Røst airport. (Photo: Ørjan Arntsen)

INTRODUCTION OF ELECTRIC AVIATION IN NORWAY

Feasibility study by Green Future AS

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Feasibility study assigned by:
Avinor - Norwegian administrator of state owned airports and navigation service
NLF - Norwegian Airsport Federation
NHO Luftfart - Federation of Norwegian Aviation Industries, represented by SAS and Widerøe

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GREEN FUTURE

Green Future AS provides advisory services and analyses evaluating future development trends and strategies for technologies including renewable energy, energy management, battery powered drive systems, wireless communication, Internet of things and autonomous systems.

AVINOR

Avinor administers the 45 state-owned airports and air navigation services for civilian and military aviation in Norway. Avinor is a driving force in environmental work in aviation and a driving force to reduce the combined greenhouse gas emissions from Norwegian aviation. The company has a leading role in the work on developing and delivering biofuel for aircraft. Every year, Avinor contributes to safe and efficient travel for around 50 million airline passengers. Around half travel to and from Oslo Airport. More than 3,000 employees are responsible for planning, developing and operating airports and air navigation services. Avinor is funded by aviation fees and commercial sales at the airports.

NLF - NORWEGIAN AIRSPORT FEDERATION

Norges Luftsportforbund (Norwegian Air Sports Federation – established 1909) is the main organization for General Aviation (GA) and air sports in Norway, with a membership of approx. 17,000 and a staff of 15 employees. NLF organizes and promotes activities such as parachute jumping and flying with light aircraft, microlights, sailplanes, hot air balloons, hang gliders, paragliders, speed gliders and model aircraft. Innovation and electrification of light aircraft are key focus areas for NLF.

NHO – LUFTFART - FEDERATION OF NORWEGIAN AVIATION INDUSTRIES

The Federation of Norwegian Aviation Industries (NHO Luftfart) is an organization that supports aviation industry companies in Norway. The association has over 50 member companies employing over 12.000 people. NHO Luftfart is affiliated to the Confederation of Norwegian Enterprise (NHO). It organizes companies within the domain of airline businesses, helicopter services, airports, technical services, ground handling and other aviation related businesses. Objective: NHO Luftfart shall strive to develop a stable and healthy regulatory framework, a strong corporate identity and profitability for the aviation industry.

WIDERØE

Widerøe is the largest regional airline in Scandinavia, with a staff of 3,000 and a turnover of NOK 3.5 billion. The company carries around 2.8 million passengers annually and flies to 46 domestic and international destinations. Widerøe operates more than 450 flights every day and operates to more than twice as many airports in Norway than any other airline. Today its network consists of 60% commercial routes, and 40% PSO routes (Public Services Obligations).

SAS

SAS is a Scandinavian based airline with regional and international flights, 120 destinations and close to 30 million passengers yearly. The fleet consist of approximately 155 aircraft whereof 33 are by wet lease. In Norway SAS operates from 15 airports with a staff of 4 200 and a turnover of more than 10 billion kroner.

DISCLAIMER

Green Future AS takes no responsibility for statements, assumptions, conclusions or other information in this study that may not be correct. All information in this study is based on publicly available sources and interviews with a number of people and companies. Some statements are based on Green Futures' views, expectations or assumptions on future development that may involve known as well as unknown risks, and which may change the future outcome significantly.

SUMMARY AND CONCLUSIONS

This study presents how the opportunities for electrification of aviation may contribute to future sustainable and low-emission air transport in Norway. It is a part of Avinor's ongoing efforts toward the electrification of Norwegian aviation and is a follow-up from a short, initial study on the same subject presented in June 2017.

Electrification of aviation is high on the political agenda in Norway. In December 2015, Avinor accepted an invitation from the Norwegian Air Sports Organization (NLF) to participate in a long term project towards exploring the possibilities for electrification of Norwegian aviation. The thematic has later been mentioned in documents from the Norwegian Government.

The latest Norwegian National Transport Plan (NTP 2018-2029), released in the summer of 2017, outlines how the Government intends to prioritize resources within the transportation sector over the current decade, from 2018 to 2029. The overall goal of the NTP is to develop "a transport system that is safe, promotes economic growth and contributes to the transition into a low-emission society." As is well-documented worldwide, a high degree of population mobility, enabled largely by efficient transportation that benefits from adequately maintained infrastructure, is an engine for both economic growth and social welfare.

At the same time, however, increased use of transportation leads to increased transportation-related emissions of pollutants, including climate-altering greenhouse gases, as well as potential safety issues and local disturbances, such as noise and traffic. Towards its overall goal, and for the first time, the most recent NTP includes an innovative strategy where new technologies and business models are to receive higher priority to speed the country's transition to more efficient, low-emission modes of transportation. It furthermore states that the government supports Avinor and NLF's initiative towards electrification of Norwegian aviation.

This message is reiterated in the Ministry of Climate and Environment's White Paper to the Parliament on Norway's climate strategy towards 2030 (Meld. St. 41 (2016–2017)) and strengthened in the political platform for the new conservative coalition government from January 2018, the latter explicitly tasking Avinor with developing a program for electrification of commercial aviation in Norway.

Summary of Key Points

More than 20 destinations/routes in the Norwegian short airfield network have distances ranging from 38 – 170 km, all of which can easily be flown by a battery-powered electric aircraft. The first electric aircraft to operate in this network is likely to be configured as a hybrid electric (that is, an electric aircraft with a standard mode of fuel-powered generator as a backup electricity source), but will be capable of being operated via electric power only. For a few destinations, the aircraft can continue to the next airport or return to its origin without charging and still fly using electric power only because the overall distances flown are fairly short. With the flexibility provided by the hybrid electric aircraft approach, the implementation of electric aviation can be made step-by-step, thus reducing the risks of irregularities during the introduction phase.

Within a timeframe of 10 – 15 years, battery technology will offer sufficient capacity for pure electric aircraft to accommodate approximately 1-hour flights or more than 500 km. When implemented, this electric transport option would have wide-ranging and immediate impact, considering that most of the flights in the Norwegian short airfield network (initialised as FOT in Norwegian and PSO - Public Service Obligation in English) cover distances of less than 200 km. (Flights in the PSO routes network receive government subsidies to maintain the routes as the passenger numbers are insufficient for commercial operation.)

Technology development for electric aircraft is advancing steadily and has broad support in the aviation industry, involving leading manufacturers such as Boeing and Airbus, in addition to major suppliers including Siemens, Rolls Royce, Safran, and a range of new ventures who are leading in many sectors. A number of aircraft are under development for entry into service by the early 2020s, including from Volocopter, KittyHawk, Airbus, Lilium, Joby for urban vertical take-off, Eviation for regional conventional take-off, and Zunum.

Much of the progress in setting the stage for the electrification of aviation directly relates to the rapid development of batteries and electronics pursued by the automotive industry over the last couple decades. The increasing range, lowering costs, and growing customer appeal in the electric automobile sector since the introduction of the first mass-market hybrid electric vehicle, the Toyota Prius in the 1990s, are all trending toward wider adoption of electric transportation technologies.

Beyond batteries, whose charge capacity and performance are all anticipated to continue markedly improving year-on-year, there are no major technical obstacles for hybrid and even all-electric aircraft seating up to 100 passengers. The first pure electric two-seater aircraft are already in production and operation. These electric light aircraft are expected to be eagerly adopted for pilot training due to their significantly lower operational costs, reduced noise, and zero local emissions. Small airfields will welcome electric aircraft because they will economically enable increased aviation activity, yet with less disturbance to the surrounding community. Regional hybrid electric aircraft with 20- to 70-seat capacities are likely to enter commercial operation in various countries within 10 years. For larger regional aircraft the timeframe may be 15 – 20 years, and for long haul intercontinental flights it is likely that there will be new hybrid solutions where batteries and electric motors reduce fuel consumption and increase overall efficiency.

Let us enumerate and look at these advantages of electric aviation in further detail:

- **Reduced emissions**. There is the potential to reduce the emission of 1 200 000 tons of CO_2 equivalents if all domestic air transportation in Norway converts to electric power. Converting to electricity eliminates emissions of greenhouse gases as well as nitrous oxides (NOx), hydrocarbons, and particulate matter. In the case of Norway, 98% of the country's electricity is generated via hydropower, ensuring that the batteries' electricity comes almost solely from a renewable source.

- **Reduced energy consumption**. An electric motor is much more efficient than a fuel-burning engine. In general terms, the electric motor is more than 3 times as efficient at converting electricity to shaft power versus fossil fuel. The combustion of hydrocarbons does release considerably more energy, but much of that energy is wasted as heat compared to the electric motor.

- **Noise reduction**. Electric motors produce significantly less noise compared with the combustion inherent to fuel-burning engines. Electric motors combined with the new development of efficient, low-pressure ducted fans for aircraft serving 20 – 100 passengers may reduce noise significantly compared with a similarly sized, conventional turboprop aircraft.

- **Short-field operation**. Electric motors are light, responsive, and can be designed to provide extra power boosts for acceleration to enable take-offs on short runways and reversed trust for rapid slow down after landing.

- **Reduced cost for maintenance and operations**. Scheduled engine maintenance for electric aircraft is expected to be significantly reduced and unplanned repairs similarly reduced compared to conventional aircraft, thus vastly reducing costly aircraft out-of-service time. The electricity cost may be lower than the cost of today’s fuel. The additional cost for amortization of batteries is highly dependent on the cycle life of future batteries.

- **Vertical take-off and landing**. The scalability of electric motors may also allow new aircraft designs with multiple motors permitting vertical take-off and landing capacities. A number of innovative projects for short haul (less than 100 km) air transport, akin to an air taxi, are under way for 1- to 4-seater aircraft and may reasonably be in commercial operation within 5 years. This type of technological approach could ultimately make sense for larger aircraft as well if it can be combined with a lift-based and less energy-consuming cruise mode.

Conclusions
This study concludes that new aircraft with electric propulsion are suitable for regional flight routes in Norway.

The battery technology of today is sufficiently capable to store electric power for scheduled flights to the more than 20 short destinations/routes operated by Dash 8 aircraft today.

The first commercial electric aircraft are expected to be hybrid electric in order to provide more flexibility and accommodate the mandatory energy reserve for such commercial operations.

Norway is well-positioned to be a pioneer in this nascent field because of the availability of renewable hydropower and a well-structured network of short field airports owned by Avinor. The government subsidy program (PSO) is one of several instruments that can be structured to encourage operation of electric aircraft.

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1. INTRODUCTION

The history of transportation has proceeded as a series of disruptive breakthroughs. From the invention of the wheel to the harnessing of animal power and the wind millennia ago, and from the steam of the industrial age to the development of the internal combustion engine barely a century ago, humanity's means for getting from place to place have changed dramatically. The latest of these disruptions appears to be upon us in the form of widespread electrification. Although the innovation of electric vehicles actually goes back to the 1830s, the necessary economic, societal, and technological conditions for their robust adoption have only now been met.

Fundamentally, the current, deeply established travel paradigm based on fossil fuels is unsustainable. It is unsustainable both in regard to the consuming of limited resources, as well as the emitting of climate-altering gases into the atmosphere from the burning of these resources. The problems of dwindling fuel supply paired with rising emissions are exacerbated by soaring rates of individual car ownership, especially in rapidly developing, high-population countries including China and India, additionally contributing to societal hardships such as congestion in urban areas.

In addressing the myriad issues posed by fossil fuel use, the electrification of road traffic is on an upward trend. In a few countries, electric vehicles have now arguably reached the tipping point where their adoption will accelerate organically without regulatory measures from politicians. Generally low fossil fuel prices in recent years have forestalled some of the progress towards electrification in other countries, but the outlook remains very positive. More than a dozen major car manufacturers worldwide are now selling substantial stocks of hybrid and all-electric vehicles, up from the handful at the turn of the millennium that struggled for market share.

At the core of this revolution is battery development, strengthened by a growing market and the motivation for designing ever-better batteries. In parallel, sustainable, renewable energy production has taken hold in many countries, with an alignment of strategic government policies and commercial interests working to all but guarantee the continuing rapid expansion of generation capacity and utilization.

In this overall picture, the electrification of air travel emerges as a consequence of the international consensus to target reductions in fossil fuel consumption in aviation.

There will continue to be arguments that electrification is not solving sustainability and emissions problems because some production of electricity is through the burning of fossil fuels, including the most pollution-generating source, coal. Yet as energy production steadily shifts toward renewable sources, the advantages of electrification will likewise be further realized.

In Norway at least, this argument against electrification for aviation does not hold, because 98% of the country's electricity generation is from renewable hydropower. Furthermore, the Norwegian distribution network is fairly well-developed, and through proper planning, the distributing of energy to power both road transport and aviation is not considered a challenge.

The particularities of the Norwegian air travel market, and more broadly Scandinavia, also align with the prospect of more efficient aviation with reduced emissions. According to Avinor, on average Norwegian citizens embarks on one return domestic flight per year, and one return international flight per year. This has remained largely unchanged since 2012, with foreign citizens representing most of the traffic growth. Other means of transport besides flying become prohibitively costly and time-consuming because of as the relatively long distances between settled areas in Scandinavia and often uncompromising topography, such as fjords, mountains, and seas.

Alongside the latest disruption in human transportation that electrification poses, another revolution is looming: autonomy. Driverless vehicles are already beginning to enter service in select areas. The widespread rollout of this technology for road travel, anticipated next decade, will promote newly efficient personal transport with significant reductions in accidents.

Thanks to electrification, along with advances in aeronautics and aerodynamics hastened by the rise of unmanned aerial vehicles, also known as drones, the future of air travel should be in store for a similarly sweeping leap forward. The vast majority of air travel today flows through a tiny fraction of the available air fields, concentrated in hub airports usually near major metropolitan centers. This hub-and-spoke model makes air travel attractive only for trips of several hundred kilometres or more, with local and regional trips instead taken by road, further adding to vehicle use, congestion, and emissions. A new fleet of economical-to-run, electrified aircraft could make regional and even local air travel feasible, especially if employing short- or vertical take-offs. Unlike the air travel the world has known for decades, the air travel of this near-future could be personalized, independent, and on-demand. Indeed, transportation by wheel, and by wing and by blade, is poised for truly disruptive change, so long as governments, societies, and individuals are willing to seize the moment.

2. SCOPE

Green Future AS, assigned by Avinor, has made this study with the aim of giving greater insight into the future possibilities of electric aviation in general and opportunities for Norway in particular. This information may provide background for making informed decisions that will ensure that Norway can plan and develop infrastructure to incorporate future electric aviation as part of a sustainable transport sector that is cost-, energy-, and emissions-efficient.

The intent of the study is to point out possible opportunities not only related to meeting infrastructure requirements, but also to enable involvement in technology development that ensures new electric aircraft are suitable to operate in Norway.

3. METHODOLOGY

This study is based on information from public sources including white papers, research papers, books, news media articles, journal perspective articles, interviews with companies and stakeholders, and more. During the work with this study we have met with Siemens, Bauhaus, Airbus, Ampaire, Zunum, Uber Elevate, Pipistrel, and Eviation.

Different companies are included to exemplify activities and products, but it should be noted that there may be other companies equally skilled or with better products that may not be mentioned. This study has not evaluated the quality of the different projects and future technologies presented.

4. GOVERNMENT POLICIES

Government policy has historically had a major impact on the transportation's sector movement towards wider electrification. In the years ahead, government initiatives will likewise weigh heavily in the aviation industry moving towards electrification.

A key historical example, involving ground vehicles, is the California Zero Emission Vehicle (ZEV) rule, adopted in 1990. In a 2008 study, researchers at the Institute of Transportation Studies at the University of California at Davis described ZEV as "arguably one of the most daring and controversial air quality policies ever adopted," adding that "some consider it a policy failure, while others credit it with launching a revolution in clean automotive technology." The mandate required all car manufacturers to have a zero-emission vehicle available for sale in

California, which, as a highly populous state with some 30 million residents at the time (around 40 million today), had significant auto market clout. The mandate was heavily fought by the automotive and oil industries. Despite the debate, nearly all car manufacturers accordingly bolstered their relevant R&D programs and unveiled prototypes of electric vehicles. Today, 28 years later, electric vehicles are poised to become the only kind of vehicle in some of the world's major countries. China, the U.K. and France are just a few of the nations preparing to phase out petrol cars in the future. Overall, there is a strong tailwind for electrification of road transport.

The aviation sector is likewise under governmental pressure to reduce emissions significantly. In Norway, for example, policymakers have called for all short-haul flights to be electric by 2040. It is understood that aviation cannot shift entirely to electricity, but there is a clear expectation that this may be possible for regional flights and certainly for General Aviation and light aircraft. The Scandinavian nation is also one of 73 countries to have signed up to the United Nation's International Civil Aviation Organization's voluntary programme of carbon-neutral air travel growth, called Carbon Offsetting Scheme for International Aviation (CORSIA), which will begin in 2020. CORSIA is a global market-based measure to keep international aviation-related carbon dioxide emissions at 2020 levels through the obtaining of carbon offset units through the worldwide carbon market.

Avinor, which operates 45 airports in Norway, has also taken a proactive role in the efforts to curb the growing carbon emissions of the aviation industry, having looked since 2007 into sustainable aviation fuels (SAF) through a number of initiatives. In January 2016, Avinor's Oslo Airport became the first hub in the world to offer sustainable jet biofuel to all airlines refuelling there. The project was extended to Bergen airport in 2017.

Within the European Union (EU), the EU Commission expects that the aviation industry will deliver technology solutions that leverage sustainable energy supplies to mitigate impacts on the climate. A 2011 report from the Commission[1] proposes key goals for aviation as a whole to attain in the first half of the 21st century. These goals include, to quote from the report, by "2050, technologies and procedures available [should] allow a 75% reduction in CO2 emissions per passenger kilometre and a 90% reduction in NOx emissions. The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000." A 2017 EU Commission report[2] further lays out a specific target for small commercial electric aircraft with up to 30 seats and medium ranges of up to 200 km to be operational by 2035.

In the United States, the change in government in the 2016 election has slowed much of the forward trajectory with regard to initiatives that might promote electric aviation. During the previous Obama Administration, which embraced the global consensus on climate change science, the agency responsible for air transport, the Federal Aviation Administration (FAA), set an aspirational goal in 2012 (reiterated in 2015) of "achieving carbon-neutral growth for U.S. commercial aviation by 2020, using 2005 emissions as a baseline."

This goal was to have been pursued through energy efficiency improvements in engines and airframes enabled by public-private sector partnerships. The chief initiative in this regard is the Continuous Lower Energy, Emissions and Noise (CLEEN) Program, announced in 2010 and succeeded by the CLEEN II Program in 2015, intended to run through 2020. In the programs, the FAA has partnered with industry in cost-sharing to accelerate research and development, primarily into alternative fuels and cleaner-burning combustion engines. None of the technologies or

[1] Kallas, S., and M. Geoghegan-Quiin. "Flightpath 2050: Europe's Vision for Aviation: Report of the High Level Group on Aviation Research." (2011);
https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf
[2] European Commission Directorate General for Research and Innovation. "Electrification of the Transport System, Studies and Report." (2017); ec.europa.eu/newsroom/horizon2020/document.cfm?doc_id=46372 [pdf]

projects explicitly identified for funding involve hybrid or pure-electric aircraft propulsion, and funding remains uncertain.

Furthermore, the current Trump Administration is questioning whether to uphold commitments made under the previous Obama Administration to participate in the initial phase of CORSIA. Where government-funded efforts toward electrifying aviation have continued in the U.S. are through its space agency, NASA, which will be covered later in this study.

So far, China has not made any explicit or substantial national policy with regard to electric aviation. A two-seater electric light aircraft, the RX1E, is about to enter mass production, having taken its maiden flight in November 2017, but the overall market for it is small. Given China's increasingly prominent efforts in addressing environmental issues and climate concerns, however, there is indeed reason to believe that the world's most populous country will soon align with the EU and to an extent the U.S. in striving toward cleaner aviation, or even setting more aggressive targets.

