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ORIGINAL PAPER

Technology selection for holistic analysis of hybrid-electric commuter aircraft

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Abstract

Electric powertrains have different characteristics than conventional powertrains with combustion engines and require unconventional aircraft designs to evolve their full potential. Therefore, this paper describes a method to identify potential aircraft designs with electrified powertrains. Promising technology options in the fields of powertrain architecture, aerodynamic interactions, onboard systems and operating strategies were collected by the project partners of the LuFo project GNOSIS. The effect of the technology options on a commuter aircraft was evaluated in terms of global emissions (CO_2), local emissions (NO_X and noise) and operating costs. The evaluation considers an entry into service in 2025 and 2050 and is based on the reference aircraft Beechcraft 1900D. Literature review and simplified calculations enabled the evaluation of the aerodynamic interactions, systems and operating strategies. A preliminary aircraft design tool assessed the different powertrain architectures by introducing the two parameters 'power hybridization' and 'power split'. Afterwards, compatible technology options were compiled into technology baskets and ranked using the shortest euclidean distance to the ideal solution and the farthest euclidean distance to the worst solution (Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method). An analysis of the CS 23 regulations leads to a high-wing design and excluded the partial turbo-electric powertrain architecture with the gas turbine in the aircraft tail. For 2025, a partial turbo-electric powertrain with two additional electric driven wingtip propellers was selected. A serial hybrid powertrain, which uses a gas turbine or fuel cell in combination with a battery, powers distributed electric propulsors at the wing leading edge in 2050. In both scenarios, the aircraft design includes an electric environmental control system, an electric driven landing gear and electro-hydraulic actuators for the primary flight control and landing gear.

Keywords Aircraft design · Electrification · Commuter aircraft · Hybrid-electric propulsion · Certification

List of symbols

H_P	Power hybridization (–)
H_{PS}	Power split (–)
P	Power (W)

Abbreviations

AMC	Acceptable Means of Compliance
BASA	Base of Aircraft Data
CS	Certification Specification
EASA	European Union Aviation Safety Agency
EIS	Entry Into Service
HTP	Horizontal Tail Plane
ICAO	International Civil Aviation Organization
KTAS	Knots True Air Speed
LuFo	Luftfahrtforschungsprogramm
MSL	Mean Sea Level
MTOM	Maximum Takeoff Mass
NASA	National Aeronautics and Space Administration
PAX	Passengers
PMAD	Power Management And Distribution
SOC	State Of Charge
TCM	Technology Compatibility Matrix
TMS	Thermal Management System
TO	Takeoff
TOC	Top Of Climb

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TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
T1, T2, T3	Technology options 1, 2, 3
UNICADO	University Conceptual Aircraft Design and Optimization
VTP	Vertical Tail Plane

Subscripts

bat	Battery
elec	Electrical
i	Index of the technology option
j	Index of the evaluation parameter
mech	Mechanical
opt	Optimal
tot	Total
TS	Turboshaft
*	Optimum solution
−	Worst solution

1 Introduction

In 1973, the first manned electric powered aircraft, the MB-E1, took off [1]. Since then, many technologies using electric power were further developed. In aviation, new electric drive-system components bring different advantages and disadvantages with them, which have to be considered during the aircraft design process [2]. On the one hand, electric motors have a higher power to weight ratio (up to 2 MW design power) and a three to four times higher power efficiency compared to conventional engines, which is almost independent of the motor size. Moreover, for a comparable power output they are smaller and have a higher reliability. On the other hand, the supply of electrical energy is heavy and expensive. When these advantages and disadvantages are considered, the mere change of the propulsion system leads to non-optimal designs. Instead, they require new design alternatives.

The impact of unconventional designs have already been investigated in existing prototypes as the Eviation Alice, the NASA X-57 and the e-Genius as well as in theoretical studies [3–6]. But these prototypes and developed concept aircraft transport a maximum of nine passengers. Hence, this paper will investigate, which technology combinations promise the lowest emissions and operating costs while being integrated in a commuter aircraft for 19 passengers and ensuring an acceptable level of safety. To show the possible evolution of electric propulsion and the associated technologies in the next 30 years, this will be done for two scenarios in 2025 and 2050.

The holistic analysis of the electrification of a commuter aircraft considers a wide range of possible technology options and different evaluation criteria, which require a structured down selection process. This paper describes the first step of this process towards a detailed evaluation of an electrified aircraft design.

The powertrain architecture and technology selection depends on the application intent and mission [2]. Therefore, a reference commuter aircraft for 19 passengers and a design mission is selected in Sect. 2. Then, possible technology options are collected in Sect. 3 and evaluated in Sect. 4. Afterwards, compatible technologies are compiled in technology baskets and ranked in Sect. 5. Finally, the best ranked technology baskets are analyzed with regard to regulatory aspects in Sect. 6. This leads to the selected aircraft designs with EIS in 2025 and 2050 (Sect. 7) and the conclusion (Sect. 8).

2 The conventional reference aircraft

The evaluation and selection of different technology options depend heavily on the aircraft type and its design mission. Hence, a suitable commuter aircraft with a capacity of 19 passengers was selected and will be described in this chapter.

In 2019, the Beechcraft 1900D flew 18,620 h in Europe according to the airline schedules data from OAG Aviation Worldwide Limited [7]. Compared to other commuter aircraft with the same capacity, this aircraft type constituted the highest market share and was, therefore, selected as the reference aircraft.

