DESIGN AND OFF-DESIGN PERFORMANCE OF ELECTRIC SYSTEM ARCHITECTURES FOR ELECTRIC POWERED AIRCRAFT

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Abstract

Electric power trains for aircraft propulsion systems are a potential key enabling technology that allows for synergistic system integration options to potentially increase the overall vehicular efficiency. These electric power train concepts are mainly applied in turbo-electric, hybrid-electric and universally-electric aircraft. The following paper presents a method to generate electric architecture design charts and off-design performance maps for turbo-electric and hybrid-electric power trains. The presented method is applied to a short range narrow body aircraft using featuring in addition to podded power plants an aft-fuselage installed ducted fan serving the purpose of enhancing vehicular propulsive efficiency by means of fuselage wake filling. For that purpose a turbo-electric and a hybrid-electric power train are compared to identify the CO_2 reduction potential at the integrated overall aircraft level.

Nomenclature

ACARE – Advisory Council of Aviation Research in Europe
CSV – Constant System Voltage
DC – Direct Current
DPH – Discrete Parallel Hybrid-Electric
EIS – Entry Into Service
EPS – Energy and Power System
ESA – Electric System Architecture
ESAR – Energy Specific Air Range
G – Generator
GT – Gas Turbine
GTF – Geared Turbofan
HTS – High Temperature Superconducting
L/D – Lift-to-Drag
M – Motor
MTOW – Maximum Take-Off Weight
NASA – National Aeronautics and Space Administration
OEW – Operating Empty Weight
PFC – Propulsive Fuselage Concept
PMAD – Power Management and Distribution System
PTE – Partial Turbo-Electric
PS – Power Switch
SFC – Specifc Fuel Consumption
SoC – State of Charge
TOC – Top of Climb
VSV – Variable System Voltage

1 Introduction and Motivation

The reduction of global greenhouse gas emissions is a central research topic in the aviation community for future transport aircraft. Several emission reduction targets are unveiled for CO_2, NO_X or perceived noise. The most common environmental targets are defined by the Advisory Council of Aviation Research in Europe (ACARE) [1] with the Strategic Research and Innovation Agenda (SRIA) and by the National Aeronautics and Space Administration (NASA) with the Environmentally Responsible Aviation N+ series in the United States. The SRIA claims a reduction of the generated CO_2 of 75% for the year 2050 (compared to a 2000 year datum aircraft) [1]. A potential solution to tackle these targets has been identified with electric power trains. Different concepts of turbo-electric, hybrid-electric and even universally-electric power trains are available. The main advantage of such propulsion systems is the separation of the power sources and the power loads. This decoupling allows for new degrees of freedom when integrating such a propulsion system at the overall aircraft level. Universally-electric aircraft are the ultimate target of electric propulsion systems, because this power train concept offers the highest inner efficiency above 90% [2], [3]. However, the current showstopper for this concept is the required battery mass for high power applications and design ranges greater than 1,000 nm [2], [3]. For that reason turbo-electric or hybrid-electric power trains seems to be an option to take advantage of the electric transmission capabilities without being confronted with the full disadvantage of the battery system. Turbo-electric and parallel hybrid-electric topologies have the advantage that the electric power train has not to be sized for the entire propulsive power of the aircraft [4]. Several studies investigated the system level and aircraft level performance of full turbo-electric [5], partial turbo-electric (PTE) [6], [7] and different variants of parallel hybrid-electric power train concepts [4], [8]–[10]. A main research gap that has been identified is that the gas turbine is usually modelled with high fidelity methods while the electric system is handled only as black box system with constant efficiencies over the mission. For a reasonable comparison of turbo-electric and hybrid-electric power trains the main contributor gas turbine and electric architecture have to cover a comparable fidelity-level.

1.1 Objectives

The aim of this paper is to identify optimal design parameters and system trends for an electric system architecture (ESA) with different supply options (turbo-electric and battery supply). This includes the consideration of electric off-design performances. Furthermore, the comparison of a turbo-electric and a battery supplied hybrid-electric ESA will be investigated for typical power demands of a short to medium range aircraft. For that purpose, performance and mass models are implemented for the different involved components. For the assessment at the overall aircraft level the block fuel savings, masses and the Energy Specific Air Range (ESAR) according to [11] are used. A pure hybridization on power train level has been identified as not sufficient to fulfill the SRIA targets [12]. Therefore, targeting the exploitation of additional aero-propulsive synergies, an arrangement featuring an aft-fuselage installed propulsor in conjunction to underwing podded turbofans, the “Propulsive Fuselage Concept” (PFC), is considered in the present paper. This concept has been identified to significantly reduce the block fuel by up to 12% for medium to long range aircraft as shown by several designs studies such as STARC-ABL with a design range of 3500 nm [7], DisPURSAL with 4800 nm [6] and CENTRELINE with 6500 nm [13]. In the current study this technology is applied to a short range aircraft.

1.2 Reference Platform and Electric Derivative

For the evaluation of the potentials of electric power trains a reference aircraft in the A320 class is used representing a comparable technology standard for an EIS of 2035 (Figure 1). The reference aircraft accommodates 180 PAX and was downscaled to a design range of 1300 nm based on [14]. This design range has been identified as a potential mission range for battery supplied aircraft with a specifc energy of 2 kWh/kg and it covers 90% of projected cumulative stage lengths [14].

