Think:Act

navigating complexity

July 2018

Aircraft Electrical Propulsion – Onwards and Upwards

It is not a question of if, but when

Roland Berger

THE BIG 3

INTERVIEW WITH JOHAN LUNDGREN
CEO AT EASYJET
→ P. 23

~100

electrically propelled aircraft are in development around the world today.

Page 5

~10% OR UP TO ~25%

Will be aviation's share of global CO_2 emissions by 2050 unless significant technological change occurs.

Page 12

2032

The year when Roland Berger's panel of industry experts expects the first >50 seat hybrid-electric aircraft to make a fare-paying flight between London and Paris.

Page 17

Electrical propulsion seems to be on track to shake up the aerospace and aviation industries.

In 2017, Roland Berger wrote about the new and burgeoning trend of electrical propulsion emerging in the aerospace industry. In 2018, the trend has continued: ongoing around the world, there is occurring a confluence of factors contributing to electrical propulsion becoming a reality.

From technological development and investment by new entrants, to activity by major aerospace incumbents – the industry seems to be set for a dramatic shift. Consumers, airlines, environmentalists and regulators alike, buoyed by the pace of change in the automotive sector, are beginning to call for action in aerospace and aviation, too.

Electrical propulsion promises several benefits: the potential for low- or zero-emission flight, the potential to open up new missions for aircraft, the possibility of safer flight enabled by fewer modes of failure and less hazardous power storage, and crucially the design flexibility enabled by distributed propulsion and very high acceleration and high "jerk" capabilities.

There are also several drawbacks hindering the trend to electrical propulsion: the current low technological maturity, the necessity for a complex battery/power management system, as well as the need for aircraft to carry more weight for longer due to low battery energy densities (aircraft weight would not reduce over the flight cycle as it does for conventional propulsion as fuel is consumed).

In this update to our ongoing analysis, we cover the latest developments and how they seem to be impacting the world of aerospace and aviation.

We begin by tracking the progress that has been made to overcome the various barriers to electrical propulsion, from technology, to regulation, to market demand.

Next we describe how aviation's share of global CO_2 emissions could increase rapidly to 2050 if current trends continue.

We then detail a significant update to our electrical propulsion database, including updates on developments in general aviation, urban air taxis (UATs), regional/business aircraft and large commercial aircraft (LCAs).

Next we highlight key potential implications and potential shifts in the current industry structure in aerospace and aviation, including the possibility of a new regional boom, the potential unexpected end to open rotor technology development, a bubbling jostle for supremacy for power system development – and crucially, the potential impact of China's big bet on electrical transportation.

Finally, we showcase perspectives on electrical propulsion from senior industry leaders in the aerospace and aviation industries, including a perspective from easyJet on why airlines may be motivated to adopt electric propulsion.

Tracking progress against the barriers to electrical propulsion.

2017 was a record year with ~40 new electrically-propelled aircraft development programmes being announced, and the trend seems to have continued strongly into 2018. Much of this ramp up was due to the upsurge in new eVTOL/Urban Air Taxi developments. However, the interest continued to increase in other segments of electric aviation also, with a number of new development programmes in general aviation, regional and even large commercial aircraft over 2017-2018. → A

However, there are significant barriers these development programmes must overcome before realising their ambitions. As introduced in our previous study, there are three broad barriers to electrical propulsion: Technological Development, Regulation and Market Demand.

General aviation (GA)

Private or recreational aviation, typically to/from small airports

- Passengers: 1-4
- Power range: 15-300 kW

Pictured GA example: Solar Impulse 2

TECHNOLOGICAL DEVELOPMENT

The technological gap to electrical propulsion is fundamentally driven by the power output required for flight, which varies by platform. For this analysis, we considered four basic platform archetypes, the power output required varies widely.

Technologies required for power output required for general aviation are broadly available today. By contrast, we are a long way away from the technologies needed for electrical propulsion in large commercial aircraft.

Battery technology remains a significant limiting factor for electric aircraft.

Lithium-ion batteries are expected to remain the most attractive for aerospace use due to their relatively higher energy densities and ability to withstand a large number of cycles. Like-for-like, it would take a battery with a gravimetric density of ~500 Wh/kg for electrical propulsion to begin to become competitive with today's traditional propulsion systems; this is not expected to occur before 2030. → B

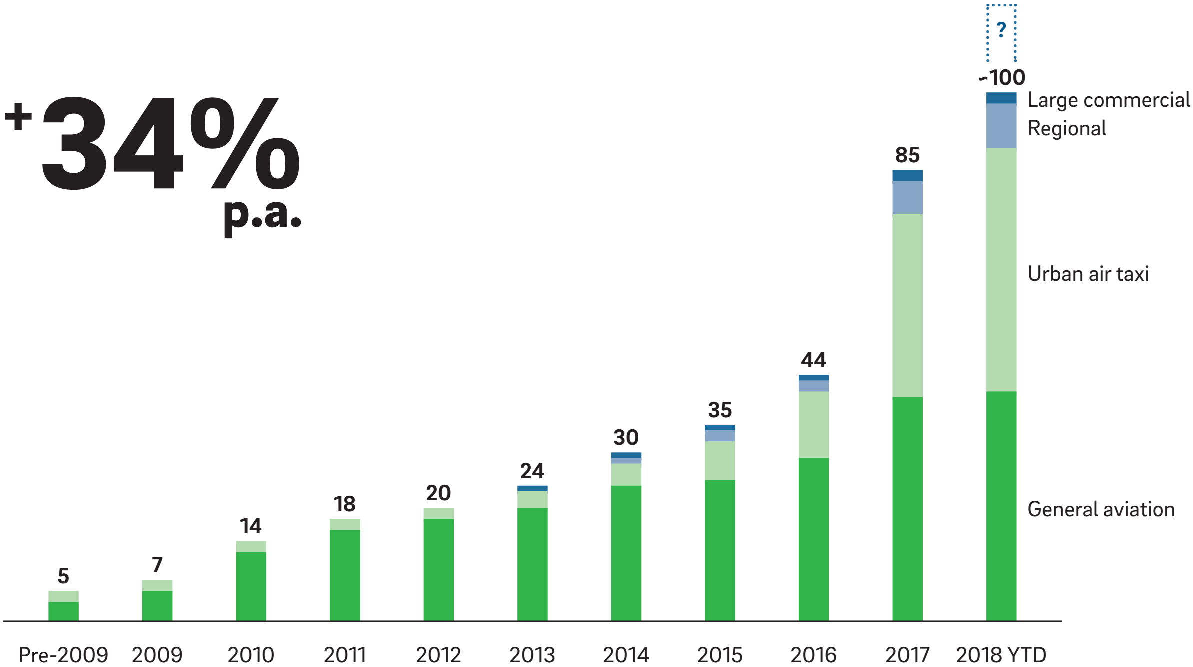
Current indications suggest that the automotive manufacturers that are currently leading on battery development, and are by nature more interested in volumetric density, would likely be satisfied with a gravimetric density of ~350-400 Wh/kg. If so, aerospace developers may have to "take up the baton" to ensure new battery technology keeps getting investment beyond this point.

Electric motors need to further evolve on several fronts to enable regional or large commercial aviation. Sheer power output is not the challenge: the exact amount of power output required from motors will depend on the aircraft architecture, and many land-based motors are already large and powerful enough. Instead, a high power-to-weight ratio and good thermal management are key.

A

KNOWN DEVELOPMENTS BY DATE OF ANNOUNCEMENT (CUMULATIVE, 2009-MAY 2018)[1]

The pace of introduction of new developments has risen very sharply in the past few years.



1 Only including developments with first flights after 2010; excluding UAVs and purely recreational developments

Source: Secondary research, Roland Berger

The highest gravimetric density motors today are claimed to have power-to-weight ratios of 8-10 kW/kg, with companies such as Emrax, Siemens and Remy in the lead (by comparison, the Toyota Prius motor has a ratio of ~1.5 kW/kg). Thermal management is perhaps an even larger problem at the high duty cycles required in aerospace: heat is generated in a motor and thus efficient heat extraction to prevent damage during constant operation is essential. Underlying thermal management is motor efficiency: studies by NASA have shown that increasing motor efficiency from 96% to 99% in aerospace applications can reduce fuel burn by 2% and improve thermal management by a factor of four. New materials (for advanced magnetic and thermal properties) and new manufacturing techniques (such as 3D printing which could open up novel motor architectures) will likely need to play a role to achieve this in aerospace.

An alternative to motors would be a rim driven architecture, which would do away with the heavy shaft and gearbox and instead electromagnets to rotate the thruster. Such technology is already used in marine and UAV applications, however, comes with the drawback of being less efficient than a direct drive motor.

For hybrid-electric[1] architectures, **generators** are required and can be used for additional power as well as range extension for electric aircraft. An electric generator is largely a motor in reverse and must again have a high power-to-weight ratio and good thermal management.

1 The term "hybrid-electric architecture" can apply to a mix of power sources (e.g. solar, hydrogen fuel cells, batteries and turbo-electric generators). For the purpose of this document, we use the term hybrid-electric to mean a gas turbine/battery turbo-electric hybrid configuration

B

THE LITHIUM-ION ROADMAP

Technological progress is enabling significant battery density increases, with improvements up to 500 Wh/kg possible by 2030.