2.1 Beechcraft 1900D

The turboprop aircraft, which is illustrated in Fig. 1 and made its first flight in March 1990, uses two Pratt&Whitney PT6A-67D engines [8]. Each of them produces a maximum takeoff power of 954.5 kW and drives a four-bladed constant speed and full-feathering propeller. The cabin is pressurized and can be accessed through airstairs. The aircraft structure is made of aluminum alloy. Additionally, the aircraft holds a single pilot approval under Federal Aviation Regulations

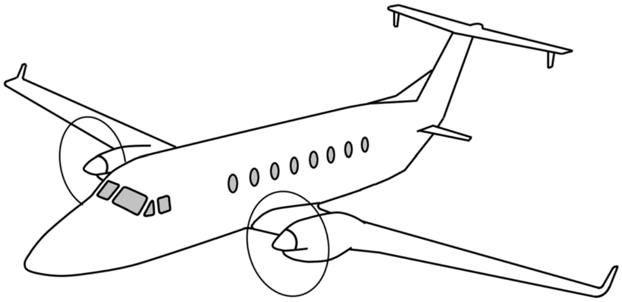

Fig. 1 Reference aircraft Beechcraft 1900D

Table 1 Key characteristics of the Beechcraft 1900D

Parameter	Unit	Value
Maximum takeoff mass	kg	7765
Maximum operating empty mass	kg	4847
Maximum payload	kg	2105
Ceiling height	ft	25000
Maximum cruise speed at 25,000 ft	KTAS	287
Maximum range with 19 PAX, high-speed cruise power at 25,000 ft	NM	690
Wing span	m	17.65 (ICAO aerodrome category B)
Takeoff field length	m	1140

Table 2 Reference mission

Parameter	Unit	Value
Payload (19 PAX)	kg	1767
Taxi time (departure)	min	10
Time to climb	min	13.69
Cruise altitude	ft	23,000
Cruise speed	KTAS	242
Time to descend	min	19.73
Taxi time (arrival)	min	10
Range	NM	510

FAR 135 Appendix A. Table 1 shows further key characteristics of the Beechcraft 1900D [9].

At system level, pneumatic de-icing boots are installed at the wing and stablizer leading edges. Cables and rods actuate the primary flight controls, whereas the landing gear is retracted hydraulically [9, 10].

Basic performance data from the BADA database [11] and Specific Range Solutions Ltd. [12] include fuel consumption, altitudes and air speeds of the Beechcraft 1900D, which enabled an initial derivation of the design mission for the following investigations. Table 2 lists important parameters of the obtained reference mission. The reserves include a holding of 45 min and an alternate flight of 100 NM.

2.2 Regulatory background

As the aircraft shall transport 19 passengers, the aeroplane will be subject to the certification specification CS 23 in its current released amendment 5. CS 23 [13] specifies a maximum certified takeoff mass (MTOM) of 8618 kg (19,000 lbs) and the aircraft is categorized as certification level 4. Further guidance material has to be considered, e.g., the advisory circular AC 20-128A [14] for uncontained turbine engine rotor failure.

3 Collection of eligible technology options

Possible technology options were collected at a workshop with the heads of institute and involved research assistants of all research entities in the project GNOSIS based on personal experiences and best guesses. Subsequently, they were structured in the four categories powertrain architecture, aerodynamic interaction, system technologies and operating strategies. Initially, the applicability of the technologies to the previously described reference aircraft was not taken into account. Following technology options were identified:

Powertrain architecture:

- Serial hybrid with gas turbine / piston engine / fuel cell
- Cycle integrated
- Turbo-electric (partial / full)
- Parallel hybrid (on one spool or separated)

Aerodynamic interaction:

- Distributed propulsion
- Wingtip mounted propulsion
- Thrust control for steering
- Wake / boundary layer ingestion
- High-lift propellers
- Tail mounted propellers
- Ducted propellers
- Windmilling operation of the propeller
- Folding propellers

System technologies:

- Primary flight controls with electro hydraulic actuators or electro mechanic actuators
- Distributed actuation system for trailing edge flaps
- Landing gear actuation with electro hydraulic actuators
- Electric de-/anti-icing
- Electric environmental control system
- Electric taxiing
- Fuel cell as auxiliary power unit

Operating strategies:

- Steep departure
- Landing with engines switched off
- Steep approach with recuperation

4 Evaluation of eligible technology options

After the technology options had been identified, their applicability and potential were evaluated in terms of global emissions (CO_2 equivalent), local emissions (NO_X equivalent and noise), operating costs and safety aspects for the different scenarios in 2025 and 2050. The chair of Material Flow Management and Resource Economics at the TU Darmstadt conducted an initial scenario analysis to ensure consistent assumptions for the equivalent emissions and price per energy quantity of kerosene and electricity during production and operation within the evaluation. The equivalent emission values of kerosene in Table 3 are based on the ecoinvent database 2019 for Europe without Switzerland and conversion factors of the UK Government [15–17]. The price of kerosene takes into account the average price per gallon between 2014 and 2019 [18] and a doubling of the CO_2 certificate price [19] in 2050. The emissions and price of electricity in Table 3 cover only Germany [20, 21].

Production and maintenance costs of an upcoming technology option will likely change due to scaling effects and design changes. Therefore, the evaluation considers only the operational phase. Based on the design parameters and reference mission of the Beechcraft 1900D, the emissions and operating costs of the technologies were calculated.

The evaluation determines the relative changes of the four parameters global emissions (CO_2), local emissions (NO_X and noise) and operating costs in reference to the original Beechcraft 1900D. Relevant safety aspects were analyzed, but not transferred to a numerical number. The determination of the global CO_2 emissions was based on the energy consumption during the reference mission and the emission of the energy carrier (kerosene or electricity) during production and usage. Analogously, the calculation of the NO_X emissions referred to the ICAO landing and takeoff cycle, [23], and considered only the required energy of the reference mission below a flight altitude of 3,000 ft above MSL. Energy costs, which constitute 20% of the total operational costs [24], took the changes of the operating costs into account. The evaluation of noise compares the flight trajectory and operating strategy of the new operating technologies and the reference mission. Within this context, the propeller noise was estimated by an empirical equation from Galloway and Wilby [25]. The evaluation did not distinct between different operational phases of the propeller. Hence, constant operations of the distributed propellers and wingtip propellers throughout the entire mission were assumed.

Table 3 Equivalent emissions and costs associated with production, provision and use of kerosene and electricity in 2025 and 2050

Scenario parameter	2025	2050
1 kWh Kerosene[a]		
CO_2 eq. emissions (kg)	0.3038	0.3038
NO_X eq. emissions (kg)	0.0015	0.0015
Price (€)	0.052	0.059
1 kWh Electricity		
CO_2 eq. emissions (kg)	0.3091	0.0600
NO_X eq. emissions (kg)	0.0005	0.0001
Price (€)	0.040	0.031

[a] Assumption: 1 kg kerosene contains 11.979 kWh energy [22]

Each technology option was evaluated by at least two project partners. The assessment of systems, aerodynamic interactions and operating strategies was based mainly on literature research (see Sect. 4.1), whereas a preliminary aircraft design tool analyzed different powertrain architectures (see Sect. 4.2).

