Chapter 5

Electric Drives for Propulsion System of Transport Aircraft

Clément Pornet

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61506

Abstract

Following the hybridization or complete electrification strategy of the electric drive pursued on terrestrial vehicles, the aviation industry is considering with great attention the application of electrical technology and power electronics for transport aircraft. The growing interest towards electric application in transport aircraft is driven by the ambitious targets for aviation declared by Europe and by the United-States of America and is motivated by the growing evidence that evolutionary improvement of the technologies might not be sufficient to fulfill these targets. As a result, the introduction of disruptive technologies turns out to be essential. With respect to the progress and perspective in electrical technology, electric drive applications to transport aircraft reveals itself to be a promising field in view of meeting the future goals.

The focus of this chapter is the assessment of the electrification of the propulsion system of transport aircraft. While aiming for the ultimate goal of universally-electric aircraft, hybrid-electric approach will be first necessary to match the requirement of aircraft propulsion system and the development pace of the electrical components technology. The combinatorial variety of hybrid-electric and universally-electric propulsion system topology considered for transport aircraft application as well as key enabling technologies are first reviewed. A compendium of hybrid-electric and universally-electric advanced aircraft concepts is then proposed to obtain a notion of the cloud of aircraft configurations and electric drive options investigated up to this point in time. Finally, the integrated prospects of hybrid-electric aircraft are investigated to establish the feasibility of hybrid-electric aircraft for future market segments.

Keywords: Hybrid-electric aircraft, Universally-electric aircraft, Hybrid-electric propulsion topology, Battery-fuel hybrid propulsion system, Aircraft conceptual design, Aircraft Sizing, Aircraft Performance

1. Introduction

Following the hybridization or complete electrification strategy of the electric drive pursued on terrestrial vehicles, the aviation industry is considering with great attention the application of electrical technology and power electronics for transport aircraft. The growing interest towards electric application in transport aircraft is driven first by the ambitious emissions and external noise reduction targets declared by Europe in the Flightpath 2050 program and the corresponding Strategic Research and Innovation Agenda (SRIA) [1] and by the United-States of America in the NASA Environmentally Responsible Aviation N+ series [2]. It is then motivated by the growing evidence that evolutionary improvement of the technologies might not be sufficient to fulfill these targets. Investigations [3] have shown that the reduction potentials might fall short of the 2035 targets and that the deficit becomes even more substantial towards the 2050 goals. This trend can be best explained by the very high maturity reached by contemporary technologies, in particular the propulsion system technology implemented in transport aircraft. Prospects for technological improvements have consequently reached an asymptote leaving not enough potentials for achieving the aggressive targets. As a result, the introduction of disruptive technologies turns out to be essential in view of meeting the future aviation goals. Finally, the progress and perspective in electrical technology development trigger the initiatives and the extensive research activities deployed by the aeronautical community to investigate the feasibility and the potentials of electric technology application to transport aircraft.

A current application of electrical technology for transport aircraft is the so-called more-electric aircraft [67-71]. The objective of the more-electric aircraft initiative, which targets the aircraft power systems, is basically to replace pneumatic and hydraulic systems by electrical systems. The Boeing B787 is the first aircraft utilizing a more electric power system architecture. A logical future conceivable step is the electrification of the propulsion system of the aircraft which is the topic of this chapter. While aiming for the ultimate goal of an universally-electric aircraft, hybrid-electric approach will be first necessary to match the requirement of aircraft propulsion system and the development pace of the electrical components technology. Hybrid-electric aircraft feature typically a combined conventional and electrical propulsion system. The combinatorial variety of hybrid-electric and universally-electric propulsion system topology considered for transport aircraft application as well as enabling technologies are first discussed in Section 2. A compendium of hybrid and universally-electric advanced aircraft concepts is then proposed in Section 3 to obtain a notion of the cloud of aircraft configurations and electric drive options investigated up to this point in time. The feasibility of hybrid-electric aircraft needs to be established for future market segments. On the basis of selected concepts, the integrated prospects of hybrid-electric aircraft are finally investigated in Section 4.

2. Hybrid-electric and universally-electric propulsion system architecture

An overview of the topological variety of propulsion systems featuring an electric drive approach is presented in this section. Electric approaches to aircraft propulsion system are known as hybrid-electric and universally-electric [4]. By distinguishing between the generation and the transmission to the drive-shaft, the components and their possible combination for the layout of hybrid-electric and universally-electric propulsion system architecture can be illustrated as in Figure 1 [5]. Focusing on the propulsion system, the consumer of electric power is the propulsive device. Ducted and unducted propulsors are typically considered to provide the thrust required to propel transport aircraft. The commonly known-term ducted-fan is understood to be covered by the category ducted propulsor while unducted propulsor includes propeller and open-rotor arrangements.

In a conventional propulsion system, shaft power is generated by burning fuel in a gas-turbine. A gas-turbine converts chemical energy into mechanical power through an aero-thermodynamical process. In an electrical propulsion system, shaft power is produced through a process that can be subdivided into the generation, the distribution and the conversion of electrical energy into mechanical power.

For transport aircraft application, batteries and fuel cells are considered for the generation of electrical energy. Even if not explicitly shown in Figure 1, supercapacitors or flywheels could be also considered in a layout of a hybrid-electric propulsion system [6]. Another means of producing electrical power is through the utilization of a generator driven by a conventional gas-turbine. Known under the terminology of turboelectric, it is discussed in more detail in Section 2.1.1. The electric energy is monitored and distributed from the sources to the consumers by a Power Management and Distribution system (PMAD). The PMAD is typically composed of controllers, converters, inverters, cables, electrical buses and circuit breakers. The layout of the PMAD system is a rather complex task. Optimum layout of the PMAD system results from the analysis of system efficiency, mass, bill-of-material, reliability and maintenance under constraints of abnormal mode of operation. Another important aspect related to the electrical system is thermal regulation to provide for every operating condition an appropriate thermal environment to the electrical and power electronics components. The consideration of thermal management is essential in the early design phase of the integrated electric drive due to its highly-interlaced interactions with the propulsion and power systems. Presenting the development of a framework for concurrent sizing of the powertrain and the thermal management system, Freeman et al. [7] highlighted the design options and implications of thermal management. Three main options for thermal regulation were discussed [7] including air cooling, liquid cooling and cryogenic cooling system providing the advantages and drawbacks of each options in terms of system performance, integration implications, complexity and bill-of-material. The critical importance of adequate flow rate for heat transfer ensuring a proper thermal regulation of the electrical components was highlighted. Freeman et al. [7] predicted the revival of radiator technology due to the introduction of electric drive. The design considerations of radiators were described as well as their interactions with the propulsion system and the implications at aircraft level in terms of weight and parasitic drag. The potential synergistic use of the excess heat produced by the electrical components for anti-icing system, cabin Environmental Control System and galleys were also indicated [7]. The thermal management system needs to be integrated globally. The necessity of a transverse approach is argued by Liscouet-Hanke [8] in order to avoid developing localized dedicated engineered thermal management solutions for each of the electrical components.

In order to drive the propulsor device, the electric energy is converted into shaft power by an electric motor (see Section 4.2). It can drive by itself the propulsor device or it can be mounted on the shaft of a combustion engine to support its operations. This latest arrangement known as a parallel system is discussed in Section 2.1.2. Due to the nature of the electric energy which can be easily partitioned, the field of distributed propulsion which aims to achieve highly coupled structural-aero-propulsive configurations, is often combined to hybrid-electric and universally-electric approaches (see Section 2.2.3).

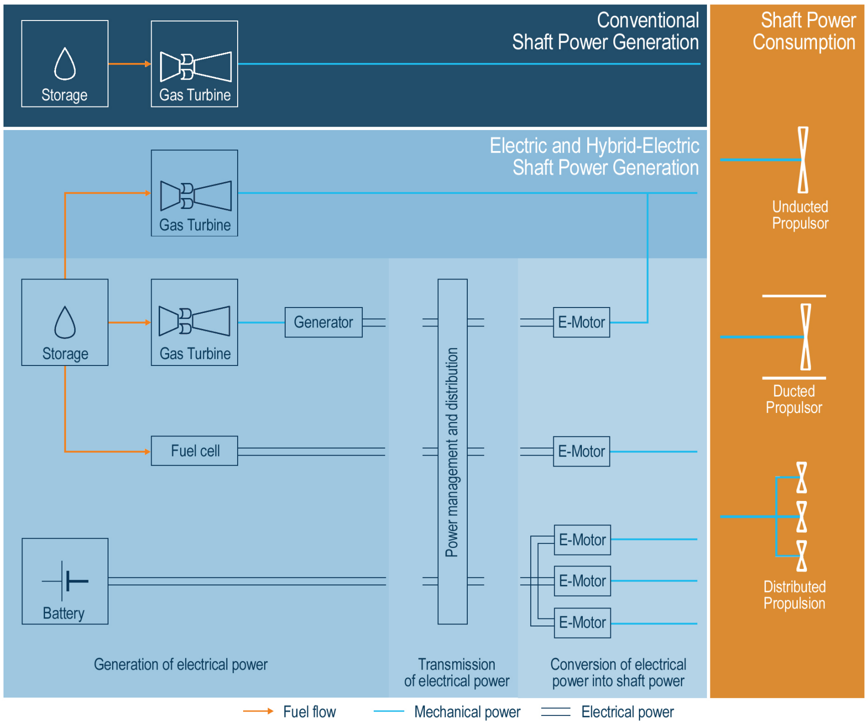

Figure 1. Conventional, hybrid and universally-electric propulsion system topology [5]

2.1. Topological options for electric drive application

The topological options for the application of electric drives to the propulsion system of transport aircraft are detailed in the following sections. The discussion covers serial, parallel as well as integrated arrangements.

2.1.1. Serial system

A general characterization of a serial system is given by the electrical nature of the node connecting the different systems composing the propulsion power-train. The most common serial arrangement is known as turboelectric [9–12]. It denotes a serial system where electric power is produced by a generator driven by a combustion engine typically a gas-turbine. Efficiency improvement in the propulsion system results notably from the advantage that the gas-turbine operation is now decoupled from the operational constraints of the propulsor [9, 13]. The system efficiency and mass can consequently be optimized by operating the gas-turbine and the propulsor close to their peak efficiency. However, because of the greater bill-of-material due to the additional electrical components, in the propulsion chain, the weight of the system is expected to increase compared to a conventional propulsion system [9]. In order to make this approach viable at aircraft level, this penalizing aspect needs to be overcome by any improvements in system efficiency and/or structural-aero-propulsive integration (see Section 2.2.3).