	First serial application in vehicles	Volumetric energy density[1] [Wh/L]	Gravimetric energy density[1] [Wh/kg]
Adv. chem.			
Potential Li air technology	2030	-	>500
Li-Metal/Solid state technologies			
Cathode: Ni-rich Anode: Li-Metal Electrolyte: Ceramic based structure	2025	>1,000	>400
Cathode: Ni-rich Anode: Li-Metal Electrolyte: Polymer based structure	2022	>1,000	>400
Cathode: Mn-rich Anode: Li-Metal Electrolyte: Stabilised "liquid"	2025	>1,000	>350
Adv. LiT formulations			
Cathode: Mn-rich Anode: Graphite (<85%)/Silicon (>15%)	2024	900-1,000	250-300
Cathode: Ni-rich/HV-Spinels Anode: Graphite (<90%)/Silicon (>10%)	2021	~900	250-300
Next gen LiT formulations			
Cathode: NCM721 Anode: Graphite (<90%)/Silicon (>10%)	2020	800-900	>240
Cathode: Advanced NCA Anode: Graphite (90%)/Silicon (10%)	2019	780-800	290-300
Cathode: NCM622-NCM811 Anode: Graphite (95%)/Silicon (5%)	2018	350-600	180-280
Current LiT formulations			
Cathode: NCA Anode: Graphite (95%)/Silicon (5%)	2014	650-690	230-260
Cathode: NCM523-NCM622 Anode: Graphite (100%)	2016	220-400	150-180
Cathode: NCM111-NCM523 Anode: Graphite (100%)	2014	220-250	150-160

1 On cell level/"stacked electrodes" only

Source: Interviews, Roland Berger

Urban air taxi (UAT)/eVTOL

Short intra-city hops, typically with vertical take-off and landing

- Passengers: 2-8
- Power range: 100-800 kW

Pictured UAT example: CityAirbus

In high powered regional and large commercial applications, gas turbines are likely to be used as the fuel-burning component in the hybrid set-up. Important design considerations would include system integration, as well as what on-design and off-design parameters to apply. Current gas turbines are required to provide thrust through the entire flight envelope, dealing with different input air velocities and a whole host of off-design conditions. Conversely, a hybrid-electric engine would have much fewer off-design scenarios and will be able to run at the "design" rotation speed throughout the entire flight envelope, with batteries to help manage peaks and troughs in power output during take-off, landing/thrust reversal and in-flight incidents. Consequently, it is possible that hybrid-electric gas turbines will suffer less damage and will need less maintenance, creating a potential area of cost reduction for operators.

High voltage wiring will also be required in aerospace applications. Traditionally, aerospace designers have only had to worry about relatively low voltages in power electronics and cabling in aircraft typically operating at the relatively low voltages of 28V DC/115V AC[1], with higher voltages only being handled when managing lightning strike discharge. A future consisting of electric propulsion – whether hybrid- or all-electric – would necessarily require much more advanced design involving higher power coursing through electric cabling on aircraft than ever before achieved. These cables can either be large (high cross-sectional area and heavy), thereby carrying relatively safe low voltages, or small (low cross-sectional area and light weight), thus carrying relatively more hazardous higher voltages.

Since weight must always be a consideration in aerospace applications, engineers are likely to select higher voltages for higher power future configurations and thus have to consider how to make high voltage cables lighter and safer. Key to safety considerations are "arcing" and "sparking" (as governed by Paschen's Law), which at their worst can cause material damage and potentially fires. A potential solution would be additional insulation for high voltage cabling, which of course comes with its own weight and volume penalty – and must be sturdy enough to mitigate the risks of arcing and sparking.

Power electronics will also be an essential area for development as they connect power inputs (e.g. batteries, hybrid-electric generators, solar panels, etc.) and power outputs (e.g. multiple distributed thrusting and lifting propellers).

Today's power electronics are based on legacy IGBT[2] technology and are not efficient in terms of energy losses as IGBTs are mostly optimised for stationary machines in industrial automation. A newer generation of power electronics, based on so-called wide-band gap materials offer significant advantages. Two different technologies are currently competing in the race: Silicon Carbide (SiC) and Gallium Nitride (GaN).

GaN is more competitive on cost as it can be produced on existing equipment, but is currently limited in voltage to approximately 600V, which may prove too low for future aerospace applications. GaN has its foundations in the consumer electronics Industries (e.g. computer power supply units) and is trying to push upwards to automotive applications.

SiC is produced on different semiconductor equipment, making it much more expensive but it is not voltage-restricted and could be more applicable to future electric aircraft. SiC is currently used in high-end Industries and niche applications (e.g. space systems) and is trying to extend downwards to mass-market applications (in particular automotive).

Significant investment is flowing into both technologies mainly for development in consumer electronics and automotive. SiC is expected to achieve higher production volumes resulting in lower cost, while GaN technology is expected to advance enabling higher voltage applications, perhaps up to 900V. → C

1 Up to 400V AC in some large commercial aircraft and 270V DC for the F-35 Joint Strike Fighter; 2 Insulated Gate Bipolar Transistor

SiC is expected to remain more relevant for aerospace applications given the higher voltage capabilities and greater cost-tolerance. With either technology, size/weight of power electronics modules could be reduced.

Effective system integration is also essential to unlock the benefits electric propulsion can bring. Two key considerations for system-level designers are the integration of the hybrid-electric generator and the integration of batteries into the aircraft.

In most currently envisioned hybrid configurations, generators must get shaft power from an air-breathing gas turbine, and system architecture is all-important.

Placing the gas turbine on a wing would provide the optimal air inlet, but necessitate either a heavy generator in the wing, or a large inefficient shaft back into the aircraft fuselage. Conversely, placing the gas turbine in the fuselage would imply a curved and less efficient inlet. Further, the gas turbine and generator must be optimised together for total power system weight and efficiency (land-based closed-cycle gas turbine plants are already optimised together, though generally for minimal cost).

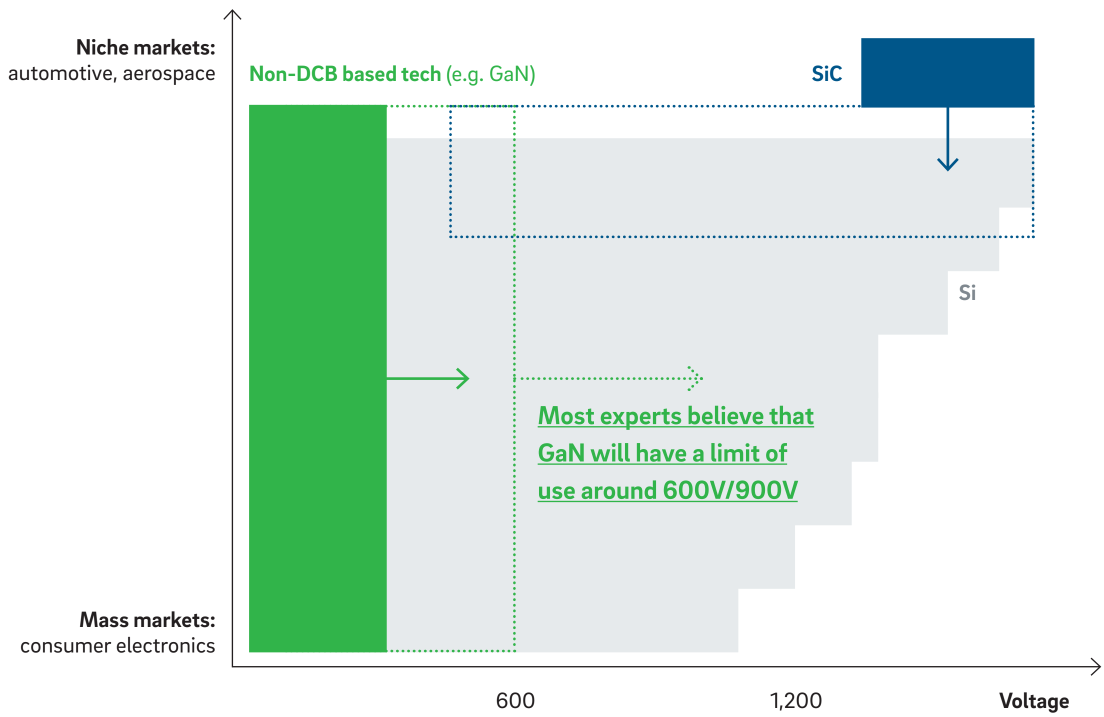
Systems thinking may also provide a solution to technology gap in batteries. Currently, it is not clear what the chemical limit of battery technologies is, or how much R&D investment it would take to advance battery technology to 500 Wh/kg.

A potential part of the solution for aerospace manufacturers could come from the dramatic cost reductions

C

SHIFT IN MARKET SEGMENTS AND TECHNOLOGIES (VIEW UNTIL 2025)

SiC is expected to get less expensive, while GaN is expected to become applicable to higher voltages.



Source: Roland Berger

expected due to capacity growth fuelled by automotive manufacturing capacity growth. Lithium-ion batteries have continuously become more cost effective and uptake in the automotive sectors is expected to drive the industry to even lower cost points over the 2020s. → **D**

This may allow system-level designers to allocate greater recurring cost budget towards higher power-to-weight ratios in the power system (motors, generators, power electronics, wiring, and supporting infrastructure) or select materials and manufacturing techniques allowing the airframe and other aircraft systems to be lighter.

Given the scale of change electrical propulsion represents, it is an opportunity for manufacturers to consider other improvement opportunities including aircraft architecture changes. The blended wing body airframe and boundary layer ingestion are examples of architectural choices which could be utilised to further improve efficiency. Boundary layer ingestion, for example, can deliver a ~10% efficiency improvement even above existing engines, or ~5% net of weight issues (weight penalty of an architecture required to place the engines at typically the back of the aircraft and the associated extra fuselage and bodywork).

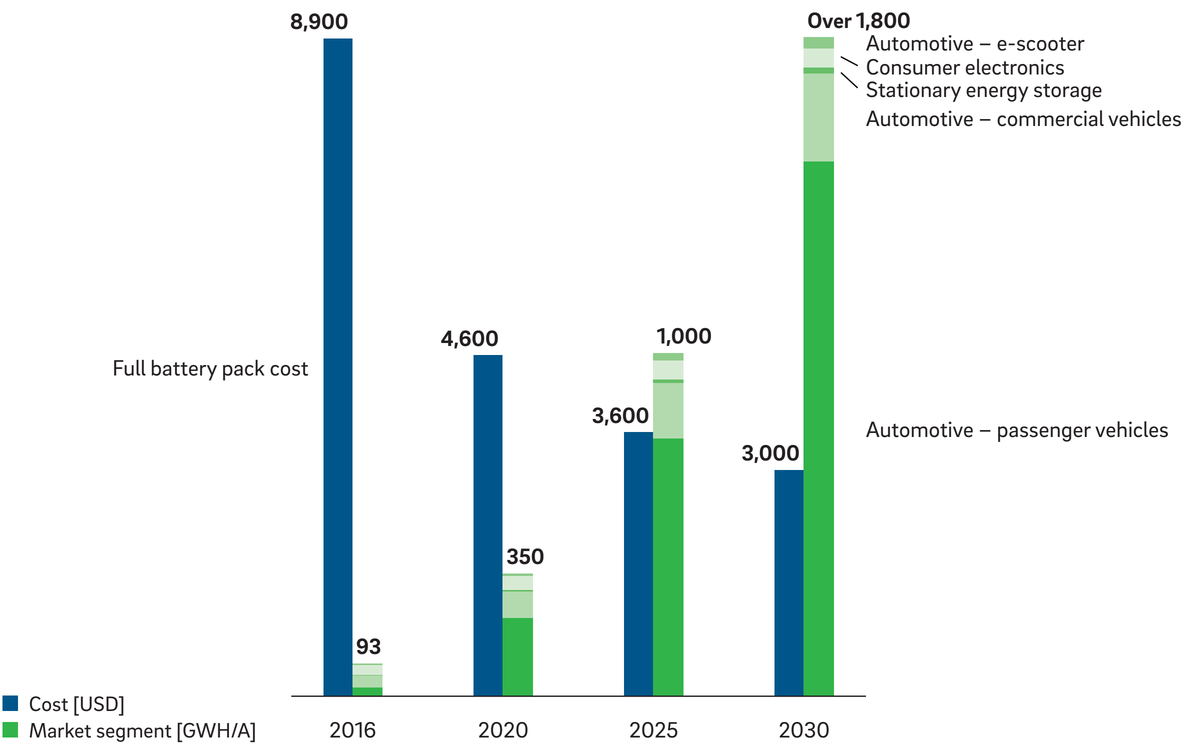
To explore both new propulsion systems and new architectures together, players in the industry are currently employing one of two methods:

