Parametric Modeling and Mission Optimization for the Hybrid Electric Turboprop Commercial Freighter (HETCOF) Concept

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The Hybrid Electric Turboprop Commercial Freighter (HETCOF) Concept is a large, four-engine turboprop freighter retrofitted with a multi-Megawatt parallel-hybrid electric propulsion system that aims to reduce emissions, noise, and fuel consumption for narrowbody cargo operations. This paper provides a detailed overview of the parametric modeling of HETCOF configurations across varying technology levels and optimization of the power-split profiles and mission trajectories for both the long range 2,400 NM economic mission and 750 NM hybrid-electric design mission. Results demonstrate that the HETCOF concept can achieve 11-13% fuel savings for the maximum range 2,400 NM mission with up to 38% fuel savings for the hybrid-electric 750 NM mission assuming all-electric cruise. Trade-offs in payload capacity are driven by weight of electric power and energy storage systems which can be minimized through coupled motor-propeller optimization and refined engine controls throughout the multi-phase design mission. Preliminary results demonstrate that HETCOF can realize meaningful operational benefits that scale with improved technology levels, where future work will aim to quantify the fleet-level impacts.

I. Introduction

Improving the environmental impact and sustainability of commercial flight operations has become an urgent priority underscored by U.S. Climate Action Plan set forth by the Federal Aviation Administration (FAA) in 2021 that establishes a goal of net-zero greenhouse gas emissions (GHG) from the U.S. aviation sector by 2050 [1]. To achieve significant reductions in fuel consumption, noise, and carbon emissions, novel powertrain and energy storage systems have been explored across the transportation sector, where electric aircraft propulsion (EAP) systems have gained traction over the past decade [2]. Efforts such as NASA's Electrified Powertrain Flight Demonstration (EPFD) project are bridging the gap between EAP technology development to demonstration, collaborating with U.S. industry partners such as General Electric and magniX to develop Megawatt (MW) class hybrid-electric propulsion systems that operate in parallel with gas turbine engines [2]. While past research and development efforts have been focused on electrification of 19-seat to mid-sized EAP concepts representing the regional airliner market, recent studies by Wishart et al. have extended the electrified market space into larger narrowbody freighters [3]. Based on NASA-sponsored studies on power and electric energy systems for the subsonic single aft engine (SUSAN) regional narrowbody concept [4] and design space exploration of a hybrid-electric powertrain retrofitted Lockheed C-130H concept [5], the Hybrid Electric Turboprop Commercial Freighter (HETCOF) concept was introduced as a four-engine turboprop with a parallel electric and gas turbine drive system.

The initial HETCOF study by Jansen et al. outlined intended mission profiles, EAP system sizing specifications based on projected performance and Technology Readiness Level (TRL), and a vehicle benefit assessment for the 750 NM range which corresponds to 73% market coverage for narrowbody cargo freighter operations [4]. However, the targeted maximum range could not be achieved for hybrid-electric cruise and only the TRL 1-2 configuration supported a full-electric 750 NM mission, in part due to the engine control constraints that allowed either the gas turbine (turbine at normal rated power) or electric machine (motor at normal rated power) to serve as the primary power source where the secondary system supplied the remaining thrust [5]. Additionally, the desired mission trajectory in terms of altitude and speed for each flight phase was fixed based on profiles defined by baseline C-130H operations rather than optimized based on management of the power and energy system. Recent advancements in numerical optimization and control such as coupled motor-propeller performance and power-split profiling presented by Margolis et al. bridge this gap by enabling parametric optimization of the HETCOF vehicle design and mission trajectory to meet the target range requirements proposed in the initial HETCOF paper [6]. The objective of this paper is to provide further detail of the parametrically sized HETCOF configurations using the EAP systems sized in Ref. [4], utilize the optimization capabilities provided by the NASA-developed multidisciplinary analysis tool Gascon to define the trajectory and power-split profile to meet the 2,400 NM maximum range and 750 NM economic range mission requirements, and provide a comprehensive design space exploration to determine the payload/range sensitivities and capabilities of the HETCOF concept. These results will be used to inform fleet-wide impacts based on flight time, fuel savings, and maintenance/operating cost savings that can be realized with replacement of conventional narrowbody freighters with HETCOF concepts of varying TRL.

