ELECTRIC AIRCRAFT

Flightpath of the Future of Air Travel

Citi GPS: Global Perspectives & Solutions

September 2019

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Remember the good old days of flying? When you dressed up to board the plane, had a luxurious meal, and drank free liquor from tiny airplane bottles? You could walk straight from the ticket counter to the gate without going through metal detectors, taking your shoes off, or removing your laptop from your bag. Then you settled into your assigned seat and… Wait, hold on? Why does this plane in my daydream look just like the one I took to New York last month?

In the transportation world, we've seen a tipping point in the acceleration of the 'Car of the Future' where we are now moving decidedly in the areas of electric and autonomous vehicles. We've even seen all-electric technology expand into trucking with production and sales of new electric models set to begin next year. But in the area of civil aerospace, although there have been advancements in systems, materials, and fuel efficiency, aircraft built today look and operate much like those built 60 years ago.

But change is coming. Electric power is already being used in several non-propulsive systems on an aircraft and technology has recently advanced to the point where electric engines are becoming a viable alternative to jet turbofan engines. Why switch? One major driver is because air travel is responsible for ~2% of man-made CO_2 emissions and with air traffic forecast to grow at 4-5% for the next 10+ years, electric engines could reduce carbon emissions for the industry by 50%. Equally important, electric engines save on operating costs as they have less moving parts than jet engines and therefore require less maintenance, are more reliable, and are quieter to operate.

In the report that follows, we focus on the activities that directly impact the aircraft and engine OEMs looking ahead to 2030 in four key areas: aviation/pilot training, general aviation, urban mobility/air taxis, and regional aircraft. Together, we forecast electric aircraft to have an addressable market value of over $17 billion. More surprisingly, this revenue opportunity isn't something way out in the future. Electric aircraft for pilot training exists today and we expect launches in general aviation in 2022, air taxis in 2025, and regional aircraft in 2030. To date around the world there are almost 170 electrically-propelled aircraft projects under development.

The futuristic vision involving flying cars and air taxis with vertical take-off and landing (VTOL) capabilities and electric-propulsion technology is coming closer to reality as well as cities look for ways to cope with growing populations. We expect to see multicopter and hybrid prototypes for passengers emerge in the next 2-3 years and urban mobility services to start operating as early as 2025.

Of course there are some key limiting factors to electric aircraft implementation — most importantly current battery technology isn't where it needs to be in terms of energy density and charge times to support full implementation for larger planes and longer distances. Public perception and safety is also a headwind as running out of charge in an electric vehicle on the highway is a lot different from running out of charge in an electric aircraft at 10,000 feet. But progress is being made and we expect advances in battery technology to drive accelerated uptake of electric aircraft while regulators are already looking at ways to make the new technologies safe.

Electric Aircraft Takeoff Checklist

ELECTRIC-POWERED AIRCRAFT HAVE THE POTENTIAL TO TRANSFORM PARTS OF THE INDUSTRY BUT THERE ARE BOTH BENEFITS AND LIMITATIONS TO ELECTRIC PROPULSION

Benefits

- Reduced emissions
- Reduced maintenance costs and increased reliability
- Reduced operating costs
- Reduced noise pollution leading to increased convenience and latent demand
- Lower infrastructure costs vs. other modes of travel

Limitations

- Battery technology not there yet
- Significant upfront investment on new technology
- Investment in charging infrastructure
- Regulation and safety considerations
- Public perception needs to be won over

AVIATION'S SHARE OF GLOBAL CO_2 EMISSIONS HAVE REMAINED CONSTANT AT ~2.6% SINCE THE EARLY 2000s

Going forward, capacity growth, reduced advancements in fuel efficiency, new types of air travel including supersonic, and regulatory driven changes in other industries means the share of CO_2 emissions from aviation could rise

Rising CO_2 emissions

can be reduced

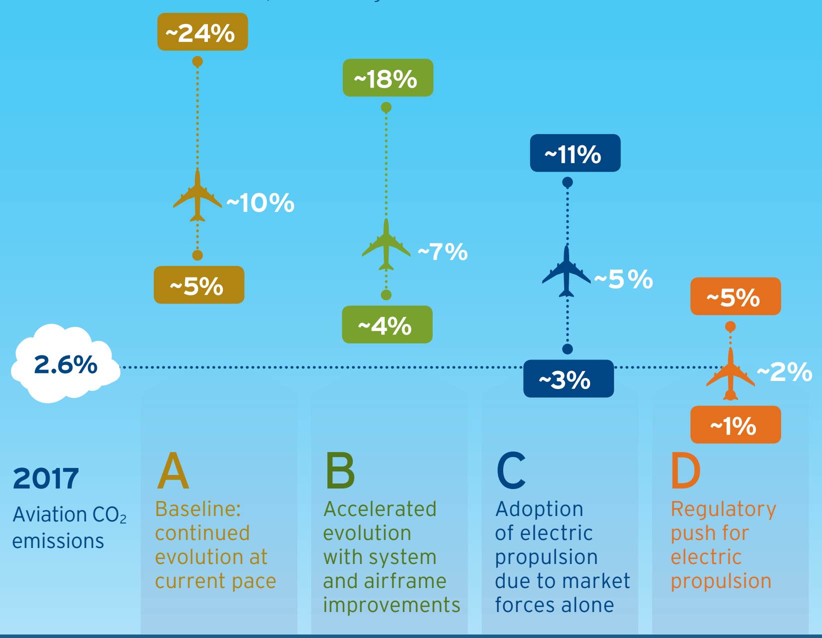
Adoption of electric propulsion is going to significantly reduce the CO_2 emissions of aviation sector as a percentage of world emissions

CO_2 emissions

FORECAST OF AVIATION SHARE OF GLOBAL CO_2 EMISSIONS UP TO 2050

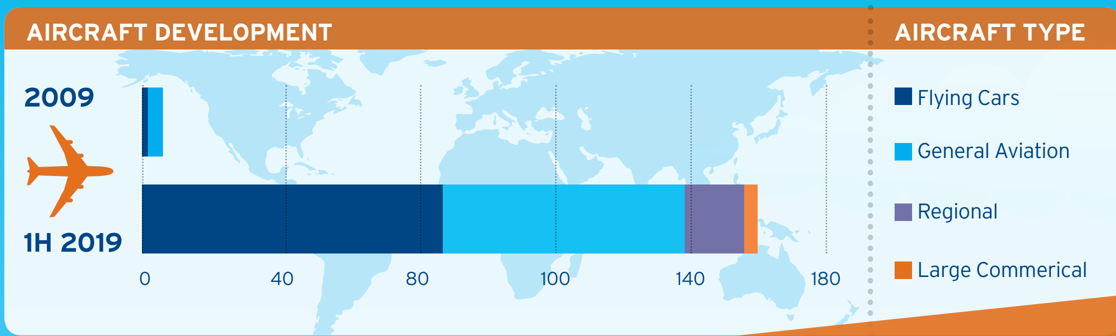
For each scenario, the range is obtained by considering different global emissions Representative Concentration Pathways (RCPs)

Source: IPCC, Roland Berger

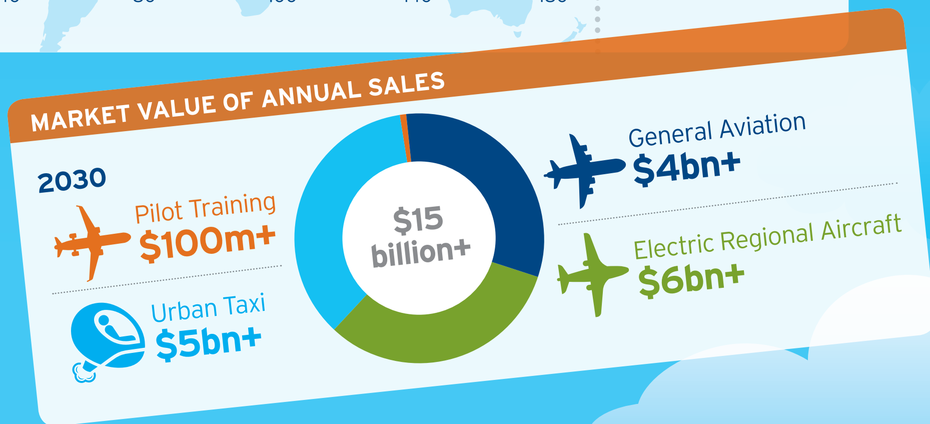


WHAT COULD AN ELECTRIC-POWERED AIRCRAFT DO?

There are ~170 electric aircraft developments around the world today in large commercial, general aviation, regional jets, and urban air mobility ('flying cars'), up from just 8 in 2009...



...and the potential addressable market by aviation activity in 2030 is over $15 billion in annual sales



FLIGHTPATH TO ELECTRIC AIRCRAFT ADOPTION

Contents

Introduction

Electric-powered aircraft have the potential to transform parts of the industry

Innovation in civil aerospace has arguably lagged other sectors such as automobiles, technology, and broader industrials. Although we have had significant improvements in fuel efficiency, reliability, systems, materials (composites), and processes (additive manufacturing), there have been few revolutionary changes and aircraft built today look and operate much like those built 60 years ago. Electric-powered aircraft have the potential to transform parts of the industry, creating opportunities and challenges for original equipment manufacturers (OEMs) and the supply chain. For instance, after decades of high barriers to entry and supply chain consolidation, we could start to see new players emerge as the civil aerospace industry evolves.

We expect them to initially target niche markets, but extend later to regional routes

Like many potential disruptive changes, we expect electric aircraft to initially target niche markets, such as flight training, urban mobility, and general aviation. We believe the market for electric aircraft may extend to regional routes (up to 1,000 miles), such as London to Rome or New York to Chicago, which make up ~60% of the short haul flights and could therefore pose a threat to established players in that space. However, foreseeable improvements in battery power density are unlikely to be sufficient to allow significant penetration of longer routes unless through hybrid or turboelectric technologies.

Figure 1. Aircraft in the 1950s

Source: Citi GPS

Figure 2. Aircraft in 2019

Source: Citi GPS

Figure 3. Car in the 1950s

Source: Citi GPS

Figure 4. Car in 2019

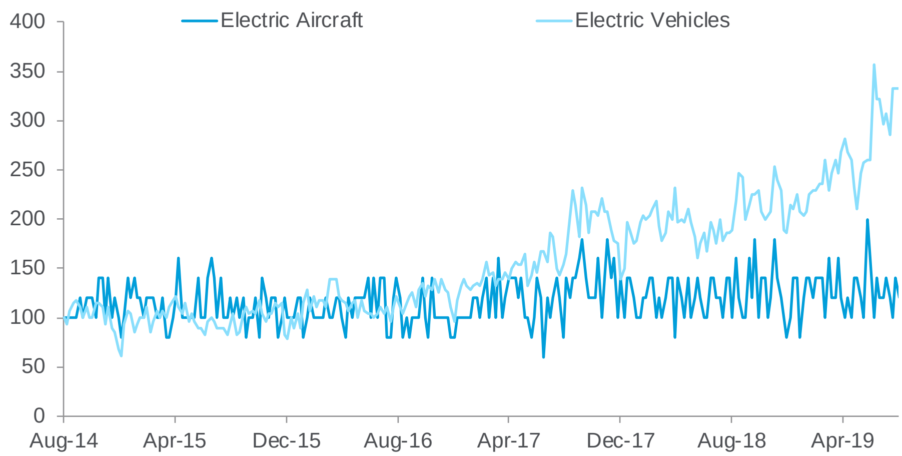
Source: Citi GPS

Electric planes are still at the very early stages of development as current battery technology is still challenging

All-electric cars are starting to become more mainstream. Currently penetration is only at 1% but we expect this to grow to 10% by 2030 (see our recent Citi GPS report Electric Vehicles - Ready(ing) For Adoption for more on electric vehicles) driven by improvements in range, infrastructure, battery degradation, and cost, in addition to government support (taxes and incentives). Citi GPS has also extensively covered networked mobility in our Car of the Future series. Over the last couple of years, we have started to see all-electric technology expand to trucks, where production and sales are set to begin in 2019/2020. However, electric planes are still at the very early stages of development with the key challenge being how to store enough energy to power a flight while leaving enough room for passengers and cargo. In short, the physics just don't work. For example, to power an A320 at full range using current electric battery technology, we estimate the battery weight would need to be around 500,000kg, which is approximately 6-8x the maximum takeoff weight (MTOW) of the aircraft (70-75,000 kg).

While electric vehicles are seeing a significant increase in public interest and media focus, electric aircraft are still 'flying' under the radar from a broad consciousness perspective (Figure 5).

Figure 5. Electric Vehicles Have Seen a Significant Increase in Public Interest vs. Electric Aircraft – Now 15-20x More Searches Compared to 2-3x More for 'Vehicles' vs. 'Aircraft'



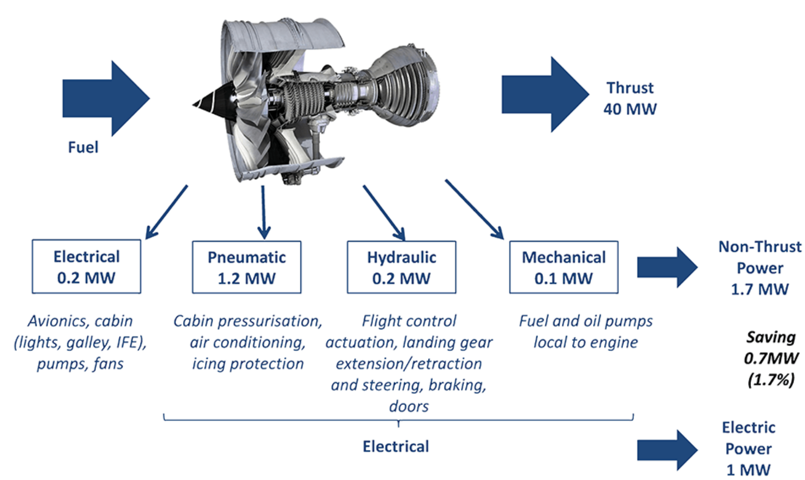
*Represents search interest relative to the highest point. A value of 100 is the peak popularity for the term. A value of 50 means that the term is half as popular.
Source: Citi GPS, Google Trends

Electric is Already Present in Non-Propulsion Systems

There's already a lot of electric power aircraft, just not yet for propulsion

Electric power is already being used for several non-propulsive systems on an aircraft, through the expansion of 'More Electric Aircraft (MEA)' systems, first introduced in the 1980s. This involves using electric power for systems traditionally driven by a combination of hydraulic, pneumatic, electrical, and mechanical power sources — including cabin pressurization, air conditioning, flight control actuation, fuel pumping, and landing gear/braking doors. As shown in Figure 6, powering more systems with electricity can create a 2% fuel savings.

Figure 6. More Electric is Already Prevalent on Recent Aircraft — Using Electric in Place of Pneumatic, Hydraulic, and Mechanical Non-propulsive Systems



Source: Citi GPS, Engine picture – Rolls-Royce Trent 1000, University of Nottingham: The More Electric Aircraft – Why Aerospace Needs Power Electronics

The focus of this report is electric propulsion in an aircraft

Instead of focusing on all the electric powered pieces of an aircraft, this report will focus only on electric propulsion, where an electric motor/engine is used to provide some or all of the thrust/propulsion for an aircraft.

Electric Engines: Fewer Steps than a Jet Engine

Electric engines have far fewer parts than jet engines

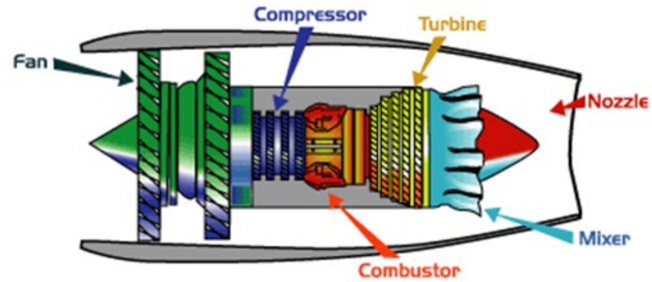
An electric engine works similar to a regular passenger jet turbofan engine, sucking in air, compressing it, and pushing it out back. The key difference is the compressor fan in the front is turned by an electric motor rather than a gas turbine.

An ordinary jet turbofan engine works with the following parts:

1. **Fan:** Accelerates air into (1) the core of the engine via the shaft, and (2) the duct surrounding the core (i.e., 'bypasses' the core).
2. **Compressor:** Squeezes air to high pressures, resulting in increased energy.
3. **Combustor:** Compressed air is mixed with fuel and ignited giving off hot exhaust gases.
4. **Turbine:** These gases spin the turbine blades, which are connected to a long axle, which also turns the compressor and the fan.
5. **Nozzle:** Hot exhaust gases exit at speeds of over 2100 km/h (1300mph), much faster than the cold bypassed air, thereby producing thrust.

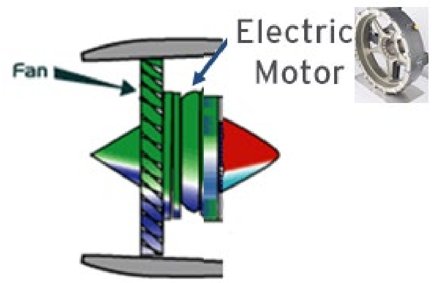
An electric engine skips steps 2-5 and simply uses an electric motor to turn the fan.

Figure 7. Component Breakdown of a Typical Turbofan Engine



Source: Citi GPS, NASA

Figure 8. Component Breakdown of an Electric Engine



Source: Citi GPS, NASA, Motor – Siemens eAircraft SP200D

Electric engines in aircraft are very different than those in automobiles

Electric motors in aircraft are very different than those popularized in automobiles. First, airborne electric engines need to be extremely reliable as there is no room for error at 30,000 feet. Compared to an electric auto engine, they can be made lighter since they don't need as much power at low revolutions per minute given there is less inertia to overcome while slowly accelerating on a runway versus a car, which is stopping and starting constantly. Additionally, electric motors in an aircraft do not need to be as rugged as those used in cars, which encounter potholes and are frequently stressed by torque, and so can avoid heavy casings.

Electric propulsion is particularly effective in stop/start applications, where regenerative braking recovers the kinetic energy and recharges the battery rather than wasting it as heat in the brakes. This gives the greatest benefit in city driving. Aircraft tend to take off, accelerate to cruise speed, and remain at that speed until coming in to land meaning there's limited opportunity for regenerative braking. .

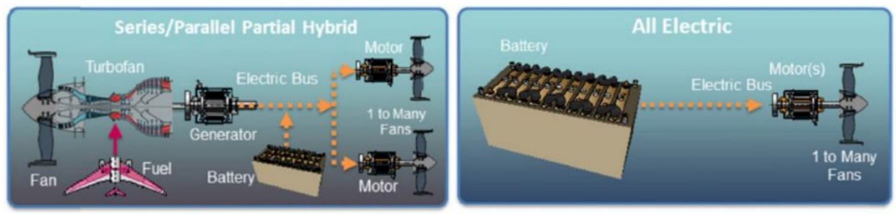
There are three ways in which electric-propulsion can be set up:

1. **All-electric System:** Using batteries as the only source of propulsion power on the aircraft.

2. **Series/Parallel Hybrid System:** Using gas turbine engines for propulsion and to charge batteries which are used during one or more phases of the flight.

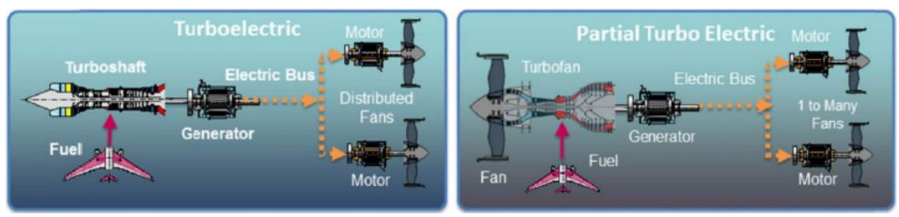
3. **(Partial) Turboelectric System:** No batteries are used, instead a turbine-driven generator is the only or partial power source. Partial turboelectric systems can use liquefied natural gas instead of jet fuel and generate electricity in-flight by integrating a solid oxide fuel cell with the turbine engine.

Figure 9. Series/Parallel Partial Hybrid and All-electric Systems



Source: Citi GPS, NASA

Figure 10. Turboelectric and Partial Turbo-Electric Systems



Source: Citi GPS, NASA

All-electric and hybrid setups are beneficial for short-range and urban mobility, while turboelectric is more fuel-efficient and is appropriate for larger jets. In fact, there are several regional jet partial turboelectric and parallel hybrid potential offerings targeted for entry into service in the 2030s, while building a long-term vision for fully turboelectric.

Electric Propulsion has Many Benefits

Reduced Emissions

Emissions from air travel could more than triple by 2050

Air travel is responsible for ~2% of global man-made carbon dioxide (CO_2) emissions (897 million tons in 2018) according to the International Air Transport Association (IATA). With air traffic forecast to continue it's 4-5% per year growth through the mid-2030s, CO_2 emissions from the industry could more than triple by 2050. Electrical propulsion has the potential to significantly reduce aviation's impact on global climate change, particularly important as the EU's Flight Path 2050 program targets a 75% reduction in CO_2 emissions per passenger kilometer, and the United Nation's CORSIA scheme aims to ensure any rise in international aviation emissions beyond 2022 are offset elsewhere.

Switching to hybrid- and all-electric propulsion systems would limit aviation's share of global CO^2 emissions

Consultant Roland Berger have estimated a market-driven switch to hybrid and all-electric propulsion systems would mean the aviation share of global CO_2 emissions would be limited to 5% of total emissions, while regulation-driven change could lower this even further. Additionally, infrastructure for urban mobility solutions such as air taxis and regional electric aircraft produce significantly less emissions relative to roads and high-speed rail, which use a lot of concrete (very high CO_2 consumption).