- Building the entire architecture bottom-up (an approach taken on by many new entrants, from the Joby

D

LIB DEMAND FORECAST BY MARKET SEGMENT[1] VS. COST[2] 2016-2030

Automotive demand will dominate total LiB market from 2020 onwards – Increasing share of 63% to 81% in 2030.



1 Indicative estimation for 2030: numbers assumed to be as in 2025; 2 Average full battery pack cost of selected vehicles such as the Tesla S 100KwH/the ZOE 41KwH, and the Bolt 60KwH

Source: Avicenne Report, Roland Berger

S2, to the Stirling Jet – to any of the dozens of eVTOL concepts being launched).

- Retrofitting an existing platform to first explore and develop a new propulsion system, and then separately develop a new aircraft architecture around it (e.g. the BAe 146 conversion for E-Fan X).

While the former approach is more bullish on electric propulsion and could result in faster development, it may create a higher barrier for airworthiness certification and adoption in service. The latter approach is perhaps slower and steadier allowing technologies to be trialled and proven in a more deliberate fashion, which may be more amenable airworthiness certification.

Finally, **autonomous flight** is a trend that is running in parallel with propulsion system electrification – and it may be a key building block for certain use cases such as Urban Air Taxis/eVTOLs. Significant progress is certainly required to enable a future in which passenger and unmanned drones can fly in an unsegregated airspace with general/commercial aviation traffic, safely navigating around city infrastructure to complete their missions.

To handle this complex environment, aircraft will rely first on advanced onboard autonomous piloting and "sense and avoid" technologies. Advanced sensors, increased processing power and decision-making processes relying on machine learning/artificial intelligence may constitute some key aspects of these technologies.

A logical starting point and precursor to widescale autonomous manned flight could be the development of systems for safe low-altitude unmanned aerial system (UAS) operations. Experiments involving fleets of drones are already technologically feasible today and could provide valuable information. For example, one key area of development would be a system to coordinate communication: UASs will need to rely on a distributed but integrated infrastructure to communicate with each other and the surrounding environment to prevent collisions, establish prioritisation, guarantee data integrity, and ensure safety. A reliable communications network will be instrumental in allowing data exchanges between control centres, Air Traffic Management, landing sites, UAS systems and existing air traffic.

There are a number of notable initiatives already underway in this area in the US (such as the collaboration between UberAir and NASA), and in Europe with the EIP-SCC-UAM initiative in Hamburg, Geneva and Ingolstadt setting up pilot projects to test the first UAS integration into air traffic.

Regional aviation

Medium range point-to-point journeys

- Passengers: 20-100
- Power range: 450 kW-12 MW

Pictured regional aviation example: Zunum Aero

REGULATION

We have seen the power of regulation to drive technological advancement in recent years. From solar and wind energy installation triggered by path-breaking incentives by governments in Germany and California, to the quickening uptake of electric vehicles enabled by the stance of governments like Norway and China, regulations to drive reduced emissions have thus been a force for significant change in several industries.

Equally, in the aerospace and aviation industries, we have decades of experience of regulators and airworthiness authorities tightly controlling technology through certification and monitoring to ensure safety in the sector. Often this all-important safety focus is a force towards more careful incremental development, rather than significant change.

It is the complexity created by these two often opposing forces that electric propulsion developments must navigate to succeed.

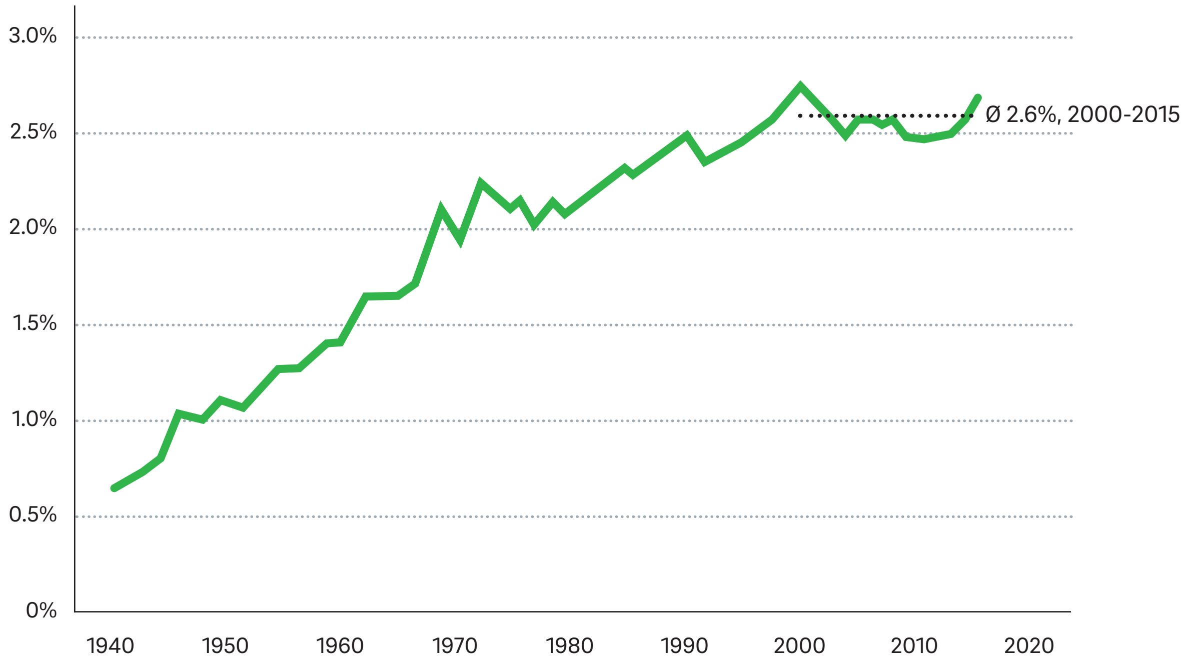
Indeed, emission regulations may become a future driver for a shift to electrical propulsion in aerospace as they have in other sectors.

Driven by fuel cost reduction pressures, airframe and engine companies have succeeded in reducing fuel burn per seat by ~1-2% p.a. over the past 50 years, resulting in marked emissions reductions for new generations of aircraft. However, commercial aviation has underpinned economic and social development and grew at ~1.5 times faster than global GDP, with average annual capacity growing at 4-5%. Thus, in sum, aviation greenhouse gas emissions have been growing at ~3% p.a. This was roughly in-

E

AVIATION SHARE OF GLOBAL CO_2 EMISSIONS, 1940-2015 [%]

After steadily growing through the 20th century, aviation's share of global anthropogenic CO_2 emissions has stayed flat at ~2.6% in recent years.



Source: Atmospheric Environment, IPCC, Roland Berger

line with total global emissions growth and thus, aviation's share has plateaued at ~2.6% since the early 2000s. → **E**

Our analysis suggests that aviation's share of emissions may be on the verge of increasing dramatically due to the combination of three factors:

- → Ongoing growth of revenue passenger miles, which both Airbus and Boeing forecast will continue at ~4-5% p.a. into the mid-2030s.
- → A slowing down in the rate of reduction in fuel burn as gas turbine technology and conventional tube-and-wings architectures become increasingly mature.
- → Sharp reductions in other sectors such as power generation, with the switch to renewables, and automotive, with the growth in electric vehicles.

As per the Roland Berger emissions model, even if fuel consumption improvements were to carry on at 1-2% p.a., aviation could account for ~10% of CO_2 emissions by 2050, and this figure could be as high as 25% of all CO_2 emissions if other industries improve their carbon footprint as rapidly as some projections suggest.

