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Electric Propulsion for Fixed Wing Aircrafts – A Review on Classifications, Designs, and Challenges

Aravind Karthik,[1] Dundesh S Chiniwar,[2,*] Mayukh Das,[1] Prashanth Pai M,[3] Phalguni Prabhu,[4] Prashant A Mulimani,[5] Kaustubh Samanth[6] and Nithesh Naik[7]

Abstract

With the growing concern of depleting fossil fuel remains and their impact on the environment, there rises an increasing urgency to switch over for alternative sources of fuel in the aviation sector, inducing a rapidly gaining momentum towards more green and clean sources for propulsion. This concern leads to the scrutinization by governmental agencies and corporate players to focus and invest in adopting electric propulsion architecture. A detailed and systematic literature review was conducted according to the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines, to identify all potentially relevant studies using the Springer®, Scopus®, and Web of Science®. Various papers and reviews on the electric cryogenic and non-cryogenic engines were analyzed and selectively reviewed here systematically. This review discusses the field of fixed-wing electric propulsion and analyses several engineering metrics and influencing factors for the same. This review primarily classifies the different available architectures proposed or implemented for electric propulsion. A brief overview is presented to discuss the current implementations of this futuristic technology and also the upcoming prototypes of electric propulsion architectures. The pros and cons of electric propulsion and its influences on aeroplane performance are highlighted. Inferences can be drawn that the electric aircraft design problem forms new networks and bridges between conventional aircraft design disciplines and emerging subsystems to render high fidelity to solve arising issues and prospective goals. For a favourable design of non-conventional aircraft with efficient performance, high specific power (HSP) is required. Non-cryogenic systems are the backbone for several concepts and prototypes on electric aircraft. Hybrid engines enable the pilot to selectively prefer specific means of propulsion according to the phase of the flight being undertaken.

Keywords: Electric aircraft; High-temperature superconductor; Non-cryogenic engines; Propulsion; Turboelectric.
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1. Introduction

Aviation Industry is one of the most interdisciplinary and magnanimous discipline enabling man to become airborne despite his biological restrictions.[1,2] Ever since the maturation of the first successful flight by the Wrights, the technology involving aviation is advancing and taking long bold strides every time. It was not just the design, but it was also the propulsion system that improved and supported greatly the aircraft we have currently. From relying just on air for the motion to accelerating flux of air by mechanical means to attain supersonic speeds, the propulsion industry greatly enhanced and nurtured to meet the generation requirements and open gates for the future. The current modern aviation industry makes use of a fuel-based; Thermodynamics cycle that relied upon engines. These include turboshaft, turboprop, turbofan, turbojet, ramjet engines and several other variants to enhance the range and efficiency of the aircraft. The necessity and utilization of these engines depend on the speed of operation of the aircraft, the economic aspects, and the distance and time of operation. The development of these engines enabled us to break the sound barrier and travel at high speeds like never before.

But all such advancements were achieved at the cost of the environment. According to the statistics by Abas *et al.*,[1] the fossil fuel sources are exponentially declining and the fuel sources may perish very soon. Despite the consideration of the quantity of fossil fuels available, the extent of pollution these

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[1] *Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India.*

[2] *Department of Mechatronics Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India.*

airborne vehicles cause upon burning massive amounts of fuel is also to be scrutinized. An international flight undertaking 10 hours of travel will require at least 36000 gallons. Now considering all other flights in the world and the number of trips they make and the economic needs of these airliners, we realize that the fuel used is enormous and the pollution extent is extensive. As different ranges of flight have different energy demands, there is also heavy variation in the extent of CO_2 emission. According to the statistical analysis by Mavris *et al.*[2] the fuel demands for each kind of aircraft are shown in Fig. 1.

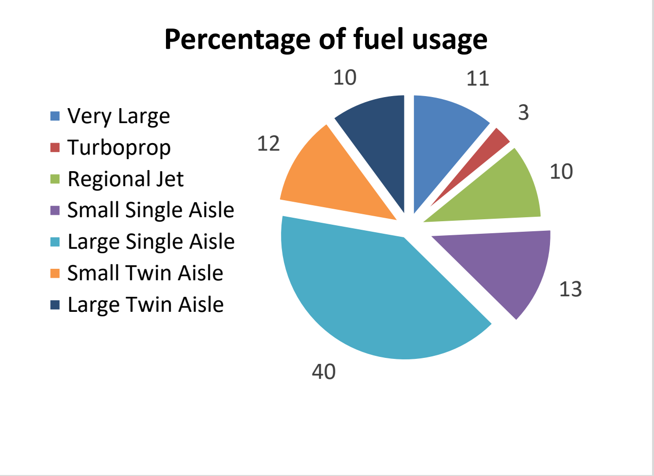

Fig. 1 Percentage of fuel usage for different variants of fixed-wing aircraft. Reproduced with the permission form [2]. Copyright@ Langley Research Center.

There is also huge noise pollution in neighborhood of the airport and other air vehicle stations. The growing need to look for an alternative source for airborne vehicles and the need for a clean, green and economical means of aviation sprouted the need for electric aircraft propulsion. This paper discusses only the electric propulsion for fixed-wing aircraft.

Over the last decade, the concept of electric aircraft propulsion lured the attention of several governmental firms, big corporate players, and even the public, leading to greater interest in this field of innovation. Several biz firms are working to commercialize this means of transportation and make it more affordable and reliable to the public. The rise of air taxi concepts by Uber, Volocopter,[3] and several other young firms are few examples to be highlighted. The inclination of the greater mob towards this propulsion architecture is far beyond mere fuel savings. The advantages offered are diverse. With 70% fuel savings, it also offers a very high efficiency of about 95% for the same power offered by conventional jet engines. In addition, it also experiences less loss of energy as the only source of energy loss is transmission loss due to the heating effect of resistance. It also requires fewer maintenance costs and greatly reduces the size of the propulsive component required. In addition, it also allows propulsion airframe integration which otherwise would not have been possible in conventional propulsion systems. The central inquisitiveness is the electrical distribution of propulsive power due to its flexibility in design. Drawbacks are the additional system weight and loss mechanisms, which affect the advantages of electrical propulsion. This has paved paths for new opportunities and lucrative markets thus giving rise to the technology of the future. Thomson *et al.*[3] presented a detailed overview of an aviation electrification from a business perspective. Hepperle[4] uses Breguet equations to address a few of the basic electric propulsion (EP) architectures. The practical conceptual propulsion architecture of hybrid electric passenger aircraft was covered by C. Pornet et.al serving as a basis for integrated propulsion designs[5].

Electrification of a fixed-wing aircraft is a big shelter under which various variants are used or suggested to attain specific engineering goals. One of the key parameters for classification remains the specific power criteria and the degree of Hybridization, which parametrizes the power of the engine used.[6] This data helps us identify situation-specific designs and engine models and establishes a quantitative relationship among different engines suggested. For a unit mass of fuel, greater power output is usually expected and hence a higher specific power is usually preferred. The degree of Hybridization is a dimensionless quantity used as a parameter of classification for power and energy sources.[7] It is defined as the ratio of motor power [Pm] to that of the total power or the battery energy to that of the total energy (Ptot) as shown in equation (1).

$$H_p = P_m/P_{tot} \quad (1)$$

The degree of hybridization for energy source (H_e), which is applicable in hybrid and fusion configurations of electric aircraft, acts as a pivotal parameter in several early aircraft design stages, especially for vehicles that uses next generation fuel systems and electric propulsion means.[7] It is defined as the ratio of battery power [Eb] to that of the total power or the battery energy to that of the total energy (Etot) as shown in equation (2)

$$H_e = E_b/E_{tot} \quad (2)$$

Depending on these criteria, electric propulsion can be broadly classified as cryogenic engine propulsion and non-cryogenic engine propulsion. A conventional aircraft utilizing just the mechanical engines have H_p and H_e as 0 as there isn't any presence of motor or battery to give their contribution to the overall power generated. This measure can be taken as the

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[3] *Department of Mechanical Engineering, P.A. College of Engineering, Mangalore, Karnataka 574153, India.*
[4] *Department of Aeronautical Engineering, Srinivas Institute of Technology, Mangalore, Karnataka 574143, India.*
[5] *Smt Kamala and Sri Venkappa M. Agadi College of Engineering & Technology, Lakshmeshwar, SH 6, Gadag, Karnataka 582116, India.*
[6] *Department of Aerospace and Geodesy, Technical University of Munich, 85521 Ottobrunn, München, Germany.*
[7] *Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India.*
**E-mail:* dundesh.sc@manipal.edu (D. S. Chiniwar)

pivot point for further classification.

Other key parameters that are necessary for analyzing the potential of electric propulsion today are specific energy and specific power. Specific power is a relevant parameter to relate the energy storage devices, electric motors, and other electronic convertors. On the other hand, Specific energy is used to parametrize batteries of various kinds. Due to the non-lucid literature explanations on the appropriate abbreviations for these terms, all specific terminologies are represented in their lower-case forms.