Response to 'Flight Shaming'

This could be a response to the growing trend in 'Flight Shaming'

Flight shaming describes the social guilt associated with carbon emissions resulting from air travel journeys. This trend is gaining popularity and has resulted in many passengers vowing to reduce their air travel footprint by seeking alternative means of transport or avoid traveling altogether. This is particularly prominent in Europe, where activists such as Greta Thunberg have publicized the Swedish term 'Flygskam', aka flight shaming, while other countries have their own versions of the phrase (Lentohapea in Finnish, Vliegschaamte in Dutch and Flugscham in German). Electric propulsion could be a response from aviation companies to tackle this increasing trend, given that electric aircraft has the potential to significantly reduce emissions, with even fewer emissions than trains, when taking into account building the infrastructure required for operation.

Reduced Maintenance Costs and Increased Reliability

Electric propulsion has only one moving part therefore lower maintenance costs and higher reliability

In an all-electric motor, there is a lower risk of mechanical failure and fluid leaking as there is only one moving part. As a result, electric aircraft should theoretically have fewer failures than traditional aircraft. This is particularly beneficial in general aviation, which tends to have a higher accident rate due to a variety of reasons, including reciprocating engines, shorter flights, irregularity of operations, and potentially less rigorous maintenance.

Quieter Operation

Proposed electric air taxis are 10x quieter than helicopters and closer to the sound of a vacuum cleaner

An all-electric motor reduces noise pollution. Beyond lower noise levels being a more pleasant experience for all involved, quiet operations allow aircraft to operate closer to big cities and densely populated areas. This is particularly pivotal in urban mobility, where many of the proposed 'air taxis' are targeting running sound levels of 60-70 decibels (dB) — at most equivalent to the sound of an air conditioner/vacuum cleaner. This is about 10x quieter than a helicopter (~100 dB). Both the U.S. and Europe have strict noise thresholds which need to be addressed in the more urbanized centers where an increase in airborne solutions is being considered. For instance, the U.S. Federal Aviation Authority (FAA) has set a threshold for community noise at a 65 dB day-night level (a day-night level is defined as the average noise level over a 24-hour period with a further 10 dB added to noise between 10pm-7am to be more conservative of any noise between these times). In Europe, the standard is to split the weighting into 3, adding 5 dB for evening and 10 dB for night. However, community noise threshold levels will likely differ by type of neighborhood — industrial vs. residential vs. suburban. The point is there are regulatory limits to how, when, and where different sorts of aircraft can operate. Quieter aircraft could significantly expand the operations envelope.

Reduced Operating Costs

Fuel is the largest operating expense of an airline, making up 20-35% of overall costs. All-electric and hybrid-propelled aircraft would reduce the operating expense burden significantly. More efficient operations (due to noise and/or capability) can also cut costs. And there are further potential benefits from the introduction of unmanned operations as pilot wages are approximately one-third of all staff costs. To be sure, it will take longer for unmanned operations to gain the public trust and regulatory approval necessary to drive material cost benefits.

Convenience and Latent Demand

Reduced noise pollution would allow an electric aircraft to land and take off closer to city centers, which would open up 'latent demand', i.e., demand for trips to locations that did not previously make sense — too far for a car, but not worth going to the airport to catch a flight.

Infrastructure Costs

Infrastructure costs are lower as roads and rails don't need to be built or maintained

There are no roads or rails to maintain with air travel, therefore infrastructure spending is significantly less. The World Bank estimates the infrastructure cost of high speed rail (tunnels, viaducts etc.) could cost around $25-$50 million per kilometer in Europe or the U.S. and $17-$20 million per kilometer in China. A vertical take-off and landing (VTOL) air taxi 'just' needs landing pads with charging facilities, which could be integrated into pre-existing structures.

Electric Propulsion Also has Some Key Limitations

Technology

Current battery technology doesn't have enough energy density for large planes or large distances

The energy density in current battery technology is not high enough for large planes and/or long distances. To power an A320 with batteries you need around 500,000 kg of battery versus 15-20,000 kg of jet fuel. That required weight is 6-8x heavier than the maximum takeoff weight (MTOW) of the aircraft itself (70-75,000 kg). As a result, we would need to see a step-change in battery technology, such as developments in lithium-sulfur or lithium-oxygen, before we see mass adoption, certainly in larger aircraft flying longer routes. We discuss this in more detail in the next section.

Investment Costs

Similar to any new technology, significant investment would need to be made in design, production, and testing before an electric aircraft could enter service. This is particularly true for new concepts, such as air taxis, where a significant number of new players have emerged over the last few years attempting to develop a leading solution to target this market.

Charging and Other Infrastructure

Investments will need to be made in charging infrastructure — either quick-charge capabilities or battery replacement

With increased electric aircraft adoption, airports will need to invest in charging infrastructure. This infrastructure could be in the form or either quick-charge capabilities or battery replacement depending on how operators choose to maximize utilization and minimize downtime. To ensure attractive pricing for customers, asset utilization is key for airlines to ensure planes maximize revenue-generating airtime, and as a result, airlines may choose (dependent on technology and charging time required) to simply replace the battery with a fully-charged one when prepping the plane for its next trip.

Given the cost of batteries is likely to be a material element of the system, having quick-change batteries will increase the required investment, reducing return on assets. For air taxi operations, spending would also need to focus on landing pads, which need to be in convenient locations (e.g., near city centers) such as on top of existing buildings and/or in open spaces. In short, while all of this spending is theoretically possible, it needs to drive required returns to make the investment worthwhile.

Regulation and Safety

Regulators are already starting to think about electric aircraft…

The Federal Aviation Authority (FAA) and European Union Aviation Safety Agency (EASA) are the leading global aviation authorities, but each country has their own specific local authorities (e.g., the U.K. Civil Aviation Authority). Current regulations will need to be expanded to include hybrid-electric and all-electric aircraft. Research on increasing safety in civil aerospace has been relentless and each new technology has had to show it is at least as safe as the preceding technology. Similar to their piston-engine peers, the level of safety requirements for electric aircraft will be different depending on the purpose of the aircraft. For example, the safety requirements for a sports/leisure aircraft is 100 times lower than an aircraft used for commercial operations.

…but regulations for air taxis will need to be created from scratch

For urban mobility/air taxis, regulations will have to be created from scratch given they fall between rules for fixed-wing craft (airplanes) and rotorcraft (helicopters). It will take some time to develop these regulations as the market is still immature, marked by multiple concepts and a lack of experience (little actual flight time). There is also added complexity for eVTOL vehicles. Similar to extended-range twin-engine operating performance standards (ETOPS) for planes, air taxis will likely also be limited to operating at a maximum distance from a landing pad in case of an emergency landing. They will also have flight path and airspace restrictions and as is the case with current aircraft travel, various stakeholders will need to ensure security to avoid any potential threats (e.g., terrorism).

Public Perception

The public might resist electric aircraft on perceptions of safety

Assuming advancements in battery technology and appropriate testing/flight hours with relevant redundancy/fail-safe mechanisms are in place, electrical-propelled and hybrid planes will likely prove advantageous relatively quickly given the benefits from lower noise pollution, reduced operating costs (which should filter through to ticket prices), and reduced emissions. But beyond just business and operations concerns, public perception could also be a hindrance as air travel is still considered a relatively risky form of travel (despite data to the contrary). Using new technology that might look different or removing a human from operations could also generate mental blocks for travelers.

Emissions – Electric Could Reduce Emissions By 50%

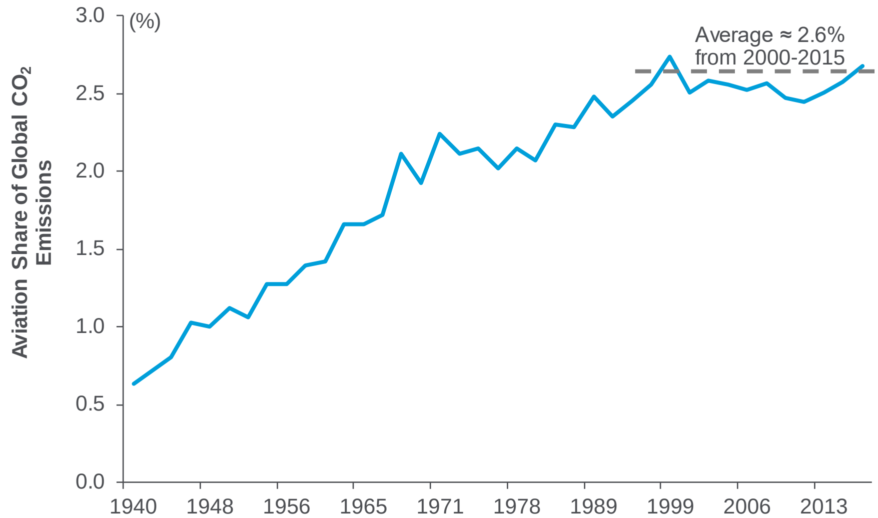
Managing Down Aviation's Impact on Emissions

Aviation's share of global CO_2 emissions has remained constant at 2.6% since the early 2000s

In the past 50 years, improvements in fuel consumption and the corresponding CO_2 emissions per seat were largely market-driven ways to reduce costs. Fuel burn per seat has decreased 1-2% per year while annual capacity has grown by 4-5%, leading to a ~3% annual increase in aviation CO_2 emissions. This increase was approximately in line with total global emissions growth and as a result, aviation's share of global CO_2 emissions has remained constant at 2.6% since the early 2000s.

Figure 11. After Growing Steadily Through the 20th Century, the Aviation Share of Global CO_2 Emissions have Stayed Flat at ~2.6% in the Last ~15 Years

Aviation share of global CO_2 emissions over 1940-2015



Source: IPCC, Atmospheric Environment, Roland Berger

However, this share is likely to increase going forward due to four factors:

1. Revenue passenger kilometers are forecast to continue growing at 4-5% per year into the mid-2030s, according to estimates by leading aerospace OEMs. This expected pace is ahead of general GDP growth.

2. The rate of reduction in fuel burn is likely to slow as gas turbine technology and the conventional tube-and-wings architecture of aircraft become increasingly mature.

3. New technologies, such as supersonic and urban mobility (if hybrid is used) risk increasing emissions even further if aviation further penetrates the transportation landscape.

4. New regulations are forcing other industries to change, leveraging technology that may or may not already exist. As a result, aviation has to 'keep up', which in some cases requires new technology like electrification.

Aviation could account for 10% of global CO_2 emissions by 2050, with this figure possibly increasing up to ~24% of global emissions

Roland Berger's emissions model estimates if aircraft fuel consumption continues to improve 1-2% per year by market forces alone, aviation could account for 10% of global CO_2 emissions by 2050, with this figure possibly increasing up to ~24% of global emissions should other industries reduce their emissions as quickly as the most optimistic projections suggest. Under a scenario where additional new systems and airframe architectures lead to greater improvements in fuel consumption, aviation's share of global CO_2 emissions could still more than double to 7% by 2050. So it would be best for the aviation industry to get ahead of this issue.

Electrical propulsion is probably required if we are to see further improvements. Modeling a market-driven switch to hybrid- and all-electric propulsion systems, aviation's share of global CO_2 emissions is limited to 5% of total emissions.

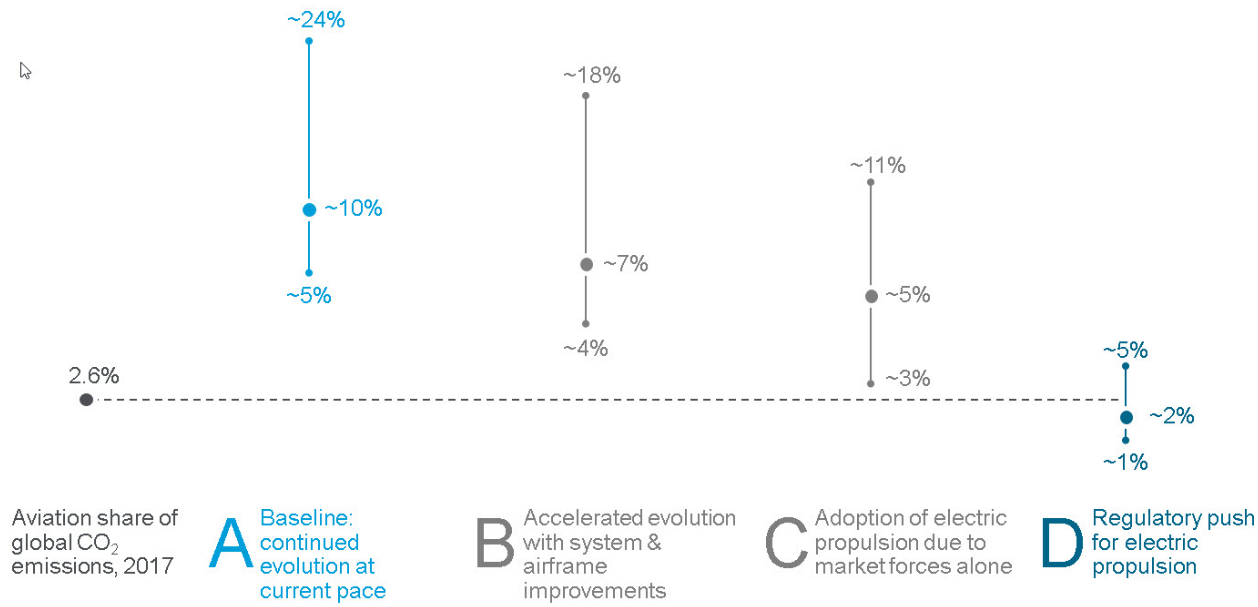
By incentivizing aircraft operators to switch to electric aircraft more rapidly aviation share of global CO_2 emission could decrease to 2%

The main factor limiting a faster reduction in CO_2 is the longevity of aircraft — a typical aircraft remains in service for 25 years on average, leading to very slow fleet turnover. By incentivizing aircraft operators to switch to electric aircraft more rapidly — perhaps via regulation — aviation share of global CO_2 emission could decrease to 2%.

Improvements here are essential in helping the aviation industry reach various goals. This includes the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) goals, set by the International Civil Aviation Authority (ICAO) at the United Nations, which aim to make all growth in international aviation after 2020 carbon neutral. Beyond this, electrification will also be pivotal in supporting the European Union's 'Flight Path 2050' target of cutting CO_2 emissions per passenger kilometer by 75%.

Figure 12. Adoption of Electric Propulsion to Significantly Reduce the CO_2 Emissions of Aviation Sector as Percentage of World Emissions

Forecast of aviation share of global CO_2 emissions up to 2050. For each scenario, the range is obtained by considering different global emissions Representative Concentration Pathways.



Source: IPCC, Roland Berger

Just as market forces provide the innovation and technological advancements required for the electrification of aircraft, regulatory bodies are equally important in enabling electric aviation, both to incentivize stakeholders to adopt the nascent but promising technology and to create the safest and most progressive environment for innovation.

It's a good sign that both the FAA and the EASA are beginning to adapt regulations to accommodate possible certification of electric aircraft in the future

Although fully-electric regional and large commercial aircraft are years from entering the aviation market, it's a good sign that both the FAA and the EASA are beginning to adapt regulations to accommodate possible certification of electric aircraft in the future. The EASA has revamped its rules (CS-23) to remove specific technical design requirements which are less relevant for electric aircraft, replacing them with safety-focused objectives. In 2018, the FAA approved testing for the electric vertical takeoff and landing (eVTOL) Surefly by providing an experimental airworthiness certificate, signaling the FAA's support in the development of electrical propulsion systems.

It's Not Just Carbon Emissions

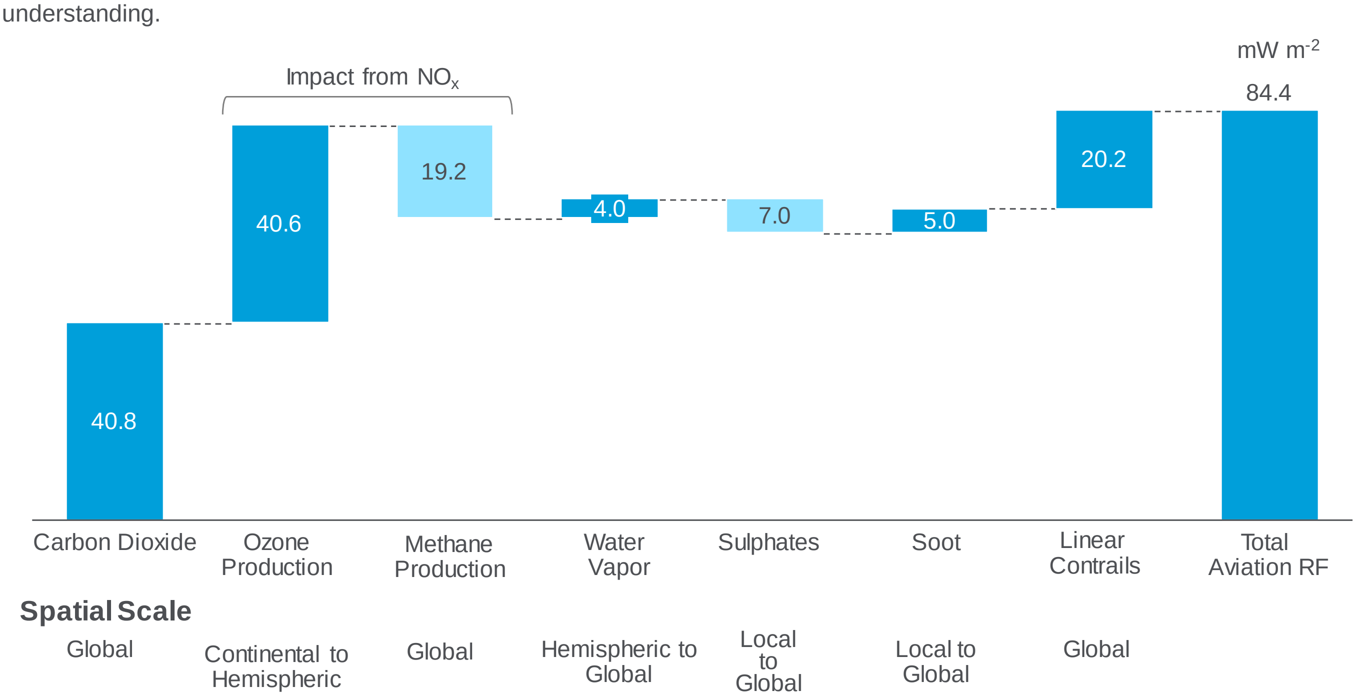
Aviation not only emits CO^2 but also contributes to radiative forcing

Interest in the impact of aviation on the climate is not new. Research started in the 1970s on the possible depletion of ozone (O_3) in the stratosphere due to supersonic aircraft. In the 1980s, scientific research shifted towards studying the impact of nitrogen oxides (NO_x) and greenhouse gases generated from both subsonic and supersonic aircraft. In their 1999 report, the Intergovernmental Panel on Climate Change (IPCC) focused on the metric of 'radiative forcing' (RF) as a way to more comprehensively study the impact of aviation emissions on the climate. RF, measured in units of W/m^2, refers to the perturbation of the energy budget of the Earth, caused by changes in the concentration of various gases and particles in the atmosphere or other factors that affect the absorbance of solar radiation. A positive RF value refers to an increase in energy on Earth, implying a rise in temperatures, and vice versa.

Today, it is well established that aviation contributes to the following components of radiative forcing, as shown in Figure 13.

Figure 13. CO2 Emissions Are Expected to Make Up the Largest Component of Radiative Forcing by Global Aviation

Estimated radiative forcing due to global aviation in 2020, and breakdown by contributing effect (adapted from Lee et al in Atmospheric Environment). RF due to induced cirrus cloudiness has been excluded due to the poor level of scientific understanding.



Source: IPCC, Atmospheric Environment, Roland Berger

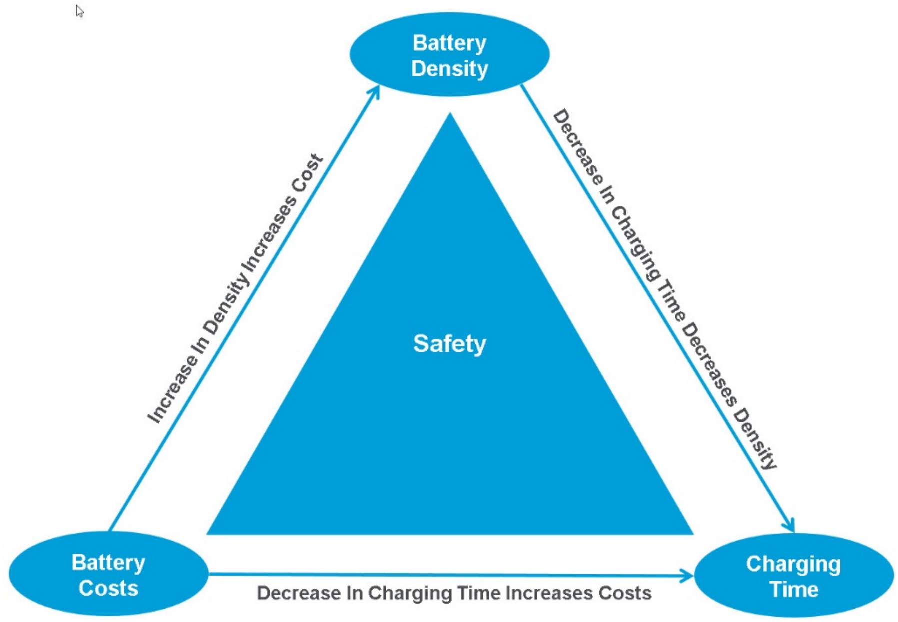
Battery Technology – A Key Limiting Factor

Battery technology is the main limiting factor in the adoption of electric aircraft

Carrying sufficient energy to fly far enough is the main limiting factor in the adoption of electric aircraft. The most common energy source component for electric aircraft are batteries given the relatively better energy density and advanced developments for use in the auto sector. However, while the auto sector is focused on volumetric energy density (Watt-hour per liter), the key limiting factor for aircraft is weight, and hence the focus is more on gravimetric energy density (Watt-hour per kg). Other potential technologies include fuel cells (hydrogen/oxygen), solar cells, and ultracapacitors. We focus on batteries in this report, which we see as the most popular choice in electric aircraft developments. Despite the focus on volume over weight, it is likely electric aircraft batteries will piggyback on the advances made in the electric vehicle market given the relative size of the market and investment.

