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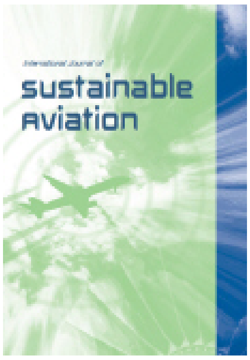

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Challenges with the electrification of aircraft for a sustainable and greener aviation

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Challenges with the electrification of aircraft for a sustainable and greener aviation

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Abstract: Electric aircraft is a promising technological development in the aviation industry, and it will help reduce greenhouse gas emissions and fuel costs while increasing the efficiency of aircraft. There are also some challenges with electric aircraft, as in every new technology. These are storage technology, electric propulsion system comprising electric machine and power electronics converters, protection devices, wiring, thermal management of components, certification, and system/component integration. Electrification is once started with more electric aircraft, and ongoing research and development projects will light the way for the fully electric aircraft era in the future. This paper highlights the challenges of aircraft electrification and presents the current situation on electrification.

Keywords: electrification; sustainable aviation; electric aircraft; aviation; technological challenges.

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1 Introduction

Electrification of the aircraft is an important issue in searching for sustainable and greener aviation. Greenhouse gases (GHG) emission reduction, cost reduction, noise reduction are major advantages of electrification aircraft. Electrification is a rising issue thanks to new technological developments. The aviation sector is also affected by electrification, and the more electric aircraft (MEA) concept is introduced. The most known examples of electric aircraft are Airbus A380 and Boeing B787. Hydraulic, pneumatic, and mechanical systems in conventional aircraft are replaced with electrical ones in MEA. For instance, the pneumatic wing ice protection system of B787 is turned into an electro-thermal ice protection system (Sinnett, 2007). Besides, engine starting and environmental control systems are also replaced with electrical architecture and all these replacements reduce 20% CO_2 and fuel. Furthermore, reduction in noise and NOX are obtained as 60% and 28%, respectively.

Hybrid-electric aircraft (HEA) is another concept of electrification, and it defines an electric aircraft with two power sources: battery and fuel. HEA presents flexibility in operation and configuration that makes it advantageous over conventional aircraft because of parallel redundancy. Besides MEA and HEA concepts, there is a fully electrified version of aircraft: all-electric aircraft (AEA). AEA is an aircraft with a battery as its sole propulsion power source.

Although these electrification concepts of aircraft present efficient and sustainable aviation, there are several challenges for electric aircraft. For example, power storage is a major challenge in AEA. Charging the aircraft battery will require charging stations in the airport. The closeness to the electric power grid or distributed generation units for an airport will be important for flight schedules. Dwell time of aircraft while charging the battery will be another limiting factor for aviation firms. Electrification of traditional components of an aircraft reduces the weight and fuel cost and increases the aircraft efficiency, but the cost of these improvements is the increasing complexity.

This work presents a survey on the challenges of electrification of aircraft and identifies the requirements for a reliable and safe flight experience in sustainable aviation.

2 Environmental impact of aviation industry

Aviation shares 12% of CO_2 emissions in transportation and 2.1% of overall human-made CO_2 emissions (Carbon Dioxide Information Analysis Center, 2016). According to a study, although passenger operations around the world become more fuel-efficient, this change is not adequate to keep up with the growth of aviation traffic. When the change between the years 2013 and 2019 is compared, CO_2 emissions of commercial aviation have increased by a third (Graver et al., 2020).

Water vapour and contrail are the other environmental problems related to aircraft. Noise is also an issue of aviation, and it also affects the quality of human life. The carbon footprint of aviation will be reduced by new technological developments and efforts of aviation regulators. For instance, Advisory Council for Aviation Research and Innovation (ACARE, 2018) set goals for emission reduction. According to the IATA (2021a), the aviation sector may reach emission goals with four approaches: sustainable aviation fuels (SAF), land/air traffic operations, technology, and carbon offset.

SAF from biological or waste-derived resources is seen as one of the solutions for greener aviation. SAF has the potential for emission reduction of up to 80% compared to kerosene. SAF can be blended with jet fuel without any adjustment need of the fuelling infrastructure of aircraft. Even though the combustion of conventional jet fuel and SAF produce nearly the same CO_2 emissions, remarkable emission reductions may be provided during the production of SAF. However, there are concerns about biological fuels that may affect the food supply as some of their sources are oilseeds and corn grains.

