Article

Design to Deployment: Flight Schedule-Based Analysis of Hybrid-Electric Aircraft Variants in U.S. Regional Carrier Operations

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Abstract: This study evaluates the feasibility and benefits of introducing battery-powered hybrid electric aircraft (HEA) into regional airline operations. Using 2019 U.S. domestic flight data, the ERJ175LR is selected as a representative aircraft, and several HEA variants are designed to match its mission profile under different battery technologies and power management strategies. These configurations are then tested across over 800 actual daily flight sequences flown by a regional airline. The results show that well-designed HEA can achieve 3-7% fuel savings compared to conventional aircraft, with several variants able to complete all scheduled missions without disrupting turnaround times. These findings suggest that HEA can be integrated into today's airline operations, particularly for short-haul routes, without the need for major infrastructure or scheduling changes, and highlight opportunities for future co-optimization of aircraft design and operations.

Keywords: Electrified Aircraft Design; Electrified Aircraft Operations; Airline Operations; Fleet Planning

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1. Introduction

Rising fuel costs and competitive fleet economics have renewed interest in propulsion architectures that can lower operating expenses. Hybrid-electric aircraft (HEA), which augment gas turbines with electric propulsion components, offer a potential path to reduced fuel burn and more effective engine utilization. By supplying supplemental power during high-demand segments of flight – such as takeoff and climb – HEA may significantly improve overall propulsion system efficiency [1–3]. Whether these benefits can be achieved without disrupting airline operations, however, remains uncertain. Addressing this question requires integrated analysis that links aircraft design choices with realistic operational constraints.

Recent airline activity underscores the growing interest in such technologies. In the United States, both Delta Airlines and United Airlines have expressed interest in advanced aircraft concepts. Delta has partnered with JetZero to explore high-efficiency hybrid designs [4,5], while United has announced plans to acquire electric aircraft from Heart Aerospace [6]. These efforts reflect an industry-wide push toward improving operational efficiency through emerging technologies.

A prominent implementation of hybrid-electric propulsion is the parallel hybrid-electric (PHE) architecture, in which the gas turbine engine and electric motor are mechanically coupled – typically via a power split gearbox – and together drive a common propulsor, such as a fan or propeller, as notionally depicted in Fig. 1. This architecture allows either power source to contribute torque independently or jointly, depending on the phase of flight and the selected power management strategy.

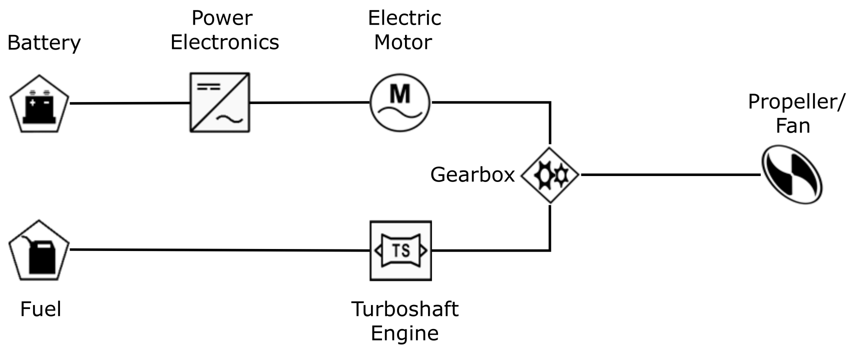

Figure 1. Parallel hybrid electric propulsion system.

In the PHE architecture, electric power can be used to downsize the turboshaft engine, enabling it to operate more efficiently during cruise and other low-thrust segments. Lents et al. [7] demonstrated this potential through the conceptual design of a single-aisle PHE airliner, finding that modest electric assistance during takeoff and climb reduced the engine's thrust-specific fuel consumption (TSFC) during cruise by 2.3% and direct operating costs by about 5%.

Despite these advantages, battery performance remains a critical limiting factor. State-of-the-art lithium-ion batteries offer gravimetric specific energies around 200 Wh/kg, significantly lower than jet fuel's energy density of 11,900 Wh/kg. This large disparity introduces substantial weight penalties that heavily restrict range and payload capacity, in particularly large aircraft [8]. This is further substantiated by Wrobleski and Ansell's work modeling a single-aisle aircraft with a PHE propulsion architecture with a 200 Wh/kg battery [9]. They found that the battery technology modeled was insufficient for design ranges on the order of 3,700 km.

Consequently, short-haul missions present a more practical use case for early HEA deployment [10]. These routes, traditionally served by regional aircraft carrying 60-90 passengers, offer opportunities to harness electrified propulsion benefits while mitigating the penalties of onboard battery mass. Electrifying regional fleets may thus provide a viable near-term path toward more efficient operations under current battery limitations.

Within the literature, two complementary approaches have emerged for incorporating operational data into HEA design. One stream of work focuses on using airline market data—such as route structure and demand patterns—to define aircraft performance requirements and sizing objectives. The other investigates how to operate HEA effectively, accounting for mission profiles, battery charging logistics, and turnaround constraints. This paper aims to bridge these perspectives by evaluating HEA configurations within actual airline schedules, thus jointly addressing the challenges of sizing and operational integration.

1.1. Utilizing Market Data

In prior studies, data from airline markets has been used to establish requirements for future aircraft designs. McDonald [11] established design requirements for two aircraft – a Cessna 208 for FedEx and a Boeing 737-700 for Southwest Airlines – based on how each airline uses its respective aircraft. It was emphasized that future aircraft designs are usually driven by previously designed aircraft's capabilities, not necessarily their utility (i.e., how the airlines use them). To this end, data was collected from the Bureau of Transportation Statistics (BTS) and other sources to generate a set of design requirements for multiple candidate Cessna 208 designs and one Boeing 737-700 design. These candidate designs were found to have smaller design ranges and payloads than the current aircraft being flown. This finding has broader implications for designing HEA in the future – an aircraft with a shorter design range may still satisfy the airlines' operational needs.

Other studies consider passenger demand given a set network of cities that need to be served. Jansen et al. [12] coupled both aircraft family sizing and fleet allocation assignments based on passenger demand. They found that the sized aircraft burned less fuel and allowed the airlines additional operational flexibility to meet varying passenger demands. However, the designed aircraft fly slower than those in existing commercial fleets. From an operational perspective, airlines would not desire this because they would need to adjust their schedules to adapt to the performance limitations of such aircraft.

Davendralingam et al. [13] connects airline operations with aircraft design by sizing new aircraft based on an airline's projected passenger demand in a robust optimization framework. The payload and range for the candidate aircraft are selected by maximizing the airline's future profit. After the aircraft is designed to minimize its direct operating cost, it is then introduced into the airline's operational network and allocated to maximize profits while meeting passenger demands. This work is essential in understanding how airline operations choices impact their ability to serve a target market.

1.2. Electrified Aircraft Operations

Exploring how to operate electrified aircraft is essential for reaping the maximum benefits from these novel designs. Geiß et al. predicted a 3% fuel savings if the propulsion system was operated using optimum fuel consumption parameters as opposed to a default operational strategy [14]. Despite the fact that the aircraft considered carries only two passengers, it establishes a foundation for considering similar strategies in larger aircraft.

Cinar et al. demonstrated that significant fuel savings could be obtained by co-designing the aircraft, its propulsion system, energy and power management strategy, and flight operations [3]. In this study, conceptual PHE designs were developed using notional Beechcraft 1900D and ATR 42-600 configurations as reference points for sizing and performance benchmarking, and were evaluated under different operational scenarios to explore optimal battery usage. One key finding was that charging the batteries in-flight limited the potential fuel burn savings from flying an electrified aircraft. This work suggests that exploring different power management strategies for HEA during the design phase is critical to flying these aircraft as efficiently as possible.

Aside from HEA configurations, other studies explored explored fully electric aircraft operations for routes less than 185 to 370 km. Mitici et al. [15] considered a fleet of electric Embraer ERJ175 aircraft flying round-trip missions out of Amsterdam and developed an optimization problem to find the optimal fleet size and number of charging stations required at the airport. They also considered when it was advantageous to swap a depleted battery for a fully charged battery rather than waiting for the depleted battery to be fully recharged.

Hamilton et al. [16] identified optimal airspeeds to fly an electric aircraft such that the battery's state of charge (SOC) difference between successive flight departures was minimized. By varying the airspeed flown, a tradeoff between the energy consumed while flying and the energy acquired while re-charging was revealed. While they only modeled the mission as a single cruise segment, details were provided on extending this optimization problem to a mission profile with multiple segments, such as climb, cruise, and descent.

To ensure computational tractability, the optimization problems introduced by Mitici et al. [15] and Hamilton et al. [16] are smaller in scale. This work differs from the literature by considering operations within an actual airline network. Rather than formulating an optimization problem, the optimally designed aircraft are flown with a fixed schedule to assess the feasibility of flying such routes with HEA. This is critical for better understanding the time necessary to charge a battery while ensuring seamless integration into an airline's fleet.

2. Research Scope: HEA Integration into Regional Airline Operations

To fully exploit the potential of HEA, it is essential to ensure that they can successfully operate within a regional airline network, thus accounting for airline scheduling practices and passenger connectivity demands. The main research objective is to rapidly model HEA operations for commercial fleets, with the higher-level goal of integrating system design tools with operations modeling capabilities, allowing for an iterative analysis. After modeling HEA operations, further explorations can be performed to determine which short- and medium-haul aircraft routes should be replaced with ultra-efficient, next-generation aircraft.

In this paper, aircraft sizing is considered in the context of existing airline operations. This is done by analyzing existing flight data across short-haul, domestic US markets from 2019 to identify a representative aircraft for analysis.

After identifying an aircraft, it is re-designed as a HEA and then flown on hundreds of sequences (representing a day of operations) scheduled by an US-based regional airline. Once the sequences are flown, they are assessed to determine which ones could be flown by HEA, particularly with respect to fuel savings.

In summary, this paper aims to present a comprehensive analysis of HEA in the context of both design and operations and identifying opportunities for further research and development. By examining various power management scenarios and actual sequences flown by regional airlines, valuable insights are provided into the feasibility and benefits of HEA for short-haul aircraft routes, setting the stage for more efficient commercial aviation operations in the future.

The remainder of the paper is structured as follows. Sections 3 through 5 review the three-step approach to model HEA operations and predict fuel burn trends for an aircraft serving the regional market. This includes the market analysis and representative aircraft identification, HEA sizing, and HEA integration into regional airline operations. Lastly, Section 6 summarizes the work performed and suggests areas for future study.

3. Market Analysis and Representative Aircraft Identification

First, the regional airline market was surveyed to identify a representative aircraft that could be replaced by HEA in the future. To survey the regional market, BTS T-100 [17] data for domestic carriers and on-time performance data [18] during January 2019 was selected to reflect the regional market trends prior to the COVID-19 pandemic. The main metrics collected were:

1. Mission Range: the distance flown by the aircraft from its origin to its destination, collected from BTS T-100 data.
2. Computerized Reservation System (CRS) Departure and Arrival Times: the times that the aircraft is scheduled to depart and arrive at the gate, based on the airline's reservation system, collected from BTS on-time performance data.

3. Air Time: the wheels-up (lifting off during takeoff) to wheels-down (touchdown upon landing) time, measured in minutes and collected from BTS on-time performance data.
4. Departures Performed: the number of times that an aircraft departs from a given origin airport over the course of one month, collected from BTS T-100 data.
5. Passengers: average number of non-stop segment passengers transported, collected from BTS T-100 data.
6. Payload: payload transported on a given flight, collected from BTS T-100 data.

Before processing, the data was cleaned to exclude erroneous data. Any flight with a mission range longer than 16,670 km or an airtime longer than 18 hr was not considered in the subsequent analysis. Also, flights with no recorded mission range or departures performed were considered erroneous and removed from the data set.

Additionally, some BTS data metrics are aggregated across all flights made between a single origin-destination pair (OD-pair): payload, passengers, and airtime. The values of these parameters were divided by the number of recorded departures between that OD-pair to obtain an average number for further analysis.

To better understand the market shares flown by regional airlines, a subset of the routes were plotted on a map of the United States. Figure 2 illustrates all of the routes flown by Mesa Airlines, a subsidiary airline for both American and United Airlines[1]. This figure represents only a portion of the regional market and is for illustrative purposes only. All regional airlines are considered in the subsequent data analysis.