5. ELECTRIC AIRCRAFT – HOW DO THEY WORK

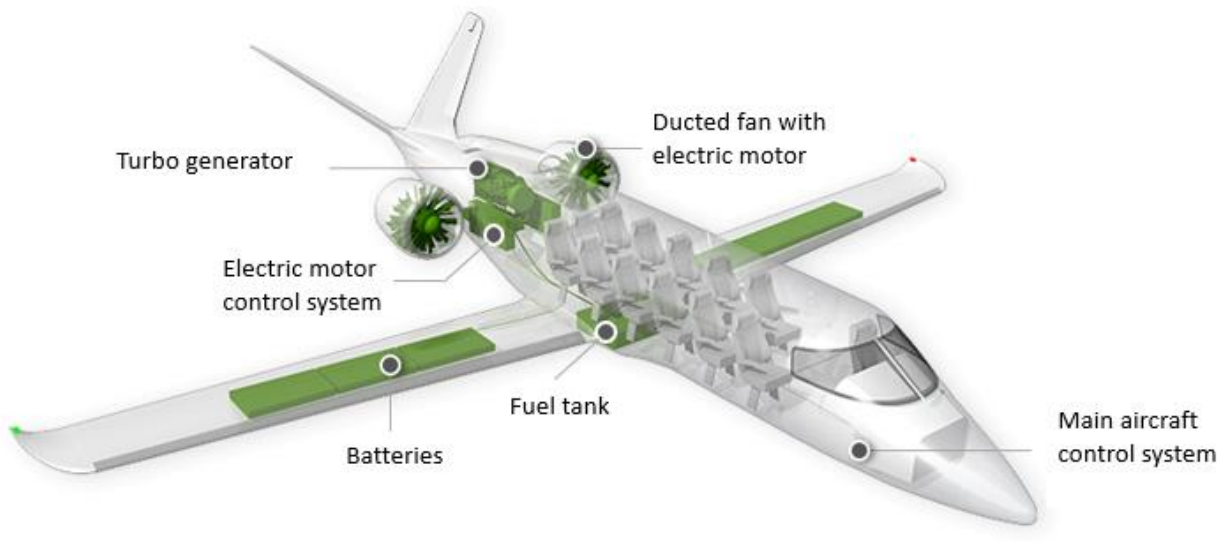
The term "electric aircraft" can refer to both pure-electric aircraft and hybrid electric aircraft, the latter of which incorporates a second energy source in the form of a conventional fossil fuel, biofuel or Hydrogen.

A pure electric aircraft is powered by a battery or another source of electric power. Electric motors may replace today's turbine engines, as well as turboprop and turbofan engines. An electric motor can be designed and dimensioned to drive a fan engine for high-speed, large aircraft such as the Airbus 350 or the Boeing 787, or to power propellers on a medium range, smaller aircraft like the Bombardier Dash 8. An electric motor is well-suited for air transport because it offers high efficiency in all practical sizes over a wide range of revolutions-per-minute, along with superior reliability.

The Pipistrel Alpha Electro by the Slovenia-based company Pipistrel. This light aircraft for pilot training entered serial production in 2017, with more than 35 aircraft produced so far. (Credit: Pipistrel)

Charging a Pipistrel Alpha Electro aircraft. (Credit: Pipistrel)

A hybrid electric aircraft is powered via a combination of electricity from batteries or another electric energy storage source and an internal combustion engine. Various configurations for these aircraft exist, with two major configurations known as serial and parallel. A serial hybrid can use only electric motors for propulsion but relies on a combustion engine coupled to a generator to produce extra electricity as needed. A parallel hybrid directly uses an electric motor and a combustion engine for propulsion.



Zunum Aero, a company based in the United States, is designing serial hybrid electric aircraft with fossil fuel-powered range extenders. (Credit: Zunum Aero)

The appeal of the hybrid approach reflects the intrinsic limitation of electric aircraft at this point in their technological development, which is the capacity and weight of the batteries necessary for longer flights. By the year 2025, however, a battery energy density of around 500 Wh/kg is widely anticipated, approximately twice that which is readily available today. With batteries of this energy density, an aircraft may be able to carry enough "juice" to cover distances of approximately 500 km, not taking into account the energy reserves required for emergency situations where the aircraft cannot land at the intended airport and must divert to another.

5.1 WHY ELECTRIC?

Electric motors, first invented in the 1830s, are a highly efficient way to convert electric energy to rotational power. A combustion engine produces motion based on controlled explosions or burning fuel in a turbine. This combustion generates more heat than motion, wasting a significant portion of the potentially available energy. In contrast, the electric motor experiences only a small loss from electric resistance when creating an electric field. Overall, the efficiency of an electric drive train may be higher than 90% from battery to shaft, while a turboprop engine normally falls in the range of 20 to 25% for short, 30-minute flights; for longer flights at higher altitude, the turboprop may reach 35% efficiency. A turbofan engine can offer higher efficiency, but still not in the regime attainable via electric drive trains.

Without mechanical contact between parts and the absence of the high temperatures needed for burning fuel, electric engines suffer little wear-and-tear, thus requiring far less maintenance than conventional combustion engines. For aircraft with very high utilization rates and intended long service lives, this reliability becomes a huge advantage. It should be emphasized that maintenance in an electric system will be predictive rather than event-based. The electric systems can "self-check" their health over time much more readily than a traditional engine aircraft and thus know in advance when performance is degrading to the point where maintenance will be required. Engine maintenance may be reduced in the range of more than 50% and unplanned repairs reduced equally compared to conventional aircraft, thus vastly reducing costly aircraft out-of-service time.

Compared to combustion engines, electric engines are also more reactive and easier to control. The motor is controlled by digital signals and reacts within milliseconds. Additionally, electric motors are scalable and maintain the same efficiency regardless of whether they are small or large motors. This combination of reactiveness and scalability makes electric propulsion systems ideal for distributed propulsion systems described later in the study.

Although the engines used in electric aircraft would be "new," they are just manifestations of tried-and-true technologies, whose underlying physics and engineering are extremely well-understood.

6. CERTIFICATION

The challenges in developing an electric aircraft are not only technical, but also a complex matter of regulations and rules for aircraft design and operations. The rapid developments of batteries and drive systems for road vehicles are in many ways the enablers for electric aviation, though automotive systems do not have to fulfil redundancy and other requirements that will be set for aviation.

The requirements to obtain the desired level of safety are formed by standards and regulations, and these have yet to be defined for electric aviation. The regulatory authorities must work hand-in-hand with the aviation industry in establishing a path for matching technology development with new regulations.

The initial airworthiness certification for electric powered aircraft will pose certain challenges, given the novel sorts of components and architectures involved compared to conventional, fossil-fuel powered aircraft. On the other hand, continuous airworthiness certification, which takes into account maintenance and other factors, can be expected to hew more closely to the regime for conventional aircraft.

The applicable certification requirements for electric aircraft depend on the aircraft's maximum take-off mass and maximum number of passengers. Certification Standard 23 (CS23) applies to aircraft up to a take-off mass of 8 618 kg and 19 passengers, also known as the Commuter category, and Certification Standard 25 (CS25) applies to larger aircraft that exceed these criteria. The CS23 and CS25 standards have similar structures, however CS25 has a stricter regime with more certification requirements and a closer scrutiny by the relevant competent authority. Those authorities for example will be the European Aviation Safety Agency (EASA) in Europe and the Federal Aviation Administration (FAA) in the U.S.

An important task to be performed early on in an electric powered aircraft project will be to assess the certification basis. This is so design engineers will know which requirements their part of the design shall comply with, and for that matter to set parameters moving forward on the levels of innovation that could pass muster. Most of the CS23 or CS25 requirements will be inherently applicable to an electric powered aircraft, for instance in flight characteristics, structure, systems, and documentation. There are, however, currently no specific requirements for electric aircraft propulsion and storage and transmission of significant amounts of electrical energy. The appropriate requirements will either have to be adapted from corresponding fossil fuel aircraft requirements or written anew in certain cases.

Broadly, the electric powered aircraft certification basis will consist of:

a) Existing certification requirements which will apply unchanged; and
b) Existing certification requirements which will be adapted to electric propulsion; and
c) New certification requirements for electrical propulsion ("Special Conditions," "Certification Review Items"); and
d) Unique certification requirements for the specific project.

A part of the certification basis work will be to establish the Means of Compliance for each requirement, which stipulates if compliance shall be shown by analysis, calculations, simulations, ground test, flight tests, et cetera, or combinations of these means.

7. BATTERY STATUS

Energy storage technology is an enabler of the transition from an unsustainable paradigm based on fossil fuel consumption to a sustainable energy ecosystem based on consumption from renewable sources.

In order to shift the transportation sector to electricity, there is a dire need for energy storage solutions with high energy densities. Vehicles such as cars and airplanes cannot be directly connected to a constant energy source via the grid, as for instance rail lines can. Furthermore, cars and airplanes both have size and mass constraints, which requires all the energy for their operation to fit within a relatively small volume. Today, batteries look to be the best-suited technology, but considerable research and development resources are also being invested in alternative technologies including fuel cells and supercapacitors.

Electric cars will be the main driver of battery development and adoption for the transportation sector. This battery development will not, however, occur in bespoke isolation. A major, parallel driver for advances in battery storage technology is renewable energy production from solar and wind sources, which in order to increase their reliability and market penetrance must pack away some of their generated energy for when the Sun does not shine and the wind does not blow. Per these two sectors' considerable energy storage appetites, the battery industry will grow rapidly in the years ahead.

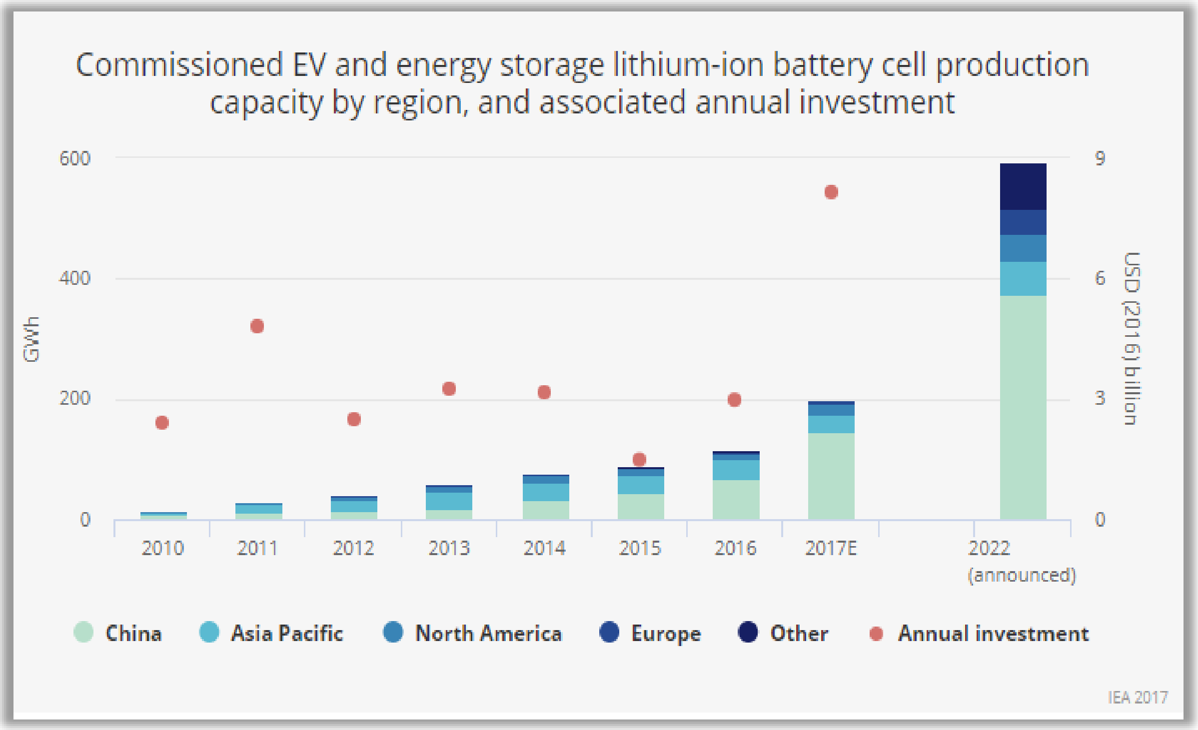
Over the past 25 years, scientists have successfully improved battery performance by modifying or replacing materials to create more efficient chemistries and form factors. The cost per unit of stored energy has plummeted by an order of magnitude over this single generational period.

Increased performance and dramatically lower cost have brought electric cars to the point where they can travel more than 500 km on a single charge. Grid storage for renewable energy is poised to become competitive. Nor is there any end in sight, for battery efficiencies continue to improve and are outpacing many observers' predictions.

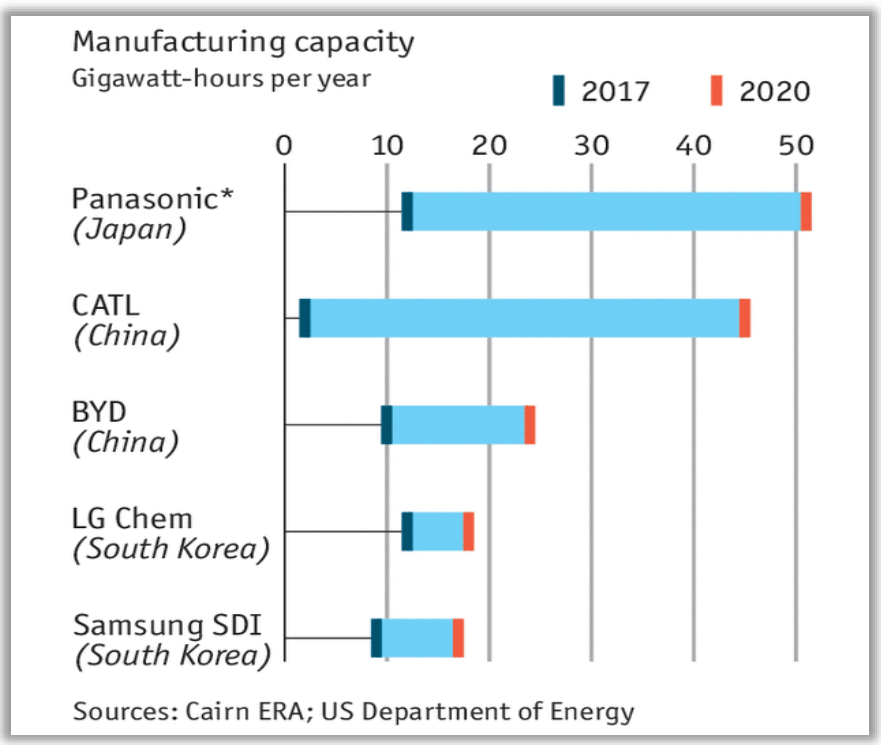
7.1 BATTERY PRODUCERS

The high levels of activity and jockeying within the battery technology development sector, along with the push to establish robust production capacity, is often dubbed the “battery battle.” Although investment is surging, it of course remains a limiting factor. Given the number of competing teams and companies in this burgeoning sector, available information may be influenced by differing agendas as well as legitimately differing organizational views. Politicians and governments are naturally involved as well, seeking to ensure that as an increasingly strategic sector, battery development and production are located in their region or country. An additional key aspect to the enterprise of batteries is secured access to raw materials.

Reflecting the just-described battery battle, last year, 2017, set the record as the year with the largest amount of investment in new battery manufacturing capacity in any single year, reaching almost $8 billion. There are now over 200 such factories in operation around the world, with most of the capacity is in China, cranking out the industry standard battery type based on lithium-ion technology. Among the top manufacturers are automakers, such as BYD and Tesla, with the latter in cooperation with Panasonic, itself a top manufacturer alongside fellow major electronics firm Samsung, plus a chemical company, LG Chem, and newcomer battery specialists like CATL and Guoxuan High-Tech.



Battery production capacity by region (may not include all relevant data and some reports will estimate higher capacity. (Credit: IEA)



Battery production capacity by producer. (Credit: Economist.com)

What follows are profiles of some of these and other top battery manufacturers.

CATL - CONTEMPORARY AMPEREX TECHNOLOGY LTD.

CATL is a rapidly growing Chinese company supported by the Chinese government that is aiming to be a global leader in supplying the automotive industry with batteries. The company plans to raise 13.1 billion yuan ($2 billion) to finance construction of a battery cell plant nearly the size of Tesla's Gigafactory in Nevada. CATL already sells the most batteries to the biggest electric vehicle makers in China, and its lithium-ion batteries will go inside locally made electric vehicles from major automakers Volkswagen, BMW, and Hyundai. Toyota, Honda, and Nissan are also considering CATL batteries for planned China-made vehicles. Domestic companies using the batteries include BAIC Motor Corp., the biggest EV seller in China, and Zhengzhou Yutong Group Co., the world's biggest maker of buses. CATL is expanding by establishing offices in Europe and the U.S. The company has acquired 22% of Finland's Valmet Automotive Oy, a contract manufacturer for Daimler's Mercedes-Benz and supplier to Porsche and Volkswagen's Lamborghini.

BYD

Based in Shenzhen, BYD – which stands for "Build Your Dream" – is a Hong Kong-listed, Chinese car company that in 2016 produced almost 500 000 cars and buses, approximately 100 000 of which were electric vehicles or plug-in hybrids. Consistent with BYD's strategy of vertical integration, it also has 20 GWh of battery cell capacity and is China's largest battery maker. The company is strongly supported by the Chinese government in ensuring the transition to zero emissions vehicles in the transport sector.

LG CHEM

LG Chem entered the electric vehicle battery business in 2009. The company has supplied batteries to global carmakers such as Audi and Nissan. It currently operates battery plants in China, the U. S., and its home country of South Korea. In 2017, the company invested in a European factory expected to annually produce up to 100 000 electric vehicle batteries in Poland starting from 2018. (Based on the typical capacity of a mid-market compact car like the Nissan Leaf, 100 000 car batteries are equivalent to 4 GWh.)

SAMSUNG SDI

Also based in South Korea, Samsung is best known as an electronics manufacturer. The company also has a dedicated renewable energy storage arm, Samsung SDI, that is developing future electric vehicle batteries. Recently, the company announced battery cells with energy densities high enough to propel electric vehicles as far as 600 kilometres after a just 20-minute charge. SDI is additionally conducting research into "solid-state batteries," a technology that offers improved capacity and safety compared to traditional lithium-ion cells. Internationally, Samsung SDI has established production in Hungary with a production goal in 2018 of 50 000 EV's.

PANASONIC

Panasonic is the world's biggest supplier of lithium-ion batteries for cars with production facilities in Japan, China and the U.S. The company continues to invest in additional capacity at all three facilities. Panasonic makes battery cells for Tesla's Model S and Model X, as well as the newest model the Model 3, at Tesla's Gigafactory 1 in Nevada. The facility is also manufacturing batteries for Tesla's stationary energy storage products. At the Gigafactory 1 alone, Panasonic is aiming for a record 35 GWh of battery cell capacity in 2018 with plans for significant increase by 2020. Furthering its work in electric vehicles, Panasonic recently announced a plan with Toyota to collaborate in developing solid state batteries, building on a joint venture the companies have shared for over two decades.

