In-Depth System-Level Energy Analysis of Hybrid Electrified Commuter Aircraft for Improved Energy Efficiency

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Abstract

This work presents a comprehensive analysis of hybrid electric propulsion systems in commuter aircraft, aimed at enhancing energy efficiency. The study utilizes an aircraft conceptual design library, OpenConcept, to perform evaluations of various aircraft components and their interrelationships. The methodology integrates aerodynamics, propulsion, and mission analysis within a common framework to optimize the aircraft design. The analysis focuses on a 19-passenger commuter aircraft, employing a series/parallel hybrid-electric architecture. The gradient-based Sequential Least Squares Programming optimizer is utilized to optimize design variables such as battery weight, engine power, and the selected power ratios, while adhering to operational constraints. Through a rigorous Design of Experiments study, the paper highlights that even when considering the current battery technology, hybrid-electric propulsion yields substantial energy savings for short-haul missions. The fuel and energy consumption reductions are evident, particularly for shorter ranges. However, for extended missions, the critical role of advanced battery energy density is emphasized to achieve significant energy efficiency improvements.

1 Introduction

Aerospace sustainability has received considerable focus over the past years. Aviation's environmental impact, particularly greenhouse gas emissions and noise pollution are the main drivers of making aviation more efficient and, hence, more sustainable. This is reflected by the sustainability goals (Darecki et al., 2011; Mangelsdorf, 2012) set by various organizations across the globe. Despite the operation disruptions due to the pandemic, the sector is gradually returning to normal operations and is expected to exceed pre-pandemic levels (IATA, 2022). Therefore, there is a need for more sustainable aircraft in the coming future.

Electrified propulsion is a promising technology which is receiving increasing attention in the last decades. Due to the current energy storage technology and inherit additional weight, fully-electric propulsion is only feasible for limited range. Hybrid-electric propulsion systems are considered as the stepping-stone towards zero-emission aircraft. These aircraft concepts combine traditional gas turbines with electrical motors and energy storage systems. They present potential to reduce fuel consumption, emissions and improve the overall system energy efficiency (Felder, 2016; Pornet & Isikveren, 2015).

The electrification of aircraft industry focuses on different market segments. One of them is the short-haul segment, where light commuter aircraft applications are covering distances of maximum 600-800 nautical miles. Such applications use turboprops and small regional jets with turboprops prioritizing fuel efficiency while turbofans and turbojets offer higher cruise speeds.

Several benefit estimations have been presented in the open literature based on conceptual design of hybrid-electric aircraft. As it was reported by (Kruger et al., 2018), different architectures have different optimal applications with hybrid-electric being suitable for intermediate ranges ($\leq$ 800 NM). This work was extended with the mission analysis of commuter aircraft (Kruger & Uranga, 2020) and it was presented that hybrid-electric configuration can lead to a 63% reduction in energy consumption, with a cost of 52% increase in the take-off weight. (Zamboni et al., 2019) analysed different hybrid-electric architectures with the series/parallel one emerging as the most promising due to the combination of benefits in both aerodynamic performance and propulsion system efficiency. The authors reported a 28% and 14% reduction in fuel and energy consumption respectively compared to the baseline aircraft considered. In addition, the ELICA EU-funded project reported a 56% reduction in total energy consumed for a series/parallel partial hybrid commuter aircraft with Entry-Into-Service (EIS) 2025 when compared to a reference aircraft with EIS 2014 (Nicolosi et al., 2022). Finally, (Schäfer et al., 2019) estimated that short-haul electrified aircraft has the potential to replace up to 15% of global revenue passenger kilometers and a substantial number of global departures.

The addition of extra electrical components can lead to increased complexity to the system, requiring a thorough evaluation of its effects. The generation of thrust relies on two sources: traditional fuel and electrical energy from hybrid systems. Deciding when to use each energy source involves various factors and needs in-depth investigation. Many design choices depend the components' efficiency, weights, and interrelations (Moore, 2014). Instead of the traditional approach of designing aircraft, there's a growing need to shift towards more comprehensive methodologies. These combine exploring different design possibilities with optimization techniques while taking into account a range of aspects from different areas of aircraft design. This shift is based on the understanding that the connections between these different disciplines have considerable effects on the system performance (Martins & Lambe, 2013). Therefore, there is a requirement for flexible and efficient design tools that can handle various aspects of aircraft design and their complex relationships. Such tools allow for a holistic approach that not only considers the efficiency of individual parts but also takes into consideration the broader effects and interactions within the entire system.