A serial system using fuel-cells as means of electrical energy generation can be entertained. The efficiency of advanced fuel cells including the balance-of-plant is forecast to reach efficiency levels comparable to that of advanced gas-turbines. However, the power density of fuel cell stack is expected to remain much lower than that of a gas-turbine [14]. The weight penalty might consequently outweigh potential benefits. The unique utilization of fuel cells for providing the power requirement for the propulsion of transport aircraft remains consequently challenging [15].

A serial system whose electrical energy providers are batteries solely was dubbed as universally-electric architecture [4]. The clear advantage of utilizing battery in a propulsion system is the efficiency. With values remaining above 90% during a complete mission profile [16] significant improvement in overall propulsion system efficiency can be achieved compared to a conventional system. However, the gravimetric specific energy (the amount of energy content per unit mass) of advanced batteries is expected to remain relatively low, with a factor of about 8 compared to fossil fuel based on a complete system exergy analysis [17]. Consequently, the weight of the battery and its detrimental sizing cascading impacts on the overall aircraft penalizes the efficiency benefit.

As a result of all these considerations, serial arrangement combining for instance a turboelectric system with battery and/or fuel cell system are considered [14] to draw the advantages of each of the system and to create system synergies in order to achieve greater system performance to the detriment of a higher system complexity. This is notably the approach undertaken by Airbus with the E-Thrust concept [18], which combines a turboelectric system with batteries. Innovative, synergistic integrated serial systems need to be further investigated at aircraft level in order to assess the full potential of hybrid-electric serial propulsion system.

2.1.2. Parallel system

A parallel system is characterized by mechanical nodes that connect the different systems. The most common parallel approach is the installation of an electric motor on the low-pressure shaft of a gas-turbine in order to support the operations of the gas-turbine or even drive by itself the propulsor device during segments of the mission [19–22]. Because of the benefit of utilizing battery on the overall propulsion system efficiency, the electric motor is commonly powered by batteries but the utilization of fuel cells is also conceivable. However, it was found that driving simultaneously the shaft of the gas-turbine by an electric motor influences dramatically the operation of the gas-turbine. The simultaneous operation of the electric motor forced notably the gas-turbine to operate into part-load impairing its efficiency. Moreover, due to the modification of the operating line of the gas-turbine components, the margin to surge might also become critical. Practical engineering solutions need to be envisioned for the integration of the electric motor in the environment of the gas-turbine. Parallel integration of an electric motor on the low-pressure shaft could consequently disrupt contemporary design axioms of gas-turbines.

2.1.3. Distributed parallel system

In view of these challenges and motivated by the search for more synergistic integration, an innovative approach to a parallel hybrid-electric propulsion system was proposed by Pornet and Isikveren [23] taking advantage of distributed propulsion technology (see Section 2.2.3). Instead of coupling the electric motor to the shaft of the gas-turbine, the electric motor is coupled directly to the shaft of the propulsor and the combination electric motor and propulsive device (called electric-fan) is integrated on the aircraft as an additional bill-of-material item to the conventional combustion based engines. Concrete aircraft concepts would be a tri-fan aircraft with two fans conventionally powered by gas-turbines while the remaining fan is driven by an electric motor (or vice versa with two electric fans and one turbofan aft-fuselage mounted), or, as a quad-fan aircraft equipped with two turbofans and two electric fans. The integrated prospects of this latest concept are the subject of the investigation presented in Section 4.4. This approach offers numerous advantages compared to mounting the electric motor on the low-pressure shaft of the gas-turbine. As the conventional system is decoupled from the electrical system, design and operation of the conventional and electrical system are independent. As a result, contemporary design and off-design heuristics of the gas-turbine are not perturbed by the introduction of the electrical system. Moreover, it reduces the system complexity and clears out the integration challenges of the electric motor in the environment of a gas-turbine. By thoughtful sizing and operational strategy of the gas-turbine and the electric motor, the efficiency of the hybrid propulsion system can be optimized by running the conventional and electrical system close to their peak efficiencies. This innovative parallel hybrid arrangement marries up perfectly with distributed propulsion technology opening potentials for tightly aero-propulsive-structural integration.

While in the architecture investigated in [23], the electric motors are powered solely by batteries, a further topological evolution of the distributed propulsion system can be conceived with the introduction of a turboelectric approach. By equipping the gas-turbine with a generator, additional electric power can be transmitted to the electric motors. This system approach reduces the technological level requirement imposed to the battery in terms of gravimetric specific energy while enabling significant increase in system efficiency when using the highly efficient battery system for propulsion. This topology is also interesting as it enables the possible combination of charge sustaining and charge depleting strategies of the batteries for optimum energy management [24, 25]. Charge sustaining strategy, recharging the battery with the generator utilizing excess power of the gas-turbine during segments of the mission, would reduce the integrated battery pack mass and volume requirement. A schematic representation of this topology is given in Figure 2.

2.1.4. Integrated system

While not illustrated in Figure 1, another recent approach for hybrid-electric system to be considered is the so-called integrated system [26, 27] which consists of electrifying part of the core cycle of a gas-turbine. A possible configuration for hybrid-electric integrated system was proposed by Schmitz and Hornung [28] investigating the electrification of the high-pressure compressor stages of a gas-turbine. Still in a pioneering phase, few publications are currently available on this topic but it is definitely an application to follow closely as it gathers momentum.

2.2. Enabling technologies for electric drive application to transport aircraft

Technologies considered as key enablers for the deployment of electric drives to the propulsion system of transport aircraft are discussed in this section. The application of the field of superconductivity to electric propulsion system is first reviewed followed by a discussion about distributed propulsion technology.

2.2.1. Energy storage

Technology improvement of the electrical components discussed in Section 2 in terms of gravimetric specific power and efficiency are of particular importance for the application

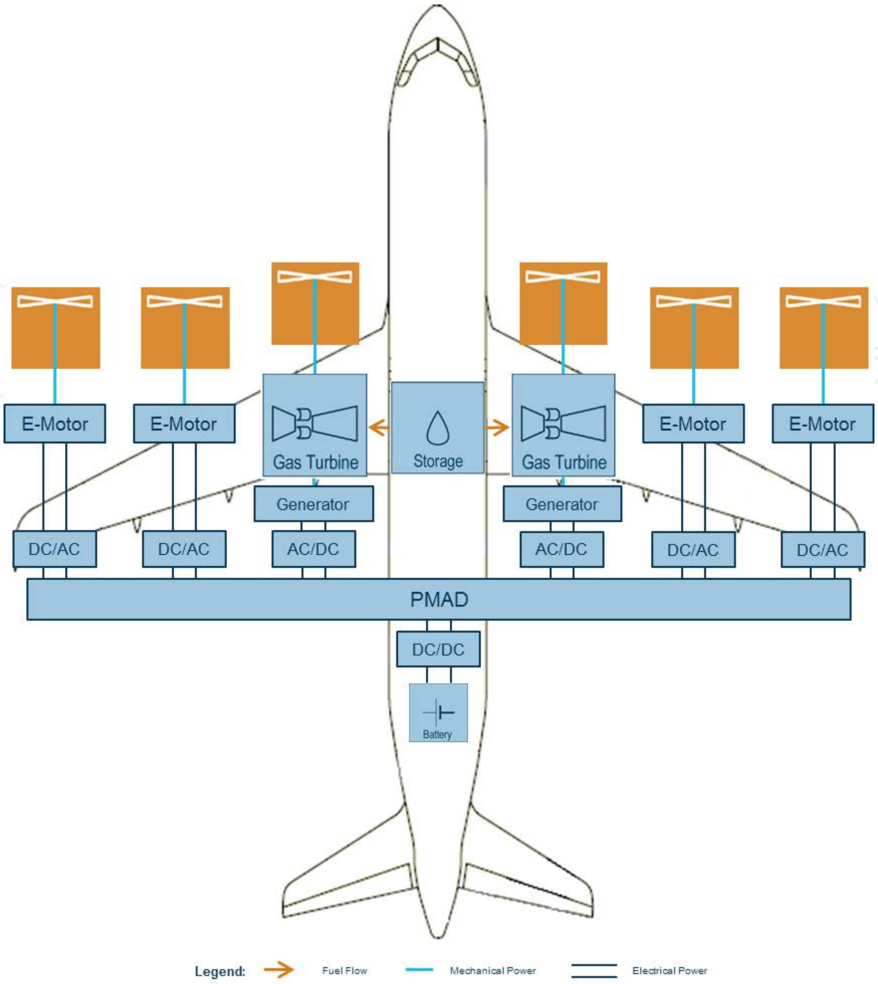

Figure 2. Distributed parallel hybrid-electric topology for distributed fans arrangement

of electric drive to transport aircraft. But most importantly, the evolution of energy storage capability, in particular, the progress made in battery technology is of great relevance for establishing the competitiveness of hybrid-electric and universally-electric aircraft. Gravimetric specific power (the amount of power delivered per unit of mass) and gravimetric specific energy (amount of energy contained per unit of mass) are the key metrics for evaluating the battery application. These parameters are not independent characteristics and they are determined during battery design [29]. As a result, the combined enhancement of the specific energy and the specific power turns out to be a greater technological challenge than the single criterion optimization. Additional aspects such as gravimetric specific energy density, efficiency, design service goal, operating temperature, discharge behavior, safety, reliability and environmental sustainability need also to be considered when selecting the battery technology [30].

Lithium battery technology is regarded as a promising option for application in aviation. State-of-the-art lithium batteries reach specific energy of circa 200 Wh/kg at cell-level [31]. Extensive research focusing on improving the cathode and anode materials as well as on enhancing electrolyte properties [30, 32] aim to scale up the power and energy capability of batteries for aircraft application. Specific energy of around 400 Wh/kg is predicted to be achieved at cell-level through future progress in lithium battery technology [33].

Breakthrough in battery technology could be achieved through the development of innovative battery concept as indicated by open battery systems like zinc-air, aluminium-air and lithium-air [32, 34]. Lithium-air batteries are considered with attention for aircraft application with estimated theoretical gravimetric specific energy from 1000 Wh/kg [33, 35] up to 2000 Wh/kg [36] at cell-level. Not currently commercially available, market readiness of lithium-air is expected for a time-line horizon of 2030 [37].

