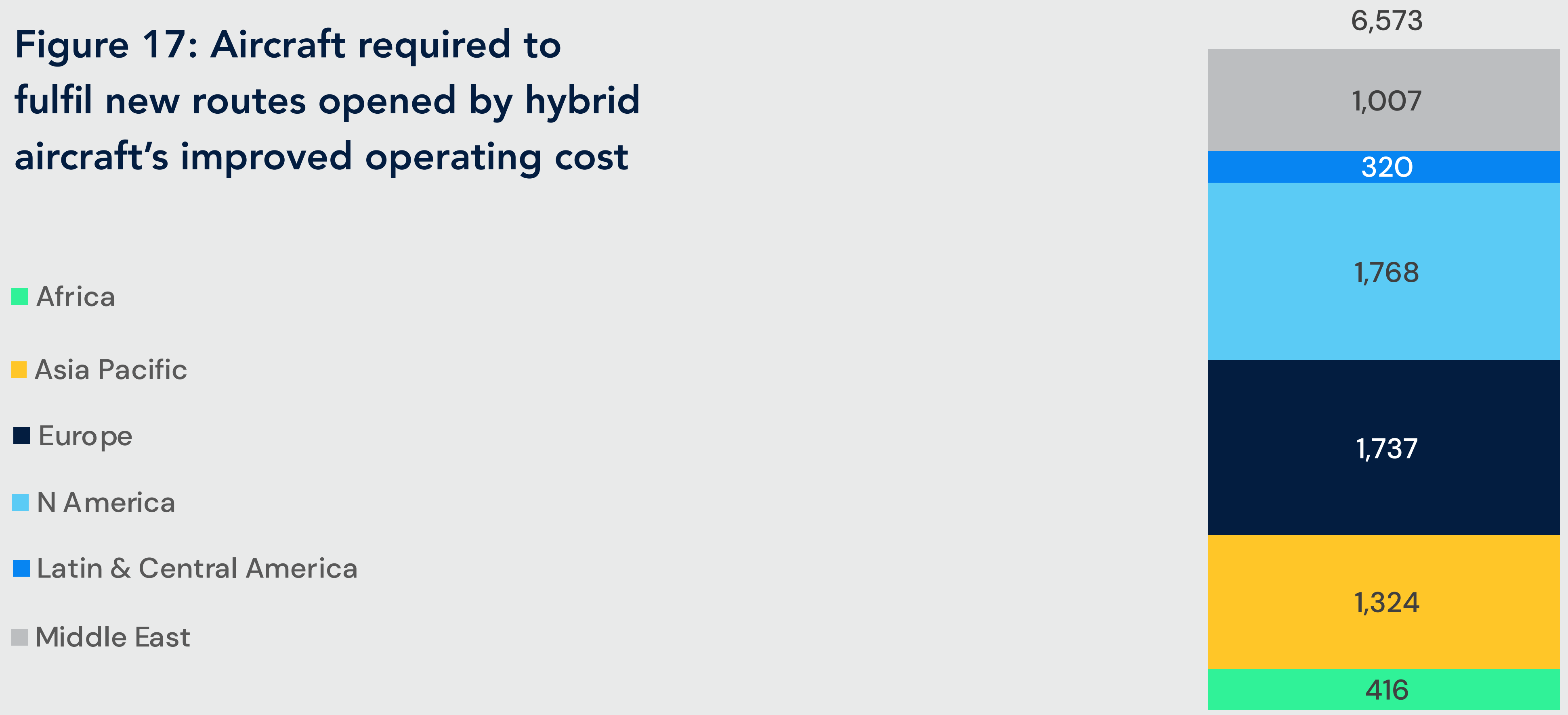
Source: Ty v. Marien

Figure 16: Heart ES-30 direct operating cost reduction versus conventional aircraft



Source: Heart Aerospace

Figure 17: Aircraft required to fulfil new routes opened by hybrid aircraft's improved operating cost



