Performance Scaling of Multi-Class Parallel Hybrid-Electric Regional Turboprop Airliner Concepts

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***Abstract*— Parallel hybrid-electric propulsion systems have been researched and are under development for retrofitting regional turboprop airliners to reduce fuel/energy consumption, carbon emissions, and heat losses compared to current gas turbine propulsion systems. Performance benefits and capabilities of such electrified aircraft propulsion concepts are highly sensitive to vehicle, powertrain, and energy storage system sizing, where the current regional turboprop market is composed of airliners of varying capacity. The objective of this study is to examine how performance benefits and design trade-offs scale for hybrid-electric regional turboprop transport across varying seat classes and operational ranges.**

Keywords—aircraft electrification, hybrid-electric powertrains

I. Introduction

NASA's Electrified Powertrain Flight Demonstration (EPFD) project is developing Megawatt (MW) class parallel-hybrid electric propulsion systems for regional turboprop demonstrators with the aim to realize significant reductions in fuel burn, energy usage, and CO_2 emissions [1]. While electrified aircraft propulsion (EAP) systems offer thermal conversion efficiencies of 90-95% and reduced hot section maintenance costs compared to state-of-the-art gas turbine engines, these benefits are offset by the increased system weight due to the relatively low specific energy of state-of-the-art Lithium-ion batteries compared to Jet Fuel A1, resulting in reduced range and payload capabilities for electrified aircraft [2]. However, these operational characteristics align with the regional airliner market where shorter distance routes serving low passenger loads can be replaced by commuter turboprops retrofit with hybrid-electric powertrains. Hybrid electric aircraft may potentially offer lower operational cost in comparison with the turboprop aircraft of today. For the near-term, hybrid electric propulsion systems offer a balanced solution by leveraging the improved thermodynamic and propulsive efficiencies of EAP systems while also keeping the power and range capabilities offered by conventional fuel-burning combustion engines since the weight penalty is less severe than that of fully electrified aircraft concepts [3] that are not currently feasible. The advantages from hybrid-electrification are further capitalized upon when employing a true parallel hybrid (TPH) electric powertrain system like that used in NASA's Hybrid-Electric Turboprop Commercial Freighter Opportunity (HETCOF) concept. The HETCOF TPH system consists of a dual-sided, parallel drive system where the fuel and electrical systems separately power the turbine-driven and motor-driven propulsors, respectively [2,4]. TPH systems allow for improved flexibility in design and operations because the electric propulsion unit (EPU) is maintained separately from the gas turbine engine. The decoupled nature of the hybrid powertrain allows for a varying power split throughout the operational mission profile. Margolis et al. demonstrated how optimized power scheduling can result in greater realized benefits for TPH concepts, particularly for lower ranges [5]. Cai et al. studied the impacts of electrification for a mid-capacity, 50-pax true parallel hybrid concept and showed that, for a 500 NM mission and 20-30% payload reduction, a block fuel savings of 16% could be realized. Pham et al. focused on a higher capacity TPH concept for freighter operations that demonstrated higher payload, range, and fuel savings capabilities based on operating mode [6,7]. Trade-offs between fuel savings were made with payload/range capabilities, addressing the possibility of performance benefits scaling with increased vehicle and electric powertrain sizing. Range capabilities were impacted significantly when off-loading fuel capacity to accommodate the electric energy storage (ESS) systems [6,7]. The HETCOF study led by Jansen et al. demonstrated that for a fixed vehicle concept with varying MW-class powertrain systems, EAP systems with higher specific power and energy densities result in decreased payload weight penalties and increased fuel savings [2].

The key design trade-off dictating the TPH concept design space can be summarized as follows: assuming a fixed gross takeoff weight, as the operating weight increases due to electrification to account for the weight of the EAP system and the electric battery, the available payload and fuel capacity becomes constrained [6,7]. Previous systems-level design explorations have focused on quantifying these performance sensitivities for a specific concept or fixed passenger-class configurations, but the U.S. regional turboprop market encompasses a diverse range of vehicle and engine sizes [6]. Thus, the purpose of this paper is threefold: (1) provide a consistent analysis methodology for parametric sizing and hybridization of multi-class regional turboprop airliners; (2) evaluate how the impacts of hybrid-electrification scale for low-capacity (LCT), mid-capacity (MCT), and high-capacity (HCT) turboprop concepts representative of existing vehicles in the U.S. regional airliner fleet; and (3) assess how hybridization impacts operational route accessibility based on 19 to 76 PAX regional turboprop operations sourced from the 2023 Federal Aviation Administration (FAA) T-100 database provided courtesy of the Bureau of Transportation (BTS).