II. Concept Development and Overview

The Hybrid Electric Turboprop Commercial Freighter (HETCOF) concept is a four-engine hybrid-electric freighter developed based on EAP systems under development by NASA, ARPA-E, U.S. industry, and academic research where Ref. [4] provides the key performance parameters of the TRL 5+, TRL 3-4, and TRL 1-2 power, thermal, and electric energy systems. Table 1 provides the background behind the KPP definitions used in Ref. [4].

Table 1. Key Performance Parameter (KPP) Definition

KPP Level	KPP Level Description	Sources for KPP Values
TRL 5+	State of the art	• Commercial product datasheets • Commercial product test data • Other published test data or analysis of TRL 5+ technologies
TRL 3-4	Current research	• Testing and analysis from NASA internal technology development • Testing and analysis from NASA-funded technology development • Other published test data or analysis of TRL 3-4 technologies
TRL 1-2	Future projections	• Projections based on higher TRL level data and analysis • Published analysis of TRL 1-2 technologies

First, a baseline vehicle model was established, it is a four-engine turboprop aircraft based on the Lockheed C-130H aircraft with a gross takeoff weight of 155,000 lb where the engines were upgraded from the original Allison T56-A-15 turboprop engines to the Allison AE2100-D3 powerplant. Upgrading the baseline turboprop engine model allows for higher efficiency operations that extend baseline range capabilities by approximately 200 to 400 NM depending on cruise altitude.

Table 2. Baseline HETCOF Parametric Model

Parameter	Value
Length	97.75 ft
Height	14.07 ft
Wingspan	132.6 ft
Horizontal Tail Span	52.67 ft
Power Plant	Rolls-Royce AE2100-D3 (x4) @ 3,458 kW

Max. Takeoff Weight	155,000 lb
Operating Empty Weight	73,621 lb
Max. Payload Weight	40,670 lb
Range (Max. Payload)	2,354 NM
Max. Zero Fuel Weight	114,300 lb
Max. Operating Speed	278 knots
Max. Fuel Weight	41,379 lb
Takeoff Field Length	5,745 ft

Table 2 summarizes the baseline powertrain and vehicle characteristics of the four-engine baseline conventional concept that serves as the starting point for the HETCOF design where the impacts of electrification will be quantified relative to the established baseline model. The HETCOF power, thermal, and electric energy systems are defined and provided in detail within Ref. [4], where the outboard engines are replaced by the electric engine and impose added system weight, energy constraints based on available battery capacity that displaces fuel-based energy sources, and introduce the electric motor-generator as an additional power source that operates parallel to the baseline gas turbine propulsion system.