In a study conducted by Barke et al. (2022), different types of SAF are compared with fossil kerosene, and it is seen that although the environmental impacts of the SAFs are lower than kerosene, they are not competitive economically. Moreover, SAFs are advantageous in reducing health-damaging and climate-damaging emissions, especially. However, the agricultural land occupation (ALO) value, one of the environmental impact categories, is higher than conventional fuel's value. The study explains this result by the conversion of fossil fuels to electricity to produce biofuel and the land need for feedstock cultivation for biokerosene. A study conducted by Buchspies and Kaltschmitt (2018) has shown that there is a strong dependence on the sustainable feedstock supply and environmentally friendly biokerosene. Feedstock cultivation and inappropriate land-use affect water and soil (by erosion, leaching of nutrients, and agrochemicals). Also, from a socio-economic aspect, biofuels affect food prices, and there are issues with the volatility of food prices because of the existing biofuel policy.

In addition, SAFs are currently more expensive than jet fuels as the SAF production facilities are small and not on a greater scale as wanted. The increasing investment in SAFs will bring down the cost of SAFs (Hileman and Stratton, 2014). As a result, alternative fuel technologies seem promising for sustainable aviation and CO_2 emission reduction, but everything for SAF, from production to usage in the aviation sector, should be considered and evaluated carefully.

Land and air traffic operations are also effective in reducing GHG emissions. Reduction of the traffic for take-offs and landings will decrease the emissions. A continuous descent to the airport is also a possible solution for air traffic.

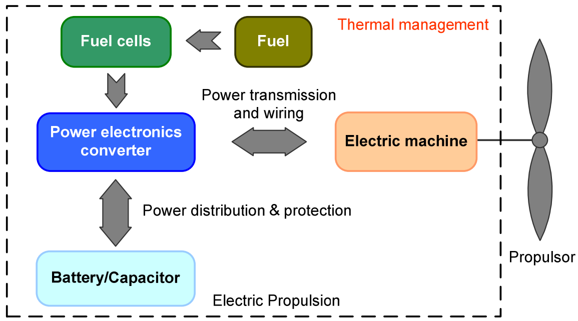
Carbon offsetting is an action to compensate the GHG emissions with equivalent GHG savings. Offsetting is a temporary solution to deal with the emission problem, and it gains time to investments in technological developments like aerodynamic-based improved aircraft designs.

Intention to curb emissions, noise, and flight costs related to aircraft brings a new technological development: electric aircraft. Electric aircraft is a promising technology to reduce GHG emissions and increase flight efficiency. Transitioning electric aircraft from conventional aircraft is immature for commercial flight levels, but developments bring hope for a greener and sustainable aviation experience.

3 Challenges on electrified aircraft

Electrification of aircraft curbs emission, maintenance and fuel cost, aircraft weight and gains importance with developing technology in the aviation industry. Cutting-edge technology is used for the electrification of aircraft, and there are research and development (R&D) studies on electric aircraft that are promising for the near future of zero-emission flights. The basic components of an aircraft propulsion architecture are seen in Figure 1. In this architecture, every component has challenges on its own characteristics and integration with the other components.

Figure 1 Components of electric propulsion of an aircraft (see online version for colours)



Electrification has benefits on environment and economical; however, it increases the complexity in aircraft's power train. Maintaining a high-power source and integrating different systems and components brings difficulty in electric aircraft. Many challenges come across in electric aircraft, summarised in this paper.

3.1 Energy storage systems

Energy storage is the main limiting factor in electric aircraft as the power need changes between 2–5 MW levels. This power need must be met and ready to use reliably and safely when it demands. Several energy storage technologies include batteries, capacitors, fuel cells, and flywheels.

3.1.1 Capacitors

Capacitors, especially supercapacitors, can be used for energy storage. Capacitors are light among the storage systems compared to the weight, but they have short storage capability, which is inadequate to meet high power demand. Fast charging/discharging characteristics of capacitors make them suitable for short power needs. Furthermore, supercapacitor as the only source of the powertrain is not possible with current technology. Airbus A380 has supercapacitors for regular operation (also in the case of emergency) of doors.

3.1.2 Batteries

Batteries are the most prevalent technology in aircraft. Lead-acid (Pb-acid), nickel-metal-hydride (NiMH), and nickel-cadmium (NiCd) batteries are used in general aviation and larger aircraft. Especially, NiCd batteries have a longer lifetime and present durable and safe operation. Lithium-ion batteries are used in aircraft thanks to their higher energy density than Pb-acid and NiCd batteries. However, a case reported on Li-ion batteries raised safety concerns (National Transportation Safety Board, 2013).