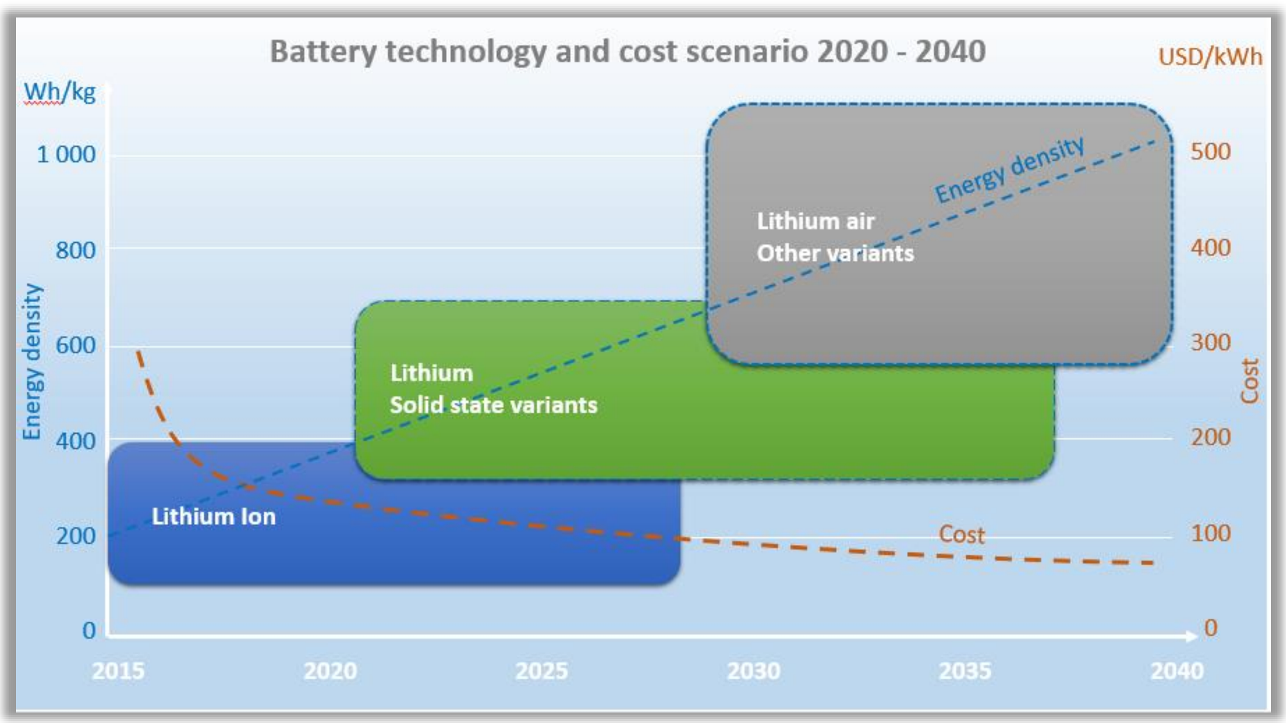
EUROPEAN BATTERY PRODUCTION

Europe's battery demand is projected to reach 200 GWh by 2025 – a market worth an estimated €250 billion annually (compared to 600 GWh globally), according to European Commission Vice-President Maroš Šefčovič. Although European carmakers assemble battery packs for electric cars, with the essential building blocks coming mostly from Asia, the continent has no significant player in battery cells. The Commission has therefore branded batteries as "a key enabler" in its flagship project to establish an Energy Union, saying their development and production play a strategic role in the modernisation of Europe's industry.

Among different initiatives, Northvolt is the most ambitious project at this point in time. Founded in Sweden in 2016, Northvolt's mission is to build the world's greenest battery. The proposed battery will have a minimal carbon footprint and be recyclable. The project is constructing a next-generation battery factory that would be the largest in Europe and produce 32 GWh-worth of battery capacity annually. In 2018, the European Investment Bank approved €52.5 million in financing, alongside the Swedish government, for the Northvolt battery production project.

7.2 BATTERY DEVELOPMENT

The trajectory of battery development over the next decade or more will largely be determined by the automotive industry, because the majority of batteries produced will be intended to meet the increasing demand for electric vehicles. While it is expected that the next generation battery will be a solid-state battery, the huge and increasing investment in battery research and development makes it is difficult to predict the next-next generation's energy density. A conservative expectation is that energy density will maintain its recent historical rate of gain, which is at least 8% per year.



A simplified illustration of battery chemistry and a scenario for battery development. (Credit: Green Future AS)

There is some common ground between the requirements and ideal enabling thresholds for car batteries and aircraft batteries, but there are also differences. The parameters may be set up in a matrix as follows:

	Cars	Aircraft
Lifetime	Design lifetime of a car, typically 6 years and 200 000 km, is less than 1 000 cycles. Requirements for commercial road transport and all-day autonomous driving may change this figure	A commercial regional aircraft may fly more than 10 hours every day. Will aim for at least 5 000 cycles
Safety	Important	More important than on the ground, given that failure in mid-air would be catastrophic. Safer battery chemistries, while more expensive up front, could save costs on battery enclosure and ventilation for extra safety from less stable chemistries and designs
Cost	Very important. The car industry will propel low-cost solutions	The ideal battery for commercial aircraft will serve a longer duty. Costs for aircraft batteries are directly related to lifetime and may accept significantly higher initial costs if lifetimes are longer
Second use	Automotive industry is already for second use. Preferably, the initial design of battery modules fits directly into applications for second use without any modifications	Likely to be similar opportunities for aircraft batteries

The following sections will now provide further details about certain critical battery properties.

7.3 FAST CHARGING

Batteries may be charged at the same rate as they are capable of discharging. The lithium-ion batteries preferred for most automotive applications today can deliver power 5 times the capacity, for a so-called C rating of 5C. These batteries can be charged with the same high power 5C, given sufficient thermal management. Until the battery reaches an 80% or 90% full state of charge, the internal battery resistance is low and the battery temperature can be controlled. During the last charging 10% to 20% of topping up, however, the battery loss increases and more heat is released, during which time the charging power is reduced.

The automotive industry is targeting fast charging as high as 10C, which means down to 5 minutes for charging up to an 80% to 90% state of charge. Because a car rarely is completely empty of charge when charging starts, the goal of charging to at least near-full in under 5 minutes should clearly be within reach. Next-generation batteries with these sorts of power and charging capacity may as well be suited for electric/hybrid aircraft.

In terms of chemistry, lithium sulphur batteries are considered a possible next-generation battery, offering higher energy density but they may be less capable in power discharge and fast charging. As mentioned prior, solid state lithium batteries are another promising battery type.

7.4 THERMAL CONTROL

Internal temperature is an important parameter for batteries, impacting the rate of charging, capacity, and lifetime. Ideal temperatures may (as an example) be between 15 and 30 degrees Celsius; if the temperature can be maintained within those limits, then batteries should perform according to their maximal design specifications. Operations of batteries outside their prescribed limits will negatively influence performance.

Obviously, temperature management is extremely important for ensuring an optimal and finely-tuned battery system for aircraft propulsion. During discharge and charging, there will be a certain efficiency loss (resistance) internally in the battery, creating heat that needs to be controlled. In addition, the ambient environmental temperature may heat or cool the battery. For an aircraft, the cooling demand will be during fast charging and high-power output during the take-off and climb phases. During descent and low-power output during high-altitude cruise, there will be a demand to conserve the heat in order to prevent the temperature from falling to suboptimal levels.

It is expected that battery systems for commercial aircraft propulsion purposes will be liquid-cooled. This method is not only well-proven and efficient, it also can maintain a reasonably even temperature throughout all the cells in the battery module. Air-cooling is challenging because it is less efficient than liquid cooling and difficult to maintain the airflow in such a manner that allows for even cooling.

That said, the availability of cold air at high altitudes may be a huge advantage for the thermal management of aircraft batteries, given the ability to cool to the optimal temperature during cruise and descent and in preparation for subsequent fast charging once on the ground. During fast charging at the airport, the aircraft battery cooling system may also receive additional ground grid power for efficient cooling in preparation for take-off in warm climates. These additional energy needs should be relatively minimal, given that during climb the outside air temperature will gradually grow colder to provide efficient cooling as required.

7.5 BATTERY SWAPPING SYSTEMS

An alternative solution to fast charging is battery swapping at the airport. As its name implies, it involves simply replacing mostly depleted battery modules with freshly charged modules. This approach is also under consideration in earnest for electric vehicles where fast charging is not fast enough, so to speak, and quickly getting a vehicle back on the road with a fully topped battery is a high priority.

7.6 BATTERY LIFETIME

Batteries for aircraft propulsion will rely on the highest possible energy densities because weight is a critical factor. The battery also must deliver a certain amount of power at different states of charge. Battery lifetime will be defined by a certain reduction in capacity, reduction in available power, or a combination of the two.

For automotive use, end-of-life is typically defined as a 75% to 80% reduction in capacity; reduction in available power is not regarded as a critical such parameter for most car utilization situations. For an aircraft battery, end-of-life may also be defined at a certain reduction in ability to deliver power to the propulsion because this power may be critical for safety during take-off.

An additional key point regarding battery lifetime is the concept of second use, in which a battery first serves an automotive (or aviation) application, then is reused in a secondary application for grid storage, for instance. This approach extracts significantly more value out of a singly manufactured battery, ultimately cutting down on lifetime and thus upfront costs. Accordingly, battery modules for aircraft will likely be designed to serve both first and second use applications.

7.7 LIMITED SUPPLY OF RAW MATERIALS FOR BATTERY PRODUCTION

The increasing production of electric vehicles, coupled with expected growth in the use of grid-connected battery systems for storing electricity from renewable sources, has made the adequate supplying of raw materials a looming issue for lithium-ion batteries, the dominant type of rechargeable product on the market. Lithium batteries rely on a host of materials, including of course lithium, but also nickel, cobalt, and graphite. Some electric motors additionally require so-called rare-earth elements.

For the near future, no absolute limitations are anticipated on battery manufacture due to shortages of the critical metals. But according to an analysis published in the journal *Joule* in late 2017 that evaluates the next 15 years, temporary slowdowns in production could arise from short-term bottlenecks in the supplies of some key metals, especially lithium and cobalt.[3] In the latter's case, it is not poor availability of the metal, but political and economic precariousness that threaten its supply. More than half of the world's cobalt is mined in the Democratic Republic of the Congo, a nation with a long history of armed conflict and corruption. Flaring tensions there have contributed to the price of the bluish grey metal going up more than 190% over the past 18 months. Given the favourable forecasts for electric vehicle uptake and continued government initiatives to move past fossil-fuelled engines, carmakers and battery producers are rapidly locking in supply agreements with mining companies.[4]

Overall, ample material for mass adoption of batteries for electric cars, as well as aircraft, is out there; it is only a question of mining capacity to ensure supply.

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[3] Olivetti, Elsa A., Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu. "Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals." *Joule* 1, no. 2 (2017): 229-243.
[4] Sanderson, Henry. "Electric vehicle ambitions spark race for raw materials." *Financial Times*, October 24, 2017.

8. ALTERNATIVES TO BATTERIES

Batteries are currently the preferred energy storage standard for electric aircraft propulsion as well as electric cars. Fuel cell technology is the closest alternative to batteries and has been used in space applications for many years. A fuel cell converts fuel directly to electricity without any emissions but requires fuel to be brought with it. Liquid hydrogen is the most likely fuel source, having four times the energy content of kerosene jet fuel. A tremendous amount of research and development is going into this technology and it is debated if this technology may replace batteries in the future. So far, fuel cells can provide an on-board energy conversion efficiency of 50%, with the potential to improve further. Still, there remain additional challenges such as energy-efficient production of hydrogen, along with infrastructure for transport, storage, and on-board tanks for liquid hydrogen, which must be kept at minus 250 Celsius.

The German research institute DLR has equipped this flying test platform with a 45 kW hydrogen fuel cell combined with a 22 kWh battery. The aircraft can cruise at 145 km/h and has a range of 750 – 1 500 km. (Credit: DLR)

9. INDUSTRY ACTIVITY AND PROJECTS

While electric propulsion represents a radical change from today's propulsion technologies, the technologies behind it are not radically new. As mentioned previously, the electric motor dates back to the 1830s, and in 1884, the battery-powered airship *La France* made its maiden flight.

Since then, many electrically powered aircraft have been built, but all as prototypes for demonstration or light aircraft. With battery storage capacities and weight now becoming high and low enough, respectively, per a given volume for commercial aviation consideration, the only debated uncertainty in the aviation industry is the timeline for when the advantages from electrification can be implemented for the different aircraft and engine categories. In the commercial aircraft manufacturer sector, there are a handful of projects for regional aircraft, though it is possible there are other projects that have not been publicly announced. The aviation supplier industry is also participating in electrification and is spending considerable resources to position itself for future supplying of the manufacturer sector. Again, for some of the projects there will be public information available, but not for others.

Beyond the increasing interest from the existing aviation industry, there are also other industries and financial investors highly intrigued by electric propulsion. In a new segment of urban air transport or "air taxis," more than 70 projects are underway. As one would expect, a high number of projects have also started in the light aircraft segment. Finally, there are many universities and research organisations that are involved in doing studies on many aspects of electrification.

This section of the study will now offer an overview of the main activities within different aviation segments, including large aircraft, regional aircraft, light aircraft, and urban air transport.

9.1 COMMERCIAL AIRCRAFT

Developing, certifying and producing large commercial aircraft will require a very competent organisation with experienced personnel and substantial financial resources. A production organization and facility will further be required. Because the investment in an aircraft fleet is a long-term commitment, customers will need a reliable supplier.

These basic arguments point in the direction of existing aircraft manufacturers playing a primary role in the electrification of commercial air transport, and large aircraft in particular. Although those arguments are pointing in the direction of established companies, disruptive technological breakthroughs can also present great opportunities for newcomers such as Tesla, which has been a bellwether in the automotive industries' shift to electric cars.

As important as the aircraft manufacturer is, it will be critical that component suppliers participate in the development. A collaborative project recently announced by Airbus, Rolls Royce, and Siemens—described later in this study—is the ideal model to drive electrification.

Furthermore, ATR, Bombardier and other significant manufacturers of regional turboprop aircraft have not pursued the same level of development progress over the last 20 years as they have for the larger aircraft in their fleet families. Because the majority of the aircraft in this regional segment are due for replacement the next 15 years, the technology shift to more efficient aircraft with low-noise electric propulsion may be a great opportunity for manufacturers in this segment.

BOEING

We will begin with Boeing, which identifies itself as "the world's largest aerospace company and leading manufacturer of commercial jetliners." The company website offers the following high-level profile of the firm: "With corporate offices in Chicago, Boeing employs more than 140,000 people across the United States and in more than 65 countries. Today, the company manufactures the 737, 747, 767, 777 and 787 families of airplanes and the Boeing Business Jet range. New product development efforts include the Boeing 787-10 Dreamliner, the 737 MAX, and the 777X. More than 10,000 Boeing-built commercial jetliners are in service worldwide, which is almost half the world fleet. The company also offers the most complete family of freighters, and about 90 percent of the world’s cargo is carried onboard Boeing planes. In addition to commercial jetliners Boeing also delivers products and services in the defence, space and security sector."

The company has numerous efforts underway that are addressing the electrification of aviation. One example is Boeing HorizonX, a newly established venture capital wing with a mission to "unlock the next generation of game-changing ideas, products, and markets." In practice, this means allocating capital to assist in technology commercialization and market access for new startups developing "revolutionary concepts . . . to get their ideas off the ground," as Boeing HorizonX says on its website. One of the first investments has been in Zunum Aero, a startup developing hybrid electric regional aircraft.

Another project related to electrification, and ongoing since as far back as 2006, is the Sugar Volt. The Sugar (Subsonic Ultra Green Aircraft Research) project began as a brainstorm about futuristic, environmentally friendly aircraft design. The Sugar Volt concept has since become based on a hybrid electric propulsion drive system with a number of innovative new technologies to reduce drag and energy consumption. The project aims for a reduction in fuel burn of more than 70% and radically lower noise. The new technologies are targeted for commercial aviation in the timeframe of 2030 – 2040, though the company has not yet decided if, or when, any of the new technologies will be incorporated into Boeing aircraft.

An artist's impression of the Boeing SUGAR Volt. (Credit: Boeing)

AIRBUS

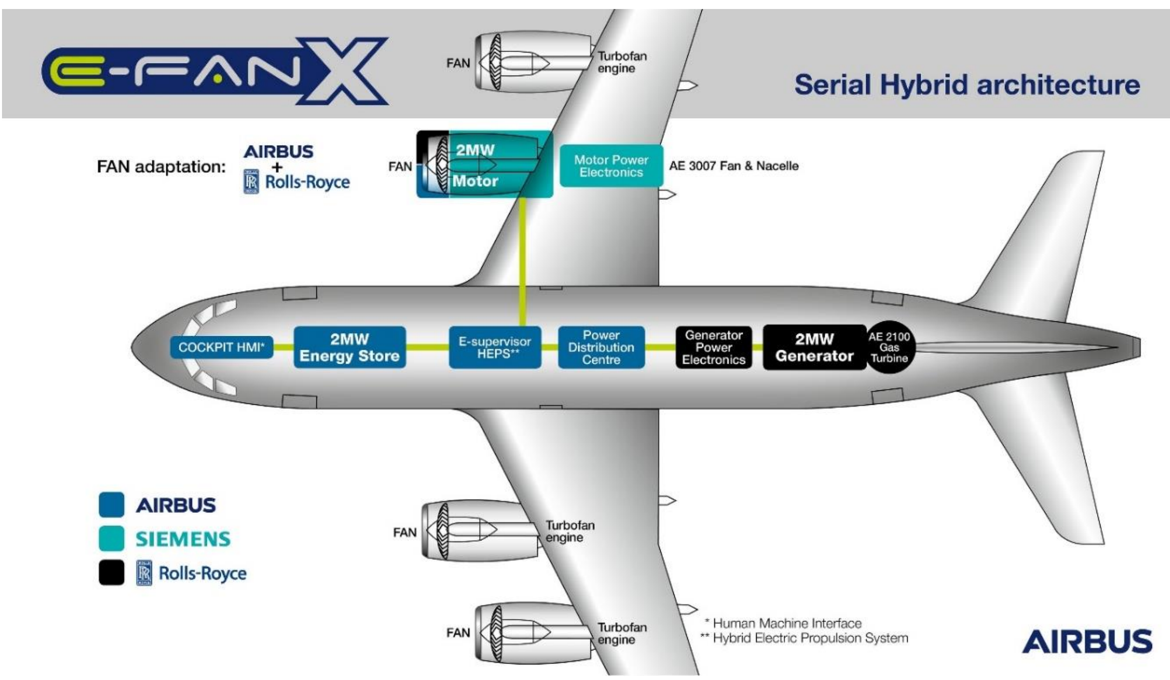
Airbus is the European equivalent to Boeing, producing large commercial aircraft. The Airbus Group has approximately 130 000 employees. At its website, the company describes "comprises highly successful families of aircraft, ranging from 100 to more than 500 seats: the single-aisle A320 Family, including the A320neo, the best-selling aircraft in aviation history; the widebody, long-range A330 Family; the all-new, next-generation A350 XWB Family; and the double-deck A380." Airbus also produces military aircraft, rotorcraft and space equipment.

The company is ambitiously working on a variety of projects in the electrification space, ranging from unmanned delivery drones and air taxi concepts to full-size passenger aircraft. Expressing its interest and intentions in electric propulsion, Airbus includes the following statement on its website: "Electric and hybrid-electric propulsion is the most promising technology to develop means of transportation with improved environmental performance that are less reliant on fossil fuels and use energy more efficiently. That’s why Airbus is investing heavily in research dedicated to developing all necessary technologies, and partnering with the best to make it a reality."

One of the Airbus projects was founded in May 2015 and is called A³ (“A-cubed”). It is the advanced projects outpost of the company in Silicon Valley. A³ focuses on projects centered around three traits: speed, transparency, and a commitment to culminating in producible demonstrators at convincing scale. One of the projects is the VTOL Vahana described in this study.

E-Fan X is another activity, following several years of development and testing of the one-seater E-Fan prototype. The company has now targeted the electrification of larger aircraft, intended for test flights in 2020. The BAe 146 flying testbed for E-Fan X will initially have one of its four gas turbines swapped out for a 2 MW motor to power a ducted fan. In November 2017, Airbus announced that the company is partnering with Rolls-Royce and Siemens to develop this near-term flight demonstrator, which the firms agree will be a significant advance in hybrid electric propulsion for commercial aircraft.

A graphic depicting the E-Fan X hybrid electric demonstrator. (Credit: Airbus)



A schematic showing where the partnering companies behind the E-Fan X will direct their expertise in contributing to the project. (Credit: Airbus)

ATR

Owned by Airbus Group and the Italian company Leonardo, ATR manufactures two sizes of turboprop aircraft, the 70-seat ATR 72 and the 50-seat ATR 42. The company makes approximately 80 aircraft a year, has produced an approximate total of 1 400 aircraft, employs 1 300 people and sees about $1 800 million in annual revenue. ATR's only business is turboprops and it utilizes a high amount (approximately 20%) of composite materials in its products.