2.2.2. Superconductivity

Superconductivity is considered as an enabling technology for electric drive application to transport aircraft [13, 38, 39]. Through the utilization of High-Temperature Superconducting (HTS) materials, the gravimetric specific power and the efficiency of the electrical component can be significantly improved. The most common application of HTS materials at this point in time is for electric motors and generators [38, 40, 41]. The application of HTS technology to the transmission cable is also considered [10, 11]. The necessity of developing fully superconducting network (including the fault management, protection and switching implications) was argued by Malkin and Pagonis [42]. The challenge of HTS application for transport aircraft lies essentially on the requirement to operate at cryogenic temperature and the resulting complex integration of the cooling system. Instead of using fossil fuels to operate the aircraft, the utilization of cryogenic fuel such as liquid hydrogen can result in strong synergies with the layout of HTS electrical system as the coolant is already available [10, 13, 39]. Handling safety related issues [43], the negative integration impacts of the cryogenic tank on aircraft design [44] and the infrastructural challenges to supply the liquid hydrogen to the operated airports all are issues that remain unresolved [45, 46].

2.2.3. Distributed propulsion

The investigation of hybrid-electric or universally-electric system is often coupled with distributed propulsion technology [72-75]. This combination is explained by the nature of the electric energy, which can be easily distributed and by the search for aero-structural benefits through higher integration of the propulsive device with the airframe. The field of Boundary Layer Ingestion (BLI) [47, 75] consisting of re-energizing the low momentum boundary layer in view of aerodynamic efficiency improvement, becomes central. This is mainly the reason why distributed propulsion has been intensively investigated on Blended Wing Body (BWB) configuration [12, 48] as it offers large potential for application of BLI by distributing buried propulsion devices along the trailing-edge of the fuselage (see Section 3). For BLI application on tube and wing configurations, the Propulsive Fuselage configuration, which is characterized by a large fan encircling the rear end of the fuselage, was evaluated as most promising and was the center of several investigations [49–53].

Electric distributed propulsion technology is expected to disrupt the traditional aircraft design paradigms [54–56]. A salient example is the redesign of the wing for optimum efficiency in cruise enabled by distributing propellers along the leading-edge as initiated in the LeapTech Project [57] (see Section 3). Usually, wing design is constrained by low-speed operations in order to achieve according to the properties of the high-lift system acceptable takeoff and landing field performance. Benefiting from the propeller slip-stream effect on the wing, the low-speed requirement on high-lift devices and wing design could be reduced, opening the design space for optimum wing design for en-route operations. Moreover differential thrust could be applied to control the aircraft reducing the requirement on flight control surfaces. The distribution of thrust along the wingspan could enable for instance the control of the aircraft yawing motion resulting in reducing or even conceived the complete removal of the rudder. The one-engine-inoperative case is a very stringent low-speed condition for the sizing of the propulsion system, vertical stabilizer and flight control surfaces in order to comply to the airworthiness regulations and the aircraft top-level field performance requirement. Because of the intrinsic redundancy in thrust production provided by distributed propulsion technology and through a proper redundancy definition in the energy and power system, failure modes either energy/power system inoperative or propulsive device inoperative would result in less severe penalty on system sizing [58, 59]. It is also conceivable that the airworthiness regulations notably with respect to the climb gradient requirements will need to be revisited to adapt to the characteristics of aircraft employing distributed propulsion technology. These highlighted potential benefits in aircraft design demonstrate that the full-benefit of hybrid-electric and universally-electric propulsion system can only be assessed through a holistic integration at aircraft level.

3. Compendium of hybrid- and universally-electric aircraft

While the first fixed-wing electric flight took place for over 9 min in 1973 with the Brditschka′s MB-E124, it took around 30 years before reconsidering seriously electric propulsion system for transport aircraft application. This time lapse observed in the interest revival for electric drive application to aircraft propulsion is explained first by the time required for electrical component technology to evolve to a level applicable to the propulsion system requirement of transport aircraft. Secondly, it is driven by the growing environmental awareness and the search for an alternative to a fossil fuel economy. The late 1990 witnessed the birth of several electric experimental and commercial aircraft targeting the general aviation sector in the one or two seater category. While mainly motivated by engineering curiosity through the impulse of pioneers, the industry is currently demonstrating a strong growing interest in the development of hybrid-electric and universally-electric aircraft. A compendium of experimental, commercial as well as advanced hybrid-electric and universally-electric aircraft concepts, was proposed by Pornet and Isikveren [23]. By illustrating the cloud of concepts in Figure 3 evaluating the number of passenger (PAX) versus the design range (evaluated in nautical miles [nm]) certain clusters and trends in design can be identified.

This compendium comprises universally-electric aircraft concepts using battery as energy source with the four seater Airbus E-Fan [18], the four seater LeapTech concept [56, 57], the Dornier Do328-LBM [60] , the Voltair concept [61] and the BHL Ce-Liner [4] as well as hybrid-electric aircraft, integrating a battery-fuel system either in serial or parallel topology, with the NXG-50 [62], the Sugar-Volt [19], the Bauhaus Luftfahrt Twin-Fan [22] (see Section 4.3) and the Bauhaus Luftfahrt Quad-Fan [23] (see Section 4.4). On the upper right corner, BWB configuration using turboelectric distributed approach are represented with the BW-11 [48] and the N3-X [12].

As highlighted by [54], electric propulsion technology will emerge first in general aviation as it provides benefit advantages for early market success and will evolve with respect to the maturation and the development of electric technology towards application for commuter, regional and narrow-body transport aircraft. A noticeable design implication of utilizing

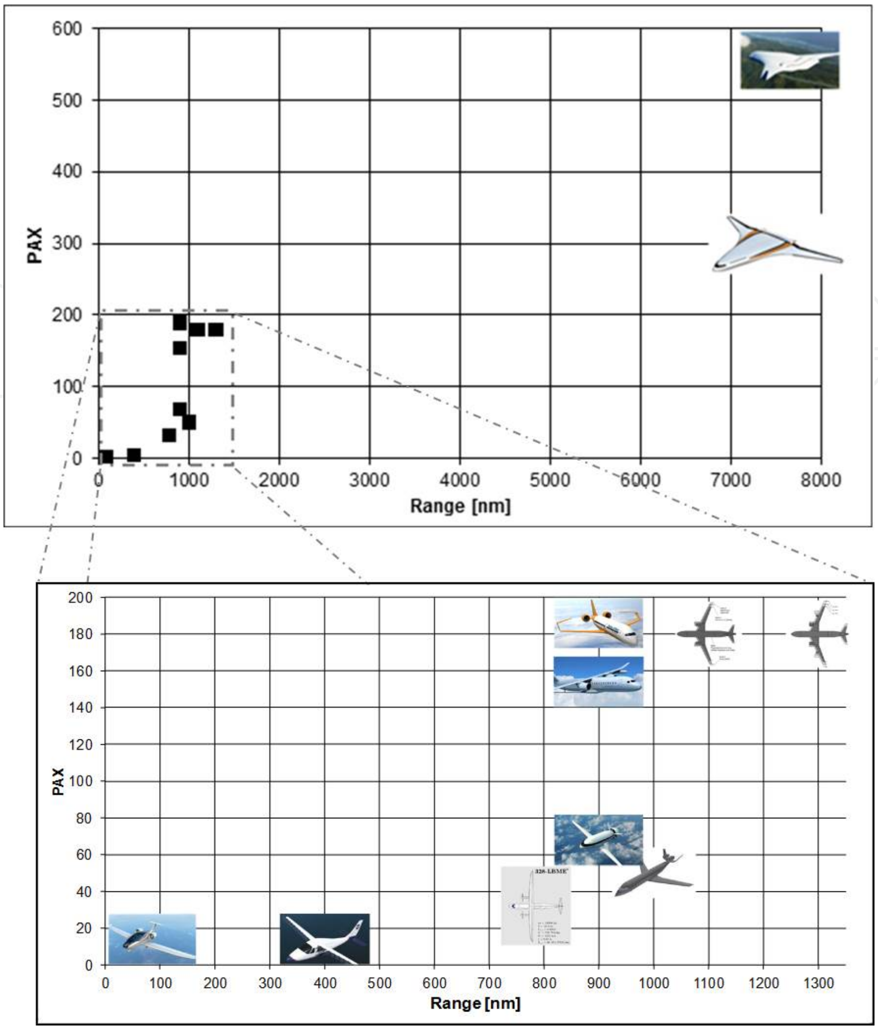

Figure 3. Compendium of advanced hybrid- and universally-electric aircraft. Adapted from [23]

an electric drive relying on battery technology is the achievable design range as indicated by the low range end on the left corner of the chart which reflects more of the regional market segment. With regards to morphology, besides the BWB configuration, no large departure from the traditional "tube and wing" were foreseen due to the implementation of hybrid-electric propulsion system. Outcome of pre-design studies investigated by Isikveren et al. [63] indicated that unless significant departure in the propulsion system integration is entertained, considering for instance distributed propulsion technology, the contemporary tube-and-wing morphology was still considered to be appropriate. Distributed propulsion technology could considerably disrupt contemporary aircraft design paradigm. This was exemplified by the LeapTech concept through distribution of multiple propellers on the wing leading-edge (see Section 2.2.3) and the Propulsive Fuselage configuration selected for the Voltair concept (see Section 2.2.3). The aviation community is in the midst of a pioneering era with regards to electro-mobility and faces an explosion of combinatorial possibilities at system level and aircraft level. Innovative approaches to electrically driven propulsion system needs to be further analyzed and thoughtfully integrated at aircraft level to determine the full potentials. With growing understanding of the technology and its implication at aircraft level, innovative advanced aircraft configurations designed through more ambitious holistically integrated electric propulsion system are expected to emerge.

4. Insights regarding integrated hybrid-electric transport aircraft

By reviewing concepts out of the cloud illustrated in Figure 3, insights regarding the integrated prospects of hybrid-electric transport aircraft are presented in this section. The development of algebraic parameters and figure-of-merits to enable the assessment of aircraft utilizing electric drive for the propulsion system are introduced first. The integration implications of the hybrid-electric propulsion system on aircraft overall sizing and performance are then detailed based on three investigated hybrid-electric narrow-body transport aircraft concepts.