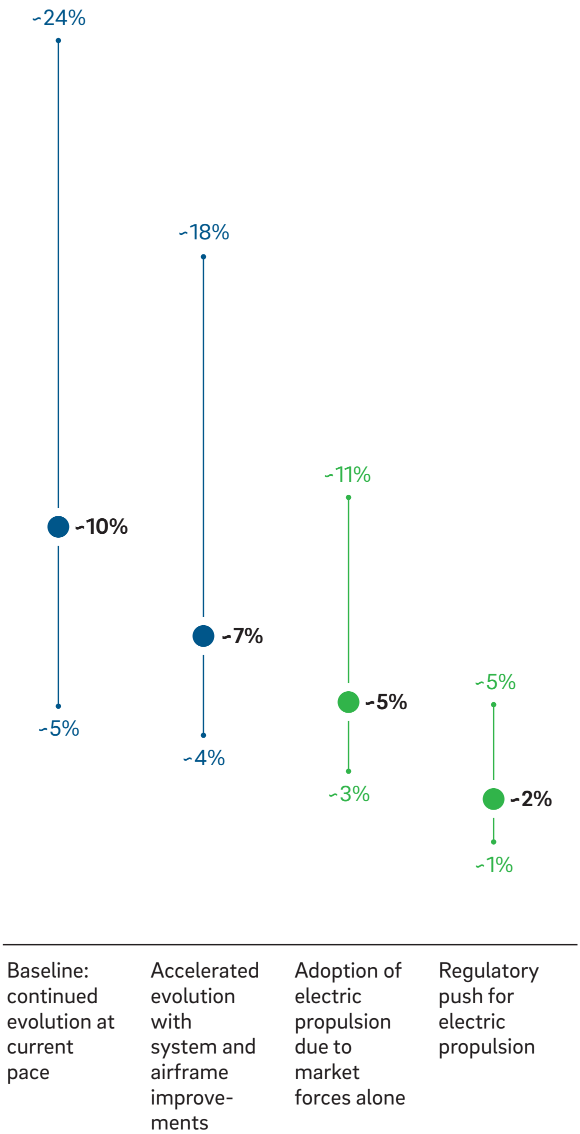
Groups such as ACARE and the Clean Sky Joint Undertaking have proposed new architectures and system level changes that would limit this increase – however, without a step change in the propulsion system, these improvements would limit aviation's share to ~7%. If we model a market-driven switch to hybrid- and all-electric propulsion, we could see a more significant drop to ~5%, which is still almost twice as much as today's levels, and significantly higher in terms of volume of emissions. → **F**

The factor limiting the shift is the longevity of commercial aircraft in service: a typical 25+ year aircraft life results in a very slow fleet turnover, making old technology difficult to refresh. This is where regulation could

F

FORECAST AVIATION SHARE OF GLOBAL CO_2 EMISSIONS IN 2050 [%]

Without dedicated action to reduce emissions, aviation's share of anthropogenic CO_2 could increase to 10%, and possibly as much as 24% depending on the underlying global emissions scenario.



Source: Roland Berger

play a major part: by either incentivising or forcing operators to switch to electric configurations, aviation's share of global carbon dioxide emissions could drop to ~2% according to the Roland Berger emissions model.

So far, international aviation has been left out of UN agreements on climate change such as the Kyoto Protocol, and COP21 Paris Agreement. The industry's UN-regulator, International Civil Aviation Organization (ICAO), has so far only set up a carbon offset scheme (CORSIA) which has the potential to reduce net emissions but only by transferring the emissions – and cost – outside of the industry.

The opportunity presented by electric propulsion may change the arithmetic and allow aviation to go through an energy transition self-sufficiently without the requirement for a carbon offset. However, the consequences of such a rapid transition for the industry would be dramatic – aircraft manufacturers and their suppliers would need to invest heavily in new generations of electrically-propelled aircraft, whilst the residual values of aircraft then in service would collapse, potentially bankrupting the leasing sector.

Airworthiness certification however remains key – any advance in aerospace can only occur if safety concerns are sufficiently addressed.

In this context, innovative components and solutions used in electrical aircraft may pose challenges to the airworthiness certification standards in place for conventional aircraft. Thus, the adaptation, or even creation, of new regulations by authorities such as EASA and the FAA may be necessary to enable the trend.

A major first step has already been taken by both institutions to slowly adapt their regulations for small general aviation (GA) airplanes, paving the way for easier certification of new solutions. The FAA recently overhauled the airworthiness standards detailed in the Part 23 with more flexible performance-based standards. Similarly, EASA revamped CS-23 rules and removed specific technical design requirements, replacing them with safety-focused objectives. Furthermore, in 2018, the FAA publicly approved testing for the eVTOL Workhorse Surefly by providing an Experimental Airworthiness Certificate.

However, specific standards have yet to be defined for electrically-propelled aircrafts and, with the Boeing 787 battery fire episode still relatively recent, it is unclear what increased voltages and power settings will mean for certification of more electric aircraft and electric propulsion. Just as we are seeing technological experimentation, a key enabler for electric aviation may be regulatory bodies, cities and countries that are willing to take risks to experiment with different regulatory and certification regimes to see which create the safest and most progressive environment for innovation.

MARKET DEMAND

The majority of publicly known development in electric propulsion is being conducted by incumbents and new entrants in aerospace manufacturing for commercial applications. Market demand is thus necessarily composed of demand from operators to adopt new platforms, and demand from passengers to fly on them.

Operators must ultimately take on the risk of flying new electrically propelled platforms before electric propulsion can become widespread. Operators can be broken into three types based on the aircraft platform:

- **Large commercial operators**, which can be expected to convert to electric propulsion later due to the more advanced technological requirements.
- **Regional/charter operators**, which are potentially a strong market in the medium-term for electric propulsion developers (exemplified by JetSuite, which has agreed to order up to 100 of Zunum's aircraft after they are certified). Indeed, electric propulsion may drive a new boom in regional aviation.
- A potential new segment of **urban air taxi operators**.

Operators may benefit from lifecycle cost reductions enabled by electric propulsion, driven by increased efficiency and reduced energy costs (depending on the grid delivering low-cost electricity), and potentially reduced maintenance costs. In the highly competitive airline industry, operators may benefit by passing on these savings to passengers, but may also get a competitive edge by developing better "green" credentials by using electrically propelled aircraft. Once proven and with enough practical implementation, electric aircraft may also be safer, with fewer failure modes than traditionally propelled aircraft, and potentially more degrees of redundancy due to distributed propulsion.

Conversely, operators will be concerned about the ramp up to the new technology: proving out and actually realising the potential cost reductions, safety/reliability improvements and maintenance benefits. They will also likely be worried about the ability for supporting infrastructure at airports to adapt to electric propulsion and potentially new architectures.

In sum, for operators to switch to electric aviation, electrically propelled aircraft must be able to drive revenue, be cost-competitive, and not negatively impact operators' risk profiles. However, if targets such as those adopted by Norway become more prevalent, operators may be incentivised to switch faster.

Passengers may also be excited by and willing to pay for "greener" travel. However, in today's highly competitive environment, most consumers of aviation are driven by cost, certainly for large commercial aircraft. For regional aviation, passengers may also be motivated by the greater convenience that can be enabled by electrical propulsion (which, being quieter, could result in more regional airports in city centres), though cost is likely to remain a key consideration even in this market.

A definite new area of interest and excitement for consumers is the possibility of urban air mobility. The "flying car" certainly has an ability to capture the consumer imagination, and may also drive greater convenience for commuters with travelling distances cut to a fraction of the current time. Moreover, Uber's analysis on the topic suggests that eVTOL aircraft could actually be cheaper.

Over the coming years, this could provide sufficient consumer pull to reinforce the investment and development ongoing in this area and allow the first commercial operators to ignite this new burgeoning market. However, manufacturers, airworthiness authorities and operators alike will have to work to ensure high safety and security levels in urban air travel, while managing a carefully considered communication campaign to assure consumers of their safety and, in particular, their comfort with autonomous flight.

Large commercial aircraft

Medium-long range inter-city and international flights

- Passengers: 100+
- Power range: 10-85 MW

Pictured LCA example: Wright Electric

Electrical propulsion is finally on the map: Almost 100 electrically propelled aircraft are already in development globally.

In our previous Think:Act publication: Aircraft Electrical Propulsion – The Next Chapter of Aviation, we had identified ~70 electric propulsion developments with first flights in 2010 or later. Today, the number of developments stands at ~100, with a break-neck increase in investment flowing into new electric aircraft and the number of new developments launched. Out of these, more than half were announced in 2017 or later. → G

To fully appreciate the scale of the activity, we mapped the developments to their native geographies and assessed the type of aircraft architecture they are experimenting with.

Most developments are currently working on general aviation or urban air taxi architectures. Given the current state of technological advancement, this is unsurprising as these smaller architectures require less total power and are less limited by constraints such as battery and motor gravimetric densities.

The majority of development is occurring in the traditional centres of aerospace technology: Europe and the USA, with 45% and 40% of developments, respectively. However, there are developments in other geographies, also, with notably Ehang's eVTOL in China, Eviation's regional aircraft in Israel and Brazil's Embraer's collaborating with Uber Elevate with an air taxi concept.

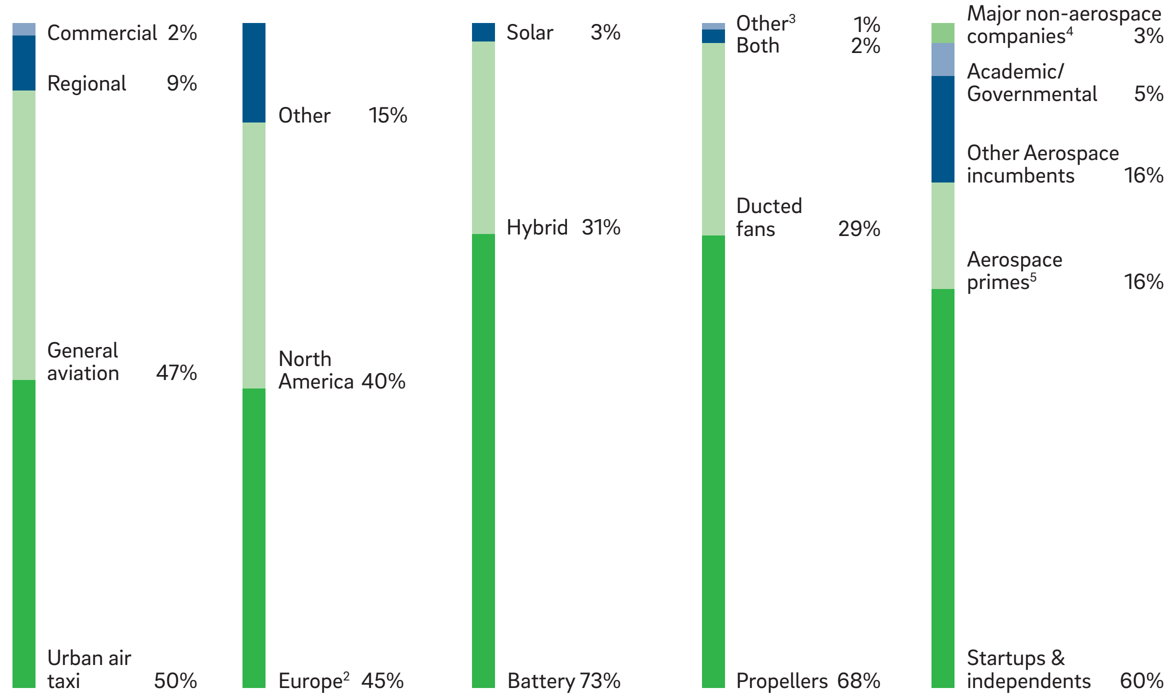
The majority of developments are all-electric with only batteries as their power source, mainly driven by general aviation and urban air taxi developments

> "For the first time, our industry can envisage a future which isn't wholly reliant on jet fuel."
>
> Johan Lundgren, Chief Executive Officer at easyJet

G

DISTRIBUTION OF ELECTRICAL PROPULSION DEVELOPMENTS, MAY 2018[1]

There is a burgeoning landscape for developments in electrical propulsion, with startups and independents contributing ~60% of the programmes.