II. METHODOLOGY

To evaluate system-wide and operational performance impacts from hybrid-electric turboprop fleet introduction across varying size classes, it is imperative to incorporate operational metrics— such as annual domestic U.S. operations of regional turboprop airliners and passenger loads included in the BTS T-100 database— into the vehicle synthesis process by utilizing these parameters to define the design/mission requirements. This necessitated the development of a compact, structured methodology to enable parametric scaling studies that capture both system-level and system-wide performance impacts within targeted market segments. The analysis methodology is built around four key stages:

1. **P**erformance Requirements: To initialize the analysis, operational fleet databases are indexed for the target market to gather departure data, identifying characteristic seat classes, range, and passenger loads. This information is used to define the design and mission requirements of the baseline representative fleet. Baseline configurations representative of low-capacity, mid-capacity, and high-capacity vehicles are sized to meet the target designs where the gross takeoff weight, fuel required for the primary and reserve mission, and engine sizing are constrained by the target design and payload. Cruise is performed at constant altitude and speed and based on operating at minimized brake-specific energy fuel consumption (BSFC) for best endurance speed, as performed in Ref. [8].
2. **H**ybridization of Baseline Concepts: Once baseline configurations are established, hybrid-electrification of the reference vehicles is performed, where the gas turbine and electric drive systems are sized to meet the design range requirement (this process is detailed in Ref. [6,7]) assuming EAP system specifications comparable to state-of-the-art power electronics and energy system technologies [9]. The TPH architecture utilized in this study is defined in Ref. [2]. Unlike conventional thermal combustion engines, electric motors can be produced at different power ratings while maintaining similar efficiencies [3]. An example motor performance map is shown in Figure 1.

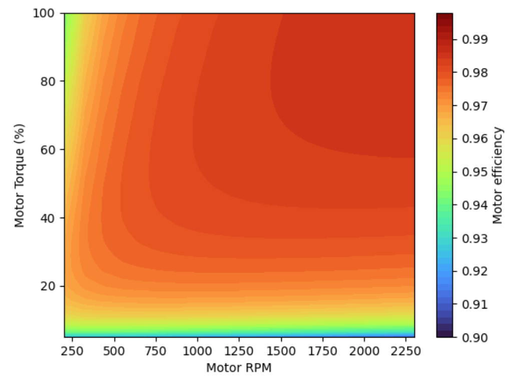

Figure 1. Electric Motor Performance Model

The mission energy requirements (e.g., total fuel and battery energy required) are based on meeting both the primary and reserve mission requirements for the design range. Two main optimization objectives dictate the TPH power requirements: minimizing the energy rate for each flight phase and minimizing the battery weight required, a capability demonstrated in Margolis et al. for the TPH C-130H concept [5]. The electrified system specifications used in the current study are listed in Table 1.

TABLE I: ELECTRIFIED SYSTEM SPECIFICATIONS

Parameter	Value
Inverter Specific Power, hp/lb	12.6
Inverter Efficiency	98.5%
Minimum State of Charge	15%
Battery Efficiency	90.3%
Motor Specific Power, hp/lb	10.34
Thermal Management System Specific Power, lb/hp	0.125

3. **A**irspace Accessibility: Hybridization results in weight penalties that reduce effective payload capacity and range performance. This assessment determines the percentage of feasible operational routes retained for each configuration. Vehicle and powertrain scaling may impact mission capture rates for the hybridized concepts. This step incorporates design/mission energy constraints to reflect how fleet-wide accessibility is impacted by vehicle performance.
4. **M**ission Analysis: Block fuel and energy use were evaluated across operational mission ranges (150 to 650 NM for regional airliners) for both baseline and hybridized LCT, MCT, and HCT concepts. To assess the trade-offs inherent in hybrid-electric designs, fuel burn per passenger mile was used as a normalized metric to account for the reduction in payload capacity due to battery weight. As mission range increases,

both fuel consumption and battery capacity requirements grow to support the combined electric and fuel power systems, further constraining payload capacity. By comparing this metric across mission ranges, potential breakeven points can be identified where the payload penalty is offset by sustained fuel and energy savings. While the baseline configurations fly these shorter-range missions at lower gross takeoff weights, hybridized concepts in previous studies have shown a tendency to utilize the full available weight capacity, trading payload with battery capacity required to complete specified mission [9].