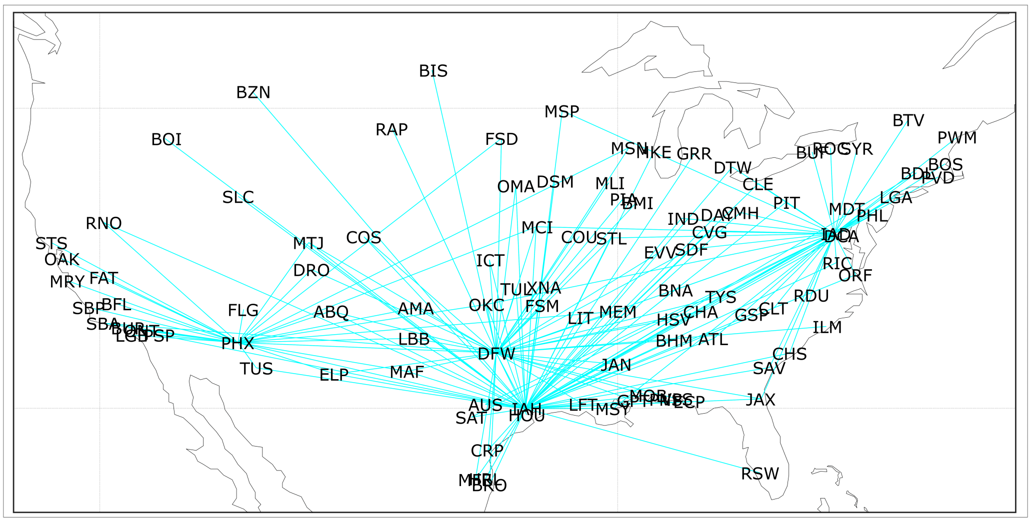

Figure 2. Mesa Airlines network in January 2019.

One observation made from the plot is that most routes begin/end in a major city. These larger airports, defined as “hub” airports, accommodate high traffic volumes and connect passengers between smaller cities. The airports in smaller cities are defined as “spoke” airports, and service fewer passengers due to their smaller resident populations. This route model is known as the “hub-and-spoke” model – airlines fly their regional aircraft to all of the spokes and schedule them to arrive at one hub all around the same time. Based on the routes in Fig. 2, Mesa Airlines’ hubs are Phoenix (PHX), Dallas-Fort Worth (DFW), Houston (IAH), and Washington, D.C. (IAD).

[1] Currently, Mesa Airlines only provides service for United Airlines. However, Mesa Airlines flew routes for both American and United Airlines in 2019.

The BTS data was examined to identify the aircraft most frequently operated by all regional airlines. Figure 3 illustrates that the Embraer ERJ175 and Canadair RJ-200/700/900 fly most of the routes. There are 316 Embraer ERJ175 aircraft registered in the United States [19]. Of these 316 aircraft, 289 of them are the Embraer ERJ175LR, a long-range variant of the ERJ175LR. Due to this aircraft's dominance in the regional market, it was selected as the representative reference aircraft for this study. Its 3,980 km design range [20] well-exceeds the mission range of most regional flights, allowing it to cover more than 90% of the potential market shares.

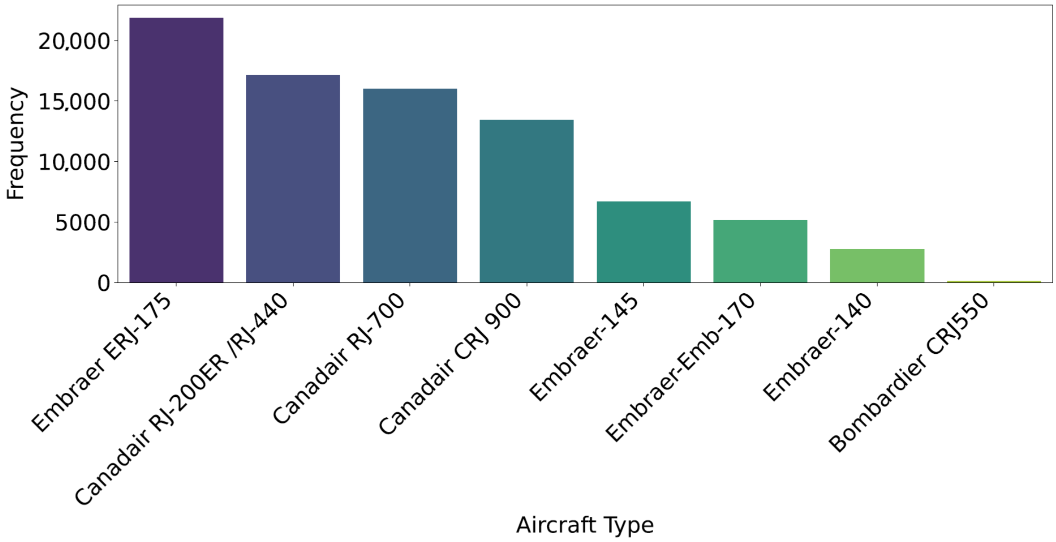

Figure 3. Regional jet usage.

To determine the design range for a future electrified aircraft, recall that the literature revealed that it is best to operate electrified aircraft on short-haul missions [8]. Therefore, the design range of any future aircraft design must be restricted to account for the limited battery technology available. Figure 4 illustrates the mission ranges flown by regional aircraft in a histogram.

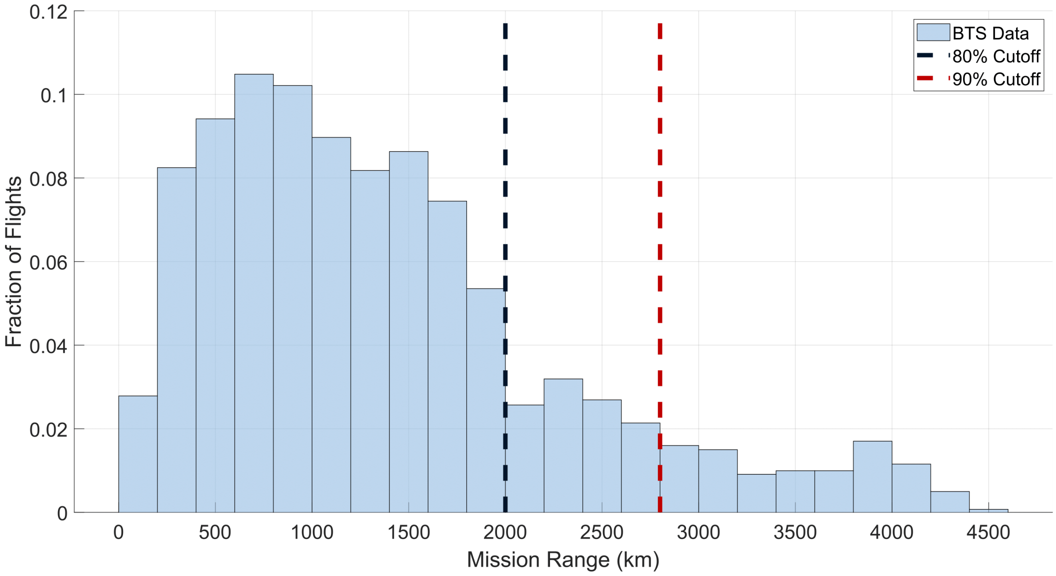

Figure 4. Mission ranges for regional domestic flights.

The data in Fig. 4 reveals that 76%, 80% and 90% of regional domestic flights are shorter than 1,850, 2,010 and 2,780 km, respectively. From the market data available, a reasonable design range for a future electrified aircraft is 1,850 km because it allows over 75% of existing regional flights to be flown. Therefore, in addition to modeling hybrid electric variants after a notional ERJ175LR, a clean-sheet HEA designed to fly 1,850 km will also be designed.

4. Hybrid Electric Aircraft Sizing

Two selected reference aircraft from the market analysis were modeled to serve as a comparison between the HEA variants that will be designed:

1. A "baseline" aircraft that flies 3,980 km, the range that the ERJ175LR was designed for [20],
2. A "reduced range" aircraft that flies 1,850 km, the mission range that covers 83% of regional airline services explored in the market analysis

All aircraft were sized using the Future Aircraft Sizing Tool (FAST) [21], an open-source software specifically developed for the rapid sizing of electrified aircraft concepts. A design structure matrix illustrating FAST's workflow is provided in Fig. 5 [2]. Each gray box represents an overarching analysis module in FAST. The blue boxes represent a collection on modules and are the major functionalities that FAST is built upon.

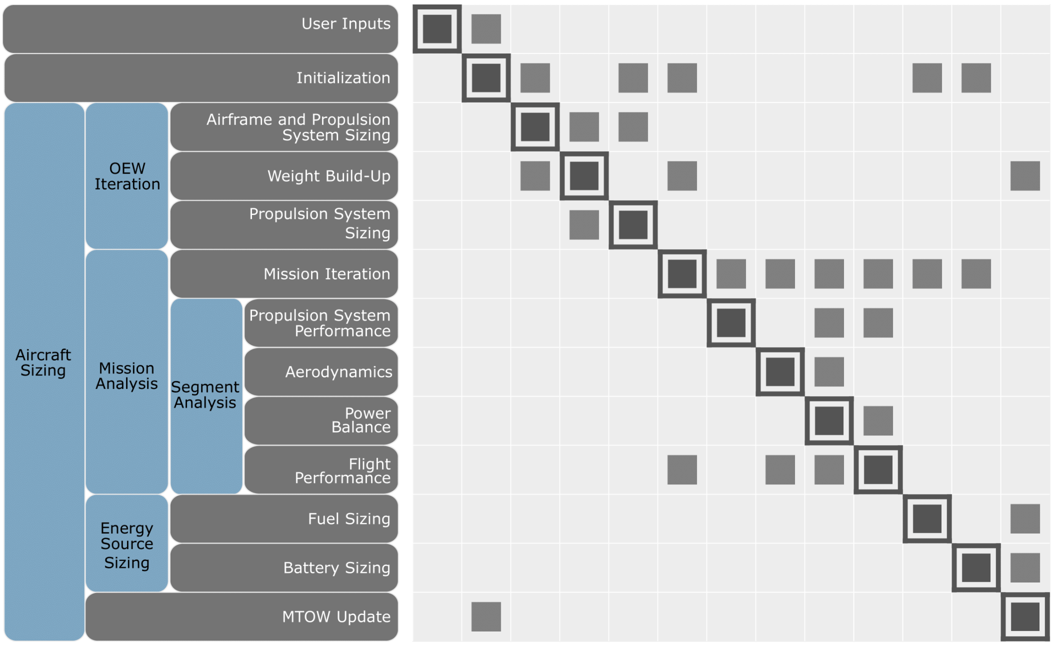

Figure 5. Design structure matrix for FAST's workflow.

To size an aircraft in FAST, an aircraft specification file is provided, detailing the high-level aircraft performance parameters (such as MTOW, thrust-weight ratio, wing loading, design range, etc.), and a mission profile, describing how the aircraft design should be flown. Then, two nested fixed-point iterations are executed to size the aircraft until a user-prescribed convergence tolerance is met. The outer iteration sizes the vehicle and its energy sources (fuel, battery, etc.) based on the mission profile flown (Aircraft Sizing block). The inner iteration sizes the vehicle's structure and propulsion system (OEW iteration block).

[2] All design structure matrices in this paper were produced using OpenMDAO [22].

In the context of this study, FAST was used to size and calibrate the baseline model. After this, the aircraft specifications were modified to fly at a different design range or incorporate a PHE propulsion system into the model. For the configurations with a PHE propulsion system, the battery technology and power management strategy were varied in the aircraft specification file. All configurations flew the same parametric mission profile (described in Appendix A) – the only difference is the duration of the cruise segment, depending on the range being designed for. After sizing the aircraft, FAST is used to simulate a day of regional airline operations, which is discussed further in Section 5.