Despite the ardent need to switch over to non-conventional sources for powering the metal birds, for the sake of commercial benefit, their range is intended to be significant enough to make them robust enough for their usage. Breguet's equations very well represent the dependencies of the range of a flight on various parameters depending on the source of powering.[8] Specific quantities, specifically specific energy seems to have a vital impact in influencing the range of a flight For conventional fueled aircraft, the Breguet equation (3) is given

$$R_f = \frac{L}{D}\eta_p\eta_{int}\eta_{eng}\frac{e_f}{g}\ln\left[\frac{1}{1-\frac{m_f}{m_{To}}}\right] \tag{3}$$

where,

- $\frac{L}{D}$ is lift-to-drag ratio,
- η_p is the propulsive efficiency,
- η_{int} is the efficiency due to propulsion integration losses,
- η_{eng} is the engine thermal efficiency,
- e_f is the fuel specific energy,
- $\frac{m_f}{m_{To}}$ is the ratio of fuel weight to takeoff gross weight.

Breguet range equation for battery-powered aircraft (4) is,[4,9]

$$R_b = \frac{L}{D}\eta_p\eta_{int}\eta_e\frac{e_b}{g}\frac{m_b}{m_{To}} \tag{4}$$

where,

- η_e is the total efficiency stack up of the electric propulsion system,
- e_b is the battery specific energy,
- $\frac{m_b}{m_{To}}$ is the ratio of battery weight to takeoff gross weight.

With a reduction in the fuel mass/battery mass, there is a significant reduction in the range noticed, due to the creeping of induced drag during a flight period. It is noticed that specific energy (SE) is directly proportional to the range of the aircraft for both conventional and electric (battery-powered) aircraft. As the SE drops, take-off gross weight (TOGW) gradually adds on, making the lifting capability of an aircraft quite difficult. So SE is a powerful but sensitive property.

Another important engineering metric is the volumetric energy density (VED),[4] a measure linked to energy storage devices. Comparing various sources of energy, our conventional jet fuel tends to have optimal e_f and VED. On the contrary, hydrogen has a very high e_f, but its VED is very low lying. Li-ion batteries have low VED and low e_f. [4]

One of the major technological parameters influencing the architecture of the aircraft is the specific power of electrical devices (p_e).[10] It is a practice to rate an electric motor based on the instantaneous discharge power rather than maximum continuous power. This discharge power is usually higher than the maximum continuous power. Similar to SE influencing the take-off weight of an aircraft, specific power (SP) also affects the weight of the aircraft in the design and operation phase. A lower SP results in heavy flight rendering the flight vehicle inefficient.

The flight of an airborne vehicle is composed of many phases, each unique in its power requirements. It is obvious that to get the plane off from the ground, a higher power is required than that required for a cruise up in high altitudes. The requirement of a higher power is not just for taking off the weight from the ground but is also bounded by several other constraints like runway length, airplane build, and fuel efficiency. So, in such phases of flight, where high power is required, the SP of the batteries is expected to be higher. For an all-electric based propulsion, batteries are expected to instantly pump out enough juice to meet this power demand and hence higher SP. But on the dark side, a higher SP trades off with SE which in turn may influence the range of the aircraft, which is very significant from the commercial aviation industry point of view.

Now that the key technological influencers are discussed, the classification of the propulsive systems based on these metrics becomes necessary. With many designs and models suggested, an optimal and appropriate design with a suitable powering system facilitates the electrification of the aviation industry.

2. Search strategy

2.1 Study selection flow chart

Preferred Reporting Items for Systematic Reviews and Meta-analysis [PRISMA] guidelines were adhered, to identify all potentially relevant studies using the Springer®, Scopus®, and Web of Science® for this evidence-based research. Meticulous analysis of relevant papers for the study was done and finally selected 57 relevant articles in the current review as shown in Fig. 2.

2.1.1 Inclusion criteria

- Specification of various variants of propulsion and analysis of several non-conventional electric-based propulsion.
- Scientific pieces of literature involving the analysis of efficiency, specific power, and other engineering metrics are required for the analysis of different variants of Propulsion.

  Articles discussing the shortcomings of the adoption of electric propulsion for fixed-wing aircraft.

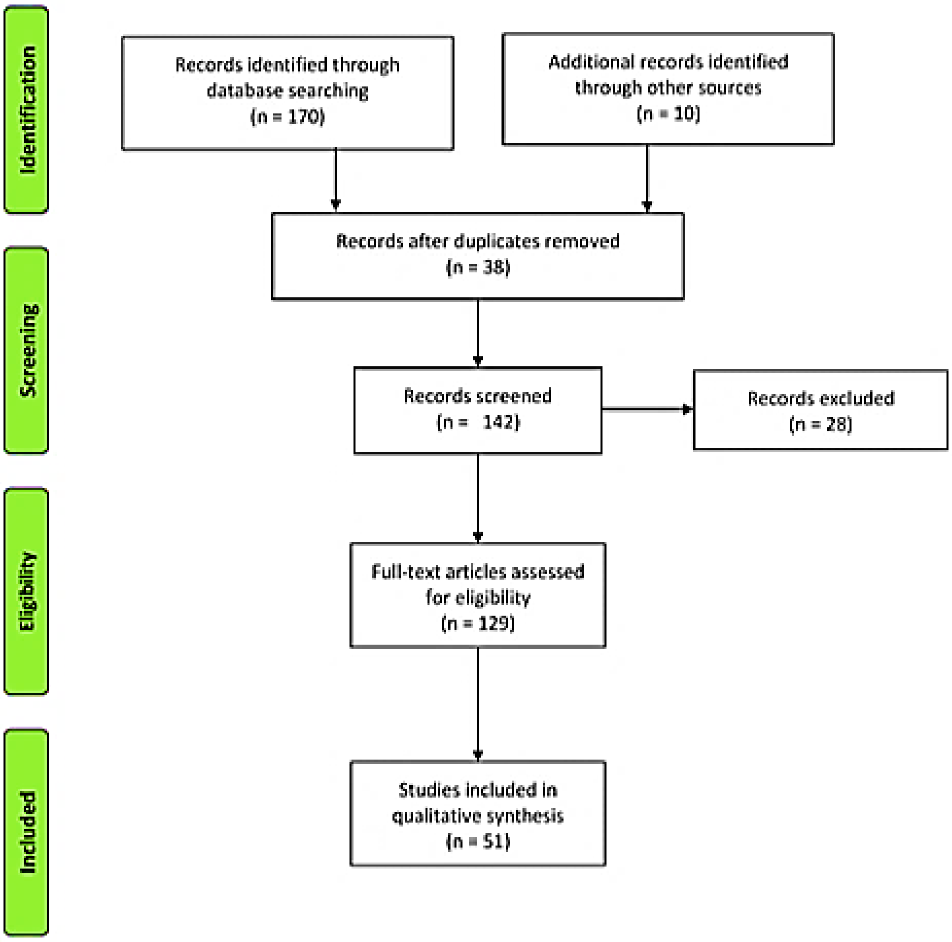

Fig. 2 Study Selection Process (PRISMA).

2.1.2 Exclusion criteria

- The studies included the theory of classifications of different electric propulsion systems; however, no emphasis is given on the motors and generator preference for the specific applications for these propulsion systems.
- Although studies addressed both cryogenic and non-cryogenic based propulsions, major emphasis is given to non-cryogenic electric propulsion systems.
- Studies from keynotes, non-English publications.

3. Advancements in electrical propulsion aircrafts

3.1 Classification of electric propulsion variants

With the evolution of flight design and propulsion systems, several non-conventional methods of powering the aircraft have been suggested. With the maturation of technological advancements, more robust and target-oriented engine designs were suggested with minimal or zero CO_2 emissions. Electric propulsion concepts, which were quite non-feasible 2 decades ago, now seem to be like a gate to the future in the neighborhood. According to the statistics provided by Toptal,[11] in Fig. 3, the rate of inclination towards this technology is rapidly increasing and a projection of the data till 2050 indicates that, by that time, electric propulsion will be the major/only source for powering an aircraft.

On a broader aspect, electric engines can be classified as cryogenic and non-cryogenic engines. The classification criteria are based on the utilization of sub-zero coolants (see Fig. 7) and superconducting materials.

3.1.1 Cryogenic electric engine propulsion

This variant of the electric engine makes use of low-temperature sources to drop the operating temperature of the superconductors below its critical temperature to enhance the electrical conductivity[12] and result in a highly efficient engine design and functionality to yield high efficiency and fuel economy.

Despite the various variants and mods proposed for cryogenic electric engines, a simplified representation can be depicted as shown in Fig 4.