Source: OAG, ICF analysis

Equating to a total estimated global addressable market of 18,200 hybrid aircraft by 2050. When the estimated global hybrid aircraft requirement is compared to the anticipated production rates of Heart's ES-30 and its plans to scale to larger seat capacities, Heart's production in isolation remains below the number of aircraft required to cater for existing routes—with the exception of 2040. From 2040, the introduction of Heart's later aircraft variants drives an increase in the number of aircraft required through the opening of new routes. This maintains global aircraft requirement for existing routes exceeding supply of hybrid aircraft. When compared to both existing and new routes, Heart's production does not surpass 50% of the total hybrid aircraft market share for both existing and new routes. This shortfall of anticipated Heart production rates versus demand shows the potential for Heart, or other OEMs, to increase production capacity plans to meet expected demand in a concentrated market.

A 50% and 25% market share for Heart scenarios were applied and **supply never exceeds demand in the 50% market share scenario** and **supply only exceeds demand after 2040 in a 25% market share scenario**, assuming identical entry into service and rates of production.

However, at present there not many OEMs present in the hybrid space with the leading aircraft OEMs having refocused their efforts on hydrogen and battery electric. The impact of this being that the supply of

Figure 18: Annual aircraft required to fulfil all hybrid replaceable and new routes

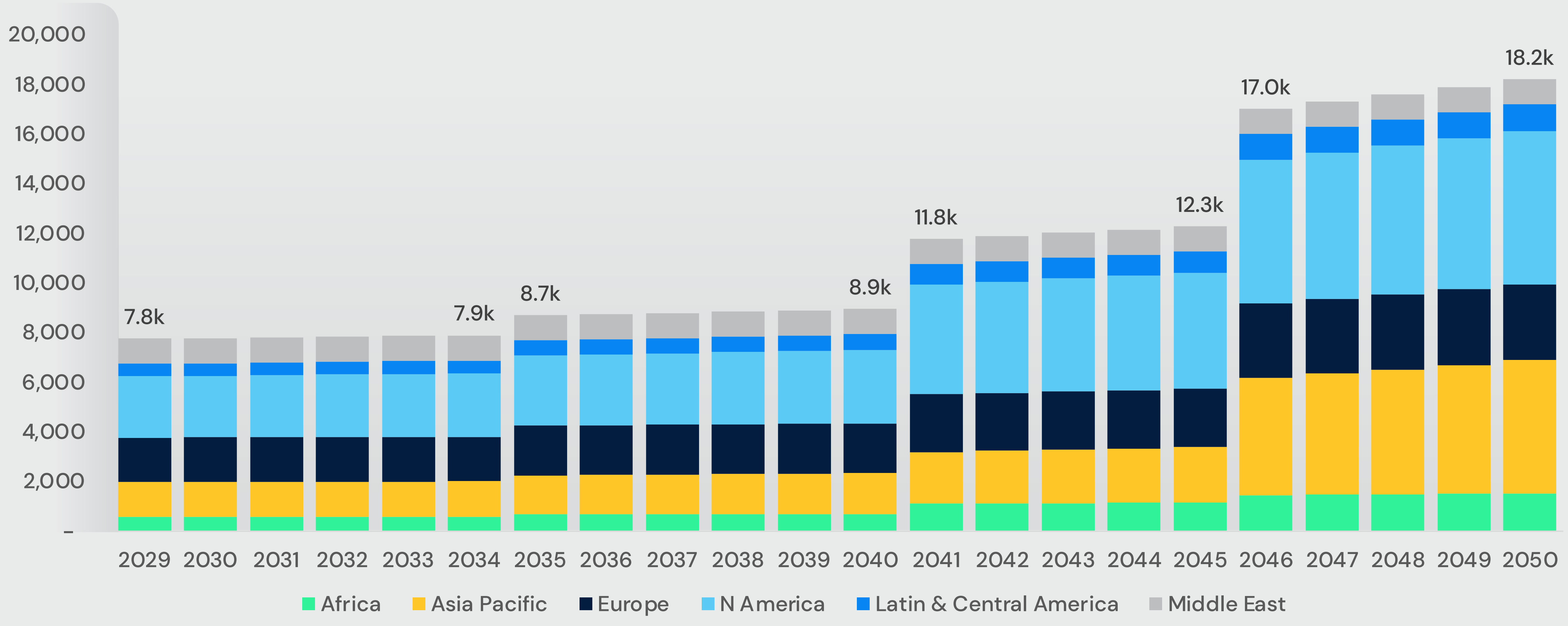
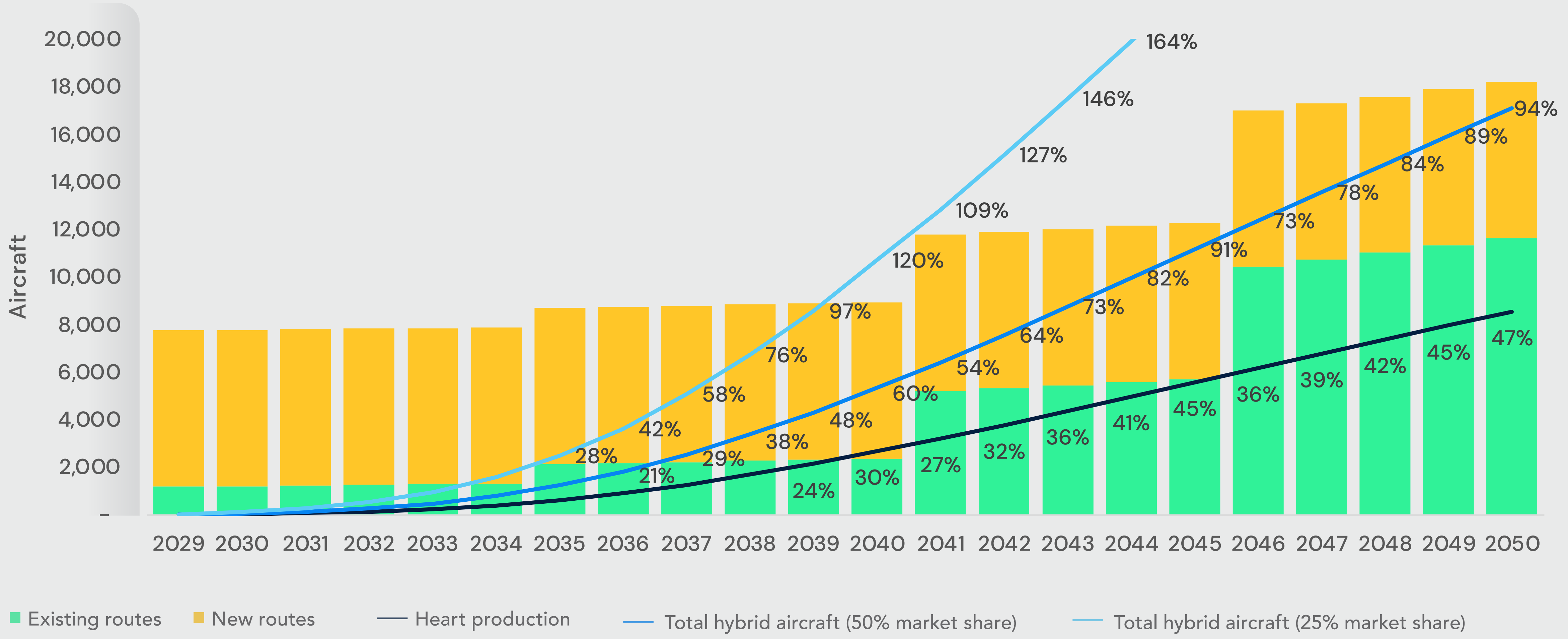


Figure 19: Cumulative aircraft produced compared to the global requirement



Source: OAG, ICF analysis

hybrid aircraft will be limited to Heart and a small number of additional OEMs in the years following the introduction of hybrid aircraft to market.