FAST's distinguishing features leveraged in this study include:

1. Rapid aircraft sizing to facilitate design space exploration.
2. Database of over 450 aircraft used to drive regressions for predicting unknown aircraft performance and design parameters.
3. Ability to model any propulsion architecture, opening the possibility to compare disparate aircraft concepts at a conceptual design-level.
4. Detailed turbofan models for engine sizing analysis.

4.1. Baseline ERJ175LR Modeling

In Section 3, the ERJ175LR was selected as the reference aircraft for this study. A baseline model was designed using publicly available aircraft [20,23–25] and engine [26] data from the literature. Then, the model was sized in FAST based on the top-level aircraft requirements (TLARs) and reference aircraft's design mission profile. Table 1 lists the TLARs used to size the aircraft.

Table 1. TLARs obtained from literature [20,23–25].

Payload [kg]	7,430
Range [km]	3,980
Cruise Altitude [m]	10,668
Cruise Speed [Mach]	0.78
Thrust-Weight Ratio	0.3392
Wing Loading [kg/m^2]	533

The entire design mission profile (including reserve missions) used to size the configuration is illustrated in Fig. 6. The boundary conditions for all mission segments are provided in Appendix A. The reserve mission segments are also included in Appendix A and include: 1) a 185 km diversion; and 2) a 45-minute loiter.

While sizing the baseline model, four calibration factors were included to align the sized aircraft's TOGW, OEW, and block fuel (fuel carried to fly both the design and reserve missions) with those found from literature: 1) airframe weight; 2) fuel flow; 3) cruise lift-drag ratio; and 4) climb/descent lift-drag ratio. For simplicity, the climb and descent lift-drag ratios were assumed to be the same. The selected calibration factors along with a rationale for why they were chosen is presented in Appendix B.

The weights and performance parameters for the calibrated baseline and reduced range aircraft are presented in Tab. 2. The parameters for both configurations are compared to the literature values (italicized quantities).

As seen in Tab. 2, the baseline model closely aligns with the actual aircraft. In contrast, the reduced range configuration poses sizable weight and performance differences. Despite the reduced fuel burn, the average cruise TSFC for the reduced range aircraft is about 25% higher than that of the baseline aircraft. This is because the engines are downsized to meet the less demanding thrust requirements. Since the turbofan engine is downsized, it becomes less efficient, thus increasing the TSFC drastically.

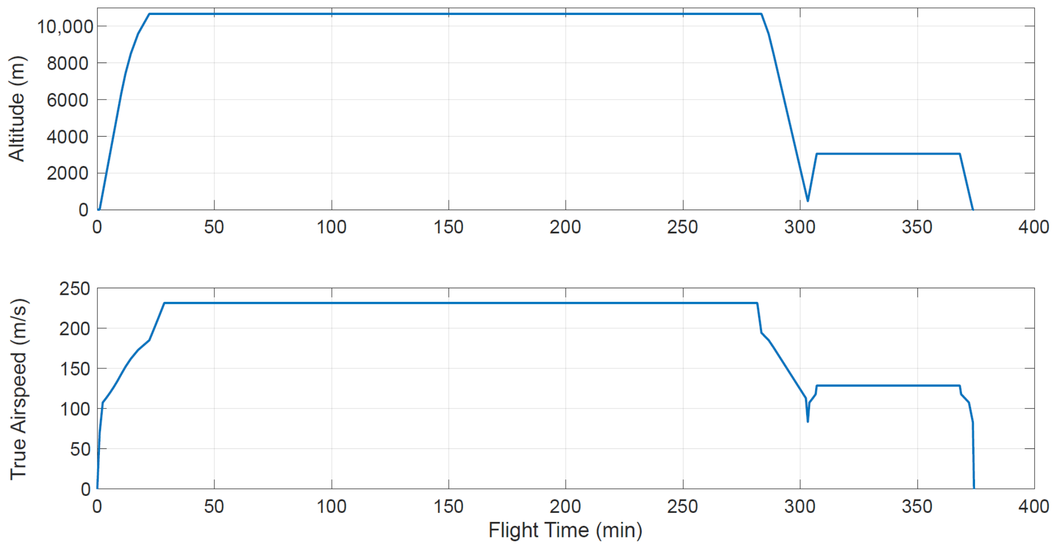

Figure 6. Mission profile used for sizing.

Table 2. Sized conventional aircraft and comparison to literature values.

	Literature	Baseline	Reduced Range
Range [km]	3,980	3,980	1,850
MTOW [kg]	38,790	38,637	26,634
		(-0.39%)	*(-31.07%)*
OEW [kg]	21,500	21,545	13,932
		(+0.21%)	*(-35.33%)*
Block Fuel [kg]	9,428	9,398	5,008
		(-0.33%)	*(-46.71%)*
Total Engine Weight [kg]	2,856	2,926	1,978
SLS Engine Thrust [kN]	60.14	61.71	42.54
Avg. Cruise TSFC $\left[\frac{\text{mg}}{\text{N s}}\right]$	19.26	19.62	24.40
Wing Area $\left[\text{m}^2\right]$	72.74	72.46	49.98

In an operational context, replacing the baseline model with a reduced range aircraft provides fuel burn benefits because the it is sized for 75% of the regional market shares rather than the entire regional market. However, the airlines lose operational flexibility and could not utilize the reduced range aircraft on longer routes. This makes a shorter-range aircraft less desirable from an operations perspective but more favorable from an efficiency perspective.

4.2. HEA Variant Design

For each range target, separate HEA were sized with 250 and 500 Wh/kg batteries, representing near-term and far-term battery technologies, respectively. While sizing the HEA, it was assumed that the electric motor had a 10 kW/kg power-weight ratio and operated at a constant efficiency of 96%. The battery cells integrated into the HEA were assumed to be Lithium-ion cells, each of which has a voltage and capacity of 3.6 V and 2.6 Ah, respectively.

To determine the size of the battery carried onboard, a power management strategy must be determined prior to sizing the configuration. The power management strategy involves determining the size of each component in the propulsion system and how they are operated while flying. As seen in Fig. 1, there are two propulsion system branches providing power – one from the gas turbine engine and fuel, and one from the electric motor and battery. The power provided by each branch is governed by the power split between the gas turbine engine and electric motor, defined as λ in Eq. 1:

$$\lambda = \frac{P_{\text{EM}}}{P_{\text{EM}} + P_{\text{GT}}} \quad (1)$$

The numerator represents the electric motor power and the denominator represents the total gearbox power, accounting for the contributions from both the gas turbine engine and electric motor.

Two operational power splits govern the fraction of power supplied by the electric motor during takeoff and climb, namely the "Takeoff Power Split" and "Climb Power Split", respectively. To size the HEA, there is a sizing power split that determines the size of the electric motor. This power split is set equal to the Takeoff Power Split to ensure that all electric motor power is used on takeoff.

The power management strategies involve analyzing multiple combinations of takeoff and climb power splits from 0-10% and 0-5%, respectively. If the takeoff power split is larger than 10%, the HEA design does not converge because the gas turbine engine becomes too small to cruise without electric motor power. If the climb power split is larger than 5%, then the energy provided by the battery increases. As a result, the battery weight also increases, thus requiring a larger aircraft to carry the battery under the same performance requirements. Once the aircraft becomes heavier, an even larger battery is necessary to fly the mission. Thus, there exists a point at which increasing the power split will not compensate for the additional fuel required to fly with a heavier battery. This point was found to be at a climb power split of 5%.

To summarize, Tab. 3 lists the parameters varied for HEA design. Additionally, the point performance requirements were assumed to be matched by maintaining the baseline aircraft's thrust-weight ratio and wing loading.

Table 3. HEA variant design parameters.

Parameter	**Units**	**Minimum Value**	**Maximum Value**
Design Range	km	1,850	3,980
Battery Gravimetric Specific Energy	Wh/kg	250	500
Takeoff Power Split	%	0	10
Climb Power Split	%	0	5

The configurations requiring the least fuel to fly the mission are carried on to the operations analysis (detailed next) to assess the potential benefits of electrifying a regional aircraft fleet.

For each combination of the selected design range and battery technology level, the HEAs' block fuel is plotted as a function of the design power splits. Figure 7 illustrates the percent change over the conventional baseline of block fuel required for the HEAs sized for a 3,980 km range and 250 Wh/kg battery. On the plot, each marker represents a different aircraft design. The lines with the same marker shape correspond to a constant climb power split while the takeoff power split varies.

For the configurations that only electrify takeoff (blue curve with circle markers), the minimum block fuel exists at an 8.5% power split. This is because the high takeoff power split requires a larger electric motor, thus downsizing the gas turbine engine. As a result, the downsized gas turbine engine performs more efficiently at cruise because it operates closer to its design conditions, thus saving additional fuel. For any takeoff power split greater than 8.5%, the aircraft's climb performance is degraded due to the lapsed engine, burning more fuel in the process. For larger takeoff power splits beyond the optimum

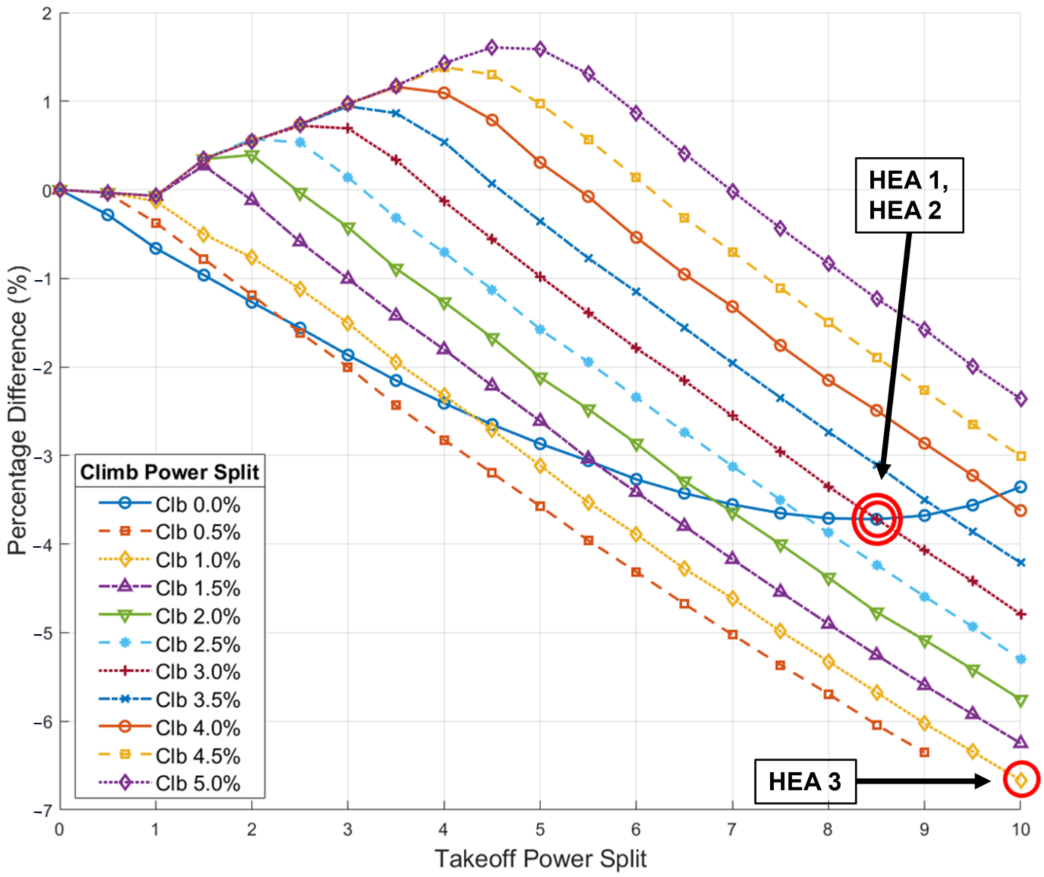

Figure 7. Block fuel burn of HEA variants relative to conventional baseline as a function of takeoff and climb sizing power split, 3,980 km design range and 250 Wh/kg battery.

value, the gas turbine engine continues to shrink, eventually providing insufficient power for cruise and failing to close on a design.