1 Only including developments with first flights after 2010; excluding UAVs and purely recreational developments; 2 Russia included in Other; 3 Thruster and fan; 4 Includes Kalashnikov, Siemens and Workhorse (public US company manufacturing electrically powered delivery and utility vehicles); 5 Includes Airbus, Cessna, Embraer and Boeing

Source: Roland Berger

which are predominantly all-electrically propelled. Crucially, larger developments targeting the regional and large commercial aircraft markets are mainly hybrid-electric and use traditional hydro-carbon based fuels for greater power output and/or range extension.

Most developments are currently using propellers, with approximately a third using ducted fans. Ducted fans offer the advantages of lower noise (at comparable diameters) greater safety, and greater efficiency for static/low velocity applications. Propellers are, however, more efficient during cruise, have a less transverse drag, can generate thrust efficiently operating at lower RPMs, and are lighter. Notably, certain developments, such as the Embraer X eVTOL concept, are using a combination of propellers both ducted fans and propellers. Additionally, the AirisOne uses eight thrusters in combination with its main fan.

Fuelled by private and venture funding, ~60% of the developments are being conducted by startups and independents. Aerospace incumbents compose ~30% of developments, of which major OEMs are responsible for about half. The remaining developers are from academic/governmental organisations such as NASA, as well as major non-aerospace companies such as Siemens and Kalashnikov.

Implications of the potential revolution: how might the industry change?

Electrical propulsion stands to potentially cause several shifts in the aerospace and aviation industries. In this section we cover four potential changes that may come to pass if electrical propulsion takes off.

A JOSTLE FOR SUPREMACY

Due to the power density offered by aviation fuel over batteries (12 kWh/kg vs. ~300 Wh/kg today), regional and large aircraft are more likely to first transition to hybrid-electric configurations, which afford the benefits of electrical propulsion, while not compromising on range or peak power. Aerospace experts expect revenue generating hybrid-electric aircraft to enter service as early as 2032 in regional applications, and perhaps soon after in large commercial aircraft. → H

Today, there are broadly two major players involved in each aircraft: the engine manufacturer and the airframer. It is understood that both the airframe and engine are complex systems in their own right – both engine and airframe manufacturers have separate certification requirements and departments within the regulatory authorities – and they share the resulting control and influence on the final aircraft.

In a hybrid-electric future, there will possibly be three types of players: an engine company, an electrical systems company and an airframer (as exemplified by the Airbus/Siemens/Rolls-Royce E-Fan X). But which of the three players will have the greatest share of control and influence?

The engine maker would be a natural choice: the complexity of designing and delivering the high power-to-weight ratio aero gas turbine may necessitate that it continues to be the power systems lead, with simply an extension to existing power generation being supplied by the electrical systems provider. Alternatively, it may be discovered that the required electrical system is so complex that an electrical systems manufacturer must be the power systems lead, with better knowledge of how to optimise across multiple electrical sources and sinks – and with a gas turbine supplied in as just one component. Finally, it may also be that the airframer maintains its "Tier 0" status with integration of the entire system being the highest value activity: indeed, the airframer may have to subsume both engine and electrical work for initial developments as new architectures are explored.

Certification will remain a crucial factor and whatever balance of responsibilities are assigned by airworthiness authorities such as the FAA and EASA may ultimately determine where the power lies.

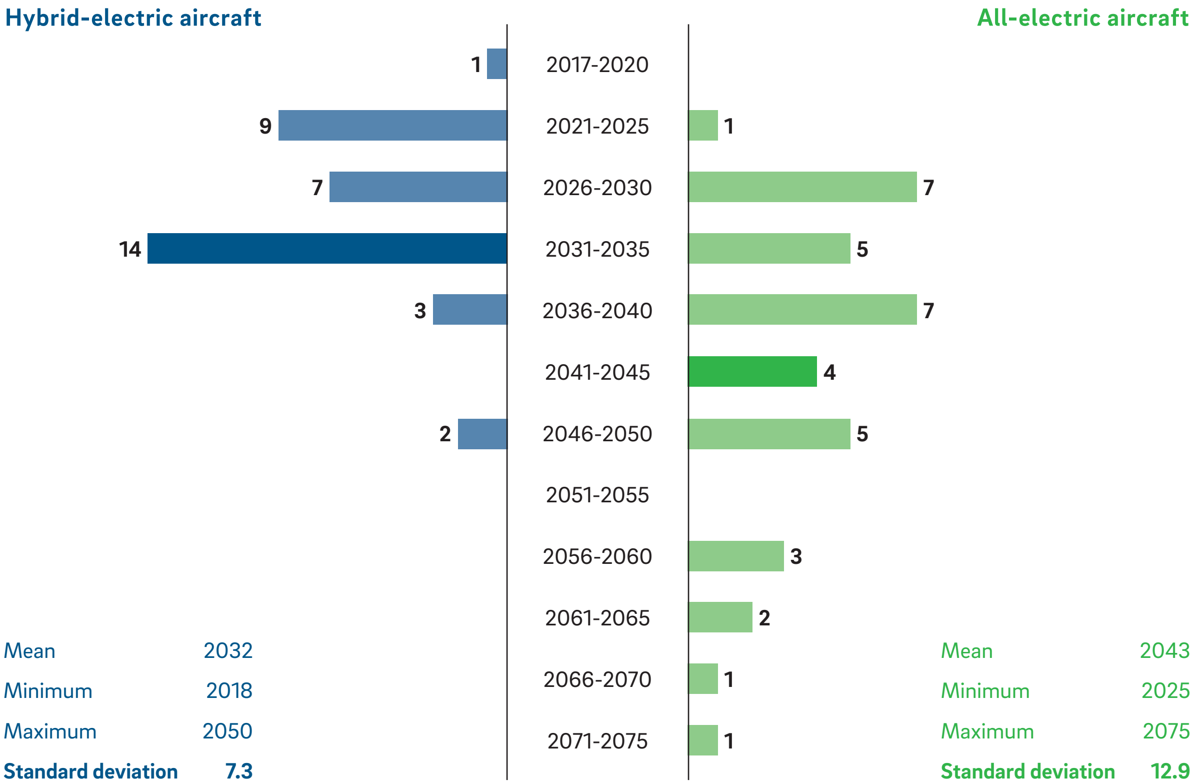
In either case, this question will need to be addressed soon. If the experts are correct, a major hybrid-electric aircraft may be in-service by the early 2030s – just in time for the anticipated Airbus and Boeing contenders for the Next Generation Single Aisle.

H

RESULTS FROM ROLAND BERGER SURVEY OF AEROSPACE & DEFENSE PROFESSIONALS[1]

A&D professionals broadly agree that a hybrid-electric aircraft could enter commercial service by around 2030, while all-electric is less clear.

Question asked: in what year do you think an over-50 seat electrically propelled (either hybrid- or all-electric) passenger aircraft will make its first revenue-earning flight from London to Paris?



1 Results based on a 2017-2018 survey of ~40 Aerospace & Defense professionals

Source: Roland Berger

DEATH OF THE OPEN ROTOR

The development of electrical propulsion may also mean the death of the Open Rotor. This engine configuration is a development of today's aero-engines, which have evolved towards ever higher by-pass ratios in order to obtain higher propulsive efficiencies and hence lower fuel burn. The logical next step is to move to fan blades that are completely unenclosed by any form of engine casing (hence the term "open rotor" or "un-ducted fan"), and which generate even higher propulsive efficiency.

The open rotor concept re-surfaces regularly at times of high oil prices, having originally been tested by NASA and GE in the 1980s, and then encountering a resurgence of interest around 2008 when the oil price peaked at USD 147 per barrel. Despite this interest, practical application of the open rotor concept has been bedevilled by concerns over noise and vibration, along with the challenge of certifying a new configuration that would be inherently less safe than current designs owing to the risk of a fan blade becoming detached in operation (which aircraft chief engineer will sign up to that?).

Even with these drawbacks, the potential reduction in fuel burn offered by the open rotor has – until now – remained alluring. However, electrical propulsion with multiple, electrically-powered fans distributed around the aircraft could offer an even higher propulsive efficiency than an open rotor, with fewer of the noise and safety concerns. Thus, the demise of the open rotor concept may be upon us, even before it has been flight tested in earnest.

A NEW REGIONAL BOOM?

A key reason why the regional aircraft market has recently not grown at the same pace as the large commercial aircraft market is because land-based inter-city transport options (trains and buses) have been cost-competitive and often more convenient. This, in turn, has been driven by the need for airports to be further away from cities due to noise considerations.

Electrical (especially all-electric) propulsion promises to be quieter and could mitigate this concern. Authorities in countries such as China and India, which are beginning to develop significant domestic travel volumes, may thus choose to build electric-only airports in cities rather than develop a more expensive rail network, potentially opening up a significant new regional market.

Other countries may have geographical reasons to adopt electric regional air transport. Norway and Scotland with much of their geography dominated by fjords and small islands, for example, both have a need for short regional flights. Currently, helicopters and other regional operators already cater to this market[1], but fuel costs are high due to logistical reasons. Further, tourist hotspots with many islands or mountainous terrain such as Belize, the Canary Islands or Nepal, have 100s of scheduled flights less than 45 mins provided by regional operators again with high fuel costs due to the logistical issues of transporting heavy fuel to multiple locations.

Electrical propulsion, with aircraft more easily powered by existing grid infrastructure or wind/solar installations in highly remote areas, could solve this issue and bring cleaner, more convenient and potentially cheaper travel to commuters in such geographies. Indeed, this is perhaps a driver behind Norway's move to restrict all domestic aviation to electric only platforms by 2040.

CHINA'S BIG BET

Today's publicly known electrical propulsion developments are mainly in Europe and the USA. China currently hosts only one known development – the EHANG 184, a single passenger carrying, all-electric, autonomous drone.