These key analysis stages form the foundation of the Performance-Hybridization-Airspace-Mission (PHAM) methodology developed for this study. PHAM provides a comprehensive process for conducting first-order evaluations of performance sensitivities and fleet-wide impacts of hybrid-electrification across different aircraft size classes, helping to assess the scalability of both vehicle-level and system-wide benefits. By integrating real-world operational data from the BTS T-100 Database, along with parametric vehicle sizing and mission analysis tools (e.g., Generalized Aircraft Synthesis Program (GASP) and Gascon, as referenced in [2,6,7]), PHAM systematically incorporates real-world operational considerations into the systems analysis process to provide data-driven insights on the scalability of hybrid-electric regional turboprop concepts.

III. ANALYSIS OVERVIEW

A. *Baseline Vehicle and Reference Mission Specifications*

To establish representative turboprop aircraft concepts, publicly available data from the U.S. Department of Transportation (DoT) BTS T-100 database from 2023 was analyzed to identify characteristic route lengths and passenger capacities serviced by the regional turboprop market. Based on the operational data collected, the vehicles were sized to accommodate maximum payloads of 34, 50, and 80 PAX. These are the baseline LCT, MCT, and HCT configurations respectively.

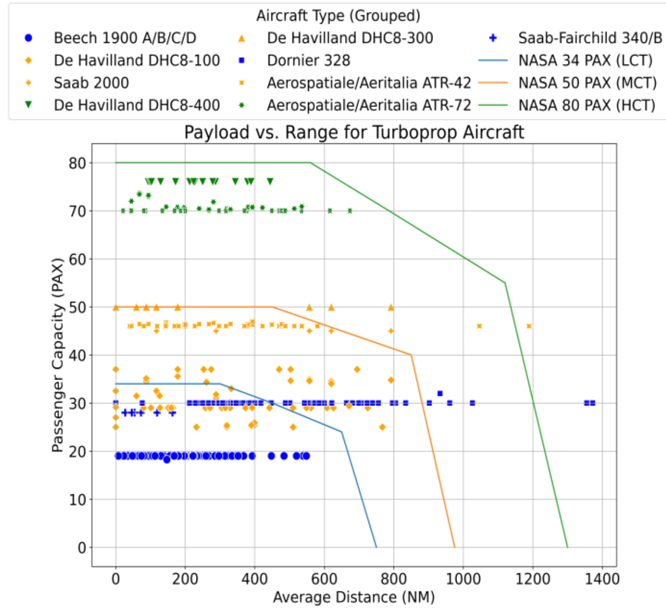

Figure 2. Payload-Range Analysis of Regional Turboprop Aircraft (2023 BTS T-100 Database)

The three baseline concepts were sized to meet the payload and range requirements presented in Figure 2. These concepts are representative of three distinct seat classes of 19-34 PAX, 35-50 PAX, and 60-80 PAX with takeoff wing loading and power loading sized to meet FAR Part 25 requirements for the stall/approach speed, one engine inoperative (OEI) takeoff/climb rate, maximum power, and 2nd segment minimum climb gradient. Total power was assumed to be distributed across four propulsors to facilitate future TPH architecture integration. The baseline turboprop engines used for vehicle sizing of the baseline LCT, MCT, and HCT concepts were modeled using the Numerical Propulsion System Simulation (NPSS) tool where a genericized turboprop engine was scaled to meet the power requirements. A summary of the three baseline configurations is presented in Table II.