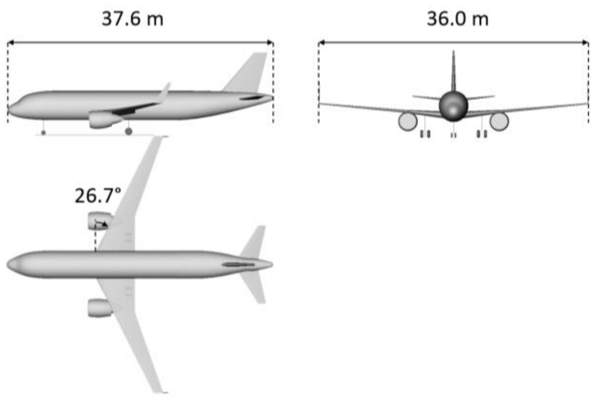

Figure 1: Three-view of a 2035 reference aircraft for 1300 nm

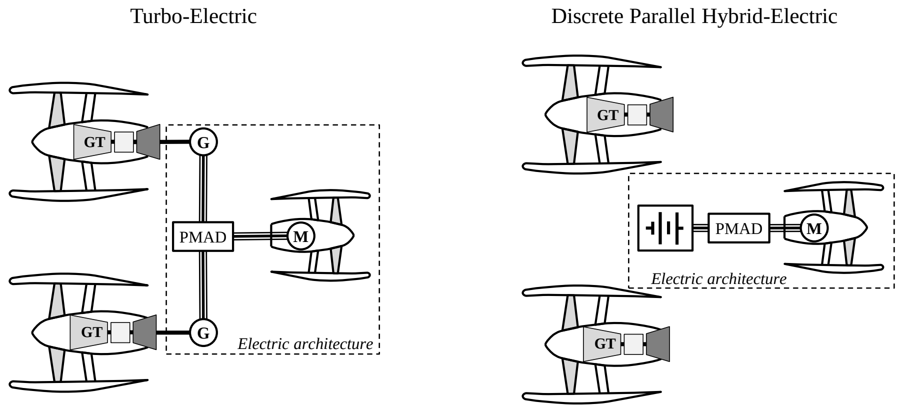

Figure 2: Electric power train topologies of turbo-electric (left) and discrete parallel hybrid-electric (right) configuration

The designs should meet the requirements of ICAO Annex 14 Code C limitations (36 m box) and an approach speed of 130 kts.

In this paper, a boundary layer ingestion ducted fan encircling the very aft section of the fuselage, is taken as investigation platform to assess the impact of the different electric power trains. This approach to synergistic propulsion-airframe integration, also known as PFC, is based on the effect of fuselage wake filling. It promises a reduction in propulsive power through reduced jet over velocities enabled by reduced kinetic energy losses in the aircraft wake. As part of an initial multi-disciplinary investigation, for a medium-to-long range, wide body application a PFC with a turbo-electrically driven fuselage fan was predicted to yield a block fuel reduction of 7.3% versus an equally advanced reference aircraft [15]. The effects of wake filling on aircraft net thrust requirements are estimated with a simplified method discussed in [16]. This method is based on the scaling of CFD-computed fuselage flow profiles using empirical correlations for turbulent flow. As an important assumption and consistent with common practice in typical gas turbine performance simulation software, the bookkeeping scheme is geared to the propulsion system streamtube [17]. This means, all aerodynamic effects occurring ahead of the fuselage propulsor inlet are incorporated within the power plant sizing and performance. Hence, the fuselage viscous drag portion inside the power plant streamtube, which is ingested into the propulsive device, is removed from the aircraft drag balance, while any remaining viscous fuselage drag spilled around the nacelle is still existent within the drag bookkeeping scheme [18]. The momentum deficit due to viscous flow effects on the fuselage surface translates into a reduced intake total pressure recovery ratio relative to the total pressure ratio obtained at free stream conditions. Based on [16], this property was determined by averaging the scaled flow profiles at the representative longitudinal inlet position. Note that additional integration effects emanating e.g. from pressure forces on the aft-fuselage and within the propulsor ducting have not been included in the present context.

As mentioned, electric power trains offer new ways to power such concepts. Figure 2 left shows the example of a partial turbo-electric (PTE) power train. In this configuration a part of the generated power of the gas turbines is distributed with the help of generators to an electric motor. Another power train configuration is the discrete parallel hybrid-electric (DPH) concept supplied by batteries. This configuration offers a higher transmission efficiency compared to the PTE power train, but suffers from the mass penalty caused by the battery system.

The simulation of the aircraft models is mainly based on aerodynamic methods according to Torenbeek [19] and mass estimations according to Raymer [20], Torenbeek [19] and LTH [21].

The methods are implemented in the aircraft preliminary design environment Pacelab APD [22]. The mission performance is based on an extended numerical mission simulation considering the characteristics of the gas turbine and the electric architectures via performance maps. The component modeling approach of the gas turbine and the electric power train is presented in the next section. The results of the overall aircraft design are shown in Section 5.1.

2 Component Technologies

The following section gives an overview of the considered technologies and subsystems required for turbo-electric and hybrid-electric power trains. For the expected EIS year of 2035+ eligible component technologies are mentioned.

2.1 Gas Turbine Design

The gas turbine design is representing an advanced geared turbofan (GTF) with technology components projected to the EIS year 2035. In accordance to the technology level, a bleed-less engine architecture is assumed and adaptions in component efficiencies and pressure losses have been made. The flow path sizing point is defined at top-of-climb (TOC) conditions at flight level FL350, Mach number 0.78 and ISA conditions. For the scope of the design studies the GTF is designed for mechanical power off-takes of 250 kW. This power demand represents the on-board subsystem power off-takes for the conventional non-electric power train reference aircraft and the parallel hybrid-electric aircraft. The GTFs for the PTE power derivative have additionally to deliver the power of the propulsive fuselage fan and are sized for higher power off-takes. As modelling environment an in-house developed propulsion system sizing and performance framework is employed using methods described in [23]. The integration of the propulsion system characteristics in the aircraft sizing environment is performed via engine design decks covering the masses and geometry of the power plants, and off-design performance decks delivering the fuel flow and available thrust in each flight state. The generated design and off-design decks cover design net thrust levels from 18 kN to 26 kN and power off-takes between 250 kW and 3,500 kW. This arrangement is required to perform an overall aircraft level assessment covering the necessary snowball effects.

2.2 Electric Components

The second important subsystem is the electric power train. The following section summarizes the methods used to model the main electric power train subsystems. The subsystem can be grouped independently from the underlying topology into to following three types

- Energy and Power Supply (EPS)
- Power Management and Distribution (PMAD) system
- Power consumers

For the scope of this study, the electric components cover the main sensitivities for aircraft conceptual design with regard to power, voltage and switching frequencies.