However, China could play a leading role in an electrically propelled future due to its combination of investment in technology consumer demand, regulation, and current lack of incumbency in aerospace.

Technologically, China is already a world-leading player in electric vehicle technology. Among all global regions/countries, China is expected to see the fastest year-on-year growth in new EV sales (~35% over 2016-2025). Spurred on by enabling government regulations, greater than 95% of global electric bus (PHEV and BEV) sales and ~90% of sales of 2- and 3-wheeled BEVs are sold in China 2016, with the market dominating demand expected to continue unabated into 2025. With such high levels of vehicle installation, companies in China are likely to understand hybrid- and all-electric vehicle operation better than in any other country. → I

Chinese OEMs also already have the largest global EV manufacturing footprint, with ~50% of global EVs manufactured in China in 2017 (a share that increased from just 7% in 2013), with majority locally-sourced content as mandated by Chinese authorities. Further, about 60% of global battery manufacturing capacity is in China (2015), with plans for significant further investment in capacity growth.

This investment in capacity, combined with lower labour and energy costs has resulted in Chinese battery manufacturers currently being the lowest cost in the world. The majority of electric motors used in these vehicles are also manufactured in China (generally in-sourced by the OEMs). Moreover, China has the world's largest reserves of rare-earth metals (essential to both battery and motor production), giving it a natural supply chain advantage. With such high levels of

1 Commuters may also drive long distances or take ferries, which can both be costly and/or inconvenient

production and constant scale-ups in capacity, companies in China can be expected to retain the lowest-cost position in these major electric propulsion technologies, including perhaps the system integration of electric powertrains. → I

Consumer demand is also significant in China. In a recent consumer survey conducted by Roland Berger in China, France, Germany, Netherlands, Sweden and UK, Chinese consumers were by far the most interested in their next car being a BEV, with the greatest desire to upgrade to autonomous driving technology in the future. This suggests that Chinese consumers would also be more willing and excited for electric aviation. Combined with the massive growth of domestic and international aviation in China, and the potential for a new regional market, Chinese consumer demand for electrical propulsion is likely to exceed other markets in the coming years.

Regulation has been the driving force for much of this uptake: the Chinese government has shown remarkable resolve in driving the change to an electric future in vehicles, possibly driven by the established need for solutions to China's pollution woes. Multiple governmental bodies have coordinated to institute regulatory change, including the State Council, National Development and Reform Commission, Ministry of Finance and Ministry of Science & Technology. Regulatory initiatives for EVs have ranged from the announcement of "Made in China 2025" which targets "global leadership" in multiple technologies and industries, to setting the framework for developments and ventures to receive financial support, to putting in place measures for vehicle charging infrastructure implementation. A key sector within Made in China 2025 is aerospace & defence – so a deeper future commitment by Chinese law makers into electric aircraft would not be surprising.

Finally, China currently lacks a significant incumbency in aerospace. Though COMAC and the C919 are on the path to some success, much of the underlying technology was developed outside China and bought in by COMAC. In particular, aero gas turbine technology, developed over decades in the Western world, has particularly high barriers to entry (both financial and technological); the COMAC C919 uses CFM's LEAP-1C engine. COMAC's share of global aircraft production is expected to be <1% even into the late 2020s.

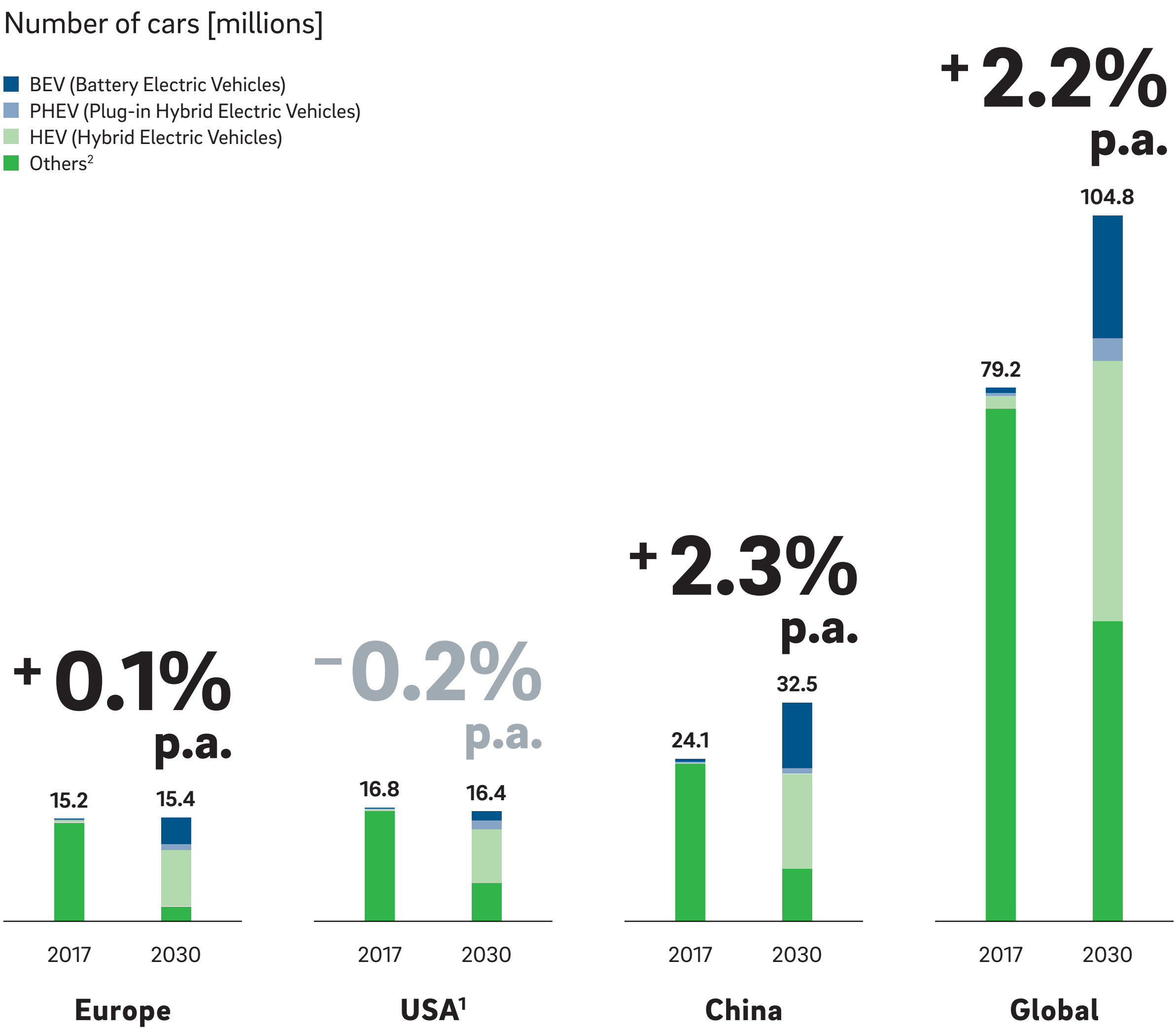
However, this puts China in a unique position. While in the West, electric propulsion could potentially spell significant upheaval and disruption in the supply chain in the coming decades, China does not have a major legacy incumbency in either airframe or engine technology whose success would be risked in the potential electrically propelled future. Indeed, COMAC, China and potential future Chinese aerospace OEMs are incentivised to "skip" internal combustion and progress quickly to electric propulsion to maximise their global competitiveness.

China thus has the technological building blocks, regulatory will, consumer demand, and competitive need to keep pushing the electric transportation agenda – whether this translates into success on a global stage in electric aircraft remains to be seen. What is very likely, however, is that the EHANG 184 will be just the tip of the iceberg.

CHINA'S BIG BET

Lessons learnt from the automotive industry

As a front-running growth market for automobiles, demand in China is a major driver of EV adoption. Battery electric and hybrid-electric vehicles are expected to have the greatest uptake, overtaking internal combustion engine vehicles globally by 2030.

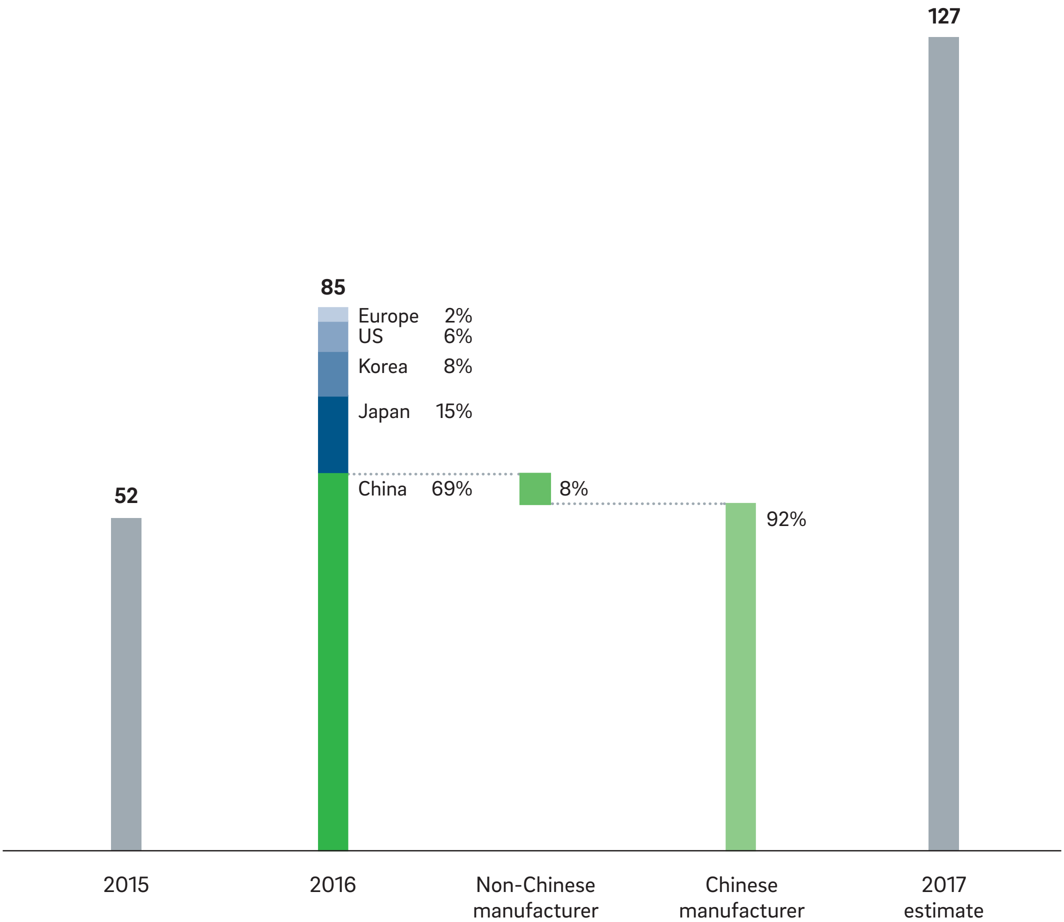


1 Including Mexico and Canada; 2 Including internal combustion engine vehicles

Source: IHS, Roland Berger

Battery manufacturing capacity is increasing at a rapid pace – also mainly due to China's investment into electrical vehicle and battery manufacturing. In 2016, China's share of global battery manufacturing capacity was ~70%, with the vast majority made by Chinese manufacturers.