This study delves into the advantages presented by a series/parallel partial hybrid-electric concept designed for a 19-passenger commuter aircraft. The architecture incorporates a conventional turboprop engine and a motor-driven e-propeller per wing. In addition, an on-board battery system is integrated while the turboprop engines coupled with generators. This arrangement enables the e-propeller to operate using either battery or engine-generated energy. To facilitate these investigations, a flexible aircraft conceptual design tool, built upon the OpenConcept library (Brelje & Martins, 2018), is developed. Notably, essential adaptations to the computational scheme are introduced, enabling fast and approximate calculations crucial for mission performance analysis. By integrating different disciplines, the study paves the way for the design and operation of hybrid-electric aircraft, with a strong focus on advancing fuel and energy efficiency. By employing a comprehensive design of experiments (DOE) approach, the research focuses on two pivotal variables: the mission range (measured in nautical miles) and the battery energy density (Wh/kg). These key factors are strategically selected for their profound influence on the aircraft's operational capabilities and overall efficiency. A comprehensive understanding of the interplay between these variables facilitates an assessment of the feasibility to achieve the desired mission range while optimizing the battery offering the potential to elevate the aircraft's holistic performance.

2 Methodology

2.1 Aircraft conceptual design framework

The present work employs a general purpose aircraft design toolkit which includes different aircraft component models to perform individual calculations while taking into consideration their interrelations. The framework is based on the OpenConcept developed by (Brelje & Martins, 2018) which is an open-source python library. OpenConcept is an adaptable, low-fidelity aircraft design library and its main purpose is to provide fast mission results for aircraft conceptual design.

The user provides a set of parameters to the library; aircraft geometry characteristics, typical aircraft weights such as the maximum take-off weight (MTOW), propulsion component characteristics and finally mission profile parameters for all mission phases. The library uses the set of input parameters and the pre-defined mission to perform weight estimations, basic aerodynamic calculations and finally mission performance analysis to compute high-level variables such as fuel and energy consumed. It employs a non-linear Newton solver in order to set an appropriate lift coefficient and throttle of different powertrain components to satisfy the pre-defined mission requirements.

The OpenConcept library has a variety of different size aircraft models available as well as series hybrid-electric and parallel hybrid-electric modelling capabilities (Adler et al., 2022; Fouda et al., 2022). It is important to note that the weight estimation calculations are based on textbook calculations using empirical formulas (Raymer, 2018; Roskam, 2019; Torenbeek, 2013) and different calculations are implemented based on the aircraft class considered. Furthermore, the employed library is built on top of the OpenMDAO framework and is extensively discussed in the work of (Gray et al., 2019). Any of the aforementioned input variables can be used as an optimization design variable, and, hence, the analysis and optimization of the aircraft system is enabled.

Within the present work, a conventional 19-passenger aircraft model has been developed to enable the investigation of hybrid-electric commuter aircraft concepts. The conventional model is based on the Beechcraft 1900D aircraft featuring two turboprop engines. The main aircraft design parameters, such as the wing area and Operating empty weight (OEW) are matched with the publicly available data for the Beechcraft 1900D (Beech Commuter Airliners, 2000). The aircraft model matches the value of OEW with a very small deviation of 0.04%. This ensures that the model correlations can closely capture the reference aircraft. Finally, it is important to note that the conventional Beechcraft 1900D aircraft serves as the reference aircraft throughout this work.

2.2 Series/parallel partial hybrid-electric architecture

The work focuses on the series/parallel partial hybrid-electric architecture. The Therefore, a hybrid-electric aircraft model has been developed for the purposes of this work using the OpenConcept library. The model is based on the conventional 19-passenger Beechcraft 1900D model mentioned in the previous subsection.
A schematic of the propulsion model used is presented in Figure 1. The powertrain architecture includes two turboprop conventional engines, a battery system, a Power Management and Distribution (PMAD) system and two e-propellers driven by electrical motors. The PMAD system shown in Figure 1 is introduced in the model to ensure a consistent power supply from different energy sources. The powertrain architecture has been modified accordingly in the model to include the required components.