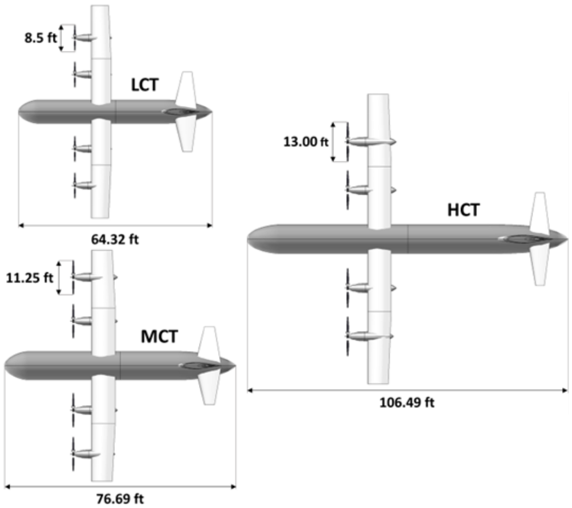

Figure 3. Baseline LCT, MCT, and HCT configurations

TABLE II: SUMMARY OF BASELINE CONCEPTS

Parameter	Low-Capacity Turboprop (LCT)	Mid-Capacity Turboprop (MCT)	High-Capacity Turboprop (HCT)
Maximum Gross Takeoff Weight, lb	29,000	42,000	63,380
Operating Empty Weight, lb	18,330	25,689	37,577
Passenger Capacity (200 lb/ each)	30-34	45-50	76-80
Takeoff Power-to-Weight Ratio, hp/lb	0.121	0.107	0.290
Takeoff Wing Loading, psf	64.44	72.04	86.77
Percent of Total Departures Captured	35.99%	77.06%	99.48%
Percent of Total Trip Miles Captured	20.14%	66.79%	99.65%
Percent of "Class" Departures Captured	94.3%	92.73%	99.93%
Percent of "Class" Trip Miles Captured	83.73%	85.43%	99.87%

Figure 3 presents the key dimensions and geometry of the baseline LCT, MCT, and HCT concepts used in OpenVSP. All the configurations were evaluated for their coverage of routes from the 2023 BTS T-100 dataset both on an overall basis and on a "class" basis where the departures and trip miles were separated into bands based on the three seat classes (19-34 PAX, 35-50 PAX, 60-80 PAX). The "class" capture metric provides insight into how well a given configuration would perform if targeted to replace specific aircraft, however, in practice, network strategies and business models can influence aircraft deployment across routes. To account for this, both the overall ("total") and "class" metrics were calculated, with the "class" metric being most useful for evaluating the concept's effectiveness as a drop-in replacement for specific contemporary aircraft. The HCT was able to capture 99.48% of the 31,243 total regional turboprop departures in 2023 and all configurations captured over 80% of their respective classes.

B. Hybrid-Electric Configuration Development

The hybrid-electric concepts were developed by analyzing the energy and weight requirements across the operational range envelope for each concept and assuming a TPH powertrain architecture where the in-board engines are the conventional turboprop engines sized for the baseline concepts and the out-board propulsors are replaced with EAP systems with total maximum sea-level static (SLS) power ratings of 1.3 MW, 1.7 MW, and 3.5 MW scaled based on the electric motor performance model in Figure 1 and EAP component values in Table 1. To determine the mission capabilities of the varying hybrid LCT, MCT, and HCT concepts, the energy and weight requirements were analyzed across the operational range envelope. The weight allocation for the battery and payload is constrained by the operating empty weight (increased compared to the baseline as it includes the installed EAP and ESS system weights), capped at the maximum allowable gross takeoff weight. To leverage the design flexibility and realized benefits of the TPH configuration, Gascon was used to formulate the optimization problem to determine the balance between turbine and electric power throughout the mission. The goal was to minimize energy consumption and minimize weight accumulation by relaxing battery capacity requirements due to optimal power-split balance between the turbine and electric powered systems using the methodology developed by Margolis et al. [5].

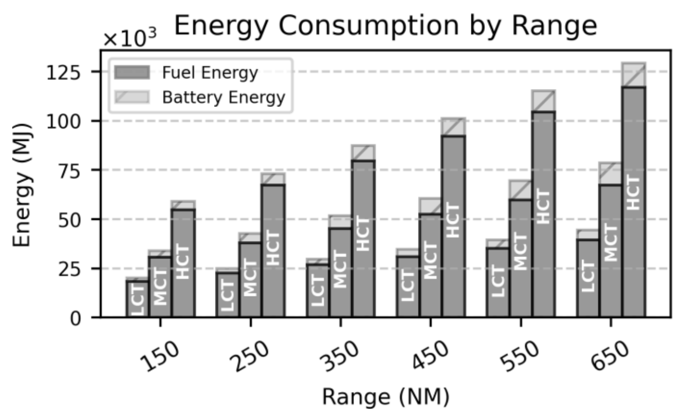

Figure 4. Hybrid-Electric Mission Energy Requirements

The results of the power-split optimization and energy analysis are presented in Figure 4, showing consistent scaling of the required loaded fuel and battery capacity required to meet the mission requirements and account for the minimum state-of-charge constraint. Through iterative analysis, a minimum required pack-level specific energy was identified to be 650 Wh/kg which was held constant for the resulting analysis and aligned with 2040 timeframe technology projections anticipated by the NASA Glenn Research Center study from 2022 on battery technology levels for enabling EAP concepts. [10].