The energy density of commercially available Li-ion batteries is in the neighbourhood of 260 Wh/kg at the cell level. Researchers in battery technology have continually searched for new technologies and materials to reach higher energy densities. The battery technologies with the highest energy density at the R&D level have been announced by Sion Power (2020) with 400 Wh/kg and Oxis Energy (2020) with 471 kW/kg (number represents the power densities in cell level). Recently, Amprius Technologies (2022) announced the shipment of the first commercially available 450 Wh/kg Li-ion cells to a new generation of high-altitude pseudo satellites (HAPS) project.

High theoretical energy densities of new battery technologies look promising for the energy storage problem, but practical energy densities due to physical constraints are so far from building battery-powered commercial aircraft. The major conundrum of the batteries that limits the use of batteries for commercial aviation is their weights. Batteries are much heavier than liquid fuel, and they constitute a constant weight in the aircraft, unlike liquid fuel whose weight is reduced as it is burned during flight.

A study compares the efficiency of electrical and conventional propulsion systems, and it is seen that usable energy contained in a kg of kerosene is equivalent to about 10–14 kg of batteries (Rohacs and Rohacs, 2019). Therefore batteries' weight and long charging period limit their usage on commercial and long-haul flights. Long charging periods will affect the flight schedules and availability of aircraft. Charge stations are necessary for the airport, and investment in the available power grid is required to meet power demand.

A battery management system (BMS) is required to monitor the operating condition of batteries. If the batteries go out of the safe operation frame (operating over voltage and temperature limits, overcharging, and over-discharging), the possibility of catastrophic failure increases. Because BMS prevents overcharging, over-discharging, and operating beyond the minimum and maximum temperature levels, BMS is an essential part of the battery-powered systems. Though the protection systems for batteries, there is still a risk of igniting and even explosion of batteries (Williard et al., 2013).

3.1.3 Fuel cells

Fuel cells are used for electricity generation from hydrogen through an electrochemical reaction. The fuel cell does not have any moving parts, so they do not need maintenance. Also, it is a silent and clean power storage technology due to no pollutants included. Hydrogen fuel cells encourage the zero-carbon energy strategy and reduce aviation's carbon footprint. The fuel cell's operation cost is lower than battery cycling and renewal cost. However, the obstacle of fuel cells is the high investment cost for hydrogen fuelling infrastructure. The fuel cell has a limitation on onboard storage (due to the flammability of hydrogen), and it requires storing facilities in the airport. Apart from storage, transportation of hydrogen also brings additional costs.

Researchers have studied lifecycle assessment (LCA) of hydrogen production, and it is seen that hydrogen production also affects the climate impact (Bhandari et al., 2014; Boyano et al., 2011; Dincer and Acar, 2016; Dufour et al., 2009; Koroneos et al., 2004). It may not be true to say that the LCA of hydrogen is small compared to other energy sources. For example, a study of environmental impact comparison between the water electrolysis using renewable energy (solar photovoltaic, wind, hydropower, and solar thermal) and steam methane reforming shows that solar photovoltaic electrolysis has the highest environmental effects (Al-Qahtani et al., 2021). The photovoltaic panel production stage explains this result. Hence the possible solutions to overcome this problem are using lower emission impact material for panels or reducing the required materials of the PV panel.

Hydrogen production technologies are water electrolysis, coal gasification, methane pyrolysis, and steam methane reforming. Production of hydrogen is not an easy task, and each production technology has economic, technological [technology readiness levels (TRL)], and environmental challenges. Recently, a colour palette that considers the production process and energy source has been used to refer to the cleanness level of hydrogen production (Osman et al., 2022). The colour spectrum and hydrogen production technologies are summarised in Figure 2. Hydrogen production shares are about 48% from natural gas, 30% from crude oil products, and 18% from coal, respectively (Staffell et al., 2019). Water electrolysis, the low carbon producing way, currently accounts for only 4% of global hydrogen production. According to a report of IEA, emission from global hydrogen production is 830 MtCO2/yr, which corresponds to the sum of the annual CO2 emissions of the UK and Indonesia (International Energy Agency, 2019).