4.1 Evaluation of systems, aerodynamic interactions of propulsors and operating strategies

Literature review, simplified calculations (e.g., force and moment equilibrium) and results from other studies of the project partners enabled the evaluation of the systems, aerodynamic interactions of the propulsors and the operating strategies. During the evaluation, the applicability of the technology option for the Beechcraft 1900D was proven. This leads to the exclusion of cycle-integrated electrified engine (too complex for preliminary design), distributed actuation system for trailing edge flaps (only simple high-lift system of the reference aircraft) and fuel cell as auxiliary power unit (no auxiliary power unit in the reference aircraft). Table 4 lists the most relevant technology options and the relative changes of the evaluation parameters with respect to the original reference aircraft Beechcraft 1900D. Important references for the evaluation of technology options are given in the first column. If a technology option leads to a negligible change of an evaluation parameter, the change was assumed to be 0%. New operating strategies enable a high reduction of emissions, especially noise. Furthermore, electric taxiing and an electric environmental control system can decrease the NO_X emissions below a flight altitude of 3000 ft. New aerodynamic integration forms of the propulsors require less power over the whole mission, which can lead to a lower emission of pollutants and energy costs.

4.2 Aircraft level assessment of powertrain hybridization effects

Besides the evaluation above, a design space exploration was performed to assess the effects of the powertrain hybridization. This was done on a simplified conceptual level, such

Table 4 Selected technology options and their evaluation parameters in 2025 and 2050

Technology option	2025				2050			
	CO_2 emissions (%)	NO_X emissions (%)	Energy costs (%)	Noise (%)	CO_2 emissions (%)	NO_X emissions (%)	Energy costs (%)	Noise (%)
Landing with engines switched off [25, 26]	– 9.5	– 5.5	– 2.0	– 86.0	– 9.5	– 5.5	– 2.0	– 86.0
Steep approach with recuperation (windmilling) [25, 27]	– 1.0	– 3.4	– 0.2	– 68.4	– 1.0	– 3.4	– 0.2	– 68.4
Electric taxiing [28, 29]	– 4.0	– 46.0	– 0.8	N/A	– 4.0	– 46.0	– 0.8	N/A
Electro hydraulic landing gear actuators	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electro hydraulic primary flight control actuators [30]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electric environmental control system [31]	– 4.6	– 41.7	– 1.0	0.0	– 5.6	– 43.9	– 1.2	0.0
Electric de-/anti-icing [32]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distributed propulsion [33]	– 12.5	– 1.6	– 2.5	N/A	– 12.5	– 1.6	– 2.5	N/A
Wingtip mounted propulsion [34, 35]	– 10.0	– 1.6	– 2.0	N/A	– 10.0	– 1.6	– 2.0	N/A
Fuselage propulsion (wake ingestion) [36]	– 5.0	– 0.7	– 1.0	N/A	– 5.0	– 0.7	– 1.0	N/A

that general hybridization trends could be investigated without diving into specific aircraft configurations.

4.2.1 Modeling approach

Spanning the design space for the aircraft-level propulsion studies required the introduction of hybridization parameters as well as a proper setup of the aircraft design environment, including the integration of numerous parameters provided by the different partners. Use was made of a Bauhaus Luftfahrt internal aircraft design environment, which is implemented in Remote Component Environment (RCE [37]), and consists of various modules representing the main disciplines. This setup allows an easy exchange of modules with different fidelity, although for this study handbook and semi-empirical methods are used exclusively. The Common Parametric Aircraft Configuration Schema (CPACS [38]) is used to exchange data between the various modules. A publication describing the aircraft-design environment in more detail is planned for the near future.

To efficiently map the different hybridization strategies and degrees, two key parameters were used: power hybridization (H_P, see Eq. 1) and power split (H_{PS}, see Eq. 2). Here, H_P indicates which fraction of the total power on aircraft level (battery power plus gas turbine power) is provided by the battery. This parametrization ensures always a correctly sized battery for the given study boundary conditions. H_{PS} is indispensable for most hybridization variants, as it determines what portion of the total power provided by the gas turbine is converted into electric power through electric generator(s). It should be noted that this coefficient is independent from the amount of power provided by the battery, unless H_P equals 1, in which case no power is generated by the gas turbine and, therefore, H_{PS} becomes meaningless.

$$H_P = \frac{P_{bat}}{P_{tot}} = \frac{P_{bat}}{P_{bat} + P_{TS,tot}}, \tag{1}$$

$$H_{PS} = \frac{P_{TS,elec}}{P_{TS,tot}} = \frac{P_{TS,elec}}{P_{TS,elec} + P_{TS,mech}}. \tag{2}$$

It is important to notice that, depending on how the propulsion system is integrated, not all combinations of H_P and H_{PS} lead to a feasible aircraft configuration. For example: for a conventional two-propeller aircraft configuration, having one propeller driven by a gas turbine and the second by an electric motor, the power to each propeller should be equal to avoid thrust asymmetry, which, therefore, restricts feasible value combinations of H_P and H_{PS}. The two parameters formed two of the main inputs in the design-space exploration and have been kept constant throughout the mission. This means, that no operational hybridization strategy and its direct impact on emission levels (e.g., boosted TO with reduced NO_X) has been considered.