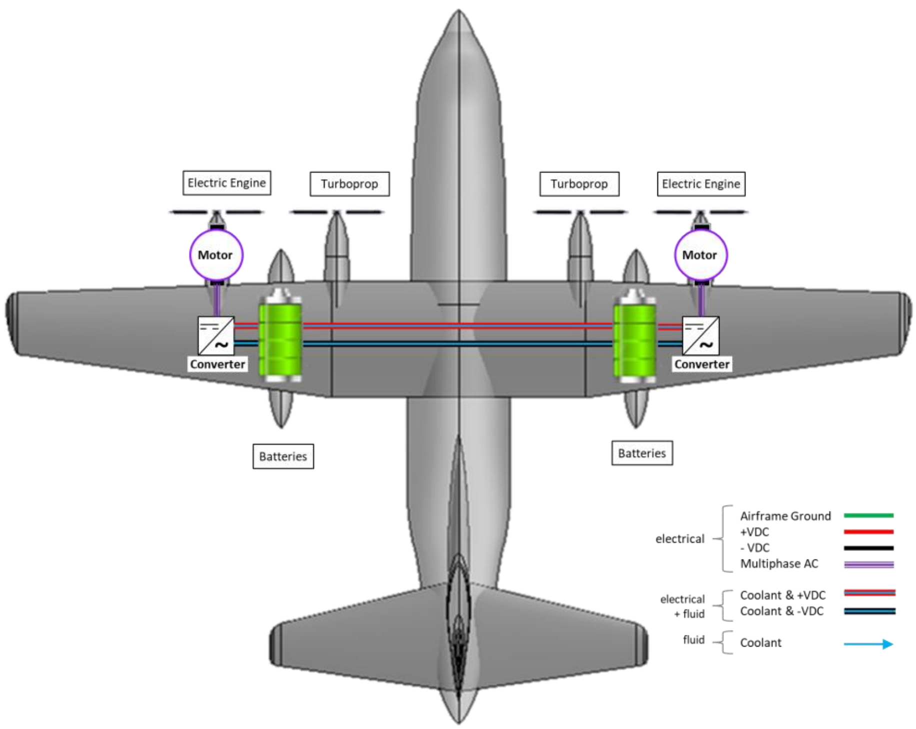


Figure 1. HETCOF System Diagram

Table 3. Summary of EAP System Weight, Power, and Energy Capacity from Ref. [4]

Parameters from Ref. [4]	**TRL 5+**	**TRL 3-4**	**TRL 1-2**
Total EAP System Weight, lb	48,508	21,557	22,651
Battery Capacity, kWh	5,080	6,550	13,468
Max. Motor Power, shp	2,212	2,816	5,990

Figure 1 and Table 3 provide a summary of the HETCOF EAP system diagram, power, weight, and battery capacity that will be parametrically infused into the baseline vehicle model. As the operating empty weight increases due to the added battery weight and EAP system integration, the available payload weight available is penalized as the vehicle remains constrained to the maximum gross takeoff weight. These impacts are explored with respect to optimization of the vehicle trajectory and power scheduling throughout the mission for the 2,400 NM and 750 NM cases.

III. Methodology

Gascon is a Python-based adaptation of the legacy FORTRAN vehicle synthesis and analysis tool the General Aviation Synthesis Program (GASP) software that has been updated to provide coupled propeller-motor performance and component-based parametrization of vehicle concepts that allow for flexible modeling of configurations featuring novel power and energy systems such as EAP systems that utilize both Jet A fuel and Li-ion battery sources [6]. The improved subassembly design capabilities allow for further control of torque-speed operating lines to determine optimal propeller and motor speeds to result in improved propulsive and thermal efficiencies, which in turn improves range capabilities and minimizes energy consumption. Optimization of power-split to satisfy the thrust requirements at cruise while minimizing fuel burn subject to a target range is one of the key capabilities leveraged within Gascon, where the fuel available is sized to meet the fuel required for the long-range 2,400 NM mission.

minimize	fuel burn
with respect to	thrust split at start of cruise thrust split at end of cruise
subject to	fuel loaded weight + battery weight = available weight fuel burn ≤ fuel available battery energy used ≤ battery energy available range flown = target range

Additionally, the cruise altitude and speed where thrust required is minimized was assessed to determine where the thrust requirement could be satisfied by the two inboard gas turbine systems without requiring additional power from the electric powertrain for the long range cruise mission.

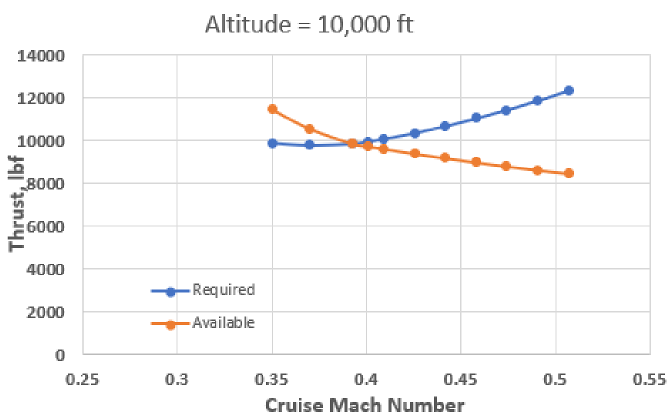
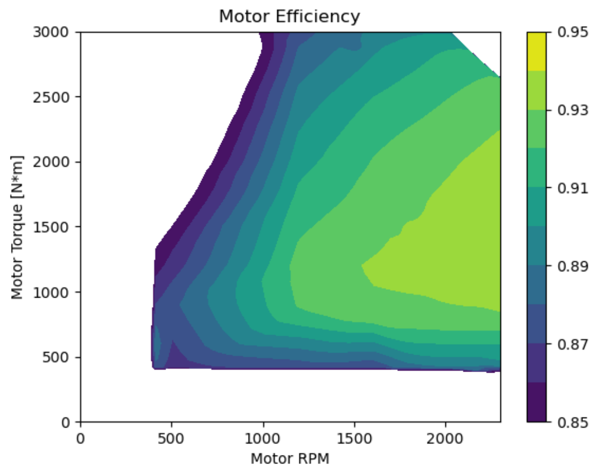