As discussed in our Citi GPS report on Electric Vehicles, the interplay between battery size and efficiency, charge time, and cost is problematic, with the added complexity of higher levels of safety required for aviation.

Figure 14. Citi's Battery Challenges Diagram



Source: Citi GPS: Electric Vehicles

Lithium-ion batteries are the most prevalent being explore for aviation

The most prevalent battery type being explored for aviation is lithium-ion, although there are other options (shown in Figure 15); however, as the figure shows, current battery technology needs to improve in terms of energy density as it still lags significantly behind gasoline.

Magnesium batteries have a better energy density, but are likely decades from commercial readiness. Solid-state lithium is safer because it's non-flammable, however it has a shorter life due to its limited number of charging cycles. Sodium-ion batteries on the other hand, have a long life cycle, but a low energy density. New developments into lithium-sulfur and lithium-oxygen (aka lithium-air) could also be a potential solution with higher energy densities potentially reaching 4,000 watt-hours/kg. Lithium-oxygen can also be beneficially integrating into existing systems used in many aircraft and the oxygen that is pumped in during use can be recovered while charging and reused.

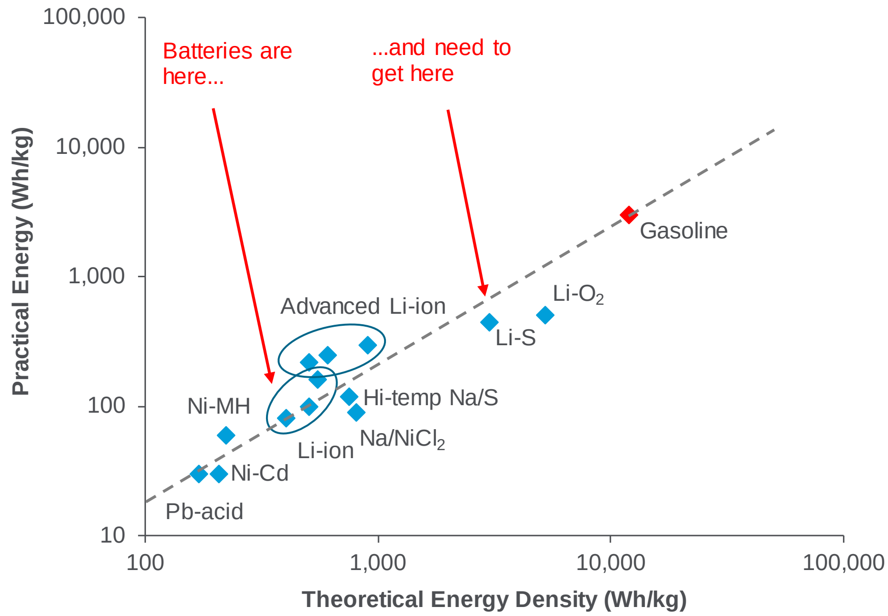
Focus on battery technology is widespread and goals of 500 Wh/kg and a 1,000 cycle life are targeted

There is a significant focus from governments, research bodies, and companies on battery technology. In 2016, the U.S. Department of Energy established a consortium (Battery500), which included several universities and corporates, to build a battery pack with a specific energy of 500 Wh/kg and a 1,000 cycle life. To achieve this goal, the group is focusing on (1) a high nickel content cathode with a Li-metal anode, (2) sulfur cathode and Li-metal anode; and (3) varying electrode and cell design. Additionally, in Japan, there is a corporate focus to commercialize 400 Wh/kg Li-Sulphur battery packs by 2020, along with high energy chargers capable of recharging in ~10 minutes.

High-energy chargers are also a focus

Equally exciting are developments in high-energy chargers which would be capable of recharging in as little as 10 minutes. Additional research into pulse chargers is already showing improved cycle life and improved maintenance of maximum charge capacity over time. Achieving rapid charging for large battery packs is as important if not more important than achieving high specific energy batteries, given the importance of utilization in commercial aviation.

Figure 15. Practical vs. Theoretical Energy Densities of Several Electric Batteries and Gasoline



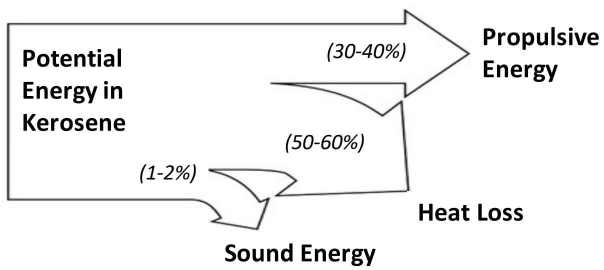
Source: Citi GPS, The Royal Society of Chemistry

Jet Fuel Generates 20x the Power per Kilogram vs. Current Batteries

Jet fuel has an energy density that is 70x larger than batteries

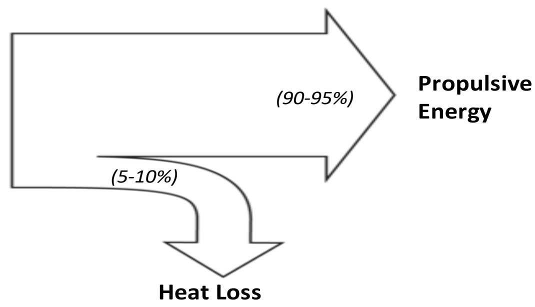
Jet fuel has an energy density that is 70x larger than batteries. One kilogram (kg) of jet fuel stores around 12,000 Watt Hours (Wh) of energy, while one kg of lithium-ion battery stores 150-300 Wh of energy. Offsetting this, an electric motor is more efficient in converting this to thrust (Figure 16 and Figure 17).

Figure 16. Sankey Diagram of Energy Output for Kerosene



Source: Citi GPS

Figure 17. Sankey Diagram of Energy Output of an Electric Battery



Source: Citi GPS

If we calculate the horsepower generated by a jet engine and an electric engine to the propeller/fan per hour for each kilogram of fuel, we get the following:

- **Jet Engine:** Jet engine efficiencies typically range from 30-40% (e.g., CFM56 is 30.5%, LEAP is around 35% and GE9X is 40%) so 12,000 Wh x 35% gives us 4,200 or 5.6 hp of shaft power to the fan per hour.
- **Electric:** Electric engines have an efficiency of around 95%, with 10% lost in the power electronics, so 250 Wh x 95% x (1-10%) giving us 214 or 0.28 hp of shaft power to the fan per hour.

As a result, the jet engine generates about 20x the hp to the fan/propeller per hour for each kilogram of fuel versus batteries.

Current Battery Technology Limits a Narrow Body Aircraft Range to 250 Miles

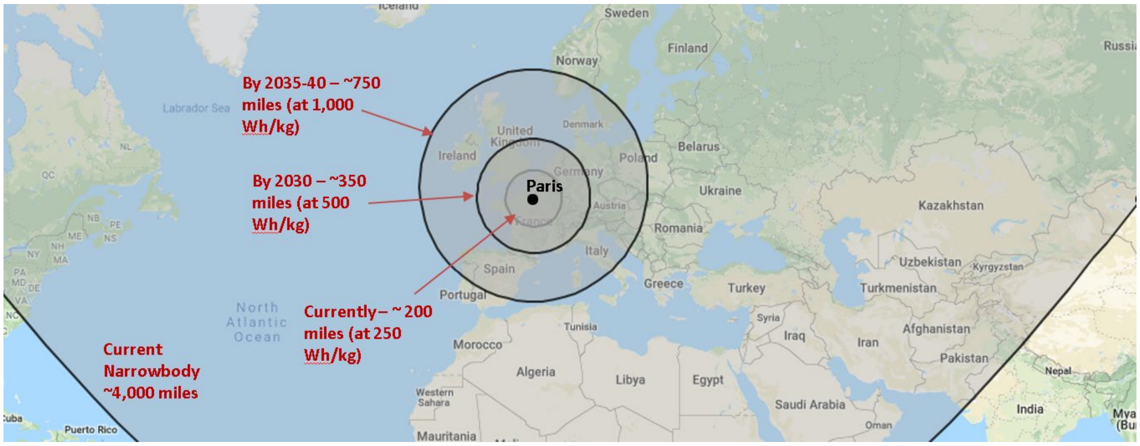
At current densities, the weight of the battery to carry about 180 passengers, would need to be around 500,000 kg

At current densities, the weight of a battery required to carry about 180 passengers, would need to be around 500,000 kg, which is 6-8x the maximum take-off weight of an A320 (70-75,000 kg) versus15-20,000 kg of fuel for a jet engine. Even more challenging is that the total weight of the aircraft would need to be over 1,000,000 kg which is more than 2x the weight of a full A380.

Alternatively, if we assume 15-20,000 kg of batteries (the same as the current A320 fuel load), we estimate a practical range of 150-200 miles at current energy densities and 300-400 miles at 500 Wh/kg. This practical range takes into account a buffer as some distance can be lost due to winds, weather, and diversion, in addition to landing with 5-10% reserves.

At the blue sky level (maybe by 2040) of 1,000 Wh/kg, we estimate a 70,000 kg A320-sized electric aircraft might have a practical range of 700-800 miles (vs 3,500-4,000 miles today), which could be enough to be used for regional travel.

Figure 18. By 2040, Developments in Energy Densities Could Mean an A320-sized Electric Aircraft Could Fly a Practical Range of 700-800 Miles



Source: Citi GPS, *Great circle routes mercator distortion

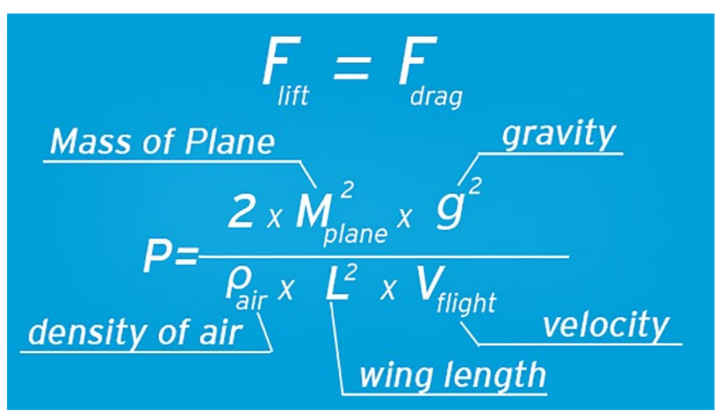
However, there are some limiting factors here impacting comparability. First, this does not fully take into account the fact that battery weight stays the same throughout an electric aircraft flight while the jet engine aircraft becomes lighter over the duration of the flight as fuel is being burned, reducing the fuel burn rate — long-range jets typically land at 60% of their takeoff weight.

It is also worth noting that electric aircraft under development are targeting speeds more aligned with turboprops at 300-400 mph rather than the ~500 mph that narrow-body aircraft travel. This means flight times can take ~1.5x longer for an electrically-propelled aircraft compared to a traditional turbojet narrow-body. This probably is immaterial for shorter flights, where time at the airport and delays make up a significant proportion of total travelling time, but for longer distances may prove to be unacceptable, even if technically feasible.

Smaller aircraft are more likely to benefit from changing battery technology before larger planes

This becomes more viable for smaller aircraft. As shown in the equation in Figure 19, the amount of power required rises with the square of the weight — if the weight of the aircraft is ½, the power needed to drive the aircraft is reduced by a factor of four (i.e., ¼). For example, to fly a Cessna 172, the weight of the battery would need to be around 500 kg (approx. 2/3rd of the maximum takeoff weight). Assuming no reduction in flight speed or increases in energy used per flight, this reduces flight time from four hours to two hours, which is much more reasonable.

Figure 19. Equation of Power Needed for Lift of an Aircraft



Source: Citi GPS, YouTube: Real Engineering channel

Government 'Push' Factors Are Needed

Government will need to push demand through safety certification and regulation plus infrastructure and logistics

The use of electric in general aviation (2-14 passengers), pilot training, and urban mobility (10-20 minutes flight time) is within sight of current battery technology. But for this to be widespread, electric aircraft have to be certified safe to fly with even more stringent requirements for consumer use. Infrastructure (e.g., charging) and logistics (permissible flight paths) are still a challenge, in addition to the significant cost and R&D involved in developing electric aircraft.

Figure 20. Fjords in Norway Mean Travel Routes by Road Are Very Inefficient

Source: Citi GPS, Google Maps

The adoption of electric cars has been helped by 'push' factors from the government to drive demand (taxes, incentives, regulations), despite the clear benefits to consumers (less noise, less pollution) and operators (lower operating and maintenance costs). Similarly with the adoption of electric aircraft, push factors from the government would likely be needed until the technology is proven given the high associated cost and initial regulatory challenges, despite the clear benefits However, given the longer life cycle of an aircraft (typically 20-25 years for a traditional commercial aircraft vs. 8-10 years for a car) adoption will likely be slower than in autos.

Norway has already pledged to make all domestic aviation electrically powered by 2040 based on a conducive landscape (fjords and disparate small airports) and a commitment to emission reduction. A few of the local carriers are aiming to have electric flights in operation by 2025. Figure 20 shows how a ~20 km, 30 minute drive could be replaced by a two-minute flight. However, a crash during a test in August 2019 could set back these plans.

As battery energy density is improved, the use case for electric aircraft proven, and media coverage picks up, we expect to see other countries setting targets. The autos sector has already seen this shift with bans on new gasoline and diesel car sales in the Netherlands by 2030, and in France and the U.K. by 2040; while Norway is targeting for all new cars sold as soon as 2025 to be zero emissions.

What Don't We Cover in this Report?

In this report, we have explored what we believe are potential target markets for electric aircraft by 2030 and highlighted the potential for hybrid-electric aircraft on narrow-body routes beyond 2030.

Autonomous flight is also a topic which has been running in parallel with the electric aircraft discussion, particularly as the technology for autonomous cars continues to improve. Autonomous cars are already being tested on real roads and many auto companies have committed to a producing a driverless car by 2021. (See our January 2019 Citi GPS on the Car of the Future.)

We don't expand on the implications of autonomous flight in this report

We do not expand on the implications of autonomous flight in this report, but as we mentioned in our 2017 Citi GPS Disruptive Innovations V report, autonomous flight should, in theory, reduce risks from human error and increase utilization rates of aircraft. Pilots account for one-third of airline labor costs and airlines quite often pay for training costs, which can be significant for larger planes. As a result, autonomous flight could materially reduce expenses for airlines, with the added benefit of reducing delays/cancellations from (1) pilots falling ill; (2) safety rules requiring certain amounts of rest after extended work shifts; (3) pilot strikes; and (4) pilot shortages, which are becoming a growing concern.

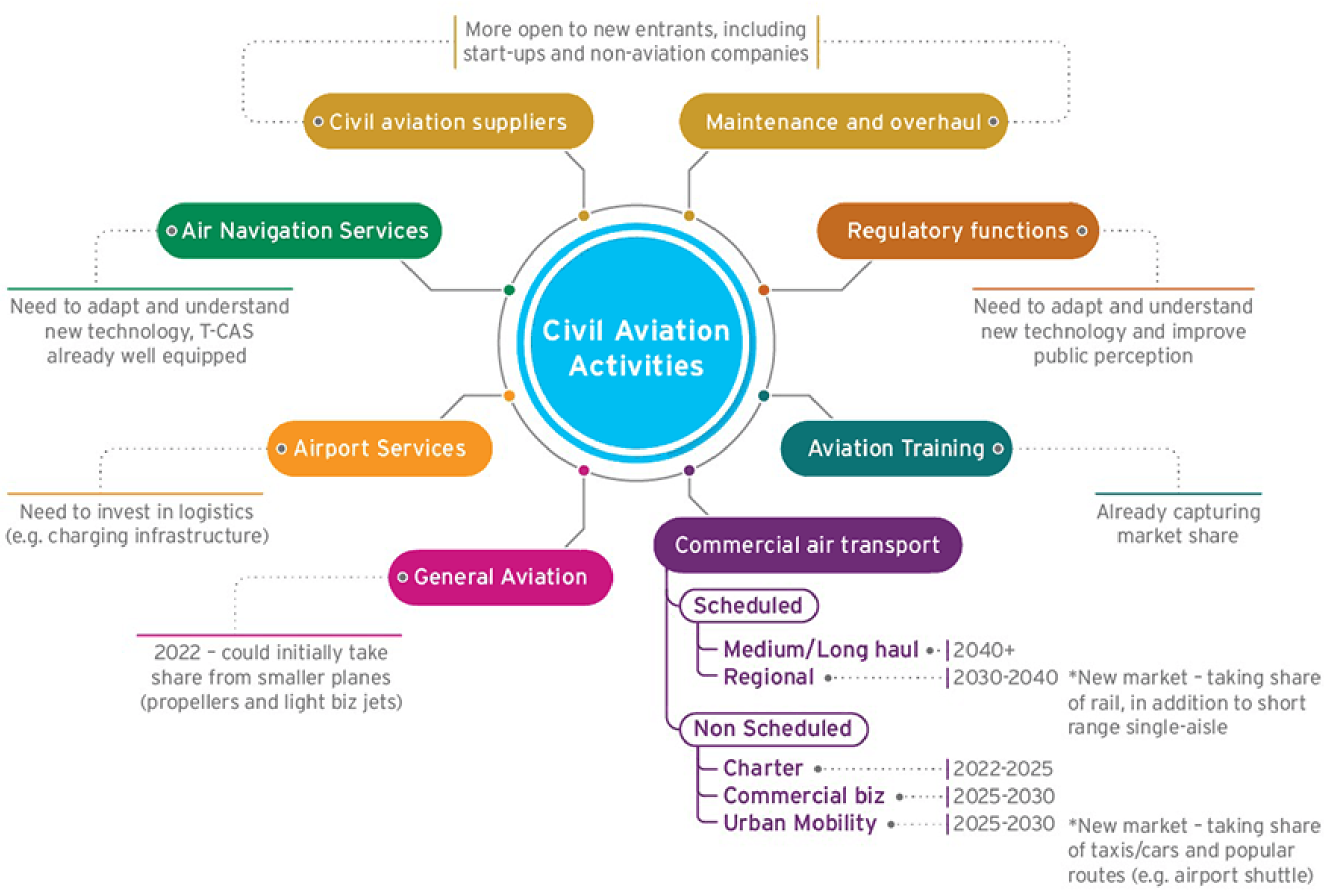
Logistically, automating air traffic should be easier than vehicle traffic given the lack of pedestrians and given that some systems, such as T-CAS which is a traffic collision avoidance system, are already in place to reduce incidences of mid-air collisions while the ICAO requires most commercial aircraft to be equipped with transponders (aircraft with maximum take-off weight of over 7,500kg or carrying more than 19 passengers). However, customer acceptance is still a key headwind for the prospects of autonomous flights. As a result, we expect to see single pilot freighters first, followed by single pilot passenger aircraft (currently most airline require two pilots in the cockpit at all times). Once confidence in the technology builds, we think we will then start to see fully autonomous flights. This is particularly important in smaller aircraft and air taxis, where the weight of the pilot is a significant proportion of the useful payload and therefore will limit its economic viability.

What Could an Electric-Powered Aircraft Do?

Electric aircraft will touch the whole commercial aerospace ecosystem

Developments in electric aircraft technology will have a significant impact across the aerospace industry — from infrastructure spend at airports (charging capabilities) and re-training staff (cabin crew, ground staff, mechanics), to opening up the supply chain and OEMs to completely new entrants/competitors. Regulators will also need to adapt and understand these new technologies in order to properly govern and set procedures in place which will be crucial in building customer confidence and perception. Figure 21 shows the variety of impacts electric aircraft could have civil aviation.

Figure 21. Impact of Electric Aircraft on the Commercial Aerospace Industry (Defined by ICAO's Classification of Civil Aviation Activities)

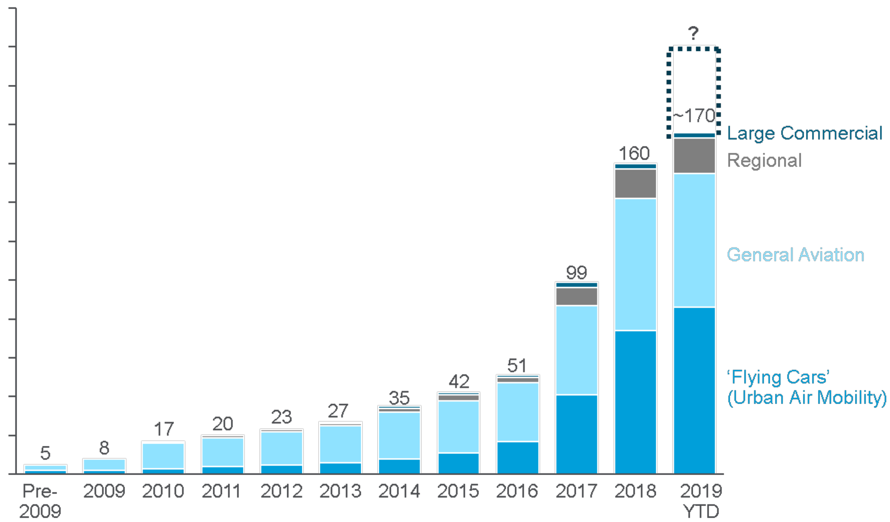


Source: Citi Research

Electric Aircraft Around the World

The first electric aircraft was born in the early 1880s. It consisted of a lighter-than-air dirigible, to which the Tissandier brothers attached an electric motor. However, the rise of oil and commercialization of the internal combustion engine proved oil-derived fuels to be more effective than electric in powering flight. Driven by significant improvements in electrical technologies (especially batteries), it was not until the late 2000s that a resurgence in electric aircraft development began.