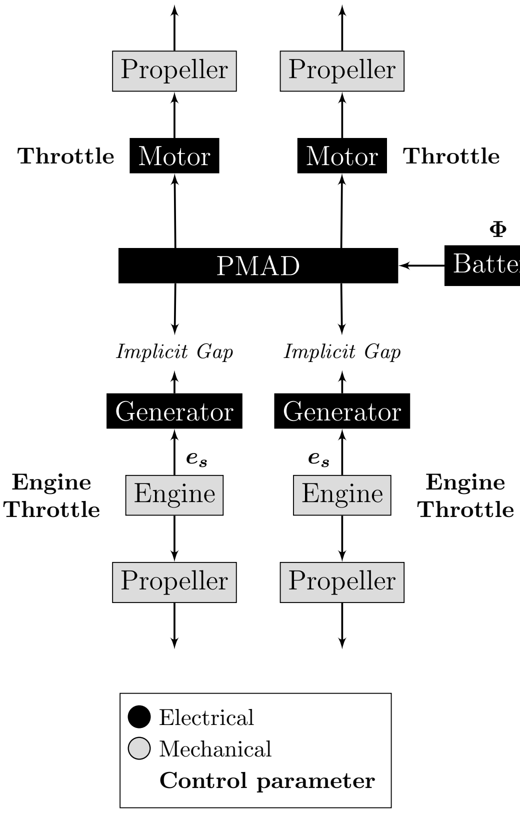

Figure 1. Schematic of a twin-engine series/parallel partial hybrid electric propulsion model in OpenConcept.

As shown in Figure 1, the computational scheme is updated as well, as both thermal and electrical components can contribute to the thrust generation in this concept. The turboprop engines can deliver power to both the propeller (denoted by P_{prop}) and the generator (denoted by P_{hybrid}). Therefore an engine power split is defined within the model as shown here:

$$e_S = \frac{P_{prop}}{P_{prop} + P_{hybrid}} \tag{1}$$

The e_S is set by the user (or optimizer) and is kept at the same level for the two engines to achieve thrust balance. Furthermore, it can take different values for different mission phases but is selected to remain constant throughout each phase.
In addition, to determine the battery contribution on the thrust produced by the e-propellers, the supply power ratio Φ is introduced in the PMAD system, following the definition presented by (Isikveren et al., 2014; de Vries et al., 2019):

$$\Phi = \frac{P_{bat}}{P_{bat} + P_{gen,1} + P_{gen,2}} \tag{2}$$

where, P_{bat} is the power delivered by the battery and P_{gen} is the power delivered by the generator to the PMAD. To be able to match the power requirement from the motors, an implicit gap is exposed to the Newton solver. The engines' throttle is set by the solver in order to achieve the PMAD power requirement P_{hybrid}, whereas the Φ is set by the user. Finally, it is important to highlight that the thrust split between the mechanical and electrical propeller is not set directly but is a result of the power calculated by the combination of e_S and Φ. The motors' throttle is set again by the solver in order to achieve steady flight conditions as it will be discussed in subsection 2.3.
The main model assumptions for individual powertrain components are summarized in Table 1. The time-frame under consideration for the entry into service (EIS) of the concept is set to 2035. This is reflected on the assumptions for the electrical component efficiencies. For the turboprop engines, the model performance characteristics are based on the Pratt & Whitney PT6A-67D unit (Badger et al., 1994).

2.3 Mission analysis

The nominal mission profile selected is presented in Figure 2. The mission analysis includes a main mission, where the high-level parameters are extracted and a diversion mission of 100 nautical miles to consider the scenario in which the aircraft must land in a different airport. Finally, according to the CS-23 certification requirements (EASA, 2018) for 19 passenger commuter aircraft, the aircraft shall be able to fly for 30mins at 1500ft using only one energy source. This requirement is included in the mission analysis and aircraft design as a loiter phase.

Table 1. Powertrain technology assumptions (EIS 2035).