An image of the ATR 72. (Credit: ATR)

ATR and its partners are participating in the Clean Sky Project, which describes itself as the "largest European research programme developing innovative, cutting-edge technology aimed at reducing CO_2, gas emissions and noise levels produced by aircraft. Funded by the EU's Horizon 2020 programme, Clean Sky contributes to strengthening European aero-industry collaboration, global leadership and competitiveness."

The ATR 42 may be a suitable platform to convert to hybrid electric propulsion, and some concept work has been pursued. There are no known plans for electrification of propulsion at ATR today, but this may change as more hybrid electric propulsions systems for this class of aircraft become available.

BOMBARDIER

Bombardier, a Canadian company, describes itself as "the world's leading manufacturer of both planes and trains." The firm has about 69 500 employees, with the aerospace department employing around 30 000 people. Bombardier manufactures business aircraft in the Learjet, Challenger, and Global aircraft families, as well as commercial aircraft, such as the C Series, CRJ Series, and Q Series.

The C Series is a newly developed, single-aisle aircraft specifically designed to accommodate 100 to 150 seats. Financial challenges in Bombardier have troubled the program and led to a joint venture agreement with Airbus for manufacturing the C-series. The CRJ Series family is a popular regional jet designed for 60 to 100 seats, with more than 1 900 having been ordered worldwide. The Q400 is a turboprop designed for up to 90 seats with a cruise speed of 360 knots. It is the latest model in the former Dash 8 series, which has sold a total of 1 200 aircraft with more than half that number representing the Q400 model.

Of note, the Widerøe fleet of 42 turboprop aircraft is drawn from this Bombardier family, from the Dash 8-100 to the latest Q400. The latter is an excellent candidate for hybrid electric propulsion. As with ATR, this possibility is likely to be explored when hybrid electric propulsion systems become more mature.

EMBRAER

Embraer is a Brazilian company with 18 000 employees that has produced more than 8 000 aircraft in different segments. Today the company is producing 200 commercial jets per year but is no longer making turboprops. The relatively new E-Jet family is designed for 70 to 130 seats and the ERJ family is designed for 37 to 50 seats. Embraer also produces a broad range of business jets, military aircraft and small planes for agricultural use. (Of note, Widerøe has purchased two E-Jets from Embraer.)

The company has recently pursued some intriguing partnerships. In December 2017, Embraer confirmed that the company is engaged in discussions with Boeing regarding a potential combination, the basis of which remains under discussion. Back in April 2017, Embraer announced an agreement with the ride sharing, food delivery, and transportation network company Uber to explore the concept of small electric vertical take-off and landing vehicles (VTOLs) for short urban commutes. Paulo Cesar de Souza e Silva, Embraer's CEO, said the following in a press release: "We firmly believe we need to explore several new business concepts that may impact air transportation in the future. This is a unique opportunity to complement the air transport knowledge of a visionary and revolutionary ground transport company. On exercising this partnership, we will be developing new technologies, new products and new business models which could generate opportunities for Embraer in the future."

The Uber collaboration, which plausibly involves electric aviation platforms, is the lone such announcement to date, but Embraer certainly has the competence and capability and is likely to enter the electrification arena soon.

TEXTRON GROUP

Textron Inc. is a U.S.-based multi-industry company, with brands such as Bell Helicopter, Cessna, Beechcraft, E-Z-GO, and Jacobsen. The $14.2 billion company employs 35 000 people and has a presence in more than 25 countries.

The Beechcraft, Cessna, and Hawker brands account for more than half of all general aviation flying. On its website, the company says it "has a broad range of products include[ing] Citation business jets, Beechcraft King Air and Cessna Caravan turboprops, Beechcraft and Cessna piston engine aircraft and the T-6 military trainer aircraft."

Bell Helicopter, one of the largest manufacturers of commercial and military vertical take-off vehicles in the U.S., announced in 2017 its partnership with other aircraft manufacturers to collaborate with Uber in creating an on-demand network of electric VTOL aircraft. The first step is readying a hybrid electric aircraft for flight by Uber's target demonstration date of 2020, according to media reports, with a dully certified aircraft five years later. In public comments at the Las Vegas Consumer Electronics Show (CES0 show in January 2018, Bell Helicopter President and CEO Mitch Snyder said: "Bell Helicopter is innovating at the limits of vertical flight and challenging the traditional notion of aviation to solve real-world problems. The future of urban air taxi is closer than many people realize. We believe in the positive impact our design will have on addressing transportation concerns in cities worldwide."

Textron Group is known for innovative new solutions, and its shareholders will probably expect the company to be looking towards the future and taking part in other segments for electrification as well.

Bell Helicopter concept for an air taxi cabin displayed at CES 2018. (Credit: Bell Helicopter)

ZUNUM AERO

Founded in 2013, Zunum Aero is headquartered in Seattle, with development centers in Chicago and Indianapolis. The company has a strong management team and has recruited a team of highly skilled engineers with experience from the different aviation disciplines, including aircraft, propulsion and electricals. Zunum is often referred to as "the Tesla of the aviation industry."

Zunum expresses that its mission is to establish electric aviation as the primary mode of fast short-haul transit, lighting up tens of thousands of airports offering air service with door-to-door times and costs 2 to 4 times better than today. To achieve this, Zunum is developing range-optimized hybrid-to-electric aircraft and propulsion to bring airliner economics to mid-sized aircraft, with ranges from 700 miles in the early 2020s to over 1 500 miles by 2035, scaling from 12 seats in 2022 to 50 seats in the mid-2020s and airliners by 2030.

Zunum's ultimate goal is to enable point-to-point air service to tens of thousands of secondary airports and feeders to hubs, offering high-speed transit to communities everywhere, while placing short-haul on a path to zero emissions by 2040, eliminating 50% of all commercial aviation emissions. The company offered this quote: “A quick drive to a nearby airport where you can walk onto quiet, electric aircraft much as you would board a bus today, for a fast flight to an airport closer than ever to your destination — all while leaving neighbours undisturbed and the planet healthy.”

Zunum is developing a 12-seat hybrid electric aircraft for 2022 entry to service with 700 miles range and operating cost of 8 cents per ASM. It is maturing hybrid electric technologies via a rapid prototyping cycle, progressing from a full-scale ground prototype of the power system in test already, to a flying testbed in 2019, leading to a flying prototype in 2020. It is also developing key components, such as MW-class lightweight motors and power convertors, low-pressure quiet fans, thermal systems, wing-integrated battery packs. The first prototypes of several of these will be in test later this year. Zunum is also a leading producer of regulation for electric aircraft as founding member of the FAA/ASTM Electric Aircraft Working group since 2013.

Zunum continues to have a close partnership with Boeing, and in advanced discussion with several of the engine majors on collaboration around several critical elements of the powertrain, such as the range extending turbo generator. Zunum is also engaged in market development and legislative efforts across the U.S., EU and Asia, and will soon be announcing a launch customer. Zunum is funded by Boeing, JetBlue and the State of Washington, and is currently raising funds to support development through 2020.

The envisioned Zunum Aero family of aircraft. (Credit: Zunum Aero)

The following table offers data on the proposed Zunum aircraft:

Data	Zunum ZA10	Zunum ZA50
Seat capacity	12	48 – 60
Maximum propulsion power (MW)	1.0	4.5 – 5.2
Cruise speed (km/h)	500	700
Energy consumption battery power (kWh / seat / km)	0.12	0.10
Maximum take-off weight (kg)	5 136	22 000 – 27 000
Maximum battery pack weight (kg)	688	3,470
Maximum fuel weight (kg)	590	2,050
Electric / Hybrid Range, Battery 500 Wh/kg (km)	175 / 1 160	250 / 1 300
Electric / Hybrid Range, Battery 900 Wh/kg (km)	330 / 1 350	450 / 1 600

Energy Assumptions: 92% total efficiency from Battery to propeller shaft, 30% efficiency for generation, dominated by the gas turbine.

AMPAIRE

Ampaire is an innovative aircraft company with 9 employees established in 2016 and based in Los Angeles. The company is working on a project featuring all-electric propulsion with a unique and advanced design, taking advantage of the latest aerodynamic inventions. The company has a strong engineering team with recent experience from world-leading, advanced aviation projects.

Ampaire aims to fly its crewed demonstrator aircraft by the end of 2018, with the goal of using the aircraft in experimental pilot demonstration programs in 2019. Ampaire further goal is to have a 9 passenger retrofit aircraft using our propulsion system certified with an STC and on sale by the end of 2020, with a 19-passenger retrofit to follow. Both aircraft retrofit programs will leverage Ampaire partner companies.

Ampaire's clean-sheet new build aircraft named TailWind is planned to be commercially introduced in the mid-2020s. The TailWind is planned with two propulsion alternatives. The first is the TailWind-E, powered by an all-electric propulsion system and "configured inside a sleek, lightweight package tailored to maximize efficiency," as the company says on its website. The second is the TailWind-H, a hybrid electric version of the aircraft, designed for longer-range flights.

(Credit: Ampaire)

EVIATION

The newly formed company in Israel has an ambitious project utilizing benefits with new light composites, new aircraft design and all electric propulsion. The team behind the project is highly experienced, both from leading a number of successful venture companies and product developments related to composites and advanced power electronics.

Eviation describes its 9-passenger aircraft, named Alice, as using "distributed propulsion with one main pusher propeller at the tail and two pusher propellers at the wingtips to reduce drag, create redundancy, improve efficiency, allow for augmented stability and turbulence mitigation." A fully composite structure with optimal aerodynamic design is envisioned. Alice is envisioned with a total weight of 6 350 kg and 900 kWh battery.

As of the last Paris airshow in June 2017, the company is flight testing an unmanned, sub-scale model of the aircraft that is 350 kg ad has a 5 m wingspan. Construction of the full-scale aircraft has been taking place since early 2017. The Alice prototype incorporates Siemens motors, Kokam battery cells, Honeywell flight deck and avionics, Magnaghi Aeronautica landing gear, and Hartzel propellers. Eviation has risk sharing arrangements or supply agreements with all of the companies, with the Kokam agreement being the most recently announced. Eviation has also secured early adopter client agreements in several territories and will announce them early next year.

The company is backed by private investor money. The Eviation Alice is expected to fly its first flight as early as Q2 2019, and to receive its TC by mid-2020. About five years down the road, the company is further on planning to max the FAR 23 category (19 PAX) based on the Alice platform with more or less the same design, just bigger, and with preliminary design done. Additionally, a FAR 25 version is planned to carry a larger number of passengers (like today's ATRs and up). The design will be different from Alice for the FAR 25 variant.

(Credit: Eviaton)

WRIGHT ELECTRIC

Wright Electric is an airplane company founded in 2016 with the ultimate goal for every short flight to be zero-emissions within 20 years. The company intends to build an airliner designed for flights like from closely located, major cities, like from New York to Boston and London to Paris. Wright Electric has teamed up with EasyJet to design a 186-seater passenger aircraft with distributed propulsion. The company expects the plane to have a 540 km (335 mile) range (plus IFR reserves) with 500 wh/kg batteries. The team has built a 500 kW test stand in collaboration with Yates Electrospace Corporation in California. According to the company blog, the first step is to retrofit a Piper Cherokee and in parallel design a ground-up nine-seater with electric propulsion. The company has an open design approach and invites engineers to comment and participate in a network collaboration. Wright is bullish about the long-term prospects for batteries and unconventional energy storage materials. The company expects major developments in solid state and metal-air batteries within roughly a six-year timeframe.

(Credit: Wright Electric)

Others

There are most likely other aircraft producers that have started or will start projects but no public information is found. Some of these makers include Antonov, Tupolev, Lockheed Martin, Mitsubishi, Comac, and Dornier. Many more should be capable.

9.2 RESEARCH PROJECTS

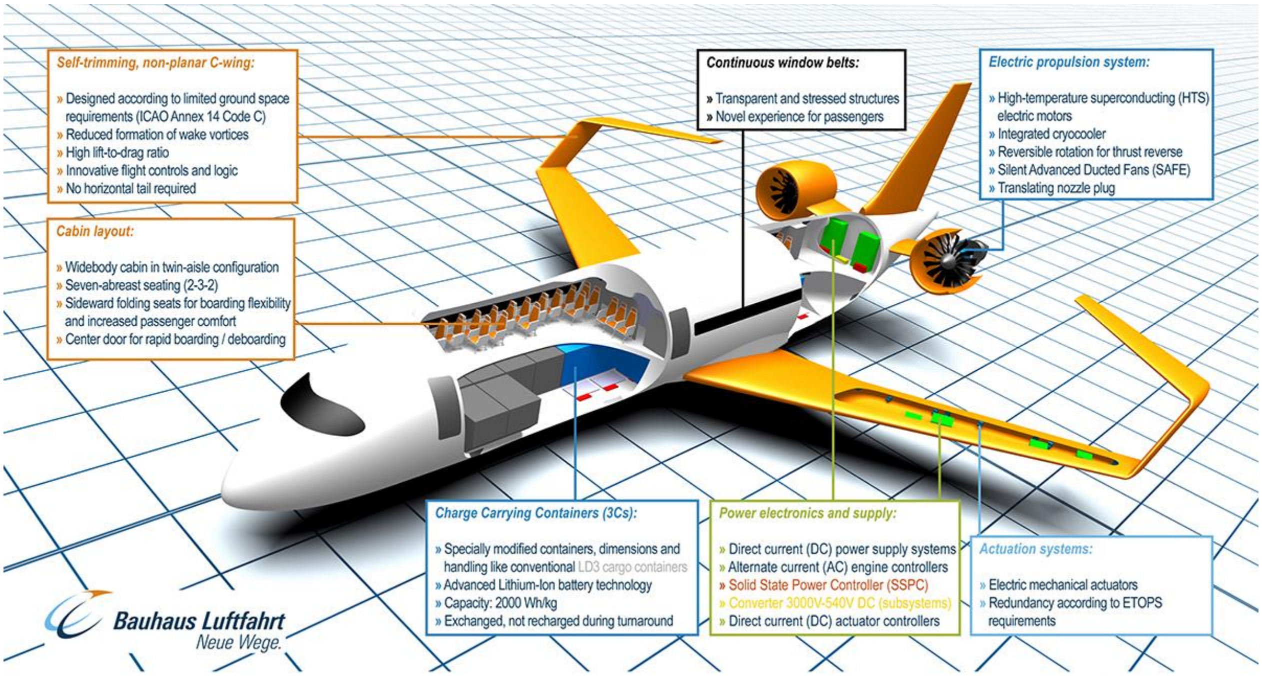
Although hard to put a firm number on, it is fair to say that there are hundreds of universities and research organization that are engaged in activities related to electric aviation. The reason for this is the excitement and enthusiasm shared among researchers and engineers for the virtually unlimited new opportunities and design freedom introduced by using electric motors. We will review a few of these efforts in the following.

BAUHAUS LUFTFAHRT

Germany-based Bauhaus Luftfahrt was founded in 2005, its website describes, "as an independent non-profit research institution in reference to the historical Bauhaus in Dessau. Since 2013, it has received institutional funding from the Free State of Bavaria, having its office at the Ludwig Bölkow Campus near Munich since 2015." Bauhaus has produced many interesting studies related to electric aviation in the last years:

CE-LINER

This new concept design from Bauhaus Luftfahrt has a range of 1 667 kilometres, a cruising altitude of ten kilometres, and a cruise speed of 808 km/h. Three studied versions of the conceptualized aircraft would seat anywhere from 140 to 233 passengers. The research organization says about the idea: "The most significant novelty of the Ce-Liner lies in its all-electric propulsion system, which enables the concept to potentially exceed even the ambitious emission targets of Flightpath 2050 . . . Its two ducted fans are driven by high-temperature superconducting electric motors fed through a universally electric systems architecture (UESA) with energy from advanced lithium-ion batteries." The required energy density is estimated to be 2 000 Watt-hours per kilogram, or "roughly eight to ten times as much as state-of-the-art batteries achieve today." Bauhaus Luftfahrt says the battery modules would be installed in specially adapted cargo containers.



(Credit: Bauhaus Luftfahrt)

CENTAIRSTATION AIRPORT CONCEPT

Another interesting concept by Bauhaus Luftfahrt is utilization of the space above train stations for short inner-city airports connecting directly to public transport hubs. The concept makes a lot of sense in combination with new, low-noise electric aircraft concepts with STOL (Short Take Off and Landing) abilities.

The research organization describes the concept as follows: "The CentAirStation building with a length of 640 m and a width of 90 m consists of at least four levels," with each platform featuring escalators and lifts for efficient passenger transit. "The predominantly vertical passenger routes through the CentAirStation building allow very short processing times: Departing passengers will need only 15 minutes from arrival at the airport through to take-off of the aircraft. Arriving passengers will be able to exit the building just ten minutes after they got out of the aircraft in the gate position."

CentAirStation. (Credit: Bauhaus Luftfahrt)

CITYBIRD

CityBird, as its name implies, is an urban air transport concept. The research organization behind it says: "The CityBird has been specially designed as an aircraft for inner-city operation. The high population density in cities and the limited available space put high requirements on noise protection, safety and short take-off and landing capability (STOL) of the aircraft. Furthermore, the aircraft must be efficient and fast enough to achieve the goal of four hours door-to-door over the required range. Operation on conventional airports without affecting the running processes is provided. The long list of specifications poses major challenges for aircraft design that are addressed, among others, through the use of new technologies: a low wing configuration with aft-mounted engines, a small and faired landing gear as well as a simple high-lift system along the entire span of the wing."

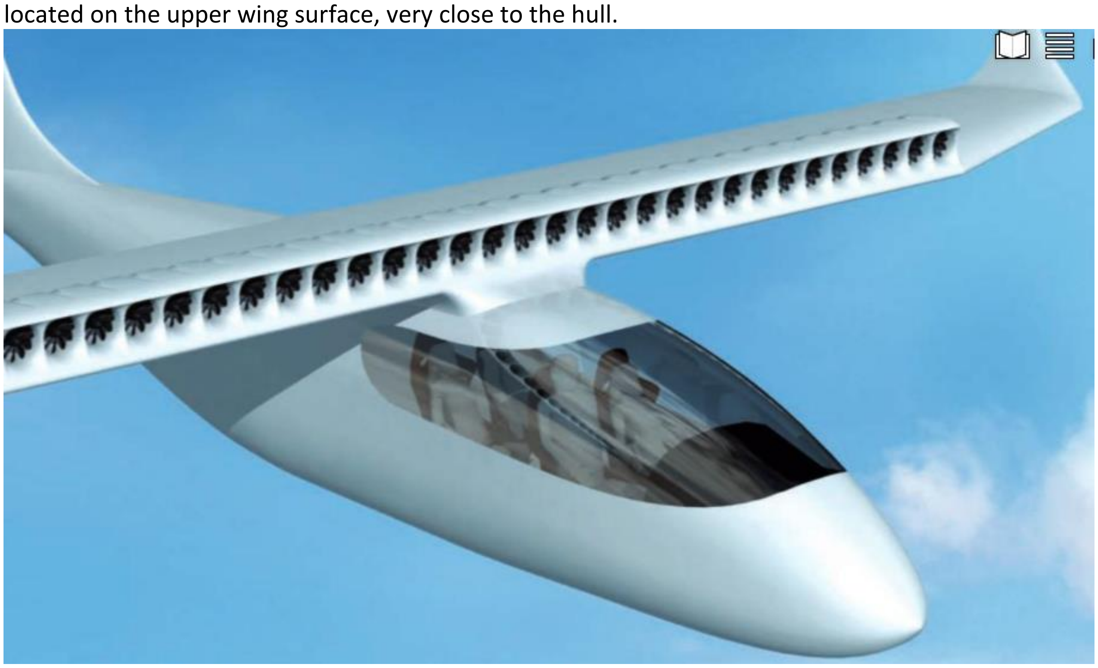
CityBird. (Credit: Bauhaus Luftfahrt)

ONERA

ONERA (Office National d’Etudes et Recherches Aérospatiales) is the French national aerospace research centre. The organization describes itself as "a public research establishment, with eight major facilities in France and about 2,000 employees, including 1,500 scientists, engineers and technicians. ONERA was created by the French government in 1946 to conduct aeronautical research."