Figure 22. There Are ~170 Electrical Aircraft Under Development Around the World Today



Note: Only includes with first flights after 2010

Source: Roland Berger Electric Aircraft Database

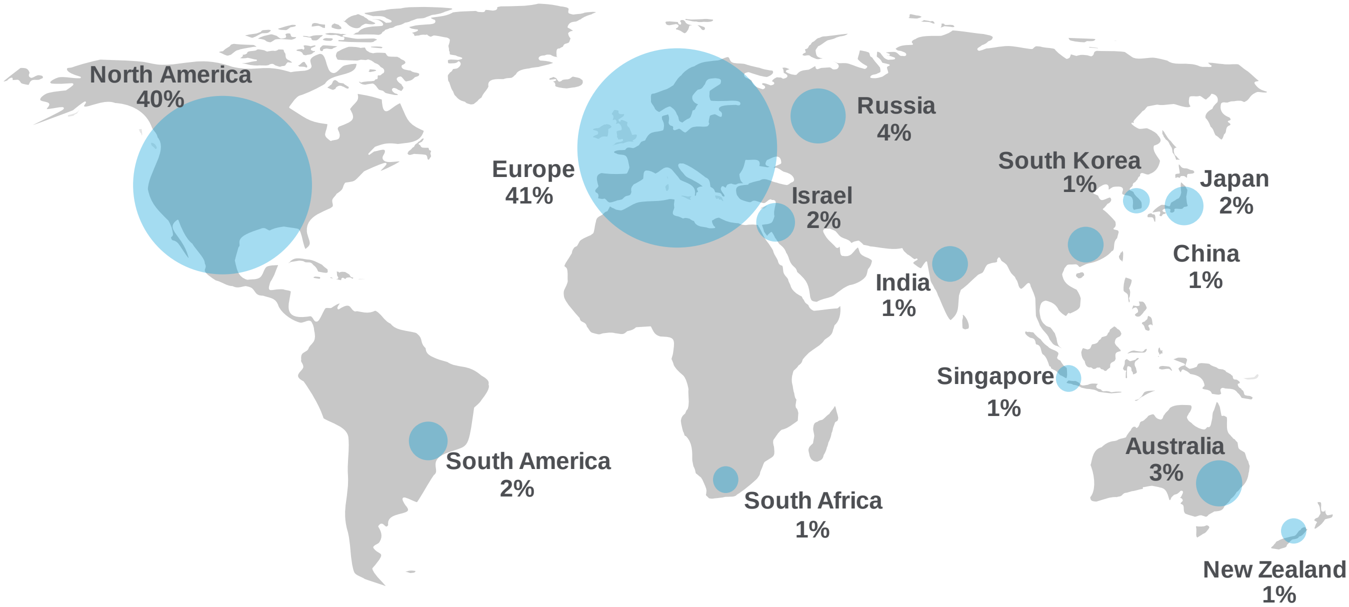
Announcements on electric aircraft under development was steady from 2009 to 2016 but a flood of announcements started in 2017

A steady stream of news regarding new electric aircraft under development started around 2009 and the number of new announcements grew about 30% year-over--year through 2016. In 2017, a flood of announcements began with the number of electric aircraft under development increasing 50% per year from ~50 to ~170. Emblematic of the pioneering spirit guiding electric aircraft development, this rapid growth has been driven primarily by start-ups which now constitute ~70% of aspiring OEMs in this market. Purely academic groups have also increased involvement recently and now make up around 5% of new projects. Large aerospace companies have been relatively slower to announce developments but still constitute ~16% of projects.

Urban air mobility announcements have been a driver of growth

Another driver of growth has been the emergence of the urban air mobility (UAM) trend, which is now being increasingly legitimized by travel authority and government engagement. UAM developments have grown at a faster pace than all other aircraft segments, at ~90% per year since 2016, and as expected, the fastest growing platform type is the electric Vertical Take-Off and Landing (eVTOL) aircraft.

Figure 23. Most Electric Offerings Are Centered in North America and Europe



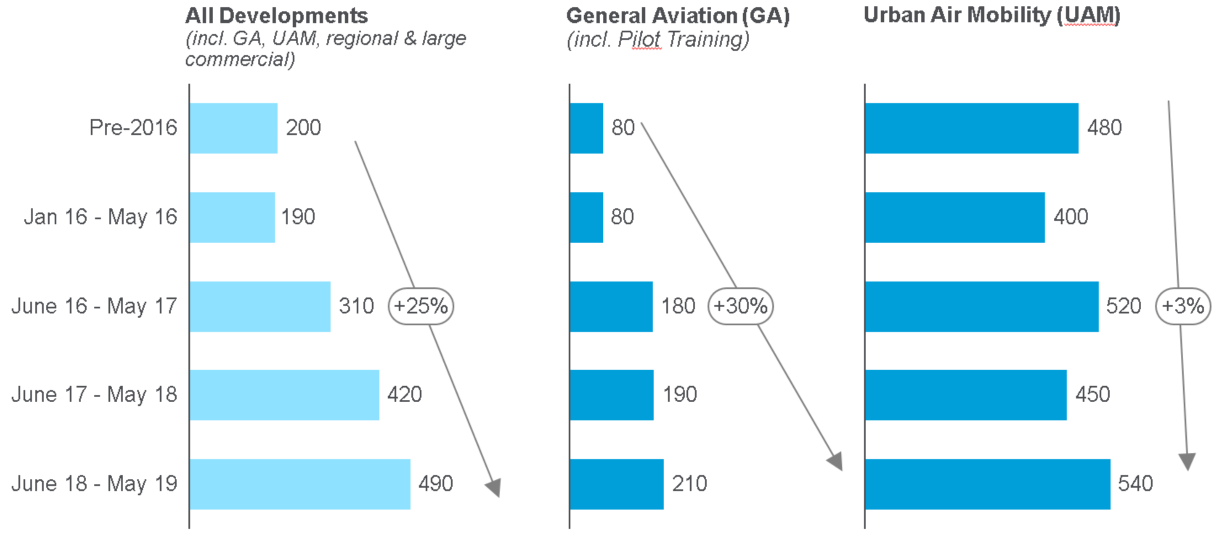
Source: Roland Berger Electric Aircraft Database

Urban air mobility announcements have been mainly from North America and RoW

Though European companies were early to begin work on electric aircraft, North America and the rest of the world (RoW) have outpaced them since 2016, growing at almost 70%. Interestingly, while urban air mobility developments dominate in North America and RoW, the majority of developments in Europe center around general aviation, constituting around half of developments.

The share of hybrid developments has stayed stable at about one-third of all aircraft since 2016. However, the average engine power of developments has increased, with developments averaging ~750 kW in mid-2019 (see Figure 24). Although an increase in the proportion of regional/business aircraft and certain large announcements — such as the E-Fan X — have undoubtedly boosted the average, engine powers of the typically less powerful urban air taxi and general aviation (including pilot training) segments have also slowly increased; as funding grows and technology maturity advances, we will likely continue to see both bigger aircraft and more powerful propulsion systems.

Figure 24. Average Total Engine Power of Electric Developments Has Increased Since 2016, Even in the Typically Less-powerful UAT and GA Segments



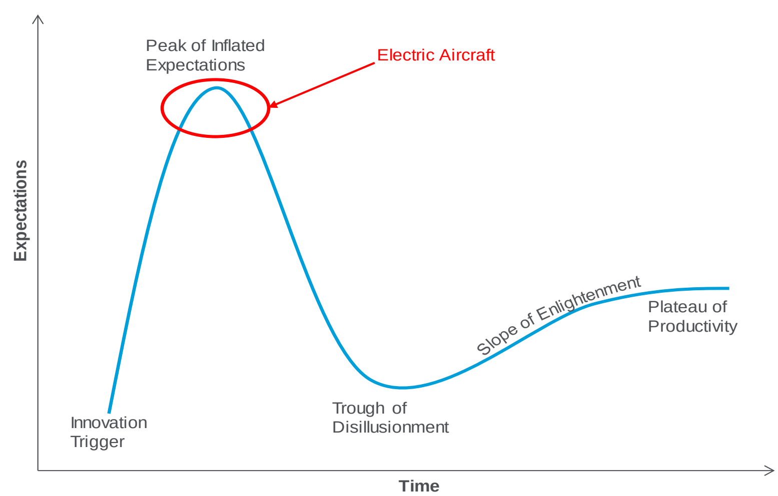
Note: Figure represents cumulative average engine power of electric aircraft by announcement period (kW) and these averages pertain to the ~60 developments (out of a total of ~170 which publicly declare their electrical power rating.
Source: Roland Berger Electric Aircraft Database

Hype Cycle: Approaching Peak of Inflated Expectations

We believe electric aircraft technology is approaching the Peak of Inflated Expectations

The Gartner hype cycle is a graphical presentation of the maturity, adoption, and social application of new technologies (see Figure 25). From this perspective, we believe electric aircraft technology is approaching the 'Peak of Inflated Expectations' phase of the cycle given the proliferation of electric developments, relatively large media recognition, and optimistic expectations, particularly in the air taxi segment where the first air taxies are expected to operating by 2023. The increase in hype is largely driven by societal focus on emissions and sustainability, the growing need for urban mobility solutions, and the significant disruption and explosive growth in parallel industries.

Figure 25. We Believe Electric Aircraft Technology is Approaching the Peak of Inflated Expectations in the Hype Cycle Rubric



Source: Citi GPS, Gartner

According to the Gartner cycle, the period following the 'Peak of Inflated Expectations' is typically characterized by negative press and significant consolidation or failures among OE manufacturers, which will bring electric aircraft expectations back meaningfully and mark the slide into the 'Trough of Disillusionment'.

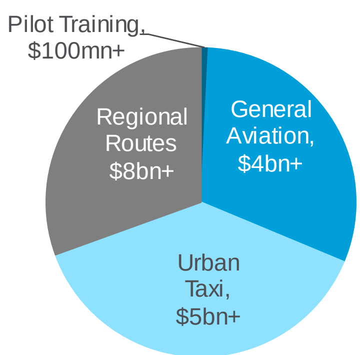
As the technology climbs the 'Slope of Enlightenment', we will likely see slow adoption by customers and further electric aircraft iterations, as expectations rise to a more reasonable level, before plateauing after best practices and mass production methodologies are developed.

The Focus of this Report?

In this report, we focus on the activities which directly impact the aircraft and engine OEMs looking ahead to 2030 and estimate the addressable market value in annual revenues as follows:

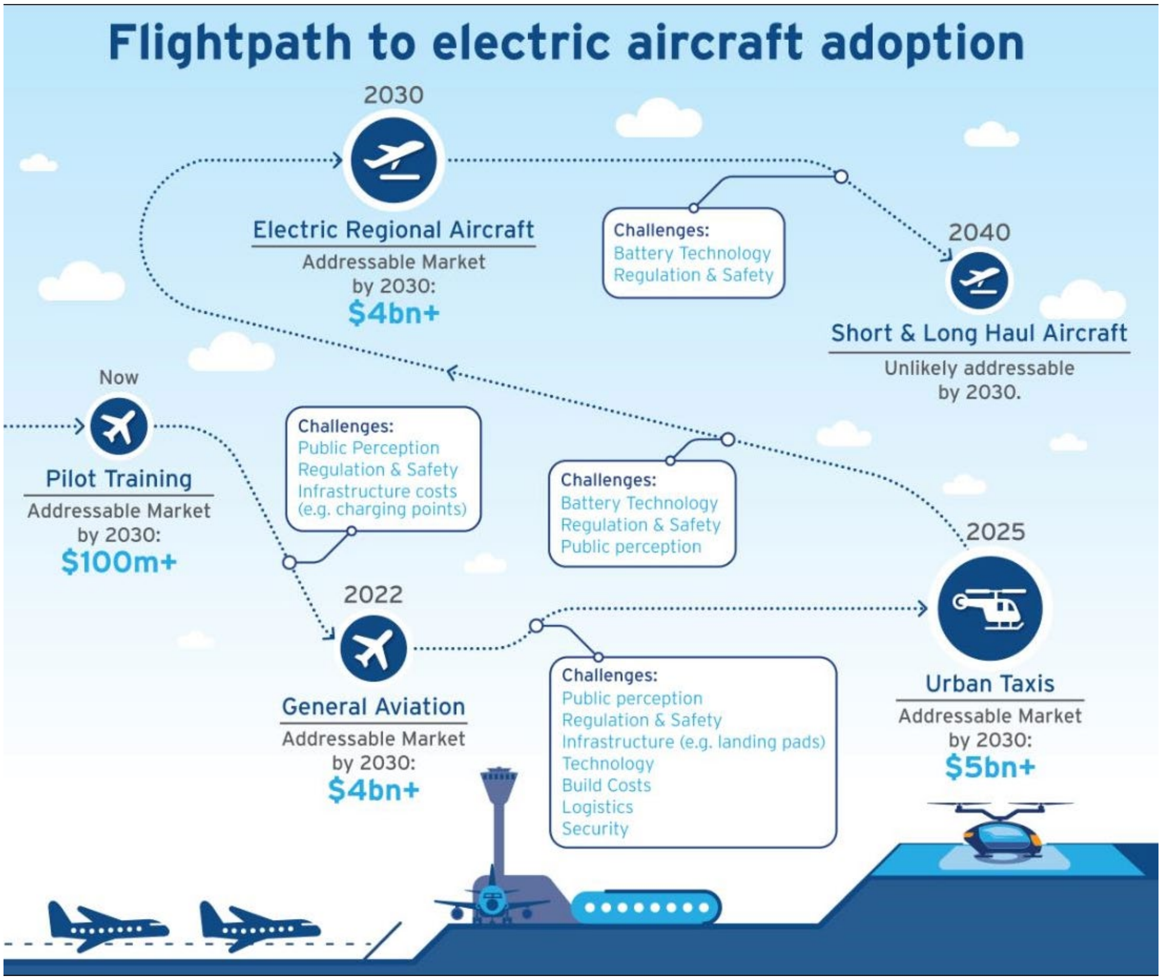
1. Aviation Training - $100m+ market opportunity
2. General Aviation - $4bn+ market opportunity
3. Urban Mobility - $5bn+ market opportunity
4. Regional routes (up to 1,000 miles) - $8bn+ market opportunity

Figure 26. Estimated 2030 Addressable Market by Aviation Activity



Source: Citi Research

Figure 27. Our Forecast of the Path to Electric Aircraft Adoption and Estimated Market Value of Annual Sales by 2030



Source: Citi Research

Pilot Training

The Size of the Market

Pilot training can cost up to $200k to complete the required flight hours

The FAA requires commercial pilots to have a minimum of 1,500 flight hours (hours actually in the air) for a commercial pilots license (CPL). Renting a small trainer plane can cost between $130 and $150 per hour, which works out to around $200,000 for the full requirement — often partly covered by an airline. Flight schools typically cover around 250 hours in trainer planes and many pilots take up jobs (e.g., flight instructors, advertising/flying banners) to cover the rest — some of which could either use larger general aviation planes or light trainer planes. Common training aircraft have a significant overlap to the light business jets used in general aviation.

We estimate the market for trainer aircraft to be worth $80-$120 million in annual sales by 2030

We estimate the market for trainer aircraft to be worth $80-$120 million in annual sales by 2030. This is based on training an average of 30,000 pilots a year up to 2030 and that two-thirds of the flight hours required (i.e., 1,000 hours) are completed using trainer jets with the remaining hours completed using other aircraft. Boeing's 2018 Pilot & Technician Outlook suggests about 730,000 commercial and business pilots are needed over the next 20 years — i.e., 36,500 a year on average over the period with a higher number required at the end of the period. Based on a six hour per day max flight time and a 250-working day year, we calculate expected demand for 15-20,000 planes, or 750-1,000 planes per year given an aircraft's 20-year average life. At a price range of $50,000 to $150,000 for a trainer aircraft, we arrive at our estimate for the market of $80-$120 million in annual sales.

Electric Trainer Aircraft Have Significant Cost Benefits

Operating and maintenance costs are lower in electric trainer aircraft

Key benefits to using electrically-propelled trainer aircraft include cheaper operating costs as no fuel is needed, and lower maintenance costs as there are fewer moving parts and less ongoing wear (i.e., the engine doesn't need to go through a thermal cycle every time you start it). Charging the batteries on an electrically-propelled trainer aircraft is estimated to cost $2-$3 per flight hour vs. ~$40 per flight hour for aviation gasoline (6-10 gallons consumed over a one hour flight at ~$5 a gallon).

In their first 40 hours of flying, aspiring pilots can save ~$1,500 in 'fuel' costs alone by using electric. This is crucial as the high costs associated with pilot training are one of the key drivers of the reduction in pilots. We note that Embry Riddle (a leading aeronautical university in the U.S.) is scheduled to begin a course focused on the fundamentals of electrified propulsion and battery technology this year.

Battery technology is already sufficient enough to create a training aircraft; recharge times, however, is a key limitation

A key limitation to the adoption of electric across larger planes is battery technology since battery energy density is still too low. However, battery technology is already sufficient enough to power a training aircraft as they only need 1-2 seats and most flights only last for around an hour. A key limitation, however, is recharge times, which are currently at a ~0.75-1:1 ratio (i.e., 45 minutes to one hour charging time for a one hour flight), but this is improving (towards15-25 minutes charge time for a one hour flight) making electric training aircraft more attractive. In a typical scenario, the aircraft could be charging while the instructor is reviewing the previous students flying lesson and briefing the next student, which would allow the aircraft enough time to recharge for the next one hour lesson. Another key limitation is battery replacement — operators will likely spend 2-3x more on battery replacement than on engine overhaul; however, the savings from fuel and maintenance costs will likely more than offset that additional cost.

Lower noise levels allows students to converse with instructors without headphones

There is also a significant noise benefit (electric planes are ~30 db quieter than non-electric), which can allow the student to converse with an instructor without needing headphones, and a lack of vibration, which means more comfort and less fatigue for the instructor and the student. However, this could mean the aircraft may have to be fitted with a warning indicator (such as a horn), especially in crowded air fields.

Who is Targeting This Market?

A study by Roland Berger suggests that around ~6% of the c.170 electrically propelled aircraft projects have either announced their intentions for, or are highly suited to, the pilot training market.

Figure 28. Examples of Developments in the Pilot Testing Market

Source: Pipistrel, Bye Aerospace

Interview with Ivo Boscaro, Founder & CEO Pipistrel Group

Pipistrel manufactures and services light aircraft, including the world's first commercially available all-electric offering, the Pipistrel Alpha Electro, and are currently working on a 5-seater eVTOL air taxi.

What inspired the need to develop an electric trainer aircraft? Why would customers choose an electric trainer offering over an internal combustion engine aircraft?
The vision of our general manager and of our company is that aviation must be clean, quiet, and affordable. It must not be heating the atmosphere and it must not depend on the producers of fossil fuels, so electricity is the logical outcome. It's cleaner, quieter, easy to fly, and also much cheaper — electricity costs just a fraction of the expense of fossil fuels.

How has demand been for the Alpha Electro? How many do you produce?
We have already delivered 65 Alpha Electros. We produce six per month and for single orders, if they are not highly customized, we can offer a very short delivery time (within a month).

Do you envisage users changing the battery between flights or recharging on the aircraft?
We have designed the aircraft to allow both. For a one hour flight, the aircraft takes ~45 minutes to charge using a 20 kW charger, about one and a half hours using a 10 kW charger and six hours using a 3 kW charger. Changing the battery would be the most efficient use of time between flights and how we envisage the majority of users will operate, until battery technology improves — we have designed the aircraft so that the battery can easily be unscrewed and unplugged, which takes around five minutes. A spare battery costs ~€13,000 and each battery pack weighs 53 kg.

What is the lifespan of the batteries?
Approximately 15-20 years depending on charge cycles/use. The battery will drop to 75% of the original capacity after 300-700 cycles.

Is there the possibility to install solar panels on the wings?
The wing surface is so small that there are not enough benefits, it simply can't be justified.

How important was it to achieve the first FAA airworthiness certificate for an electric aircraft offering? How long did the process take and how difficult was this to achieve?
Different authorities accept the new technologies in different times and in different ways. The FAA Permit to Fly is important only for the U.S., but we are at the moment selling to 97 countries and each single country's Permit to Fly is important for us.

What has client feedback been like?
Most customers comment on the low operating costs and are surprised by the low noise levels during takeoff and landing. With the first major inspection at 2,000 flight hours on a lifespan of around 6,000 hours (2,000 x 3 service series), many also highlight the inexpensive maintenance costs.

Advancements in Flight Simulators Are a Headwind

Improvements in flight simulator technology is a headwind for electric pilot training aircraft

Technological developments could be a double-edged sword for the electrical aircraft opportunity in the trainer aircraft market. Currently out of the 1,500 flight hours required for a commercial pilot's license, a maximum of 100 hours can be completed in a full-flight simulator (FFS) or 25 hours in a flight navigation and procedures trainer (FNPT). Flight simulators more efficiently replicate the movement of a real flight, including acceleration, G-force, and braking.

As flight simulators become more advanced, we expect the 100 hour limit to likely be increased, particularly as pilot shortages become more widespread and disruptive. The result of this would likely be market share gains for simulators at the expense of physical trainer aircraft, given the ease of use, versatility of being able to simulate different situations, and some cost advantage for fixed-base simulators (see Figure 29).

But simulator hours are limited by regulators and are expensive

However, today, given the limited maximum number of hours currently allowed to be completed in a simulator and the high cost of full-flight simulators (see Figure 29), simulators are rarely used in primary training, but instead for more aircraft specific training, for example moving to a new aircraft.