Each component has its significance in giving the final output. The high-temperature superconductor (HTS) is subjected to operation under critical temperatures to offer almost zero resistance and hence almost negligible thermal losses during transmission.[14] This helps us get higher efficiencies for the same power compared to a conventional engine. The HTS motor here is backed by a group of alternating current (AC)/AC converters. From an electrical

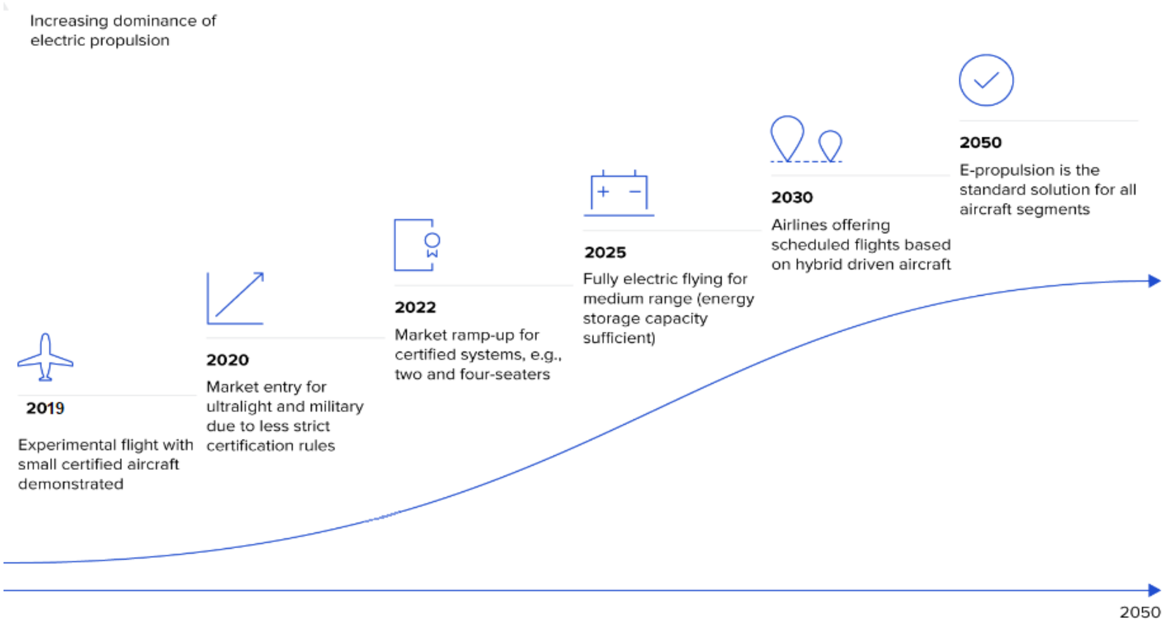

Fig. 3 Statistical Trend in the development and expansion of electric aircraft propulsion. Reproduced with the permission form [11]. Copyright@ toptal.com

standpoint, their presence is necessary. However, they could be removed to decrease the complexity and mass additions. Direct current (DC) transmission may be quite suitable if cable AC losses are very high.

Cryogenic systems can be used even with gas turbine engines. These conventional engines can still be located under the wings of the airliner. Some of the obtained power can be used to drive the huge superconducting generators. This way, a significant amount of thrust required for the aircraft is generated by the electric fans run by the cryogenic systems, and thus the entire dependency on fuel usage is reduced effectively. A commercial airliner will have high power necessities for thrust ranging from 5 MW to 100 MW. With the effective usage of this method, the complete reliance on the fuel entirely is ruled out.

The backbone of cryogenic engines is the method of cooling to attain the zero-resistance capability of the superconductor as quickly and efficiently, keeping in mind the time and economics as well. Primarily, few significant methodologies adopted for cooling the superconducting network - can be divided into three types.[13]

(1) Fully decentralized: Each machine or subsystem of components has a separate closed cooling loop with a cryocooler, so cooling is performed locally.

(2) Partly centralized: Localized cryocoolers are used to provide the operating temperature. A medium-temperature circuit is maintained by major coolers.

(3) Fully centralized: Large cryocoolers are used to maintain a closed-loop of cold fluid at the superconducting operating temperature.

Power demands decide the utility of a specific engine. Although reciprocating Cryogenic engines seems unfit for large scale applications, for meeting the low power aerospace needs, which is the level of operation for most private and

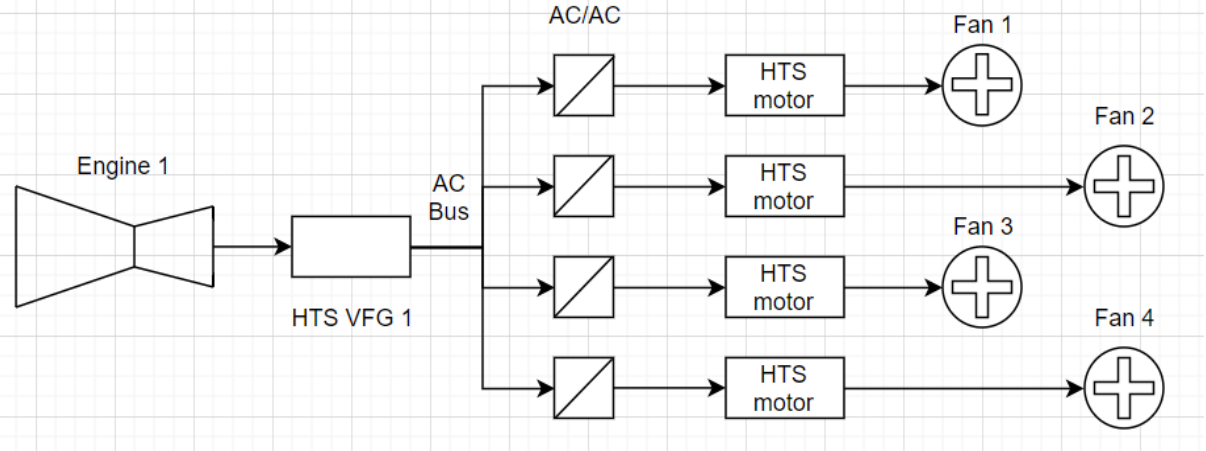

Fig. 4 General representation of Cryogenic Electric propulsion system. Reproduced with the permission form [6,13]. Copyright@ IEEE Trans. Transp. Electrification

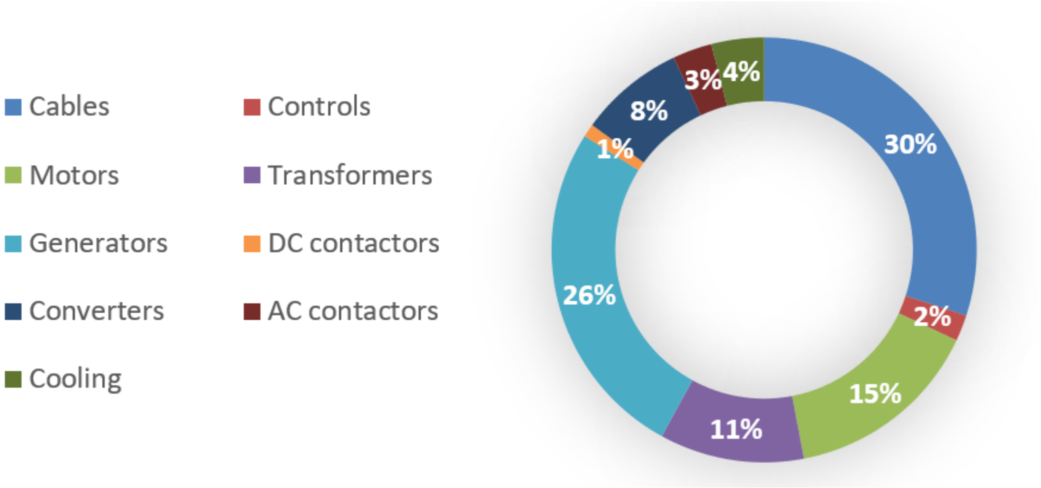

Fig. 5 Weight distribution of various electronic components in EP. Reproduced with the permission form [17]. Copyright@ Progress in Aerospace Sciences

recreational jets, this tends to be more suitable. However, taking the sizing and the reliability into account, which is a vital aspect for cryogenic electric engines, a reverse Brayton cycle-based cryocoolers using the 2nd or 3rd method of cooling seems more promising. There is expected to be a general improvement in cryocooler power density with overall input power. Assuming that the losses due to insulation are negligible compared to machine losses, a significant improvement in the utilization of cryocoolers is noticed when the 3rd method of cooling is adopted.

An electric propulsion system is more robust when it has an efficiency of more than 90% for the aerodynamic benefits to be experienced. Especially for a cryogenic superconducting system, an end-to-end efficiency of greater than 95% is expected after the possible losses through transmission and power electronic losses.[15] If the total mass of the electrical components is greater than 10% of operating empty weight (OEW), then the adoption of this propulsion system turns meaningless as it doesn't yield any benefits.[16] The cryogenics may be expected to make up around 2/3rd of the electrical system mass. The mass distribution of electrical components can be given in a rough figure using this graphical representation.

The conductivity of semiconductors tends to increase with reducing temperature. Despite yttrium barium copper oxide (YBCO) and bismuth strontium calcium copper oxide (BSCCO) turns out to be superconductive at a temperature of about 77 K, their performance will not be feasible enough.[13] The operating temperatures would lie between 15 and 50 K. The critical temperature of Magnesium diboride (MgB_2) is 39 K and its engineering performance can be reasonably better below 30 K. MgB_2 wires show good potential for creating windings and can be filamented to reduce AC losses. In the cryosystem, the performance of the aircraft depends upon the method of disposal of the waste residual heat and the weight distribution of the associated components (Fig. 5). Based on simple calculations using ambient air, even at high altitudes, due to the achievable low thermal efficiency, the final heat sink will lead to challenging design constraints. The power requirement for a cryocooler engine can be determined by;

$$P_{cc} = \frac{\dot{Q}}{\eta_{fc}}\left[\frac{T_H - T_C}{T_C}\right] \tag{9}$$

The complex design constraints with the ambient air as sink arises the necessity to seek for a better sink in a system. For a system based on a centralized cooling architecture, usage of liquid hydrogen (LH_2) or liquid methane (LCH_4) as heat sinks yields better results. For complex ambient air and LCH_4 as the heat sink, the percent of the power required is depicted in Table 1, depending on the Carnot efficiencies achieved and the attained heat sink temperature.