Parameter	Value
P&W PT6A-67D	2 × 950 kW
PSFC*	0.074/0.094/0.1* g/(kW*s) (climb/cruise/loiter)
Motor power density	10 kW/kg
Generator power density	10 kW/kg
Motor efficiency	0.95
Generator efficiency	0.96
Battery efficiency	0.97
PMAD efficiency	0.99

* *estimation*

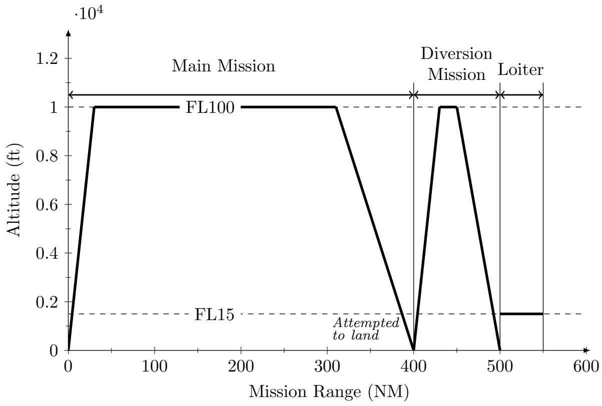

Figure 2. Typical mission profile for commuter aircraft.

Each mission phase is split into segments by using intermediate points, in which the vertical and horizontal speed are pre-defined. For each flight segment, the library calculates the value of the residual R_{thrust} using the following equation:

$$R_{thrust} = T - D - mg\sin\gamma \tag{3}$$

where, T is the thrust, D is the drag, m is the current aircraft weight, g is the gravitational acceleration and finally γ is the aircraft angle. The OpenMDAO's Newton solver is responsible to estimate the primary thrust control parameter (engine or motor throttle) in order to achieve zero horizontal acceleration. Furthermore, in the climb and descent phases the excess thrust or drag respectively are achieved in such a way to match the vertical speed, whereas in the case of cruise and loiter, the thrust and drag forces should be equal. Finally, for each segment, the aircraft weight is updated based on the fuel consumed in the previous segment. Parameters such as fuel and energy consumed are integrated with respect to time using the Simpson's rule. The diversion mission and loiter phase fuel and energy are not directly presented in this work, however they do affect the aircraft design as according to the CS-23 certification requirements, the maximum MTOW is 8618 kg. The model calculations are considering that enough fuel or electrical energy is on board to satisfy the main mission along with diversion mission and loiter.

Finally, the top level aircraft requirements (TLARs) selected for the concept under investigation are summarized in Table 2. The TLARs of the concept are based on the limitations imposed by the CS-23 certification. The payload is calculated based on the numbers of passengers, passenger weight and baggage weight as shown in 2.

Table 2. TLARs for hybrid-electric concept.

Parameter	Value
MTOW	≤ 8618 kg
Number of passengers	19
Payload	1881kg 19*(87 + 12)
Nominal Mission	740.8 km (400 NM)
Cruise altitude	3048 m (10000 ft)
Loiter altitude	457.2 m (1500 ft)
Cruise Mach number	0.35
Rate of climb (MTOW, SL, ISA)	≥ 6.35 m/s
Approach speed	≤ 62 m/s

2.4 *Optimization problem*

The OpenConcept library is developed to enable for conceptual design optimizations. In this work, the hybrid-electric concept is optimized for different mission ranges and battery technology assumptions. The Sequential Least Squares Programming approach (Bonnans et al., 2006) is used to size the propulsion system components for minimum fuel burn on the selected mission.

The optimization problem is presented in Table 3. The MTOW, battery weight, supply power ratio Φ and engine power split e_S are varied in order to minimize the block fuel. The block fuel in this study denotes the main mission fuel. For Φ, only the climb, cruise and descent phases are considered and therefore number of design variables for Φ is 3. The diversion mission and loiter Φ are not considered directly in the optimization and assumed to be zero. For the diversion mission, this choice is made to ensure that the fuel consumption and therefore environmental benefit takes place during the main mission, which is the primary flight scenario in most cases. However, the diversion mission fuel consumption has an effect on the optimization results mainly due to the fact that MTOW contains the total fuel and the MTOW is limited to 8618kg. For the loiter phase, this choice is aligned with the certification requirements.

On the other hand, the e_S is selected to be varied by the optimizer for all mission phases included in the study. Therefore, the final count of design variables from e_S in the optimization problem is 7. This choice is made to ensure safe operation for all powertrain components during the whole mission. Finally, the rated power for the generator and motor are varied to size the components based on the maximum power they can deliver during the mission.