2.2.1 Electric Motor and Generator Design

An electric machine is required to convert electric power into mechanical power, which is referred to as an electric motor, or vice versa mechanical power to electrical power defined as a generator. For the design of an electric machine the principle motor architecture of a Permanent Magnet Synchronous Motor (PMSM) is used. This motor type has been identified as the most eligible motor type in a previous study for aviation application [24]. Furthermore, this architecture can be extended using high-temperature superconducting (HTS) materials. HTS is a material state, where the conductor loses its ohmic resistance below a critical temperature, normally around 70K, depending on the considered HTS material. By replacing the conventional copper coils and permanent magnets with HTS based coils, the electromagnetic performance can be significantly increased. This has a positive impact on the overall machine mass and efficiency. However, special cooling systems such as cryocoolers are required to keep such systems operable. The methods described in [24] are used for the mass and efficiency estimations. For the non-cryogenic machines liquid cooling systems are used according to [25]. The electric machine architecture is identical for motor and generator design and, therefore, the described methods are valid for both types.

The electric motor model covers the estimation of the mass for a broad range of design power and rotational speed demands. The mass and efficiency estimation is based on [24]. According to this method, Figure 3 shows the results of the specific power for different shaft rotational speeds, power demands and motor architectures. The design efficiency can be treated as constant. The conventional machine shows design efficiencies of around 95.8% including cooling, the full HTS of around 98.6%. The electric motor drive of the propulsive fuselage is considered to be a HTS motor. This type offers the most eligible mass and efficiency trade-off according to [26], cot considering, in the first instance, possible negative implications in system complexity, ground-operations and maintenance. The generators required for the PTE drive train represent a non-cryogenic conventional copper coil architecture, mainly driven by the operating temperature environment.

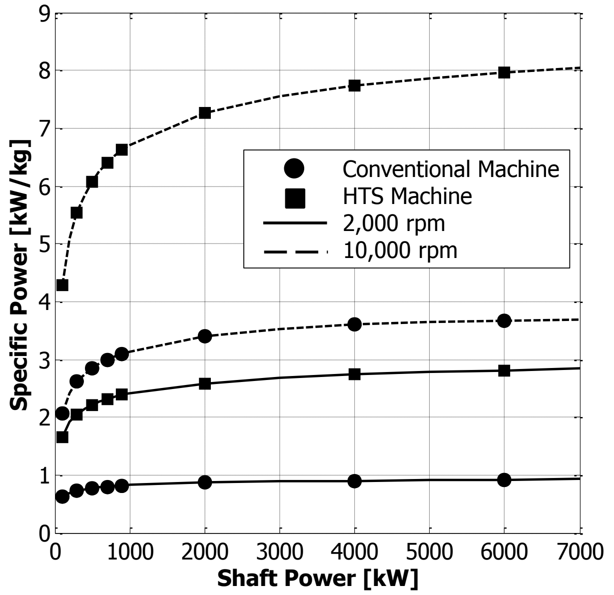

Figure 3: Specific power including cooling of different shaft power demands, rotational speeds and machine architectures

The efficiency estimation to generate a generic performance chart is based on an existing electric motor type that is scaled with the help of handbook methods and design heuristics based on [24]. The required off-design voltage is calculated using the common voltage factor, K_V, in combination with the actual rotational speed of the motor.

2.2.2 Battery Design

A battery is an electrochemical storage device consisting of different anode, cathode and electrolyte materials in order to fulfill a certain power and energy task. In electric power trains, mainly in the automotive sector, rechargeable lithium based battery cells are used. The operational behavior with regard to output voltage and in turn efficiency of such cells is strongly non-linear and depends on the actual state-of-charge (SoC) and the current discharge or C-rate as visualized in Figure 4.

This non-linearity is caused by the internal resistance of the battery cell. An example of a generic lithium based discharge curve is visualized in Figure 4 generated with the model described in [27]. This discharge behavior only represents an example and can vary depending on the used cell materials. The area of the strong voltage decrease at the end of the discharge process should be avoided in normal operation. In this area the electrochemical process can damage the battery cells [27]. The life span of the battery cell can therefore be strongly negative influenced. For that reason an operation above this area should be pursued. This can be ensured by defining a minimum SoC at the end of the block mission. For this design study it was set to 20%.

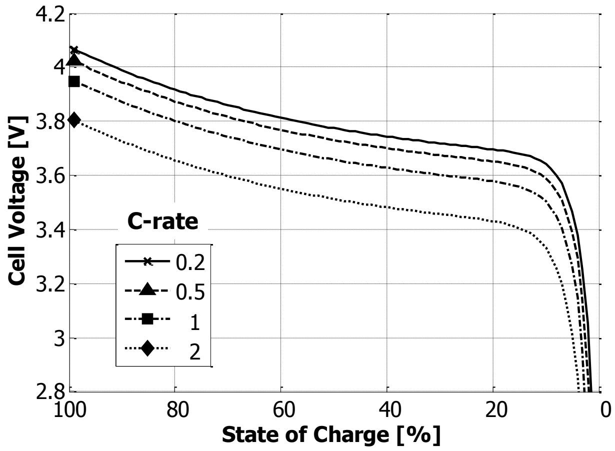

Figure 4: Generic lithium based discharge curve of a battery cell. Based on [27]

For the battery pack design, the battery cells are connected in series and in parallel to reach a certain output power, voltage and energy capacity. The mass of this system is calculated using the specific energy and power as listed in Table 1. For the sizing of the battery pack a specific energy of 1 kWh/kg is assumed. This specific energy is in the range of potential cell chemistry combinations according to [28], but still an aggressive technology target.