Among the configurations that electrify takeoff and climb, the greatest fuel burn savings exist for operational strategies with higher takeoff and lower climb power splits with respect to the minimum/maximum ones selected. Higher takeoff power splits require a larger electric motor, thus downsizing the gas turbine engine. The smaller climb power splits help save fuel while keeping the battery from becoming too large and adding unnecessary weight to the aircraft. These results suggest that the optimum power management strategy uses: 1) a higher takeoff power split to downsize the engine for a more efficient cruise; and 2) a lower climb power split to augment climb performance while ensuring that the battery does not pose a significant weight penalty.

After sizing all HEA variants, three were chosen for further operational analysis, circled in red on Fig. 7. The first variant, HEA 1, only uses an 8.5% power split on takeoff. The second variant, HEA 2, uses an 8.5% power split on takeoff and a 3% power split during climb. This configuration was chosen because it requires the same block fuel as HEA 1, but both takeoff and climb are electrified. This allows for further comparison of the power management strategies on varying missions. Finally, the third variant, HEA 3, uses a 10% power split on takeoff and a 1% power split during climb. This configuration was selected because it requires the least fuel of all the designs.

The selected HEA designs are compared against the baseline in Tab. 4. The percent difference with respect to the baseline configuration is also reported for some quantities in parenthesis.

Table 4. HEA variants compared to the baseline: 3,980 km design range and 250 Wh/kg battery.

	Baseline	**HEA 1**	**HEA 2**	**HEA 3**
Takeoff Power Split [%]	-	8.5	8.5	10.0
Climb Power Split [%]	-	0.0	3.0	1.0
MTOW [kg]	38,637	37,121	38,952	36,775
		(-3.92%)	*(+0.82%)*	*(-4.82%)*
OEW [kg]	21,545	20,321	21,583	20,057
		(-5.68%)	*(+0.18%)*	*(-6.91%)*
Block Fuel [kg]	9,398	9,048	9,048	8,771
		(-3.72%)	*(-3.72%)*	*(-6.67%)*
Battery Weight [kg]	-	58	627	253
Total Engine Weight [kg]	2,925	2,563	2,694	2,495
Total Thrust [kN]	123.4	118.6	124.4	117.5
SLS Engine Thrust [kN]	61.7	54.3	56.8	52.9
		(-12.37%)	*(-7.91%)*	*(-14.70%)*
Avg. Climb TSFC $\left[\frac{mg}{N\,s}\right]$	14.76	14.36	13.87	14.28
Avg. Cruise TSFC $\left[\frac{mg}{N\,s}\right]$	19.62	19.23	18.73	19.18
Wing Area $\left[m^2\right]$	72.46	69.58	73.02	68.93
Electric Motor Power [kW]	-	700	735	816
Electric Motor Weight [kg]	-	70.0	73.5	81.6

The results indicate that all of three of the chosen HEA variants have fuel burn benefits over the baseline aircraft. HEA 3 has the largest weight savings for three reasons. First, HEA 3 uses the maximum takeoff power split (10%), meaning that the gas turbine engine is as small as possible. This downsizes the gas turbine engine, making it less efficient. However, since HEA 3 has a smaller MTOW, the thrust required to cruise is also smaller. Therefore, the reduced thrust requirement outweighs the slightly greater TSFC, thus reducing fuel burn.

Second, the reduced engine size on HEA 3 diminishes climb performance, increasing the time required to reach cruise altitude. Since the average climb TSFC is about 25% smaller than the cruise TSFC, this actually saves more fuel. Despite the fuel savings, the airlines may not desire this because it shortens their time to serve in-flight refreshments to the customers.

Third, despite the fact that HEA 3 flies a longer climb segment and uses more battery, the climb power split is small enough that the battery is not egregiously large, preventing additional flight performance penalties. Relative to takeoff, which is modeled with using maximum thrust for one-minute, climb can take 20 minutes or more, thus driving the battery size even though the power demand is lower than that of takeoff.

HEAs 1 and 2 are sized based on different power management strategies, but require the same block fuel. This comparison illustrates that one can achieve similar fuel burn using different power management strategies. However, the different power management strategies can penalize the resulting aircraft performance capabilities or weights. In HEA 2, the climb power split is 3%, requiring a battery about ten-times larger than that of HEA 1. Despite the lower climb and cruise TSFC than HEA 1, the heavy battery imposes a significant performance penalty on HEA 2. This is also reflected in the weight breakdown of each aircraft – HEA 2 is the only configuration to weigh more than the baseline, despite the fuel savings.

To better illustrate the size differences reported in Tab. 4, the aircraft were also visualized in FAST. Their renderings are depicted in Fig. 8. The baseline aircraft is plotted in blue and the respective HEA variants are overlaid in red.

The same analysis was performed for HEA configurations sized on a 1,850 km design mission range with a 250 Wh/kg battery. The results are displayed in Fig. 9. Again,

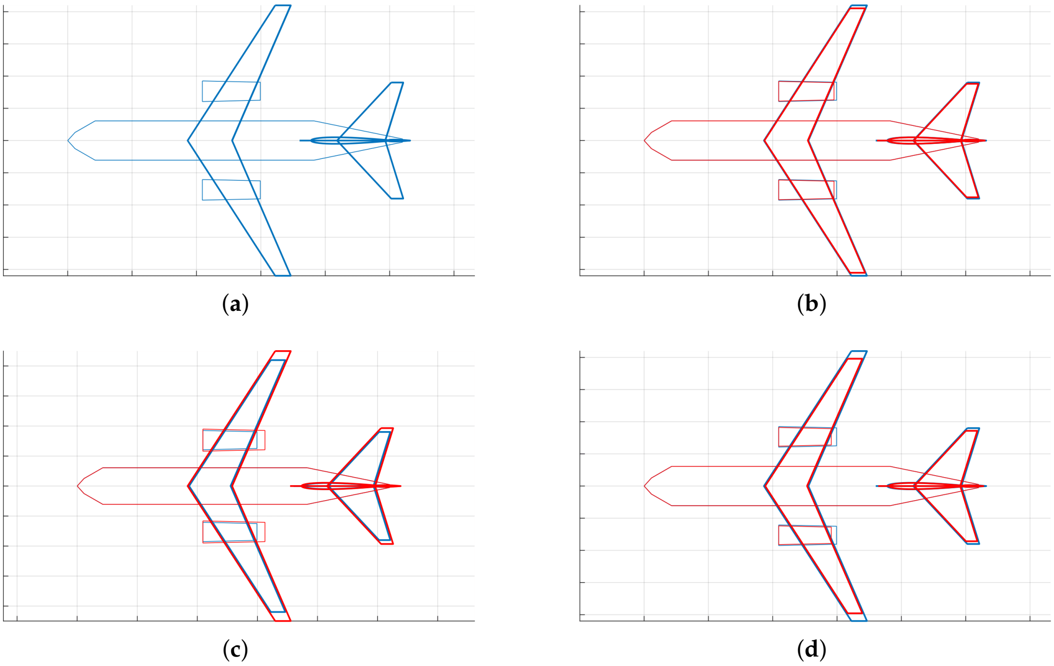

Figure 8. Sized aircraft configurations. (a) Baseline. (b) HEA 1. (c) HEA 2. (d) HEA 3.

each point on the plot represents a different aircraft with its own power management strategy. The percent change in block fuel was computed with respect to the reduced range configuration.

All HEA configurations sized save fuel relative to the corresponding baseline. The results indicate that the power management strategy heavily impacts the fuel required to fly. For the aircraft sized for a 1,850 km design range, electrifying takeoff only saves less than 2% fuel compared to its same range conventional counterpart. However, by electrifying takeoff and climb, up to 5% fuel can be saved.

For the 1,850 km mission, the optimum power management strategy is the same as the 3,980 km mission – fly with a higher takeoff power split and a lower climb power split. This higher takeoff power split downsizes the engine, requiring it to be operating at a higher throttle setting, closer to its design point (and more efficiently). The low climb power split prevents the battery from becoming excessively large, though requiring additional time to climb.

The two HEA models designed with 0.5% climb and 8/9.5% takeoff power splits do not follow the general trend, burning more fuel than expected. In FAST, the battery is comprised of discrete numbers of cells in series and parallel. Thus, those HEA required a larger battery size than the other configurations, resulting in a larger fuel burn due to the added battery weight onboard.

From these configurations, two were selected for the operational analysis. The first one selected, HEA 4, electrifies takeoff only at a power split of 6.5%. The second variant, HEA 5, electrifies takeoff at a 10% power split and climb at a 1% power split. Both of the selected HEA designs are compared against the reduced range aircraft in Tab. 5.

Both HEA configurations save fuel due to the improved TSFC during cruise from operating the gas turbine engines more efficiently. As a result of the decreased design range, less fuel is being carried onboard, thus decreasing the overall aircraft weight. This reduces the battery size, making them lighter than the other HEA designed thus far.

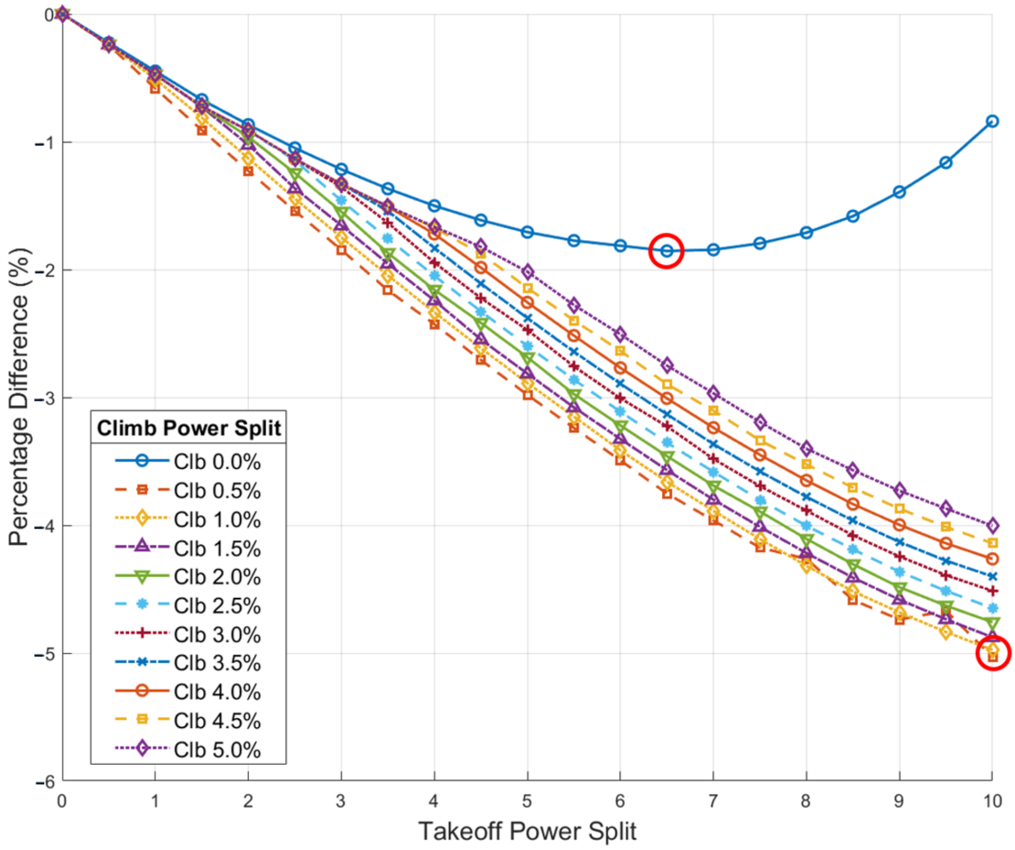

Figure 9. Block fuel burn of HEA variants relative to conventional baseline as a function of takeoff and climb sizing power split, 1,850 km design range and 250 Wh/kg battery.

Table 5. HEA variants compared to the reduced range: 1,850 km design range and 250 Wh/kg battery.