Table 3. Optimization problem definition for hybrid-electric aircraft.

	Variable	Quantity
minimize:	Block fuel	1
by varying:		
	MTOW	1
	W_{batt}	1
	P^*_{motor} (rated)	1
	P^*_{gen} (rated)	1
	Φ	3
	e_s	7
subject to:		
	$0 \leq R_{MTOW} \leq 5$	1
	$0.2 \leq SOC_{batt,loiter}$	1
	$0.1 \leq throttle \leq 1$	7
	$0.1 \leq eng\ throttle \leq 1$	7

After the weight calculations and mission analysis take place within the library, the residual MTOW is calculated as shown here:

$$R_{MTOW} = (MTOW - OEW - W_{fuel} - W_{batt} - W_{payload}) \quad (4)$$

where, $MTOW$ is a design variable, OEW is calculated, W_{fuel} is integrated from the fuel flow rate with respect to time for the whole mission, W_{bat} is a design variable and $W_{payload}$ is set by the TLARs in Table 2. The optimizer constrains the R_{MTOW} to small values (between 0 and 5kg). Furthermore, the state of charge (SOC) of the battery at the loiter phase (end of mission) shall be greater than 20% in order to make sure that the battery is not fully discharged at the end of the mission and ensure its safe operation. Finally, the motors' and engines' throttles are constrained to ensure their realistic operation within the flight envelope. The component throttles are defined as the ratio between the power delivered by the component and the maximum (rated) power of the component.

2.5 *Design of Experiments (DOE)*

A DOE study is conducted considering two variables, the main mission range and the battery energy density. The selection of the main mission range variable aims to explore various aircraft operations and assess the potential advantages of introducing commuter aircraft for short-haul flights. The battery specific energy density variable is closely tied to the assumptions regarding technology. By examining different levels of energy density, valuable conclusions can be drawn regarding the potential of electrified aircraft technology, particularly for aircraft falling under CS-23 certification.
A full factorial design with 20 levels, and, hence 20^2 samples, is selected for this study. For each combination of mission range and battery energy density, an optimization is conducted as presented in Table 3 in order to minimize the block fuel. A uniform distribution of the examined points in the design space is selected, with optimizations of different range and energy density taking place for each sampling point.

3 Results

The results for the MTOW and battery weight ratio are depicted in Figures 3 and 4 respectively. The results confirm that electrifying short-haul aircraft leads to a significant challenge in terms of MTOW. The upper limit of 8618 kg on MTOW imposed by the CS-23 certification, is reached for the majority of optimized designs. Lowering the MTOW values would require disruptive advancements in battery technology, especially for longer missions.

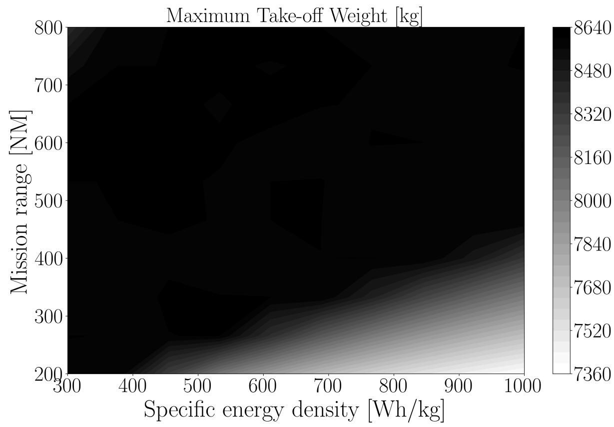

Figure 3. Maximum Take-off weight (MTOW).

Figure 4 shows that for shorter missions as the battery specific energy density increases, the available battery on board is reduced. This is expected as for higher energy density, the required energy can be achieved for lower weight. On the contrary, for the longer missions, a different trend is observed. As the battery energy density decreases, the available battery weight starts decreasing. This is a result of the MTOW upper limit. For longer missions, the upper limit of MTOW weight is reached and therefore, it affects the amount of available battery weight on board.