6. Estimated emission reduction of hybrid aircraft

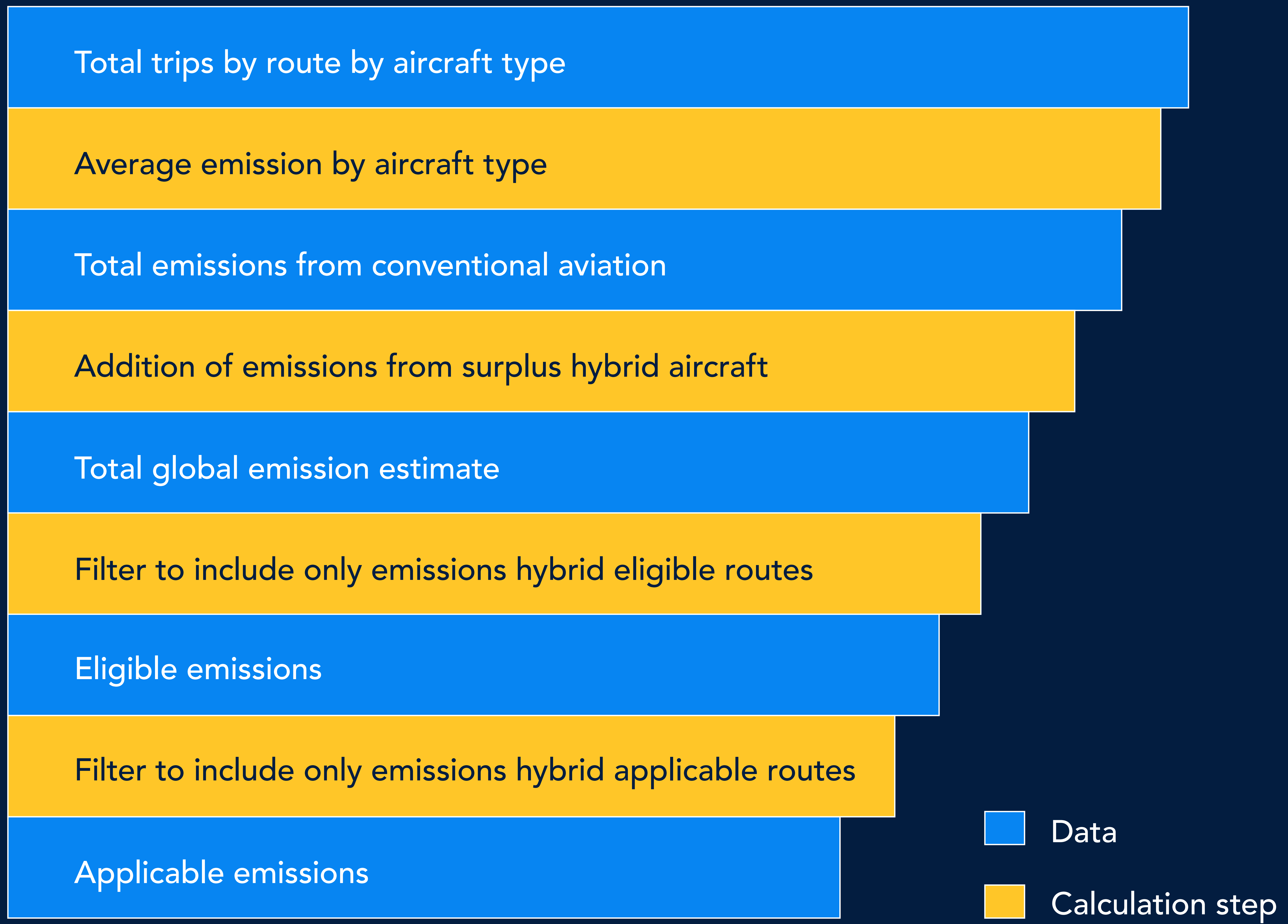
ICF firstly attempted to estimate the emissions that could be mitigated by hybrid aircraft by calculating the number of applicable emissions, attributed to routes that hybrid aircraft could operate on, to demonstrate the maximum possible impact of an unrestricted supply of hybrid aircraft.