An ongoing research program by ONERA is Ampere, which is validating an all-electric aircraft capable of transporting 4 to 6 people over 500 km in two hours, close to cities. To address this challenge, ONERA has proposed distributed electric propulsion and a complete rethinking of aircraft design. Within the framework of this program, Ampere is a coherent assembly that allows technologies to be integrated and tested. Aero-propulsion integration has already been the subject of initial computer simulations and validations in a wind tunnel with positive results, ONERA has reported. The research centre has set 2025 as a realistic goal for the Ampere project. Its engineers are already thinking ahead to 2040, with the idea of a regional transport aircraft based on the same principles, offering a capacity of 50 to 80 seats, and a 1 000 km flight range.

ONERA has indicated several advantages to distributed. One of these is take-offs and landings over short distances with the engines having a wing ducting effect, increasing lift at low speeds; a 200 m runway would be sufficient. Other advantages include: stabilization of the aircraft through the management propulsion thrust; improvement of flight safety thanks to redundancy by many propulsion units; power supply may be distributed with fuel cells and/or lithium-ion batteries; potential reduction of energy losses due to friction, thanks to the effect of 32 fans located on the upper wing surface, very close to the hull.



ONERA distributed propulsion concept. (Credit: ONERA)

NASA

NASA (National Aeronautics and Space Administration) is an independent federal agency in the U.S., responsible for the civilian space program, along with aeronautics and aerospace research. A highlight of NASA's work in the electric aviation realm is the X-57 Maxwell. NASA has described this project as "the first step into a new era of aviation. The project will validate the theory that many propellers ahead of the wing will result in a reduction of five times the energy (including the benefit of battery operation) required for a private plane at 175 km/h. NASA believes total operating costs can be reduced by 40% with this technology." The X-57 Maxwell will be covered in further detail in a later section of this study.

The X-57 Maxwell. (Credit: NASA)

9.3 URBAN AIR TRANSPORT

Remarkable activity is taking place in a new segment of aircraft called urban air transport or urban air taxi. More than 70 projects for are currently designing 1 to 4 passenger vehicles targeting a range of up to 100 km, utilizing vertical take-off and landing (VTOL). The projects are funded by the aviation and car industries, innovative transportation companies like Uber, technology giants such as Google, and a variety of other investors.

Several of the companies are based or have activities in Silicon Valley, significant investments are being made, and all are hiring engineers. There will certainly be some interesting outcomes from all this activity. Both Airbus and Boeing are also participating, Airbus is making test flights with their Vahana project, and Boeing recently bought Aurora Flight Sciences, a maker of automated drones. Most of the projects are based on autonomous and pilot-free flight, but some projects, like Uber Elevate, are indicating that the first flights will be with a pilot.

Uber's strategy is to establish a network of urban air transport in the largest cities, but their plan is not to develop their own vehicle. To get available vehicles, Uber Elevate has established its own team and encouraged competition by entering into intentional agreements with several companies including Aurora Flight Sciences, Pipistrel Aircraft, Embraer, Mooney, and Bell Helicopter. Uber Elevate's white paper "Fast-Forwarding to a Future of On-Demand Urban Air Transportation"[5] gives a good overview of the background challenges for this segment.

[5] Holden, Jeff, and Nikhil Goel. "Fast-Forwarding to a Future of On-Demand Urban Air Transportation." *San Francisco, CA* (2016). https://www.uber.com/elevate.pdf?state=Rdpy_dk1G4SUZOGHuxZI_YD6EYnPUMsPouVLKVmZ8gI%3D&_csid=ylRmOIUhxX_uhFLE9kMzTQ#_[pdf]

First test flight of the Airbus Vahana air taxi. (Credit: Airbus)

UBER ELEVATE

To dig a little deeper into the Uber Elevate initiative, its goal is to establish individual, low-cost, urban air transport. The key features: Four seats, fully electric, vertical take-off and 258 km/h (160 mph) top speeds with a range of about 100 to 160 km (60 to 100 miles). The aerial vehicles will require a safety record nearly as good as a fixed wing General Aviation aircraft. In a second step, the Uber Elevate aircraft shall fly autonomously. In April 2017, Uber held a very successful Elevate conference event, with companies like Bell Helicopter, Embraer, GE, Boeing, Airbus, Siemens Kawasaki, Honda, and Mercedes Benz all participating, as well as investment companies looking for promising startups. A new Elevate summit will be held in Los Angeles this year.

The Uber Elevate vision. (Credit: Uber Elevate)

VAHANA

Vahana is a single-seat, fully electric VTOL vehicle designed by Airbus A^3 based in Santa Clara, California. Vahana is a tandem tiltwing aircraft, where four variable-speed, variable-pitch propellers are mounted both on the forward and the main wing. The propellers and the wings tilt up during vertical takeoff and tilt horizontal for cruise flight. The demonstrator uses 45 kW motors and lithium polymer batteries. The current version of Vahana is a single-seater designed for autonomous ride-sharing or air taxi services. The first unmanned, fully autonomous flight was performed on January 31, 2018, reaching 20 feet of altitude and lasting for about 1 minute of hovering. The plan is to have a certifiable and producible vehicle with two seats available in 2020.

Vahana on the test pad in Oregon. (Credit: Vahana aero)

OTHERS

There are a high number VTOL activities and projects, maybe as many as 100, and many of them are funded by resourceful investors and capable organisations. The few examples mentioned above are only to give a glimpse of what is going on in this exciting new sector of air transport.

9.4 LIGHT SPORT AIRCRAFT

Most of the development activities for new electric aircraft starts in the segment of General Aviation/Light Sport Aircraft/Recreational Aircraft. This segment allows for more experimental designs and serves as an ideal platform for propulsion testing on the small scale. Siemens is providing systems for this segment, and the all-electric demonstrator Extra 330LE by Germany-based Extra Aircraft had its first flight in 2016 with Siemens systems onboard. Airbus' E-Fan program, described earlier in this study, started with a full electric one-seater equipped with two electric ducted fans.

Not only does this class of aircraft serve as an ideal testbed for further development, it also has the first fully electric aircraft already in serial production as of 2017. The Pipistrel aircraft from Alpha Electro has reached the first stage of certification, and more than 35 aircraft have been produced with more already in the order book. In

Norway, Avinor, in collaboration with NLF, has ordered one Pipistrel to start a test program as the first step of introduction of electric aviation in Norway.

PIPISTREL

Pipistrel was established in 1987 and today has 150 employees. The company produces 1 700 different aerial vehicles, ranging from powered hang gliders to light aircraft. The company has received many awards for innovation and is continuing to pursue new solutions with a strong research and development team focusing on environmentally friendly aircraft. The company is addressing all aspects of electric aircraft development inhouse, including electric engine design, battery packaging and power electronics.

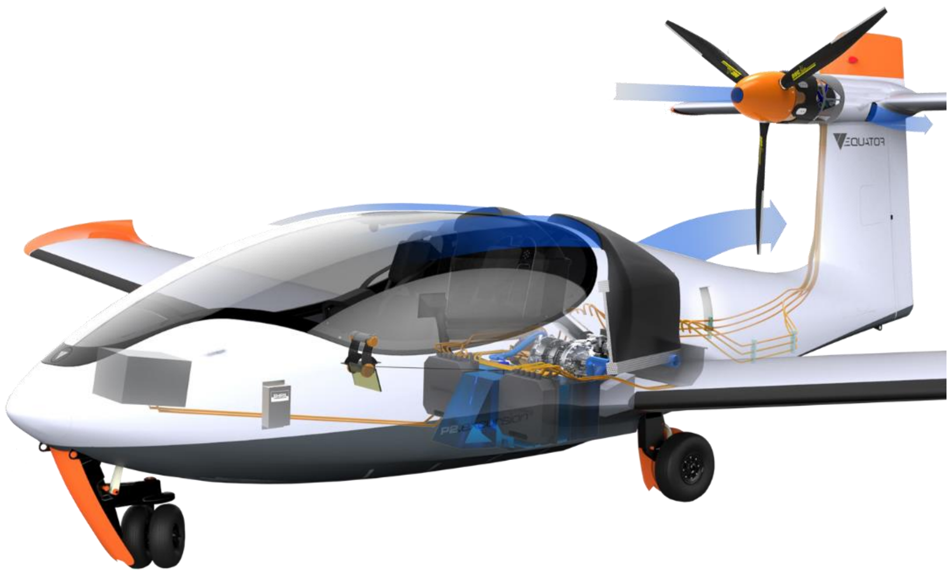
Pipistrel is participating in the EU's Horizon 2020 research and innovation program and the electric aircraft Alpha Electro is partly developed under this program. As just noted, Pipistrel has started serial production in 2017 of the pure electric 2-seater Alpha Electro, with more than 35 already produced and more are in order.

Additionally, a new 4-seater aircraft, named Panthera, is under development and is to be certified with a combustion engine and later with the option of a hybrid or pure-electric propulsion system. The Panthera hybrid electric powertrain will be 200 kW, supported by a battery and range-extender generator unit. The hybrid solution will enable low noise, pure-electric take-offs and landings, short-field, powerful climb and low drag for long-range flights. The Panthera Electro will be pure-electric with a 200 kW powertrain. The goal is to demonstrate the ability of covering 400 km (215 NM) using zero-emissions flight at the low cost provided by electric power. The platform is open and ready to accept future generations of battery technologies, which will increase the operating range.

Panthera test flight. (Credit: Pipistrel)

EQUATOR AIRCRAFT NORWAY

Equator is a Norway-based company established in 2010 by a team of passionate Norwegian designers and engineers. The company is developing an electric seaplane designed as a sport utility aircraft with the option of hybrid electric or pure electric aircraft. The testing of the aircraft has started with on-ground taxiing and is expected to fly during 2018. The hybrid propulsion system is developed through a partnership with German Engiro GmbH. Equator has received 450 000 euros in government funding through the Norwegian Transnova program.



The P2 Xcursion. (Credit: Equator)

Equator explains that its 2-seat aircraft, named the P2 Xcursion, can achieve performance in line with that of land planes, and at the same time utilize water as a landing surface. The aircraft prototype is pure electric and has a max takeoff weight of 750 kg and 18 kWh battery. The company also have a hybrid under way that will be developed to a fully certified standard through the “FlightSmart” project (2018-2021) that was just started through the Norwegian Research Council BIA program, with partners Sintef, NTNU and Maritime Robotics.

The company is further planning to scale the aircraft to larger types as they gain experience in the light aircraft arena. Aircraft ranging from 4 to 10 seats can be made on the same design properties as the smaller 2-seater version. The work by Equator promises to be an interesting addition to future air taxi systems that could also then include water ways, fjords, and lakes as potential hubs for transport. Finally, the aircraft is also well-suited to become a drone. Equator has now partnered with UAV company Maritime Robotics in contemplating the development of the P2 into a drone system called the PXdrone.

First taxi testing 2018. (Credit: Equator)

AERO ELECTRIC AIRCRAFT CORPORATION

This U.S.-based company was established in February 2014. The highly competent management team includes Charlie Johnson, the former president of Cessna, along with a number of other very skilled people from the aviation industry. The company has developed a two-seater Sun Flyer with an 80 kW motor and the intention is to bring it to market soon in order to serve General Aviation and flight schools by delivering a clean, renewable energy-based, solar-electric training aircraft. The Sun Flyer's first public appearance was in May 2016. Sun Flyer is a composite made, low-wing trainer that features solar cells on the wings, lithium-ion battery packs and an electric motor. The aircraft will come with a training program developed in partnership with Redbird Flight. The company also has a four-seat model currently undergoing design with 130 kw of propulsion.

The Sun Flyer. (Credit: Aero Electric Aircraft Corporation)

OTHER PROJECTS

This Light Sport Aircraft segment overall has a large number of electrification projects at the prototype and testing level.

10. TECHNOLOGY

Electric propulsion for aircraft may accommodate completely new aircraft designs, propulsion systems and control methodologies, so besides the electric drive system's development, the pursuit of electrification may also foster new innovations. And as with all disruptive technology development, completely new solution that no one has foreseen today may be discovered.

10.1 ELECTRIC PROPULSION SYSTEMS

Electric motors have the potential to replace piston and turbine engines, driving different variations of propellers and ducted fan. Electric engines are scalable in size and may also be integrated with combustion engines (parallel hybrid architectures) to sum power across the two as required. The electric motor responds immediately and on a multiengine aircraft, it may be possible to replace some control surfaces with motor control, if redundancy and the safety aspect can be maintained. An electric motor will also be able to increase power for short periods for take-off or fault recovery.

The major aircraft engine manufacturers are closely following the activity related to the electrification of aviation. We are likely to see more announcement like the collaboration E-Fan X between Rolls Royce, Siemens, and Airbus. In the E-fan X program, Rolls Royce is modifying a business jet engine, the AE 3007, by replacing the compressor and turbine with a 2 MW electric motor from Siemens.

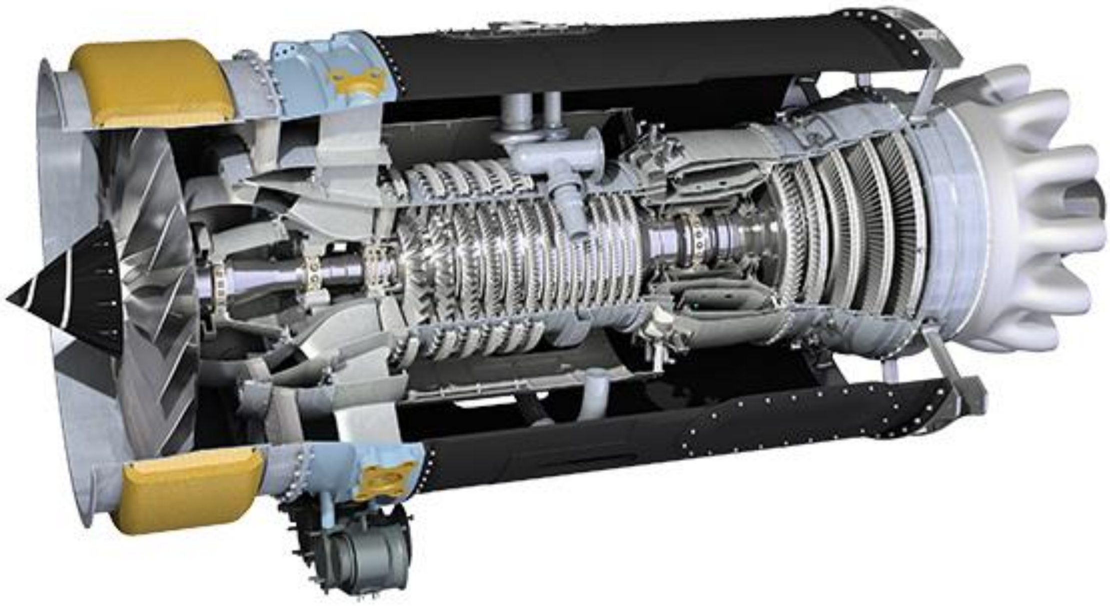
Different types of propulsion designs may be combined with an electric motor and powered by batteries, a generator set, or a combination of a generator and batteries. We list them below and then describe each thereafter:

- Ducted fans, High-pressure fans (Airbus e-Fan X)
- Ducted fans, Low-pressure fans (Airbus e-Fan, Zunum Aero, Bauhaus CE-Liner)
- Ducted fans combined with boundary layer ingestion (Faradair, NASA STARC-ABL, Ampaire)
- Ducted fans combined with distributed propulsion (NASA/ES-Aero, Lilium, Wright Electric)
- Open fan (Safran and other research projects)
- Propellers combined with distributed propulsion (Joby Electric, Volocopter, NASA Maxwell, Eviation)
- Regular propellers

DUCTED FANS

Ducted fans are used by all jet aircraft, business jets, and airliners, powered by an inline turbine engine; these are high pressure turbofans, designed for high speed transonic cruise. The vast majority of fan development work over the past decades has been focused on increasing the bypass ratio on large turbofan engines. While the higher bypass does lead to a lower pressure ratio, the fans are still optimized for large transport aircraft flying long range at high speed.

For regional aircraft with under 90 seats, propellers powered by turboshaft engines are the most common solution. Limited engineering effort has been spent on ducted fans optimized for these size ranges, which require much lower pressure ratios to achieve highly efficiency propulsion.



The Rolls Royce AE 3007 engine, originally used for Cessna Citation and other business jets. The compressor and turbine are replaced by a 2 MW Siemens motor to be tested in the E-Fan X program. (Credit: Rolls Royce)

Zunum Aero is developing a low-pressure ducted fan for their size range of aircraft (9 to 50 passengers) and according to Zunum's experienced development team, there is a strong engineering basis for achieving efficiencies better than open propellers for cruise speeds above 200 kts. This view is also backed by Airbus, which selected two ducted fans to power the electric engine in their E-Fan project, as well as for the new E-Fan X program, which is designed for higher speeds but still substantially lower pressure ratios than the turbofans being replaced.

An electric ducted fan has the potential to significantly reduce noise and at the same time increase static thrust for improved acceleration and short take-off. Noise sources are primarily the tip speed of the fan, and jet velocity from the combustion core; with the electric fan, tip speeds are much lower, optimized for aero efficiency without having to match a turbine cycle, and there is no combustion jet. Compared to an open propeller, tip speeds are lower and frequencies are higher, which leads to faster sound dissipation, and most importantly, the dominant tone from the propeller-tip is blocked by the duct. In addition to noise benefits, the duct provides higher thrust during the take-off roll than an equivalent open propeller, resulting in a shorter take-off distance. The compact design reduces cost of the structure and enables very efficient integration with a variety of aircraft designs.

The Airbus E-Fan project used two ducted fan modules. (Credit: Airbus)

Zunum Aero is developing low thrust ducted fans for their new aircraft. (Credit: Zunum Aero)

BOUNDARY LAYER INGESTION

Ducted fans have also been coupled with boundary layer ingestion (BLI) concepts for efficiency, although the engineering of these is far less developed. The boundary layer refers to the layer of slow-moving air that develops on the skin of an aircraft as it flies. The slow air creates drag. Aircraft today just accept this drag because with internal combustion engines, it is more efficient to place them away from the aircraft body's boundary layer—for instance, out on the wings—in order to have faster-moving air enter the motors.

The BLI design suggests doing the opposite by positioning an engine to ingest the slower air passing around the fuselage. The result is overall lower drag and thus reduced fuel or energy consumption. So far, research into this method has indicated an overall drag reduction nearing 10%, which is considerable.

BLI engines could be placed at the extreme rear of the aircraft, right on the fuselage, where they can ingest the thickest portion of the boundary layer and help an aircraft get back some its drag losses. There are several challenges to overcome, but aerodynamic experts are bullish that this design will be implemented for future aircraft.

While there are theoretical efficiency gains to be made with BLI, these can be significantly reduced by real world installation effects, and also result in higher noise and structural challenges for the fan. These are compounded in the low-pressure fan, where the total efficiency is even more sensitive to distortion in the airflow.

The Faradair BEHA (Bio-Electric-Hybrid-Aircraft), a 6-Seat aircraft with a Hybrid propulsion system. (Credit: Faradair)

The NASA STARC-ABL, which stands for Single-Aisle Turboelectric Aircraft with Aft Boundary Layer propulsion. (Credit: NASA)

The Ampaire team has designed their futuristic aircraft with a tail electric ducted fan. (Credit: Ampaire)

DISTRIBUTED PROPULSION

Other ducted fan concepts leverage distributed electric propulsion (DEP), which is enabled by scalable electric motors which are easy to integrate. This technology may open a new avenue for aircraft design from the largest to the smallest aircraft and is most advantageous on various vertical take-off and landing (VTOL) designs. DEP may also include small ducted fans, like on the Lilium project, or on larger aircraft like the intended design of aircraft from the partnership between U.S. startup Wright Electric and British airline EasyJet.