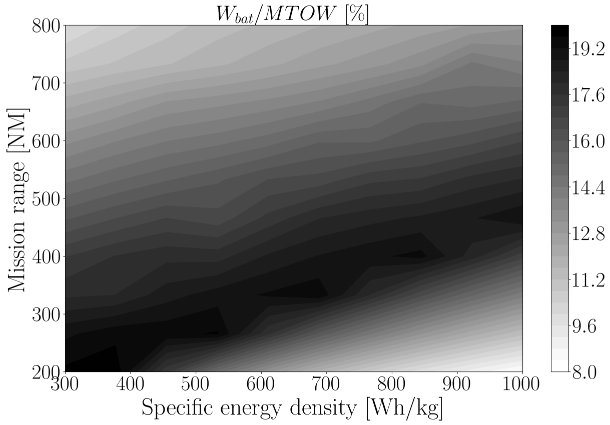

Figure 4. Battery weight on board divided by the MTOW.

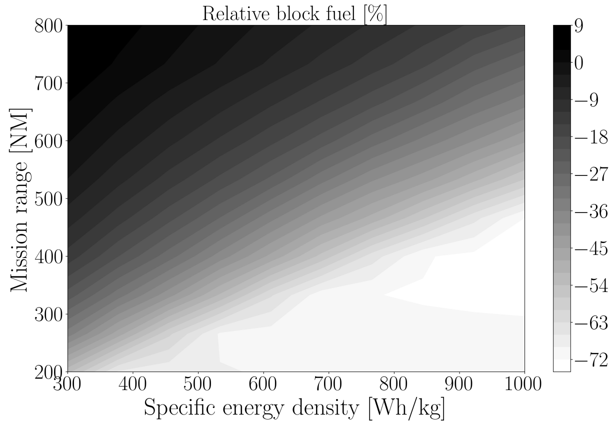

Figure 5. Relative block fuel burn compared to the conventional aircraft.

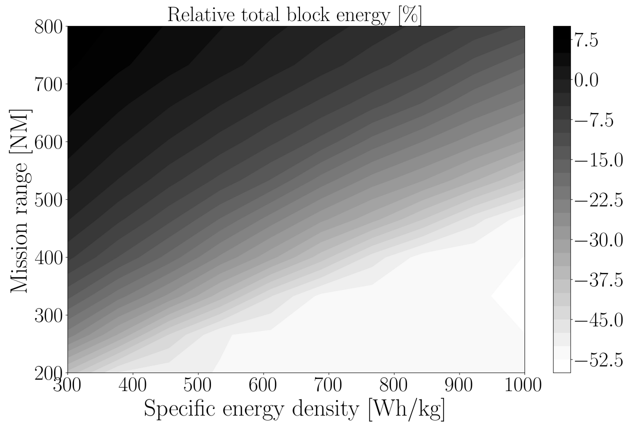

Figure 6. Relative block total energy compared to the conventional aircraft.

The energy consumption aspects of the optimized design are also investigated. The block fuel and total energy results are normalized against the corresponding values per mission range derived from the conventional aircraft model as discussed in subsection 2.1. The equation below is used for both quantities of interest:

$$Q_{hybrid}[\%] = \frac{Q_{hybrid} - Q_{conv}}{Q_{conv}} * 100\% \quad (5)$$

It is important to note that for the hybrid-electric aircraft, both electrical and fuel energy are considered in the total energy consumption whereas for the conventional aircraft the lower heating value of the Jet-A fuel is used in order to calculate the energy from the fuel consumed. The lower heating value of the fuel is assumed to be 42.8 MJ/kg. The relative results are presented in Figures 5 and 6. It is evident from the graphs, that the series/parallel hybrid-electric aircraft can achieve not only lower fuel consumption but also lower total energy consumption. This improvement is more substantial for higher battery energy density, as expected. However, for short mission ranges a considerable improvement is shown, even with the current battery technology (300 Wh/kg).

Finally, the ratio between the electrical and total energy is shown in Figure 7. This ratio is the degree of hybridization (DoH) for hybrid-electric aircraft concepts. It is important to note that when increased electrical energy consumption is enabled, the total energy consumption is reduced. Therefore, Figures 6 and 7 have opposite trends. This is because of higher efficiencies achieved through the introduction of electrical components. This observation confirms the benefits of high DoH in short-haul aircraft applications.