To determine the potential emissions impact of produced hybrid aircraft, the carbon emission reduction from the replacement of a regional aircraft[6] by a hybrid aircraft was determined and applied to the number of produced aircraft on hybrid applicable routes to determine the total emission saving.

The methodology to be able to compete this outlined forecast, that will be expanded upon in more detail through the remainder of this report, is illustrated.

[6] Turboprops and regional jets

Figure 20: Emission reduction estimation methodology



Source: ICF

6.1 Baseline eligible and applicable CO_2 emissions

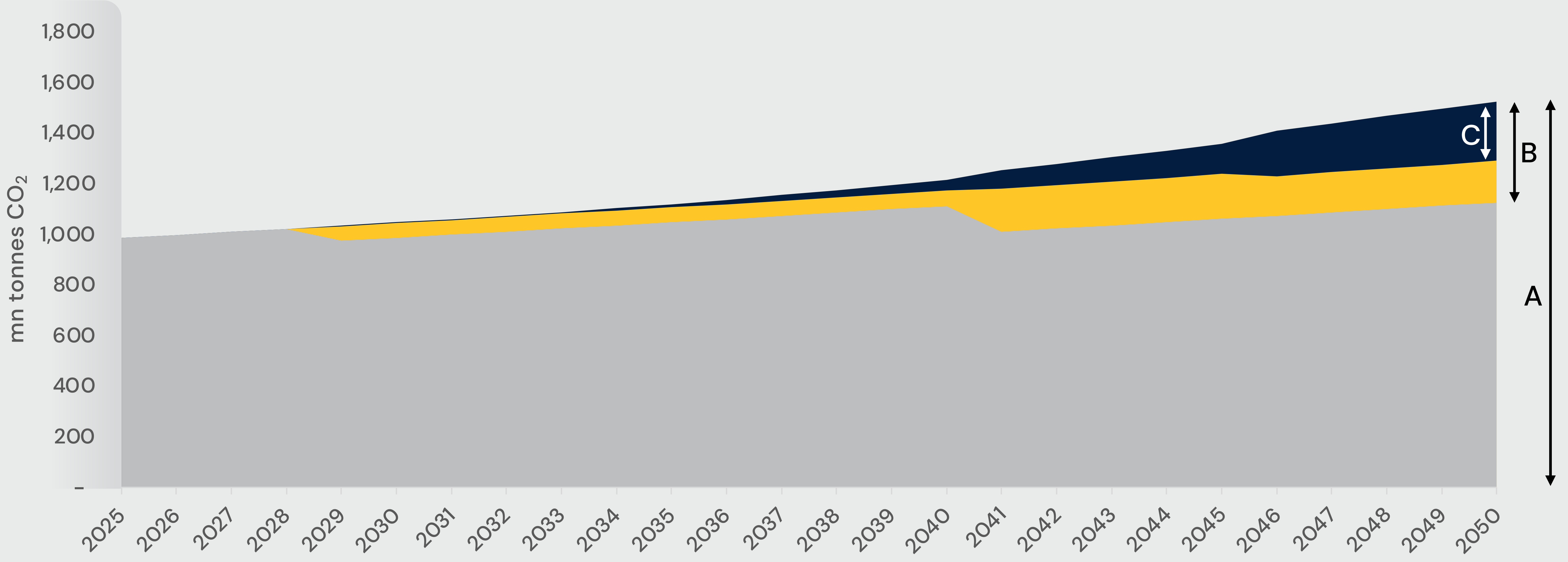
The average CO_2 emissions by aircraft categories (of widebody, narrowbody, turboprop and regional jet) was calculated using a sample of passenger aircraft and the average CO_2 emissions per trip was applied to the number of forecast trips per route to get the total estimated CO_2 emissions that would be emitted by conventional aviation.