Figure 2 Colour spectrum of hydrogen (see online version for colours)

Source: GEI (2021)

Thus far, the carbon footprint of hydrogen production is mainly described. However, hydrogen also has some stages, such as compression, transportation, and conversion to electricity using a fuel cell to use it as the fuel.

Under atmospheric conditions, the hydrogen has low energy density, so transmission over long distances or local distribution is difficult. In order to store or transport hydrogen, it must be liquefied or compressed. The liquefication process needs more energy than compression, and the carbon intensity of liquefication may be higher because of the electricity source used for this process. Transportation and distribution of the hydrogen need infrastructure; however, existing pipelines for natural gas may be used for these processes. The hydrogen may be blended with the natural gas, and then it may separate for usage. As the blend limits (up to about 15% hydrogen) depend on the condition of available pipeline material and the design, pipeline transport for hydrogen may not be suitable for large-scale hydrogen needs (Melaina et al., 2013). A truck or rail is also a way for liquefied or compressed hydrogen transportation. However, the carbon footprint of this transportation way is higher than pipelines.

As a result, it is seen that the hydrogen production process is not easy, and there are some challenges in the stages of compression/liquefication, transportation, and conversion to electricity after the production. When the overall carbon footprint of the hydrogen lifecycle is considered, the effect of the hydrogen may not be as small as thought. Carbon emission related to these stages is also challenging for greener energy source production. When the challenges concerned about cost-effective production methods, transportation, safety issue, and hydrogen infrastructure are overcome, green hydrogen has the potential to curb carbon footprint.

3.1.4 Flywheels

Flywheel is the oldest mechanical energy storage technology, and it stores and releases power quickly. Although flywheel has a high specific power density, it stores power very limited time duration.

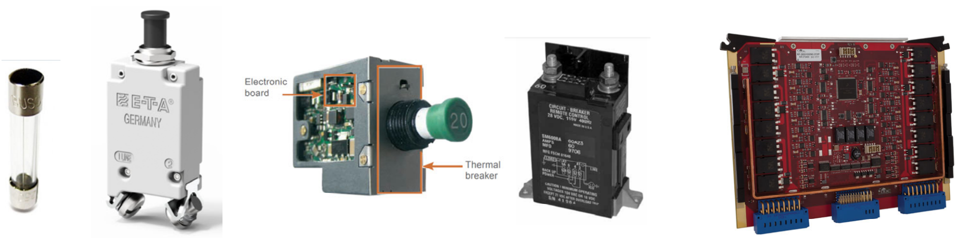
As the technological revolutions continue, storage technologies will meet high power needs. Current energy storage technologies are inadequate to meet the MW-level power need of long-haul commercial flights, but they are used for short-haul flights and small aircraft. Advancement in storage technologies will increase the flight distance in the future.

3.2 Circuit protection devices (CPD)

CPD are the key components of the systems to maintain safe operation. CPDs are essential for flight safety and used for the cables and components protection in aircraft power distribution systems (PDS). In the case of a fault (overloading and short circuit) in a system, electrical insulation is ensured by CPDs (Izquierdo et al., 2011). Fuse, circuit breaker (CB), arc fault circuit breaker (AFCB), remote-controlled CB (RCCB), and solid-state power controller (SSPC) are the onboard CPDs. These CPDs are seen in Figure 3.

Fuse is widely used electronics equipment, and it is low-weighted. Fuse has a sensitive structure to ambient temperature variations, and this behaviour limits the usage of the fuse. CB is an electro-mechanical CPD, and when a fault emerges in the system, CB disconnects the electrical power flow. AFCB is a type of CB; however, it also protects against arc fault. CB shows poor performance at the high DC voltage and is not suitable for the DC bus of PDS. CB and AFCB are not remote-controlled, and monitoring these CPSs needs monitoring units that increase the complexity. RCCB is another type of CB, and it is a combination of relay and CB. RCCB has remote control from the flight deck with its electronics circuits, unlike CB and AFCB. However, as RCCB is a type of CB, it also has problems with DC voltage like CB. A new electronic CB technology is introduced to solve described issues about CB: SSPC. SSPC is a semiconductor devices-based (MOSFET or IGBT) CPD that controls the power supplied from a secondary power distribution bus to a load. The advantages of SSPC are reliable switching, fast fault detection, and reduction of the length/size of the wiring. Expectations from a CPD are wiring reduction, low weight/volume, robustness, and low complexity. Among all CPDs described above, SSPC is the most suitable technology for aircraft.