4 Summary and Discussions

The investigation of the advantages offered by the series/parallel partial hybrid-electric concept for a 19-passenger commuter aircraft is the focus of this work. To achieve this objective, a novel aircraft conceptual design framework is developed and thoroughly presented, leveraging the OpenConcept library. The presented framework integrates a variety of aircraft disciplines within the design process. The hybrid-electric aircraft model, based on the well-established Beechcraft 1900D aircraft, undergoes tailored computational developments to consider pivotal control parameters such as the supply power ratio (Φ) and engine power split (e_S). This modification enables the analysis and optimization of the aircraft's application. The central focus of this study lies in mission analysis and the system performance evaluation, considering a typical commuter aircraft mission profile. A comprehensive examination of both main and diversion missions, along with a dedicated 30-minute loiter phase, sheds light on critical high-level system variables, including fuel and energy consumption. The overall optimization objective revolves around optimizing the size of propulsion system components to minimize fuel consumption during the main mission.

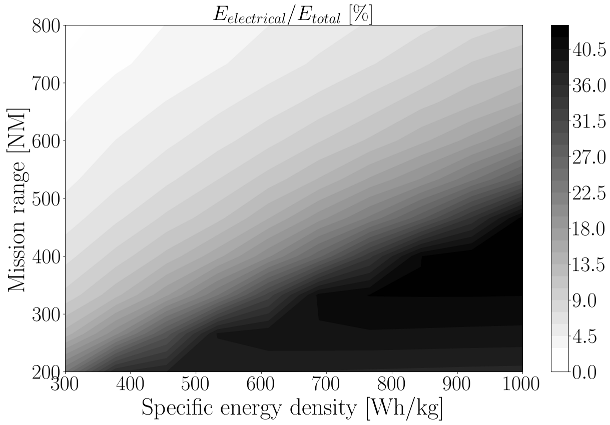

Figure 7. Electrical block energy consumed.

The findings of this study validate the benefits of the series/parallel partial hybrid-electric architecture. The optimized designs present considerable reductions in fuel burn and energy consumption. Notably, the study highlights the importance of improved battery technology in achieving substantial reductions in fuel and energy consumption for long-range missions, while also pointing out the advantages of a range of battery energy densities for shorter missions.

This work fundamentally highlights the significance of considering interdisciplinary design tools and optimization methodologies. As the aviation industry strives for enhanced sustainability, the integration of hybrid-electric propulsion systems into short-haul aircraft emerges as a straightforward way to achieve reductions in both energy and fuel usage.

Future work should include the integration of a detailed engine model for a more realistic estimation of fuel consumption when the engine is either redesigned or working in part-load conditions. In addition, a detailed investigation of the optimized power management for a range of different battery technology projections and mission ranges will provide valuable insights into the trade-offs in hybrid-electric aircraft systems for short-haul operation.

References

Adler, E. J., Brelje, B. J., & Martins, J. R. R. A. (2022). Thermal management system optimization for a parallel hybrid aircraft considering mission fuel burn. *Aerospace*, *9*(5). doi: 10.3390/aerospace9050243

Badger, M., Julien, A., LeBlanc, A. D., Moustapha, S. H., Prabhu, A., & Smailys, A. A. (1994). The PT6 Engine: 30 Years of Gas Turbine Technology Evolution. *Journal of Engineering for Gas Turbines and Power*, *116*(2), 322-330. doi: 10.1115/1.2906823

Beech Commuter Airliners. (2000). *Beech 1900 airliner pilot training manual*. Flushing, New York: FlightSafety International, Inc.

Bonnans, J.-F., Gilbert, J. C., Lemaréchal, C., & Sagastizábal, C. A. (2006). *Numerical optimization: Theoretical and practical aspects*. Springer Berlin, Heidelberg. doi: 10.1007/978-3-540-35447-5

Brelje, B. J., & Martins, J. R. R. A. (2018). Development of a conceptual design model for aircraft electric propulsion with efficient gradients. In *Proceedings of the aiaa/ieee electric aircraft technologies symposium*. Cincinnati, OH: AIAA. doi: 10.2514/6.2018-4979

Darecki, M., King, I., Edelstenne, C., Ky, P., Enders, T., Mathieu, M., … Wörner, J. D. (2011). *Flightpath 2050:Europe's Vision for Aviation: Report of the High-Level Group*. Publications Office of the European Union, Luxembourg.

de Vries, R., Brown, M., & Vos, R. (2019). Preliminary sizing method for hybrid-electric distributed-propulsion aircraft. *Journal of Aircraft*, *56*(6), 2172-2188. doi: 10.2514/1.C035388

EASA. (2018). *Easy access rules for normal, utility aerobatic and commuter category aeroplanes (cs-23) (initial issue).* Brussels, Belgium: European Aviation Safety Agency. (Acccesed on May 29, 2023)

Felder, J. L. (2016). *NASA electric propulsion system studies* (Tech. Rep. No. GRC-E-DAA-TN28410). National Aeronautics and Space Administration (NASA).