4.1. Algebraic descriptors and figure-of-merits

The algebraic description of a hybrid-electric propulsion requires the establishment of two parametric descriptors [63, 64]: the Degree of Hybridization for Power (Hp) and the Degree of Hybridization for Energy (He). The parameter Hp describes the amount of electrical power relative to the overall total power. Commonly, the installed power or the useful power (power measured at the propulsor) is quoted. In the analyzes provided in the following, Hp referring to the useful power is denoted with Hp_{use}. The parameter He is the ratio of electric energy consumed over the total energy and it characterizes the so-called energy split. The quantity He is evaluated along a specified segment or mission. The parameter He_{block} refers, for instance, to the block mission. The need for the dual set of parametric descriptors is elucidated by Isikveren et al. [63] considering the following examples:

- Conventional kerosene based gas turbine propulsion system are described by a Hp and a He equal to zero.
- Pure serial hybrid-electric architecture where only electrical power is provided at the propulsive devices but the energy storage is solely kerosene based. In this case Hp equals 1 and He equals 0.
- Universally-electric aircraft where the energy storage is batteries only which is characterized by an Hp of 1 and an He of 1.

In addition to the algebraic descriptors characterizing the type of propulsion system, the establishment of figure-of-merits for the assessment of the vehicular efficiency is essential. Related to their instantaneous form, they are used for flight technique optimization to determine optimum altitude-speed technique as a function of the aircraft gross-weight, the aerodynamic efficiency and the overall propulsion system efficiency. The integrated form of the metrics along a given mission enables comparing the efficiency of different vehicles to complete an identical transport task. The traditional figure-of-merit used for vehicular efficiency assessment of fuel-based aircraft is the Specific Air Range (SAR). It characterizes the distance traveled per unit of fuel consumed. Optimizing an aircraft for maximum SAR results in minimizing its fuel consumption. This metric is however limited to aircraft using an energy type characterized by a mass flow. A generalization of the SAR was introduced by Seitz et al. [65] with the Energy Specific Air Range (ESAR) which determines the distance traveled per energy consumed. Maximizing ESAR results in minimizing the energy consumption of the aircraft. Optimizing for instance a universally-electric aircraft with respect to ESAR results in minimizing its electrical energy consumption. To enable the optimization of hybrid-energy transport aircraft for minimum energy cost, the COst Specific

Air Range (COSAR) was published by Pornet et al. [66]. The cost of the energy is not the only factor contributing to the total operating cost of an aircraft. Fixed costs and time dependent costs need to be also taken into account. Interested in minimizing the overall cost, airlines base their aircraft fleet operation on so-called Cost-Index which relates basically the cost of time to the cost of energy. A review of the Cost-Index traditionally used for fuel-based aircraft and the establishment of Cost-Index metric for hybrid-energy aircraft are found in [66].

4.2. Aircraft retrofit with hybrid-electric propulsion system

Retrofitting an existing aircraft with a hybrid-electric propulsion system enables having first insights about design parameters and constraints, the behavior of the propulsion system as well as in establishing the right interfaces between the propulsion system and any other aircraft systems. An under-wing podded twin engine narrow-body transport aircraft retrofitted with a hybrid-electric propulsion was investigated by Pornet et al. [21]. The retrofitting of the propulsion system consists of mounting an electric motor powered bybatteries in parallel to the low-pressure shaft of the gas-turbine to supportits operation during some segments of the mission. Due to the intrinsic nature of an aircraft retrofit, the certified Maximum Take-Off Weight (MTOW) of the baseline aircraft represents a design constraint not to be exceeded. The electrical system components including the batteries represent additional weight items. To provide the installation of the electrical system at aircraft level and still respect the MTOW limitation, the hybrid-electric propulsion system is utilized in off-design operations. As the baseline aircraft takes-off at a Take-Off Weight (TOW) lower than MTOW since less fuel is required to perform the off-design stage length, the delta weight available between TOW and MTOW makes the installation the electrical system possible. Sizing of the hybrid-electric propulsion system is the result of an interplay between the maximum power of the installed electric motor, which mainly determines the mass of the electrical system, the total battery mass required, the potential fuel burnreduction and the battery State-Of-Charge (SOC). The SOC characterizes the amount of energy available relative to the total energy of the battery. In order to protect the battery from any damage and to prolong design service goal suitable for use in aerospace, the battery must not be discharged below a certain SOC limit typically set at 20%. The design parameters and constraints are illustrated in the design chart in Figure 4.

It represents the sizing characteristics of the hybrid-electric propulsion system for the case of utilizing the electric motor during cruise only assuming a battery specific energy of 1500 Wh/kg at cell-level. The objective of this assessment was to achieve minimum fuel consumption at a stage length corresponding to peak in the utilization spectrum. For the baseline aircraft, the maximum utilization stage length was found to be 900 nm (1667 km). The total installed maximum power of the electric motor $\mathrm{P}_{maxEM,totalinst.}$ is varied between 4 to 8 MW and the power setting of the electric motor during cruise $(P/P_{max})_{EM,cruise}$ between 0% to 100%. To maximize the number of installed batteries, the TOW of the hybrid-electric aircraft was set equal to MTOW. The total mass of the installed battery was consequently an outcome of the sizing process. When the electric motor is not used during cruise as indicated by the power setting of 0%, the hybrid-electric aircraft consumes more fuel than the baseline aircraft due to the higher aircraft weight. When increasing the power setting of theelectric motor, more electric energy is consumed increasing the potential block fuel reduction. According to the electric maximum power installed, the battery SOC can become

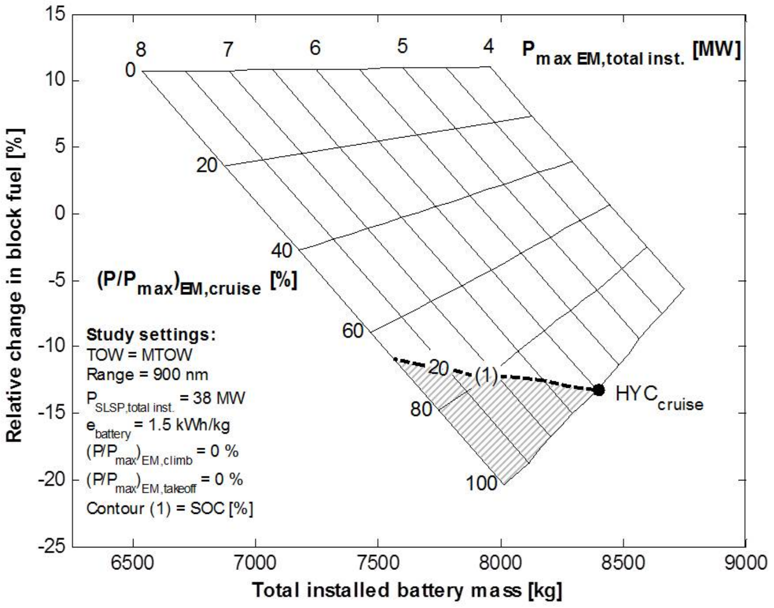

Figure 4. Design chart for hybrid-electric propulsion system in cruise [21]

a limiting factor. The optimum sizing of the hybrid-electric propulsion system in view of achieving minimum fuel burn, indicated in the chart by HYC_{cruise}, results in selecting the maximum power of the electric motor which can be used at 100% under the constraint of the 20% SOC limit of the battery. In the context of this analysis, the optimum sizing results in a 13% block fuel reduction compared to the baseline aircraft by installing a total electric motor power of 6 MW and 8400 kg of batteries. Further investigation presented in [21] demonstrated a potential block fuel reduction of 16% when utilizing the electric motor during climb and cruise. The prospects in block fuel reduction depend strongly on the assumption made in terms of battery technology level. For a battery specific energy of 1000 Wh/kg at cell-level,results shown that the potential reduction block fuel were reduced by almost 50% compared to results obtained for 1500 Wh/kg [21].

In view of examining the sizing effects resulting from the integration of hybrid-electric propulsion at aircraft level and of investigating the potential market range application of hybrid-electric aircraft, clean sheet design of hybrid-electric aircraft need to be considered.

4.3. Hybrid-electric clean sheet design

A hybrid-electric clean sheet design was investigated on a twin engine narrow body transport aircraft by Pornet et al. [22]. The topological approach of the hybrid-electric propulsion system is identical to the one presented in Section 4.2. Driving an electric motor on the low-pressure shaft has strong influences on the gas-turbine operational characteristics as highlighted in Section 2.1.2. These aspects become more predominant with increasing electric motor power. In order to not modify the contemporary design heuristics of the gas-turbine and to avoid the negative operational influence of the electric motor, the operational strategy selected in this design was to switch-off the gas-turbine during cruise while the electric motor drives by itself the shaft of the propulsor. By equipping only one gas-turbine with an electric motor, the useful degree-of-hybridization Hp_{use} achieved during cruise is 50%.

The other segments of the mission are performed conventionally using the two gas-turbines. By comparing the integrating performance of the hybrid-electric transport aircraft sized for interval design ranges between 500 nm (926 km) and 2100 nm (3889 km) against a suitably projected conventional twin-engine narrow-body aircraft, the prospects in terms of block fuel reduction, change in aircraft size and in vehicular efficiency were investigated for different range applications. In addition, the effect of the battery technology level was assessed for gravimetric specific energy at cell-level varying between 750 Wh/kg and 1500 Wh/kg.

The analysis of the relative change in block fuel versus the relative change in block ESAR is illustrated in Figure 5. When assuming a battery gravimetric specific energy of 1500 Wh/kg, the highest potential block fuel burn reduction of 20% was achieved at a design range of 1100 nm (2037 km). Block fuel reduction is achieved due to the utilization of the electrical energy and because of the increase in overall propulsion system efficiency resulting from the use of the highly efficient electrical system. An improvement in overall propulsion system efficiency of 30% during cruise was evaluated. At 1100 nm (2037 km), around a neutral change in vehicular efficiency was reached compared to an advanced gas-turbine only reference aircraft. It was observed that for increasing design ranges the potential inblock fuel reduction decreases, however, the vehicular efficiency is significantly diminished. In other words, the hybrid-electric transport aircraft requires more energy than the reference aircraft for the same transport task. This trend is explained by the increasing electrical energy demand during cruise, which results in increasing the total battery mass required. The resulting sizing cascade effects, leading to a large increase in MTOW as indicated in Figure 6, are the main cause of the block ESAR reduction. At 1100 nm (2037 km), the MTOW of the hybrid-electric aircraft is increased by 25% compared to an advanced gas-turbine only aircraft. While remaining energy neutral, the block fuel potential reduces for lower design ranges. It is explained by the fact that less electrical energy is used during the reduced portion of the cruise and consequently less block fuel reduction can be achieved. Because of the less pronounced sizing effects and the improvement in overall propulsive efficiency, the total energy consumption remains about neutral. When evaluating hybrid-electric aircraft, it is important to focus not only on fuel burn reduction but to consider also the overall energy consumption. The consumption of electrical energy will affect the operating cost of the hybrid aircraft with respect to the fluctuation of the electric energy price and moreover as the electrical energy might certainly not be produced only through renewable energy sources, its production will impact any carbon life cycle assessments that are undertaken.