Global Battery manufacturing capacity [GWh/a]



Source: Bank of America, B3 Report, ITRI/IEK, Yuanta Company Report, Company information, Press research, Interviews with market participants, Roland Berger

Roland Berger interviewed senior aerospace and aviation leaders to try and better characterise the trend.

We approached leaders in aerospace manufacturing, airlines, universities, public-private partnerships – as well as leaders at the new startups entering the field.

Johan Lundgren, Chief Executive Officer of easyJet, outlined his airline's interest in, and motivation, for electrical propulsion, and how it may link in with easyJet's branding as a disruptor in the aviation industry.

We also spoke with Ashish Kumar, Founder and Chief Executive Officer at Zunum Aero on how to start and scale up an electric aviation startup, especially in light of Given Zunum's significant goals and recent agreement with JetSuite.

Andreas Thellmann, Project Executive, Economics of Urban Air Mobility at Airbus, laid out how Airbus is working to spearhead the eVTOL revolution. Airbus has several projects under work, from the CityAirbus and A³ Vahana technology concepts, to the helicopter operator Voom experimenting with the air taxi model, to the Pop.Up which is being pioneered in coordination with Audi and Italdesign.

We asked Starburst's François Chopard (CEO – Starburst Venture) & Mathias de Dampierre (Director at Starburst Aerospace Accelerator) about their thoughts on trends and funding in the industry and what role additional stakeholders such as city governments will have to play in the potential eVTOL boom.

To understand the emissions issue and how the industry must move to solve it, we spoke with Professor Richard J Parker, Chairman of the Board, Clean Sky Joint Undertaking on what role electric aviation could play to accelerate the transition.

Given their decades of experience in certifying aircraft as an independent body, Paul Hutton, Chief Executive Officer at Cranfield Aerospace Solutions, explained how the challenges of certifying an electrically propelled aircraft can be overcome, and how his company is already working with electrical aircraft development programmes to do just that.

Last but certainly not least, we learnt from Professor Pat Wheeler, Head of Department of Electrical & Electronic Engineering, University of Nottingham about the electrical technological enablers for electric aviation, and what a shift to electrical propulsion may mean for the future of aerospace engineering education.

We are constantly speaking with senior leaders on the trend of electrical propulsion – further information and interviews can be found on our website.

Johan Lundgren

Chief Executive Officer at easyJet

Why is easyJet interested in electrical propulsion? What are the key motivators?
For the first time, our industry can envisage a future which isn't wholly reliant on jet fuel, thus reducing its associated CO_2 emissions and where our noise footprint is significantly reduced for all flights. The decarbonisation of other forms of transport like road and rail is advancing quickly and could in future be matched by aviation. Our newest aircraft have already enabled us to reduce our carbon by 38% since 2000 and the noise footprint by 50% compared to current aircraft. Electric aircraft will not only reduce our impact on the environment but will also provide respite for communities living near airports. easyJet is collaborating with US company Wright Electric to support their goal for short haul flights to be operated by all-electric planes within 10 years.

easyJet has been an innovator in aviation from its inception, disrupting the industry – how does this fit with electrical propulsion?
Innovation is in our DNA and that means that we are always looking at new ways for the industry to progress and do so with sustainability front of mind. While the industry has been working on reducing its impact on the environment electric aircraft have the potential to step change this.

Would electrically propelled aircraft need to deliver lower cost per seat mile to succeed in the market?
Electrically powered aircraft will need to offer competitive operating economics however the cost of jet fuel isn't static and any calculation has also to take into account the effect of any further environmental charges or taxes levied on conventionally powered aircraft.

Ashish Kumar

Founder and Chief Executive Officer at Zunum Aero

What is Zunum's development path?

All our focus is on the 6 to 12 seat, 700-mile aircraft we are developing for entry to service in 2022. This will kick-off the commercial electric era with breakthrough economics, 8c per seat-mile, and door-to-door times, half that of commercial air today. However, we have architected the underlying technologies for extensibility to larger platforms and longer ranges. Our roadmap is to scale from this 1 MW aircraft to roughly 4 MW on a 50-seat 1,000-mile aircraft in the mid-2020s. And then to 17 MW on a 100-seat 1,500 mile aircraft (Mach 0.7) around 2030. Each of these platforms offer disruptive economics relative to the fleet today, together with quiet and short runway capabilities for fast door-to-door travel through nearly 40,000 airfields worldwide, relieving congestion at the hubs. Crucially, this roadmap would place aviation on path to eliminate all short-haul emissions by 2040, equating to 50% of all emission from the sector, aligned with the goal set by Norway.

How is Zunum organising itself to meet its commitment to JetSuite to deliver 100 aircraft?

We are excited to partner with JetSuite for our launch. The innovative JetSuiteX service whisks travellers city to city, avoiding hubs and queues, to offer a business jet-like experience at fares that approach commercial. Building on roots in California, JetSuite is now scaling this service nationwide. We expect this form of fast, convenient travel to become universal in the 2020s, boosted by the disruptive economics of our hybrid-to-electric aircraft, helped along by improving autonomy, biometrics and intermodal connectivity. We are on track to production commitments and focused on reducing risks on our "conservatively aggressive" schedule. Our approach is three-fold. First and most critically, our baseline technology is highly de-risked, combining TRL-9 aviation technologies with best-in-class ground EV battery modules. The hybrid-to-electric powertrain is well suited to rapid prototyping on 12-month cycles, enabling us to mature the technology ahead of introduction. Meanwhile, our architecture enables choice of all-electric or hybrid variants, and the ability to transition the hybrids to all-electric based on development of battery technologies. Second, we are very fortunate to have attracted a deep pool of seasoned engineers with highly relevant experiences. Our early focus was on Electric power and Propulsion. More recently, we have expanded to key aircraft disciplines, drawing talent from Pilatus, Embraer, Gulfstream, Honda Jet, Bombardier. We are also engaged with Boeing in several areas and benefit hugely from their leadership of the sector. Third, we are actively engaged with the aviation supply chain on many aspects of our program and expect to make several announcements later this year that will define our partnerships.

Andreas Thellmann

Project Executive, Economics of Urban Air Mobility at Airbus

What can electric propulsion bring to aerospace and aviation?
Electric propulsion is a major enabler for distributed propulsion. Distributed propulsion, in turn, represents the third aerospace revolution: it is the game changer that allowed new designs by offering more degrees of freedom. If we can optimise aircraft range, payload and speed, we could see new architectures emerging. Our experimental helicopter ride-sharing project Voom in Sao Paulo has shown that most missions last very short at moderate cruise speed. We believe all-electric propulsion could be achieved in this segment, while hybrid propulsion would be more suitable for longer range/regional flights.

Will the various possible architectures ultimately coalesce to one type, or will there be many?
It will be hardly possible to develop a one-size-fit-all concept -not even with tilt-wing aircrafts- as mission profiles vary too much. For example, multi-copters (without significant wings), especially low surface load concepts, are good at providing hovering stability and efficiency, but are not well suited for high speeds. Tilt-rotor/tilt-wing aircraft, conversely, can provide good forward speed, but are more complex and less energy efficient for hovering. Different use cases and segment will emerge served by different designs.

What is the main obstacle to creating these kinds of aircraft?
Battery technology, which has some way to go. For typical inner-urban operation, we believe an aircraft would need a battery capacity of 30 minutes to make economic sense. This may soon be possible since experts believe that battery energy densities of up to 800 Wh/L are possible in the not too distant future.

Will new business models emerge?
We will have to wait and see which models industry and cities are willing to set up. New business models will have a tremendous impact on the ticket price of an urban air flight. Just by sharing helicopter rides combined with an efficient routing/flight operations we see that much lower ticket prices are possible even today. And our future business models will focus more on the end consumer.

What role do regulators have to play?
Regulators will be essential, especially in working with cities to adapt solutions to local specifics. Providing the right certification is key: safety is our top priority. There is no compromise on it to accelerate the pace of development. Control of airspaces is also key: currently 95% of helicopter flights are VFR (Visual Flight Rules), which will not be viable with hundreds flying over a city at the same time. Regulators will thus probably accelerate autonomous flight options to allow a truly integrated and unsegregated urban airspace.

How does city infrastructure development fit in?
Sufficient landing pads will have to be built – but with sufficient utilisation to justify the use case. Integrated autonomous systems will again be essential here to ensure vehicle availability, optimise routes, minimise waiting/hovering time/energy use, etc. to minimise infrastructure requirements and investments.

François Chopard

CEO at Starburst Venture

Mathias de Dampierre

Director at Starburst Venture

What is your perspective on the developments in electric propulsion today?
There is a buzzing ecosystem of projects happening today! From early drawings to flying prototypes, and from new announcements just out of "stealth mode" to well-funded Round B ventures. We are still seeing an influx of 1-2 projects per week which is a major change in the industry. What we do not see yet is a clear trend of venture capitalists putting money on the table as they did for space applications (satellites constellations, new launchers, etc.) – this is perhaps driven by the currently unknown evolutions of the regulatory environment and business models. For example, on the eVTOL segment, startups are generally not yet ready to be acquired, and corporates are not yet ready to buy them. Once an eVTOL has been certified, this may change. Electric aircraft now have more adapted standards for certification due to recent changes in FAR23 rules – but nothing is currently in place for eVTOLs.

