DOI: 10.13009/EUCASS2023-273
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Consideration of Technology Scalability in the Design of Electric Propulsion System Architectures

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Abstract

This work presents an investigation of alternative propulsion systems with the focus on technology scaling opportunities across different aircraft categories. Combining the conceptual aircraft design capabilities at Politecnico di Milano and the system architecture sizing and evaluation tools at Collins Aerospace, five aircraft categories are studied based on six novel propulsion system architectures considering different future technology scenarios. The results suggest that hydrogen-powered architectures combined with a customized utilization of fuel cells have the potential to reduce mission energy and thereby climate impact making them a promising option to reach sustainability goals.

1. Introduction

The aviation community has committed to a net-emission free, which requires radical technology advancements on overall aircraft and subsystem level. Both electric and hybrid-electric propulsion represent promising concepts to achieve this goal.[12] While traditional combustion engines only leave small room for further improvement, electric propulsion systems open a new design space with various possibilities for propulsion layout and subsystem architectures. Therefore, large research and development efforts have been put into electric proplusion concepts within recent years.[7] Full-electric propulsion systems are already flying today in aircraft of the general aviation (GA) category.[19] On the other hand, for large commercial aircraft, combinations of hybrid-electric propulsion (HEP), aero-propulsive coupling technologies and utilization of alternative fuels such as hydrogen are more likely to be realized.[13,20]
Previous research in the field suggests that there is no "one-fits-all" optimal propulsion system layout for the different aircraft sizes.[12,16] This has led to multiple solutions being developed in parallel in which the focus is set on a single specific aircraft category or application, resulting in a lack of scalability for the technologies used. Instead of optimizing a system architecture for each aircraft category and specific use case, this work, which is part of the European project SIENA (Scalability Investigation of hybrid Electric concepts for Next-generation Aircraft),[1,14] takes a novel approach. The focus of the project lies on the aspect of scalability in the design process answering the question whether there is the potential for a propulsion system architecture that offers re-usability of the underlying technologies over a wider range of applications. The experience from small aircraft categories, where electric propulsion is feasible today, can reduce the time for entry into service significantly towards larger aircraft categories. In this context, "seams" in the design space of aircraft categories and system architectures where optimal technology options change, are investigated. Based on a pre-selection of candidate system architectures, this work presents a vehicle-level evaluation of these architectures for five aircraft categories ranging from nine-seat general aviation aircraft up to large, long-range commercial transport aircraft. The key performance indicators for the evaluation on vehicle level used here is the payload-range energy efficiency. The evaluation includes battery-powered electric and hybrid-electric systems as well as hydrogen-powered solutions including hydrogen combustion and fuel-cell driven architectures.

2. Application

The presented study aims to perform an assessment of scalability opportunities for alternative propulsion systems across five aircraft categories. Therefore, in the following the scope of application is first set in terms of reference aircraft, baseline system architectures, and technology assumptions underlying the analysis.

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2.1 Baseline aircraft models

Within the scope of this work, five aircraft categories have been selected across the range of commercial aviation from general aviation up to long-range wide-body aircraft.

The smallest aircraft category investigated is the category of light general aviation aircraft and referred to here as category 1. The selected reference vehicle is the Pilatus PC-12, which has a capacity of six to nine passengers and is equipped with a single-engine turboprop. For the scope of this work, the PC-12 NGX has been selected, which is the newest version of the aircraft introduced in 2006 and has an integrated avionics suite and an upgraded Pratt & Whitney Canada PT6A-67P engine.[18]

Category 2 (commuter) represents the upper limit of the CS-23 segment in terms of payload with aircraft up to 19 passengers. The twin-turboprop-driven L 410 NG by Czech aircraft manufacturer Aircraft Industries (formerly Let Kunovice) has been selected as a reference aircraft in this context, which is an update of the aircraft introduced in 2018.[5]

The third aircraft category is the category of regional aircraft. It is currently considered the key aircraft category for the transition to net-zero-emission aviation with the earliest predicted entry into service of all aircraft within the part 25 certification specifications. As the market is dominated by French-Italian aircraft manufacturer ATR with more than 1700 ATR 42 and ATR 72 units built to date, the ATR 72-600, a twin-turboprop with a passenger capacity of 68 to 78 and a range of 1500 km, has been chosen for the scope of this work.[6]