An example of a distributed electric propulsion design from Empirical Systems Aerospace (ESAero) for NASA. (Credit: ESAero)

An EasyJet concept designed with DEP with Wright Electric. (Credit: Wright Electric)


Lilium project using DEP for VTOL aircraft. (Credit: Lilium)

Joby Aviation S2 VTOL (Credit: Joby Aviation)

NASA is testing an experimental 31-foot aircraft wing with 18 electric motors placed along the leading edge. This unusual setup is called Leading Edge Asynchronous Propeller Technology (LEAPTech), and according to NASA this could result in a new and more energy-efficient propulsion system, which may be an enabler for new aircraft designs. The project is named X-57 Maxwell, and after testing of the new wing equipped with the propulsion system on the ground, it will replace the original wing of an Italian TECNAM P2006T twin-engine four-seat aircraft to be used as a testbed.

NASA's X-57 Maxwell will be powered by a battery system that consists of 16 battery modules. The system will comprise 800 pounds of the aircraft's total weight. X-57 will demonstrate that electric propulsion can make planes quieter and more efficient, with fewer carbon emissions in flight. (Credit: NASA)

As described in an Electrek article, "NASA's aeronautical innovators hope to validate the idea that distributing electric power across a number of motors integrated with an aircraft in this way will result in a five-time reduction in the energy required for a private plane to cruise at 175 mph." The majority of this reduction is from the efficiency of the electric powertrain with the remainder due to anticipated benefits of the distributed propulsion and reduced wing size. In addition, NASA is planning for lower noise of operation by modulating propeller frequency to reduce the strong single tone from a standard propeller.

According to NASA, there will be several other benefits as well, to quote from the project website:

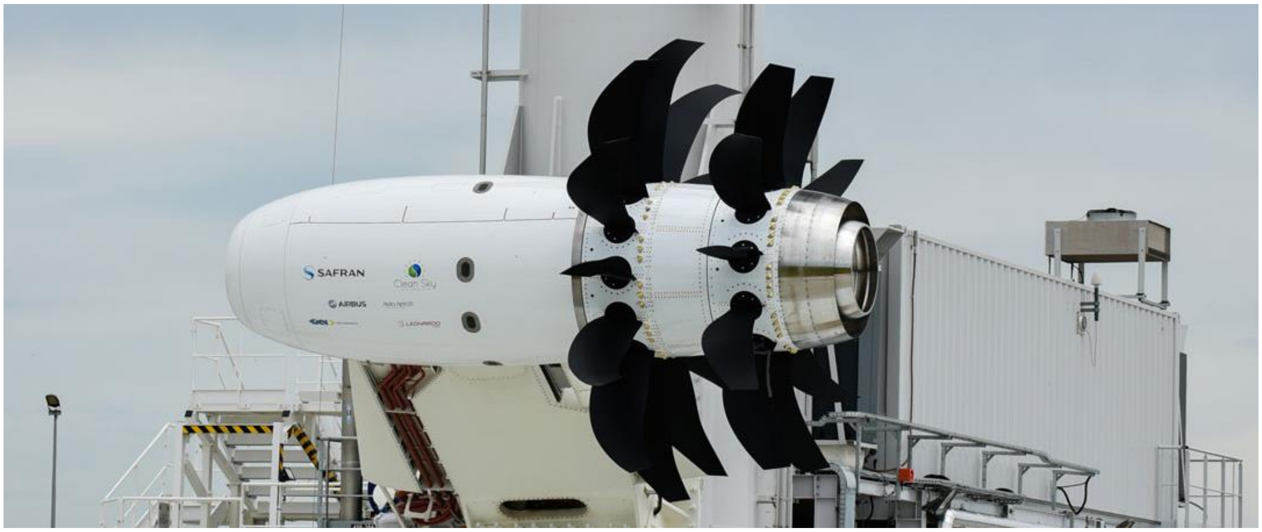
- "'Maxwell' will be powered only by batteries, eliminating carbon emissions and demonstrating how demand would shrink for lead-based aviation fuel still in use by general aviation.
- Energy efficiency at cruise altitude using X-57 technology could benefit travellers by reducing flight times, fuel usage, as well as reducing overall operational costs for small aircraft by as much as 40 percent." The distributed propulsion is being used to reduce runway requirements without increasing wing size, which allows for an increase in high efficiency cruise speed.
- "Finally, electric motors are more quiet than conventional piston engines. The X-57's electric propulsion technology is expected to significantly decrease aircraft noise, making it less annoying to the public."

NASA is expected to start flying in March 2018 first with two fully electric motors until May 2018. After that, then the standard wing will be replaced with a high aspect ratio wing and the electric motors relocated to the wingtips. The final configuration of X-57 will feature the addition of 12 smaller electric high-lift motors, to be used during take-off and landing, in addition to the wingtip cruise motors.

Included in the project for the new propulsion system is also a battery that fulfils requirements for aviation standards. In December 2017, NASA engineers announced that they had reached a major milestone by successfully testing the battery system. In a press release, NASA described the results as follows: "The testing validated that the battery system has the necessary capacity to safely power X-57 Maxwell for an entire flight profile. The test also confirmed the battery design's ability to isolate potential overheating issues to single battery cells, preventing unsafe conditions from spreading to the rest of the battery system." This has direct benefits to all electric aircraft where a lightweight, safe battery system is an essential requirement.

OPEN ROTOR SYSTEM

Another intriguing idea is an open rotor system. As described in an *AINonline* article from October 2017, "The breakthrough of the open rotor stems from a significant increase in the bypass ratio, from 11:1 on the Leap to more than 30:1. The lack of a nacelle covering makes it possible to increase the size of fans, thus the increase in bypass ratio. The higher the bypass ratio, the better the energy efficiency of the engine. The disadvantage lies with the need to completely reconfigure the aircraft and possibly noise profile. An open-rotor engine cannot mount on a wing, but must attach to the rear of the fuselage.



Safran open-rotor demonstrator. The engine configuration could burn 15 percent less fuel than the CFM Leap. (Photo: Safran)

PROPELLERS

Open propeller technology has steadily developed since the very beginning of aviation. It is highly efficient at low- to medium-speeds and is used on a large number of aircraft. The combination of a propeller and an electric motor is ideal. The electric motor responds instantly with high torque and may also provide a short power boost for ~30 seconds. In combination with variable pitch, this is a very flexible and powerful propulsion system for low- and medium-speed aircraft.

When it comes to noise, the experience from piston engine aircraft has shown there to be a significant noise reduction due to the absence of the exhaust and the inherent engine racket. It is also expected that turboprop aircraft will get reductions in high tone noise from the turbine and exhaust outlet. In both cases, the propeller noise will naturally depend on advanced propeller designs optimized for low noise.

Electric engine with propeller seen on NASA's X-57 Maxwell's wingtip cruise motor/propeller. (Credit: NASA)

WINGTIP MOUNTED PROPULSION

Accommodating the wingtip is a very challenging part of aircraft design. The pressure differences above and below the wing create a significant drag and a vortex behind the wing. Additionally, this effect disturbs and reduces lift at the outer wing surface. Different wing tip devices, such as like winglets, are used to reduce the effect. The introduction of electric propulsion could leverage this technique by mounted the engine units themselves right at the wingtips, thus reducing drag and neutralizing vortex formation. A secondary benefit could be that reducing the strength of wingtip vortices also reduces turbulence, which can pose a possible hazard to aircraft following behind.

Eviation aims for a highly efficient composite aircraft with wing tip and tail electric propulsion. (Credit: Eviation)

10.2 DRIVE SYSTEMS AND ELECTRIC MOTORS

Although power electronics that are used to control electric motors are based on well-known technologies, they still must be further developed to meet the coming requirements for reliability, safety, performance, and regulation for aircraft. Toward this end, Siemens, Airbus, and Rolls Royce have teamed up to develop high-performance electric drive and propulsion systems. GE has designed an advanced 1 MW hybrid system with a turbo generator and a super-efficient (98%) electric motor for propeller propulsion. It should be expected that more of these sorts of projects will be forthcoming from the aviation industry soon.

As standards and regulations today do not cover electric propulsion, there is a significant challenge to establish new rules and further to match the many ongoing technology developments to these new standards. The segment of General Aviation and Light Aircraft is important for this development activity. The first projects in this segment have replaced the combustion engines in existing aircraft with electric motor power electronics. A variety of in-house development, along with companies supplying drive systems components to those projects, is providing valuable experience both for regulatory purposes and system designs.

SIEMENS

Siemens strategy is to become a system supplier for electric and hybrid electric aircraft and to supply complete drive train including power electronics and motor as well as battery pack design and integration including BMS (Battery Management System). According to Siemens, hybrid electric propulsion may have the potential to reduce block-energy by up to 20% compared to conventionally powered aircraft and significantly reduce CO_2, NOx and noise emissions.

Starting from 2011, Siemens has been working with a number of electric aircraft projects and closely with Airbus Group and other OEMs in order to build hands-on experience with battery powered electric drive systems. In 2015, Siemens unveiled an electric motor that is capable of powering larger aircraft with take-off weights of up to two tonnes and has demonstrated the system in-flight. The electric motor power-to-weight ratio achieved is 5 kilowatts per kilogram and has a continuous mechanical power of 260 kilowatts with a weight of 50 kilograms.

Siemens has publicly released information about several other propulsion units, most notably for the CityAirbus VTOL (200kW, 1500Nm, 1300rpm, 20Nm/kg) and the recently announced E-Fan X project (2 MW). Other large-scale demonstrators are rumoured to be in the works. Together with Airbus, Siemens' developers are working to turn the vision of electrically powered flight into a reality. In a press release, Airbus CEO Tom Enders said: "We believe that by 2030 passenger aircraft below 100 seats could be propelled by hybrid propulsion systems."

260 kw motor - 50 kg. (Credit: Siemens)

MGM COMPRO

MGM COMPRO, a Czech Republic company, has developed electric propulsion units ranging from large systems to special custom-made units for Airbus, NASA and a number of other electric aircraft projects. As the company states on its website, "MGM COMPRO innovative concepts bring a lot of advantages for every project of our customers, whether it comes to electric propulsion systems for airplanes, gliders, vehicles, boats, multicopters, UAVs, military vehicles, other EVs or any unique designs according to customer's special needs."

MGM Compro drive unit. (Credit: MGM)

Electric motor REB 50 series, 50 kW
(Credit:– MGM)

GENERAL ELECTRIC

General Electric (GE) has a strong position as a supplier of electrical power solutions for aircraft. The company has published a whitepaper on hybrid solutions for electric aircraft and is expected to play an important role in the years ahead. In the white paper, GE describes how it has modified its F110 engine (used in F-15 and F-16 fighter jets) to generate 1 MW of electric power. For propulsion, GE has also designed an advanced 1 MW electric motor with a propeller designed by Dowty, a GE subsidiary. Flightglobal, an online news aviation news site, offered the following characterization: "[t]his hybrid system could produce the same thrust as a large version of the Pratt & Whitney Canada PT6A turboshaft engine. The motor itself represents the state of the art in efficiently converting electricity into power. Whereas most aviation motors are designed to achieve 90% efficiency, the new motor demonstrated by GE is 98% efficient, the white paper claims. Importantly, such efficiency means a 1MW motor produces only 20kW of waste heat, rather than at least 100kW if a conventional aviation motor is used. GE has not revealed the size or weight of the device. By comparison, the Boeing 787 uses six generators to produce a maximum load of 1.4MW of electric power, which the aircraft uses to provide power for de-icing the wing and engine nacelles and pressurising the cabin."

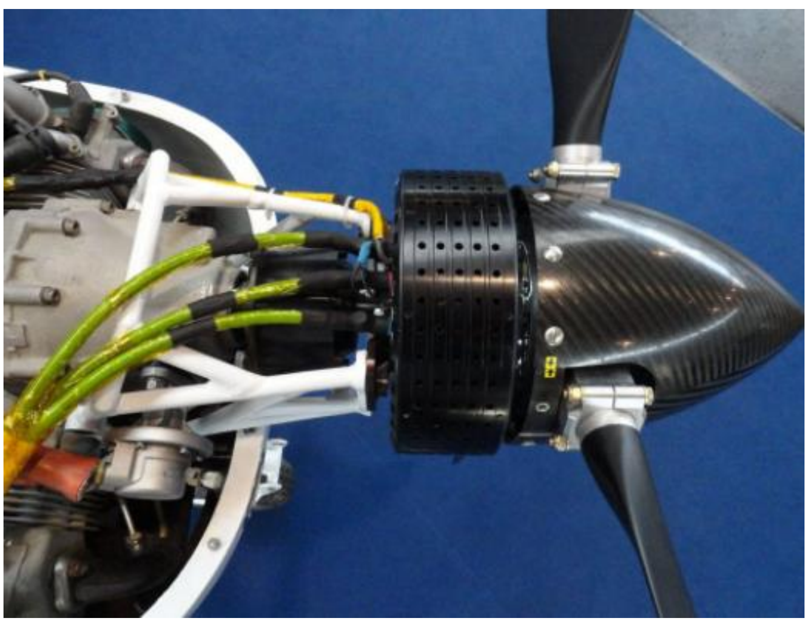
MAGNIX

Based in Australia, magniX has developed and is testing the Magni5 motor, which outputs 265 kW of continuous power at over 5 kW/kg. This is roughly equivalent to Siemens' system and is currently being productionized. On its website, magniX describes itself as "a subsidiary of Heron Energy" and "a privately-owned company based in Queensland which develops and commercializes advanced, power dense and energy-efficient motors and generators." According to the company, magniX technology utilizes superconductive materials and is capable of designing electric motors up to three times the power density of modern aircraft engines; the ultimate goal is to achieve 25 kW/kg.

The 265kW magni5 motor (Credit: magniX)

EMRAX

Based in Slovenia, EMRAX is one of the earliest electric motor suppliers to the aviation industry. Its products are currently used in powered sailplanes and light aircraft like the SORA-e. The company offers lightweight direct drive propulsion units from the 10s of kW up to 300 kW of peak power, or EMRAX TWIN variants with double the power. The motor design is based on axial flux synchronous permanent magnet motors and generators that operate on the basis of patent-pending technology.



Emrax electric motor. (Credit: Amrax)

10.3 HYBRID ELECTRIC PROPULSION SYSTEMS

The hybrid electric approach to propulsion is expected to be introduced in commercial aviation, both for smaller and larger aircraft, within the next ten years. Batteries may not yet have the necessary energy density to replace liquid fuel entirely in that time span. But even today's technology can store sufficient amounts of energy to provide additional power for larger aircraft and enough energy for shorter regional flights.

As energy density continues to increase, the battery-stored energy will play a growingly important role. To specify, this role will likely range from additional electric power for the fan section in large turbofan engines, to onboard generators that can be called upon as energy reserves to extend flight distances. At the same time, the combustion engine can be used to provide extra power during take-offs and ascents, when energy requirements reach peak levels during aircraft operation.

It is important to emphasize that a hybrid electric aircraft may function as a pure-electric aircraft, with the combustion engine and generator not being used at all and only standing by as a spare energy source if needed. Hybrid electric cars often operate in the same way, for example when driven for a daily commute to and from a work site that is within their batteries' range and charged from the grid when parked. The combustion engine just sits there within the vehicle in a reserve capacity, to be used perhaps on a long leisure trip on the weekend.

For an electric aircraft, such a configuration makes even more sense than for a car. To operate a commercial flight with passengers, an aircraft must maintain a significant energy reserve. In case of bad weather or problems at the intended destination airport, for instance, the flight may have to return or divert to another airport and need much more energy than for the original flight.

A pure electric aircraft could carry surplus batteries in order to have the required energy reserve. For a hybrid electric aircraft, this required energy reserve is instead a combustion engine and generator, often called a "range extender."

In the near future, range extenders and their liquid fuels will likely weigh and cost less than the batteries that would offer the equivalent range extension. As energy densities improve, the weight and cost equation will change to favour batteries, making combustion-based range extenders technologically and economically obsolete.

An additional use for electric propulsion via the hybrid electric approach is to engage the electric drive when taxiing on runways and otherwise moving the aircraft on the ground. Doing so reduces the emissions of greenhouse gases and other pollutants at ground level, where in the latter case they reach into the surrounding community.

Based on the arguments presented above, it is quite likely that the first regional commercial passenger aircraft will be designed as hybrid electric, although in practice they may usually operate in a pure-electric mode. For larger, long-distance aircraft, hybrid electric solutions are likely to be introduced in order to reduce fuel consumption as well as reduce emissions during ground operations.

To summarize, hybrid electric solutions for aviation can serve numerous purposes:

a) Reduce overall fuel/energy consumption by adding electric power from batteries to avoid combustion engine operation.
b) Eliminate pollution at and around airports by electrically-powered ground handling.
c) Provide additional power from combustion engines when required during take-off and climb.
d) Enable longer flight distances with the combustion engine and generator working as a range extender.

e) Maintaining an emergency energy reserve for when the battery-based range and power capacities are to be exhausted.

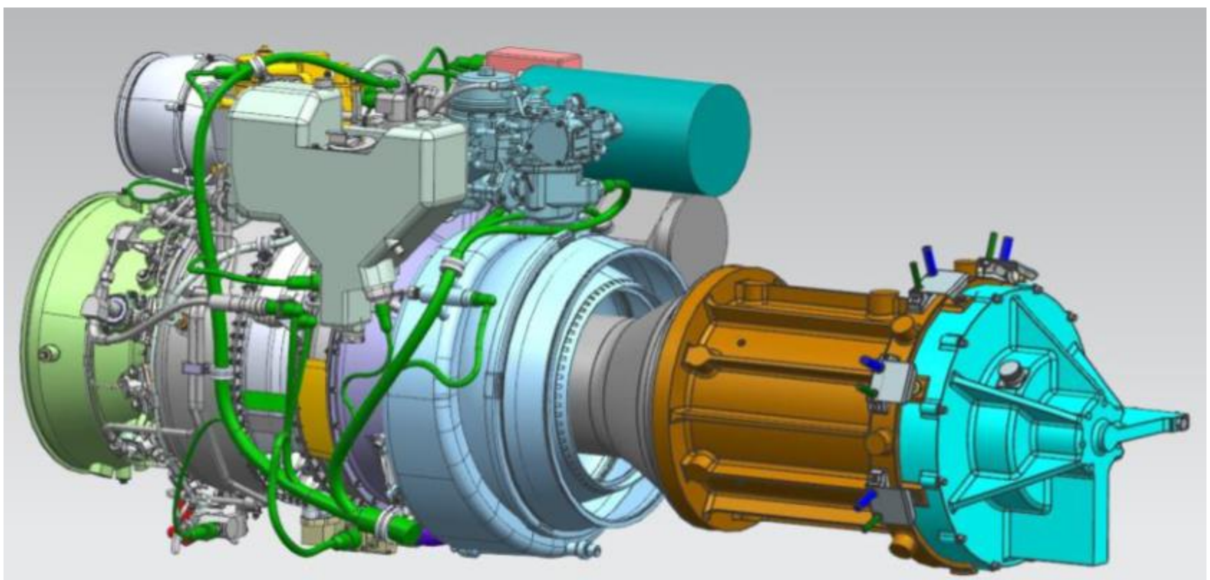
In general, hybrid electric systems fall into two categories, parallel and serial.

Parallel hybrid

This hybrid electric system is characterised by a mechanical connection between the electric motor and the combustion engine, which both add power for propulsion. The majority of hybrid electric cars utilize this design. As the combustion engine and electric motor are mechanically coupled, the electric motor can serve the purpose of being both motor and generator. The battery pack onboard delivers power and can be charged as required. Typically, the electric motor will provide additional power during acceleration and take-off, but may serve as a generator during descent.

Serial hybrid

In contrast to a parallel hybrid system, a serial hybrid system is characterised by a separate combustion engine (piston or turbine) connected to a generator, whose only purpose is to produce electricity for the battery pack. The propeller or ducted fan for propulsion is driven by electric motors only. This configuration allows for a variety of promising propulsion designs, as described in other sections in this study.



A concept design from Honeywell for a 1 MW turbo-generator range extender, based on existing technology. (Credit: Honeywell)

A final point to make in this section is that electricity production onboard an aircraft is of course not a new idea; nearly all aircraft have an APU (Auxiliary Power Unit) to supply electricity. Newer aircraft have systems and actuators that are no longer hydraulic-based and instead run on electricity. For example, the Boeing 787 is the first aircraft with an electrically powered air conditioning system, electrically powered brakes, and an electrically powered de-icing system. Integration of a range extender in a hybrid electric aircraft will be similar to an APU, and therefore be mainly covered by existing regulations and standards, thus easing adoption.