Aside from certification, what are the barriers to implementing urban air taxis/eVTOLs into cities?
Improved battery capacity still needs to be achieved, and the question is who will do this for the aerospace industry? Till now, the VTOL industry has benefited from the automotive industry spillover effects, but once vehicles reach a 500-600 km driving range, it will probably concentrate on cost, not on capacity. Additionally, cities themselves have a big role to play: the FAA may make vehicles fly, but cities will make them land. For example, the degree of freedom that will be allowed will be a key factor. Either a city can allow completely free movement within a tightly defined airspace, or it can go further and implement rules to perfectly control the exact positions of aircraft. New classes of airspace are likely to emerge, meshing with existing airspaces over cities, probably with different rules for each city.

Where is funding coming from?
Today most funding enabling technologies for electrical propulsion is still coming from the automotive industry. However, this will not be sufficient for aerospace ultimately since technological specifications are somewhat more severe for aerospace applications than automotive ones. Currently, maybe only 1-2% of venture funding in aerospace is going into electrical propulsion – how this will develop in the future remains unclear.

Professor Richard J Parker

Chairman of the Board at Clean Sky Joint Undertaking

How will aviation's share of greenhouse gas emissions evolve in the future?
The share today is 2-3%. If emission reduction efforts by other sectors succeed and aviation does nothing, aviation could be contributing up to 30-50% of global emissions by 2050. To address this fact, the Clean Sky/ACARE initiative is targeting a 70% system level reduction in emissions achievable by new aircraft introduced in 2050 relative to a year 2000 baseline; of this 70%, around half would come from airframe improvements, a little less than half from propulsion, and the balance from air traffic control. The 70% reduction represents a doubling of the rate of improvement to that of the past 50 years, and so is quite challenging. Electric propulsion could therefore support achieving this target. A key element for electric propulsion is that electric architectures can only be as clean as the electricity used to power them. This varies geographically, based on a region's electricity generation mix.

What role does regulation have to play?
Fleet turnover is a crucial issue where regulation could have an impact. Even if we develop fantastic technologies before 2050, today's pace of fleet retirement is very slow and rolling-over the in-service fleet itself to more electric propulsion would take decades. Regulation could come in here to either incentivise private companies to change, or require them to change. For example, governments could force early fleet retirement as a mechanism to bring in newer and cleaner technology faster. The latter would definitely have to be done in a coordinated and orderly way given the impact of aircraft residual values, and the whole, fragile business model of the industry.

What about certification of aircraft?
Ultimately, airworthiness certification may not be a great issue once we've got our minds around it. Electric configurations allow greater redundancy – for example, NASA's X-57 has 14 propellers and motors, but could safely operate with possibly multiple rotors going out. In addition, electrical propulsion systems might have fewer failure modes than conventional engines. However, to really prove out new technologies and understand certification better, a good method is to use demonstrators and partner with regulators. The Airbus/Siemens/Rolls-Royce E-Fan X will be a great example of this, both for developers and airworthiness authorities alike. In the Clean Sky 3 programme, starting in 2020, we hope to see even more European demonstrators for electric and hybrid aircraft supported.

Paul Hutton

CEO at Cranfield Aerospace Solutions and Cranfield Simulation

How would certification be different for electrically propelled aircraft vs. traditional aircraft?
In many respects the certification process will not be very different. It will use the same approach and demand the equivalent supporting data/provenance currently used for traditional aircraft. As with any new product/design, close collaboration with the airworthiness authorities from the beginning of the development process will be vital. In principle, if the operation of the aircraft remains largely the same then the main challenges will lie in the ability to design any new system to meet the regulations and the ability to show compliance both in development and in operations, even for large commercial aircraft.

What can authorities do to enable adoption of electric propulsion without compromising on safety?
Early and open bilateral engagement throughout the development process with aerospace organisations developing the new technologies is vital. This will enable a collaborative agreement to be reached on the certification basis for each technology and robust validation and verification process to support the demonstration of compliance. For urban air taxi/eVTOL applications, the authorities will need to also engage with all those organisations involved in contributing to the operating environment for the air vehicles, to ensure that development in the regulations and processes in all areas maintain and enhance safety when departing from the present standard approaches in civil aviation. This is something that the major airworthiness authorities already recognise.

What are the advantages and drawbacks of "starting from scratch" versus retrofitting existing technology to test electrical propulsion?
We don't see either of these approaches as, necessarily, having drawbacks – both represent progress and are simply different approaches working towards the same vision of a fully electric aviation industry. By taking the "starting from scratch" approach, be it in a disruptive autonomous passenger drone or that of a fully electric new tube & wing aircraft, it creates a vision of the landscape into which the industry will step. It provides vital R&D learning and sharing of knowledge; it encourages supporting technologies to be developed (e.g. batteries) as a potential future market seems viable. This approach tends to require more investment and experience and therefore the barriers to entry can be quite high but with the right support/partnership and funding, it's an exciting and innovate approach. By retrofitting an existing airframe with a new propulsion system, you keep the majority of the operations and the airframe the same, which simplifies the task and enables concrete progress to be made towards certifying a product for operational flight. This will then also provide valuable experience and knowledge, including to the authorities, to support the more disruptive approaches. In short, both approaches are important and necessary.

Professor Pat Wheeler

Head of Department of Electrical & Electronic Engineering, University of Nottingham

How advanced does electrical technology need to be for aerospace and where is it now?
For the all electric aircraft to be viable the motors and generators would need to be smaller and lighter than they are today. No one improvement in design would be sufficient; you would need to take advantage of improvements in power electronic converters as well as employing new materials and advanced manufacturing techniques which are emerging. It's through the process of accumulating these advancements that you will create future electrical motors and generators at the right power densities and volumes, etc. A quick win in the coming years would be to better understand the use of wide band gap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN), which allow faster switching, altering the frequency ranges possible in a machine. In electrical machines this could be transformational: for example, if SiC devices could be used to deliver a 2.5x increase in frequency over silicon, or they could be used to reduce losses by maintaining the same switching frequency range.

What about battery technologies?
Batteries are very important since they will represent a large proportion of the total power system weight. For all-electric propulsion, there's a big step needed. I don't think you will get there with incremental improvements of Lithium based batteries – you may need a technological divergence of battery chemistries relative to what other industries like consumer electronics, automotive are doing. Historically, there have been step changes in battery chemistry, and we may be due one soon. A key to such developments is to have competing research groups working on different ideas at the same time.

What is required to effectively integrate these technologies into an airframe?
It's not just about integrating a components, but about optimising the system design – that's not always easy. Part of the challenge is thinking at a much larger scale than we traditionally have in electrical systems. It's also essential that companies don't ignore safety concerns and employ the right technical expertise. For example, for a future electric propulsion system, you may need the expertise to design a high voltage DC bus (maybe 1000s of volts). This knowledge does exist, but it's a lot more specialised and there's a learning curve there that must not be underestimated.

Does engineering education need to evolve for an electrically propelled future?
The industry will need different types of people: generalist engineers who have a strong understanding of many engineering disciplines, as well as specialists who can dive deep into their specific areas. In a sense, aerospace is already a generalist field of engineering – but a further broadening of the aerospace skillset is required. To help with this, the University of Nottingham has just introduced a new undergraduate aerospace engineering course, 25% of which in based in electrical engineering.

Electric propulsion is ushering in an age of innovation in aerospace and aviation of a type not seen for decades.

There are a great many experiments occurring around the world, with the total number having more than doubled since the start of 2017. Often venture-backed and developed in an agile way, many will fail, but some may succeed. As a result, aerospace and aviation incumbents are also faced with a rare opportunity: the luxury of watching and learning with zero or minimal expense – as dozens of new architectures are developed, new power systems are electrified, and new infrastructures are put in place – ultimately gaining the ability to adapt their own strategies or acquiring the winning development(s).

Indeed, incumbents now have a responsibility to their companies, customers and shareholders to move quickly on electrical propulsion, or risk being left behind as new players with greater risk tolerance enter their markets. The change is coming about due to a combination of a push from rapidly developing technologies and a pull from the market – and it is heavily influenced by progress and regulation in other industries, notably automotive. As other polluting sectors develop solutions to mitigate their emissions, governments and regulators worldwide will have to consider how to manage the inevitable rise in the share of emissions from aviation, and how to incentivise the aerospace industry to catch up. In the coming years, regulatory pull may thus track that of the automotive industry, with many more countries (notably, China) perhaps choosing to institute electrical propulsion targets and roadmaps for the future.

However, challenges remain, and to prevent going the way of the Very Light Jet, newcomers into the industry and their backers must ensure they do not underestimate the difficulty of succeeding in aerospace.

In our original 2017 publication, we concluded that the rise of electrical propulsion was not a question of if, but when.

Through the excitement and investment, we believe that it's possible – more so than for previous "attempted disruptions" in aerospace – that significant change will occur, and that it may come sooner than anyone expects.

ABOUT US

Roland Berger, founded in 1967, is the only leading global consultancy of German heritage and European origin. With 2,400 employees working from 34 countries, we have successful operations in all major international markets. Our 50 offices are located in the key global business hubs. The consultancy is an independent partnership owned exclusively by 220 Partners.

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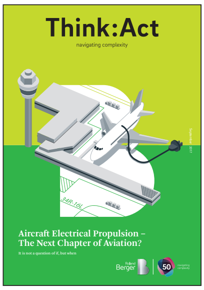
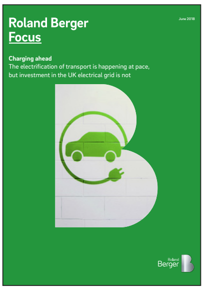
Roland Berger has been helping its clients to manage change for half a century. Looking forward to the next 50 years, we are committed to supporting our clients as they face the next frontier. To us, this means navigating the complexities that define our times. We help our clients devise and implement responsive strategies essential to lasting success.

FURTHER READING



AIRCRAFT ELECTRICAL PROPULSION – THE NEXT CHAPTER OF AVIATION?
It is not a question of if, but when

There have been consistent upward trends in the electrification of aircraft systems, research into Electrical Propulsion, and fundamentally, a greater investment of money and business effort into electric aircraft.



CHARGING AHEAD
The electrification of transport is happening at pace, but investment in the UK electrical grid is not

The Electrification of Transport is happening at pace, just as the UK regulation of distribution networks is adopting longer, slower cycles. We foresee the two falling out of step.

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