IV. RESULTS

The performance scaling across the TPH variants of the LCT, MCT, HCT representative concepts were evaluated in terms of fuel savings relative to the conventional baseline vehicles (see Table II) and the payload retention across 150-650 NM ranges (see Figs. 5-7). The crossover points mark the range at which each hybrid-electric aircraft achieves a balance between payload efficiency and energy savings relative to its baseline counterpart.

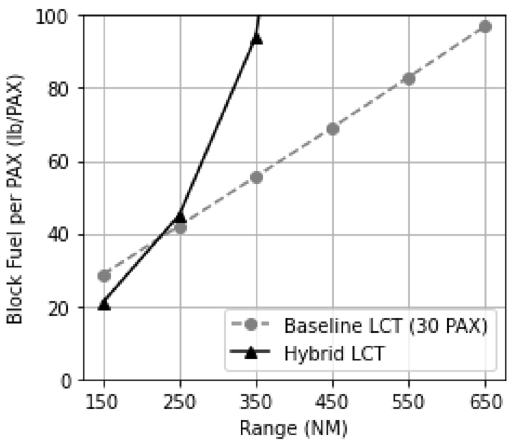

Figure 5. LCT Block Fuel Burn Per Passenger Mile

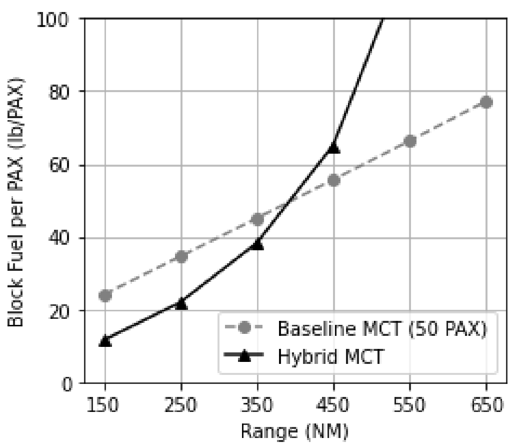

Figure 6. MCT Block Fuel Burn Per Passenger Mile

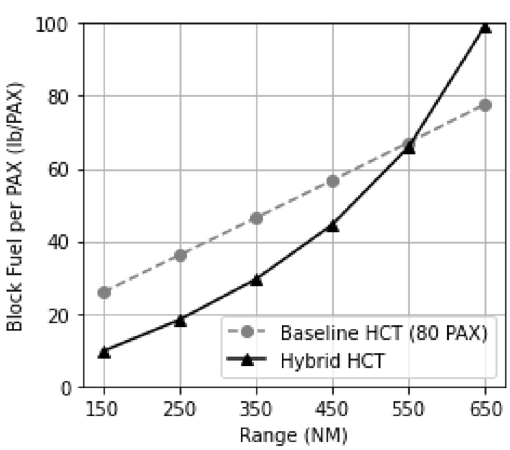

Figure 7. HCT Block Fuel Burn Per Passenger Mile

TABLE III: CROSSOVER ANALYSIS

Crossover Point	Hybrid LCT	Hybrid MCT	Hybrid HCT
Range, NM	250	400	550
Payload Efficiency (Relative to Baseline), %	53%	60%	79%
Block Fuel Savings, %	42%	40%	38%
Block Energy Savings, %	35%	31.4%	30.2%

The crossover point analysis presented in Figs. 5 to 7 and summarized in Table III highlights key trends in hybrid-electric performance across different aircraft classes. The hybrid LCT achieves its crossover point at 250 NM, while the MCT and HCT extend their optimal ranges to 400 NM and 450 NM, respectively. This indicates that larger aircraft maintain hybridization benefits over longer distances, likely due to their greater capacity to accommodate batteries with reduced payload weight penalties. At these crossover points, payload efficiency is highest for the HCT at 79%, compared to 60% for the MCT and 53% for the LCT, showing that larger aircraft better manage payload penalties. Additionally, the fuel saving benefit per passenger of hybridization increases with aircraft scale. The impacts of route accessibility were also assessed for the hybridized LCT, MCT, and HCT concepts.