Figure 29. Cost Comparison of Trainer Aircraft, Flight Simulators, and Electric Trainer Aircraft

	Capital Cost	Power Costs	Cost to student (w/o instructor)
Trainer - Internal Combustion Engine	$200-500k	$40-$60 / hr	$100-200 / hr
Flight Simulator Fixed-base (FNPT)	$200k-1m	$0-1 / hr	$20-100 / hr
Flight Simulator (FFS)	$1m-20m	$1-2 / hr	$200-1,000 / hr
Electric Trainer	$150-300k	$2-4 / hr	$50-100 / hr

Source: Citi Research

Figure 30. A350XWB Full-flight Simulator (FFS) located in the Airbus Flight Training Center in Toulouse

Source: Airbus

General Aviation

The Size of the Market and Key Players

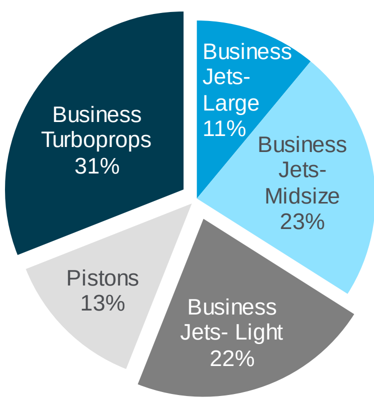
General aviation planes can vary significantly depending on their purpose, but typically seat 4-12-passengers with a range of up to 500 miles (larger for corporate jets). Typical uses of general aviation aircraft include:

- Aerial work — agriculture, construction, surveying, search and rescue, observation and patrol, advertising.
- Recreational flying.
- Non-commercial business (i.e., corporate and private jets).

We estimate that the total market for general aviation is worth $15 billion in annual sales, across 1,400 planes

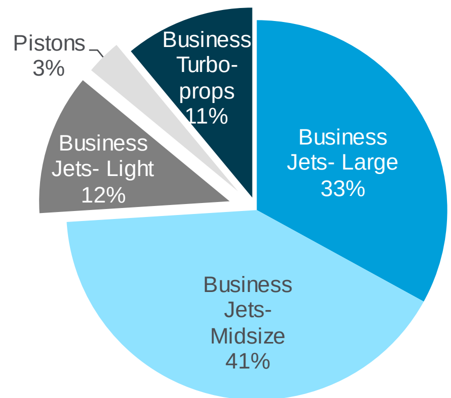
We estimate that the total market for general aviation is worth $15 billion in annual sales across 1,400 planes. To put this is in context, $15 billion is about 10-15% of the current wide-body and narrow-body annual market by value. By number of planes, this is fairly evenly spread across business jets, single-piston aircraft, and business turboprops, while by value this is dominated by large and mid-size business jets (Figure 31 & Figure 32).

Figure 31. Split of General Aviation Market by Number



Source: Citi Research, Cirium

Figure 32. Split of General Aviation Market by Value

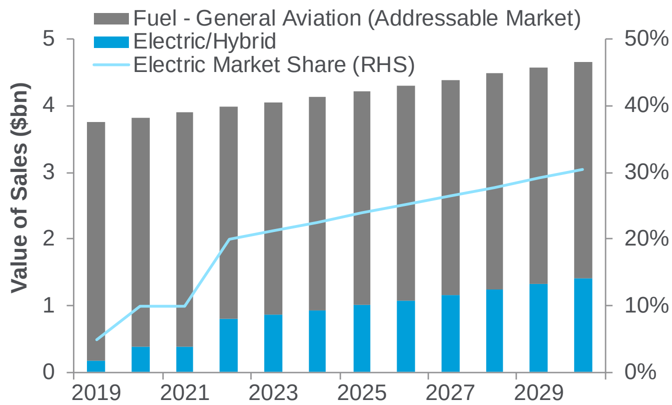


Source: Citi Research, Cirium

Electric aircraft could take share from smaller general aviation planes and represent a $1.4 billion annual sales opportunity by 2030

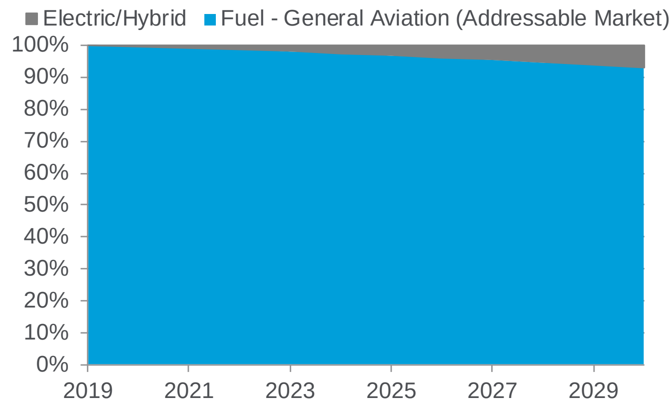
We estimate electric aircraft could take market share from the smaller planes, i.e. business turboprops, pistons and light business jets, over the next 10 years. This addressable market is about 25% of the general aviation market and could be worth up to $4.5 billion in annual sales by 2030 (Figure 33). If we assume electric aircraft penetration is 30% of the addressable market by 2030 (i.e., 8% of total general aviation), this could represent a $1.4 billion annual sales opportunity by 2030.

Figure 33. The Addressable Market in General Aviation is Worth ~$4.5bn in Annual Sales by 2030, When We Estimate Electric Penetration Could Reach 30% of New Sales



Source: Citi Research

Figure 34. As a Result, We Forecast Electric/Hybrid Aircraft Could Reach ~7% of the Addressable In-Service Fleet by 2030 and ~1.7% of the Total General Aviation Fleet



Source: Citi Research

Development to Date

Most of the development in larger electric aircraft to date started in the general aviation space given the lower energy requirement and relatively lower capital expenditures. Several projects have involved retrofitting existing aircraft, while others have involved a developing a new concept. Additionally, many companies have funded developments in general aviation to use as a test bed for larger electric aircraft projects.

30% of the almost 170 electrically-propelled aircraft projects are estimated to be in general aviation

A study by Roland Berger suggests that around 30% of the almost 170 electrically-propelled aircraft projects are in general aviation, ~70% of which are all-electric and ~30% are hybrid. Around ~5% of the almost170 of total developments projects have stated a clear interest in, or are well-suited to, serving the business aviation segment.

Figure 35. Examples of General Aviation Design Proposals

Source: HES Energy, Ampaire

Urban Mobility

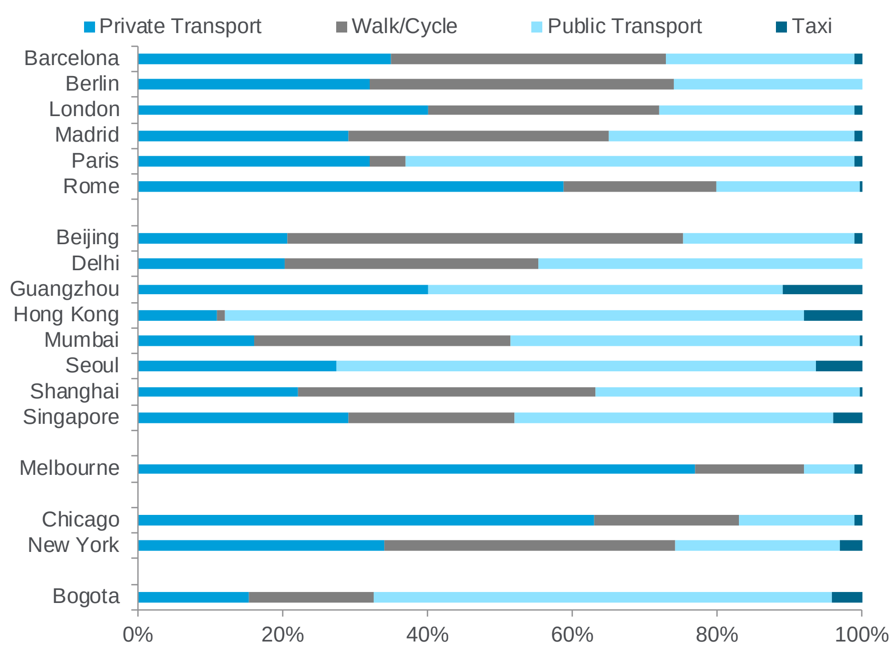
The Size of the Market

VTOL aircraft (flying cars or air taxis) are a possibility in the near future

Populations in cities continue to reach record highs — the UN estimates 68% of the world population will live in cities by 2050, up from 55% currently. As a result, cities are facing growing problems including congestion, pollution, and accidents. This has fueled the need for new and innovative urban mobility solutions, which have spurred developments in 'air taxis' — vehicles with ranges starting at 50 miles and beyond for short journeys of typically 10-20 minutes. 'Air taxis' or 'flying cars' as a concept is not new (think Back To The Future or the final scenes in Grease); however, developments in VTOL capabilities and electric-propulsion technology make this concept a possibility in the near future. VTOL will allow aircraft to take off and land without requiring a runway, while all-electric propulsion delivers numerous benefits including quieter operations which allows more operation near city centers. We introduced the idea of the 'flying car' in our January 2019 Citi GPS Car of the Future v4.0.

Currently, urban mobility in large cities is dominated by public transport (~40%), followed by private transport (33%), walking/cycling (25%), and taxi's (3%). Regionally, dense cities (i.e., Guangzhou, Hong Kong, Singapore) rely more on public transport/taxis while less dense cities (most of North America ex NY, Melbourne) rely more on private cars.

Figure 36. Survey of Passenger Journeys by Main Mode of Transport



Source: Citi Research, Passenger Transport Mode Shares in World Cities (Journeys) - November 2011

Markets Electric Air Taxis Will Address

Taxi/Car Trips: The lowest hanging fruit for air taxis will be capturing share from taxis, rather than public transport (buses/trains), given (1) the price per mile and (2) smaller is better since the payload required for carrying more passengers in busses/trains would restrict the VTOL's ability to operate in cities. Private transport is another area where air taxis could potentially take share given the low utilization rates of vehicles. For instance, a study by the RAC (Royal Automobile Club) in the U.K. suggests the average car is only on the move 4% of the time, is parked at home 80% of the time, and is parked elsewhere the rest of the time.

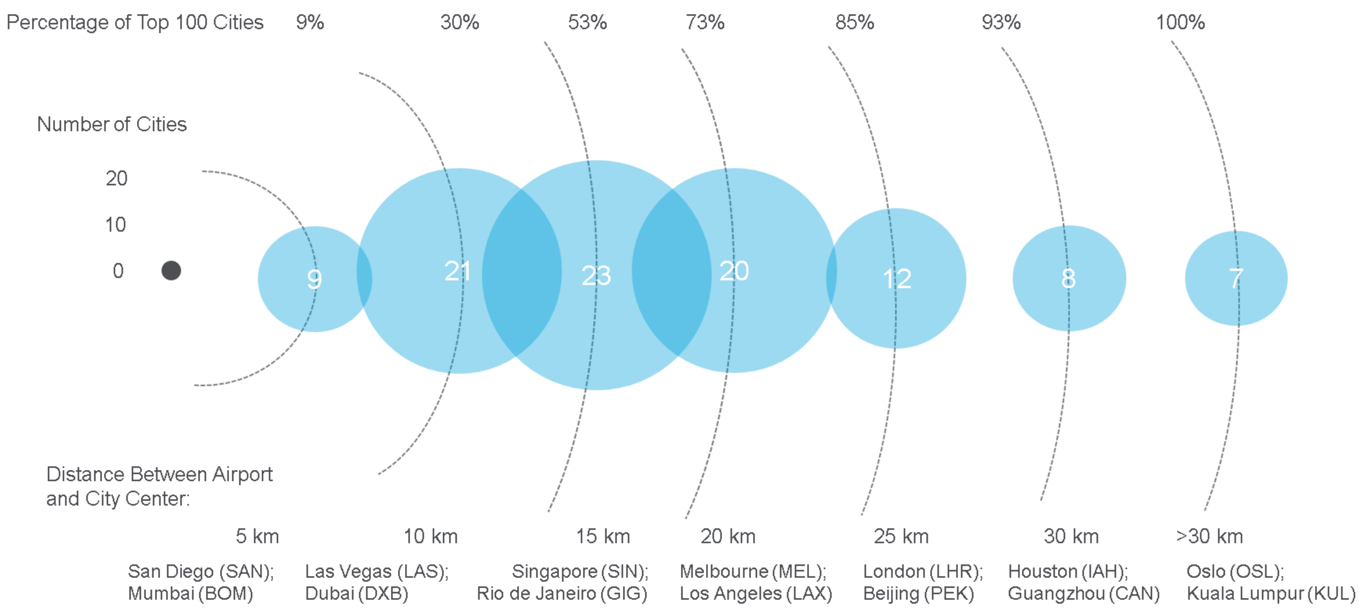
Early adopters of air taxis are likely to be airport shuttle taxi trips

We estimate there are 300,000-400,000 taxis sold per year globally, and approximately 15% of taxi trips are over 10 miles, which is likely the addressable market for air taxis as smaller distances have little economic and time benefit, except in extremely congested areas. Airport shuttle trips are also likely to be early adopters for air taxis, particularly as >90% of major airports are within 30 km of a city center (see Figure 37). Meanwhile, ride-sharing companies report that one in six (17%) of their calls are going to and from the airport.

The market value of the annual sales demand for air taxis could be up to $4.5 billion by 2030

Assuming the capital cost of an air taxi is $300,000 and 30% of trips over 10 miles will have air taxi routes in operation (e.g., airport journeys, city-center to city-center of close cities), we conclude the market value of the annual sales demand for air taxis could be up to $4.5 billion by 2030. This number is, however, highly dependent on production rates being sufficient to meet demand.

Figure 37. According to Volocopter, 93 of 100 Major Cities Studied Have a Major Airport Within 30km of their Respective City Centers



Source: Citi Research, Volocopter

We value the addressable market in annual sales for premium airport services at $50-70 million in annual sales by 2030

Premium airport services: Air taxis will likely initially be introduced on popular routes such as from city centers to airports in cities which are more open to being early-adopters — this could potentially take share from existing premium airport services rather than slower forms of public transport given the price differential (e.g., Heathrow Express at £25 rather than London underground at £6). By 2030, if we assume early adoption in cities which are more open to technological developments, i.e., Dubai, Singapore, London, New York, Hong Kong, and Shanghai, we estimate an addressable market of 70 million passengers a year across these six cities. Assuming 15 back and forth trips a day (30 including return) and an average of 3 passengers (not including a pilot), we estimate that over 2,000 air taxis will be needed. However, this assumes a uniform distribution and that 100% of the premium airport services market share is addressable. Assuming the life of an air taxi is over 10 years (short vs. 25 years for a plane due to shorter innovation cycles and mass production being more efficient), we forecast an annual demand of 230 air taxis. At a cost of ~$300k each, we value the addressable market in annual sales for premium airport services at $50-$70 million by 2030.

By 2050, assuming adoption by all major cities and using the UN's forecast of 68% of the world's population residing in cities, we estimate 200,000 air taxis will be needed to meet this demand (i.e. 20,000 air taxis a year with a 10-year life) and the market to be worth $4-$6 billion annually.

Light helicopters: Civil helicopters are also an area where air taxis could take share given the significant benefits (potentially safer, quieter, and less expensive). We estimate the civil helicopter market is approximately 800 helicopters annually over the next 10 years (vs. currently at lows of 500 to 600) and worth around $4 billion annually. The key areas where air eVTOL vehicles could take share is in the portion of light helicopters used for general utility (humanitarian aid, firefighting, transport etc.), law enforcement, and news & television, which is ~50% of helicopters in use, rather than medical services, oil & gas, and corporate as these tend to require medium/heavy helicopters. As a result, we estimate the addressable market as 50% of helicopters annually (i.e., 400), but a smaller percentage of value (given the lower cost for light helicopters) — we therefore estimate the market from light helicopters could be worth ~$1 billion in annual sales by 2030.

Adding these together, we conclude the market value of the opportunity for air taxis could be over $5 billion by 2030 or 15,000-20,000 air taxis annually.

There is the potential for further upside if:

1. **Share gains vs. private cars:** Taxis/ride-sharing captures a larger share of private cars, particularly given the low utilization rates of cars (mid-single digits globally) and the rise of the sharing economy. Airborne taxis could also gain share of private transport.

2. **The technology creates 'latent-demand'** — i.e., demand for trips to locations that will now be within reach. For example, people will be more open to living further away from work if the trip that would usually take two hours by road now takes 15 minutes by air.

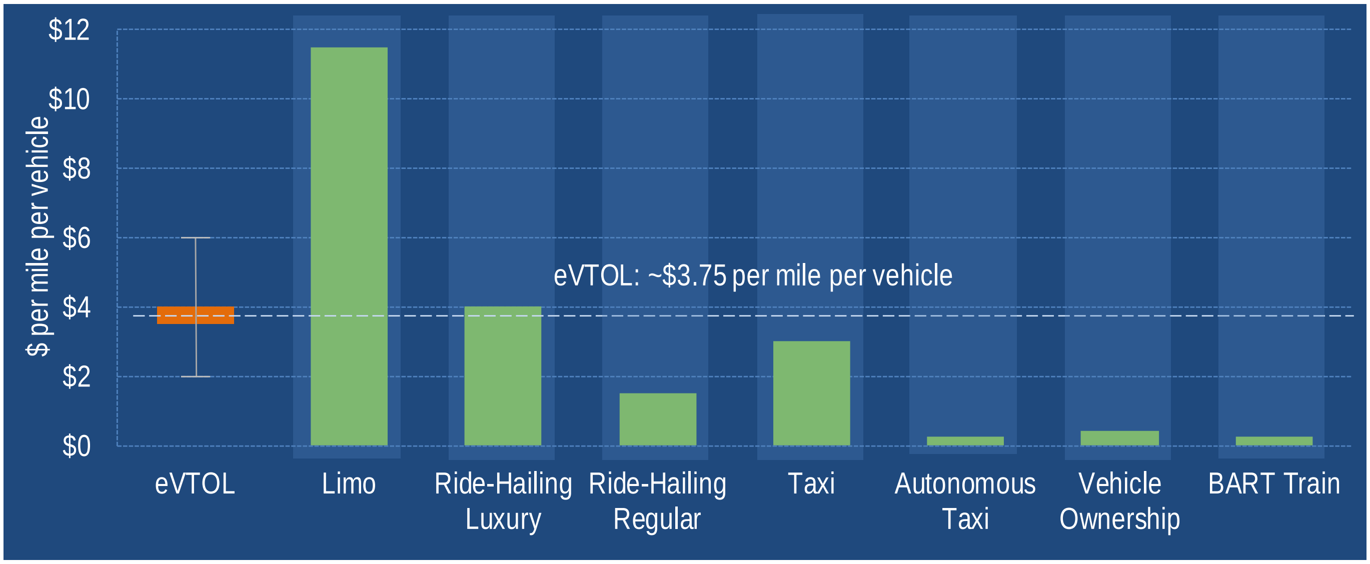
Why Use Air Taxis?

1. Will it be cheap enough?

Cost are being planned a comparable to premium ride hailing services

Comparing the estimated cost per mile for eVTOL vehicles in development with taxi services and ride hailing services, we can see the eVTOL vehicles being developed are planned to be comparable to premium ride hailing/taxi services and in some cases better. However, they are still over twice the cost of a ride-hailing ride and of course the eVTOLs figures are just targets versus current data available for other services.

Figure 38. Cost Will Not Be a Key Driver for Air Taxis — They Would Need to be Autonomous to be Somewhat Competitive on Cost, But Still Not as Cheap as Autonomous Taxis



Source: Citi GPS, Starburst

To be more affordable than ride sharing, air taxis would likely have to be autonomous

For electric air taxis to be more affordable they will likely have to be autonomous given the: (1) cost benefit from not having a pilot, and (2) higher passenger payload with weight at a premium (a 4-seater would lose 25% of its payload and potential revenues if it has to carry a pilot). Additionally, asset utilization is key as an autonomous electric air taxi will have low variable costs, so systems that maximize flight (revenue-generating) time will be key.

However, even autonomous air taxis are unlikely to have a cost advantage per mile when compared to autonomous cars. Industry players expect cost per mile for autonomous eVTOL air taxis to achieve $0.50-$1.10 per mile in the near term and $0.20-0.40 in the long term — this equates to a cost for an air taxi from the city of London to Heathrow airport of $8-$20 in the near term and $3-$6 in the long term.

Although this is better than current taxi and ride-hailing services, McKinsey estimates that pooling of autonomous road taxis will cost as low as $0.17-0.29 per mile by 2025 (depending on the number of people sharing vehicle), i.e., 30-60% cheaper than what private cars could cost ($0.43 per mile).

2. Routes Will be More Beneficial

Air taxi routes are not restricted by infrastructure and terrain

Journey by road is limited by infrastructure and terrain. Air taxis will be more beneficial in areas with poor infrastructure and lack of road connectivity, in addition to trickier terrain (e.g., rivers, mountains). Air taxis also have the optionality to add a third dimension of travel by allowing vehicles to fly at different heights to avoid congestion in the air.

Figure 39. Quickest Route from Citi's Office in Canary Wharf to Gatwick Airport by Air vs. Road (According to AA Route Planner)

Source: Citi Research, AA Route Planner

3. Time Benefit Will be a Key Driver

Time savings from air taxis is expected to be a big driver vs. conventional travel options

Air taxis will prove particularly beneficial in highly-congested areas given the possible time savings created by faster speeds and shorter routes. For example, the route in Figure 39 would take around 10-15 minutes by air versus over an hour by road, although we'd have to account for travel to and from the landing pad and check-in time.

4. Infrastructure

Air taxis will require less infrastructure investment and are more environmentally-friendly to build than road infrastructure. Un-utilized roof space and existing helicopter pads can be put to work. Air taxis might also reduce strain on existing public transport networks, which is particularly important as cities become more concentrated. They can also reduce traffic accidents given that there are no pedestrians or objects that could pose an accident risk in the sky.

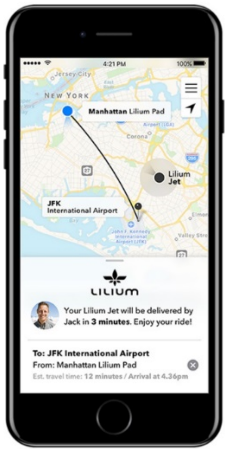
How Will it Work?