Table 1: Overview of different battery system parameters taken from [27]

Aircraft Concept	Specific Energy	Specific Power	Source
SUGAR Volt	0.7 kWh/kg	0.3 kW/kg	[8]
VoltAir	1.0 kWh/kg	0.9 kW/kg	[29]
Ce-Liner	2.0 kWh/kg	1.3 kW/kg	[30]

2.2.3 Power Management and Distribution

The PMAD system is responsible for a safe and redundant transfer of the power generated by the EPS to the loads. For the electric power transmission direct current (DC) is used. The PMAD consists of transmission cables, protection devices, cooling systems and power electronics such as rectifiers, inverters and converters. In a PMAD system the power electronics are responsible for a main part of the overall transmission losses. These components are mostly consisting of passive components such as capacitors and inductances and active components such as semiconductor based power switches (PS) and diodes. Depending on the component assembly, the electric current and voltage can be controlled. As semiconductor material Silicon or Silicon-Carbide (SiC) are eligible material types for aircraft applications. SiC enables lower switching losses, but higher conduction losses than pure Silicon [25]. In sum the total losses are smaller and therefore SiC is used in this study. In order to cope with the high power and voltage requirements of an aircraft power train multi-level designs are implemented. The main losses can be grouped into static and dynamic losses. The static losses are mainly represented by the conducting or ohmic losses given with Equation (1) according to [31]

$$P_{Cond} = I_{Out} \cdot U_0 + I_{Out,RMS}^2 \cdot R(I_{Out}) \quad (1)$$

U_0 is the threshold voltage of the PS, $I_{Out,RMS}$ the root mean square of the electric current and, R, the ohmic resistance of the PS. The second main loss group are the dynamic losses, mainly represented by the switching losses given in Equation (2) according to [31]

$$P_{SW} = f_{SW} \cdot E_{SW,Ref} \cdot \left(\frac{I_{Out}}{I_{Ref}}\right)^{K_I} \cdot \left(\frac{U_{Out}}{U_{Ref}}\right)^{K_V} \quad (2)$$

This regression is a function of the switching frequency, f_{SW}, induced by the controller, a reference switching energy, $E_{SW,Ref}$, based on a reference condition of electric current, I_{Ref}, and voltage, U_{Ref}. The power factors K_I and K_V are used to calibrate the operating line to existing data. According to [31] these values range between 1.4 and 1.6. With this regression the design and off-design performance can be determined. During design mode I_{Out} and U_{Out} are sizing the number of switches required in series and in parallel. These numbers of components are fixed during off-design. Beside the power electronics another mass driving part are the transmission cables. For the scope of this work aluminum cables are considered. There are two transmission strategies considered for the PMAD system shown in Figure 5: the Variable System Voltage (VSV) and the Constant System Voltage (CSV) architecture.

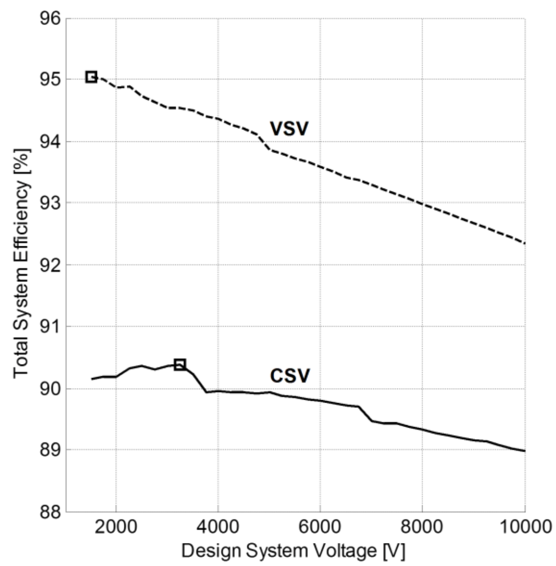

Figure 5: Design chart of the power management and distribution system for several design voltages at design power 6,000 kW and motor design voltage of 1000 V. Taken from [25]

The VSV architecture is not stabilizing a varying input voltage of an EPS in case of a battery to a constant output transmission voltage. In contrast, the CSV architecture stabilizes a varying EPS voltage to a constant transmission voltage with the help of converters. This transmission type can be used when connecting several different or complex power sources to the architecture e.g. two generator systems. Figure 5 gives the design results of the VSV and the CSV architecture for several design transmission voltages taken from [25]. It can be seen that the VSV enables a 4.5% higher transmission efficiency.

3 Electric Power Train Designs

For the design of the electric power trains the following general considered sizing strategies are considered:

- DC as transmission voltage type
- all loads are supplied by a central distribution bus
- each source and load is protected by an individual protection switch sized for twice the maximum design current [5]

The electric power train sizing process is visualized in Figure 6.

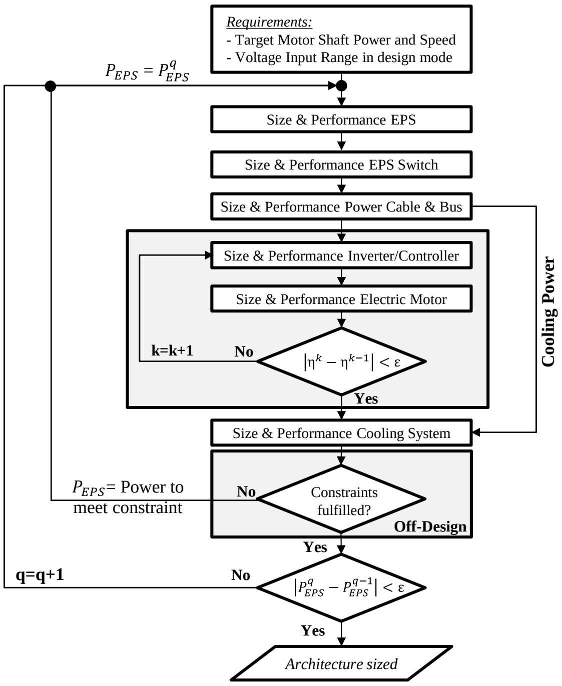

Figure 6: Sizing and performance approach of the electric power train

The components have a common input and output structure providing and receiving information about power, voltage, frequency and heat. Due to the usage of DC transmission voltage, the frequency is only relevant for the electric machines, rectifiers and inverters. In the first instance, in **design mode**, the electric