During the first step of the design space exploration the models were calibrated by modeling the Beechcraft 1900D reference aircraft and adjusting the calibration factors until the performance matched the expected values from literature. The second step added the electrified powertrain based on predetermined technology assumptions. These can be

Table 5 Overview of the hybrid-electric powertrain technology performance assumptions (partly derived from [39–53])

Component	2025	2050	2025	2050
Transmission efficiency (%)			*Specific power (kW/kg)*	
Electric machines	97.5	99.0	9.0	20.0
Power electronics	96.0	96.0	19.0	19.0
PMAD	100	100	66.12	66.12
TMS	100	100	0.9	1.1
Propeller*	88.0	90.0	−10%**	−20%**
Propeller gearbox	98.5	99.0	26.98	38.85
Transmission efficiency (%)			*Specific energy (kWh/kg)*	
Battery***	97.5	98.5	0.195	0.380
TOC fuel consumption (g/kWh)			*TO specific power (kW/kg)*	
Turbine engine	234	202	4.5	5.5

*In cruise **w.r.t. model baseline ***min/max SOC: 20/90%

found in Table 5 and may be considered rather conservative, especially for the battery. The electric components were sized based on the maximum required power by the propeller model, while considering the efficiency of each of the powertrain components. Since the study does not consider specific configuration changes, changes in for example cable lengths were not included. Additionally, an improvement in mass and aerodynamic drag was included to represent expected technological advances in 2025 and 2050 compared to the introduction of the Beechcraft 1900D in the 1980s. These adjustments are summarized in Table 6.

4.2.2 Case studies

Three main topics were investigated during the conceptual hybrid-electric commuter aircraft design space exploration:

1. The incorporation of a turboshaft based hybrid-electric powertrain aided by a battery
2. The integration of a fully electric, battery-driven powertrain ($H_P = 1$)
3. Variation in wing mass and electric propulsive efficiency

The effects of the powertrain hybridization on MTOM can be seen in Fig. 2, which also illustrates the technological progress by the sets of curves for 2025 and 2050. Mainly due to the lower energy density of the batteries for 2025, the slope of the curve in the MTOM-H_P diagram increase significantly, so that hardly any values above 5% battery feed-in lie in the realistically usable range, when considering the CS 23 MTOM certification limit. In addition, due to a worse powertrain performance and snowball effects, 2025 also experiences a stronger increase in mass for rising

Table 6 Mass and aerodynamic drag reduction breakdown acc. to EIS compared to reference

Mass item	Change (%)	
	2025	2050
Fuselage	– 10	– 20
Wing, HTP, VTP	– 10	– 20
Operator items	– 15	– 30
Hydraulic distribution	– 2.5	– 5
Electrical generation	– 5	– 20
Landing gear	– 10	– 20
Zero-lift drag item		
Fuselage	0	– 5
Wing, HTP, VTP	0	– 5

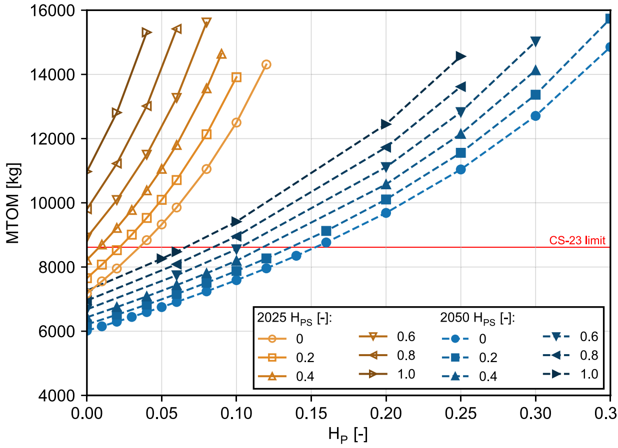

Fig. 2 Effect of hybridization degree H_P and power split H_{PS} on aircraft Maximum Takeoff Mass (MTOM)

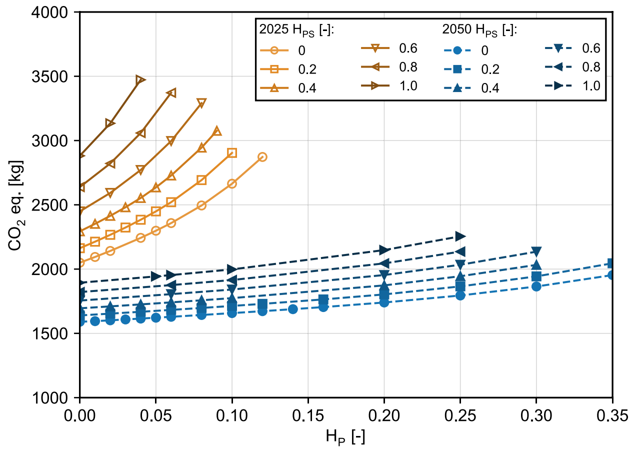

Fig. 3 Effect of hybridization degree H_P and power split H_{PS} on CO$_2$ eq. emissions

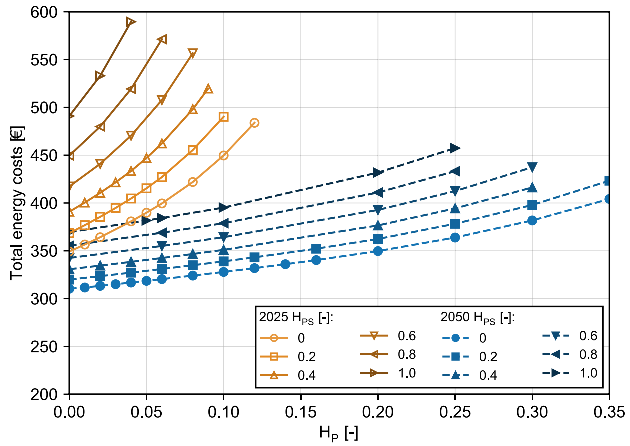

Fig. 4 Effect of hybridization degree H_P and power split H_{PS} on energy costs

H_{PS}. This can be seen by the increasing distance between the lines of the set. To not overstretch the design space and to achieve a better overview, results were capped at twice the CS 23 MTOM limit. Comparing some of the results along this limit, a sense of the relevant orders of magnitude can be developed; with $H_{PS} = 100\%$, about 6.5% battery share is feasible in 2050. The share increases to about 15% and, thus, more than double the value for $H_{PS} = 0\%$. For the year 2025, on the other hand, a maximum of approximately 55% of the generated mechanical power is convertible before the limit is exceeded. Without conversion, a battery power share of just under 4% is feasible. However, as will be shown in the next paragraph, the large mass increase has a detrimental effect on the equivalent emissions and costs.