10.4 NEW AERODYNAMIC OPPORTUNITIES

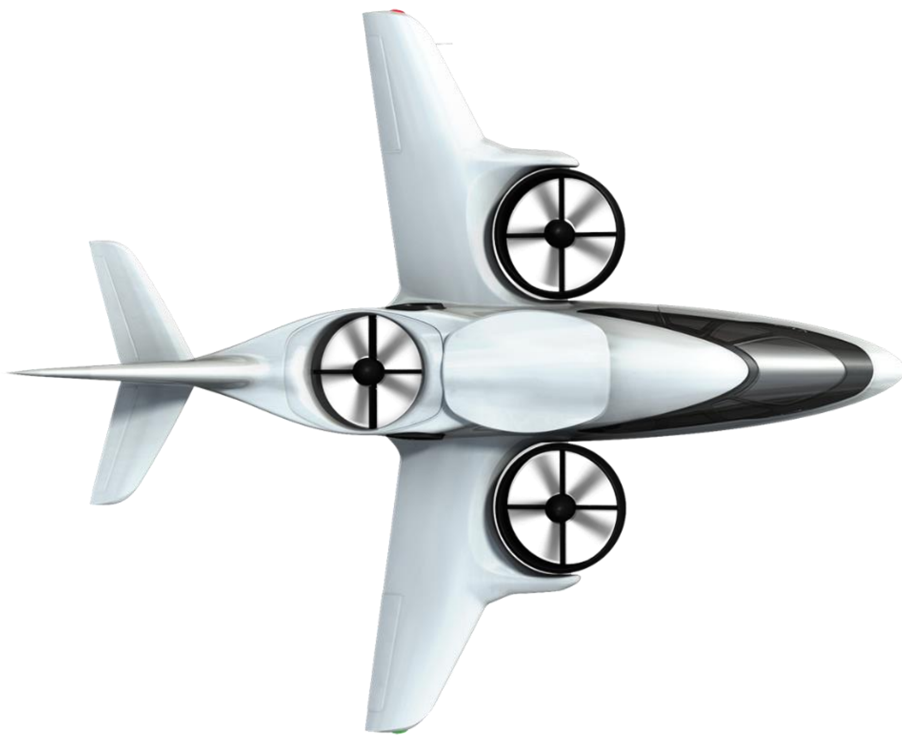
Electric propulsion may allow for entirely new aircraft designs, some already proposed and others that have not even been thought of yet.

For cars, an electric drive train is just another way to propel the wheels; there are no radical changes to the concept of a car's basic shape or design, as such. The situation may be entirely different for aircraft, which is one more reason for the enthusiasm regarding the electrification of aviation. Through a reimagining of the traditional form factors long dictated by combustion engines, electric propulsion may foster disruptive change in aircraft architectures, ushering in not only far more efficient designs than today's, but with aesthetics and consumer-oriented styles.

One especially opportunity-enabling design approach is distributed electric propulsion (DEP), where smaller engines, placed in significant number almost anywhere on a fuselage as desired to gain efficiencies, combine to yield the necessary thrust. A second design concept that electrification could advantageously enable from an aerodynamic perspective is wingtip-mounted propulsion units. Another new direction is Boundary Layer Ingestion (BLI), where the engines are placed directly on the fuselage to reduce efficiency-harming drag.

More details are covered under propulsion systems.

NASA CONCEPT: N3-X Distributed Turboelectric Propulsion System. (Credit: NASA)



XTI aircraft, a 5-seater, hybrid electric VTOL plane utilizing the flexibility granted by electric motor propulsion (Credit: XTI Aircraft)

An example of distributed propulsion with the Aurora unmanned drone, which uses 24 distributed ducted fans and a tilt wing design. (Credit: Aurora)

11. ENERGY CONSUMPTION AND GREEN HOUSE GAS EMISSIONS

With the aviation industry highly focused on emissions and fuel consumption, the specific energy consumption for aircraft has been improving for each new engine generation. The industry's customers are pushing hard as fuel is a large proportion of their expenses in the harshly competitive commercial aviation market. Additionally, politicians and governments are urging the industry to take their part in the overall societal responsibility to reduce global greenhouse gas emissions.

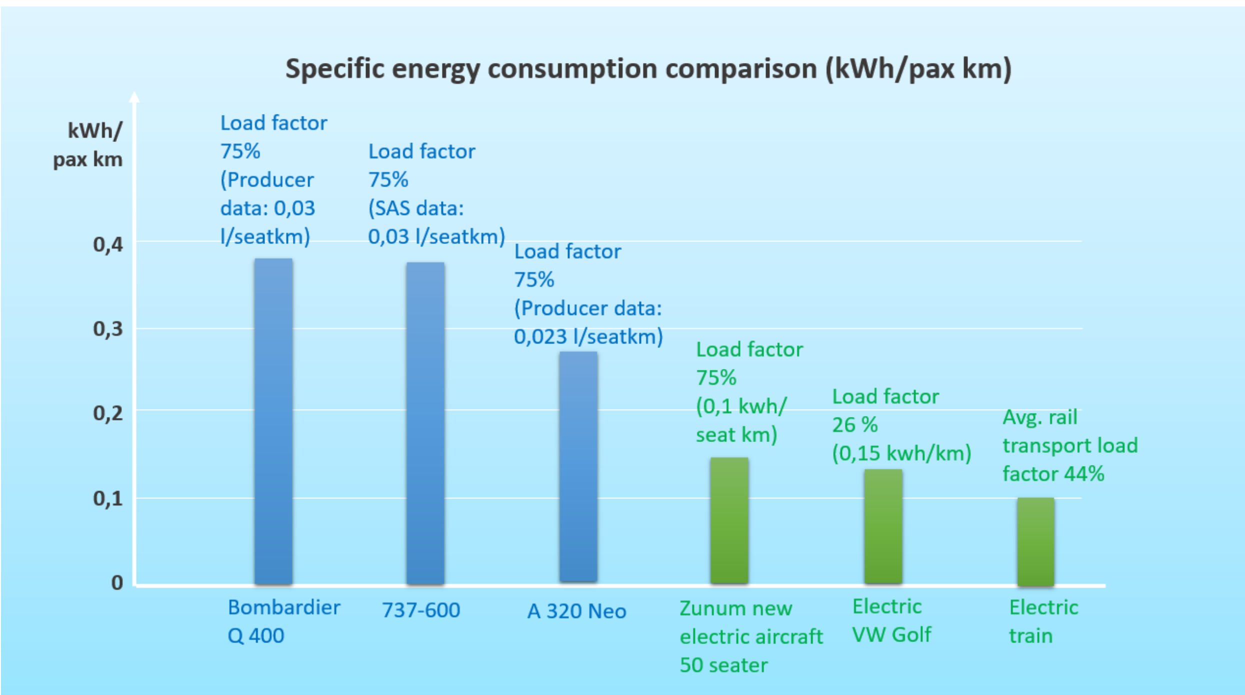
The rapid development of batteries and the race towards electrification in the automotive industry is clearly recognized by the entire aviation community, which is not wasting time and has for several years now been working on designs and solutions to bring about the electrification of aircraft as well.

The advantages are obvious and not very much debated. In general terms, the efficiency of combustion turbine/piston engine is in the range of 20% and up to 40%, depending on aircraft and flight mode. Short regional flights with traditionally designed turboprops are on the lower end, while long haul flights with new modern turbofan engines are on the high end.

Electric motors for propulsion power for aircraft is already understood to be at 85 – 90 % efficiency and may yet be slightly further improved by superconductive materials. An interesting feature of electrification is that the efficiency remains at the same high conversion rate for smaller as well as larger propulsion system and is independent of flight levels. As a result, regional aircraft and short flight routes may become as energy efficient per passenger kilometre as long-haul flights. Electric motors are also more efficient taxi on the ground and during descend in flight compared with turbine engines.

In terms of greenhouse gas emissions, electric aircraft also offer good news. Reduced specific energy consumption means reduced emissions. The use of power from batteries eliminates operational emissions for pure-electric aircraft and reduces emission from hybrid electric aircraft.

The graph below compares specific energy consumption where all numbers are converted to the energy term kilowatt hours (kWh) and the energy is either from jet fuel or electricity.



Specific energy consumption (kWh /passenger (pax) km) for different aircraft and transport modes. Numbers are from producer's information, either from web page or direct information. Numbers for VW Golf are based on assumed energy consumption of 0,15 kWh/km. Numbers for rail are from 2017 High-Speed Rail and Sustainability: Decision-making and the Political Economy of Investment by Blas Luis Pérez Henríquez and Elizabeth Deakin. (Graphics by Green Future AS)

11.1 ENERGY CONSUMPTION AND EMISSIONS OF HYBRID ELECTRIC AIRCRAFT

Reduction of specific energy consumption and emissions for hybrid electric aircraft will depend on how much energy is used from the grid and batteries versus how much is used by the fuel-powered range extender. Even for regional hybrid electric aircraft that do not utilize grid power, however, it is expected that the efficiency of a turbo generator (range extender) at optimal load will outperform traditional turboprop propulsion. Additionally, a serial hybrid aircraft may take advantage of new aircraft designs for even more energy efficiency.

As a consequence, it is expected that a hybrid electric aircraft will outperform today's designs. When regulatory matters are sorted out and certified propulsion systems become available, a relatively rapid transition to new aircraft designs therefore seems likely.

Regional aircraft in the range of 12 – 80 seats are the most straightforward to electrify and may be the most beneficial in the short term. This segment, with operations consisting of short, 30-minute flights, is likely to be operated by hybrid electric aircraft. (Likely very similar to the majority of the operations by Widerøe, the largest regional airline in the Nordic countries.) These aircraft will have cruise speeds in the range of 450 to 700 km/h (280 to 400 mph) where the battery weight will be 25 to 30% of the total take-off weight. For a 50-seater with a take-off weight of just above 20 tons, the battery weight may be 5 tons for a pure electric and slightly lower for a hybrid electric.

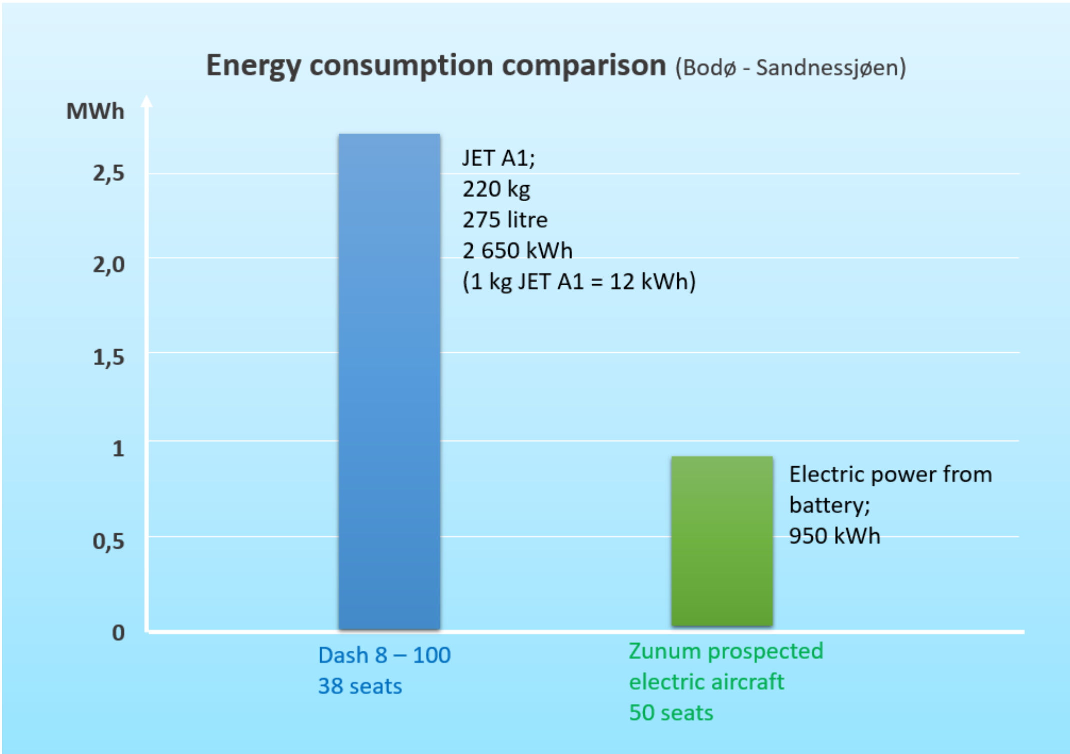
There is limited information available for all the different projects, but what is available is still fairly consistent in the specific energy consumption range of 0,1 – 0,15 kWh / seat km for aircrafts from 9 – 50 seats. It is today difficult to quantify expectations for new aerodynamic features like distributed electric propulsion, boundary layer ingestion, and wing tip propulsion, though those new designs are yet to be developed and have to be tested in aircraft configurations to validate any improvements.

Calculations have been made to understand energy consumption in different modes of the flight like taxiing, take-off, climb, cruise, descent, landing, and taxiing to the gate. For short flights, the electric aircraft has great benefit with regards to reduced energy consumption at trip initiation and taxiing and particularly at descent. An electric aircraft can descend with virtually zero propulsion power and even some regeneration. The energy consumed in the climb is then efficiently used during descent and the specific energy consumption per passenger km for electric aircraft is pretty much the same for short as for long flights.

To illustrate expected performance, comparisons of flights from Bodø to Sandnessjøen have been made. The calculated flight distance is 190 km (slightly longer than the direct line between the two airports). Fuel consumption for a real flight with a Widerøe Dash 8 is 220 kg Jet A-1 represents 2 640 kWh (1 kg Jet A-1 = 12 kWh). Now consider the slightly larger, hybrid electric 50-seater proposed by Zunum Aero, with 12 more seats and a specific consumption of 0,1 kWh/seat km. This latter aircraft will consume 5 kWh per km, so for the 190 km flight, the energy consumption will be 950 kWh.

Looking at the prospected battery capacity for the 50-seater Zunum hybrid electric aircraft, this has a capacity of 1 735 kWh (3 470 kg battery with energy density of 500 Wh/kg) or more with higher battery density. Although designed for hybrid electric propulsion, the aircraft may be operated as a pure-electric with a “sleeping” range extender as reserve. In practical terms, this means that the hybrid electric aircraft can operate by battery only and in the example above, perform the flight without engaging the range extender. The same will be the case for a majority of routes in the PSO network of airfields, where range extenders will be kept as a “sleeping” reserve.

A further reason for this propulsion arrangement being efficient is that the weight of the range extender and fuel is much lighter than the weight of a comparable battery energy reserve. The reserve is of course very important for any passenger flight to be able to divert to an alternative airport or return to base if for some reason it is not possible to land at the intended destination. For short flights, this will be a proportionally large part of the energy reserve, and maybe twice as much energy as is required for the intended flight itself.



Energy consumption comparison between a real Widerøe flight (Dash 8 – 100) and a proposed hybrid electric Zunum 50-seater for a flight from Bodø to Sandnessjøen. (Graphics by Green Future AS)

11.2 REDUCED EMISSIONS

From a Norwegian perspective, it will be possible to operate many regional flights just on pure electricity. Those flights may be done by an electric aircraft with a “sleeping” range extender, while a smaller number of flights may involve the range extender as well. Overall, emissions would be significantly reduced in comparison to using conventional propulsion systems.

The emissions reductions will be based on how much electricity is charged from the grid and how much fuel is consumed. Over the last 5 years, fuel consumption for Norwegian domestic air transport has been in the range of 500 mill liter yearly, corresponding to around 1 200 000 tons of CO_2 emission equivalents. Roughly 15% is related to Widerøe operations, representing 180 tons CO_2 equivalents.

The fuel consumption for inland traffic has reduced slightly since 2014 and may be expected to stabilize or trend downwards for the next decade, as older aircraft are replaced by newer, more energy-efficient models and biofuels become more widely used. From about 2030, the effect of electrification should start to be visible on fuel consumption and emissions, gradually starting the transition to zero emissions related to domestic aviation.

12. ECONOMICS

As stated previously in this study, aircraft with electric propulsion are expected to have lower operational costs, longer maintenance intervals, and lower engine maintenance costs compared to conventional systems. As there are of course no experiences with electric aircraft in significant commercial operation from which to draw upon, these assumptions must be based on experiences involving other products. From such experiences, electric drive systems are clearly preferred in virtually every application where electric power is an available option There is also no doubt that electric motors are both more reliable and, in most cases, require comparatively minimal maintenance. Furthermore, energy/fuel costs are significantly lower with an electric aviation solution.

12.1 ACQUISITION COST

It should be expected that from a materials and manufacturing perspective, electric motors will be less costly than turbine engines. Overall, though, the total drive system with power electronics, cooling systems, and subjection to certification processes may end up not very different cost-wise compared to the systems of today. Working in the wrong direction is the additional weight of batteries, which will proportionally require more propulsion power and structure strength.

It must also be taken into account the significant, up-front research and development work that will have gone into introducing electric aircraft to the market, and that at first will need to be amortised over a relatively limited number of drive systems. The aviation industry does not have the volume advantage of the automotive industry, and aircraft components are much more expensive in comparison to cars.

All things considered, in the short term it should be expected that acquisition costs of electric aircraft will be higher than those of traditional aircraft. That said, when the technology is more mature, the volume is going up, and there is sufficient competition among suppliers, then the price should have the potential to come down.

12.2 AIRCRAFT LIFE

Electric propulsion is not expected to have an influence on the design life of the aircraft, other than there being some indications that less vibration compared to combustion engine craft will reduce airframe fatigue in some sections.

12.3 MAINTENANCE COST

All components for electric aircraft will be designed according to the high safety standards mandated by the relevant regulatory authorities. Given the degree of reliability expected by the market for modern aviation, all components such as the electric motors, power electronics, and cooling systems will need to be produced with high-quality materials and robust designs.

The electric motor does not need a so-called Hot Section Inspection, as is required for popular conventional combustion turboprop engines such as the PT6. It may, however, be expected that components like bearings will need to be replaced during the aircraft's lifetime and damages can occur by foreign particles/objects entering the motor. Since the lifetime of commercial aircrafts is long and electric propulsion is at an early stage the motor may as well be replaced with newer and more efficient technology after a certain time.

Taking advantage of the miniaturisation of modern electronics, the electric aircraft will employ—just as ground vehicles do today—a wide array of sensor systems that will track temperatures, vibration, and other relevant data in real-time to continuously monitor the condition of the motor. Maintenance and replacement of fan blades or propellers will be similar as for today's propulsion systems.

12.4 BATTERY COST

The batteries in commercial aircraft will be frequently replaced, depending on their lifetime. The lithium-ion batteries used for cars today can approximately cycle for 1 000 full-cycle times before their capacity is reduced to 80% of a new battery. (The definition of battery life is when capacity is reduced to 75 to 80% of a new battery.) While 1 000 cycles are sufficient for the lifetime of most cars, a regional commercial aircraft may fly 10 hours every day, and the batteries may have to be replaced two times every year, depending of the size of the battery pack.

To provide a quantitative example, assuming a battery cost of 100 USD/kWh, the hourly battery amortisation cost for this aircraft will be 250 USD/hour. For this reason, the battery systems selected for future electric aircraft are likely to be designed for a lifetime of 5 000 or more cycles.

That being said, the common cost reference USD/kWh is relevant for automotive and other industries, but for aviation, this cost reference has to be compared to battery cycle life to be fully applicable. Assuming a 50-seater aircraft with an average power consumption of 2,5 MW, a battery on board with a capacity of 2,5 MWh and a cycle life of 1 000, it will need to be replaced after 1 000 hours of flight. If the battery's new price is 100 USD/kWh, then the battery cost will be 250 USD/flight hour.