The category of short/medium-range turbofan aircraft (category 4) has the biggest leverage for emission reductions due to its large market share compared to the other categories.[10,26] Since the Airbus A320 family is the currently best-selling aircraft in this category, the A320neo has been selected for the investigations, which was introduced in 2015 with improved geared turbofan engines (e.g. PW1000G) and an increased aerodynamic efficiency due to sharklets.[3]

The largest aircraft category considered in this scope is the wide-body aircraft category (category 5). Due to the high payload and range requirements in this segment, it is the most challenging category for introduction of electric propulsion. As one of the best-selling aircraft in this category, the A350-900 has been selected here, which has a passenger capacity of 440, a maximum range of 15000 km and is powered by two Rolls-Royce Trent XWB engines. To reduce structural weight compared to the previous generation of aircraft, it makes use of composite materials in the wing and fuselage.[4]

Table 1 summarizes the five reference aircraft categories and their key design characteristics considered in this work.

Table 1: Key aircraft design characteristics for the five aircraft categories

Parameter	Aircraft category					Unit
	1	2	3	4	5	
Reference aircraft	PC-12 NGX	L 410 NG	ATR72-600	A320neo	A350-900	-
Number of passengers	9	19	70	180	420	-
Range	1771	342	926	3950	10800	km
Cruise Mach number	0.43	0.32	0.4	0.78	0.85	-
Cruise altitude	28000	17000	23000	32000	35000	ft
Payload (and crew)	1114	2500	7900	19700	53800	kg
MTOM	4475	6675	22105	79020	301625	kg
OME	2570	3660	12235	43945	157025	kg
Block fuel	650	305	1185	15400	90845	kg

For the sake of applicability, some of the values given in table 1 deviate from the original manufacturer data. Also note that, in order to make a fair comparison between future electric propulsion systems and future conventional propulsion systems, expected advancements in terms of secondary on-board systems are included for all aircraft versions independent from the propulsion system. Therefore, the baseline conventional aircraft as well as the aircraft with novel propulsion systems are equipped with an all-electric secondary on-board system architecture for the evaluations in this work, i.e. bleed-less engines, electric actuation systems, electric environmental control systems, etc.

2.2 Propulsion system architectures

The second part that defines the scope of the scalability studies is the different propulsion system concepts considered. In the context of this work, six baseline architectures are under investigation as illustrated in figure 1.

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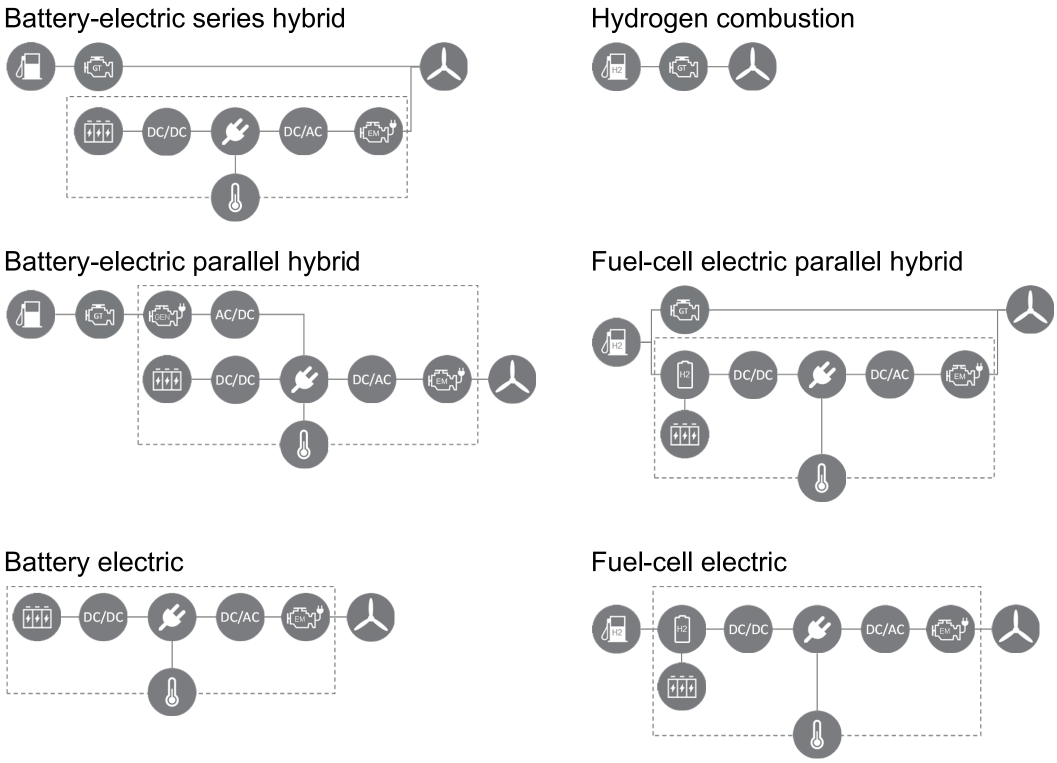