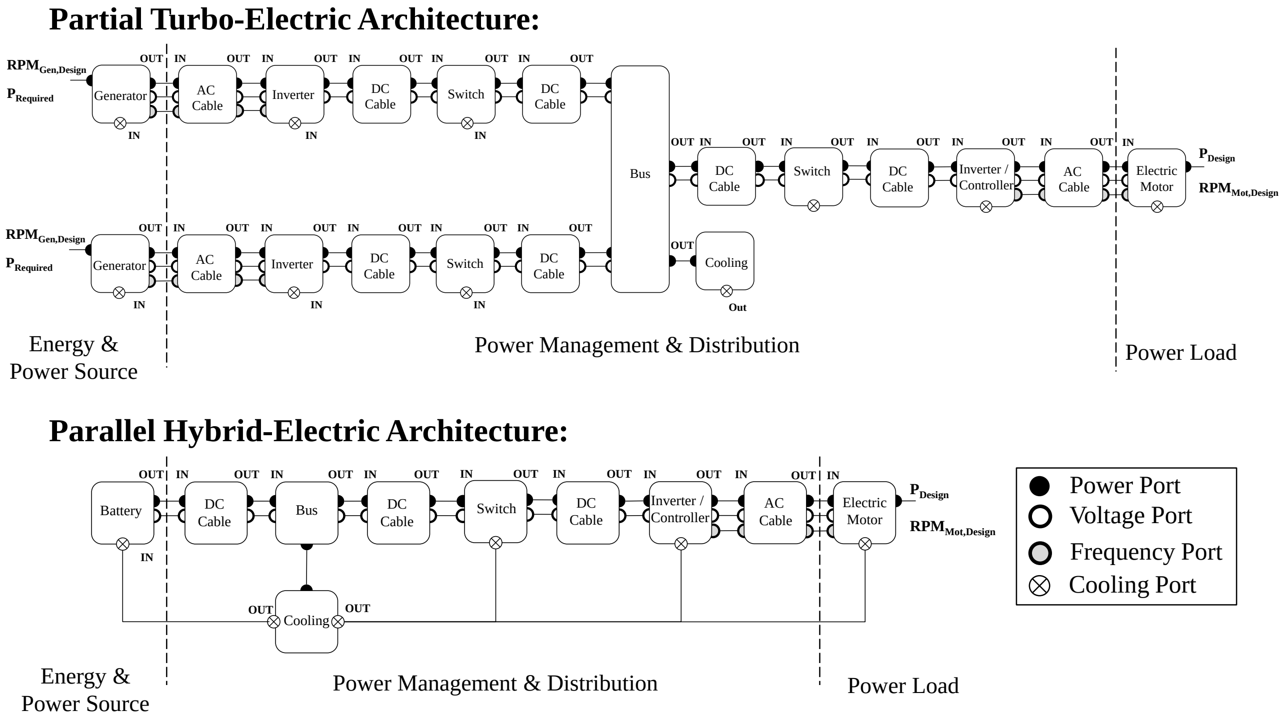

Figure 7: Electric architecture design for the turbo-electric (top) and the parallel hybrid-electric (bottom) power train

components are sized for a given targeted electric motor shaft rotational speed, shaft power and input voltage range induced by the EPS. The cooling system is dimensioned to the ejected heat of the components at this design point.

For the analysis of the **off-design** performance the same design scheme is used. In this mode the constraints of each single component are checked such as maximum allowable voltage or electric current for the required motor shaft power and rotational speed demand. If a component exceeds its design specifications, the input power and, in turn, resulting output power will be iterated that the constraints are met. In both performance cases the system converges if the input power, P_{EPS}, shows a deviation less than the defined convergence criterion, ε, between the target and the actual power requirement. For this performance approach ε is set to 10^{-6}. Based on this design scheme both electric power trains (shown in Figure 2, p.3) are sized. The principle simulation set-up of the PTE electric-power train is sketched in Figure 7 (top). It represents a CSV architecture, where the electric power and voltage generated by the generators are stabilized with the help of rectifiers. The generators of the PTE are directly connected to the low pressure turbine of the GTFs. The electric power train for the parallel hybrid-electric configuration is shown at the bottom of Figure 7. This power train represents a VSV architecture. The system voltage is defined at the rectifier and the battery output, respectively.

4 System Level Results

For the described setup, both architectures have been sized for different rotational speeds ranging from 2,000 rpm to 10,000 rpm and shaft powers up to 7,000 kW. The transmission voltage for the CSV has been identified at 2,000 V and for the VSV at 1,500 V as optimum transmission voltage for a 1,000 V electric motor in a previous study [13]. The results of the power train design mass and efficiency are shown in Figure 8. The mass of the different systems is represented by the specific power. Depending on the design strategy, the electric power train can be sized for minimum system mass ❶ or maximum efficiency ❷, representing the two main design extrema. For both architectures, the minimum system mass can be reached with high rotational speed motors of 10,000 rpm. The variation of the design speed is performed to identify the impact of a potential gear box between the fan and the electric motor. The specific power of the battery supplied power train ranges between 4.1 kW/kg and 4.7 kW/kg depending on the design shaft power excluding the battery. The power train of the PTE is ranging between 2.1 kW/kg and