Identical trends were observed for lower battery technology levels. However, a lower battery gravimetric specific energy results, for the same amount of energy required, in higher battery mass requirement, which considerably amplifies the sizing cascading effects. It leads consequently in a diminution of the potential fuel burn reduction and in a stronger degradation of the vehicular efficiency. Moreover, the design range at which the largest fuel consumption reduction occurs is reduced to 750 nm (1389 km) and to 900 nm (1667 km) at a specific energy of 750 Wh/kg and 1000 Wh/kg respectively. At these points the block fuel reduction is 9% and 14% and the change in block ESAR is -7% and -4% respectively. In these regards, the potential segment application for this concept turns out to be the regional market. In the context of this investigated concept, a battery technology level of at least 1000 Wh/kg should be reached to enable significant emissions reduction.

The integration of annexed technologies including for instance aerodynamic tailoring technology and flexible, adaptive structures [3] and the consideration of novel aircraft morphologies could lead to improvement in vehicular efficiency. However, the purpose of

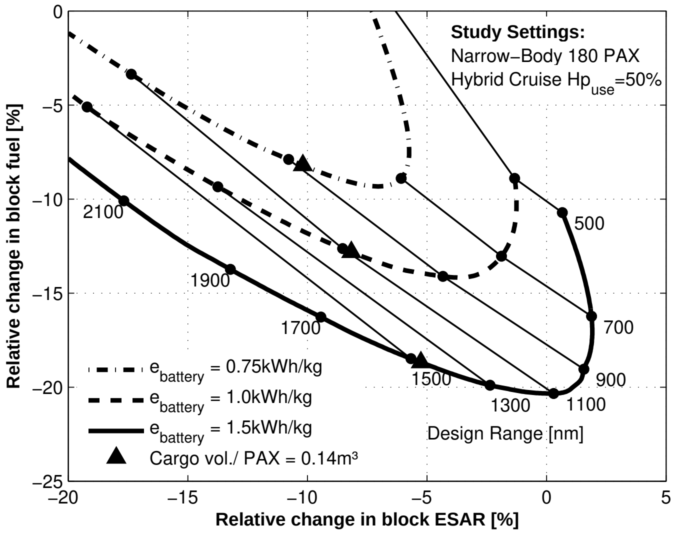

Figure 5. Relative change in block fuel and in block ESAR for a Hp$_{use}$ of 50% in cruise [22]

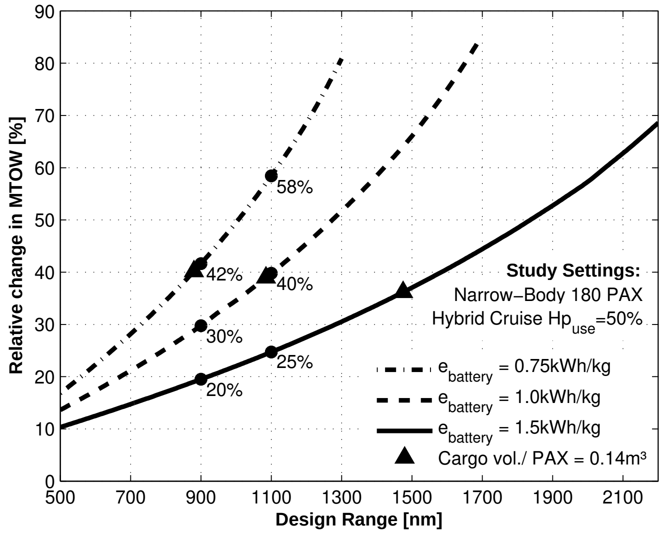

Figure 6. Relative change in MTOW for a Hp$_{use}$ of 50% in cruise [22]

this study was to capture a true potential resulting from the integration of hybrid-electric propulsion system compared to gas-turbine only aircraft.

Another aspect investigated in this study is the volumetric constraint for the housing of the battery within the cargo of the fuselage. According to an assumed density of 1000 kg/m^3 including the volume of the battery, of the thermal management and of the housing, the provision of a standard cargo volume per PAX for regional aircraft of 0.14 m^3 is indicated by a triangle in the Figures 5 and 6. For instance, assuming a battery specific energy of 1000 Wh/kg, the concept is volumetrically constrained for design ranges above 1100 nm (2037 km). Possible evolution of the fuselage geometry, with minor-to-modest aerodynamic and mass penalties, towards double-bubble cross-section could be conceived to free up the design space from this volumetric limitation.

The analysis of this clean sheet design reveals shifts in aircraft design paradigm due to the nature of the hybrid-electric propulsion system as fuel burn reduction can be achieved while the MTOW of the aircraft is increased and moreover fuel burn reduction does not mean automatically an improvement in vehicular efficiency.

While this investigation was aimed to get first insights into the sizing impact of hybrid-electric propulsion system at aircraft level, the full benefit of hybrid-electric technology will be reached through holistic integration of the propulsion system at aircraft level. As defended by Moore and Fredericks [54], the full potential of hybrid-electric aircraft will be demonstrated only once the synergistic benefits from the integration of the hybrid-electric propulsion system at aircraft level are fully understood. In this regard, an innovative hybrid-electric approach is proposed in the next section with the assessment of a distributed hybrid-electric clean sheet design.

4.4. Distributed hybrid-electric clean sheet design

Motivated by the search for higher synergies in the integration of the hybrid-electric propulsion system at aircraft level and by the interest of investigating the influence of increasing Hp on overall aircraft sizing, integrated performance and flight technique optimality, a hybrid-electric narrow-body transport aircraft employing a quad-fan arrangement was investigated by Pornet and Isikveren [23]. Featuring two conventional Geared-TurboFans (GTF) and two Electric Fans (EF), this rudimentary form of distributed propulsion offers numerous advantages compared to previously investigated hybrid-electric architecture and potentials for further evolution as enumerated in Section 2.1. Due to the greater mean time between failure of electric motor compared to gas-turbine, the electric fans are positioned on the outboard to reduce the one engine inoperative implications on performance and sizing. The sizing strategy of the hybrid-electric propulsion system was analyzed as a function of Hp_{use} [23]. The operational strategy selected was to operate the EFs at maximum thrust during the mission segments. Operational phases covering taxi-in/out, descent, landing and hold are performed only with the GTFs. The GTFs are throttled back during cruise to adjust to the instantaneous thrust requirement. This operation was assessed to be suitable up to an Hp_{use} of 45%. Above this value, the efficiency of the gas-turbine in cruise is impaired because of part-load operation resulting from the GTF thrust throttling. By sizing the aircraft for interval design ranges between 900 nm (1667 km) and 2100 nm (3889 km) and for increasing Hp_{use}, the prospects were investigated in terms of potential fuel burn reduction (Figure 7), change in vehicular efficiency (Figure 9) and change in aircraft size (Figure 11). The integrated performance are contrasted against an advanced twin-engine transport aircraft. As indicated in Figure 7, by increasing Hp_{use}, a large reduction in block fuel can be achieved due to the greater utilization of electrical energy and the improvement in overall propulsion system efficiency. Due to the utilization of batteries and because of the electrical system weight, growing Hp_{use} leads to large increase in aircraft weight as illustrated in Figure 11. This effect comes at the detriment of the vehicular efficiency which reduces with increasing Hp_{use} as indicated in Figure 9. The amplification of the sizing cascading effects, linked to the higher electrical energy requirement, explains the degradation of the integrated performance at higher design ranges. From this analysis it can be concluded that the regional market segment is the most suited segment for the application of this hybrid-electric quad-fan transport aircraft with design range between 900 nm (1667 km) to 1300 nm (2408 km). The volumetric constraint for the housing of the investigated battery

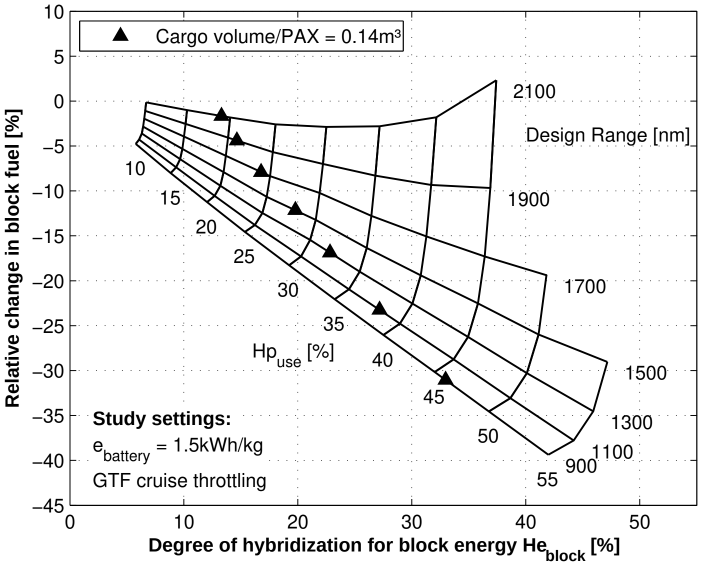

Figure 7. Relative change in block fuel versus block degree-of-hybridization for energy He_{block}. Geared-turbofan cruise throttling [23]

indicates that the cross-section of the narrow-fuselage might limit the design space. With respect to a cargo volumetric constraint of 0.14 m^3 per PAX, a standard volume allocation for regional aircraft, it was found that assuming a gravimetric specific energy of 1500 Wh/kg at cell-level, a block fuel reduction of 15% could be achieved at a design range of 1300 nm (2408 km) and an Hp_{use} of 30% while the vehicular efficiency is degraded by 6%.