Figure 1: Baseline system architectures considered for evaluation

The architectures in the figure above can be grouped into systems using

- kerosene,
- electric energy stored in batteries,
- hydrogen,

as the primary energy source. There are also hybrid systems using two energy carriers simultaneously. The following sections give a brief overview on the selected baseline architectures.

2.2.1 Battery-electric propulsion

A full-electric propulsion system powered by batteries (i.e. battery electric, BE) is the architecture with the highest powertrain efficiency, because it uses electrical energy directly with minimal conversion losses. It is also the only actual zero-emission concept as it produces no local emissions on vehicle-level during operation. However, due to the low energy density of batteries, which is currently about 50 times lower than the energy density of kerosene, these systems tend to become too heavy especially for large aircraft and long flight distances. The architecture, as illustrated in figure 1, consists of a battery pack including a converter to ensure a constant system voltage level, a power management and distribution system, an inverter to convert the direct current to three-phase alternate current (AC), an electric motor that drives the propulsion device (propeller in case of aircraft categories 1, 2, and 3, or ducted fan in case of aircraft categories 4 and 5), and a thermal management system. Note that electrical power is distributed in form of direct current (DC) for all electric propulsion system architectures considered in this work. In principle, AC distribution would be possible.However, most studies suggest that that DC will be the preferred option for electrical power distribution due to its weight reduction potential,[16,21,25] as it is already used today in aircraft like the Boeing 787.[22]

2.2.2 Battery-electric parallel-hybrid propulsion

One of the most widely recognized system layouts is the battery-electric parallel-hybrid (BEPH) system consisting of two parts, one part that is powered by a conventional gas-turbine and one electrical part powered by a battery. Considering how the two parts of the propulsion system are utilized during the flight mission, three main layouts can be distinguished,

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- a discrete system, where the electric motors and the combustion engines are decoupled from one another both driving separate propulsors,
- a mechanically integrated system, where the combustion engine and the electric motor are both driving the shaft of a propulsive device (propeller or fan) enabling the combustion engine to be designed for e.g. cruise operation while the electric system is used as a boost in high-power-demand phases like takeoff and climb,
- and a cycle-integrated system, in which the electric motor is integrated into the thermodynamic cycle of the combustion engine thereby enabling the electric motor to be used to optimize the operating point of the combustion engine or to prevent the combustion engine from critical operating points (e.g. surge line, flame-out).

Within the scope of this work, only the mechanically integrated system is considered. Additionally, the efficiency of the gas turbine in all parallel architectures is considered to be the same as for the conventional case. While it is possible to optimize the gas turbine for cruise and use the electric motor as a boost in high-power demand phases, this has not been considered in the final assessment of this study due to the modeling effort required for each individual use case.

2.2.3 Battery-electric series-hybrid propulsion

In the battery-electric series-hybrid (BESH) system, the entire propulsive power is provided by an electric motor, which is supplied by a battery and/or a gas turbine and generator. While this layout has been widely recognized in academia and research, it is mainly considered to be used in distributed propulsion systems. The reason for this is the fact that electric motors are much easier to distribute than combustion engines because they scale almost linearly with power, while the power density and efficiency of gas turbines generally increase with size. Additionally, the integration of multiple small gas turbines would be significantly more difficult than for electric motors. The main reason for the use of a distributed propulsion system is to gain aerodynamic benefits, e.g. by an active high-lift system or boundary layer ingestion. These applications, however, are outside the scope of this study. In the context of this work, the battery-electric series hybrid system also includes the turbo-electric layout. This is, if the amount of power provided by the battery is zero in all flight segments. In that case, only the gas-turbine powered part of the propulsion system is present, while the battery-powered part is automatically neglected.