Figure 3 CPD, (a) fuse, (b) circuit breaker (ETA, 2021), (c) arc fault circuit breaker (Crouzet, 2021), (d) remote-controlled circuit breaker (Safran Electrical & Power, 2021), (e) solid-state power controller (Data Device Corporation, 2021) (see online version for colours)



(a) (b) (c) (d) (e)

3.3 Power electronic converters

Electric aircraft have multi-level voltage and frequencies such as 115 VAC/400 Hz, 230 VAC/360–800 Hz, 270 VDC, and 28 VDC. Besides the existing voltage levels given above, there are R&D researches on boosting voltage level for EPS of aircraft and defining voltage regulation standards for new voltage levels. In a research conducted by (Jansen et al., 2016) for STARC-ABL power system (continuous power rating of thruster fan's motor is 3,500 hp~2.61 MW), it is seen that the variation in the voltage level from 600 V to 4,800 V has a potential to reduce total system weight by nearly 1,400 kg. However, the results are given with the negligence of the insulation thickness of cables in the study.

Although the high voltage system has the benefit of weight reduction in the power propulsion system, it also needs insulation materials with high dielectric strength. According to Paschen's law, the voltage level must be under 327 VDC so that the system does not encounter a breakdown in an air gap (Cotton et al., 2008). When the insulation issues are considered carefully including harsh operation conditions of an aircraft, operating at higher voltage levels may be getable for future aircraft systems. As for different voltage levels considered for the EPS studies, some of them are 1 kV (Jansen et al., 2016; Stückl et al., 2012), 2 kV (Barzkar and Ghassemi, 2020), 3 kV (Pornet et al., 2015; Schefer et al., 2020), 4.5 kV (Armstrong et al., 2014) and N3-X design project of NASA with 6 kV voltage level (Gemin et al., 2015). Although adaptation to the high voltage level is not possible in the near future, R&D research on both academic and industrial sides is ongoing.

Converting power to different types of equipment and systems is realised with power electronics converters (PEC). Types of the PECs are DC/DC (buck and boost), DC/AC (inverter), AC/AC (autotransformer), and AC/DC (rectifier). For example, motor drivers are used for variable speed operation, and PECs are the key components in driver technology. To maintain stable and safe power conversion, NASA has proposed efficiency and specific power density requirement for PECs. According to NASA, goals for the efficiency and power density of a PEC are 99% and 19 kW/kg with non-cryogenic cooling and > 99% and 26 kW/kg with cryogenic cooling, respectively.

There are challenges in PEC designs which are summarised in this section. Increasing complexity is a major issue in electrification. Integration with different systems such as power storage systems and electric machines is challenging for PECs. PEC must respond to the other systems' variable and immediate power needs. Failure in any power device of PEC will be catastrophic as the PECs are at the integration of various systems. Proper selection of topology and power devices is required for reliable PEC design. Therefore, wide bandgap (WBG) devices such as SiC, GaN are used for the high power demands of PECs. WBG devices have endurability to high temperatures and high-frequency switching capability. Different multi-level topologies and switch control methods help to increase the efficiency/power density of the PEC and meet the high power demands of electric propulsion. Higher power density and efficiency are obtained with high-frequency switching, but the cost of this approach is electromagnetic interference (EMI). EMI affects the systems and may abrupt the stable operation of systems. Effects of the EMI are hazardous, and it is a challenging issue in aviation electronics. EMI filter is required to overcome EMI, and it constitutes a great portion (~25%–40%) of PEC. As the EMI filter is also a weight contributor, the EMI filter will decrease the converter's power density. PEC designers must consider EMI and electromagnetic compliance (EMC) standards for their equipment. There are standards for EMC at the device and system level to maintain a stable and reliable operating environment for aviation.

Thermal management (TM) in PEC is also an issue to pay attention to in the electrification of aircraft. PECs convert high power to different forms and levels, and semiconductors technology (such as Si, SiC, and GaN) used in PEC have specific thermal operating conditions. To remove excess heat from the PEC is necessary for proper operation. Air cooling, liquid or spray-based cooling, active cooling using heat pumps, and passive heat sinks are cooling approaches. For effective cooling of PECs, the cooling approach must be light and compact.