Table 1. Comparison of cryocooler power demands as a percentage of system power, depending on heat sink temperature and the fraction of Carnot efficiency achieved.[13]

a] T_H = 225 K [air at 32,000 ft.]					
η_{fc}	0.1	0.2	0.3	0.4	0.5
Tc[K]		Power	Demand[kW]		
60	5.5%	2.8%	1.8%	1.4%	1.1%
50	7.0%	3.5%	2.3%	1.8%	1.4%
40	9.3%	4.6%	3.1%	2.3%	1.9%
30	13.0%	6.5%	4.3%	3.3%	2.6%
20	20.5%	10.3%	6.8%	5.1%	4.1%
15	28.0%	14.0%	9.3%	7.0%	5.6%
b] T_H = 111 K [LCH4 boiling point]					
η_{fc}	0.1	0.2	0.3	0.4	0.5
Tc[K]		Power	Demand[kW]		
60	1.7%	0.9%	0.6%	0.4%	0.3%
50	2.4%	1.2%	0.8%	0.6%	0.5%
40	3.6%	1.8%	1.2%	0.9%	0.7%
30	5.4%	2.7%	1.8%	1.4%	1.1%
20	9.1%	4.6%	3.0%	2.3%	1.8%
15	12.8%	6.4%	4.3%	3.2%	2.6%

In this study, insulation losses and cable AC losses are assumed to be small and the low-temperature heat exchanger is a complex arrangement of heat exchangers and pipes collecting the component losses.[18]

Methods of cooling include forced air cooling, indirect water cooling, *etc*. which may not make use of sub-zero temperatures always but aids in the cooling of the HSP machines. Xiaolong *et al*.[19] clearly explain the mechanism of HSP machines and various methodologies involved in the cooling process. A graphical representation of various mechanisms of cooling is represented in Fig. 6 and Table 2.

Table 2. Mechanism of different cryocooling methods.[19]

Type of Cooling	Mechanism
Forced Air cooling	Air is forced through ducts of radial or axial kind
Indirect Oil cooling	Cooling of stator frame using oil flowing indirectly
Oil Spray	Spraying of atomized/stream of oil over rotor end
Hollow Shaft	Oil flows through the Hollow shaft to cool the component
Indirect Water	The indirect flow of water to cool the stator frame
Liquid Bath cooling	The component to be cooled is bathed in a coolant/refrigerant/oil
Direct Liquid Cooling	The component/conductor is subjected to direct cooling by direct water or oil

3.1.2 Non-cryogenic electric engines

Unlike cryogenic engines, non-cryogenic doesn't make use of any sub-zero temperature sources for their functioning. Depending on the degree of hybridization and specific power criteria, these non-cryogenic engines can be classified as turboelectric, hybrid, and all-electric engines (Fig. 8).[20] The utilization of non-cryogenic engines is widespread in the field of electric propulsion due to their adaptive usage to use either fuel sources to run the motors or stored form of energy to run them. Distributed propulsion is the method of distributing the propulsions along the span of the wing or aircraft body for greater aerodynamics efficiencies. A distributed turboelectric propulsion system gives the massive advantage of propulsion airframe integration.[21] which otherwise would not have been possible or rather feasible with the conventional propulsion engines. Due to such integration, flight lifting and maneuvering will be a lot easier and demands less power. It also eliminates individual components and their structural issues and increases the overall structural strength of the material due to one single integrated structure. The aerodynamic advantages of such orientation are discussed in detail in the upcoming section. Turboelectric propulsion is one of the highly recognized and efficient mechanisms.

The specific power of general-purpose industrial motors (*e.g.* for fans, pumps, compressors, milling machines, *etc*.) are in the range of 0.1–0.5 kW/kg. If advanced designs and materials are put into use in the case of the automotive industry, this SP can be increased to lie between 1 and 3 kW/kg. This seems feasible and promising for most applications in the automobile industry, as the power required per kg won't be high enough. On the contrary, this won't meet the enormous need for the aviation industry. It is estimated that for a passenger class Aircraft, the SP demand would be about 10 kW/kg or even more.[22] The power demand for an electric automobile will be in kW but for the electrification of the airborne metals, a whooping power in the range of MW is required. But it is to be understood that the value of SP alone doesn't conclude the entire story. Smith *et al*.[23] reported that the performance of electric components over the 20 years for aircraft applications, the power capability of aircraft electric machines is expected to reach 1–3 MW and the SP expected to reach 9 kW/kg.

So, for a better and favorable design of non-conventional aircraft with efficient performance, HSP is required. Although superconducting machines with cryogenic systems are very promising for HSP, they don't seem to nurture and get matured enough to become a feasible technology in the next few decades. Hence, non-cryogenic systems tend to outweigh the game and hence remain the backbone for several concepts and prototypes on electric aircraft.[15]

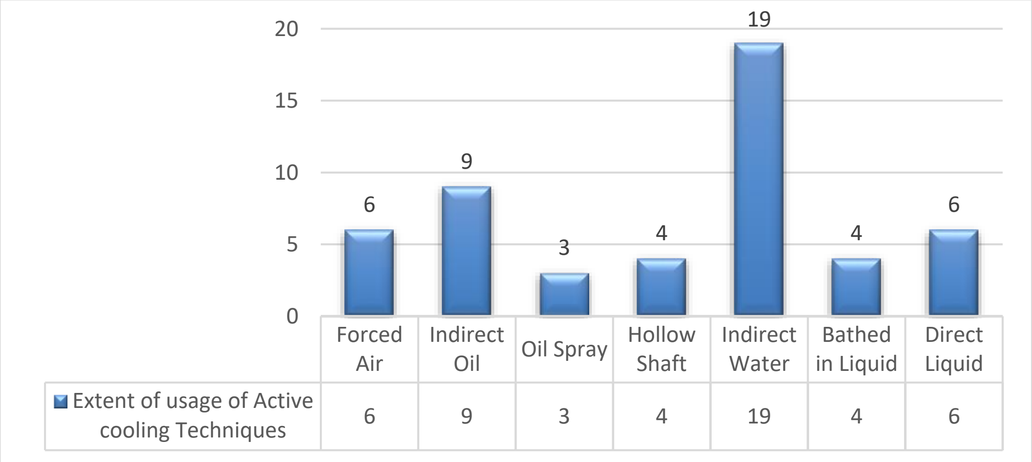

Fig. 6 Extent of usage of various active cryocooling techniques Reproduced with the permission form [19]. Copyright@ IEEE Energy Convers. Congr. Expo. (ECCE).

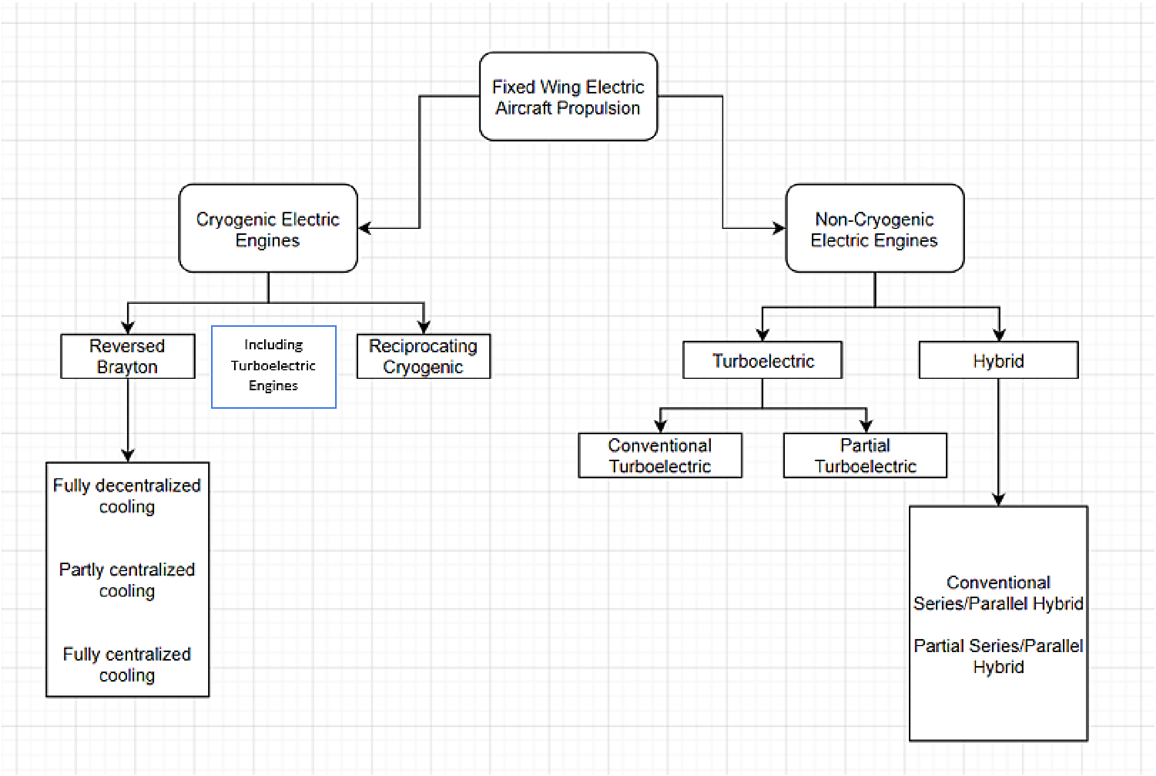

Fig. 7 Classification fixed-wing electric aircraft propulsion.