2.2.4 Hydrogen combustion propulsion

Since the beginning of commercial aviation, fossil kerosene has been the predominant energy carrier. However, in recent years, hydrogen has gained increasing attention due to its advantages in terms of energy density (about three times higher than kerosene) and its emission reduction potential. So far, the technical challenge of hydrogen storage (gaseous or liquid) is one of the main bottlenecks for an entry into the market. Additionally, the production costs (especially for green hydrogen) are currently not competitive and the production capacities not sufficient for a wide use across the aviation industry. Nevertheless, hydrogen is considered as a possible alternative energy carrier in the future, which is also reflected by the large investments across Europe like in the Clean Aviation and Clean Hydrogen research programs.[8,9] The hydrogen combustion (HC) systems considered in the scope of this work are all based on liquid hydrogen stored in cryogenic tanks at a temperature of about 20 K.
In the context of hydrogen-powered propulsion systems, the weight of the cryogenic fuel tanks is one of the main drivers for feasibility. This is often reflected by the so-called gravimetric tank index i_{grav}), which is the ratio of usable fuel compared to the accumulated weight of fuel and tank:

$$i_{\text{grav}} = \frac{m_{\text{fuel}}}{m_{\text{fuel}} + m_{\text{tank}}}. \tag{1}$$

Note that the switch from kerosene to hydrogen implies that the tank cannot be integrated into the wing and has to be located behind the cabin calling for an extension of the fuselage. While there are other possibilities for cryogenic fuel tank integration (e.g. in pods below the wing), this approach has been adopted from the recent Airbus ZEROe concepts.[2]

2.2.5 Fuel-cell electric propulsion

The fuel-cell electric system (FCE) mainly consists of the same set of elements like the battery-electric propulsion system, except that the battery is replaced by hydrogen a fuel cell. It should be noted that an additional battery is present to cope with the rather low ramp-up time of the fuel cell in case of short-term changes of the required power. Since in this system, all propulsive power is provided by electric motors, while all propulsive energy is provided by fuel, the system is quite similar to a turbo-electric propulsion system, only that instead of a gas turbine engine and generator, a fuel cell is used to generate the electric power.

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2.2.6 Fuel-cell-electric parallel hybrid

The fuel-cell-electric parallel hybrid (FCEPH) architecture is a combination of a hydrogen-powered combustion system and a fuel-cell electric system. Similar to the battery-electric parallel hybrid, the electric part of the system can be used in different ways. For the context of this work, the fuel cell is mainly considered to be used during the cruise segment, where the higher efficiency of the fuel cell compared to the combustion engine is most effective. However, to obtain a comprehensive overview, other utilization scenarios (e.g. usage of the fuel cell during high-power-demand phases) are also considered.
In this layout, the fuel cell is also used to power the secondary on-board systems. Therefore, if the hybridization is set to zero, the electric part of the powertrain still exists, but it is solely used as a generator to supply the on-board systems. As the investigations in section 4 illustrate, this is especially of interest for the larger aircraft categories, where fuel-cell-electric propulsion is not yet feasible.

2.3 Technology scenarios

The third aspect to consider for the scalability investigations is the assumed stage of technology development that underlies the analysis models. For an entry into service in the next five years, the expected technology advancements in terms of power densities and efficiencies of the electric components are significantly less than the ones for a target entry into service in 2050. To account for this, three technology scenarios are considered,

- a state-of-the-art (SOTA) scenario with currently achievable values (power and energy densities, efficiencies, etc.),
- a short-term future scenario reflecting the predictions for the year 2030,
- and a long-term future scenario with expected advancements for 2050.

The component constants and assumptions for the three scenarios are summarized in table 2

Table 2: Component constants and assumptions for the three technology scenarios

Component	Parameter	SOTA	2030	2050	Unit
E-motor, -generator	Efficiency	0.95	0.95	0.95	-
	Power density	5.75	11.1	16.45	kW/kg
DC/AC converter	Efficiency	0.95	0.97	0.99	-
	Power density	9.0	9.0	19.0	kW/kg
AC/DC converter	Efficiency	0.95	0.97	0.99	-
	Power density	9.0	9.0	19.0	kW/kg
DC/DC converter	Efficiency	0.95	0.97	0.99	-
	Power density	9.0	9.0	56.3	kW/kg
Battery	Efficiency	0.95	0.95	0.95	-
	Power density	1.365	2.275	4.2	kW/kg
	Energy density	0.21	0.35	1.15	Wh/kg
Fuel cell	Efficiency	0.6	0.6	0.6	-
	H_2 fuel efficiency	0.95	0.95	0.95	-
	Power density	0.8	4.8	8.8	kW/kg
Hydrogen tank	Gravimetric index	0.25	0.4	0.8	-
Thermal management*	Electric motor pump efficiency	0.8075	0.8075	0.8075	-
	Pump power density	0.33	0.33	0.33	kW/kg
	Specific fluid mass	0.75	0.75	0.75	kg/m
	Specific ducting mass	2.5	2.5	2.5	kg/m