Figure 2. Cruise Power Required vs. Available for Turbine-Only Cruise

Figure 2 provides the Mach versus thrust required crossover points at 10,000 feet altitude to determine the maximum cruise speed for long range cruise on the two turbine engine systems only. Within Gascon, the specifications for each HETCOF configuration were defined in the vehicle module with the objective of determining the fuel weight required to meet the 2,400 NM range. Using the specifications in Table 2, the resulting payload penalty and loaded fuel weight were determined.

Parameters for HETCOF Configuration	TRL 5+	TRL 3-4	TRL 1-2
Operating Empty Weight, lb	117,059	89,327	90,446
Payload Capacity, lb	1,900	29,700	28,700
Range, NM	2,400	2,403	2,402

For the 750 NM, the significant constraint was the battery capacity and weights provided in Ref. [4] where minimizing electric energy consumption with respect to torque and speed of the electric motor while meeting the required thrust was the primary design problem. Figure 3 provides the motor performance.



minimize	electric energy consumption
with respect to	torque rpm
subject to	thrust = thrust required

Figure 3. Motor-Propeller Optimization for Hybrid-Electric Cruise Operation

IV. Results

To meet the 2,400 NM maximum standard range target that was not achieved by the previous HETCOF sizing study, the loaded fuel weight was determined and the optimal flight profile was conducted at a reduced altitude and speed to minimize fuel burn and thrust required.