The introduction of hybrid aircraft will contribute additional emissions through the introduction of hybrid aircraft that will exceed the retirement rate of the aircraft that it will be replacing, as such, the additional emissions that these aircraft will contribute will need to be considered as part of the global emissions to 2050. To do this, the conventional emissions equivalent impact of additional hybrid aircraft was therefore added[7] to total global emissions and were included as both eligible and are applicable as they are mitigatable while being a surplus to current passenger emission growth. These additional aircraft will represent an estimated additional 15% to global emissions in 2050.

Combining the calculated total emission estimates emitted by conventional aviation and the emissions from additional aircraft produces a baseline total global emissions, A in Figure 21.

Calculating the emissions attributable to eligible routes (based solely on distance) and filtered to include the emissions attributable to applicable routes (based on distance and the transferability and capacity of a hybrid aircraft) for hybrid gave the proportion of total global emissions that are addressable[8] by hybrid aviation.

Figure 21: Total eligible and applicable hybrid CO_2 emissions



Source: ICF analysis

[7] Using Heart's entry into service and production rates for the ES-30 and ES-4X at a 25% market share

[8] Addressable emissions refers to the emissions that a hybrid aircraft will impact on a flight that would otherwise be operated by a conventional aircraft. Of these addressable emissions, hybrid aircraft will mitigate a proportion of these emissions using non-emission emitting propulsion

The proportion of eligible emissions and applicable emissions that could be addressed were calculated. In terms of eligible routes, B in Figure 21, the forecast projects that hybrid aircraft could be capable of addressing 6% to 8% between 2029 and 2041, and from 19% to 26% from 2041 to 2050 of the total emissions based off eligible routes.

When considering applicable routes, C in Figure 21, the forecast projects that hybrid aircraft could be capable of addressing 0.3% to 3% between 2029 and 2041, and from 5% to **15% of the total emissions** based off applicable routes.

6.2 Emission reduction potential

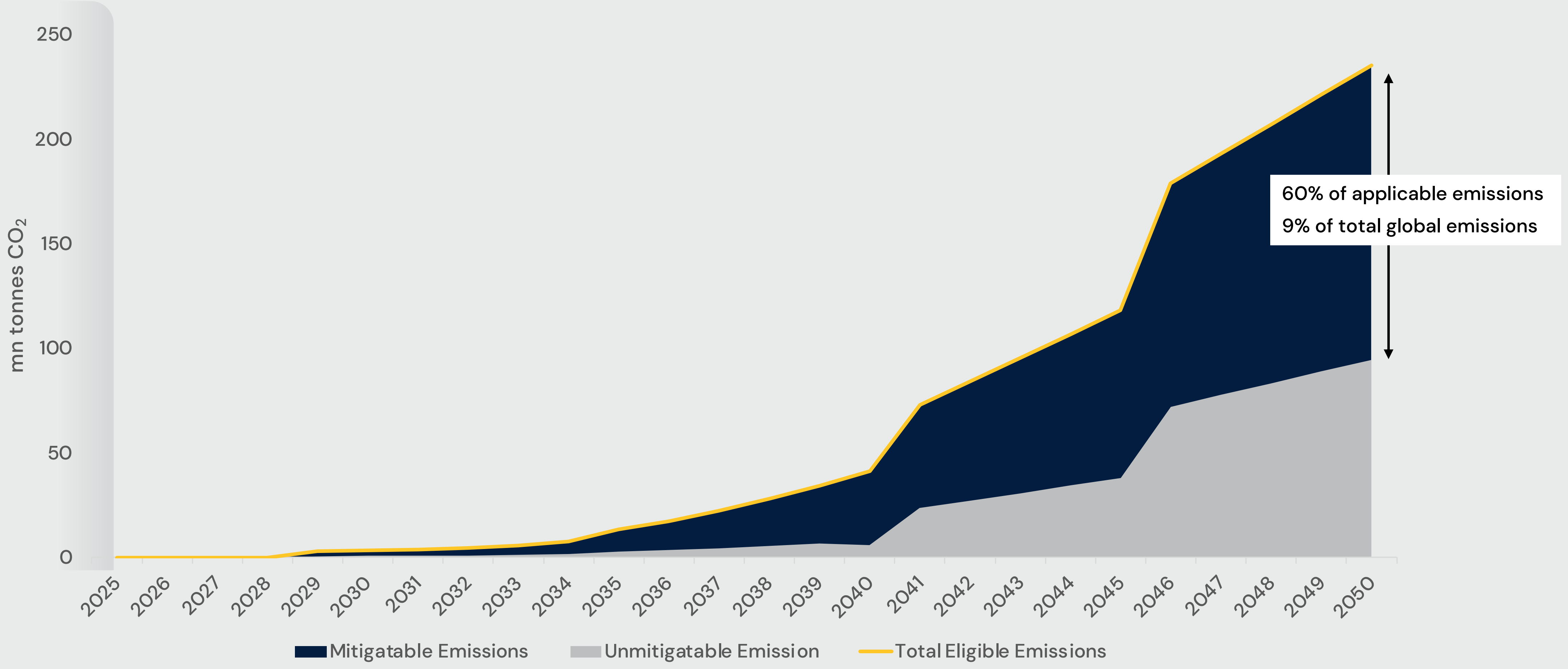
The applicable emissions were analysed further, and the maximum feasible emission reduction potential calculated based on replacing all conventional aircraft with hybrid. This calculation indicated that **60%** of all applicable CO_2 emissions from hybrid aircraft, C in Figure 21, **could be mitigated by 2050**, equating to **~9% of total global emissions**, the indicated area in Figure 22 below.