*Thermal management power demand model based on Vranty[24]

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3. Methodology

The scalability investigations targeted in this work require a detailed design and analysis capability for the entire aircraft systems architecture including the electric powertrain as well as the secondary on-board systems like flight control system, environmental control system, ice and rain protection, etc. Collins Aerospace has developed a proprietary in-house aircraft systems platform, which enables detailed sizing and analysis of the entire aircraft on-board systems architecture.[15] Besides modeling traditional architectures with bleed-air-powered pneumatic systems and hydraulic power systems, the software can also account for more- and all-electric system configurations as well as novel propulsion system layouts.

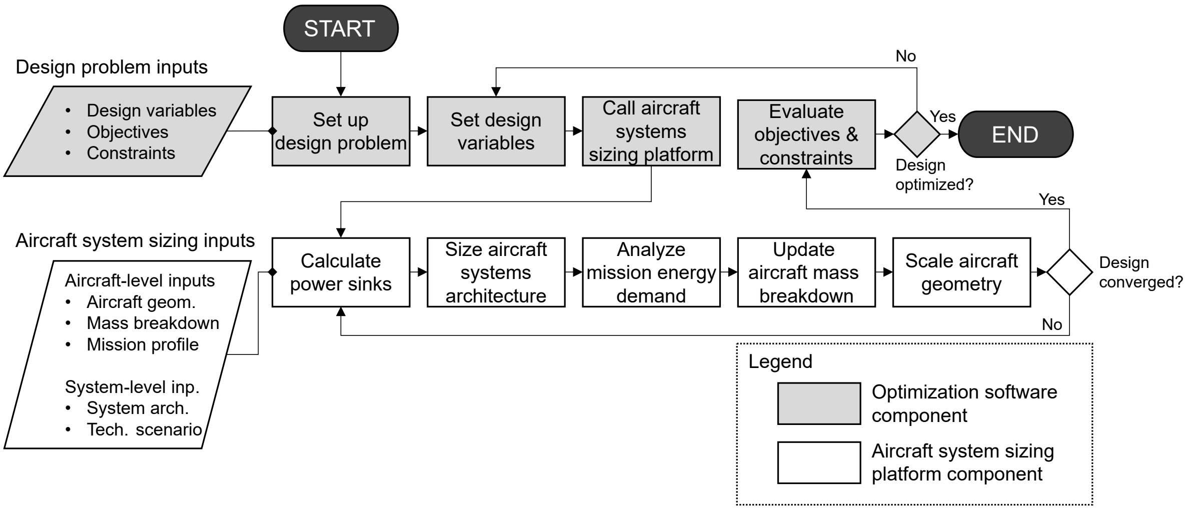

Figure 2: Process of the Collins Aerospace aircraft systems evaluation platform

To perform the systems sizing and evaluation as shown in figure 2, several aircraft-level inputs including aircraft mass breakdown, geometry information and mission performance data are required. These inputs can be obtained from pre-calculated data or by using a direct interface to external aircraft design software. In the scope of this work, the aircraft design platform HYPERION developed at the Politecnico di Milano (PoliMi) is used[23] to provide these inputs. On system level, the tool requires information about the systems architecture (i.e. systems, components and their interconnections) as well as a set of technology constants and assumptions for the underlying component models. The core element of the tool is the sizing and evaluation of the aircraft system architecture, which allows for almost arbitrary system architecture options due to a generic energy network based on a so-called "source-to-sink" approach. Here, the systems are categorized into power-consuming systems (sinks), power distribution and transfer systems (converters), and power generating systems (sources). Starting from the required power of the consumer systems, all systems downstream are sized for each segment of the flight mission as well as for critical design points, such as hot-day-takeoff. Subsequently, the power demand of the entire aircraft is integrated over the entire flight mission to calculate the total mission energy demand. Depending on the type of energy source used, the energy can be stored in electrical batteries or in fuel. Based on the newly calculated systems and fuel mass, the total aircraft mass breakdown is updated and the aircraft geometry is scaled accordingly. The change in structural weight resulting from the scaling is captured with a structural weight penalty, which has been obtained by a sensitivity study within PoliMi's HYPERION tool. The above-described process is iteratively repeated until the key aircraft mass properties, i.e. maximum takeoff mass (MTOM), operating empty mass (OEM), structural mass, systems mass, and fuel mass are converged, thereby capturing all necessary snowball effects of the sizing.