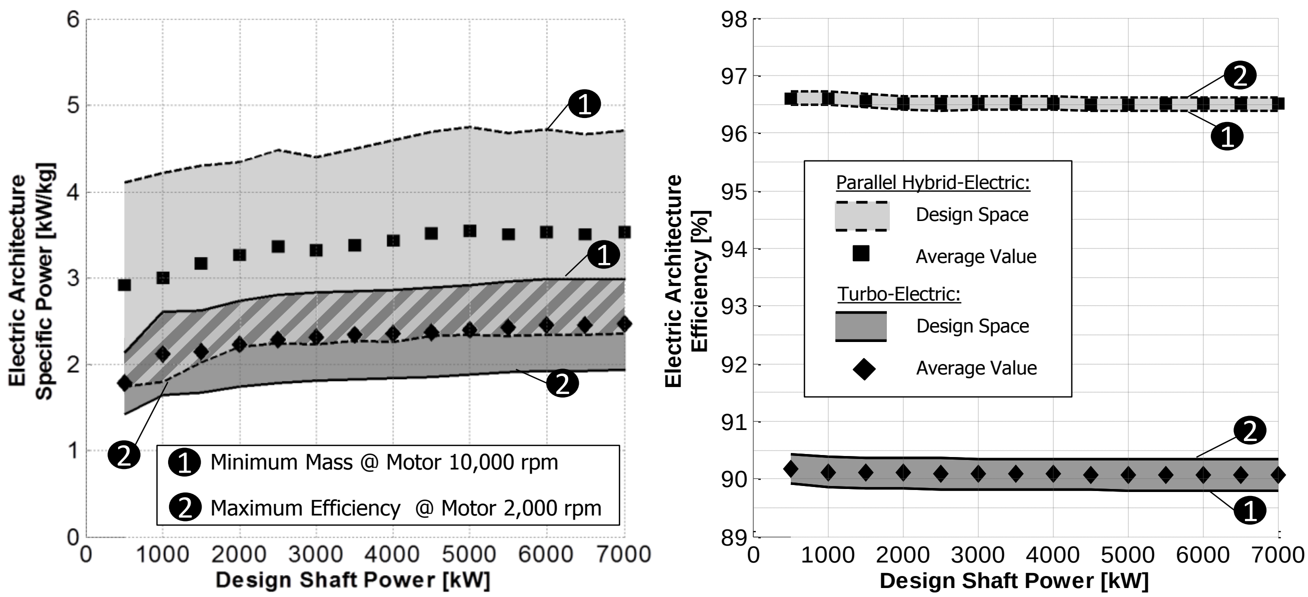

Figure 8: Design space of architecture specific power and efficiency (excluding battery system) for different electric motor shaft powers and speed ranges

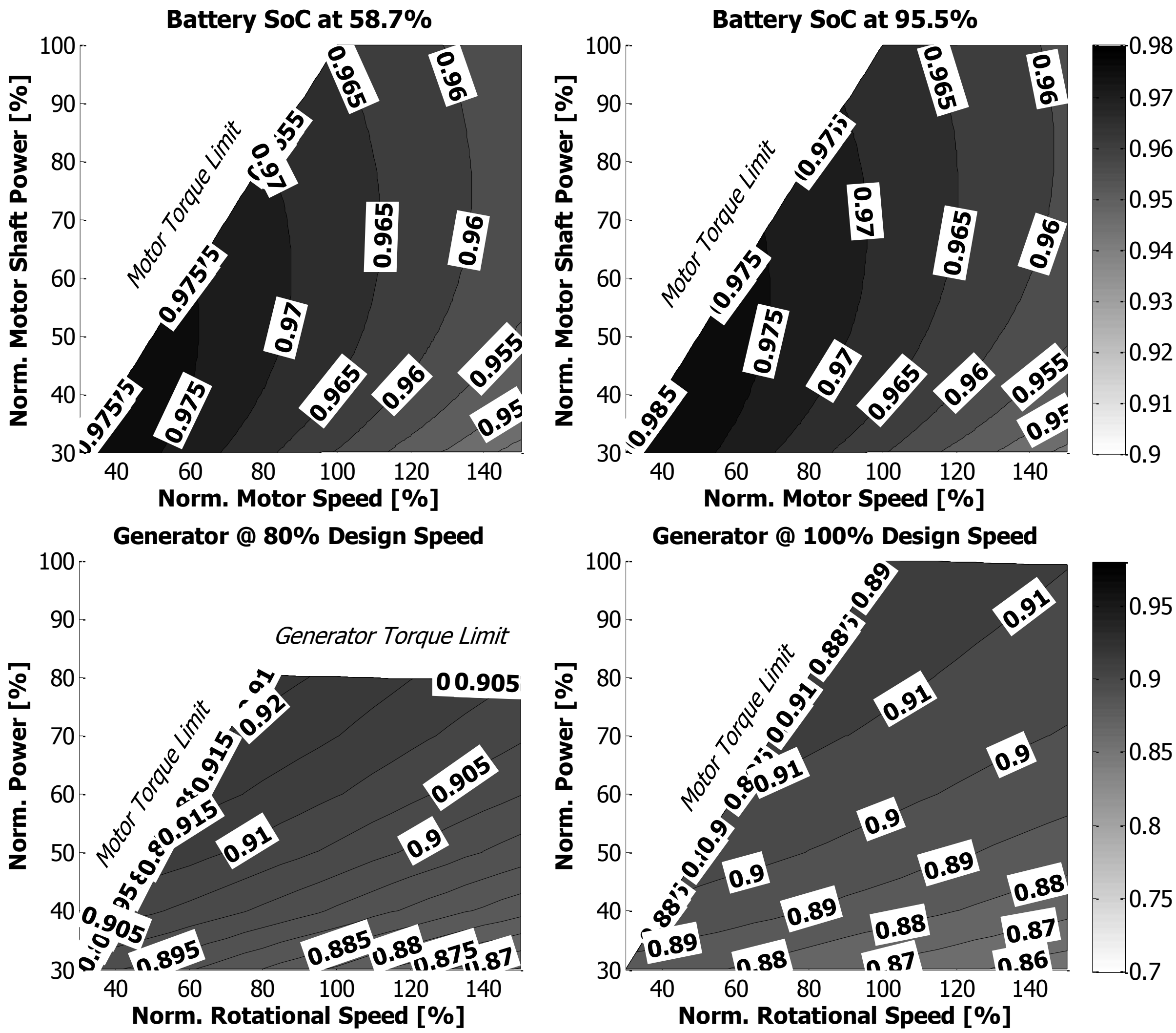

Figure 9: Performance charts of battery supplied architecture (top) at different values of SoC and turbo-electric architecture (bottom) at different generator speeds

3.0 kW/kg. The efficiency of both systems is nearly independent of the design shaft power. The parallel hybrid-electric power train reaches design efficiencies of 96.5%, the PTE power train of around 90%. The general trend for both concepts is that a high system efficiency comes along with a high system mass and vice versa. However, on a system level perspective the design focus should be set on a mass optimized system. The markers in the plots are representing the average specific powers of the corresponding shaft power.

Figure 9 (top row) shows the off-design performance charts of the battery supplied electric architecture at different SoC. It can be recognized that the optimum efficiency is at part load conditions of the electric motor between 40% and 60% rotational speed and power. The optimum efficiency area depends on the actual SoC of the battery and is shrinking with decreasing SoC. The maximum deviation in efficiency is about 3% between minimum and maximum efficiency. Due to the implementation of multi-level power electronics, the main constraining component is the electric motor. Below the design speed the electric torque and electric current are the constraining parameters. For speeds higher than the design speed, the motor power becomes the limiting restriction. In the bottom row of Figure 9 the performance charts of the PTE power train are visualized at different generator rotational speeds. The maximum efficiency area is near the design point of the electric power train. The maximum deviation of the electric efficiency is 5% between the maximum and the minimum efficiency in the considered performance envelope. During part load conditions the electric motor torque is one limiting parameter.