6.3 Aircraft emission reduction

Finally, the feasible emission reduction of hybrid aircraft based off the number of expected active, operating hybrid aircraft was calculated. Taking the applicable emissions, C in Figure 21, and applying Heart's production estimates and market share scenarios of 50% and 25%[9], an estimate for the likely emissions removed by hybrid aviation could be reached.

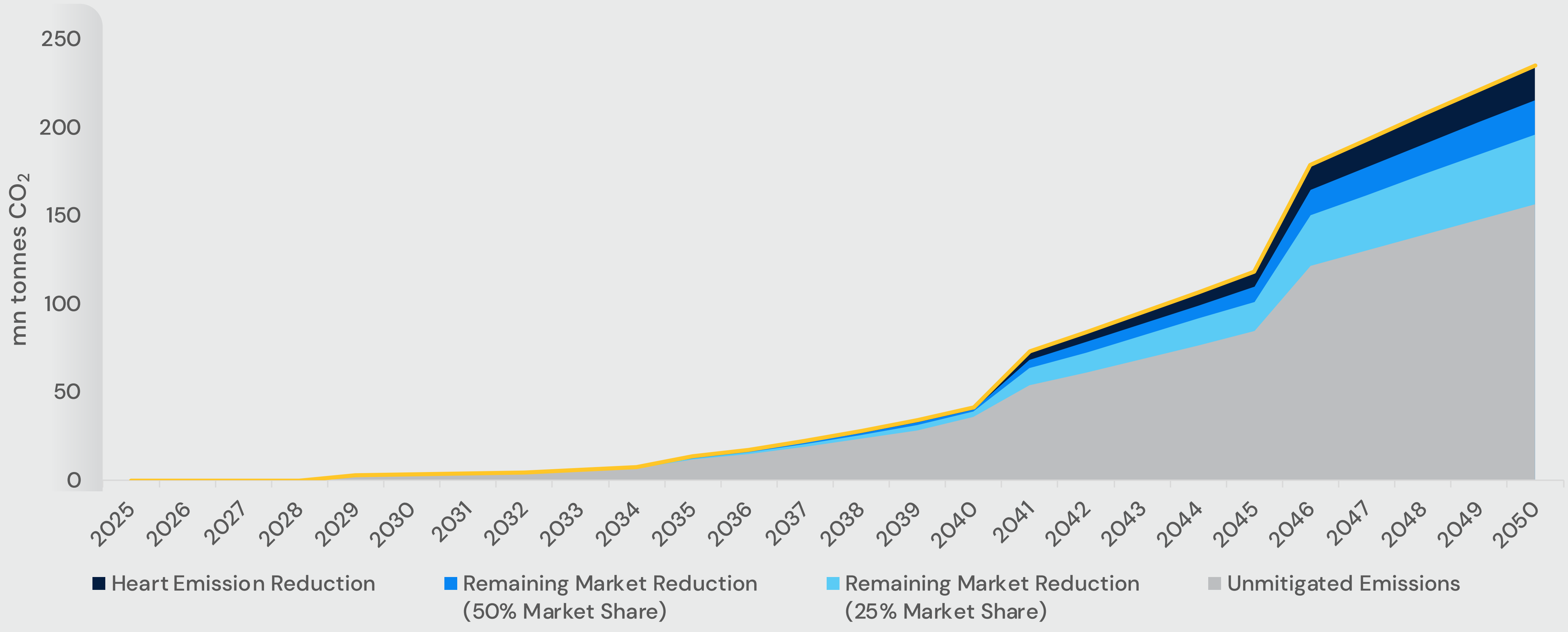
ICF determined that Heart's production could result in an 8% reduction in applicable emissions and 17% and 34% reduction with 50% and 25% market share, respectively. This equates to a **1%, 3%, and 5% reduction of total global emissions across the Heart, with 50% market share and 25% market share scenarios**, respectively, as illustrated in Figure 23 below.