The turboelectric engine makes use of burnt fuel to run the shaft of the engine. This shaft energy is used to power the generator, which converts the mechanical energy of the turbojet/shaft engine to useful electrical energy. Depending on the requirement, there may be rectifiers attached to the path of current flow to rectify the AC into DC for the functioning of the motors. Turbo-electric engines can be bifurcated as all turboelectric or conventional turboelectric engines and partial turboelectric engines. In all Turboelectric engines, there is a direct conversion of shaft's mechanical energy into electrical energy whereas in the case of a partial engine, one of the many propellers will be run by a turboshaft/jet engine, and the rotary work of the shaft is converted to electrical energy by use of the generator. In all turboelectric engines, the entire shaft power is used to run the generator, whereas, in the partial turboelectric engine, some part of the shaft energy is utilized in running the prop attached to the engine, hence, complete energy is not available to run fans attached to the generator. The power Degree of hybridization (DOH) lies greater than 0 (Hp > 0) but the energy DOH remains 0 as there is no utilization of battery for energy storage and hence the energy contribution by the battery will be zero.

Hybrid architecture can be classified as conventional series/parallel or partial series/parallel engines. These types of engines rely on a mix of fuel and electrical energy for rendering the desired power. In a parallel hybrid electric engine, either battery can be used to run the motor, which in turn runs the propeller or fuel can be used to directly run the propeller. But in the series hybrid architecture, a jet engine runs a generator, and this energy gets stored with the aid of a battery.[24] The obtained energy can be used to run the motor either by direct utilization of electrical energy from the generator or by using the stored energy from the battery. It is to be noted that the difference between all turboelectric and series hybrid engines is only in terms of energy storage. The partial hybrid engine is a combination of series and parallel hybrid wherein the engine also runs a separate propeller and also generates power to be either stored or transmitted as electrical energy to run the motor fans.[25]

In general, for the case of hybrid engines, the power DOH is greater than 0 ($Hp > 0$), and the energy degree of hybridization lies between 0 and 1 ($0 < He < 1$). In specific $Hp = 1$ for series hybrid engines and $Hp < 1$ for parallel hybrid engines (Table 3).[24,26]

In most cases of such propulsion, fuel is just used as a range extender instead of a full-scale utilization of fuel. Such hybrids enable the pilot to selectively prefer specific means of propulsion according to the phase of the flight being undertaken. For instance, the take-off and landing phase relatively requires more power than the cruise phase, during which appropriate outputs can be preferred. The possibility of utilizing various combinations of propulsors according to the energy demand and fuel efficiency gave the advantage to operate effectively. Either the conventional engine may use part of electric power to reduce the fuel usage, or the mechanical dependence for propulsion can be cut off by detaching the flywheel and enable full electric operation during specific phases of flight.

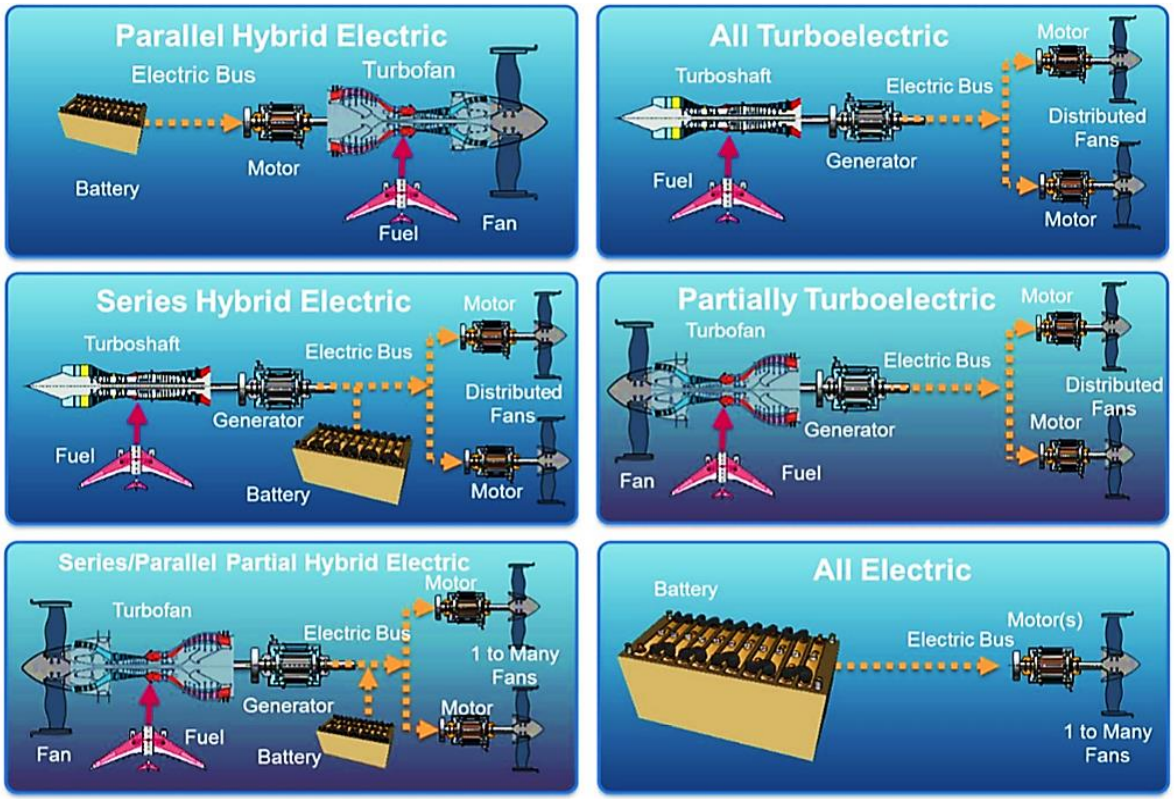

Fig. 8 Graphical representation of different variants of non-cryogenic aircraft propulsion. Reproduced with the permission form [20]. Copyright@IET Electric power applications.

Table 3. DOH for various electric propulsion variants.[27]

Type of EP system	Mechanism	Hp	He
Conventional	Fuel based; Thermodynamic cycle dependent	0	0
Cryogenic electric	Superconductor electrical conductivity	> 0	0
All electric	Battery discharge	1	1
Turboelectric	Fuel based power generation, electrical conversion to run the motor	1	0
Partial Turboelectric	Both conventional and Turboelectric	> 0	0
Series Hybrid	Turboelectric mechanism with facility for power storage	1	< 1
Parallel Hybrid	Both battery discharge and conventional mechanism	< 1	< 1
Partial Hybrid	Both battery discharge and partial turboelectric	> 0	> 0

3.2 Prototypes and concepts of electric aircraft

3.2.1 Prototypes

The onset of the 21st century marked the start-up of many electric-based aircraft, with 17 manned electric aircraft produced since 2000. Of all these aircraft, 3 of them are available for commercial usage. Despite this, there are also huge investments done in this field by top governmental agencies and several big players in the field primarily focusing on highly efficient, feasible, and robust electric aircraft propulsion systems. A glimpse of various prototypes and concepts of electric aircraft proposed/introduced are mentioned in these studies (Table 4 and Fig. 9). The national academy report consists of related work scrutinizing technology expectancies for batteries, motors, and generators.[28]

The very idea of electric aircraft propulsion was first conceived and incubated about a decade ago with the concept of the first electric airship by Santos-Dumont.[28] Ever since people started exploring more non-conventional means for powering the aircraft. NASA also researched many solar-powered high aspect ratio aircraft. Collective efforts of different pieces of research works led to the development of high-altitude long-endurance (HALE), such as the QinetiQ electric range of aircraft, yet with few technical challenges.[29]

Earlier after few trials, Brditshka MB E-1 was the first manned, fixed-wing electric aircraft.[30] This aircraft flew in the year 1973 and had a short range of operation due to the less primitive battery technologies that existed back in those days. There were also several prototypes by independent designers designed in the late 2000s. Some of them were Electraflyer C, Cri-Cri, *etc*. Aviation market rulers also got into the field and came up with their designs like Boeing HK36, SHE Diamond DA-36E and E Pipistrel Taurus Electro aircraft.[31,32]

In NASA/CAFE Foundation Green Flight challenge [2011], the three new experimental electric aircraft with extended range is a four-seat variant of the Taurus electro, Embry-riddle aeronautical university's parallel hybrid eco-eagle, and IFB Stuttgart's eGenius.[32] The range of private aircraft and trainers were electrified, like the Alpha Electro, a two-seater electric aircraft.[33] This not just reduced the risk of operation and emission generation but also made training facilities more affordable.