1. Ordering an Air Taxi

Most companies are working towards using an app interface for the user to be able to call an air taxi, similar to ride-hailing apps

Asset utilization is particularly important, as an autonomous electric aircraft will likely have high fixed costs and low variable costs, so systems that maximize flight (revenue-generating) time will be key. Most companies are working towards using an app interface for the user to hail an air taxi, similar to ride-hailing apps, by selecting the closest landing pad/air station. A few air taxis are developing their own app interface, similar to what automakers plan to do with their first fleet of autonomous cars. Others are partnering with existing ride sharing companies on their air taxi ridesharing product under development. For air taxis to be successful, systems/algorithms would need to be smart enough to predict customer demand to minimize waiting times, but also minimize dead mileage flights (empty flights).

Figure 40. Lilium's Proposed User Interface App for the Lilium eVTOL Jet



Source: Lilium

Figure 41. Volocopter's Proposed User Interface App for the Volocopter 2X

Source: Volocopter

2. Landing Pads

Landing pads will likely be located on top of buildings or protruding structures from building within cities

Landing pads will likely be located on top of buildings or protruding structures from buildings within cities (reduced noise pollution from electric engines will make this possible), while closer to airports and in areas with more space, landing pads can be located on the ground. Landing pads will also need to have charging capabilities or infrastructure to be able to change the electric batteries. There are several considerations for air taxis landing pads:

- **Location:** Initially, air taxis will likely utilize existing helipads, which would need to install charging capabilities (there are reportedly almost 6,000 helipads in the U.S. alone). Dedicated landing pads/stations could be built at a later stage, once the use-case has been proven, and could either be placed on roofs of buildings or in parking lots or all new-structures could be built. Skyports CEO, Duncan Walker, suggests that costs typically range from $1 million for a helipad conversion to $5 million for a full rooftop conversion, but this can vary depending on the existing structure (see our interview with Mr. Walker in the following section). Initially, we believe the cost would likely need to be local-government funded, similar to other infrastructure projects and the majority of global airports (the U.K. is a notable exception as it privatized over 50% of their airports). This will allow users to operate air taxis as a hub and spoke model — using air taxis to get from one landing pad to another, and then using other forms of transport to get from the landing pad/hub to their destination. Ride-sharing apps already use this model in New York, where users can be asked to walk up to 250 meters, while in London, it is estimated that 30% of all rides in the outer city boroughs end within 200 meters of a tube or train station. Depending on local regulations, VTOLs may be able to take off/land at private residences in the long-run (unlikely to be before 2030); however each location will likely have to be surveyed and approved by regulators first.

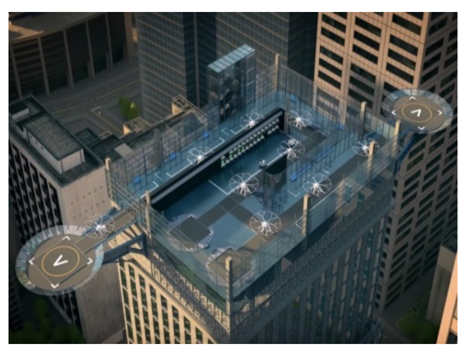
– **Size of Landing Pads:** According to the FAA's advisory circular on helicopter landing pad design (here), a helipad should include a final approach and takeoff (FATO) area, which must be at least 1.5x the length of the helicopter — so typically 50-80 feet square for 5-10 seater helicopters — in addition to a public safety area (PSA) of around 150-200 feet (except on a rooftop, which is already a controlled area). The majority of air taxi offerings fall between 20-40 feet in length and using this same multiplier, landing pads for air taxis will need to be a square with each side being at least 30-60 feet. However, each air taxi landing pad may have several landing zones so will need to have additional space to minimize operational risk.

– **Charging:** Initially, air taxis will likely be charged on refurbished helipads or small air taxi landing pads; however, in full operation, air taxis will need to move off landing pads after the passengers have disembarked to allow other vehicles to land or takeoff. Depending on the duration of time the air taxi will be parked, landing pads will likely have a combination of high voltage and low voltage charging facilities. Alternatively, fully-charged batteries can be swapped in if this can be done in a quick and efficient manner. Some air taxi developments focus on swappable batteries as a key selling point since battery charging technology is still lagging. However, buying multiple batteries per vehicle will increase the fixed costs.

– **Boarding/Security:** Landing ports need to ensure a rapid and seamless process for identity and security checks in order for air taxis to become widespread. This will ensure the air taxi retains its beneficial travel time advantage versus alternatives, and also ensures high asset utilization for the operator. VTOL offerings will naturally have quicker turnarounds than helicopters (as there is no need to wait for rotors to spin up or down) and planes (as there is no need for taxiing). Operators will also have to consider accessibility for users with reduced mobility and families with small children.

– **Other Things to Consider:** In a similar fashion to helipads, air taxi landing pads will need appropriate lights and safety features — for example, helipads are required to have green lights around the FATO perimeter, and to provide landing direction guidance (+ blue lights for edges of the taxi route), obstruction lights for difficult-to-see objects, and a heliport identification beacon.

Figure 42. Examples of Various Proposed Landing Pad Designs



Source: Pickard Chilton, Lilium, Volocopter

Interview with Duncan Walker (Co-founder and MD, Skyports)

Skyports is the first company to specialize in owning, designing, and building passenger and cargo vertiports/landing pads. The company is currently building the world's first vertiport in Singapore through a collaboration agreement with Volocopter (an air taxi manufacturer), and will be conducting flight trials in October 2019.

What will landing pads/vertiports of the future look like?
Since there are no specific standards for air taxis as yet, we have had to work off the existing helicopter standards, while building-in scope to adapt and be flexible as specific requirements are formed. Similar to a typical helipad, vertiports will have a take-off and landing pad, a number of gates, recharging facilities, other ground facilities (waiting rooms for pilots and passengers) and airport-grade security. Our initial developments, such as the vertiport in Singapore, will have a modular architecture to allow us to scale up very quickly and cost effectively, but also to include/bolt-on any additional features as flight numbers increase or requirements change.

Tell us more about the world's first ever air taxi vertiport that you are building in Singapore?
The vertiport is being built on the Marina Bay in Singapore and is on-track to be completed in October 2019 when we will be conducting trials using Volocopter's V2X multi-rotor air taxi, followed by public demonstration flights. Singapore has stood out as an early-adopter and aim to be the leaders in Asia. The vertiport itself will have one landing pad and will be designed as a demonstrator so that it can be demounted, moved and put back together in a different location.

Given the variety of air taxi offerings (size, electricity source etc.), how do you ensure standardization of the landing pads to maximize compatibility?
On size, vertiports will likely need to use the size of a large air taxi as a reference when designing the vertiport — similar to how helicopter landing pads are sized. On charging infrastructure, we are primarily focused on electric batteries as the source of power as this is the default for most of the vehicle manufacturers. However, we will build in flexibility so if other fuel sources, for example hydrogen, become commonplace, we can accommodate that. In the U.S., we are working closely with ChargePoint who operate almost 65,000 electric vehicle charging spots to develop these solutions. We also need to factor in the ability to store batteries on site, as many air taxi proposals rely on a battery change to maximize utilization of the vehicle. The biggest challenge that vertiports will face is grid capacity and availability. In addition, in the early days, there will likely be several different connectors for charging depending on the vehicle (similar to having several different phone chargers for different manufacturers) — this will hopefully be standardized in the long term.

How much does it cost to convert a helipad or to refurbish a roof terrace?
Costs typically range from $1 million to $5 million, with the lower end representing a helipad conversion and the higher end a full rooftop conversion. This includes vertical circulation (means by which the landing pad is accessed), charging capabilities, actual landing pads structure, and passenger handling facilities. However, this can vary significantly depending on the existing structure, for example existing rooftop features, slope and building management equipment already in place. Many proposed designs which have protruding landing pads may look great, but we have found that wind vectors prevent this from being a solution unless the existing infrastructure was designed for this (e.g. the Burj Al Arab helipad in Dubai).

What will make the air taxi winner(s) offering stand-out?
Although there is a first-mover advantage in obtaining certification and developing a commercially viable on-demand service, the first to market or even the best design may not necessarily win the race. The winner would also need to have a strong balance sheet to be able to produce and market the vehicles at scale. This may mean that the winning offering would need to be backed by a larger company and there will likely be significant aggregation amongst manufacturers in the early stages. The ability to demonstrate and ensure safety is also crucial — the first vehicle to have an accident may struggle to win public favor back. For the customer, there is also a clear benefit to using platform aggregators, which will pick the most appropriate vehicle for the customer's journey.

Figure 43. Rendering of the World's First Dedicated Air Taxi Vertiport

Source: Skyports, © BRANDLAB

Who is likely to own and operate landing pads – Governments or private companies?
It will likely vary by city, but will most likely be a combination of private and public partnerships. Although existing airports are often government-owned, vertiports have some key differences: (1) they are much smaller than airports; (2) they will be quite disaggregated (likely dotted around cities); and (3) airports are critical infrastructure of a city.

How do you see the growth of vertiports developing?
Overall, growth will initially be quite slow as the technology, public perception, and production costs develop. As cities take reference from first movers, we expect the ecosystem to grow very rapidly after the initial proving phase.

When do you think the first commercial air taxi will be operational?
Ehang already has a commercial air taxi operation in China. In the Western markets, we will likely start to see certification of vehicles and commercial journeys from 2021. By 2023, we expect operations to begin scaling up, with normalized on-demand commercial service by 2024/5. Cities in Asia and LatAm will likely be quicker to adopt this technology due to less regulatory hurdles and lower public perception challenges (background noise and visual pollution are less of a concern).

What are the key hurdles to air taxis becoming widespread?
Although the technology is developing well, there are still several hurdles, including vehicle certification, regulatory permission to operate in cities and public acceptance (particularly in Western markets). Also, many stakeholders underestimate the additional difficulty/costs of mass vehicle production and operating at a larger scale (which needs more pilots, maintenance regimes, etc.).

3. Operations

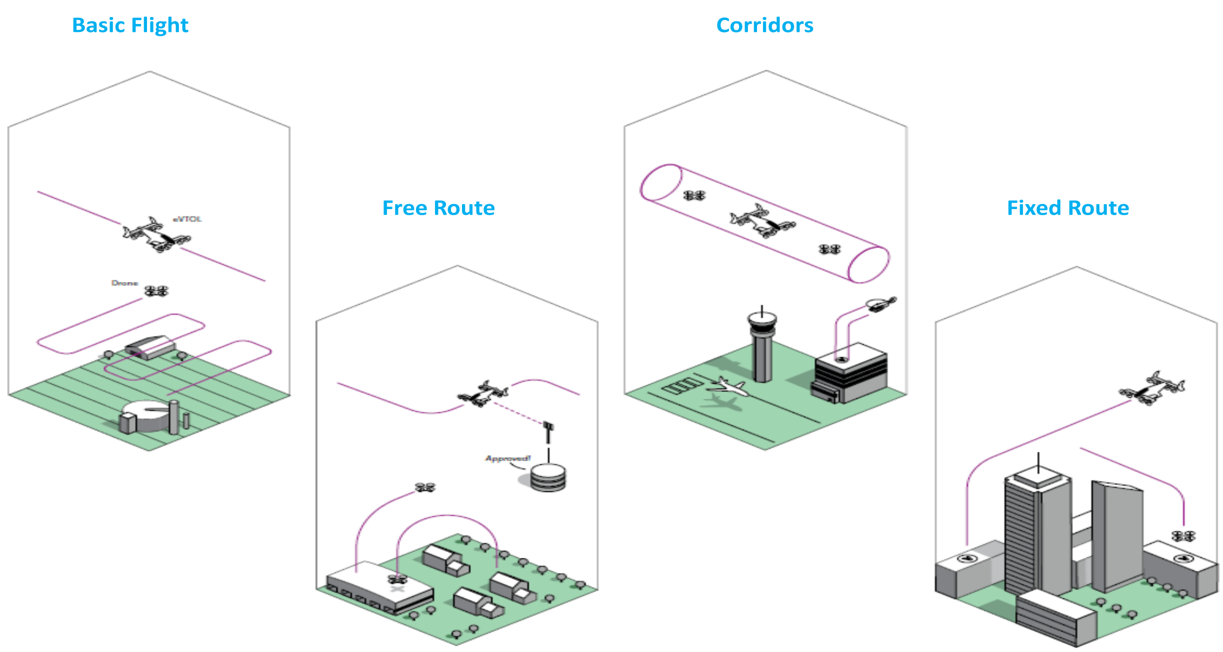
The operational planning process for on-demand air taxis differs from scheduled flights since air taxis are more customer-demand driven

The operational planning process for on-demand air taxis differs from scheduled flights since air taxis are more customer-demand driven. Applying the airline planning process to air taxis:

- **Flight Scheduling:** Airlines decide on their schedule well in advance, while air taxis can fly to different places on a day-to-day basis, leading to unpredictable routes. The air taxi operator will also need to consider when and where an air taxi will undergo scheduled maintenance and where the air taxi will be charged.
- **Fleet Assignment:** In this stage, operators decide which fleet type is assigned to each flight leg, which is determined using factors such as distance, cost efficiency, and route efficiency. Air taxi operators are unlikely to have a large range of fleet types, but may have, for example, a fleet of tilt-wing air taxis for longer routes and multicopters for shorter routes.

- **Aircraft Routing:** Operators assign each aircraft to a route, which is made up of a sequence of customer requested flight legs. There are several routing strategies, including UTM (Unmanned Traffic Management) which is creating an air traffic management solution to include air taxis and drones. UTM recently published a whitepaper which highlighted four key routing strategies (Figure 44):
  - **Basic Flight:** Aircraft take the most direct route and are responsible for maintaining separation with other aircraft through automated or manual means. Conflicts can occur as the number of aircraft increases.
  - **Free Route:** Routes need to be approved by a traffic manager, allowing aircraft to fly any path as long as there is no conflict.
  - **Corridors:** Aircraft are allowed to fly within corridors, i.e., defined volumes in space which can take many shapes.
  - **Fixed Route:** Routes are constructed (or modified dynamically), based on a pre-determined path. This ensures the highest level of safety in areas with a high density of aircraft, such as airports.

Figure 44. Operators May Choose to Use Several Routing Strategies to Allow Flexibility



Source: Airbus UTM Blueprint

A key benefit of air taxis is the route flexibility three-dimensional travel can offer versus forms of ground transport — the aviation governing bodies need to decide on which routes air taxis will be allowed to take or not, including heights. Operators can have several routing strategies, even across a single journey, to allow flexibility.

A key aim for operators will be to minimize operational costs, while accounting for operational routes, route limitations, maintenance, regulations (e.g., maximum flying time for pilots), load factors, number of passengers, weights (including luggage), and charging times. Given the unpredictability of routes, operators will likely need to use demand-predictability systems to ensure air taxis are available in popular locations between busy times.

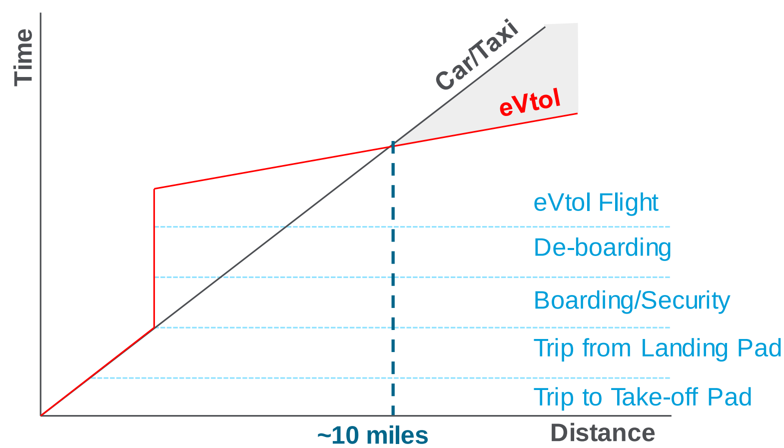
However, given it is unlikely an air taxi will always be available at a departure location, operators will need to bear the cost of some empty flights (known as deadhead/dead mileage flights). For instance, ~40% of private jet flights currently operate empty and 15-20% of taxis are unoccupied.

- **Crew Scheduling/Rostering:** For airlines, this stage involves identifying sequences of flights that start and end at the same crew base. Given the size and weight restrictions of air taxis, the vehicles will likely not have more than a single pilot onboard (and none in the long-term for autonomous), so this is less complex for air taxi operations.

Air taxis will also need to provide passengers with real-time updates on the trip, such as location, time to destination, and could even include in-flight entertainment (IFE) and advertising.

Looking purely at travel times, we estimate air taxis will save time versus cars at distances of over ~10 miles (Figure 45); however, this does not take into account the cost involved.

Figure 45. eVTOL Trips >10 Miles Are More Time Efficient than Cars/Taxis



Source: Citi Research

4. Design – What Will Air Taxis Look Like?

All air taxi designs are the moment are VTOL and the majority are all-electric

The vehicles proposed by companies to tackle the air taxi market vary in design and approach. But, they are all VTOL (vertical take-off and landing – i.e., do not need a runway) and the majority are all-electric (a few are hybrid-electric). Several proposals target sound levels of around 60-70 decibels (about the sound level of an air conditioner/vacuum cleaner), about 10x quieter than a helicopter (~100 dB). One operator has suggested noise levels of air taxi partners should be at most 67dB at 250ft altitude – comparable to a Prius driving by at 35mph on a road that is 25 feet away. VTOL and electric are both crucial components for allowing air taxis to operate in city centers and for longer periods of time (including into the late evening).

There are three different approaches to engine configuration we see in most vehicle proposals:

1. Multicopter configuration, which is wingless and resembles a helicopter with several propellers.

2. Lift and cruise, which uses motors on the wing for lift during take-off and landing and the wing for forward thrust; however this has more motor weight and, as a result, more drag.

3. Tilt-wing/rotor configuration, where the propellers are put up for vertical takeoff and landing and once airborne these gradually tilt into a horizontal position for conventional forward flight to ensure the highest propulsive and motor efficiency during cruise, as less thrust is required in forward flight than in hover.

Figure 46. Simplified Aerodynamic Vertical Mobility Concepts

	MULTIROTOR lift	LIFT AND CRUISE combination	TILT-X tilt-wing, tilt-rotor, tilt-duct
Time to market	Fastest certification	Slower certification	Slowest certification
Travel speed (indicative)	~70–120 km/h	~150–200 km/h	~150–300 km/h
Routes	Selected	All	All

Source: Citi Research, Porsche Consulting

Three types of VTOL engine configuration each have benefits and setbacks

There are some key benefits and setbacks of each configuration. The electric multirotor/multicopter configuration is more compelling at short ranges (which may limit use to intra-city trips); while the tilt-wing and lift and cruise configurations are more compelling at longer ranges and faster speeds (can be used for either intra- or inter-city). However, these two also have the benefit of reduced noise and better safety (particular crucial when operating in city centers). The multicopter has the benefit of being relatively simple (and similar to existing helicopter technology) which should mean lower costs and faster certification (rotating components in the tilt-wing configuration adds complexity). Tilt-wing/rotor configurations offer the best potential range and speed combination, but the complexity of the system also means it is the most difficult to develop and certify.

Given the different approaches are advantageous in specific scenarios, there are likely to be a few successful design types for different route types. Ride hailing apps will likely either give the user the option to choose the design type or automatically work out which is best for the trip.

5. Autonomy – How It Could Work

At a high level, an autonomous system is comprised of two building blocks — one for perception/prediction and another for behavior/controls. The approach to developing autonomous air taxis appears to share similarities with that of urban autonomous cars (AVs), but also has some notable differences.

With respect to perception/prediction, autonomous air taxis will likely adopt similar sensing modalities as AVs with a combination of vision, LiDAR and radar

With respect to perception/prediction, autonomous air taxis will likely adopt similar sensing modalities as AVs — a combination of vision, LiDAR, and radar (some of which are already common in drones and commercial aircraft today) — as well as software perception techniques stemming from classical computer vision, deep-learning, and mapping integration. Sensing involves accurately detecting and classifying relevant objects that are either on the intended flight path or potentially on course with the flight path. This usually involves placing bounding boxes around relevant objects in a scene, and then tracking their distance and path relative to your own. Sensing also involves mapping/localization techniques including identifying pre-determined landmarks along a flight path. Lastly, the sensing task requires a constant understanding of all alternative flight paths beyond the intended one ("where can I fly?"), in effect a plan to avoid any potential obstacles along the way.

Autonomous air taxis on the surface appear less complex than urban autonomous cars because they encounter fewer detectable objects but also don't have braking capabilities

From a degree of difficulty perspective, autonomous air taxis on the surface appear less complex than urban autonomous cars, assuming air taxis operate at 'level-4' or specific point-to-point routes. That's because air taxis stand to encounter fewer detectable objects relative to urban cars, and with an arguably greater degree of predictability. There some exceptions to this line of thinking, however. For one, if an AV system is required to execute an emergency landing, then this would introduce a need for active 3D ground 'free-space' detection irrespective of any pre-determined landing spots. Remote operation and/or input would be a viable redundancy layer in this regard, but we don't think this would eliminate the need for robust ground detection. Another inherent challenge in an air taxi (vs. a car) is the rate of speed (urban autonomous cars are generally being designed for lower-speeds), and the inability to avoid obstacles by merely braking to a stop. Lastly, an air taxi would require a larger field of detection, for example sensing above/below the vehicle particularly during takeoff/landing. Of course the list of 'corner cases' for air taxis would also be different than cars, such as sudden weather pattern changes, bird strikes, any optical illusions or difficult-to-detect objects on the horizon.

With respect to behavior/controls, designing an autonomous air taxi would probably prove somewhat less complex than an urban autonomous car. That's because an autonomous car must be designed to handle complex and dynamic road scenes (think of a traffic officer taking the place of a traffic signal), at times negotiating with multiple unpredictable road users while attempting to behave in a 'human-like' fashion. This creates a constant optimization challenge whereby the car must tradeoff between safety and human-level agility. An autonomous air taxi likely wouldn't need to negotiate with as many actors, and the predicted behavior and acceptable maneuverability is arguably more reasonably well-defined.