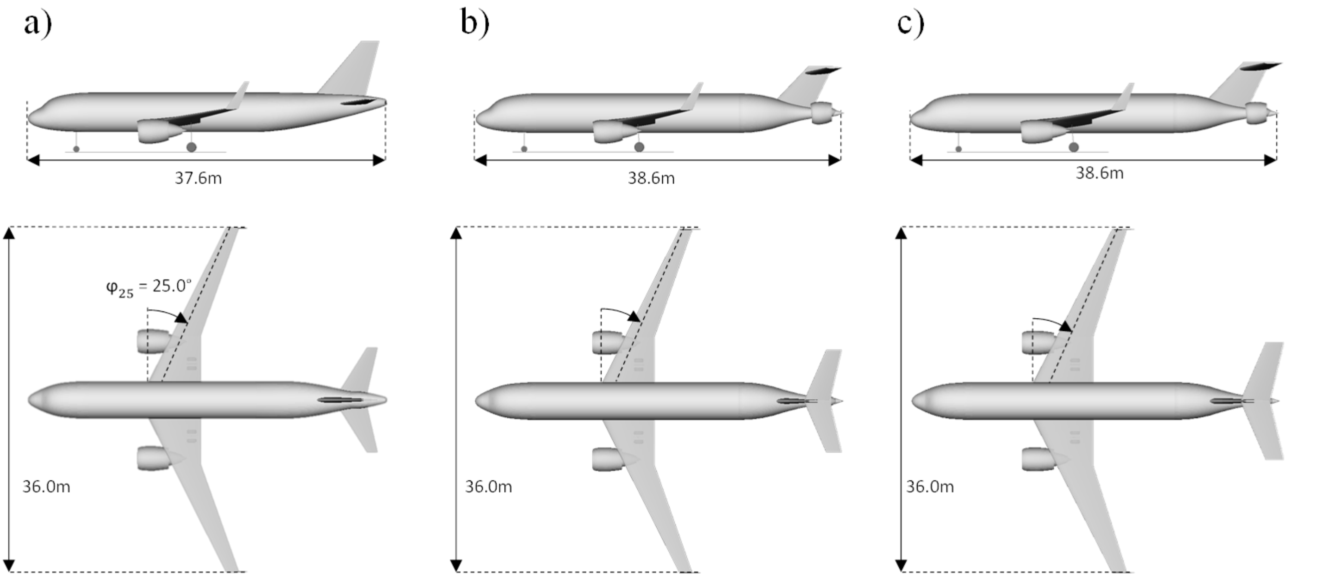

Figure 10: Side and top-view of a) baseline aircraft b) turbo-electric derivative c) parallel hybrid-electric derivative

At reduced generator speed the generator torque becomes obviously another limiting restriction. During generator part load the efficiency is getting slightly higher, due to reduced generator output voltage and better performance of the rectifier unit.

5 Impact on Overall Aircraft Level

The different electric architectures have enormous influence on the overall aircraft performance. In this section, the two aircraft (turbo-electric and parallel hybrid) are presented in detail regarding mass, energy consumption and in-flight emissions. The fuselage fan was designed for TOC conditions. As TOC conditions and fuselage shape are identical for both derivatives, the design of the fuselage fan is the same for both airplane. Its design power was estimated to be 1.6 MW for the selected application case and represents the power demand necessary for the wake filling plus an additional net thrust of 1 kN to take account for uncertainties. This additional thrust is not considered in the lift-to-drag (L/D) ratio.

5.1 Results of Electrified Aircraft

Figure 10 shows the top and side-view of the baseline aircraft and the two derivatives for the defined design mission. Figure 11 offers further details about the deviation of aircraft key parameters compared to the baseline aircraft.

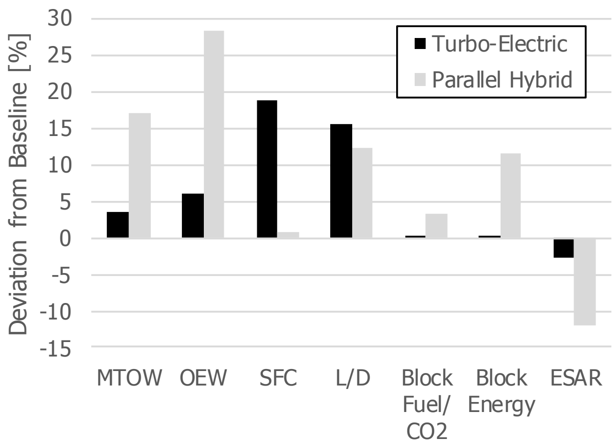

Figure 11: Deviation of MTOW, OEW, SFC, lift-to-drag ratio, block fuel/energy and ESAR to baseline

For the parallel hybrid-electric aircraft, a rise of maximum take-off weight (MTOW) of 17%, operating empty weight (OEW) of 28%, block fuel of 3.2% and block energy of 11.6% can be observed. The OEW mass increase is driven by the by the additional electric architecture, aft-fuselage propulsor mass and the battery mass plus the snow ball effects. As a result of a large fraction of the fuselage viscous drag being accounted as part of the fuselage fan power plant internal bookkeeping, the mid cruise L/D increases by 12.1% covering the effects mentioned in Section 1.2. The Specific Fuel Consumption (SFC) increases by 0.7%. This increase of mass and SFC results in a reduction of ESAR by 11.9%. For the PTE aircraft, the MTOW increases by 3.5%, the OEW by 5.9%, the mid cruise L/D increases by 15.4% and the SFC by 18.7%, thus reflecting the significantly increased power off-take. This results in a small block fuel and energy increase by 0.3%. The ESAR reduces by 2.9%. During aircraft sizing the best aerodynamic performance can be reached by taking the full advantage of the wing span. Therefore, all aircraft have the same span limited by the span restriction. The increased OEW of the added electric systems and a constant wing loading of all concepts, resulted in reduced aspect ratio (-3.5% for PTE, -27.9% for parallel hybrid-electric). This leads to an increased induced drag. However, the main increase in block fuel/energy and decrease of the ESAR in case of the parallel hybrid-electric configuration is caused by the mass impact of the battery system. The PTE configuration results in a nearly similar block fuel demand as the reference aircraft. Nevertheless, due to the span limitation, the increased SFC and the mass impact the full advantage of the wake filling effect could not be achieved as indicated by the decreasing ESAR. If the span limitation is not considered as a design requirement, a block fuel reduction of at least 0.5% can be reached with the PTE aircraft compared to the reference. NASA reported a block fuel reduction potential of 9.3% for an economic (off-design) mission of the STARC-ABL [32], however, at different top level aircraft requirements.