Chip Yates aircraft is another all-electric aircraft that achieved new feats in speed and rate of climb parameters. Siemens AG used 260-kW electrical power for its extra 300 aircraft and achieved new milestones in SP for a rated electric motor. With appropriate and timely usage of electric and conventional power, the Boeing 787's generates about 1 MW electrical energy.[34]

NASA's X-57 Maxwell is another ambitious project involving distributed electric propulsion, which aims to give high power to weight ratio, with reduced drag and enhanced aerodynamic properties. Due to the non-mechanical aspect, it offers greater freedom for aircraft designers to house appropriate components.

In late 2017, airbus, rolls-royce, and siemens teamed up to construct a hybrid electric flying aircraft concept known as "E-Fan X".[35] This demonstrator, which is built based on the Bae-146 platform, will equip itself with three turbofans and one 2MW electric motor, expected to make its first flight by late 2020. The E-Fan X will be a turboelectric configuration equipped with a gas turbine and 2 MW generator for supplying electric power in the aft section, and a large battery pack in the cargo holds, or both.

3.2.2 Concepts

One of the hugely invested and seriously studied electric aircraft concepts is the N3X turboelectric integrated propulsion aircraft, which has a similar size and range of travel to that of Boeing 777. This concept aircraft utilizes a distributed turboelectric propulsion system with measures to reduce transmission loss and noise reduction. The idea was first derived from the cumulative study undertaken by Boeing and NASA called Cruise Efficient Short Take-Off and Landing (CESTOL) in 2008. The N3X sets ambitious futuristic goals of reducing about 70% of fuel utilization and utilization of Cryogenic turboelectric systems to realize these goals. Jansen *et al*.[10] discussed the individual technologies required to implement EP at such power levels, in addition to the fabrication of soft magnetic materials, superconducting wires and electric machines, and insulators. To realize this idea, N3X ought to break a few technological barriers of the current time, for this reason, this is not an upcoming technology in the near future. A single-aisle turboelectric aircraft with an aft boundary layer propulsor [STARC-ABL] has emerged as a conceptual design study. In single-aisle turboelectric aircraft (STARC-ABL), the power for the electric propulsor is generated from the turbofans without a dedicated turbo generator.

Just like the ambitious goals of the NASA N3 series of electric aircraft, Boeing's Subsonic Ultra-Green Aircraft (SUGAR) hopes to develop a super green aircraft with promising SP and efficiency outputs. In the initial phase, all these concepts were the vision for 900 nautical miles of travel, with 154 passenger seats. Eventually, several variants in terms of fuselage structure, supports, and wing architecture were developed to enhance and meet the goals of the future. SUGAR-free uses strut and wing-based architecture. Refined SUGAR involves the use of a high AR wing supported by struts. SUGAR ray is a variant of SUGAR high which involves the usage of PHE propulsion.

One of the best research projects of NASA is scalable convergent electric propulsion technology and operations research (SCEPTOR) launched in 2014 out of four active research concepts at widely varying power scales.[35,36] The major focus of this project is on rapidly achieving ground and flight test demonstrations of higher power levels and distributed propulsion in a phased approach. SCEPTOR is similar to LEAPtech (leading edge asynchronous propellers technology) which introduces numerous small propellers across the leading edge of the wing. The objective of LEAPtech is to increase the cruise wing loading of general aviation airplanes by 2.5 times by reducing drag. This is achieved by avoiding the need for complex and heavy multi-element flap systems and increasing the maximum attainable coefficient of lift (C_{Lmax}) through a blown lift to a great extent. The maximum attainable C_{Lmax} for the wing is theoretically obtained from the lift curve corresponding to the stall angle PEGASUS (parallel electric-gas architecture with synergistic utilization scheme) is NASA's latest electric propulsion concept planned for 200 – 400 nm missions make use of turboprop engines supported by electric motors. In addition, it also makes use of tail cone pusher propeller and mid-span electric motors with folding propellers. The purpose of the wingtip propeller is to reduce the effect of drag due to wingtip vortices and utilize it advantageously, while the tail cone propeller benefits from ingesting the boundary layer of the aft fuselage.[37]

Few start-ups are also focusing on the futuristic electric aircraft concept like the Zunum Aero, which is on a mission to develop a 12 passenger HE aircraft.[36] Companies like Wright electric prefers to make ESAero ECO150 a commercial aircraft for short hops between cities. The ECO-150 concept initially showed very large fuel burn reductions

Table 4. Important engineering metrics of different concepts of aircraft.[20,27]

Prototype/Concept	Architecture	Power [W]	Specific Power[kW/Kg]	Range	Efficiency [%]
Boeing HK-36	FC	75000	-	45 min	-
Pipistrel Taurus Electro	E	40000	-	244 nm	-
Alpha Electro	E	60000	-	70 min	-
Extra 300 [Siemens AG]	E	260000	-	-	-
X-57 Maxwell	E	144000	-	-	-
Airbus E-Fan X	E	60000	-	60 min	
Boeing SUGAR Volt	PH	1000000	3 - 5	3500 nm	93
NASA N3x	TE	50000000	-	-	99.97
ESAero	TE	65000	-	-	-
ECO-150	TE	65000	-	-	-
SCEPTOR		-	-	-	-
STARC-ABL	TE	2600000^b	13	-	96

Fig. 9 Prototypes and concepts of electric aircraft.

versus a current single-aisle benchmark [− 44% conventional, − 59% superconducting]. Due to some variations in the study of fuel consumption, this study is not fully matured technology yet. Israel based start-up, Eviation focuses on developing a 9 passenger electric aircraft called ALICE, which uses a distributed propulsion system with wingtip propellers along with Boundary-layer ingestion (BLI).[38] Ampaire is focused on visualizing an E aircraft for moving passengers and goods for short distances with BLI technology and tailwind concept for achieving appropriate thrust and efficiency.[23]

3.3 Effects on flight performance – Advantages and challenges

A major benefit of Hybrid and all-electric aircraft is the replacement of fuel with electricity on shorter missions. Switching over to electric propulsion seems to be very promising with many enhancements in aircraft performance. Despite the sole effect of reducing the emission leading to pollution, all variants of electric propulsion tend to also offer better aerodynamic, propulsive, sizing, and economic advantage.[39] However, this requires a thorough knowledge of generator fuels, transmission/grid losses, and lifecycle analysis of battery production and disposal. Few other supporting modifications like the usage of advanced light-weight materials, superconducting wires and power electronics, efficient design and housing of components with effective weight management may bring the efficiency of these propulsive systems very close to 1, which is very advantageous and desirable.

3.2.3 Influence on the aerodynamics of the aircraft

Due to the adoption of distributed electric propulsion, there is a huge observed aerodynamic advantage due to several parameters like swirl cancellation, lift augmentation and a significant reduction in the parasite drag. In the case of conventional aircraft, due to the isolated presence of propulsive systems, the housing of the engine [engine nacelle] will tend to induce installation drag, which constitutes about 6% of the total drag.[40] If the propulsion system is integrated with the fuselage of the aircraft, a significant decrease in drag is noticed. Wick *et. al*.[41] reported the concept that by embedding distributed propulsors in the wing on a transonic military transport, an 8% installed drag reduction can be achieved. A reduction in drag for fixed bypass ratio or an increase in bypass ratio for fixed drag can be achieved from this report. The LEAPtech wing has been simulated in computational fluid dynamics (CFD) and is calculated to augment CL by 1.7 – 2.4 (in absolute terms).[42,43] One of the key design aspects of distributed propulsion for electric aircraft is the usage of wingtip propulsors. Their usage is expected to cancel some swirl in the wingtip vortices, however, unlike the Boundary layer Ingestion engine, their study is not backed by sufficient pieces of literature.[44] From the results published by Miranda and Brennan[45] on experimentally-validated low-fidelity, the X-57 design study booked this benefit as a drag reduction estimated between 5% and 10% using low-fidelity methods and used findings for further analysis.

3.3.2 Influence on the weight of the aircraft

One of the few predominant reasons for the non-commercialization of electric aircraft technology is the inclusion of the weight penalty. Unlike conventional turbojet aircraft, whose weight drops during the due course of the flight, electric aircraft don't shed their weight in the duration of the flight. This adds induced drag, weight, and other structural issues thus demanding more propulsive power to compensate for the effect. This again increases the weight of the aircraft as the demand for propulsive power is simply increasing the number of batteries required for propulsion. This turns out to be an endless loop. The take of ground weight [TOGW] hike is more sound in long-range missions which is penalized due to the energy storage mechanisms. Hence, they tend to carry an invisible, insignificant weight of batteries all along the course. However, the adoption of a few strategies and following few arrangements will help to topple the negative effect of aircraft into a positive one. STARC-ABL claims that a significant amount of weight can be reduced employing synergistic propulsive efficiency and turbofan sizing benefits. It was noted that there was a major decrease of about 37% was noted by switching from a triple turboshaft design to a series of hybrid electric architecture in the XTI Tri Fan aircraft. Structural weight is also affected by energy storage, electronics, and thermal management system (TMS) weight. For example, lower e_b leads to heavier batteries and higher-rated maximum takeoff weight. This leads to reduced range in a vicious cycle because of increased structural loads, structural gauge weight, and empty weight.