To gain insights into the sensitivity with regards to battery technology, integrated performance was investigated for a battery specific energy of 1000 Wh/kg [23]. As indicated in Section 4.3, sizing effects are considerably amplified for lower battery specific energies due to the higher battery mass required for a given energy demand. It results in a diminution of the potential block fuel reduction and a stronger degradation of the vehicular efficiency. The increase in energy demand with growing design range leads to more pronounced degradation of the integrated performance at greater stage lengths. Assuming a gravimetric specific energy of 1000 Wh/kg, no significant block fuel reduction was achieved for design range above 1300 nm (2408 km), whereas, correspondingly for a specific energy of 1500 Wh/kg it is above a design range of 1900 nm (3519 km).

In the outlook proposed in [23], the analysis of a different operational strategy of the hybrid-electric propulsion system was highlighted. The strategy which consists of throttling the EFs during cruise while the GTFs are operated closed to their peak efficiency is investigated in this section. The comparison of the implication of the different strategies is based on the degree-of-hybridization for block energy He_{block}. As this integrated metric includes the overall efficiency chain of the propulsion system and characterizes the integrated block value of the energy split, it is of particular relevance in order to compare the two different operational strategies during cruise. The integrated performance is compared to the identical advanced twin-engine narrow-body aircraft. The potential block fuel reduction, the change in vehicular efficiency and the change in aircraft weight are indicated in Figures 8, 10 and 12 respectively.

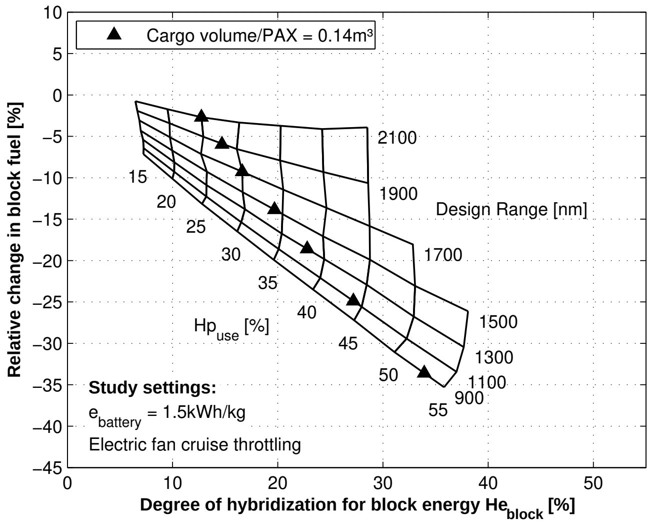

Figure 8. Relative change in block fuel versus block degree-of-hybridization for energy He$_{block}$. Electric fan cruise throttling

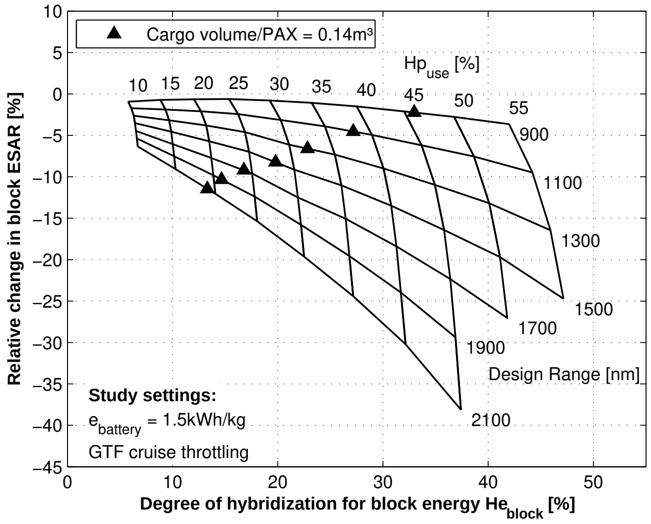

Figure 9. Relative change in block ESAR versus block degree-of-hybridization for energy He$_{block}$. Geared-turbofan cruise throttling [23]

Interestingly, for a given He$_{block}$ the benefit in terms of block fuel reduction achieved are about identical for both strategies (see Figure 7 and Figure 8). However, it is highlighted that for an identical He$_{block}$ the level of Hp$_{use}$ is larger in the case of throttling the EF during cruise. It means basically that for achieving the same block energy split, a larger electric motor power needs to be installed. This trend is understandable as less electrical energy is consumed during cruise when the EF is throttled back, compared to the first strategy for an identical Hp$_{use}$. In order to achieve the same He$_{block}$, a larger electric motor needs consequently to be installed to achieve the same block energy split for an identical block mission. This is the reason which explains the more "compact" carpet plots obtained when selecting the strategy of throttling the EF during cruise. Indeed, for the same variation of Hp$_{use}$ less electrical energy is utilized during cruise resulting in lower value of He$_{block}$.

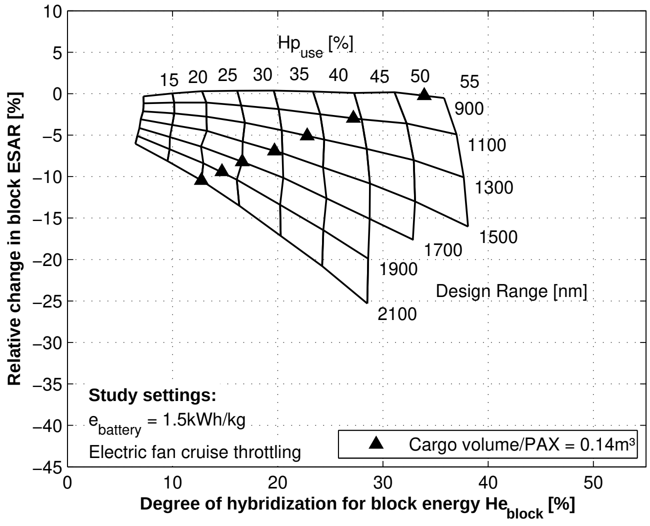

Figure 10. Relative change in block ESAR versus block degree-of-hybridization for energy He_{block}. Electric fan cruise throttling

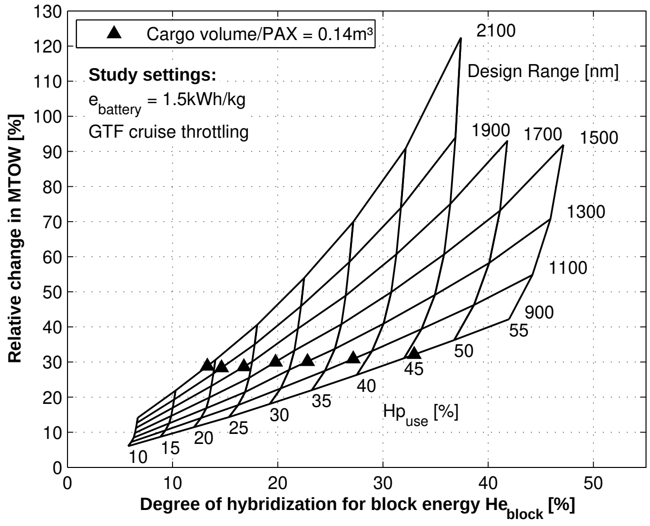

Figure 11. Relative change in MTOW versus block degree-of-hybridization for energy He_{block}. Geared-turbofan cruise throttling [23]

The analysis of the relative change in block ESAR versus He_{block} in Figures 9 and 10 reveals interesting trends resulting from the system implications of the different strategies. As highlighted in the beginning of this section considering the first strategy, an increase in Hp_{use} results in a higher level of thrust throttling of the GTFs during cruise due to the installation of larger EF. This effect contributes to a reduction of the GTF efficiency due to stronger part load operations. This operational consequence can be observed through the noticeable degradation in ESAR at higher levels of Hp_{use} indicated in Figure 7. In the second strategy, the EFs are throttled back and the GTFs run close to their maximum efficiency during cruise. As a result, block ESAR increases slightly with Hp_{use} as the overall propulsion system efficiency is improved through the use of the efficient electrical system and it remains almost independent of Hp_{use} for short design ranges. The decrease in block ESAR at higher

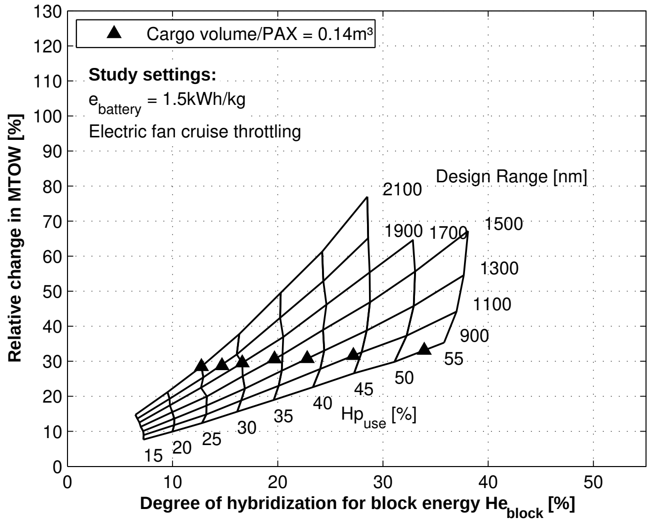

Figure 12. Relative change in MTOW versus block degree-of-hybridization for energy He_{block}. Electric fan cruise throttling

design ranges with increasing levels of Hp_{use} is attributable to sizing cascade effects resulting from the higher electric energy requirement which leads to large increase in aircraft mass (see Figure 12). However, it must be noted that for a given He_{block} the difference in delta block ESAR is small when comparing the different strategies. It is important to highlight at this point that in the current implemented electrical system model, the efficiency of the electrical components, with the exception of the battery, is assumed invariant with respect to the operational conditions and operating time. This assumption is made under the premise of an appropriate thermal management of the electric components and a thoughtful layout of the propulsion architecture. The efficiency of the electrical propulsion system chain in the model depends consequently only on the variation of the battery efficiency with respect to its discharge characteristic and upon the ducted-fan efficiency according to the flight state and the power setting. Moreover, in the current model the specific weight of the electrical components wereconsidered independent of any scale effect. With the availability of more detailed electrical system models, the dependance of the electrical components efficiency with respect to the altitude-temperature envelope and power load conditions as well as possible variations of the specific weight with scaling effects would be considered.

The impact of the hybrid-electric propulsion on aircraft size according to the EF cruise throttling strategy is illustrated by the change in MTOW versus the change in He_{block} in Figure 12. Similar trends in MTOW change between the different strategies with respect to increase in design range and growing Hp_{use} were identified. For an identical He_{block}, similar values in relative change in MTOW were observed.