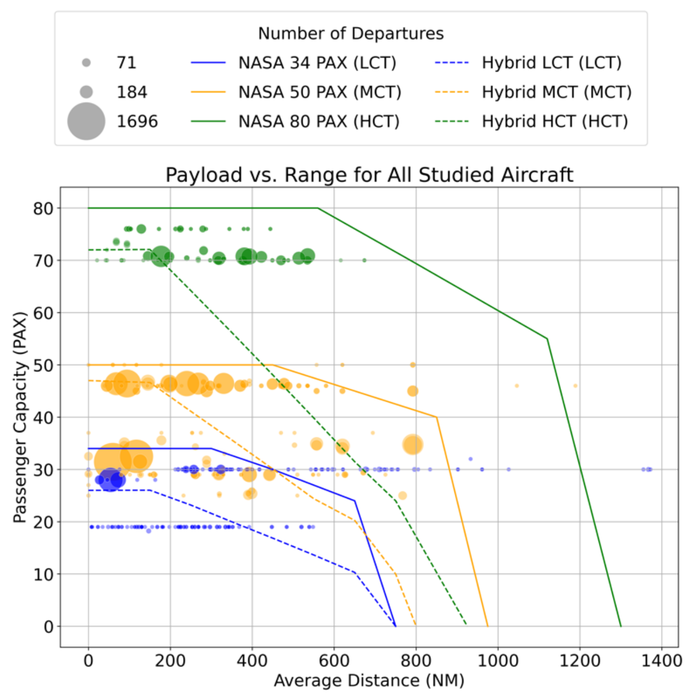

Figure 8. Hybridization Impacts on Route Accessibility

TABLE IV. SCALABILITY OF HYBRIDIZATION IMPACTS ON FLEET-WIDE ROUTE CAPTURE

Accessibility Index	**Hybrid LCT**	**Hybrid MCT**	**Hybrid HCT**
Percent of Total Departures Captured	0.59%	49.71%	71.95%
Percent of Total Trip Miles Captured	0.5%	25.79%	50.38%
Percent of “Class” Departures Captured	1.55%	30.54%	3.74%
Percent of “Class” Trip Miles Captured	2.08%	9.26%	1.58%

Figure 8 depicts the fleet-wide departure capture rates impacted by hybridization while Table IV summarizes the results of the fleet-wide route capture analysis. In general, electrification of a gas turbine concept will yield a significant reduction in mission capability due to the weight and energy density penalty from the battery pack. The Hybrid LCT is impacted the most, with a precipitous 98% loss in route accessibility relative to the baseline LCT from 11,244 departures to 185 departures (0.59% of the total departures). The MCT and HCT fare better with 35% and 28% reductions in total route coverage from their respective baseline concepts and in return can achieve 40% and 38% improvements in block fuel burn. Their coverage of 49.71% and 71.95% of all database missions, respectively, indicate that a consolidation toward higher-capacity aircraft would benefit overall mission capability while maintaining useful fuel savings. Looking to the “class” designations, the MCT and HCT have capture rates of 30.54% and 3.74% for missions in their respective classes. The MCT maintains more class coverage because of the large proportion of total departures covered by the 35 PAX DHC-8-100. The HCT exhibits the most total coverage by both departures and flight miles, but as is seen in Figure 8, it will still be forced to trade 28.05% of missions consisting of 49.6% of total flown miles for its large 38% in block fuel savings along with much of the 70+ PAX missions. Overall, route accessibility for turboprop aircraft electrification scales readily with aircraft size, to the point of requiring larger aircraft to maintain coverage for a majority of flights.

V. CONCLUSIONS

The PHAM methodology developed in this study offers a comprehensive approach to evaluating how performance sensitivities and fleet-wide impacts scale across different aircraft size classes. This integrated, flexible approach utilizes real-world U.S. operational route data analysis to define the sizing constraints of physics-based, parametric vehicle/powertrain models while leveraging analysis and optimization tools such as Gascon to define optimized trajectories that trade-off passenger load with mission energy requirements. The crossover analysis indicates that larger hybrid-electric aircraft reach the breakeven point for fuel savings per passenger mile at higher ranges compared to smaller concepts. This suggests that larger configurations have more available weight to offset the penalties associated with trading payload capacity for the weight of the EAP and ESS systems. While the fleet-wide analysis demonstrates that hybridization may limit the number of accessible routes based on reduced payload and range capabilities, the 35-50% block fuel and 25-45% block energy savings achieved by hybrid-accessible routes offset the broader accessibility impacts. The flexibility of power-split optimization in true parallel-hybrid retrofits enhances efficiency and supports the viability of hybrid-electric regional airliners, with future advancements in EAP technologies further improving performance scalability and feasibility across larger aircraft sizes and longer mission ranges. Future studies aim to leverage the National Airspace (NAS) Simulation capabilities proposed by Fong et al. [11] to further explore system-wide impacts based on airspace infrastructure, demand distribution, and operating and maintenance cost breakeven points.

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