Directly related to the hybridization strategy are the amount of fuel required for the design mission (including reserves), CO$_2$ and NO$_X$ equivalent emissions and energy costs. Similar to the effects on MTOM, the different spacing between the lines of the two sets of curves for the different EIS can be clearly seen in Figs. 3 and 4. Only in the case of energy costs, the two groups overlap due to the opposing development of electricity and kerosene prices, leading to a weakening of the difference in the diagrams. For kerosene, it is assumed that prices will rise in the coming decades due to a shortage of supply and increasing production costs. In the case of electricity prices on the other hand, it is expected that the expansion of renewable production capacities will lead to a price reduction in the long term. Nevertheless, the results confirm the statement, that it is important to consider the integration benefits that powertrain hybridization can offer, as pointed out by for example [2], as hybridization alone results in worse performance. It should be kept in mind, however, that the results presented are likely conservative, since no mission hybridization strategy optimization has been performed.

The second case study investigated the required battery energy density for the aircraft to be certifiable under CS 23 regulations in 2050. The results showed that, for the given boundary conditions, an energy supply into the propulsion system from purely electrochemical storage systems of today's design (battery specific energy values see Table 5) cannot be reasonably realized. Only starting with values as high as roughly 1.45 kWh/kg the MTOM limit can be held. As can be seen in Fig. 2, for $H_P = 0\%$ from $H_{PS} = 0\%$ to $H_{PS} = 100\%$, the electrification of the powertrain excluding power generation/storage adds an additional 1.25 t to the aircraft mass. It has to be kept in mind, that for rising battery specific energy, the MTOM degression shows an asymptotic behavior, as snowball effects cease accumulative tendencies.

As already pointed out, it is important to consider the integration benefits that powertrain hybridization can offer. As integration influences are not sufficiently represented by the studies above investigating mass and, thus, consumption, emissions and cost changes, two additional investigations were conducted in the third case study. However, these are of crucial importance, as they can lead to significant advantages over standard configurations in synergetically efficient concepts. In particular, two influencing variables were considered essential for decision-making and were analyzed in extended studies: the influence of improved electric propulsive efficiency and a variation in wing mass. The electric propulsive efficiency can be increased by various measures on aircraft level, leading to mission-level performance improvements. Examples include propulsive-fuselage concepts or wing-tip propulsors. The effect of wingtip propulsors can be considered as an increase in propulsive efficiency or a reduction in induced drag, depending on the placement of the props (tractor vs. pusher), and the method of book-keeping [54, 55]. The same rationale may be applied to

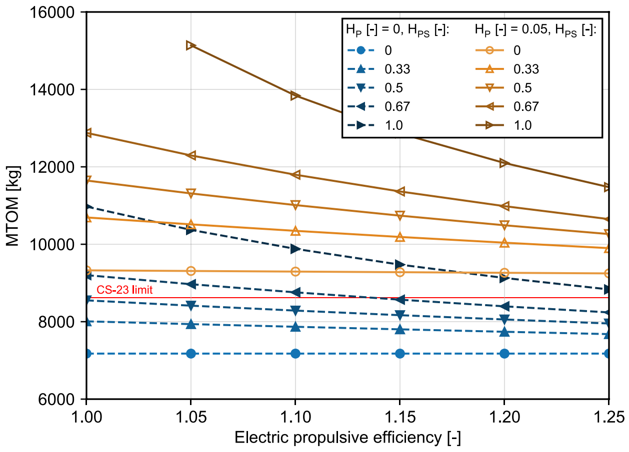

Fig. 5 Effect of electric propulsive efficiency increase on aircraft MTOM for EIS year 2025

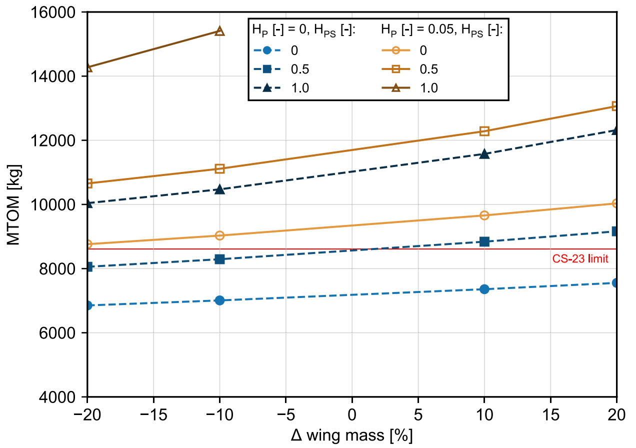

Fig. 7 Effect of change in wing mass on aircraft MTOM for EIS year 2025

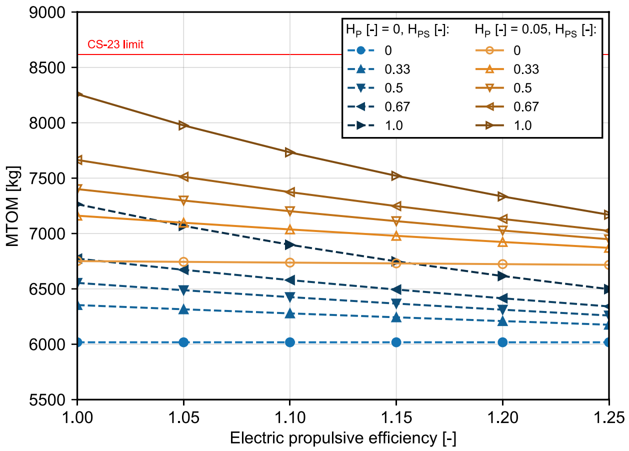

Fig. 6 Effect of electric propulsive efficiency increase on aircraft MTOM for EIS year 2050