In summary, a similar level of reduction in block fuel can be achieved when selecting the throttling of the EFs during cruise. This second operational strategy results in similar change in block fuel and block ESAR as well as in MTOW for an identical He_{block}. However, to reach the same potential in block fuel reduction, a higher level of Hp_{use} (in other words a higher useful electric power relative to the total useful power) needs to be achieved. This translates into the installation of a larger electric motor power. This system implication is rooted in the nature of the operational strategy. When throttling the EFs during cruise less electrical energy is required at an identical level of Hp_{use}.

5. Conclusion and outlook

The aeronautical community is about to revolutionize aircraft propulsion and aircraft design with the introduction of innovative electric drive approaches to the propulsion system. The full benefit of the hybrid and universally-electric aircraft can only be demonstrated by deploying a truly holistic approach to integrate hybrid-electric and universally-electric propulsion systems at aircraft level. Innovative approaches to electrically driven propulsion systems need to be further analyzed and thoughtfully integrated at aircraft level to determine the full potential. The search for synergistic integration of the propulsion system at aircraft level through tightly interlaced coupling with the airframe as well as with the other systems on-board the aircraft are expected to lead to dramatic shifts in contemporary aircraft design paradigms. Complementing the pure technical assessment of the implications of electric drives to transport aircraft, rigorous analyzes need to be expanded to measure the economical merits. The representation of metrics based on economics into the design charts would enable to select best and balance aircraft concept. Beyond the investigation at aircraft system, life cycle assessment needs to be conducted in order to measure the overall impact of electric drives to the complete chain. While for contemporary propulsion systems the conceptual design analysis of the engine can be done almost independently from the airframe, the synergistic analysis and integration of hybrid-electric or universally-electric propulsion system will result from the interdisciplinary work between the propulsion experts, the electrical systems specialists and the aircraft designer. New professional field of specialization such as electro-aero-propulsion experts could emerge from this multidisciplinarity. These interactions will influence not only the internal organization of aircraft conceptual teams but even beyond will redefine the industrial landscape of partnerships and cooperations due to the essential closer involvement of the suppliers in the early development phase of new aircraft product.

Author details

Clément Pornet*

*Address all coresspodence to: clement.pornet@bauhaus-luftfahrt.net

Bauhaus Luftfahrt, Munich, Germany

References

[1] Advisory Council for Aviation Research and Innovation in Europe (ACARE). Strategic Research and Innovation Agenda (SRIA) - Volume 1. Technical report, Brussels, 2012.

[2] NASA Environmentally Responsible Aviation. N+2 Advanced Vehicle Concepts NRA Draft Solicitation Synopsis. Technical report, 2012.

[3] Askin T. Isikveren and Michael Schmidt. Future Transport Aircraft Ultra-Low Emissions Technology Options. In *GARS Workshop Air Transport and Climate Change*, Worms, Germany, 2014.

[4] Askin T. Isikveren, Arne Seitz, Patrick C Vratny, Clément Pornet, Kay O Plötner, and Mirko Hornung. Conceptual Studies of Universally-Electric Systems Architectures Suitable for Transport Aircraft. In *Deutscher Luft- und Raumfahrt Kongress, DLRK*, Berlin, 2012. Bauhaus Luftfahrt.

[5] Clément Pornet. Hybrid and Universally-Electric Aircraft Concepts. *AccessScience, McGraw-Hill Yearbook of Sciences and Technology (McGraw-Hill Education, 2014), http://dx.doi.org/10.1036/1097-8542.YB150553.*

[6] Timothy P Dever, Kirsten P Duffy, Andrew J Provenza, Patricia L Loyselle, Benjamin B Choi, Carlos R Morrison, and Angela M Lowe. Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion. Technical Report January, NASA/Technical Report 2015-216588, Cleveland, Ohio, 2015.

[7] Jeffrey Freeman, Philip Osterkamp, Michael Green, Andrew Gibson, and Benjamin Schiltgen. Challenges and opportunities for electric aircraft thermal management. *Aircraft Engineering and Aerospace Technology*, 86(6):519–524, September 2014.

[8] Susan Liscouët-Hanke. *A Model-Based Methodology for Integrated Preliminary Sizing and Analysis of Aircraft Power System Architectures*. PhD thesis, Institut National des Sciences Appliquée - Université Paul Sabatier, 2008.

[9] James Felder, Hyun Kim, and Gerald Brown. Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid-Wing-Body Aircraft. In *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, pages 1–25, Orlando, Florida, January 2009. American Institute of Aeronautics and Astronautics.

[10] Andrew R Gibson, David Hall, Mark Waters, Benjamin Schiltgen, Trevor Foster, Jonathan Keith, and Philippe J Masson. The Potential and Challenge of TurboElectric Propulsion for Subsonic Transport Aircraft. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, number January, Orlando, Florida, 2010.

[11] Gerald V Brown. Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, 2011.

[12] Hyun Dae Kim, James L. Felder, Michael T. Tong, Jeffrey J. Berton, and William J. Haller. Turboelectric distributed propulsion benefits on the N3-X vehicle. *Aircraft Engineering and Aerospace Technology*, 86(6):558–561, September 2014.

[13] Devaiah Nalianda and Riti Singh. Turbo-electric distributed propulsion: opportunities, benefits and challenges. *Aircraft Engineering and Aerospace Technology*, 86(6):543–549, September 2014.

[14] Holger Kuhn, Arne Seitz, Larissa Lorenz, Askin T. Isikveren, and Andreas Sizmann. Progress and Perspectives of Electric Air Transport. In *28th International Congress Of The Aeronautical Sciences, ICAS*, Brisbane, 2012.

[15] Christopher A Snyder, Jeffrey J Berton, Gerald V Brown, James L Dolce, Narayan V Dravid, Dennis J Eichenberg, Joshua E Freeh, Christopher A Gallo, Scott M Jones, Krishna P Kundu, Cecil J Marek, Marc G Millis, Pappu L Murthy, Timothy M Roach, Timothy D Smith, George L Stefko, Roy M Sullivan, Robert T Tornabene, Karl A Geiselhart, and Albert Kascak. Propulsion Investigation for Zero and Near-Zero Emissions Aircraft. Technical Report May, NASA/TM-2009-215487, National Aeronautics and Space Administration, Cleaveland, Ohio, 2009.

[16] Patrick Christoph Vratny, Corin Gologan, Clément Pornet, Askin T. Isikveren, and Mirko Hornung. Battery Pack Modeling Methods for Universally-Electric Aircraft. In *4th CEAS Air & Space Conference*, pages 525–535, Linköping, Sweden, 2013. Linköping University Electronic Press.

[17] Holger Kuhn, Christoph Falter, and Andreas Sizmann. Renewable Energy Perspectives for Aviation. In *Proceedings of the 3rd CEAS Air&Space Conference and 21st AIDAA Congress*, volume 1259, pages 1249–1259, Venice, Italy, 2011.

[18] Airbus Group. The future of e-aircraft, accessed april 2015, http://www.airbusgroup.com.

[19] Marty K. Bradley and Christopher K Droney. Subsonic Ultra Green Aircraft Research : Phase I Final Report. Technical Report April, Huntington Beach, California, 2011.

[20] Marty K. Bradley and Christopher K. Droney. Subsonic Ultra Green Aircraft Research Phase II : N + 4 Advanced Concept Development. Technical report, NASA, Huntington Beach, California, 2012.

[21] Clément Pornet, Corin Gologan, Patrick C. Vratny, Arne Seitz, Oliver Schmitz, Askin T Isikveren, and Mirko Hornung. Methodology for Sizing and Performance Assessment of Hybrid Energy Aircraft. *Journal of Aircraft, Vol. 52, No. 1 (2015), pp. 341-352. doi: 10.2514/1.C032716*, pages 1–12, 2014.

[22] Clément Pornet, Sascha Kaiser, Askin T. Isikveren, and Mirko Hornung. Integrated Fuel-Battery Hybrid for a Narrow-Body Sized Transport Aircraft. *DOI 10.1108/AEAT-05-2014-0062, Aircraft Engineering and Aerospace Technology, Vol. 86, Iss. 6, pp. 568-574*, 86(6), 2014.

[23] Clément Pornet and Askin T. Isikveren. Conceptual Design of Hybrid-Electric Transport Aircraft. *Journal of Progress in Aerospace Sciences* 2015, DOI: 10.106/j.paerosci.2015.09.002

[24] R. W. Schurhoff. *The Development and Evaluation of an Optimal Powertrain Control Strategy for a Hybrid Electric Vehicle*. PhD thesis, University of California - Davis, CA, 2002.

[25] Frederick G. Harmon, Andrew A. Frank, and Jean-Jacques Chattot. Conceptual Design and Simulation of a Small Hybrid-Electric Unmanned Aerial Vehicle. *Journal of Aircraft*, 43(5):1490–1498, September 2006.

[26] Oliver Schmitz and Mirko Hornung. Methods for Simulation and Analysis of Hybrid Energy Propulsion Systems. In *Proceedings of the 62nd Deutscher Luft- und Raumfahrt Kongress (DLRK)*, Stuttgart, 2013.

[27] Oliver Schmitz. Fahrzeugtriebwerk, Fahrzeug mit diesem Fahzeugtriebwerk und Verfahren zum Betrieb dieses Fahrzeugtriebwerkes, 2012.

[28] Oliver Schmitz and Mirko Hornung. Unified Applicable Propulsion System Performance Metrics. *J. Eng. Gas Turbines Power*, 135(11):1–9, 2013.

[29] K.C. Divya and Jacob Ostergaard. Battery energy storage technology for power systems: an overview. *Electric Power Systems Research*, 79:511–520, April 2009.

[30] Bruno Scrosati and Jürgen Garche. Lithium batteries: Status, prospects and future. *Journal of Power Sources*, 195:2419–2430, May 2010.

[31] B. Ketterer, U. Karl, D. Möst, and S. Ulrich. Lithium-Ion Batteries: State of the Art and Application Potential in Hybrid-, Plug-In Hybrid- and Electric Vehicles. Technical report, Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft, Institut für Materialforschung I, 2009.

[32] William H. Woodford, R. Alan Ransil, and Yet-Ming Chiang. Advanced Batteries: Beyond Li-ion. Technical report, NPC Future Transportation Fuels Study, 2012.

[33] Jake Christensen, Paul Albertus, Roel S. Sanchez-Carrera, Timm Lohmann, Boris Kozinsky, Ralf Liedtke, Jasim Ahmed, and Aleksandar Kojic. A Critical Review of Li-Air Batteries. *Journal of The Electrochemical Society*, 159, 2012.