	Reduced Range	HEA 4	HEA 5
Takeoff Power Split [%]	—	6.5	6.5
Climb Power Split [%]	—	0.0	1.0
MTOW [kg]	26,679	26,267	26,355
		(-1.38%)	(-1.05%)
OEW [kg]	13,932	13,625	13,676
		(-2.20%)	(-1.84%)
Block Fuel [kg]	5,008	4,915	4,825
		(-1.86%)	(-3.66%)
Battery Weight [kg]	-	33	160
Total Thrust [kN]	85.1	83.9	84.2
SLS Engine Thrust [kN]	42.5	39.2	39.4
		(-7.80%)	(-7.49%)
Total Engine Weight [kg]	1,978	1,809	1,816
Avg. Climb TSFC $\left[\frac{\mathrm{mg}}{\mathrm{N\,s}}\right]$	19.39	18.70	18.61
Avg. Cruise TSFC $\left[\frac{\mathrm{mg}}{\mathrm{N\,s}}\right]$	24.44	23.76	23.70
Wing Area $\left[\mathrm{m}^2\right]$	49.98	49.24	49.42
Electric Motor Power [kW]	-	379	380
Electric Motor Weight [kg]	-	37.9	38.0

4.3. Designs Selected for Operational Analysis 407

In the operational analysis, aircraft configurations with a design ranges of 3,980 and 408
1,850 km, along with battery gravimetric specific energies of 250 and 500 Wh/kg were 409

included. The configurations sized with a 250 Wh/kg battery were presented previously. The configurations sized with a 500 Wh/kg battery are included in Appendix C. For the higher battery specific energy configurations, a lighter battery is carried onboard, thus reducing MTOW and the block fuel required to fly.

Table 6 presents the HEA configurations selected for inclusion in the operational analysis. HEA 6 through 9 were selected from the configurations sized with a battery gravimetric specific energy of 500 Wh/kg. The power management strategies identified previously are also optimum for the newly selected configurations. The only difference between these configurations is the smaller battery size – all other aircraft size and performance trends were consistent throughout the analyses.

Table 6. HEA variants selected for operational analysis.

Configuration	**Design Range [km]**	**Battery Specific Energy [Wh/kg]**	**Takeoff Power Split [%]**	**Climb Power Split [%]**
HEA 1	3,980	250	8.5	0.0
HEA 2			8.5	3.0
HEA 3			10.0	1.0
HEA 4	1,850	250	6.5	0.0
HEA 5			10.0	1.0
HEA 6	3,980	500	8.5	0.0
HEA 7			10.0	1.0
HEA 8	1,850	500	6.5	0.0
HEA 9			10.0	1.0

5. Aircraft Operations Analysis

The aircraft operations analysis involves creating a sequence of routes to simulate and then flying those routes in FAST.

5.1. Sequence Compilation

The BTS on-time performance data [18] was used to identify the routes that all ERJ175LR aircraft flew in one day. The routes were initially organized by tail number, a unique identifier for each aircraft. Using the tail numbers, the routes from a day of operations were re-arranged in chronological order to construct a "sequence" – a combination of routes and ground times that a single aircraft flies in one day.

Ground times for each flight are calculated by the difference between the CRS arrival times and departure times – the times that aircraft is scheduled to arrive and leave the gate, respectively – from the BTS data [18]. The ground time for the first flight was set to be 0 minutes because there is enough time to fully charge the overnight. In this work, it is assumed that the HEA's batteries are charged only on the ground. In-flight battery charging is not simulated and battery swapping at the gate is not considered due to regulatory concerns and uncertainties around such activity. Therefore, including the ground times in the operational analysis helps benchmark whether or not airlines will need to change their flight schedules to accommodate HEA charging.

An example of a sequence is provided in Tab 7, showing all flights flown by an ERJ175LR with the tail number N88327 on January 1, 2019. The reduced range aircraft would not be able to fly this sequence because it has two flights over 1,850 km.

Table 7. Flight Sequence for N88327 on January 1, 2019.

Origin	Destination	Mission Range (km)	Cruise Altitude (m)	Ground Time (min)
RIC (Richmond, VA)	IAD (Washington, DC)	161	3,962	—
IAD (Washington, DC)	JAX (Jacksonville, FL)	1,013	10,668	56
JAX (Jacksonville, FL)	IAH (Houston, TX)	1,313	10,668	71
IAH (Houston, TX)	DCA (Washington, DC)	1,945	10,668	57
DCA (Washington, DC)	IAH (Houston, TX)	1,945	10,668	37

5.2. Sequence Simulation

Once the sequences were assembled, they were flown as off-design missions in FAST. Each flight was followed by a battery charging period using the respective ground time from the sequence (with exception to the final route in the sequence because it stays at the airport overnight). This process repeated until all flights were flown. A detailed simulation for daily airline operations is illustrated in Fig. 10. Orange cells represent user-prescribed inputs. Light green cells represent module outputs. Dark green cells represent module inputs or intermediate values within a module.

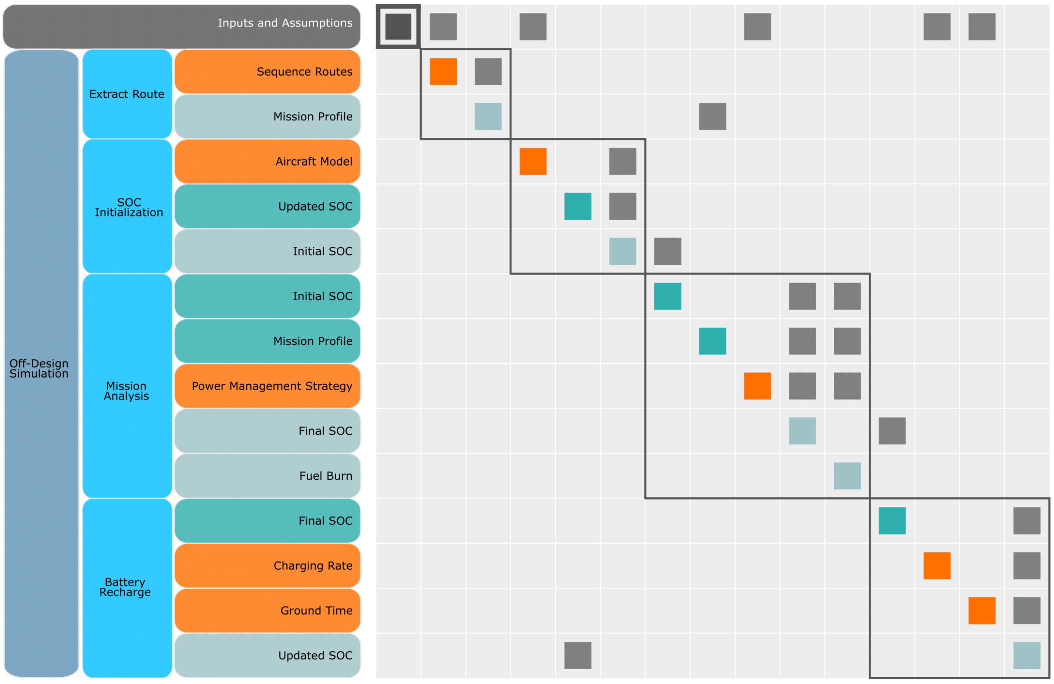

Figure 10. DSM for simulating daily airline operations with battery recharging.

The simulation process for a single route (within the sequence) is as follows. First, the mission is initialized by extracting the current route from the sequence. Then, it is converted into a mission profile that FAST can read and fly. Lastly, the SOC is initialized to either: 1) 100% if the first flight of the day is being flown; or 2) the SOC attained from recharging the battery in-between flights.

After initialization, the aircraft is flown according to the power management strategy that it was designed for (from Section 4), returning the required fuel burn and final battery SOC. In the event that the HEA cannot fly with the designated power management strategy (i.e., more battery energy is required than available), the HEA continues to operate with its gas turbine engines only.

After successfully flying the mission, the aircraft's battery recharges for the allotted ground time in-between flights. The battery is charged at a constant 150 kW/hr rate until either: 1) no more ground time remains and the aircraft must depart for the next flight; or 2) the battery SOC reaches 100% and cannot accept any more charge. The SOC after charging is the initial SOC for the next flight.

This process repeats until all flights in the sequence have been flown. The sequence simulation outputs a detailed summary of the aircraft performance, including the mission history, fuel burn, and battery SOC as a function of time. These results are used to assess the fuel burn benefits of flying the HEAs relative to their conventional counterparts.

5.3. Flight Operations Simulations

The baseline configurations and HEA variants selected in Section 4.2 are subsequently evaluated using the flight sequences constructed in Section 5. From the BTS data, 864 sequences, totaling 3,408 individual flights, were flown by Mesa Airlines' ERJ175LR aircraft during January 2019. The summary statistics of the sequences collected are provided in Tab 8. These flights were used to simulate a day of regional airline flight operations, as previously illustrated in Fig. 10. The simulations assess the HEA performance benefits over the baseline aircraft and compare HEA variants' performance across sequences.

While running the simulations, the following assumptions were made:

1. Once the battery reaches 20% SOC, it is no longer used. The aircraft only flies using its turbofan engines. Not only does this imply that the battery could be "turned off" in the middle of a takeoff or climb segment, but this renders the flight to be "infeasible", meaning that the power management strategy was not fully adhered to.
2. The battery is only used during the respective mission segments (either takeoff only or takeoff and climb). After flying the respective mission segments with the battery, any additional battery energy is not expended.
3. The battery's final SOC and fuel burn is recorded after the main mission is completed. The reserve mission is included to calculate the necessary fuel requirements.

Table 8. Test sequence statistics.

	Mean	**Std. Dev.**
Number of Flights	3.94	1.09
Total Distance per day (km)	5,057	1,409
Distance per Flight (km)	1,282	509
Charge Time (min)	59.6	19. 2

The simulation results indicate that HEA 1, 2, and 3 can fly all 864 sequences tested, and can operate according to their prescribed power management strategy without having to prematurely shut down the battery. In contrast, the reduced conventional aircraft ans HEA 4, 5, 8 and 9 can only fly 2,664 out of 3,408 missions because the mission range is beyond the design range of these aircraft. 50% of the sequences tested contained missions longer than 1,850 km. Only the 431 feasible sequences flown by these configurations are considered when analyzing fuel burn benefits next.

Using the feasible sequences identified, the fuel burn benefits of operating HEA are evaluated. For each aircraft, the average fuel burn per day is reported in Tab 9. This value is calculated by summing the total fuel burn across all flown sequences and dividing by the number of sequences.

Every variant designed saves fuel relative to the baseline. The aircraft designed with low climb and high takeoff power splits, HEA 3 and 5, have the largest fuel burn savings. However, HEA 4 and 5 are designed for a 1,850 km range and cannot fly 50% of the missions

Table 9. Average fuel burn per day of operations and comparison to the baseline.

	Average Daily Fuel Burn [kg]	Percent Difference
Conventional Baseline	10,726	-
Reduced Range Conventional*	10,505	-2.05%
HEA 1	10,171	-5.17%
HEA 2	10,319	-3.79%
HEA 3	10,007	-6.70%
HEA 4*	10,199	-4.91%
HEA 5*	9,914	-7.57%
HEA 6	10,148	-5.39%
HEA 7	9,920	-7.51%
HEA 8*	10,193	-4.97%
HEA 9*	9,877	-7.91%

* Indicates 1,850 km range aircraft, which fail to cover 50% of the missions in the simulated sequences.

simulated. Therefore, the fact that HEA 5 saves the most fuel is diminished by its inability to fly all of the missions in the regional airline network.

Although HEA 1 and 2 had the same block fuel requirement for the design mission, HEA 1 burns less fuel per day on average. This is because both takeoff and climb are electrified in HEA 2, resulting in a larger battery carried onboard. Since the missions in the sequences are shorter than the design mission, the battery is not fully depleted, causing the aircraft to operate less efficiently than it did while flying the design mission.

All designed variants achieve fuel savings compared to the relevant baseline configuration. Among these, HEA 3 and HEA 5 (which feature low climb and high takeoff power splits), demonstrate the greatest reductions in fuel burn. However, the result for HEA 5 should be interpreted with caution: although it shows the lowest average fuel consumption, it can only complete 50% of the test sequences.

Among the HEA variants with the original design range, HEA 1 and HEA 2 require the same block fuel for the design mission; however, HEA 1 exhibits lower average daily fuel consumption. This difference arises because HEA 2 electrifies both takeoff and climb segments, necessitating a larger onboard battery. In the shorter missions represented by the operational sequences, the battery in HEA 2 is not fully depleted, reducing its operational efficiency relative to its performance in the design mission.