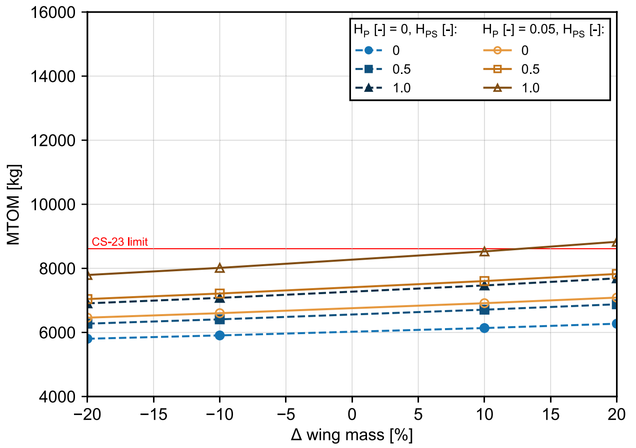

Fig. 8 Effect of change in wing mass on aircraft MTOM for EIS year 2050

propulsive-fuselage concepts (albeit with offsetting parasitic drag). Hence, to simplify the design space exploration, for this study these beneficial effects are grouped under the term propulsive efficiency increase, which is defined as decrease in the power required by the propulsor to generate a given amount of thrust, scaling with $(1/\eta_{PE})$. Or in other words: a propulsive efficiency of 1.25 means that for a given amount of thrust the power required by the propulsor is 80% (=1/1.25) compared to the baseline aircraft with a propulsive efficiency of 1. It is important to note that the propulsive efficiency increase was only applied to the electric propulsion path and not the conventional propulsion part. The main argument for this is that generally only the electric propulsors allow a propulsive efficiency increase; e.g., it is not feasible to integrate turboshaft engines at the wingtips. An efficiency increase of up to 25% was investigated to be able to derive macroscopic trends. The nonlinear influence of the propulsive efficiency on the takeoff mass is pointed out well by the asymptotic behavior of the curves for $H_{PS} = 100\%$ as depicted in Figs. 5 and 6. The cascade effects of reduced energy consumption (kerosene or electrochemical), less required energy carriers, thus reduced structural mass, etc. result in a positive trend for increasing propulsive efficiencies.

As an example for varying structural masses, a delta study was performed on the wing masses covering a ±20% shift. Its results are depicted in Figs. 7 (2025) and 8 (2050) and underline the importance of sophisticated mass distribution considerations on aircraft level. The trends show, that already a minor wing mass reduction might enable other technologies by still staying below the CS 23 MTOM limit. The wing mass is of elevated relevance, as the integration of several propulsors on the wing may provide a structural mass

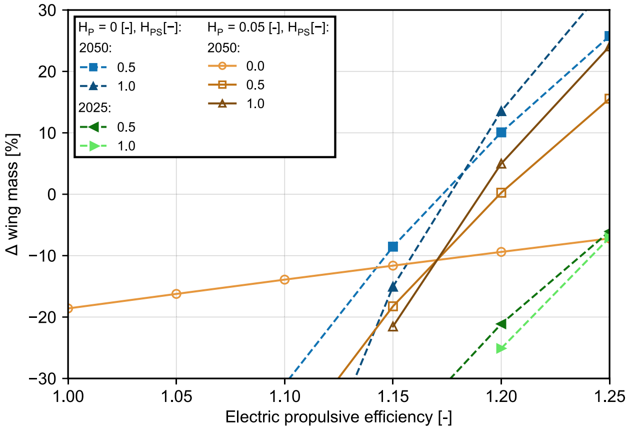

Fig. 9 Required combined change in wing mass and propulsive efficiency to reach equal CO_2 eq. emission compared to the baseline aircraft for EIS year 2025 and 2050

reduction through a reduced wing root bending moment. This positioning of multiple electric propulsors is one of the main benefits of a powertrain hybridization. However, the power reduction of internal combustion engines is only sensible down to a certain size, as gap, boundary layer and thermodynamic losses start to increase significantly and make the integration of these engines into distributed propulsion systems unattractive.

Besides the effect on MTOM, also the effects on the CO_2 equivalent and local NO_X equivalent emissions are important to consider. Hence, the required combined change in wing mass and electric propulsive efficiency to reach equal equivalent emissions compared to the baseline aircraft was calculated. The results for the CO_2 equivalent for EIS year 2025 and 2050 can be seen in Fig. 9. These results show that various combinations of a change in wing mass and electric propulsive efficiency would reduce the aircraft emissions compared to the baseline (e.g., every combination below and to the right of each curve). The 2025 results show, that only turbo-electric configurations ($H_P = 0$) can reach a net zero effect on emissions for higher propulsive efficiency increases (min. 17%) and wing mass reductions (min. 5%). For 2050, the effort to reach this condition is eased.

Lastly, it is important to point out that the trend results presented here are on a simplified conceptual level. In reality, achieving specific benefits requires careful interdisciplinary integration, e.g., see [56, 57], that will impact mass, propulsive efficiency as well as other factors. For example, a specific propulsive efficiency increase achieved by changing to wingtip propulsors would likely require longer cable lengths, as well as a significant VTP size increase. Hence, the results presented here only provide a first indication of the top level effects due to hybridization, (wing) mass change and/or propulsive efficiency increase, while more detailed analysis should be made once more details of the new aircraft configuration are known.

5 Selection of technology baskets

After the evaluation of the different technologies, combinations of compatible technology options, or in other words technology baskets, were selected. The selection was done in three steps:

1. Selection of possible powertrain architectures (hybridization degrees) (see Sect. 4.2)
2. Creation of technology baskets of compatible technology options (see Sect. 5.1)
3. Ranking of the technology baskets (see Sect. 5.2)

Steps (2) and (3) are based on the Technology Identification, Evaluation and Selection (TIES) method by Kirby [58]. The method addresses disruptive changes in the aviation industry and comprises the multidisciplinary assessment of evolving, immature technologies to obtain new design alternatives.

5.1 Creation of technology baskets

To create technology baskets, the compatibility and the evaluation parameters of each technology option were recorded in two matrices, the Technology Compatibility Matrix (Fig. 10) and the Technology Influence Matrix (Table 4). Subsequently, these two matrices were combined in a decision matrix (Table 7).

The Technology Compatibility Matrix (TCM) assesses the compatibility of all technology options and contains pairwise comparisons of two technology options. In Fig. 10, '1' means compatible and '0' means incompatible. If one technology option within a combination of technologies is not compatible with another technology, the whole combination (one column in TCM) cannot be realized.

According to Kirby [58], the following questions have to be answered to fill out the TCM:

- Does one technology option perform the same function as another option?
- Does one technology option influence the functionality / integrity of another option?
- Is the technology option only applicable for the specific type of aircraft or operating point?