[34] Alexander Kraytsberg and Yair Ein-Eli. Review on LiâĂŞair batteries: Opportunities, limitations and perspective. *Journal of Power Sources*, 196:886–893, February 2011.

[35] S Visco, E Nimon, B Katz, M Chu, and L De Jonghe. High Energy Density Lithium-Air Batteries with No Self Discharge. In *in Proceedings of the 42nd Power Sources Conference*, pages 201–203, 2006.

[36] Lonnie Johnson. The Viability of High Specific Energy Lithium Air Batteries. In *Symposium on Research Opportunities in Electrochemical Energy Storage - Beyond Lithium Ion: Materials Perspective*, Tennessee, USA, 2010.

[37] Axel Thielmann. Technologie-Roadmap Lithium-Ionen-Batterien 2030. Technical report, Fraunhofer-Institut für System- und Innovationsforschung ISI,, Karlsruhe, 2010.

[38] Philippe J Masson, Gerald V Brown, Danielle S Soban, and Cesar A Luongo. HTS machines as enabling technology for all-electric airborne vehicles. *Superconductor Science and Technology*, 20(8):748–756, August 2007.

[39] Cesar A Luongo, Philippe J Masson, Taewoo Nam, Dimitri Mavris, Hyun D Kim, Gerald V Brown, Mark Waters, and David Hall. Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors. *IEEE Transactions on applied superconductivity*, 19(3):1055–1068, 2009.

[40] Philippe J Masson and Cesar A Luongo. HTS Machines for Applications in All-Electric Aircraft. In *Proceedings of the PES Meeting*, Tampa, Florida, 2007.

[41] K. Sivasubramaniam, T. Zhang, M. Lokhandwalla, E. T. Laskaris, J. W. Bray, B. Gerstler, M. R. Shah, and J P Alexander. Development of a High Speed HTS Generator for Airborne Applications. *IEEE Transactions on applied superconductivity*, 19(3):1656–1661, 2009.

[42] Peter Malkin and Meletios Pagonis. Superconducting electric power systems for hybrid electric aircraft. *Aircraft Engineering and Aerospace Technology*, 86(6):515–518, September 2014.

[43] Paul M. Ordin. Safety Standard for Hydrogen and Hydrogen Systems. Technical report, NASA NSS1740.16, National Aeronautics and Space Administration, 2005.

[44] A Westenberger. Liquid Hydrogen Fuelled Aircraft - System Analysis. Technical Report May 2002, Final Technical Report, Cryoplane Project, 2003.

[45] The Boeing Commercial Airplane Company. An exploratory study to determine the integrated technological air transportation system gound requirements of liquid-hydrogen-fueled subsonic, long-haul civil air transports. Technical Report September 1976, NASA Contractor Report, 1976.

[46] Lockheed Company. LH2 Airport Requirements study. Technical report, NASA Contractor Report, 1976.

[47] Panagiotis Laskaridis. *Performance investigations and systems architectures for the More Electric Aircraft*. PhD thesis, Crandfield University, 2004.

[48] Howard Smith. Airframe integration for an LH2 hybrid-electric propulsion system. *Aircraft Engineering and Aerospace Technology*, 86(6):562–567, September 2014.

[49] Hans-Jörg Steiner, Arne Seitz, Kerstin Wieczorek, Kay Plötner, Askin T Isikveren, and Mirko Hornung. Multi-Disciplinary Design And Feasibility Study of Distributed Propulsion Systems. In *28th International Congress Of The Aeronautical Sciences, ICAS*, Brisbane, 2012.

[50] Askin T Isikveren, Arne Seitz, Julian Bijewitz, Mirko Hornung, Artur Mirzoyan, Alik Isyanov, Jean-luc Godard, Stefan Stückl, and Jan Van Toor. Recent Advances in Airframe-Propulsion Concepts with Distributed Propulsion. In *29th Congress of the International Council of the Aeronautical Sciences*, St. Petersburg, Russia, 2014.

[51] Arne Seitz, Julian Bijewitz, Sascha Kaiser, and Guido Wortmann. Conceptual investigation of a propulsive fuselage aircraft layout. *Aircraft Engineering and Aerospace Technology*, 86(6):464–472, September 2014.

[52] Julian Bijewitz, Arne Seitz, and Mirko Hornung. Multi-disciplinary Design Investigation of Propulsive Fuselage Aircraft Concepts. In *4th EASN Association International Workshop on Flight Physics and Aircraft Design*, Aachen , Germany, 2014.

[53] Askin T Isikveren, Arne Seitz, Julian Bijewitz, Arthur Mirzoyan, Alik Isyanov, Richard Grenon, Olivier Atinault, Jean-luc Godard, and Stefan Stückl. Distributed Propulsion and Ultra-High By-Pass Rotor Study at Aircraft Level. *The Aeronautical Journal (accepted)*, 2015.

[54] Mark D Moore and Bill Fredericks. Misconceptions of Electric Propulsion Aircraft and their Emergent Aviation Markets. In *AIAA doi/0.2514/6.2014-0535, SciTEch*, 2014.

[55] William J Fredericks, Mark D Moore, and Ronald C Busan. Benefits of Hybrid-Electric Propulsion to Achieve 4x Increase in Cruise Efficiency for a VTOL Aircraft. In *AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Los Angeles, California, 2013.

[56] William J Fredericks. Impact of Distributed Electric Propulsion (DEP) on Aircraft Design. In *Special Conference on Disruptive Green Propulsion Technologies: Beyond the Competitive Horizon*, number November, London, United Kingdom, 2014.

[57] Alex M Stoll, Joeben Bevirt, Mark D Moore, William J Fredericks, and Nicholas K Borer. Drag Reduction Through Distributed Electric Propulsion. In *Aviation Technology, Integration and Operations Conference*, number June, Atlanta, Georgia, 2014.

[58] Benjamin Schiltgen, Michael Green, and Andrew Gibson. Analysis of Terminal Area Operations and Short Field Performance of Hybrid Electric Distributed Propulsion. In *AIAA Aviation 2013*, volume 86, pages 584–590, Los Angeles, California, September 2013.

[59] Hans-Jörg Steiner, Patrick C Vratny, Corin Gologan, Kerstin Wieczorek, Askin T Isikveren, and Mirko Hornung. Optimum number of engines for transport aircraft employing electrically powered distributed propulsion. *CEAS Aeronautical Journal*, Volume 5(Issue 2):157–170, 2014.

[60] Martin Hepperle. Electric Flight - Potential and Limitations. In *NPU-DLR Workshop*, Braunschweig, 2014.

[61] Stefan Stückl, Jan van Toor, and Hans Lobentanzer. VOLTAIR - The All Electric Propulsion Concept Platform - A Vision For Atmospheric Friendly Flight. In *28th International Congress Of The Aeronautical Sciences, ICAS*, Brisbane, 2012.

[62] J. Paulson T. Banning, G. Bristow, C. Level, L. Sollmann, J. Calderon-Fernandez, D. Wells, M. Olson, N. Davis, C, Du, S. Ambadpudi. 2012-2013 FAA Design Competition for Universities Electric / Hybrid-Electric Aircraft Technology Design Category - NXG-50 - Georgia Tech. Technical report, 2013.

[63] Askin T. Isikveren, Sascha Kaiser, Clément Pornet, and Patrick C. Vratny. Pre-design Strategies and Sizing Techniques for Dual-Energy Aircraft. *DOI: 10.1108/AEAT-08-2014-0122, Aircraft Engineering and Aerospace Technology Journal, Vol. 86, Iss. 6, pp. 525-542*, 2014.

[64] Larissa Lorenz, Arne Seitz, Holger Kuhn, and Andreas Sizmann. Hybrid Power Trains for Future Mobility. In *Paper 1316, Deutscher Luft- und Raumfahrtkongress*, pages 1–17, Stuttgart, Germany, 2013.

[65] Arne Seitz, Oliver Schmitz, Askin T Isikveren, and Mirko Hornung. Electrically Powered Propulsion: Comparison and Contrast to Gas Turbines. In *Deutscher Luft- und Raumfahrt Kongress, DLRK*, Berlin, 2012. Bauhaus Luftfahrt.

[66] Clément Pornet, Sascha Kaiser, and Corin Gologan. Cost-Based Flight Technique Optimization for Hybrid Energy Aircraft. *DOI 10.1108/ AEAT-05-2014-0075, Aircraft Engineering and Aerospace Technology Journal*, 86(6), 2014.

[67] Cronin, M. Advanced Power Generation Systems for More Electric Aircraft. *SAETechnical Paper 912186*, 1991.

[68] Cronin, M. The all-electric aircraft. *IEE Review*, vol. 36, 1990, pp. 309-311.

[69] Quigley, R. E. More Electric Aircraft. *Proceedings of the 8th Applied PowerElectronics Conference and Exposition, APEC 93*, 1993, pp. 906-911.

[70] Faleiro, L. Beyond the More Electric Aircraft. *Aerospace America*, 2005.

[71] Ahmed Abdel-Hafez Power Generation and Distribution System for a More Electric Aircraft - A Review. Recent Advances in Aircraft Technology, Dr. Ramesh Agarwal (Ed.), ISBN: 978-953-51-0150-5, InTech, 2012.

[72] Gohardani, A. S., Doulgeris, G., and Singh, R. Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all electric commercial aircraft. *Progress in Aerospace Sciences*, vol. 47, Jul. 2011, pp. 369-391.

[73] Gohardani, A. S. A synergistic glance at the prospects of distributed propulsion technology and the electric aircraft concept for future unmanned air vehicles and commercial or military aviation. *Progress in Aerospace Sciences*, vol. 57, 2013, pp. 25-70.

[74] Gohardani, A. S. (Editor), *Propulsion Technology, ISBN: 978-1-62948-588-1*. Nova Science Publishers, 2014.

[75] Kirner, R., Raffaelli, L., Rolt, A., Laskaridis, P., and Singh, R. Analysis of Distributed Propulsion on Advanced Vision 2020 Aircraft Concepts. *International Society for Air Breathing Engines*, Busan, Korea: 2013.

[76] Mantic-Lugo, V., Doulgeris, G., and Singh, R. Computational Analysis of the Effects of a Boundary Layer Ingesting Propulsion System in Transonic Flow. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2012.

IntechOpen