The block fuel for the design range HEA relative to the conventional baseline for each feasible individual mission is plotted in Fig. 11.

There exists a discontinuity in the plot at a mission range of 370 km. This is because the cruise segment is significantly shorter than the climb and descent segments. Rather than cruising for an appreciable amount of time, the HEA climbs, briefly cruises, and then descends. Since the cruise segment is short, there is an additional fuel savings because the HEA is operating with only the gas turbine engines for a shorter period of time. These shorter missions are best suited to be flown by HEA because the battery can supplement a significant portion of the mission, thus reducing fuel burn.

As shown in Fig. 11, HEA 3 and 7, both of which feature climb hybridization, achieve the lowest fuel burn across all missions. This performance is primarily due to the large takeoff power split which results in downsized engines. These smaller engines generally operate closer to their design point during cruise, providing fuel savings even during non-hybridized segments. The batteries in these configurations do not significantly penalize performance, as only a 1% power split is applied during climb, making them well-suited for efficient operation across a range of mission lengths. Additionally, the improved battery technology implemented in HEA 7 yields about an extra 1% fuel burn reduction per mission

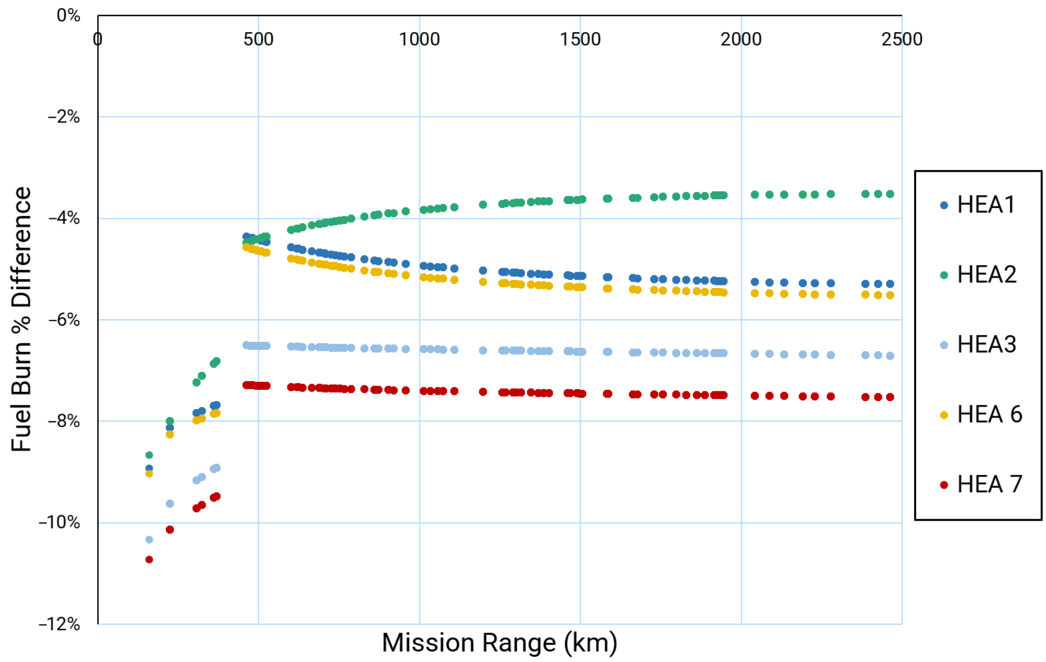

Figure 11. Block fuel burn of design range HEA relative to the baseline flown on all simulated missions.

compared to HEA 3. In contrast, HEA 2 carries the heaviest battery, which penalizes the fuel burn benefits on longer missions, since the battery must be carried through cruise even when not used.

The fuel burn on each individual mission relative to the conventional baseline for the aircraft sized on the reduced design mission is plotted in Fig. 12. For all missions, the HEA burn less fuel than the conventional baseline aircraft. However, for missions less than 556 km, the conventional aircraft designed for a reduced range burns more fuel than the baseline. The baseline is able to reach cruise on the shorter missions while the reduced range aircraft stays in climb at a higher engine setting, going straight from climb to descent. Although 2% fuel is saved on routes over 556 km, the small fuel burn savings and limited operational flexibility make it a less desirable replacement for existing aircraft in the commercial fleet.

Figure 12 reveals that HEA 5 and 9 have an 8% fuel burn savings on mission greater than 926 km. However, they were only designed for a 1,850 km range, meaning that they can only fly 78.5% of the scheduled regional airline flights. Should these aircraft be integrated into an airline's operational network, this could introduce fleet assignment complications because?

the airline loses flexibility when assigning specific aircraft to a given route. This added complexity supports integrating HEA with a larger design range, such as the ones designed for 3,980 km.

To better understand how the battery contributes to a more efficient flight, the battery energy expended per mission is illustrated in Fig. 13. As mission range increases, the battery energy expended by HEA 2, 3, 5, 7 and 9 increases at a superlinear rate. This trend is due to the aircraft carrying more fuel for longer missions, thus increasing the power required (and consequently battery energy expended) during the climb segment. HEA 2 uses the most battery energy because it has a larger climb power split (3%) than HEA 3 and 5 (1%). Markers for HEA 2, 3, and 7 at 3,980 km show the available energy for their respective batteries with a full charge. The HEA variants with hybridized climb do not fully deplete their batteries, as the climb segments in off-design missions differ from those

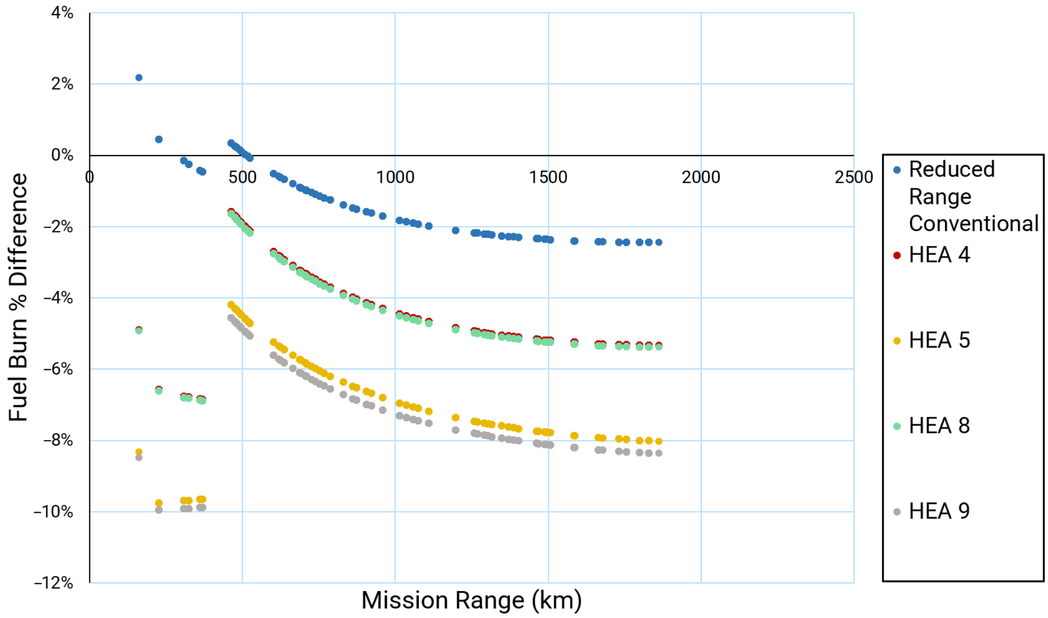

Figure 12. Fuel burn relative to the conventional baseline for reduced range aircraft flown on all simulated missions.

in the design mission. In the future, additional operational strategies could be devised to ensure that the battery is fully depleted during flight, thus maximizing fuel savings.

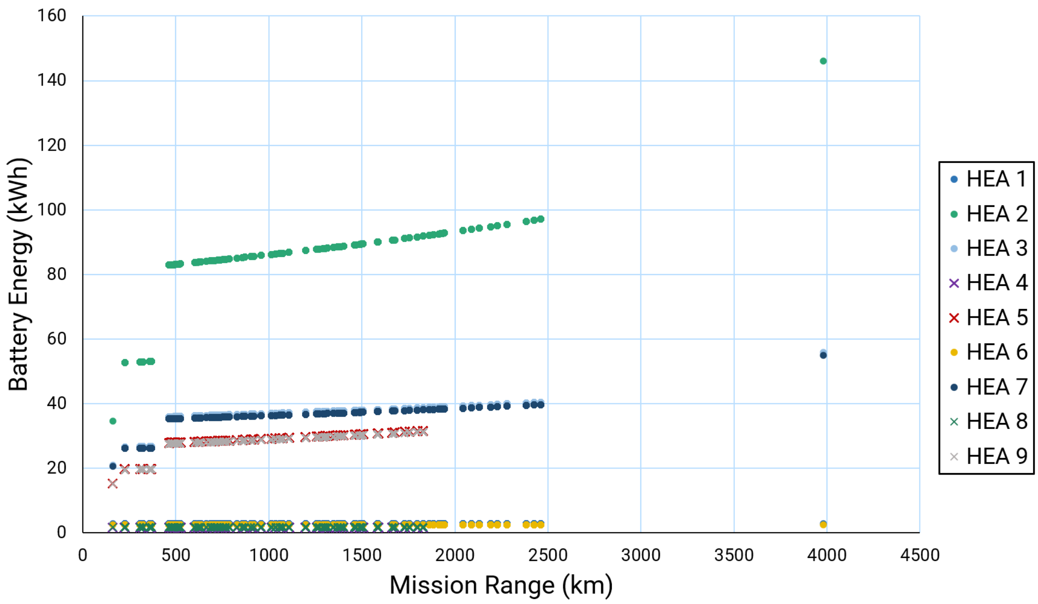

Figure 13. Battery energy used per mission versus range.

As it can be seen from Fig. 13, HEA 1, 4, and 8 use constant energy each mission because only takeoff is hybridized. This is an artifact of the modeling assumptions made in the flight mission simulations – takeoff is one minute long with the engines and electric motors set to the maximum throttle setting. Therefore, the aircraft expends the same amount of energy for each flight. HEA 1, 4, and 8 are also the only models that fully discharge their batteries every mission.

The simulation results revealed that the battery could be charged to its full capacity after each flight, regardless of the previous mission range flown. Figure 14 illustrates the change in SOC while charging the battery at the gate. In this work, it is assumed that the battery can be charged for the entire ground time. However, it is possible that battery charging would need to stop while the HEA is being refueled. Thus, the results presented in Fig. 14 are somewhat optimistic.

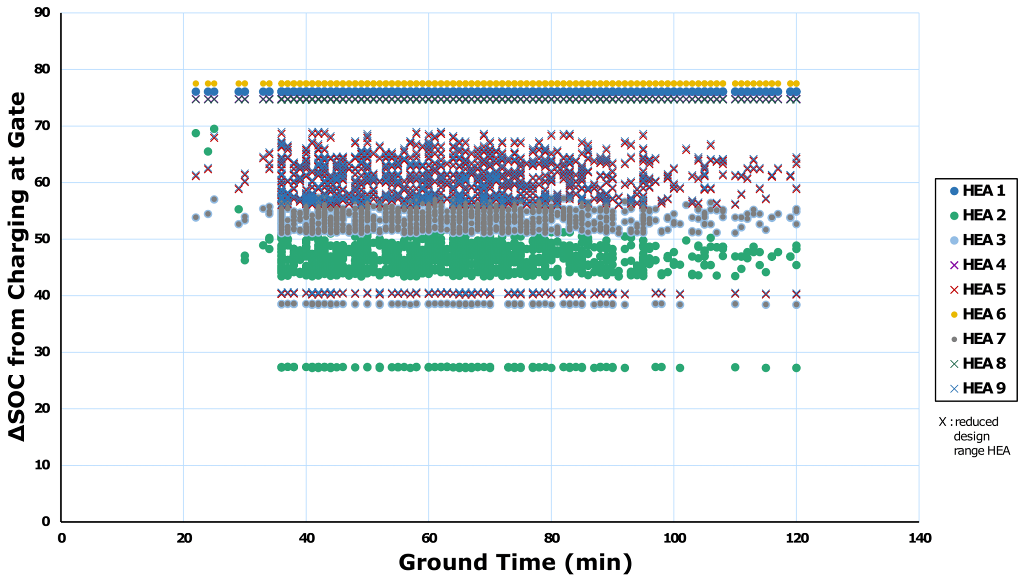

Figure 14. Change in SOC during charging for all ground times at the gate.