The two Technology Influence Matrices for the scenarios in 2025 and 2050 include the relative change of the evaluation parameters CO_2 emission, NO_X emissions, noise and operating costs for each technology option as shown in Table 4. The maximum savings of the matured technology are considered based on the estimation of the involved project partners (see Sect. 4.1). In Table 4, 'N/A' means that the relative change of a technology option could not be determined.

Compatibility	T1	T2	T3
Technology option 1 (T1)	1	0	1
Technology option 2 (T2)		1	0
Technology option 3 (T3)			1

Fig. 10 Exemplary Technology Compatibility Matrix (TCM)

Based on the TCM, compatible technology options were compiled into technology baskets. Subsequently, the evaluation parameters of the technology basket were calculated by adding the evaluation parameters of each included technology option. The influence of one technology on another technology (e.g., synergy effects) is neglected and will be investigated in a detailed preliminary design afterwards. The results of every technology basket are summarized in a decision matrix.

5.2 Ranking of the different technology baskets

The ranking of the different technology baskets in the decision matrix is done using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [59]. TOPSIS considers the optimum and worst alternative and assumes that each evaluation parameter is monotonically increasing or decreasing. Hence, the optimum can be the lowest or highest value, but not in between. The chosen alternative should have the shortest euclidean distance to the ideal solution and farthest from the worst solution. The minimum of each evaluation parameter (emissions and operating costs) presented the ideal solution.

Table 7 shows the decision matrix for the three most potential technology baskets in 2025 and 2050. Due to the CS 23 MTOM limitation in Fig. 2, only a partial turbo-electric powertrain ($H_{\mathrm{P}} = 0$ and $H_{\mathrm{PS}} = 0 - 0.5$) is feasible in 2025. In 2050, higher values of H_{P} are possible. Hence, a serial hybrid-electric powertrain with a battery and a gas turbine ($H_{\mathrm{P}} > 0$ and $H_{\mathrm{PS}} = 1$) was selected for the technology baskets in 2050. Included technology options are marked by an 'x'. Since distributed propulsion can include wingtip

Table 7 Decision matrix of potential technology baskets in 2025 and 2050

	Included technology options										**Total change**				
Powertrain	Landing with engines switched off	Steep approach with recuperation (windmilling)	Electric taxiing	Electro hydraulic landing gear actuators	Electro hydraulic primary flight control actuators	Electric environmental control system	Electric de-/anti-icing	Distributed propulsion	Wingtip mounted propulsion	Fuselage propulsion (wake ingestion)	CO_2 emissions [%]	NO_X emissions [%]	Energy costs [%]	Noise [%]	**Ranking**
Technology baskets 2025															
Partial turbo-electric		x	x	x	x	x		x		x	-27.1	-93.4	-5.5	-68.4	**1**
Partial turbo-electric		x	x	x	x	x			x	x	-24.6	-93.4	-5.0	-68.4	**2**
Partial turbo-electric			x	x	x	x			x	x	-23.6	-90.0	-4.8	0.0	**3**
Technology baskets 2050															
Serial hybrid-electric (Gas turbine / fuel cell + battery)	x		x	x	x	x	x	x		x	-36.6	-97.7	-7.5	-86.0	**1**
Serial hybrid-electric (Gas turbine / fuel cell + battery)	x		x	x	x	x	x		x	x	-34.1	-97.7	-7.0	-86.0	**2**
Serial hybrid-electric (Gas turbine / fuel cell + battery)	x		x	x	x	x	x	x			-31.6	-97.0	-6.5	-86.0	**3**

mounted propulsion as well, the two technology options exclude each other. The addition of the evaluation parameters of each included technology option leads to unrealistic high total reductions of the evaluation parameters. However, within this study, only the relative comparison of the total values between the different technology baskets is relevant for the selection process.

6 Regulatory aspects

Subsequent to the ranking of the technology baskets, an assessment of a certification for the selected hybrid-electric propulsion systems concluded the selection process. Within the assessment, an analysis of all failure conditions 'that can reasonably be expected to occur' has to be carried out according to the special condition SC E-19 issued by EASA [60]. The special condition currently excludes a stand-alone certification of a generic hybrid-electric propulsion system [61], which is common for conventional aviation engines. Instead, hybrid-electric propulsion systems shall be certified for each specific aircraft application. Figure 11, 12, 13 illustrate critical certification aspects using an exemplary layout of the electrified aircraft.

The selected technology baskets include distributed propulsion with wingtip mounted propellers to increase aerodynamic efficiency. Furthermore, a configuration with a single gas turbine mounted in the aft of the fuselage was selected to increase propulsive efficiency. The implication on certification level are discussed preliminary in the following section. Paragraph CS 23.2135 [13] states 'that the aeroplane must be controllable and maneuverable, without requiring exceptional piloting skills'. Further, clearance of the propellers is required according to CS 23.925 AMC [62]. Both aspects require a wing and landing gear design which allows a certain banked aircraft position at touch-down without the contact of a wingtip. The latter is challenging for a low-wing aircraft equipped with wingtip propulsion, as excessive dihedral or a significantly increased landing gear size are required. Longer landing gears are associated with increased mass [63] and more installation volume for the retraction mechanism is needed. Furthermore, the integration of an airstair typically required for the operation of 19-passenger aircraft is complicated considerably for increased landing gear heights. Consequently, a high-wing aircraft configuration as shown in Fig. 11 was chosen in contrast to the low-wing design of the reference aircraft Beechcraft 1900D in Fig. 1.