If Cessna and Airbus A320 are electrified utilizing battery-based power storage, it can be seen that for Cessna, there isn't much variation in the added weight for the same thrust of this aircraft for the same range because of fuel mass is equivalent to the battery mass. However, for Airbus A320, the mass of the fuel required will approximately be about 3-fold the mass of fuel required, which severely affects the take-off performance and maneuvering capability of the aircraft. Moreover, it is to be noted that with an increase in weight, we need more power which again trades with the inclusions of extra batteries. Though for small scale aircraft architecture, electrification seems favorable. For huge commercial aircraft, this doesn't seem to be a realistic idea for completely inclining to electric-based propulsion. However, the flight phase-specific usage of power by switching between conventional and non-conventional systems may prove to be useful. It can be noted from Fig. 10 how mass inclusions trade-off with the range and time of operation of an aircraft.

3.3.3 Influence in thrust and drag of the aircraft

Unlike electric aircraft propulsions, the rotatory speed of the propeller/fan is related to the operating speed of the turbine. Due to the power transmission between these mediums, complete utilization of the power is not possible as there will be some losses during transmission. In contrast, in an electric-based propulsion architecture, the fan and turbine are not directly related, they are decoupled, thus facilitating both to be operated to their maximum/ideal capacity. Due to such decoupling, there will be relatively low losses of energy during transmission. A hike in the efficiency is noted with a combined effect of about 4% to 8% for transport category turboelectric aircraft.[47] This significant benefit in efficiency is noted, even without adopting a distributed propulsion technique.

Boundary-layer ingestion is another novel idea in enhancing the propulsive efficiency of the turboelectric

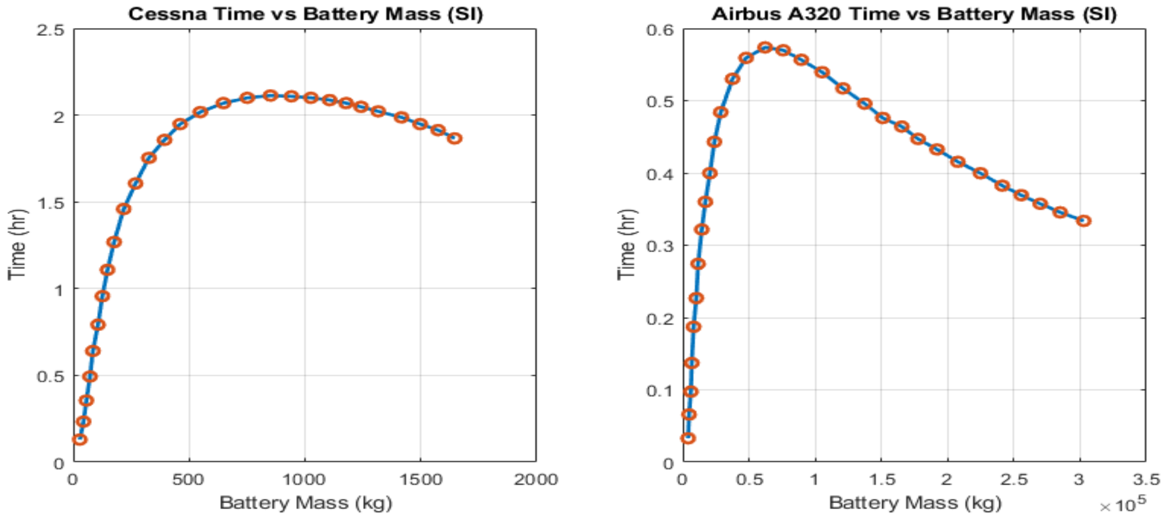

Fig. 10 Time of flight Vs. Battery mass for small private and large commercial aircraft upon electrification. Reproduced with the permission form [46]. Copyright@ Proceedings of the IEEE.

aircraft, where the boundary level slow-moving air, is accelerated with the aid of the turbine engine mostly located at the nose cone of the aircraft. The suction from the inlet of the fan brings a variation in the pressure distribution upstream, and the fan outflow will energize the wake.[22,48] Even though BLI engines (Fig. 11) are considered to enhance the overall efficiency of the aircraft, due to their mechanism in operation and there is a rising conflict as to whether consider BLI engines as drag reducers or efficiency enhancers. Due to the extension of the boundary layer over an aircraft over small thickness ranges, the collective installation of fans to accelerate flow will prove to be a lot more efficient, as large amount of slow-moving air can be accelerated and used effectively for thrust, which otherwise goes useless and induces drag. The effectiveness of the BLI engines depends on the flux of air flowing through the inlet.[49]

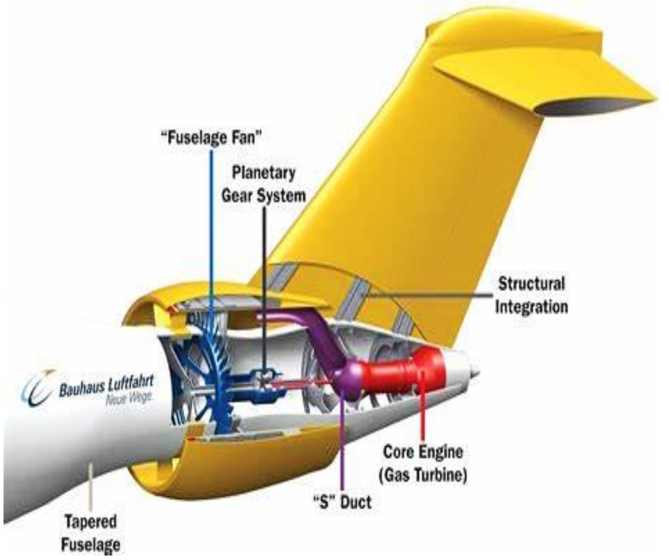

Fig. 11 Boundary Layer Ingestion Engine. Reproduced with the permission form [50]. Copyright@aerospacengineering.net.

While electric propulsion solves a few of the most intriguing problems, the complexity due to vibration and hot environments should also be taken into consideration. In addition, the design of the electronics housing, power distribution, and mechanical loading are also key parameters to be paid heed to.

3.1.3 Other effects

In defence aviation sectors, stealth and technology advancement are key aspects for an aerial advantage over the enemy troops. In such cases, reducing/elimination of heat and noise signals is much desirable to evade detection. With such electric-based architectures, the heat and noise signatures are almost eliminated. Donateo *et al*.[51] describe a UAS with an electric-only mode to avoid generating a thermal signature. The conventional combustion engines generally give weight, performance, and efficiency penalty when their size is scaled down. However, this is not the case with electric engines as these scales almost linearly.

3.2 Effects on the safety of aircraft operation

The majority of the hazards to which electric aircraft are exposed are similar to conventional aircraft, and there are direct ways of mitigating them subjected to current certification necessities. Out of several possible jeopardies in the design, construction and operation of an electric aircraft, few of the most important hazards that needs to be scrutinized along with the level of intensity are stated in Table 5.[52] While hazards do exist, there are also well researched and certified means of mitigating such cons. For example, the hazard posed by a single motor component failure is effectively mitigated by redundant motors, a control system sized for sufficient control in that engine-out case, and design and production standards on the motor component itself. In terms of this hazard, electric aircraft are the same or potentially better than conventional gas-powered vehicles. Component failure and other well-understood hazards such as structural failure do not constitute key hazard categories and thus are not discussed further.

Table 5. Key safety issues and their level of intensity.

Hazard Description	Multirotor	Distributed Electric Propulsion Powered Lift	Powered Lift	Fixed Wing
Battery Thermal Runaway	High	High	High	High
Battery Energy Uncertainty	High	High	Medium	Medium
Common Mode Power failure (Low/high Altitude)	High	High/Medium	Medium	Medium
High Level Autonomy Failure	High	High	High	High
Fly-By-Wire System Failure	High	High	Low	Low
Bird Strike	Medium	Medium	Medium	Medium

One of the major drawbacks of the electric-based propulsion system is the hazard of Thermal Runaway. A fluctuating variation in temperature and pressure within the batteries may cause fire and even explosion. Such a hazard is usually a result of excessive charging/discharging or short circuits. In such cases, toxic gases are also released, making it dangerous for the pilot and the passengers. Moreover, unlike a conventional aircraft, the fuel mass doesn't reduce with the flight. If the battery experiences thermal runaway by some chance, without proper functioning, it may add empty weight to the aircraft toppling the advantages offered. During the testing of a Li-ion battery setup for the X-57 aircraft, a major thermal runaway occurred which added an empty weight of 45 Kg to the system. This led to a major redesign of the battery module.[27] Due to the consolidated effect of power loss and the extent of structural damage that can be induced to the aircraft, Thermal runaway is placed among the top lists of critical concerns for the X-57 program.[48] Few possible ways of mitigation includes isolation of the battery pack(s) from the central passenger cabin in a weigth efficient manner to enhance the safety of the passengers had there been an unfortunate incident of continual thermal runaway. Other possible implementations include advanced lightweight fire supression technologies, improved electrical protection *etc*. However, such technologies are currently in the frills of research practical implementation and might take years before proper certification from governing bodies like FAA.