A parameter study and optimization method is wrapped around the evaluation process. It enables exploration of large design spaces with mixed variables (discrete and continuous) as well as multi-objective optimization. After the design variables, objectives, and constraints have been set, the software automatically sets up the design problem. For each combination of input design variables, the aircraft system sizing procedure is executed. The converged design is then fed back to the optimization software to evaluate the objectives and constraints before the next set of input variables is evaluated. It is also possible to perform a combination of parameter study and optimization, where for each set of study variables, the design variables are optimized. Thereby, the study variables become boundary conditions for the optimization process.

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4. Results

Combining the five aircraft categories with the six baseline architectures in each of the three technology scenarios, as described in section 2, leads to a three dimensional design space with 90 baseline cases. However, the actual number of designs to be investigated is significantly higher. This is mainly due to the numerous possibilities of utilizing the electric part of the propulsion system in the hybrid-electric architectures. To reduce the number of possibilities, three utilization strategies have been selected for these systems,

- utilization of the electric part of the propulsion system in all flight segments,
- utilization during high-power-demand phases (takeoff, climb),
- and utilization exclusively in cruise flight.

Within each of the three strategies, the degree of hybridization, i.e. the power share of the electric part of the propulsion system compared to the total power required to propel the aircraft, can be varied. In fact, the degree of hybridization during the different flight segments is one of the main design variables for optimization in hybrid-electric propulsion systems.

To perform a meaningful evaluation of alternative propulsion systems on vehicle level, it is crucial to select feasible aircraft-level metrics. While traditionally, the mission fuel consumption is often used to indicate the aircraft-level performance of new technologies, this is more complex with alternative propulsion for two reasons. First, the system architecture options considered in the investigations include different energy carriers such as conventional fuel, batteries, and hydrogen. Second, the five aircraft categories are completely different in terms of requirements as well as in terms of mass breakdown and mission fuel burn, making it hard to compare them among each other. Therefore, one of the the selected metrics in this work is the so-called payload-range energy efficiency (PREE). PREE describes the efficiency of the aircraft in performing its main task, transport of payload on a given flight distance, by setting payload (m_{PL}) and range (R) in relation to the required mission energy (E_{mission}):

$$\begin{aligned} \mathrm{PREE} &= \frac{m_{\mathrm{PL}} \cdot R \cdot g}{E_{\mathrm{mission}}}, \\ &= \frac{m_{\mathrm{PL}} \cdot R \cdot g}{\sum_i (m_{\mathrm{fuel},i} \cdot \mathrm{LHV_i}) + E_{\mathrm{bat}}}. \end{aligned} \tag{2}$$

Note that the mission energy includes all forms of energy, i.e. stored in different types of fuel, given by the fuel mass ($m_{fuel,i}$) and the lower heating value (LHV_i), as well as energy stored in batteries (E_{bat}).

Figure 3 shows the scalability assessment in terms of PREE, which has been maximized for all use cases. For all use cases, the results are provided relative to the conventional reference aircraft (red horizontal lines).

The results shown in the following section are only valid for the underlying aircraft requirements, technology assumptions, models, and evaluation metrics used. Changing towards mission fuel burn or cost as the main objective function, for instance, could change the results significantly. Also note that for some of the hybrid-electric architectures, the maximum PREE is actually achieved at zero hybridization, which would result in a conventional fuel burning engine without any electrification. In theses cases, a "mild" hybridization of 10 percent is assumed.

Considering state-of-the-art technologies, almost none of the architectures under investigation are beneficial. Hydrogen combustion seems to be possible on overall aircraft level for most categories, however not beneficial regarding PREE. Especially for longer flight distances, as it is the case for category 1, which has a quite high design range for an aircraft of its size, and with category 5 as a long-range wide-body, the large tank weights of the hydrogen powered versions outweigh the energy density advantage of hydrogen. The full-electric and battery-powered architectures do not even provide converged designs in most cases.