In Fig. 14, the change in SOC for a given ground time varies depending on the HEA flown. For example, HEA 1, 4, 6, and 8 fully deplete their battery during takeoff and fully recharge it in-between successive flights. In contrast, the SOC change for the batteries in HEA 2, 3, 5, 7, and 9 depend on the prior mission's range, cruise altitude, and block fuel burned.

The sets of markers near the 30% and 40% SOC changes are for the missions that were 370 km or shorter. This is because less battery was needed to climb to a lower cruise altitude. Additionally, the aircraft was carrying less fuel relative to a longer mission, making it lighter and requiring less battery power to fly.

Based on the results presented here, the batteries installed on the HEA configurations help save fuel and can be incorporated into an airline's fleet. Fuel was saved on all routes flown by HEA, particularly for ones shorter than 370 km. However, as the mission range increases, the fuel savings begins to plateau, indicating that there is less of a benefit for longer mission ranges. Additionally, all batteries were fully charged in the allotted time, reflecting that it is possible to charge a HEA's battery at the gate.

6. Conclusions

This study presents strong evidence supporting the integration of HEA into the existing aviation network, given the availability of necessary charging infrastructure and power supplies. This work examines how battery-powered parallel hybrid electric aircraft could be deployed within existing regional airline operations, using real-world flight schedules and operational constraints. Across more than 800 daily flight sequences, the results show that HEA can reduce fuel consumption by 3-7% compared to conventional aircraft. Strategies that combine high takeoff electrification with modest climb hybridization consistently yielded the best performance as a result of improved engine efficiency during cruise and manageable battery weight.

When flying the design mission, the HEA's fuel savings relative to the conventional aircraft were not as pronounced. The true advantage of flying HEA came from operating them on shorter range missions, which represents the existing routes that regional airlines serve. This implies that the HEA may prove beneficial for regional airlines, especially since 76% of these flights are shorter than 1,850 km. While range-limited HEA designs offer slightly greater fuel savings on individual flights, their inability to cover the full set of daily missions makes them less practical for fleet integration. In contrast, HEA designed for longer missions, though slightly less efficient, can serve the entire regional network without compromising schedule feasibility.

Furthermore, advancements in battery technology could result in even greater improvements for HEA. Batteries with a higher gravimetric specific energy could increase fuel savings and enhance overall HEA performance. This will also necessitate faster charging rates to ensure that the battery is fully recharged prior to the next mission in each sequence. Continued advancements in battery and electrical power delivery technologies will be crucial for successfully integrating HEA into the next-generation aircraft fleet.

More importantly, this study moves beyond an isolated mission analysis to consider full-day operational sequences, offering a more realistic assessment of HEA viability. It also highlights the trade-offs between fuel savings, battery weight, and operational flexibility. As battery technology improves, particularly in gravimetric specific energy and charging rate, the case for HEA will strengthen further. Even with today's assumptions, integrating HEA into the fleet appears operationally viable for many regional applications.

Some benefits that electrified aircraft can offer are not fully represented in the current model. Only constant power splits were investigated within each segment, while previous work in the literature has shown that varying the power management strategy throughout the mission can yield further fuel savings. Despite this limitation, the results from this first-order analysis are indeed promising.

Building upon the findings of this study, several next steps can be taken to better understand the advantages and limitations of HEA. A crucial next step is to explore a broader range of HEA in-flight operations by optimizing the power management strategy as a function of time. This will help maximize the fuel burn savings on each flight by accounting for the mission profile, flight conditions, and available battery power. Another similar research direction involves optimizing the power management strategy for an entire sequence of flights (or day of operations), accounting for disparate charging and refueling operations at hub and spoke airports. This approach could shed light on logistical challenges during turnaround times at airports, especially if the batteries cannot be recharged while the HEA is being refueled. In short, this approach would consider not only the technical aspects of HEA but also the strategies for navigating and managing routes, ensuring a more comprehensive understanding of the potential for HEA adoption in the aviation industry.

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Abbreviations

The following abbreviations are used in this manuscript:

BTS	Bureau of Transportation Statistics
CRS	Computerized Reservation System
FAST	Future Aircraft Sizing Tool
HEA	Hybrid Electric Aircraft
MTOW	Maximum Takeoff Weight
OD-pair	Origin-Destination pair
OEW	Operational Empty Weight
PHE	Parallel Hybrid Electric
SOC	State of Charge (%)
TLAR	Top Level Aircraft Requirement
TOGW	Takeoff Gross Weight
TSFC	Thrust-Specific Fuel Consumption

Appendix A. Baseline Aircraft Design Mission Profile

Table A1 lists the flight phases used in the design mission profile to best model of the notional ERJ175LR's design mission, which is divided into three segments. The initial and final altitudes and airspeeds are listed. For any climb/descent segments, the climb/descent rate is computed internally within FAST.

Table A1. Notional ERJ175LR design mission profile.

Mission	Segment	Initial Altitude [m]	Final Altitude [m]	Initial Airspeed (m/s or Mach)	Final Airspeed (m/s or Mach)
Main Mission – Design Range	Takeoff	0	0	0 TAS	69.45 TAS
	Initial Climb	0	914	69.45 TAS	102.89 EAS
	Main Climb	914	10,668	102.89 EAS	102.89 EAS
	Accelerate	10,668	10,668	102.89 EAS	Mach 0.78
	Cruise	10,668	10,668	Mach 0.78	Mach 0.78
	Decelerate	10,668	10,668	Mach 0.78	108.03 EAS
	Main Descent	10,668	914	108.03 EAS	108.03 EAS
	Final Descent	914	457	108.03 EAS	83.34 TAS
Reserve – 100 nmi Diversion	Initial Climb	457	914	83.34 TAS	102.89 EAS
	Main Climb	914	2,743	102.89 EAS	102.89 EAS
	Final Climb	2,743	3,048	102.89 EAS	128.61 TAS
	Divert	3,048	3,048	128.61 TAS	128.61 TAS
Reserve – 45 min Loiter	Loiter	3,048	3,048	128.61 TAS	128.61 TAS
	Initial Descent	3,048	2,743	128.61 TAS	102.89 EAS
	Main Descent	2,743	914	102.89 EAS	102.89 EAS
	Final Descent	914	0	102.89 EAS	83.34 TAS
	Landing	0	0	83.34 TAS	0 TAS

Appendix B. Calibration Factors for Baseline ERJ175LR Model

The calibration factors required to match the modeled ERJ175LR's TOGW, OEW, and block fuel are listed in Table A2, all of which are close to one. The relative error is less than 0.5% for MTOW, OEW, and block fuel, illustrating that FAST provides accurate modeling results with little tuning required. The calibration factors applied to the baseline model remain fixed while sizing and operating the HEA variants in the remainder of the study.

Table A2. Applied calibration factors for the baseline ERJ175LR model.

Calibration Factor	Value
Airframe Weight	1.018
Fuel Flow	1.029
Cruise L/D	1.002
Climb/Descent L/D	1.000

Appendix C. Sized HEA Variants

Figures A1 and A2 list the absolute values of fuel burned on the design mission.

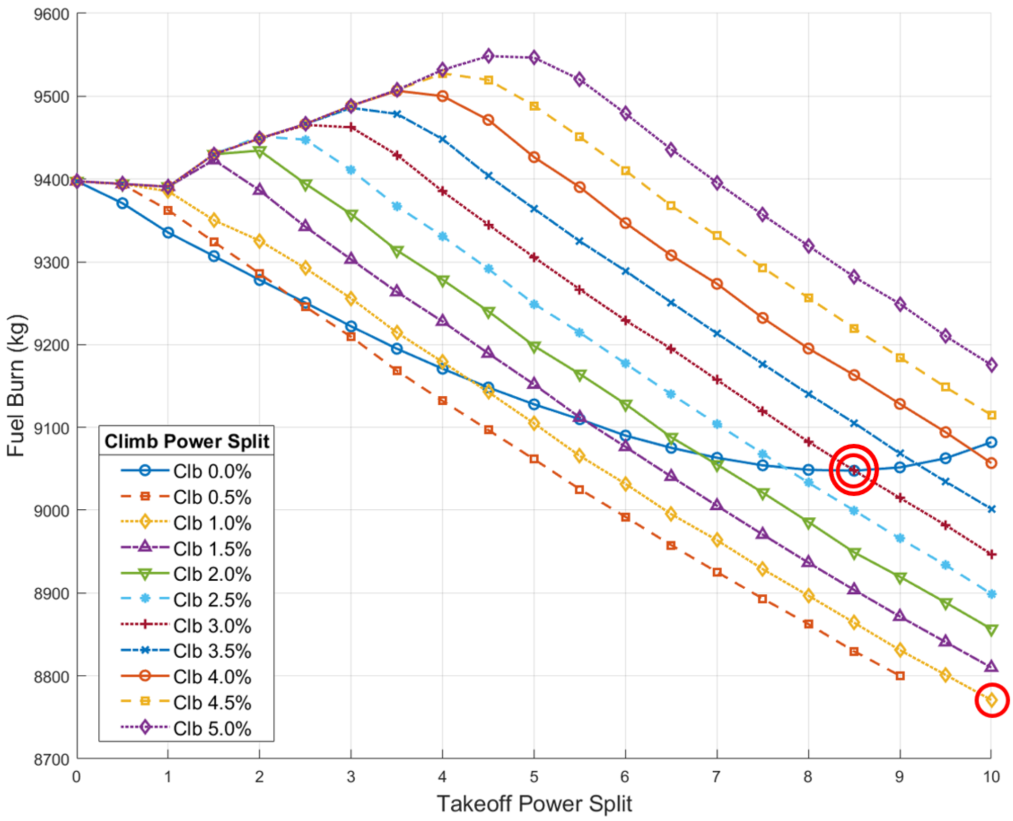


Figure A1. HEA block fuel required: 3,980 km design range and 250 Wh/kg battery.

Figure A3 illustrates the block fuel required for the HEA variants sized for a 3,980 km design range using a 500 Wh/kg battery.

Figure A4 illustrates the block fuel required for the HEA variants sized for a 1,850 km design range using a 500 Wh/kg battery.

Table A3 compares selected HEA models to conventional baseline, designed for 3,980 km and with a 500 Wh/kg battery.

Table A4 compares selected HEA models to conventional baseline, designed for 1,850 km and with a 500 Wh/kg battery.