Figure 22: Theoretical maximum emission reduction



Source: ICF analysis

Figure 23: Supply-side constrained emission reduction



Source: ICF analysis

[9] Market share of Heart, and assuming the same entry into service and production rates

7. Estimate considerations

The results of this report and the forecasts and estimates contained within were reached through the application of assumptions on existing available data and research. These were chosen based on limiting the complexity of analysis and forecasting and ICF's experience, expertise and understanding of novel propulsion technologies and their capabilities. These decisions naturally carry caveats, the central of these are outlined below.

7.1 New route estimation

The research used to estimate the potential new routes that could operate through improved operating economics only explores the impact of a maximum of 50% reduction in operating costs. This aligned with the anticipated operating performance of Heart aircraft. Should the operating performance of hybrid aircraft improve beyond this then potential number of new feasible routes could increase beyond what could be calculated using the research used in this report.

7.2 Narrowbody aircraft and Heart's 90-seater aircraft

In this report, ICF has taken the view that hybrid aircraft are unlikely to be utilised on routes where they would be replacing narrowbody aircraft.

This decision was taken due to the unlikely willingness of operators to reduce capacity by swapping from narrowbodies to hybrid aircraft, and the comparative utilisation limitations of replacing a jet powered narrowbody for a propellor powered hybrid aircraft in terms of daily sectors.

However, if hybrid aircraft were to replace narrowbody aircraft, then the market and emission reduction potential would be greater than the headline figures published within this document (9% of global aviation emissions). The estimated impact of including narrowbody aircraft in market sizing and emission reduction potential of hybrid aircraft can be seen in the eligible routes and emissions (26% of global aviation emissions).

7.3 SAF and improved efficiency of aircraft

The impact of SAF and the improved efficiency of aircraft through technological development were not considered in this analysis as their impacts are considered in isolation in most net zero pathways and so to include them in this report could amount to double counting. As such, their impacts, in combination with the impacts of hybrid, could result in further emission savings from introduction of hybrid aircraft and bring routes and operations that are net zero beyond those that have been calculated in this report.

8. Conclusion

This report shows that the market for, and the impact of, hybrid aviation is significant. With the potential to contribute meaningful reduction in emissions, both directly through the operation of hybrid aircraft and indirectly through the freeing up of other decarbonising activities and resources that can be utilised elsewhere.

Furthermore, with a concept more readily aligned with existing technologies and an arguably wider usability and "drop in" replaceability than other novel propulsion technologies, the case for hybrid aircraft could align with that of other novel propulsion technologies. As such, it is ICF's view that hybrid aviation warrants levels of attention and investment observed in other decarbonisation activities to be able to meaningfully contribute to the aviation sector's efforts in achieving net zero.

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