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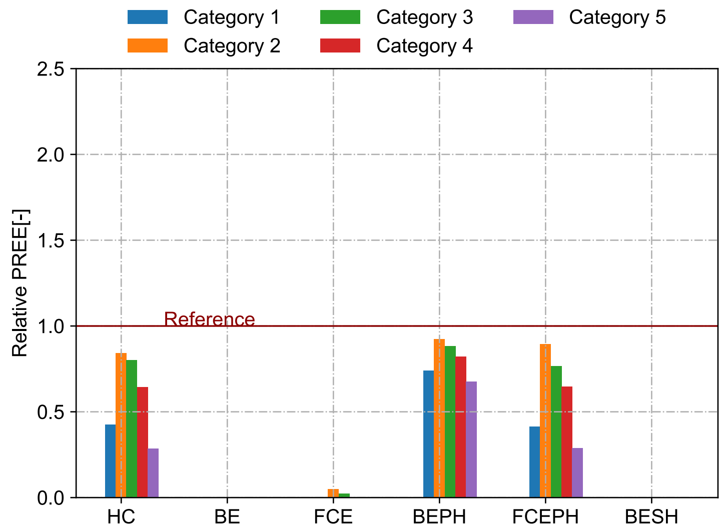
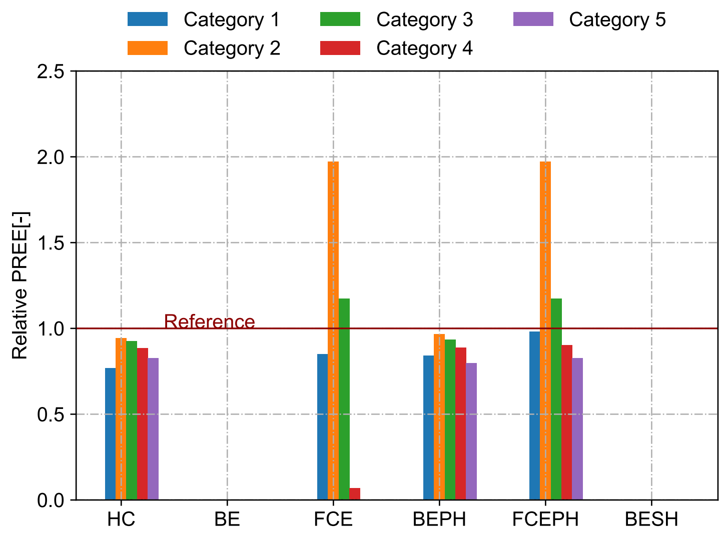
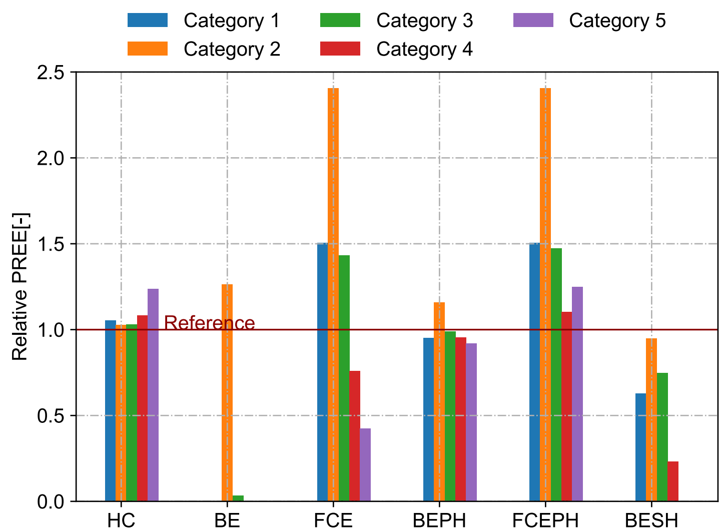