Fouda, M. E. A., Adler, E. J., Bussemaker, J., Martins, J. R., Kurtulus, D., Boggero, L., & Nagel, B. (2022). Automated hybrid propulsion model construction for conceptual aircraft design and optimization. In *33rd Congress of the International Council of the Aeronautical Sciences, ICAS 2022.*

Gray, J. S., Hwang, J. T., Martins, J. R. R. A., Moore, K. T., & Naylor, B. A. (2019). OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization. *Structural and Multidisciplinary Optimization*, *59*, 1075-1104. doi: 10.1007/s00158-019-02211-z

IATA. (2022). *Global outlook for air transport: Sustained recovery amidst strong headwinds.* `https://shorturl.at/qwBL6`. (Last accessed on May 29, 2023)

Isikveren, A., Kaiser, S., Pornet, C., & Vratny, P. (2014). Pre-design strategies and sizing techniques for dual-energy aircraft. *Aircraft Engineer-*

ing and Aerospace Technology, *86*(6), 525-542. doi: 10.1108/AEAT-08-2014-0122

Kruger, M., Byahut, S., Uranga, A., Gonzalez, J., Hall, D. K., & Dowdle, A. (2018). Electrified aircraft trade-space exploration. In *2018 aviation technology, integration, and operations conference.* doi: 10.2514/6.2018-4227

Kruger, M., & Uranga, A. (2020). The feasibility of electric propulsion for commuter aircraft. In *Aiaa scitech 2020 forum.* doi: 10.2514/6.2020-1499

Mangelsdorf, M. (2012). *Environmentally Responsible Aviation N+2 Advanced Vehicle Concepts NRA Status* (Tech. Rep. No. DFRC-E-DAA-TN3702). National Aeronautics and Space Administration (NASA).

Martins, J. R. R. A., & Lambe, A. B. (2013). Multidisciplinary design optimization: A survey of architectures. *AIAA Journal*, *51*(9), 2049-2075. doi: 10.2514/1.J051895

Moore, M. D. (2014). Misconceptions of electric aircraft and their emerging aviation markets. *52nd Aerospace Sciences Meeting*. doi: 10.2514/6.2014-0535

Nicolosi, F., Marciello, V., Cusati, V., & Orefice, F. (2022). Technology roadmap and conceptual design of hybrid and electric configurations in the commuter class. In *Proceedings of the 33rd congress of the international council of the aeronautical sciences.* Stockholm, Sweden: ICAS.

Pornet, C., & Isikveren, A. (2015). Conceptual design of hybrid-electric transport aircraft. *Progress in Aerospace Sciences*, *79*, 114-135. doi: https://doi.org/10.1016/j.paerosci.2015.09.002

Raymer, D. (2018). *Aircraft design: a conceptual approach.* (6th ed.). AIAA Education.

Roskam, J. (2019). *Airplane design part v: Component weight estimation.* Kansas: Roskam Aviation And Engineering Corp.

Schäfer, A. W., Barrett, S. R., Doyme, K., Dray, L. M., Gnadt, A. R., Self, R., … Torija, A. J. (2019). Technological, economic and environmental prospects of all-electric aircraft. *Nature Energy*, *4*(2), 160–166. doi: 10.1038/s41560-018-0294-x

Torenbeek, E. (2013). *Advanced aircraft design: Conceptual design, technology and optimization of subsonic civil airplanes.* John Wiley Sons.

Zamboni, J., Vos, R., Emeneth, M., & Schneegans, A. (2019). A method for the conceptual design of hybrid electric aircraft. In *Aiaa scitech 2019 forum.* doi: 10.2514/6.2019-1587