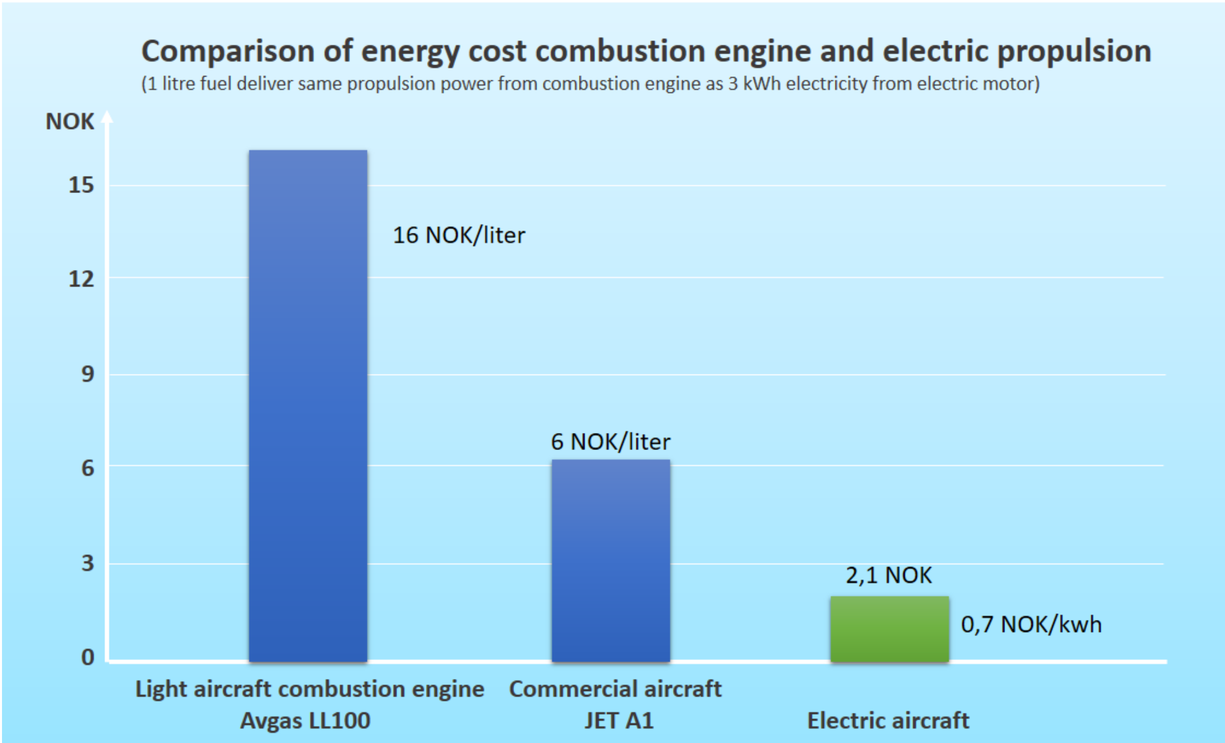
After finishing its service life in an aircraft, the battery is likely to be used in a secondary application, such as a battery bank. It is debated what value the battery will have at this stage, but it is of course likely to be more than zero and the cost for recycling will come at a later stage and be carried out by last user.

12.5 ENERGY COST

A pure electric aircraft will be subject to the grid and electricity costs in its respective market. The energy consumption for a pure electric aircraft can roughly be assumed to be less than one-third that of a conventional aircraft. If an electric aircraft consumes 3 kWh electric power a similar combustion engine aircraft will consume approximately 10 kWh (1 liter fuel) for doing the same job. The reason for this big difference is the high efficiency of electric propulsion compared to a combustion engine.

Let us now run some numbers. Including the CO_2 tax of 1,1 NOK/litre the jet fuel price may be at 6 NOK/litre, the international price is today approximately 2 USD/gallon. Looking at the Avgas 100LL price, this is in the range of 16 NOK/litre. The energy content is similar as for jet fuel. The industrial electricity price in Norway 2017 may be approximately be 0,7 NOK/kwh, including grid cost.

Drawing out a fuller example, light aircraft using expensive Avgas 100LL will benefit from a reduction in energy cost. A one-hour flight consuming 20 litres of fuel at a cost of 320 NOK will in Norway be reduced to less than 60 NOK at today's fuel and electricity costs. Commercial aircraft using the low-taxed Jet A-1 will benefit from a 50% reduction in energy cost.



Comparison based on the conservative assumption that electric propulsion reduces energy consumption to 1/3 of a fossil fuel propulsion system. (Graphics by Green Future AS)

13. ELECTRIC AIRCRAFT DESIGN FOR NORWEGIAN REQUIREMENTS

13.1 SHORT FIELD OPERATIONS

Looking forward, an important infrastructure consideration for aviation in Norway is the current number of short field airports, defined by runways of 800 – 1 199 meters / 2 600 – 3 900 feet. These runways may need to be extended and upgraded to accommodate larger aircraft, which in general require longer runways for optimal operation.

If the development of this network can be limited to below 1 200 meters, this means a significantly lower investment and operation cost. If the runway length is above 1 200 meters, it will be under a much more comprehensive certification regime with a number of additional technical, administrative, and operational requirements.

Today, the Bombardier Dash 8-100, a mainstay of the Norwegian fleet, is operating on routes to these short field airports. In ten years' time, however, those aircraft will have to be replaced, prompting a discussion about whether it may be time to extend runways to provide flexibility for more types of aircraft.

Electric regional aircraft could change this short field airport calculus moving forward, especially given the other advantages already addressed to an extent regarding cost efficiency, low noise, et cetera. The electric aircraft would have the ability to operate on short runways at small airports in Norway, as well as across Europe and the

United States. The current trend, where more and more traffic is centralized to the largest hub airports, may change when new efficient electric aircraft increasingly become available.

Electric propulsion may be more amenable to STOL (Short Take Off and Landing) designs than conventional aircraft propulsion technologies. Electric motors can be designed to provide short power boosts for acceleration and can also be reversed for braking after landing. For fixed wing aircraft, the wing must be designed accordingly to accommodate the desired STOL properties.

For more futuristic designs, such as tilting wing in combination with distributed electric propulsion, covered elsewhere in this study, there are expectations for even more extreme performance. Combinations of Vertical Take Off and Landing (VTOL) and STOL aircraft may become a reality for regional air traffic in the future.

By being an early adopter of electric aviation, Norway would be well-positioned to influence the design of electric aircraft to be suitable for operation on the Norwegian short field network of airports, as well as be prepared and engineered for the harsh climatic conditions in Northern Europe.

Røst airport and its 800-meter runway. (Credit: Ørjan Arntsen)

13.2 ELECTRIC AIRCRAFT AND NOISE

As described previously in this study, there are great expectations for noise reduction via the introduction of electric propulsion. Besides reducing air pollution, there also is a great desire to reduce noise “pollution” from aircraft. The noise created from today’s air transport limits the locations of airports and their hours of operation. At the very least, the noise from combustion engine aircraft is annoying, but the disruption and agitation the noise causes, especially if repeatedly occurring throughout the day, could pose a health hazard for neighbours of the airport. Noise reduction is therefore a high-priority parameter in any new engine designs.

For Light-Sport Aircraft activities and thousands of small airfields, electric propulsion thus comes as very good news. Noise from the first electric aircraft is not only reduced, but in many scenarios nearly eliminated. The dominant exhaust noise from piston engines is gone, and with proper propeller design, the noise from electric aircraft should be minimally disruptive.

The dramatic reduction of noise would enable the operating of airports for regional aircraft close to or from within local communities, or even inside densely populated cities. The elimination of turbine engines on turboprop regional aircraft should provide for noise reduction, with even more reduction anticipated from new, low-pressure ducted fan with electric motors.

Bodø airport, which is within walking distance from the city center. (Credit: Tom Melby)

13.3 AIRCRAFT SIZE

It is likely that the first regional electric aircraft on the market around 2025 will be limited to a seating capacity of 9 to 19 passengers. Those aircraft will be mainly directed towards a market for short, on-demand or taxi flights, but may be equipped for scheduled traffic as well. Some evaluation has been made regarding if 19-seaters may work as an alternative for some of the routes on the short airfield network, and it is not unlikely that aircraft of this size can be used for many flights in combination with some larger aircraft. In the morning and evening, some destinations will need flights to serve more than 20 passengers at a time, but for many other destinations and times of day, 19-seaters should be sufficient.

13.4 COST RELATED TO INTRODUCTION

An immediate reduction of CO_2 emissions and direct energy cost will be available from day one with electric aircraft, but the potential for reduced overall operation cost may not be available before the technologies are established and more mature. It should also be expected that there will be slightly higher acquisition costs compared to a similar combustion engine aircraft, but the aircraft manufacturer may cover this premium in order to be competitive.

In addition to aircraft related cost there may be additional administrative costs, training of personnel, infrastructure, et cetera.

There is today limited information available to do any quantification of cost other than related to energy consumption.

13.5 REQUIREMENTS FOR INFRASTRUCTURE

ELECTRICITY

The transition to electric propulsion in the transport sector will change the requirements for the supply of electricity on the distribution grid. In the big picture, the total electricity consumption in Norway is nearly 150 TWh, and the energy consumption for all inland air transport is in the range of 5 TWh (corresponding to 500 mill litre Jet A-1 fuel). It should be noted that the total amount of energy needed for comparable number of flights and distances covered as at present would be lower because electric power conversion is more efficient than conversion from fossil fuels.

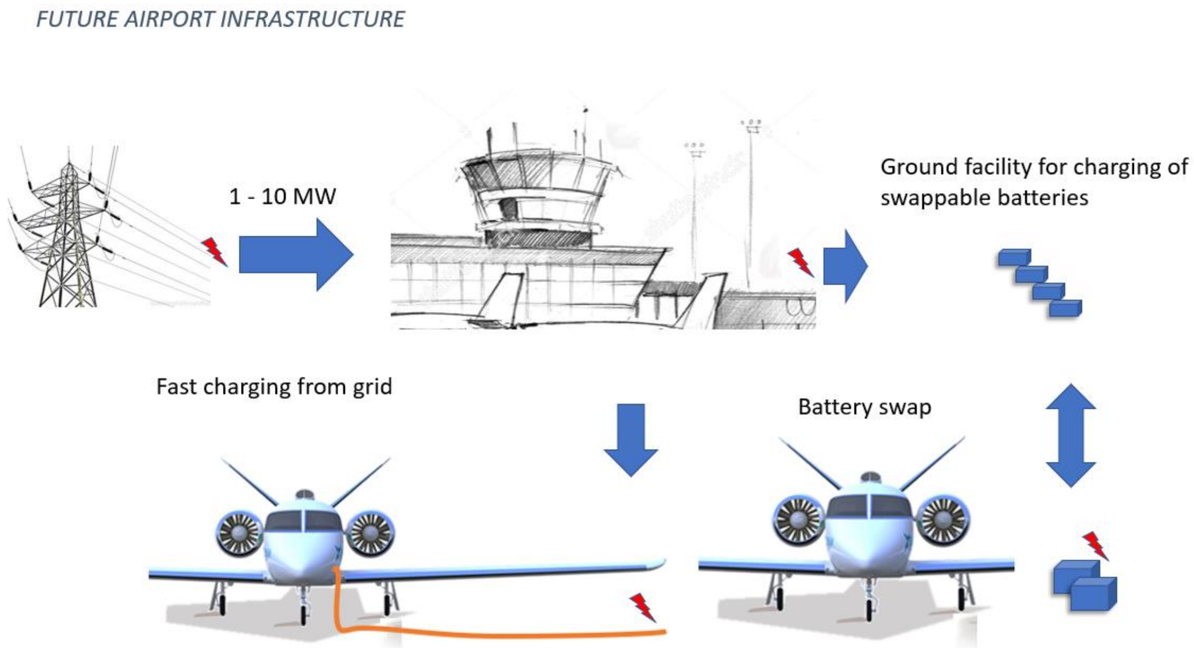
Statnett, the state-owned system operator for the Norwegian electric grid system, considers that the electrification of aviation would have a limited influence on the national supply and transmission grid. But Statnett does confirm that it will be necessary to invest in local grids in order to ensure sufficient supply to the different airport locations.

To take an example: Trondheim airport has a yearly fuel sale in the range of 60 mill litre jet fuel (600 GWh energy). If 20% of the fuel sale were exchanged with an electric power supply to electric aircraft, the airport will need an average continuous power supply of approximately 5 MW.

Delving deeper, a 50-seater regional aircraft with a battery of 3,5 MW may require an instant power of 10 MW for fast charging. For each airport, then, it must be taken into account if this amount of power can be made available directly from the grid, or if a battery bank would have to be installed. If the aircraft were using a battery swap system instead, this setup would reduce the required level of instant grid power because the battery charging can be done over a longer time interval.

A similar challenge is recognized for the Norwegian car ferries that are already in commercial service. In the case of some of the ferry operators, the charging power of 2 to 3 MW is drawn directly from the grid, while others are using battery banks where sufficient power is not easily available.

Based on the assumptions above, the requirement for grid power for electric aviation per airport is likely to be in the range of 1 to 10 MW.



Airport infrastructure and charging options. (Illustration: Green Future AS)

OTHER INFRASTRUCTURE

If electric aircraft are equipped with systems for battery swapping, this will require an in-house charging facility as well as transport/lifting equipment to move batteries around. For fast charging, there may be special equipment needed to establish safe connections between the aircraft and the charge-supplying infrastructure, again handled by trained, dedicated personnel. A battery bank would likewise require bespoke infrastructure. In all cases, trained, dedicated personnel will be required for operating this equipment.

13.6 FIRST IMPLEMENTATION OF ELECTRIC AIRCRAFT IN NORWAY

A few airports within a short distance of each other should be selected and infrastructure prepared for the first implementation of electric commercial aviation operation. The Civil Aviation Authority of Norway (Luftfartstilsynet) should be engaged as early as possible to be involved together with the aircraft manufacturer, operator, and airport owner Avinor.

The arrival of the first electric aircraft, the Alpha Electro from Pipistrel, already this spring will be very useful for the various relevant personnel to acquire a basic understanding of electric aircraft operation, charging, and maintenance. Even though the Alpha Electro is a small aircraft, it is fully equipped for professional pilot training and features remote monitoring of all data related to power consumption and charging. The aircraft represents a promising first step into the future of aviation in Norway, as well as the rest of the world.

For commercial operation of the Norwegian short airfield network, there are more than 20 destinations/routes with distances ranging from 38 – 170 km, all of which can easily be flown by pure-electric propulsion. The first electric aircraft to operate this network may be configured as hybrid electric but be operated by electric power only as airports will have charging capability available. For a few destinations, the aircraft can continue to the next airport or return to its origin without charging and still fly electric as again the distances are fairly short. With the flexibility of the hybrid electric aircraft, the implementation can be made step-by-step to reduce the risk of irregularities during the introduction phase.

13.7 DAILY OPERATION AND CHARGING

In collaboration with Avinor and based on information from Widerøe, several daily flight programs for individual aircraft have been examined in order to understand the requirements for such an operation. Some of the aircraft have a day program of up to nearly 12 hours block time and more than 20 flights. The shortest scheduled turnaround time is down to 15 minutes.

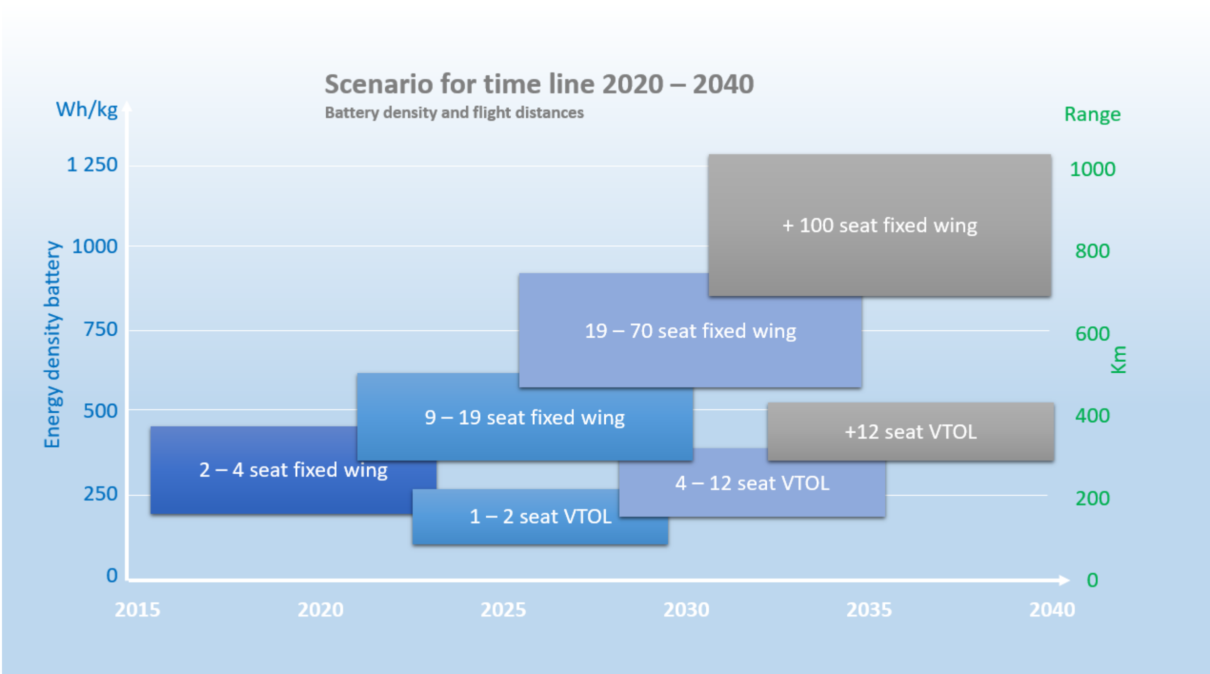
It will be important to establish goals for performance criteria for new electric aircraft and infrastructure at a similar level. The bottleneck is the available time for charging a battery or performing a battery swap, but these solutions should be achievable both from a technical and a temporal perspective.

14. TIMELINE

During the work on this study, different scenarios of timelines have been indicated by the various research papers and organizations involved with electrification. For startups, it is important to move fast in order to commercialize and get income as soon as possible. For the established aviation industry, it is instead more a balance of not moving too fast while testing new solutions thoroughly, yet also not moving too slowly and being left behind the competition and overtaken by newcomers. As seen from the example of the automotive industry and Tesla, it is possible for newcomers to take a lead even in established industries.

Over the last year it has become clearer that the entire aviation industry is serious in its efforts at electrification and to address the strong political demand to shift into less-polluting means of air transport.
An increasing number of projects and activities have started and are backed by serious funding. As noted previously in this study, it should be expected that more announcements like the Airbus, Siemens, and Rolls Royce collaboration to develop electric propulsion for aircraft will soon be made.

Certification does remain a critical factor moving forward. But seeing as those companies and individuals with top expertise in aircraft engineering, together with approval authorities, all have the same goal of safe and emission-free flight, this high-priority electrification work should make tremendous strides in the near future.



Scenario for development of electric aircraft with reference to battery density and comparable range. (Credit: Green Future AS)

15. RISK

This study has solely focused on the opportunities provided by the electrification of aviation. There are several risks associated with this development, which may affect the timeline, cost and efficiency. Mainly the risk is connected to either technical and financial risk, but there are is also political risk associated with changing priorities.

Technical and compliance risk
For different reasons, there can be delays caused by slower progress in battery development than anticipated today. Systems may not achieve the expected performance and be less efficient than anticipated. There may be technical challenges making it difficult to reach the necessary redundancy and safety level required from certification standards.

Financial risk
Startups do not get the necessary funding, or in larger organizations, investment programs may be stopped. Development may become more expensive, components more expensive, and operation more expensive.

Political risk
There is today a strong political drive towards renewable energy and reduced emission with strong initiatives benefitting the environment. The development of electric aviation will depend on a continued political drive in this direction.

16. FURTHER WORK

It will be important to continue the dialogue with the aircraft manufacturers and potential aircraft operators to maintain a focus on important specifications and performance metrics in order for new aircrafts to be able to operate on the Norwegian short airfield network.

Statnett and regional electric grid operators should also be made aware of the expected requirements for electric supply to the different airports to make sure that this is considered in their future plans.

A test and introduction plan for the first electric aircraft arriving this year should be established. Even if this introduction cannot be compared with the introduction of passenger aircraft, there are valuable experiences to be gained and familiarization that will be useful for all involved parties regarding future electrification.