(a) State-of-the-art scenario



(b) 2030 technology scenario



(c) 2050 technology scenario

Figure 3: Results of the scalability assessment for maximized PREE

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Note that for category 1 and 2, in addition to the PREE, also the MTOM has to be taken into account, as there are maximum limits in the certification specification part 23 for these aircraft (5670 kg for category 1, 8618 kg for category 2). In the state-of-the-art scenario, almost all electric system architectures exceed those limits. It should also be mentioned that, at first sight, the relatively bad performance of category 1 compared to the other categories seems surprising, as it could be expected that the novel propulsion systems would become more feasible for a smaller aircraft size. However, besides aircraft size, the required mission energy is a decisive factor for feasibility of an architecture. Category 1 has a relatively large design range compared to the other categories, which results in a large fuel mass fraction for the conventional baseline aircraft. If the fuel is replaced by another energy source like batteries or hydrogen, the impact of the low energy densities is quite high, resulting in large weights of the batteries and hydrogen tanks respectively, which makes this concept infeasible for state-of-the-art technologies.
A reduction of the design range for category 1 was investigated by the authors, resulting in more feasible results. However, these investigations, are not shown in detail here, because the aircraft requirements and mission profile for all aircraft have been thoroughly selected prior to this work, and a change of these requirements solely based on the desire to enable novel propulsion concepts is considered unreasonable at this stage.
Looking at the 2030 technology scenario, the novel propulsion system architectures appear more promising compared to the state of the art. In fact, while the battery-powered systems still remain unfeasible for most aircraft categories, the hydrogen-powered architectures become more beneficial. Especially the fuel-cell-electric parallel hybrid system performs well for all aircraft categories. For the hybrid architectures, the hybridization strategy has been optimized for each aircraft category within each technology scenario. The smaller categories have a a significant amount of propulsive power provided by the electric part of the system, while category 4 and 5 use hydrogen combustion to provide propulsive power and the fuel cell only powers the on-board subsystems.
For the 2050 technology scenario the battery-electric architectures are entering the space of beneficial solutions, albeit only for aircraft category 2 (commuter class). The fuel-cell-electric architectures, on the other hand, are by far the most beneficial ones for all aircraft categories. In fact, for category 1, 2, and 3, the FCE architecture is the optimum in the 2050 technology scenario. Again, for category, 4 and 5, the hydrogen-combustion combined with a fuel cell to power the on-board sub-systems is the most feasible solution.

5. Conclusion

Alternative propulsion concepts are one of the possible key enablers for a sustainable aviation sector of the future. While a large amount of recent years' research was focused on optimizing systems for specific aircraft and mission profiles, this paper rather aims towards bringing the aspect of scalability into the design process. Therefore, five aircraft categories from general aviation to long-range wide-body aircraft have been investigated for six baseline propulsion system architectures and three technology scenarios.
The investigations suggest that hydrogen-powered propulsion systems combined with fuel cells seem to be a viable option for all aircraft categories in the mid-term future (2030–2035). While the utilization of the fuel cell changes with aircraft category and technology scenario, the general presence of these architectures throughout the design space indicate the feasibility for the next generation of aircraft. Based on the assumed time frame for the 2030 technology scenario, an entry into service of these architectures appears feasible in a 2030–2035 time frame, if the current technological challenges especially considering integration of cryogenic fuel tanks can be overcome (e.g. COCOLIH2T project[11]).
It should be mentioned that it is not a single hydrogen-powered system that can be scaled across the categories, but rather a family of systems consisting of the same elements, namely hydrogen combustion gas turbines, hydrogen fuel cells, electric power management and DC distribution including power conversion, and a dedicated thermal management system. This family of systems has a great potential to decrease the mission energy demand and thereby also the climate impact of commercial aviation. However, some of the technical challenges with respect to hydrogen-based systems need to be tackled as soon as possible to enable an entry into the market and to pave the way for a more sustainable aviation sector. Currently planned and ongoing projects within the Clean Aviation and Clean Hydrogen programs tackle these challenges and will thereby significantly contribute to bringing hydrogen-based solutions to higher technology readiness levels.[8,9]
It should also be mentioned that battery-electric parallel hybrid systems, which are widely recognized in academia and industry, have shown a rather bad performance within the scope of this study. This, however, is mainly based on the combination of the considered mission profiles, assumptions, and evaluation metrics. A study by Lents et al., for instance, has shown that a battery-electric parallel hybrid enables fuel savings of approx. 5 % on a 900 NM mission on a turbofan-driven single-aisle, if the gas turbine performance is solely optimized for cruise while the electric motor is used to boost during high-power-demand phases.[17] Although the authors of this work obtained similar results for the category 4 aircraft with the presented framework using the assumptions by Lents et al., they have not been considered

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for the scalability investigations, as they require detailed analysis of the interaction between the electric motor and the gas turbine, which are out of scope for this study.
While the scalability assessment shows that the hydrogen-powered architectures perform well for a wide range of applications, they were not yet optimized in detail, which is part of the future work to be performed. Collins Aerospace has in-house tools which allow for exploration of large design spaces with numerous discrete design options (e.g. distributed vs. centralized systems) as well as optimization of continuous design spaces (e.g. degree of electrification for hybrid systems) thereby combining discrete and continuous variables to fully investigate the potential of novel propulsion system options.
Furthermore, while PREE is a very useful indicator to evaluate mission performance in terms of efficiency, the results might change for a different objective function. Instead of PREE, life cycle costs or life cycle climate impact would be a possible metric to include into the analysis.

6. Acknowledgments

This project has received funding from the Clean Sky 2 JU under the European Union's Horizon 2020 research and innovation program under grant agreement no. 1010007784.

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