Significant amounts of training data and regulations will likely be required for autonomous air taxis

Like any autonomous system, autonomous air taxis will likely require a significant amount of training data to classify all relevant objects at high accuracy, with pilot behavior being modeled through a mix of rules-based and imitation learning techniques. This could be done through a mix of real-world flight data as well as flight simulators, which are of course well-developed and commonly used across the aviation industry.

This brings up the issue of how one certifies safety, with one approach being self-certification and another requiring a formal industry certification process. So regulations and stakeholder acceptance can influence the timing of deployment, and this too could conceivably become a key difference between the development/deployment timeline of autonomous cars and autonomous air taxis.

When Will It Happen?

In 1940, Henry Ford famously said: "Mark my word: A combination airplane and motorcar is coming. You may smile, but it will come".

We have already started to see the use of electric-propulsion drones for cargo delivery undergoing trial stages

We have already started to see the use of electric-propulsion drones (UAVs/Unmanned Aerial vehicles) for cargo delivery undergoing trial stages. We touched on this in our Citi GPS report Technology at Work v3.0, highlighting drone delivery systems (Prime Air), which are designed to deliver parcels weighing less than 2.27kg (~6 lbs) for flights taking under 30 minutes.

We expect to see multicopter and hybrid prototypes for passengers to emerge in the next 2-3 years

Over the next 2-3 years, we expect to see multicopter (short-range routes) and hybrid prototypes (longer-range routes up to 500 miles) for passengers emerge. Hybrids will typically use motors for take-off/landing (which requires the most power) and electric for cruise or to boost power. As battery technology develops, we will start to see tilt-wing and lift and cruise eVTOLs emerge for short/medium ranges (10-50 miles), which will fly at faster speeds.

By 2020-2025, we expect to see companies focus on testing and optimizing their air taxi solutions, working closely with local authorities and global regulators. As a result of the sheer quantity of players in a still relatively small, untested market (see Figure 49), we expect consolidation via M&A, partnerships or bankruptcy with a handful of air taxis emerging as winners.

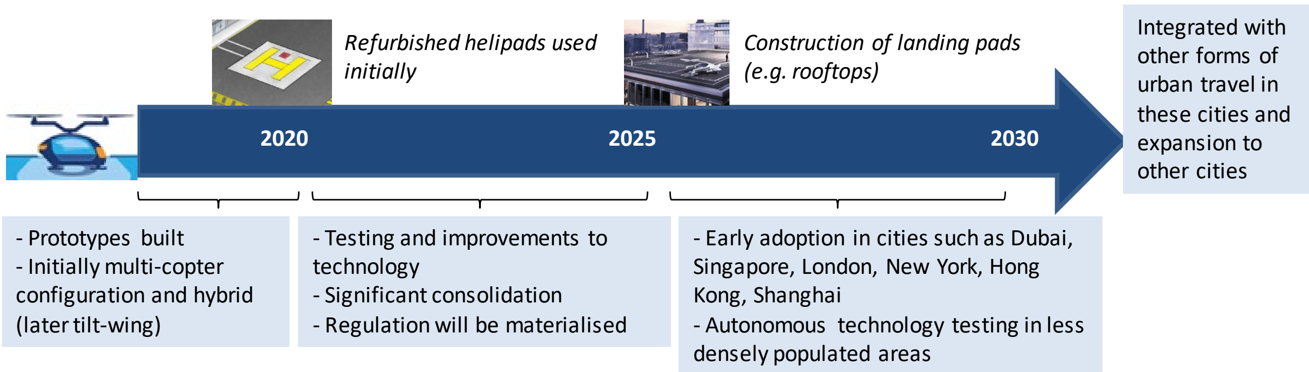
We expect air taxis to start providing urban mobility services as early as 2025 with a few companies are targeting entry into service in 2022/3

We expect air taxis to start providing urban mobility services as early as 2025 with a few companies targeting entry into service in 2022/3, but regulations are unlikely to be up to scratch by then and c public perception will certainly not be. Early adoption will likely be in cities where these benefits are maximized (i.e., congested, high consumer spending) and which are more open to advancements in technology — Dubai, Singapore, Los Angeles, Dallas already have plans to launch air taxis in the early 2020s. Services are likely to be introduced on popular routes such as city centers to airports, and between popular city-to-city routes. Similar to existing pooled ride-hailing auto offerings, services will likely pool customers together given the benefit to costs.

With regulations in place, we expect companies to begin testing autonomous technology over less densely populated areas, by 2025-2030

With regulations in place, we expect companies to begin testing autonomous technology over less densely populated areas, by 2025-2030. The introduction of autonomy (post 2030) and an increase in passenger capacity (as battery technology improves) should provide significant cost benefits for the user, which will help the technology reach mass popularity and integrate it within other forms of urban mobility (along with autonomous vehicles and trains), albeit remaining in the premium segment.

Figure 47. Our Expected Timeline of Air Taxi Adoption up to 2030



Source: Citi Research

By 2030-35, we expect these developments to start having a profound impact on urban travel in the early-adopter cities, allowing air travel within designated routes and even potentially around-the-clock (given reduced noise pollution). This would have a positive impact to productivity and general well-being by reducing travel times, delays (air taxis allows for three dimensional travel), and pollution, in addition to expanding the 'radius of life' within cities.

Key Considerations for Air Taxis

There are still several key issues to address before air taxis can be widespread:

- **Cost:** Air taxis are likely to be quite expensive, ranging from $300k to several million dollars per unit, and so will be mainly owned by operators (several of which will use financing to purchase) rather than private users. Besides the ownership cost, there are several operating costs to think about, such as pilots, maintenance and repair, and software costs. As production rates increase, vehicle price and maintenance should fall (perhaps closer to $200k) and as autonomous technology develops, operating costs will come down further (helicopter pilots typically earn ~$50-75k a year).

- **Vehicle Life:** Aircraft are designed to have a lifespan of around 25 years, which allows their costs to be amortized over a long period of time, while cars are typically designed to have a max life of around 8-10 years. We expect air taxis to have a lifespan of somewhere in between (10-15 years) — closer to cars due to shorter innovation cycles and mass production being more efficient.

- **Technology:** Battery life is developed enough to be able to fly the distances required for air taxi operations, however, charging times and battery life remain issues. In addition, sensors (e.g., collision avoidance) are not advanced enough whether its T-CAS systems used on planes or LiDAR systems used in electric vehicles. While air taxis don't have to monitor for people, they do need to operate in three dimensions (vs. just two on the ground). The advancement of 5G communication networks, however, will allow for better navigation.

- **Safety/Regulation:** Similar to air travel by plane, air taxis are likely to be highly regulated by industry-wide governing bodies (FAA, EASA) and local regulators. Regulators face further headwinds as the market is still not mature. Similar to ETOPS for planes, air taxis will likely also have a set maximum distance they can operate from a hub/landing pad, in case of an emergency landing, and would also likely be required to have recovery systems (i.e., emergency parachute).

They will also likely have traffic separation rules, i.e., minimum amount of empty space around a vehicle at all times. Regulators will also need to take into account how the air taxi will respond in different environments (temperature, humidity) and in extreme weather conditions.

The EASA released a special condition to certify VTOL vehicles in June 2019 (defined by the EASA as up to 9 seats and maximum takeoff weight of up to 7,000 lbs / 3,175 kg) on the back of opening a public consultation in October 2018. Through this special condition, VTOL vehicles will be certified in one of two categories: (1) Basic – requires air taxi to be capable of making a controlled emergency landing; or (2) Enhanced – requires air taxis to be capable of a continued safe flight and landing at the intended destination or suitable alternative after an emergency landing. This is a positive step in recognizing that current rules and regulations are insufficient for VTOL vehicles, which fall somewhere between fixed wing (e.g., planes), covered under rule CS-23, and rotorcraft (e.g., helicopters), covered under rule CS-27. Additionally, the EASA has recruited several electrical engineers and artificial intelligence specialists including cyber security specialists to focus on avoiding threats from hackers. Another complication is that the EASA has noted a lot of time is spent on education with air taxi manufactures since most companies approaching this topic are not established aerospace players and hence are not familiar with the basic rules/regulations.

Figure 48. Regulatory Needs for Air Taxis — What Is Required and Who Is Responsible

Air Taxi Production	What Regulation Is Now and What Is Required	Who Is Responsible
Air Taxi Certification	Airworthiness certification standards will need to be extended (e.g., Part 23 and Part 21 for FAA and CS-23 and CS-27 for EASA) to account for electric propulsion and related subsystems, as well as autonomy. Traditionally, a typical production certification could take 2-3 years, while a new type of aircraft requires a new certification basis and could extend the process to 4-8 years (AW609, a tilt rotorcraft, took 20 years); however, manufacturers can apply for an experimental airworthiness certificate before type certification basis is defined.	Aviation Authority (FAA, EASA)
Continuing Airworthiness	Current standards will need to be extended for air taxis. Rotorcraft standards will likely be the baseline.	Aviation Authority (FAA, EASA) and Local Regulators
Community		
Noise Requirements	Acceptable noise levels will need to be established	Aviation Authority (FAA, EASA) and Local Regulators
Airspace Zoning Restrictions	Existing restrictions will need to be adapted for low-flying vehicles. The growth in small UAVs (drones) have already sparked the need for this ahead of the introduction of air taxis.	Local Regulators
Cybersecurity	Standards for protection against forms of interferences (jamming, spoofing), need to be established.	Aviation Authority (FAA, EASA) and Local Regulators
Infrastructure Requirements	Airport and heliport standards will have to be extended to air taxi landing pads and heliport conversions.	Aviation Authority (FAA, EASA) and Local Regulators
Operations & Fleet Management		
Operator Certification	New standards for unmanned will likely be an evolution of the existing standards for piloted operations (operate under Part 135 for the FAA).	Aviation Authority (FAA, EASA)
Operator Licensing	Local regulators will likely need to implement operator licensing requirements for air taxi operators depending on jurisdiction/operation.	Local Regulators
Fleet Management	Operators of piloted aircraft follow a continuous inspection program approved by an aviation authority, which will need to be extended to air taxi operators. Operators will also require approved fleet management software.	Aviation Authority (FAA, EASA)
Air Traffic Management	Currently air traffic management is often handled by government/military (e.g., U.S. FAA) or part owned (e.g., U.K.). Air taxis will need an efficient system of air traffic management, which will need to integrate with existing systems (e.g., NAS in the U.S.).	Aviation Authority (FAA, EASA)
Air Taxi Management		
Registration	All approved aircraft are on a federal registry. This will likely extend to air taxis, in addition to an additional requirement of local authority registration in some regions.	Aviation Authority (FAA, EASA) and Local Regulators
Surveillance	It will likely be a requirement for air traffic control to track and identify the air taxi to ensure separation standards and accountability	Aviation Authority (FAA, EASA)
Pilot Licenses	Initially, pilots will likely require either a fixed-wing or rotorcraft license. As the technology becomes more widespread, there will likely be a separate license specifically for air taxi operation and possibly even separate licenses for different types of air taxis (multicopter, tilt-wing etc.). For autonomous air taxis, there is no license/certification in place for pilots of a remotely piloted eVTOL vehicle, but this will likely change as drone delivery becomes widespread.	Aviation Authority (FAA, EASA)
Autonomous Operations	Regulations need to be established for autonomous operations and technical standards.	Aviation Authority (FAA, EASA)

Source: Citi Research

- **Logistics/Communication between Air Taxis and Collision Avoidance:** In addition to communication with air traffic control/management, air taxis will need to be able to communicate with one another (across different types of air taxis as well) to avoid collisions. Many aircraft currently have TCAS (traffic collision avoidance systems) installed, mandated by the ICAO for certain aircraft, to prevent mid-air collisions; however, the air taxi systems need to be particularly effective for take-off/landing as the number of flight cycles a day will be significantly higher (and trips shorter). Military aircraft already use automatic ground collision avoidance systems, which have confirmed to have saved F-16 pilots (~75% of fatalities in F-16s were previously due to disorientation or loss of consciousness) — this could be extended to air taxis, in particular, for autonomous flight. For air traffic management, ADS-B (Automated Dependent Surveillance – Broadcast) systems, currently used in the U.S. and in some regions in Europe, to determine the precise location of an aircraft, can be extended to air taxis, but a more comprehensive low-altitude and high-density solution will be needed. NASA, the FAA, and several players in the industry, are currently working an air traffic management system for small unmanned aircraft operations, operating bellowing 400 feet.

- **Security/Threats:** Similar to plane travel, stakeholders, including manufacturers, operators and regulators of air taxis, will all need to ensure the highest level of security to avoid any potential threats (e.g., terrorism, cyber security) and have plans in place to deal with threats.

- **No-fly Zones:** No-fly/air exclusion zones will need to be determined where air taxis are not permitted to fly, such as military zones or sensitive locations (e.g., crowded areas or big sporting events). With autonomous eVTOL vehicles this should be easier as routes will automatically be restricted from flying over no-fly zones, but repercussions of flying over no-fly zones need to be determined, such as military aircraft intercepting violators and escorting them away or forcing them to land. Setting up a no-fly zone will likely need to involve a coalition of participating regions/states/countries which can be arduous, time-consuming, and expensive as well as requiring appropriate intelligence and surveillance in place.

- **Weather:** Weather is an important factor to an aircraft; particularly for smaller-sized aircraft like an air taxi (e.g., turbulence is significantly higher on smaller planes). Corporate jets tend to fly much higher to avoid weather-related issues; however air taxis will need to operate at low altitudes and, as a result, are more susceptible to bad weather, such as wind and low visibility. On the other hand, icing is less of a concern compared to commercial aircraft as air taxis are unlikely to operate at high enough altitudes. Additionally, in bad visibility, air taxis have the benefit of being able to approach at much slower speeds than conventional aircraft (similar to helicopters). The FAA requires any helicopter or fixed-wing aircraft to maintain at least a 500 foot separation from any structure — this will likely be extended to air taxi operations.

  Public Acceptance: A significant hindrance for air taxis becoming widespread is public acceptance around concerns about safety, noise, and security of both passengers and residents. Range anxiety, i.e., worries that the battery will run out before reaching the destination/charging point, has become a key concern for electric cars — this will likely be even more so the case for air taxis given the additional risk of them being off the ground.

Additionally, air travel is generally still seen to be more risky than other forms, despite the remarkable safety record relative to other forms of transport, in particular road, and the layers of redundancy systems that are in place (as a fail-safe). Also, given the premium cost relative to other means of transport, air taxis cannot be perceived as a "luxury toy for the rich" or it will not garner public support for mass adoption. As autonomy is integrated into air taxis, there is an additional concern about flying without a pilot and trust in the automated systems. Local communities will likely also have concerns on an air taxi's vulnerability to hijacking, hacking, and misuse in addition to privacy concerns. To ensure privacy, air taxis will likely have a requirement to maintain appropriate clearance above private property.

- **Variability in Passengers:** Weight will be an extremely important factor on an air taxi — operators need to decide how they will deal with passenger weights and luggage, in addition to accounting for children and passengers with special needs. Similar to commercial airlines on smaller planes, pilots may need to assess several factors, such as weight, prior to allowing passengers to board. Samoa Air (now dormant) famously charged passengers a fare based on their total weight (including luggage).

Who is Targeting this Market?

Nearly half of the over 170 electrically propelled developments are in urban air mobility with more than 150 commercial VTOL aircraft under development

There have been a significant number of companies emerge over the last two to three years that are trying to develop a solution to target the addressable market. This includes a mix of new entrants, established aerospace players (either organically, or via acquisition) and established players from other sectors such as autos, who all have strengths that they can leverage — aerospace players have experience in propulsion technology, while auto companies have experience in large scale manufacturing. Many companies are taking the more active, iterative development approach, rather than a 'wait and see' approach, spurring on a number of developments for a still relatively nascent market.

A study by Roland Berger suggests nearly half of the >170 electrically-propelled aircraft developments are in urban air mobility, while many reports suggest there are more than 150 commercial VTOL aircraft in development currently. Companies have already tested prototypes in 2017/2018 with some targeting entry into service and full commercial operations as early as 2022.

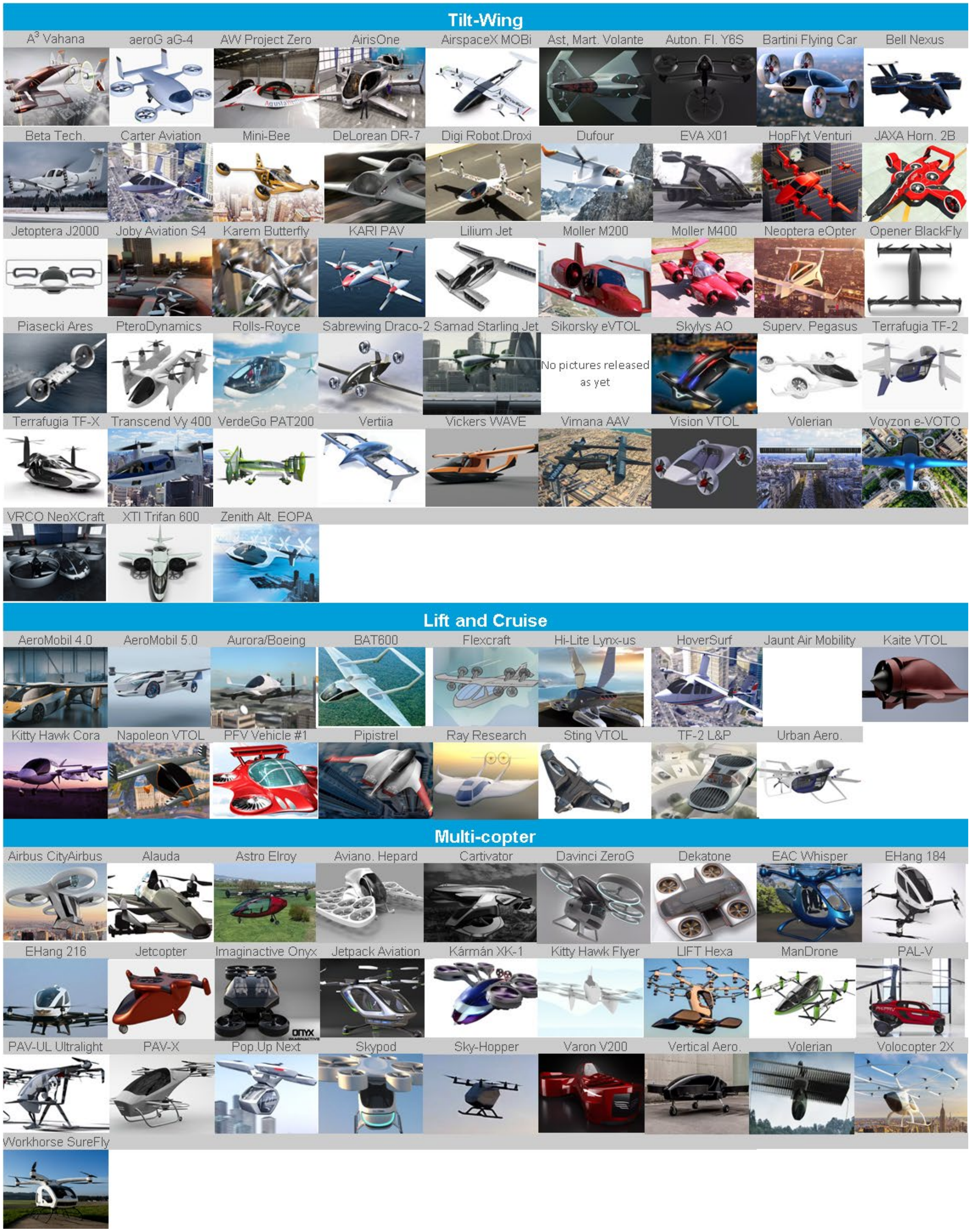
However, as a result of the sheer quantity of players that have emerged over the last two to three years (see Figure 49) for a still relevantly small, untested market:

1. There is fierce competition to be first to market and mass-produce. However, given the logistical challenges and the initial investment involved in mass production and building infrastructure, such as landing pads, the first to market may not necessarily evolve to be the dominant player.

2. There will likely be consolidation in the space, whether through M&A or through partnerships.

As a result, there will likely be a handful of air taxis that emerge as winners within a few years of entry into service.

Figure 49. There Are a Significant Number of Proposals to Target the Air Taxi Market (This list is not extensive and only represents some of the air taxis that have made their offering public)



Source: Company Websites

Interview with Ivo Boscarol (Founder & CEO, Pipistrel Group)

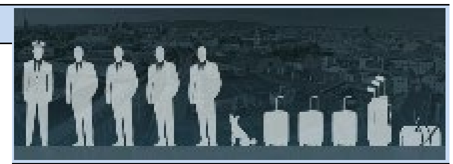
Pipistrel manufactures and services light aircraft, including the world's first commercially available all-electric offering, the Pipistrel Alpha Electro, and are currently working on a 5-seater eVTOL air taxi (801) within the Pipistrel Vertical Solutions division, which was unveiled in June 2019.

What are the technical aspects of the 801?
The 801 is a five-seater all-electric VTOL aircraft which can travel up to 60 nautical miles at speeds of 175 mph or faster. '8' refers to the eight lift-fans for take-off, landing and hover, '0' refers to no tilt-components (which means less maintenance), and the '1' refers to the one tail-mounted propeller to support high-speed cruise. The vertical life system is integrated into the wings — similar to a system of doors which open/close to allow air to move up to the fans effectively. The 801 can also land on a runway like a conventional aircraft, in addition to taking off and landing vertically. Honeywell are providing the digital fly-by-wire system, displays, navigation solutions and the sensor and radio solutions – and we are designing the vehicle with autonomy in mind.

Figure 50. Pipistrel 801 eVTOL Air Taxi

Source: Pipistrel

Figure 51. Capacity on the 801 Air Taxi



Source: Pipistrel

What measures have you taken to ensure passenger safety?
Safety is a crucial factor — the integrated lift system is fully redundant and can fly with up to two out of the eight fans being non-operational. Several parts of the aircraft are energy absorbing including the cabin frame and the seatbelts. Transitioning from hover to flying is very complex — we are currently flying different scale aircraft to prove the design.