The total transmission efficiency of the turbo-electric derivative during design mission is in the range of 88.8% to 90.0% whereas at the hybrid-electric aircraft they vary between 96.3% and 97.0%. From a conceptual design point of view, the off-design efficiency for the current operational strategy can be neglected.

5.2 Sensitivity Studies

To identify the impact of the electric power train sizing options, a sensitivity study was performed to identify if a high efficiency or low system mass power train is the best option. For that purpose the initial weight, W_{init}, of the electric system was varied in a range of -20% to +20% and the total efficiency was changed between absolute -5% and +5% for both power train options. Figure 12 and Figure 13 show a quasi-linear dependency of the block fuel concerning weight and total transmission efficiency deviation of the electrical system.

Figure 12 shows the impact on the PTE aircraft. In contrast to the turbo-electric design, this sensitivity study only considers an efficiency gain of up to 2.5% to avoid total transmission efficiency over 100%.

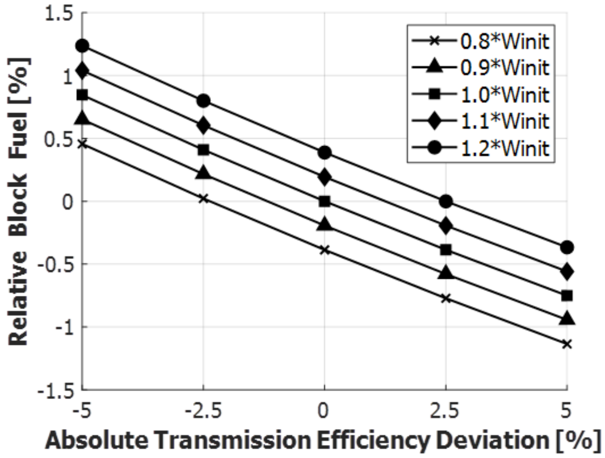

Figure 12: Block fuel sensitivity of turbo-electric aircraft dependent on transmission efficiency and weight of electric system

Figure 13 shows the results of the parallel hybrid-electric aircraft.

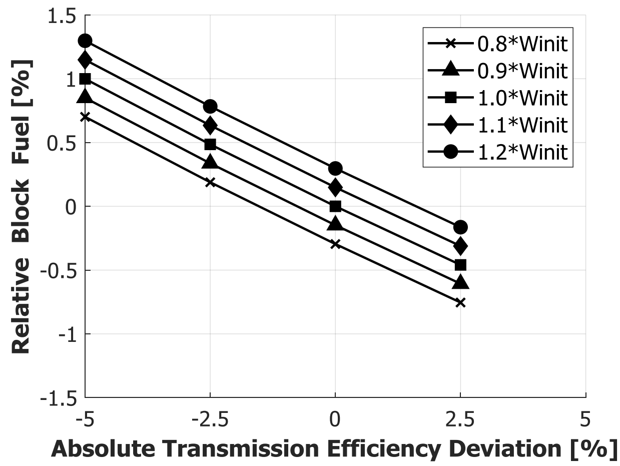

Figure 13: Block fuel sensitivity of parallel hybrid-electric aircraft dependent on transmission efficiency and weight of electric system

This implies the following design rules: On the turbo-electric system, the absolute transmission efficiency gain must be greater than 2.5% for 20% more weight to justify efficiency optimized designs. However, if the transmission efficiency can be increased by 2% without additional mass, a benefit compared to the reference aircraft can be achieved. In the case of the parallel hybrid-electric system, an optimized design is already reasonable if the absolute efficiency gain is greater than 1.6% for 20% more weight. An advantage compared to the reference aircraft cannot be attained with the parallel hybrid configuration.

It can be concluded that the electric transmission efficiency has an order of magnitude higher impact on the block fuel reduction potential than the system mass. For the current set of considered component technologies, the focus should be set to efficiency optimized electric power train systems as long as the gained benefit over-compensates the increased system mass.

6 Summary and Outlook

This paper presented an approach to generate design and off-design charts of electric power train architectures for partial turbo-electric and battery supplied hybrid-electric power trains. Design studies up to 7,000 kW motor shaft power have been performed at the system level. In this power range the design efficiency has been identified as nearly constant over the motor power and speed range, while the system mass shows a higher sensitivity with regard to the design parameters. The off-design characteristics of the electric power train depend on the underlying energy and power source and vary in a small efficiency corridor. The method has been applied to a short range aircraft utilizing an aft-fuselage propulsor. The results of the initial aircraft level assessment have shown that the electric efficiency over the mission varies marginal between 0.7% and 1.2%. The efficiency of an electric power train can be set constant for an initial aircraft level assessment. However, for a detailed system design such as sizing of the thermal management system or flight profile optimization such efficiency changes might get relevant. Furthermore, the initial assessment of a turbo-electric propulsive fuselage concept (PFC) using first order semi-empirical methods to consider the effect of wake-filling has shown that a PFC alone seems not to be sufficient to fulfill the defined environmental targets for the design ranges up to 1300 nm from an aircraft point of view as drag reduction effects are overcompensated by negative weight impacts.

For future work, the component technology for high power applications has to be investigated in more detail. This includes the change of the off-design characteristic of potential full cryogenic power trains. Also considerations of different sizing scenarios must be taken into account for several abnormal modes of operation. For the considered design range and aircraft configuration a potential solution to fulfill the set environmental targets must be identified. This also includes a detailed investigation and optimization of the aft-fuselage propulsor for single aisle short range aircraft that was not the focus in the presented study. It has to be identified if certain design parameter combinations exist that further increase the lift-to-drag ratio to overcompensate overall system mass penalty.

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