The installation of a gas turbine in the aft section of the fuselage possesses some challenges. The advisory circular AC 20-128A [14] defines a guideline to mitigate the effect of released gas turbine parts, e.g., fan blades or turbine disk fragments, where uncontained engine rotor failures represent a significant hazard. As a consequence, the guideline requires the 'location of critical components outside the fragments areas or separation, isolation, redundancy, and shielding of critical airplane components and/or systems'. As a result, control systems should be duplicated and installed in separate locations in the fuselage so that in the event of an uncontained engine rotor failure, only one control path

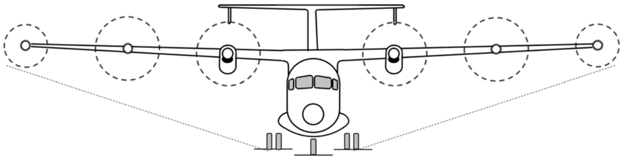

Fig. 11 Differently to the reference aircraft, a high-wing aircraft configuration is chosen

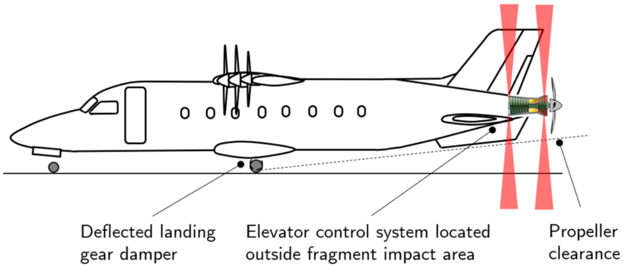

Fig. 12 A conventional empennage layout is required to separate the elevator control system from uncontained engine rotor fragments

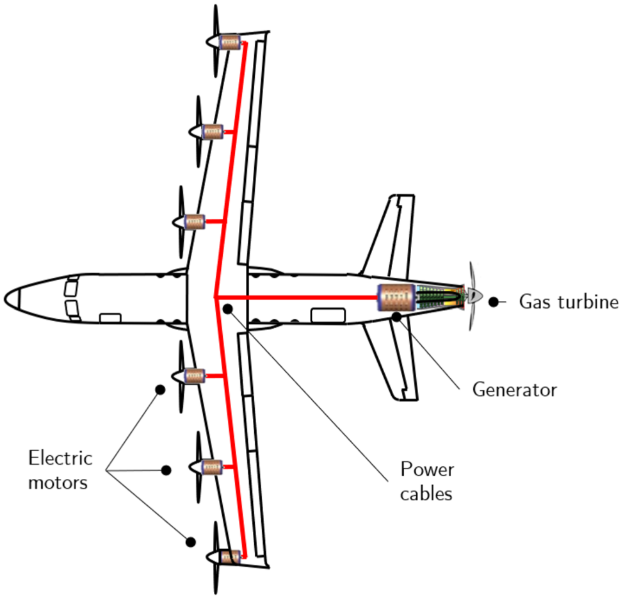

Fig. 13 Turbo-electric propulsion system with a single gas turbine contains a single point of failure

is compromised. Preliminary geometric investigation has shown that the separation of the elevator control system in the vertical section of a T-tail might not be feasible. Consequently, a conventional tail would be required as shown in Fig. 12.

In Fig. 12, the rudder is still located in the disk fragment area—however, the loss of rudder control is commonly not regarded as a catastrophic failure.

For the 2025 time horizon, one of the configurations chosen by the ranking method, was a turbo-electric propulsion system shown in Fig. 13, which was equipped with a single gas turbine. By applying a single gas turbine instead of two gas turbines, an increased overall pressure ratio can be achieved [64] and the engine efficiency increases. However, the paragraph CS 23.2410 requires a 'continued safe flight and landing after any system component failure'. The single gas turbine represents a single point of failure with a catastrophic failure condition and certification seems not feasible. As a consequence, the configuration will be investigated for the 2050 time horizon and a series hybrid-electric propulsion system will be applied, containing a battery system which can compensate the power loss associated with a failure of the single gas turbine.

7 Resulting aircraft designs for 2025 and 2050

The assessment of the different technology options leads to two different aircraft designs in 2025 and 2050. Figure 14 illustrates an exemplary design of a hybrid-electric aircraft for 19 passengers.

7.1 Aircraft design in 2025

The partial turbo-electric aircraft design in 2025 adds additional electrically driven propellers at the wing leading edge to the conventional powertrain. The conventional powertrain provides the additional electric power using one generator at each gas turbine. Operating the propellers in a windmilling mode can create additional drag to enable steep approaches. The pressurization of the cabin is done by an electric environmental control system. On ground, electric driven landing gears can reduce emissions, whereas during flight electro-hydraulic actuators retract the landing gear and move the primary control surfaces.

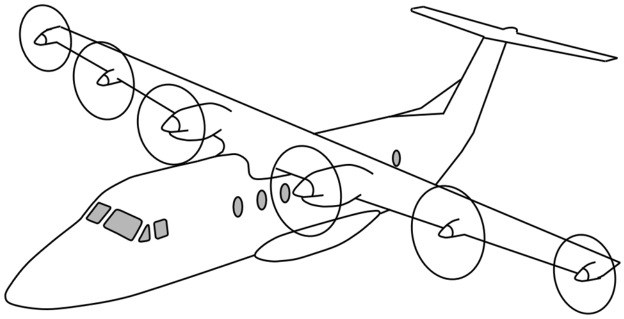

Fig. 14 Graphic vision of a hybrid-electric aircraft for 19 passengers

7.2 Aircraft design in 2050

The serial hybrid aircraft in 2050 generates electric power by a gas turbine or fuel cell in combination with a battery. The thrust is, therefore, completely generated electrically through wake ingestion at the aircraft tail and distributed propulsion at the wing leading edge. Besides the electric environmental control system, the electric driven landing gear and electro-hydraulic actuators for the landing gear and the primary flight control, an electric de- and anti-icing system and an approach with switched-off engines will be integrated in this configuration.

8 Conclusions and outlook

The electrification of aircraft introduces various new technology options, which lead to unconventional designs. According to this study, a new electrified commuter aircraft needs a gas turbine or fuel cell to generate the electric power. This will enable to fly the design range of the conventional reference aircraft. Based on the technology assumptions, batteries will only be included in an aircraft design in 2050 due to the related mass penalty. To reduce the electric power consumption, new forms of aerodynamic propulsion integration shall be applied. The consideration of current regulations showed that a high-wing configuration will be necessary and the integration of a gas turbine in the aircraft tail is not feasible.

In future, the selected technology baskets will be modeled in detail by the involved project partners. Subsequently, simplified models will be integrated in the preliminary aircraft design tool UNICADO [65] to design the hybrid-electric aircraft with EIS in 2025 and 2050.

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