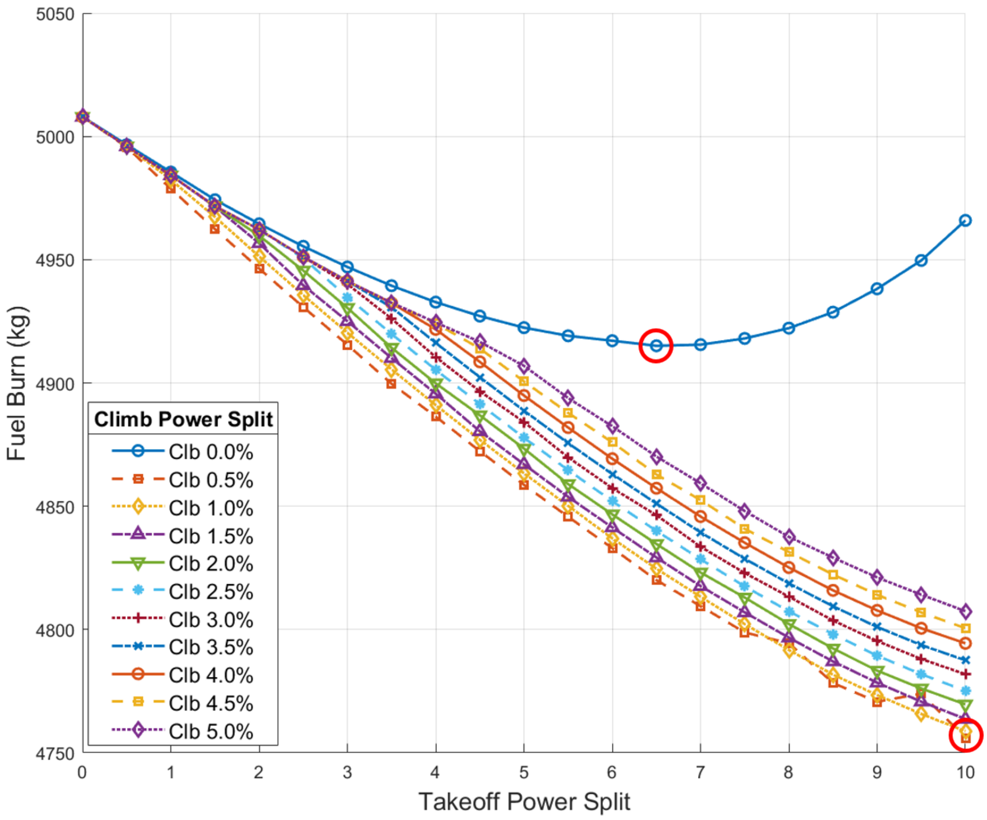
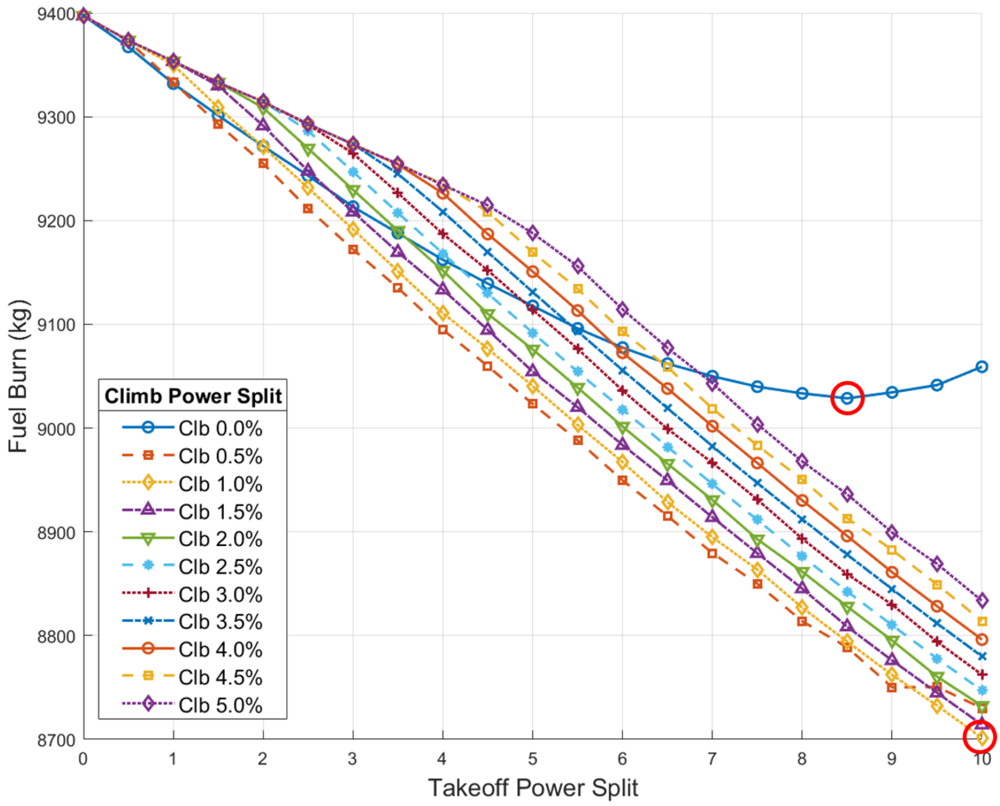


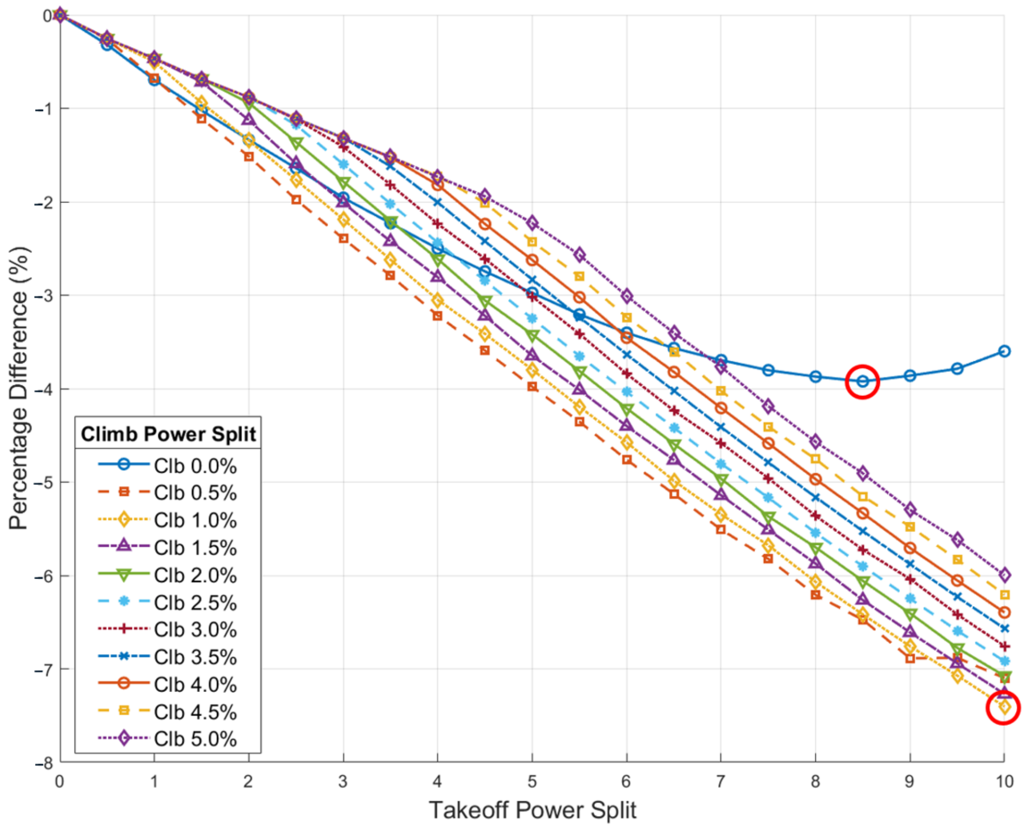
Figure A2. HEA block fuel required: 1,850 km design range and 250 Wh/kg battery.

Table A3. HEA variants compared to the baseline: 3,980 km design range and 500 Wh/kg battery.

	HEA 6	**HEA 7**
Takeoff Power Split [%]	8.5	10
Climb Power Split [%]	0.0	1.0
MTOW [kg]	36,961	36,174
OEW [kg]	20,211	19,654
Block Fuel [kg]	9,028	8,701
Battery Weight [kg]	28	124
Total Engine Weight [kg]	2,552	2,453
Total Thrust [kN]	118.1	115.6
SLS Engine Thrust [kN]	54.0	52.0
Avg. Climb TSFC $\left[\frac{mg}{N\,s}\right]$	14.40	14.62
Avg. Cruise TSFC $\left[\frac{mg}{N\,s}\right]$	19.31	19.38
Wing Area $\left[m^2\right]$	69.31	67.82
Electric Motor Power [kW]	697	803
Electric Motor Weight [kg]	69.7	80.3

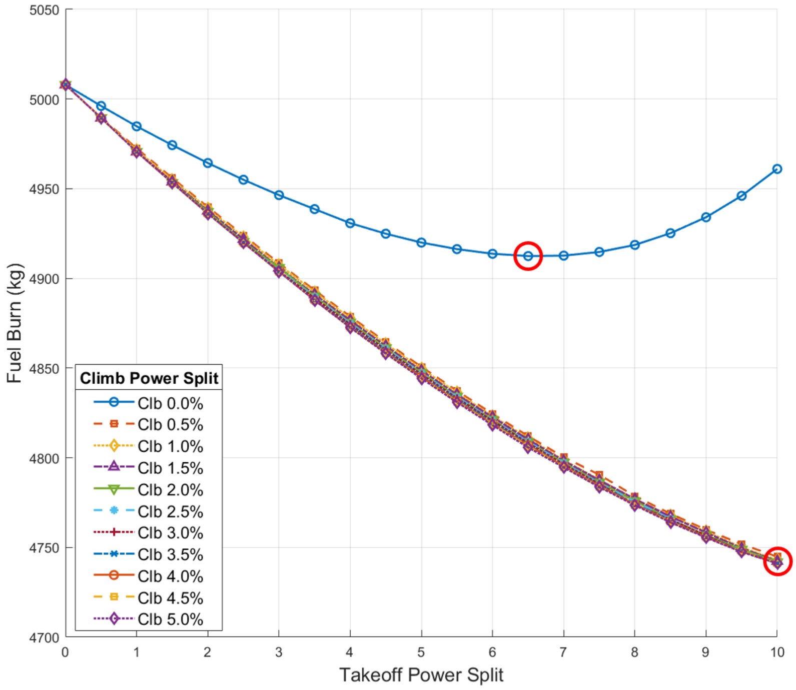


(**a**)

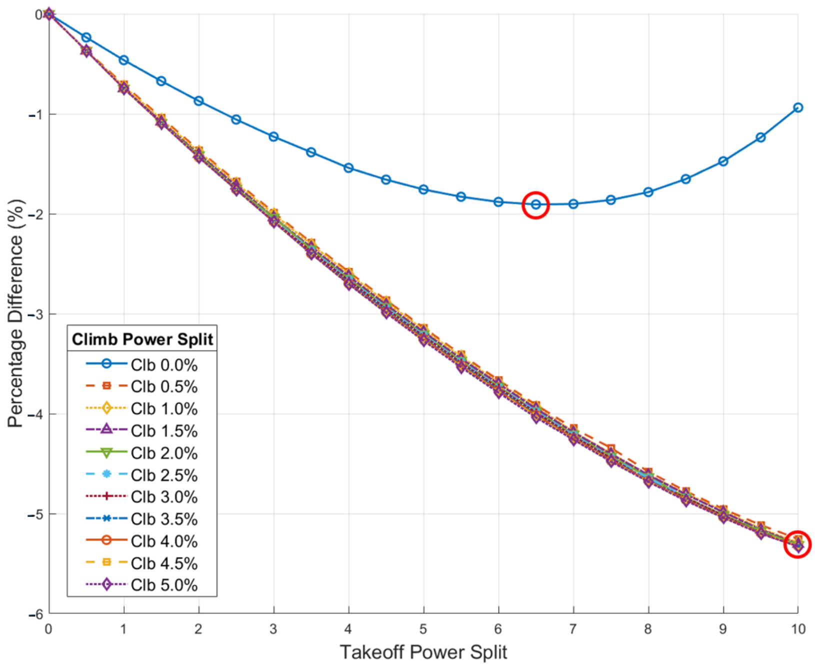


(**b**)

Figure A3. Sized HEA variants: 3,980 km range, 500 Wh/kg battery.



(**a**)



(**b**)

Figure A4. Sized HEA variants: 1,850 km range, 500 Wh/kg battery.

Table A4. HEA variants compared to the baseline: 1,000 nmi design range and 500 Wh/kg battery.

	HEA 8	**HEA 9**
Takeoff Power Split [%]	6.5	10
Climb Power Split [%]	0.0	1.0
MTOW [kg]	26,229	25,902
OEW [kg]	13,606	13,581
Block Fuel [kg]	4,912	4,743
Battery Weight [kg]	16	88
Engine Weight [kg]	1,807	1,708
Total Thrust [kN]	83.8	82.7
SLS Engine Thrust [kN]	39.2	37.2
Avg. Climb TSFC $\left[\frac{mg}{N\,s}\right]$	18.90	18.58
Avg. Cruise TSFC $\left[\frac{mg}{N\,s}\right]$	23.75	23.34
Wing Area $\left[m^2\right]$	49.15	48.50
Electric Motor Power [kW]	378	380
Electric Motor Weight [kg]	37.8	38.0

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