3.4 Wiring

Wiring is an important issue in aircraft, and proper wiring must have the endurance to harsh conditions during the flight. As seen in Section 2.3, conventional voltage levels used in the current EPS of aircraft (A380, B787, etc.) are relatively low. As the power needs increase, voltage levels increment is necessary to reduce conductor size. When the existing voltage levels are used in EPS, large-diameter Cu cables are needed due to the high power need of the power transmission system of aircraft.

Insulation materials of cables are important for reliable and safe flight. Increased power transmission requirement paves the way for new technologies in the wiring: carbon nanotubes and superconducting materials. These are promising technologies to increase the efficiency of wiring.

Wiring is the vessel of the aircraft and integrates different components and systems. Cumulative wire length of aircraft continuously increasing and may reach 500 km for civil planes like A380. Increasing length brings complexity problems as critical aircraft parts are connected with wiring. Any disconnection in wiring will bring irremediable cases.

The wiring may degrade with vibration, moisture, maintenance, heat, and installation. A high vibrating environment can cause to loss of connection between the wire and contacts over time. Also, vibrating can damage the isolation due to the cracking in the wire's insulation. Moisture increases the corrosion of wiring terminals, and high moisture areas degrade the wiring lifetime. Improper maintenance may damage the wiring, and there are procedures and standards for maintenance to meet minimum airworthiness. Scheduled maintenance is necessary for a safe flight, but it must be done carefully to not to damage wiring. Wiring exposed to high heat will be cracked and degrade, especially direct contact with heat damage insulation of wiring. The installation may also accelerate the degradation of wiring; for example, improper clamping, termination, and routing can damage the wiring. Incorrect wiring and connection between the systems can also cause EMI problems, and abnormal operation conditions will be emerged due to the EMI. According to research, 90% of the reasons for performance decrease in the systems and equipment arises from the coupling between the wires, which are the source of EMI.

3.5 Electric machines

Electric machines are lighter than conventional combustion engines, do not produce emissions, and do not need maintenance. The size of electric machines is advantageous, and they are silent compared to combustion engines. Desires from an electric machine design are high efficiency, high power/torque density, low weight/volume, and low cost. To achieve these needs, NASA set goals for the electric machines to meet adequate MW-scale power density for a flight. NASA aims for minimum efficiency with > 96% and power density with > 13.2 kW/kg in the non-cryogenic section.

There are different electric machine types for electrified aircraft: induction machine (IM), switched reluctance machine (SRM), and permanent magnet synchronous machine (PMSM). PMSM is more favourable among these machine concepts due to its characteristics, such as torque-to-inertia ratio, rotor, and winding losses, high-speed capability, and compliance with bearings (Ganev, 2007; Henke et al., 2018).

There are several design challenges in electric machines. Winding technology and wire selection, magnetic material selection, mechanical and thermal design limits, insulation, and cooling technology determine the efficiency of an electric machine. Materials of electric machines must support harsh operation conditions of aviation. For instance, superconductor materials can be used for winding, and this material help to reduce winding loss due to nearly zero electric resistance. Magnetically soft and hard materials are the components for electric machines to create an electromagnetic field. Depending on the requirement of electric machines, expectations from a magnetic material are low iron losses, high saturation magnetisation and, high yield strength.

Moreover, thermal materials and insulation used for electric machines must meet high power combined with high rotational speeds requirements. The electric machine generates heat, and excess heat causes a loss of integrity of insulation materials. The temperature rises because of the heat that decreases the machine's performance and causes mechanical stress resulting in fatigue (Deisenroth and Ohadi, 2019). Cooling approaches are necessary to remove heat from the electric machine. Oil spray cooling, water jacket cooling, and heat pipe cooling are the main approaches in electric machines.

For example, oil within the machine's housing is exposed to the rotor, stator iron, and windings in the oil spray cooling. Oil in the air gap of the machine may weaken electromagnetic efficiency. Fluid in liquid-based cooling must have high electrical resistivity and magnetic permeability. Also, this fluid must be non-flammable. As a result, selecting proper cooling is a challenging issue to increase electric machines' efficiency and power density without affecting stable operation.

Even though the goals of NASA have not been reached for a commercial flight, the highest power density has been announced by Wright Electric (2021). The test for a 2 MW with 10 kW/kg specific power electric motor began in 2021. Although the reached power levels for electric machines are not sufficient now to meet commercial aircraft power demands (changing from 2 to 5 MW), R&D projects on electric machines continue to support a zero-emission flight.