How are you approaching community acceptance?
Safety is a key factor that is always in our minds. The other is noise, which can make or break an eVTOL offering. We have tackled this passively, by shaping the fan blades, and actively, by operating each of the eight fans at different frequencies to optimize noise. The seats are also very comfortable — similar to a first-class seat on a commercial flight.

Non-Passenger eVTOL Vehicles

There is a significant market potential for non-passenger autonomous eVTOL vehicles from the surveillance and cargo markets

Although not a focus for this report, there is a significant market potential for non-passenger autonomous eVTOL vehicles from the surveillance and cargo markets. Use cases include surveying buildings/infrastructure, media (movies, photography, capturing live footage), the search element of police search and rescue missions, or delivering goods in a timely manner. These have similar benefits to air taxis when compared to alternatives via road (e.g., bike couriers). We discuss the goods delivery markets in further detail in our Citi GPS report Technology at Work v3.0.

Regional Aircraft Routes

The Size of the Market

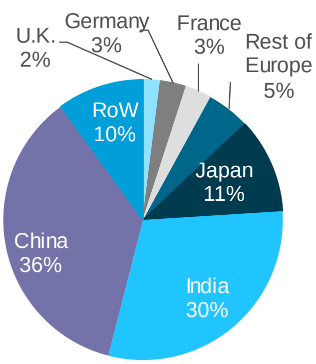
Developments in regional jets using hybrid engines are targeting entry into service over the next 5-7 years, while all-electric propulsion developments are targeting 2025-2030 and beyond

Electric aircraft developments have emerged to target regional aircraft routes such as inter-city transport, i.e. out to 1,000 miles. Given the limited energy density of electric batteries, developments using hybrid engines are targeting entry into service over the next 5-7 years, while all-electric propulsion developments are targeting 2025-2030 and beyond.

The market is currently being serviced by regional (turbojets and turboprops) and narrow-body aircraft along with ground-based transportation such as rail, coach, and is some cases car (such as in the U.S. and Australia). If we take each of these markets individually:

Regional Jets: We estimate the market value of regional turbojets (e.g. CRJ series) and turboprops (e.g. ATR, Dash-8) is worth $4 billion in sales annually. Electric aircraft developments are targeting speeds of 300-400 mph, more aligned with turboprops (~35% of regional market value) rather than the ~500 mph that turbojets travel. Assuming 30% penetration, this market could be worth $1.5 billion in annual sales with over 100-150 planes annually.

Figure 52. Addressable Market Value from Rail Split by Country



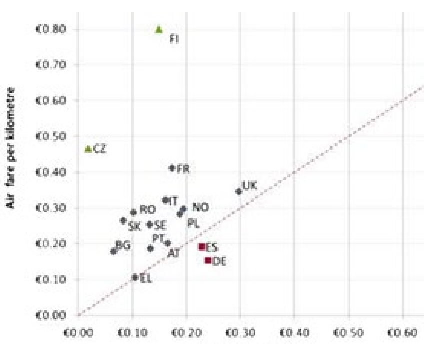
Source: Citi Research estimates

Rail: We estimate ~6-8% of passenger rail journeys and ~30-35% of passenger kilometers, represent long distance trips (>100 km), with an average travel distance of ~150 km. This does not include light rail services (e.g., metro or subway) or airport express services. According to the OECD, global passenger kilometers on train journeys are approximately 3,500 billion passenger kilometers, i.e., ~1,200 billion passenger kilometers are for long distance trips.

1,200 billion passenger kilometers would require a fleet of 20,000 aircraft (assuming 100-seat capacity, 85% load factor, and 4,500-5,000 trips per plane per year), which implies 20,000 / 20 year life = 1,000 aircraft a year, giving an addressable market of ~$20 billion in sales annually (assuming $20 million capital cost per aircraft). The 4,500-5,000 trips per plane estimate is based on an average trip taking 50 mins-1 hour (15-20 min trip time – speed of 550km/h for an average distance of 150km, 30 mins onboarding/off boarding times and 10 minutes taxing), operating 15 hours a day for 300 days a year.

However, China and India make up two-thirds of the passenger kilometers where rail travel is cheap — $0.10 a mile for 300 km/h train and $0.07 for a 200 km/h train in China, and $0.01 per mile in India. Additionally, China has already spent a significant amount setting up rail infrastructure. As a result, electric regional aircraft will not be able to compete in these regions so we estimate the addressable market in 2030 could realistically be about 10% as a conservative estimate, i.e. $2 billion.

Figure 53. Average Air and Rail Fare per km for Inter-Country Trips over 300 km Across Several European Countries



Source: Eurostat – Rail and Coach Cost for intercity Trips over 300km

Although, rail is extremely cost effective — e.g., in Europe, the average fare of inter-city journeys of over 300 km (185 miles) is around €0.15 per km (Figure 53) — travel time is significantly longer with electric aircraft being ~2-6x faster than trains. This is magnified by the ability to travel shorter routes as they aren't constrained by infrastructure and fewer/no additional stops.

Additionally, air travel requires significantly less infrastructure spend. The World Bank estimates the infrastructure cost of high speed rail (tunnels, viaducts etc.) could cost around $25-$50 million per kilometer in Europe or the U.S. and $17-$20 million per kilometer in China. This compares to $30-$100 million for a regional airport, but this can rise to $250 million to $1 billion for a large airport with 35-45 gates and a runway capable of handling a 747 or A380-sized aircraft.

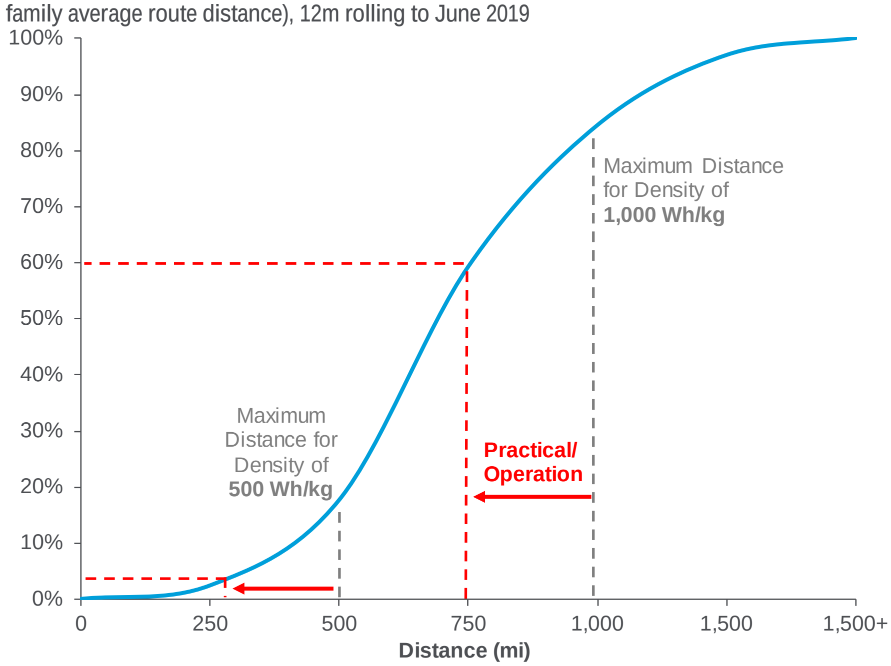
However, regional air travel infrastructure is largely in place with the exception of charging stations which we would assume is cheaper than establishing all new high-speed infrastructure. On the other hand, rail terminals tend to be in city centers, where people typically want to travel to, while even regional airports tend to be on the city outskirts, so the travel time to the airport offsets some of the speed advantage.

We believe electric could tackle narrow-body aircraft currently flying distances of up to 350-400 miles and an addressable market could be $3-6 billion

Narrow-bodies (100-200 seats) Flying Short Distances: As mentioned in the battery section, Bloomberg NEF estimates battery technology could reach around 500 WH/kg by 2030, which will enable a maximum range of ~500 miles for an A320-sized aircraft. Given required reserves, the practical/operational range is likely to be more like 300-400 miles (Figure 54).

Based on Citi Innovation Lab's proprietary analysis of global air traffic journey, which looked at routes flown by narrow-body aircraft over the last 12-months to June 2019, we estimate approximately ~3-6% of narrow-body planes fly distances of up to 300-400 miles. With a total market for narrow-body aircraft of ~$100 billion in annual sales and over 1,600-1,800 aircraft, we estimate that the addressable market for electric aircraft in 2030 could be $3-$6 billion.

Figure 54. We Estimate 3-6% of Narrow-body Planes Fly Distances of up to 300-400 Miles (A320 family average route distance), 12m rolling to June 2019



Source: Citi Research, Cirium, Flight Aware

Routes which are up to 300-400 miles can also be serviced by an electric regional jet-sized aircraft (50-100 seats). The fact that narrow planes are being used on this route instead of regional aircraft implies there is demand for larger planes. Efficiency could also be a driver as fuel efficient technology for regional aircraft has lagged narrow-body aircraft over the last few decades, driven by the larger engine providers. Smaller electric regional aircraft could make up for the demand by increasing frequency — which may, in fact, be more possible for electric if the reduction in noise pollution means planes could fly throughout the night (currently most airports have restrictions given noise pollution for nearby residents).

As a result, we estimate the total market for regional aircraft routes to be worth $6 billion+ in annual sales by 2030. There is further upside to this from:

- **Latent-demand:** i.e., demand for trips to locations that will now be within short reach relative to current modes of transport. For example, more commuters may be happy to live 200 km from work as this could now be a 30 minute flight versus a two hour train ride. However, check-in time and travel to and from an airport, which tend to be out of town (although less noise from electric means airports can move closer to urban areas), are also factors.
- **Capturing Share of Long-distance Road Journeys:** Longer trips by either car or coach are in theory addressable by electric regional aircraft, assuming appropriate infrastructure is in place to allow this. However, only a small percentage of car trips (<1%) are for long trips (over 100 km).

By 2040 Electric Could Capture up to 60% of Narrow Body Routes

Advances in battery technology could allow electric to conduct flights up to 750-800 miles

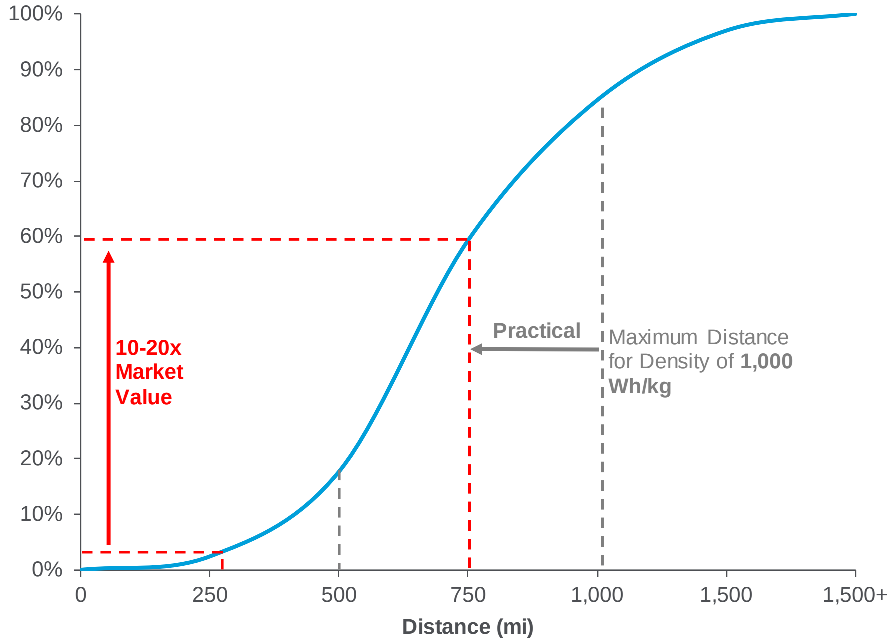
Assuming battery technology has a step-change to reach 1,000 Wh/kg (we predict this by 2035-2040 extrapolating from Bloomberg NEF's estimate of 500 Wh/kg by 2030), electric A320-sized aircraft could reach a maximum range of ~1,000 miles. This will enable these aircraft to conduct flights of up to 700-800 miles (75%-80% of maximum range).

Based on Citi Innovation Lab's proprietary analysis of global air traffic journeys looking at routes flown by narrow-body aircraft over the last 12-months to June 2019, we estimate ~60% of narrow-body planes fly distances of <750 miles (Figure 55). This suggests the addressable market could rise to ~$60 billion by 2040. However, a market of this size relies on a step-change in battery technology.

Between battery densities of 500 Wh/Kg to 1,000 Wh/kg, there is significant market value leverage in electric aircraft taking market share of narrow-body aircraft — for a 2x the improvement in battery density, the market value is 10-20x more, from ~3-6% of all narrow journeys to ~60% (Figure 55).

Figure 55. We Estimate 60% of Narrow-body Planes Fly Distances <750 Miles

A320 family average route distance, 12m rolling to June 2019

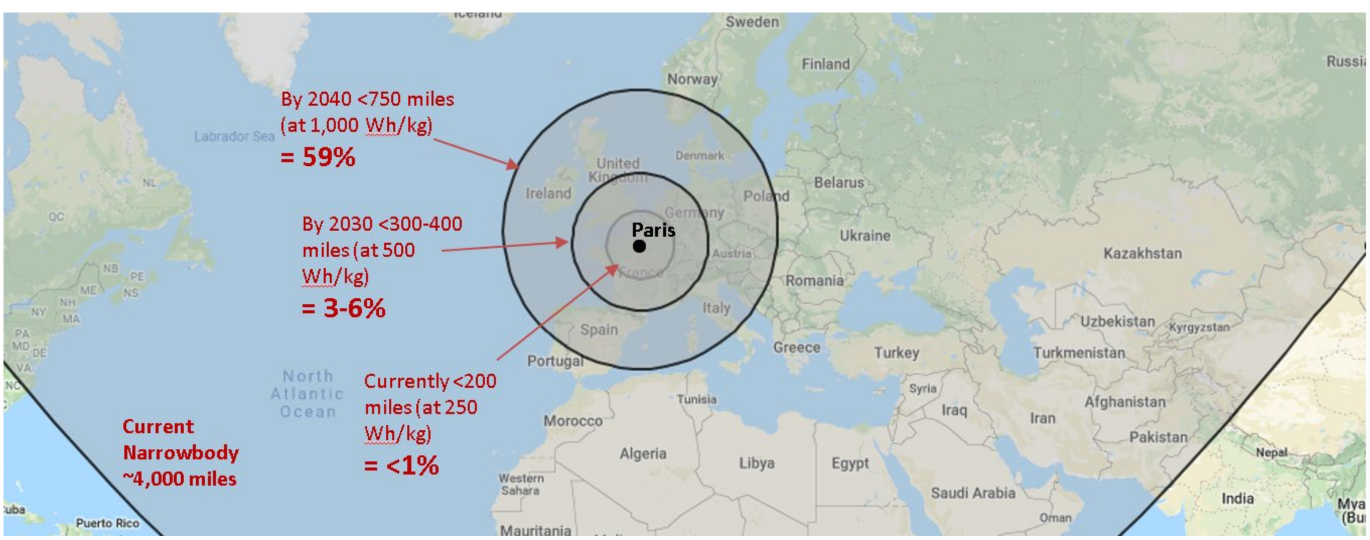


Source: Citi Research, Cirium, Flight Aware

In theory, this could limit traditional narrow-body aircraft to routes of >750 miles, i.e., 40% of the current market.

A study by Roland Berger suggests that ~7% of the almost 170 electrically-propelled aircraft projects are in regional aviation.

Figure 56. By 2040, Electric Aircraft Could be Flying Routes of up to 750 Miles, Which is ~60% of Current Narrow-body Routes



Source: Citi Research, Cirium, Flight Aware, *Great circle routes mercator distortion

What Can Electric Planes Not Do?

Traditional Long Haul Is Unrealistic Over the Next 10-15 Years

We do not see the attractive wide body market being at risk from developments in electric aircraft

There are several challenges electric aircraft (certainly all-electric) need to overcome before mainstream adoption. As we noted earlier, the challenge with electric-propulsion aircraft is to have sufficient excess lifting capacity so as to carry some sort of payload. This gets worse with longer ranges, making long-haul routes unrealistic over the next 10-15 years. As a result, we do not see the attractive wide-body market (currently worth over $50 billion in annual sales) being at risk from the developments in electric aircraft.

Short-Medium Haul – Possible, But Unlikely By 2030

Electric aircraft flying narrow-body routes of 1,000-4,000 miles with capacity of 100-200 passengers isn't likely for 15+ years

Electric aircraft flying narrow-body routes are targeting entry into service in 15+ years. These aircraft typically have routes of 1,000-4,000 miles with capacity for 100-200 passengers. This market is extremely attractive and is worth over $100 billion in annual sales. According to Roland Berger just 2% of electric propulsion projects are dedicated to large commercial aviation.

However, as noted in the Regional routes section, ~60% of narrow-body flights are sufficiently short range (<750 miles) and as a result, could be addressed by all-electric aircraft. Somewhat longer short- and medium-haul flights could additionally be addressable by hybrid- or turbo-electric aircraft.

- Hybrid- and turbo-electric aircraft have the useful feature of not having to completely rely on batteries for energy storage. Instead, hybrid (in particular, series hybrid) and turbo-electric architectures can leverage the benefits of distributed propulsion, which include:
- Increased aerodynamic and propulsive efficiency;
- Ability to create brand new aircraft architectures; and
- Potentially increased safety due to greater redundancy in propulsion systems.

Distributed propulsion emerges from the ability to remove the mechanical connection between the power source and propulsion delivery in the aircraft. Today, these two are linked in a conventional turbofan: there is a shaft which mechanically connects the gas turbine core (the power 'source', in this case) to the bypass fan, which generates the majority of forward thrust.

In electrical architectures, this is no longer required — only efficient cabling is needed as a connection. In hybrid-/turbo-electric architectures, there can still be an on-board gas turbine generating electricity, which ultimately powers electric motors and a fan. This allows for better overall optimization of the propulsion system: the gas turbine can be optimized purely for electricity generation, while the propulsive devices can be optimized purely for propulsion, increasing the overall efficiency (whereas today they must be optimized together, hampered by system limitations). If placed in series with a battery, a gas turbine can also run at constant rotational speed, as the battery can be used to manage peaks and troughs in power requirement, making it more efficient and less costly. On the other hand, distributed propulsion increases the weight of the cabling, which offsets some of the benefit.

Importantly, this also allows the historical trend of reducing the number of propulsive devices on the aircraft to be reversed. In conventional aircraft the number of propulsive devices (fans) has to equal the number of engines due to the aforementioned mechanical connection. Over time, the aerospace industry has gravitated to two-engine aircraft; any more engines have generally been a design, cost and maintenance burden.

In a future hybrid-/turbo-electric aircraft, the high cost/maintenance gas turbine is de-coupled from the propulsive devices. As a result, there can be as many fans/propulsors/etc. as required for optimal forward thrust. With more propulsive devices, there is also greater redundancy in the system, and a greater chance to recover from hazards such as bird strikes, potentially increasing overall safety.

Distributed propulsion also opens up the propulsion system design space, with the potential to easily introduce additional fans to help accurately manage air flow around the aircraft, such as wing-tip vortices or boundary layers. This can further enhance efficiency.

A major barrier, however, is aircraft architecture itself. To completely leverage the benefits of distributed propulsion, brand new architectures are required, featuring:

- Reduced flying speed of 0.7-0.75 Mach (down from 0.8-0.85 Mach) to allow the sweep of plane to decrease to reduce drag; and
- Rear-mounted engines enabling reduced nacelle drag, reduced noise for passengers, and the propulsive efficiency boost due to Boundary Layer Ingestion (which allows better propulsive efficiency by re-energizing the slower-moving boundary layer.

Figure 57. Examples of Large Design Aircraft Under Proposal
The 'Flying V' and the D8

Source: KLM, NASA

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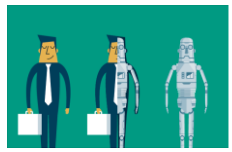

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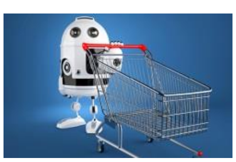

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IMPORTANT DISCLOSURES

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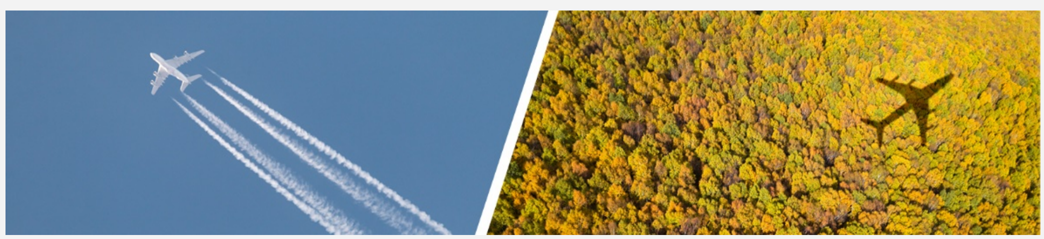
Key Insights regarding the future of Electric Aircraft

TECHNOLOGY

The current limiting factor in the adoption of electric aircraft is the evolution of the battery — especially the weight of the battery. / There is a significant focus on the development of batteries with a specific energy of 500Wh/kg and 1,000 cycle life focusing on high nickel content cathode with a Li-metal anode, sulfur cathode and Li-metal anode, and varying electrode and cell designs.

SUSTAINABILITY

Aviation's share of global CO_2 emissions stood at 2.6% but could rise to 10% or even 24% by 2050 should the industry stay static in emissions while other industries improve. / By incentivizing aircraft operators to switch to electric aircraft more rapidly and with the help of regulation, aviation's share of global CO_2 emissions could decrease to 2%.



REGULATION

For electric aircraft, existing aviation regulations and policy need to be modified to include hybrid-electric and all-electric aircraft. / For urban mobility and air taxis specifically, regulations will have to be created from scratch given they fall between rules for airplanes and helicopters. Autonomous eVTOL complicates things more.