Crashworthiness is an area of potential benefit but high uncertainty. Liquid fuel, an obvious hazard following a crash, is replaced with battery modules. While no aircraft have faced survivable crashes with sizable lithium battery packs, electric automobiles will be a valuable source of data; automotive design practices for crash-tolerance of lithium batteries are reviewed in Ref.[53]. High-voltage electrical systems present another novel hazard in aircraft design. In-flight hazards include the release of energy through short circuits and arcing. Despite the safety hazard issue by electric propulsion systems, an all-electric aircraft eliminates turbines and hence the dependencies on bladed disks. According to the safety standards of the FAA, the bursting of turbine disks is a severe threat to safety and life. If certain critical flight components are exposed to such bursting, it may prove to be very fatal.[52,54]

4. Conclusion

The alarming concern because of enormous fuel usage and extensive pollution associated with the current modern fuel-based aviation industry is to look for an alternative source for airborne vehicles and the need for a clean, green, and economical means of aviation sprouted the need for electric aircraft propulsion.

The following are the conclusions drawn from extensive research in the area:

- High power requirement is not just for taking off the weight of the plane from the ground but is also bounded by several other constraints like runway length, aeroplane build, and fuel efficiency. So, in such phases of flight, where high power is required, the SP of the batteries is expected to be higher. For an all-electric based propulsion, batteries are expected to instantly meet this power demand and hence higher SP. But on the dark side, a higher SP trades off with SE which in turn may influence the range of the aircraft, which is very significant from the commercial aviation industry point of view.
- For a better and favorable design of non-conventional aircraft with efficient performance, HSP is required. Non-cryogenic systems are the backbone for several concepts and prototypes on electric aircraft. Hybrid engines enable the pilot to selectively prefer specific means of propulsion according to the phase of the flight being undertaken.
- NASA's “X-57” Maxwell is an ambitious prototype [as compared to earlier] involving distributed electric propulsion, which aims to give high power to weight ratio, with reduced drag and enhanced aerodynamic properties. “E-Fan X” is the hybrid electric flying aircraft concept by the combined effort of Airbus, Rolls-royce, and Siemens. This demonstrator, which is built based on the Bae-146 platform, will equip itself with three turbofans and one 2 MW electric motor, expected to make its first flight by late 2020. Scalable Convergent Electric Propulsion Technology and Operations Research [SCEPTOR] is one of the best research projects of NASA launched in 2014 at widely varying power scales.
- For small scale aircraft, architecture electrification seems favorable and for huge commercial aircraft, this doesn’t seem to be a realistic idea for completely inclining to electric-based propulsion. However, the flight phase-specific usage of power by switching between conventional and non-conventional systems may prove to be useful.
- In an electric-based propulsion architecture, the fan and turbine are not directly related, they are decoupled, thus facilitating both to be operated to their maximum/ideal capacity. Due to such decoupling, there will be relatively low losses of energy during transmission.
- Boundary-Layer Ingestion is another novel idea in enhancing the propulsive efficiency of the turboelectric aircraft, where the boundary level slow-moving air, is accelerated with the aid of the turbine engine mostly located at the nose cone of the aircraft.

Nomenclature

Abbreviation	Full-Form
SP	Specific Power
SE	Specific Energy
W	Watt
DOH	Degree of Hybridization
MTOW	Maximum Take-Off Weight
HSP	High Specific Power
HTS	High-Temperature Superconductor
EP	Electric Propulsion
TOGW	Take of Gross Weight
AC	Alternating Current
DC	Direct Current

OEW	Operating Empty Weight
YBCO	Yttrium Barium Copper Oxide
BSCCO	Bismuth Strontium Calcium Copper Oxide
LH2	Liquid Hydrogen
LCH4	Liquid Methane
HALE	High-Altitude Long-Endurance
SUGAR	Subsonic Ultra-Green Aircraft
HWB	Hybrid Wing Body
SCEPTOR	Scalable Convergent Electric Propulsion Technology and Operations Research
LEAPtech	Leading Edge Asynchronous Propellers Technology
STARC	Single-Aisle Turboelectric Aircraft
PEGASUS	Parallel Electric-Gas Architecture with Synergistic Utilization Scheme
BLI	Boundary-Layer Ingestion
R	Range
nm	Nautical meters
η	efficiency
E	Electric
TO	Take-off
FAA	Federal Aviation Administration
AR	Aspect Ratio
TE	Turboelectric
HE	Hybrid Electric
SHE	Series Hybrid Electric
PHE	Parallel Hybrid Electric
PH	Partial Hybrid
FC	Fuel Cell

Conflict of interest

There are no conflicts to declare.

Supporting information

Not applicable.

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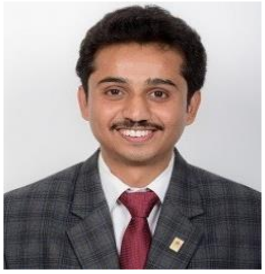
Author Information

Aravind Karthik *is a senior year aeronautics Honours student pursuing his Bachelors program at Manipal Institute of Technology, India. His primary field of interest lies in research and development on Hypersonics, Electric Propulsion, Numerical techniques & composites and has actively contributed to several research projects on the same. He has diverse experience with leading labs like Defence research & Development Laboratory to develop novel projects on scramjet propulsion. He is a currently a student affiliate in Royal Aeronautical Society, Space and Satellite Professionals International and an active contributor to the DIY community, working on exploring Reduced Order Modelling techniques for CFD optimization.*



Dundesh S Chiniwar *is currently working as an Assistant Professor in Department of Mechatronics Engineering since 2013 and is also serving as Associate NCC Officer (ANO) of 4 Karnataka Engineering Company, NCC Unit, Manipal Institute of Technology, Manipal, Karnataka. He has 10 Months work experience as a Project Assistant at CSIR Laboratory National Institute for Interdisciplinary Science and Technology (NIIST) Thiruvananthapuram, Kerala. His research interests include Additive Manufacturing, Smart Manufacturing and Casting Simulation.*

Mayukh Das *is an alumnus of Manipal Institute of Technology, currently working as a fresher at Cognizant Technology Systems. His primary fields of interest lie in research and development pertaining to Artificial Intelligence, Model Training and Internet of Things and is currently working on various projects in these fields. Trained in the Automobile Engineering discipline he possesses diverse knowledge across various backgrounds and works to create innovative long term automotive solutions using Artificial Intelligence and Neural Network tools for a better, safer and more innovative automotive.*

Prashanth Pai M *is currently working as Associate Professor and Head, Department of Mechanical Engineering, P. A. College of Engineering, Mangalore. He received Ph.D. from Visvesvaraya Technological University, Belagavi, Karnataka, India. He is having 18 years of teaching experience at UG level. His areas of research include maintenance and reliability engineering, quality control, lean manufacturing, total productive maintenance and materials engineering. He is the life member of Indian Society for Technical Education, Indian Society of Mechanical Engineers and International Association of Engineers. He has attended more than 30 faculty development programmes and presented/published technical papers in national/international conferences.*

Phalguni Prabhu *is a senior year aeronautics honours student pursuing her bachelors' program at Srinivas Institute of Technology, Mangalore, India. Her primary field of interest lies in research and development on Aircraft Propulsion, Turbomachinery & Combustion physics and has actively contributed to several research projects on the same. She has diverse experiences with leading labs like modelling and analysis and machine shop laboratory. She is currently a student affiliate in Amara association. She is currently working on performance evaluation Of Multiple Coaxial Jet Nozzle System in Combustor of Gas Turbine in Aircraft Engine.*

Prashant A Mulimani *is working as Assistant Professor at Smt Kamala and Sri Venkappa M Agadi College of Engineering and Technology Lakshmeswar, Gadag. His primary field of interest lies in research and development in Numerical techniques & composites and has actively contributed to several research projects on the same.*

Kaustubh Samanth *is a mechanical engineer, graduated from SJCE, Mysuru. He is a master's student of Aerospace at the Technical University of Munich. Composites, aerospace structures, and urban mobility are his field of interests. He is also working on different research topics in these fields. He has also worked on the design of Go-Karts, All-Terrain vehicles. He carries a work experience of 2 years with Mercedes Benz R&D, India in the field of vehicle integration.*

Nithesh Naik *is a faculty in the Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology. He has four years of industry experience in the field of planning and design of HVAC systems. He is a master graduate in Design Engineering from prestigious university Manipal Academy of Higher Education (Institute of Eminence). His research interest includes the development of FE analysis of dental sciences, artificial intelligence, composite materials and design and product development techniques. He has applied 4 patents at Indian Patent Office. He has published several research publications in international journals of repute and has keen interests in medical innovations. He received the award of South India's most exciting young teacher. His areas of expertise include FE analysis of dental and medical sciences, composite materials, design and product development, medical devices and innovations, artificial intelligence, medical web and app development.*