3.6 Integration of the different systems and components

Aircraft is the combination of different components and systems, and these systems make an ecosystem in an aircraft. Components of aircraft are designed individually, and integrating all the different characteristic components will be challenging. Data and power flow to different and multiple components make a possible fault to affect the overall integrated system.

Propulsion system integration of aircraft is challenging as the integration process comprises important interfaces between engine and aircraft components. The increasing number of components will scale up the complexity and possibility of errors. Proper operation of every component correctly individually and together must be ensured as the task of aircraft integration according to SAE ARP-4754A (SAE International, 2010). There is a need for standardised processes and highly reliable design tools to evaluate the integration issue (Behbahani et al., 2014).

According to a report released by MIT researchers on safety considerations of electric aircraft, the key hazards identified are energy uncertainty, power system fault, aircraft automation failure, and lithium-polymer battery thermal runaway (Courtin and Hansman, 2018). These failures bring to mind that a reliable integration process is required. Simulation and tests are necessary to determine the failure behaviour of integrated components. Besides complexity, safety, and reliability issues in system integration, the system's efficiency is another important challenge. Component interconnection and system architecture are required to meet high power demands and effective and reliable protection in the design of the aircraft propulsion system. As the components determine the reliability of the overall system, all components must work together to accomplish a safe flight and meet system efficiency requirements. It is intended that the efficiency of every component in the aircraft is high. However, in some cases, the efficiency of a component may be made concessions as the cost of the safety in aircraft propulsion integration.

3.7 Certification of electric aircraft

The airworthiness and safety of an aircraft are confirmed by aircraft certification. European Aviation Safety Agency (EASA) is aviation regulatory in the European Union and Federal Aviation Authority (FAA) in the United States. EASA is responsible for regulation, certification, and standardisation. Besides, EASA also carries out investigation and monitoring. According to the safety report (IATA, 2021b) released by The International Air Transport Association (IATA) for 2020, the total number of accidents declined from 52 to 38 in 2020 compared to the previous year.

Meanwhile, there is a decreasing trend in accidents; technological improvements such as electrification of aircraft are increasing. Emerging new technologies raise the certification issue for electric aircraft. There is a need to certify the special condition of electrification of aircraft components like electric engines. As the certification of electric aircraft from a regulatory is a challenge in civil aviation, aircraft manufacturers think a definition lack of specific certification stops them from entering service (Reichmann, 2021). FAA studies to form a special condition to make a guide certification for electric engine manufacturers. Nevertheless, according to FAA, one of the challenging issues on certification is different design architectures. Releasing a certification that allows aircraft manufacturers to have a guideline to follow on special conditions will overcome these challenges (Mracek Dietrich and Rajamani, 2021).

4 Conclusions

Technological developments in electric aircraft pave the way for sustainable and green aviation. In this study, the current situation of electric aircraft is assessed, and challenges on electrification are discussed. Challenges are summarised as below:

- Low technological readiness level of power storage technology is a major limiting factor in electric aircraft. Specific energy density compared to the weight of the batteries is not adequate to meet the energy of conventional aircraft fuel. Due to the energy density problem, fully electric aircraft for commercial use may be away soon. Charging batteries need investments in charging stations in airports and also raises questions on long waiting times (for battery charging) before preparing an aircraft for flight.
- Uncertainty on certification of electric propulsion stops aircraft manufacturers from entering service. A specific certification procedure must be applied to aircraft; however, certification regulators have difficulties with different propulsion design architectures, which decelerate the certification process.
- Integrating systems is another challenge as the complexity increases with every electrified component/system. As the dynamic behaviour of different components differs, bringing them together is a compelling process.
- High power demands are required at take-off and landings, so high-power flow must be ensured with the proper size of wiring. A fault at any point of the wire will affect all systems, and the importance of protection devices shows up. Protection devices are the safeguards of the systems and components and clear the fault before transfer to other components/systems. Robust and reliable operation is crucial for protection devices.
- Conversion of power and driving of electric machines is realised with PECs, and PECs must be designed to reply to transient and changing power demands with high reliability. PECs are supported with WBG devices with suitable characteristics for harsh environmental conditions of flight.

- TM of the overall system is a limiting issue in the sising of systems. Removing heat from devices increases the efficiency and lifetime of systems, and TM approaches are the weight contributors.

Although there are limiting factors to the transition of electric aircraft, the zero-emission flight will be near future with ambitions of technological developments. Nowadays, electric cars are seen on roads, and in the future, there will be fully electric aircraft for commercial aviation.

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