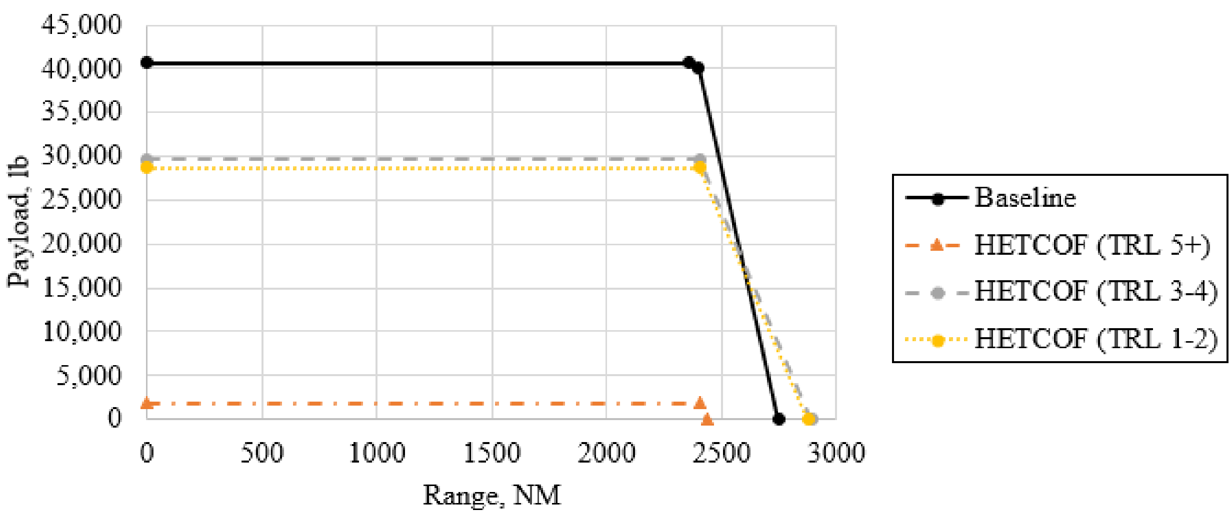


Figure 4. Payload vs. Range for HETCOF

Figure 4 summarizes the payload vs. range of the 2,400 NM capable HETCOF configurations. The performance and fuel savings relative to the baseline configuration were determined where increased motor power resulted in improved takeoff and rate of climb performance. Cruise speed and altitude were specified as Mach 0.375 and 10,000 feet based on the thrust matching diagram in Figure 2.

Table 4. 2,400 NM Economic Mission Results

Parameter	Baseline	TRL 5+ HETCOF	TRL 3-4 HETCOF	TRL 1-2 HETCOF
Payload, lb	40,000	1,900	29,700	28,700
Block Fuel, lb	38,091	33,754	33,679	33,598
Reserve Fuel, lb	3,225	2,307	2,293	2,255
Total Fuel Loaded, lb	41,379	36,041	35,973	35,854
Block Electric Energy, kWh	N/A	777	836	1,062
Reserve Electric Energy, kWh	N/A	338	386	577
Total Electric Energy, kWh	N/A	1,115	1,222	1,639
Takeoff Field Length, ft	5,740	7,248	6,636	5,389
Max. Rate of Climb, fpm	1,397	851	1,040	1,723

Table 4 presents the fuel and energy required for the 2,400 NM mission where the reduction in payload capacity occurs due to the increased weight allocated toward the EAP power, thermal, and energy storage systems for the HETCOF configurations in Ref. [4] and the required fuel load to achieve the 2,400 NM range mission. For these preliminary results, the battery weight was fixed to match the values reported from the initial HETCOF study, however it can be observed that the battery capacity required is sufficiently lower than the maximum capacity. As the 2,400 NM long range cruise is performed using only the two turboprop engines, the primary energy source for this mission is fuel-based rather than electric. The takeoff field length and rate of climb improve with increased maximum electric powertrain rated power at takeoff.

Table 5. 2,400 NM Economic Mission Fuel Savings

Performance	TRL 5+ HETCOF	TRL 3-4 HETCOF	TRL 1-2 HETCOF
Block Fuel Savings	11.4%	11.6%	11.8%
Total Fuel Savings	12.9%	13.1%	13.4%

The total loaded fuel is what constrains the payload capacity most significantly, where the fixed battery weight also impedes on payload weight availability. The final manuscript will provide updated results that remove the fixed battery weight constraint, where the 750 NM hybrid and all-electric mission is constrained by the available battery capacity more so than the fuel weight. The total fuel loaded and payload remained the same for the 750 NM mission where 40% fuel savings is anticipated as the breakeven point for the all-electric cruise achieved by the TRL 1-2 HETCOF configuration. The power-split was optimized through cruise to determine where the energy and fuel available met the mission requirements. The detailed results will be provided in the final manuscript.

Table 6. 750 NM Design Mission Performance

Parameter	Baseline	TRL 5+ HETCOF	TRL 3-4 HETCOF	TRL 1-2 HETCOF
Block Fuel, lb	12,034	9,173	7,937	7,438
Reserve Fuel, lb	3,284	2,361	2,357	2,484
Block Energy, kWh	N/A	4,203	5,435	11,594
Reserve Energy, kWh	N/A	278.7	332.8	136.6
Thrust-Split (Start of Cruise)	100% Turbine 0% Electric	85% Turbine 15% Electric	72% Turbine 28% Electric	~100% Electric Turbine @ Idle

Table 6 presents the results of the hybrid-electric and fully electric 750 NM design missions where increased technology level allowed for higher degree of electrification throughout the mission. Cruise was performed at 17,000 feet altitude at 250 KTAS; other than a 12% minimum state of charge, the full battery capacity was utilized. The final manuscript will include optimization of the propeller design and speeds to further maximize efficiency from the available battery energy provided along with multi-point design optimization based on meeting both the economic and design mission requirements for turbine only and hybrid-electric cruise. Due to the risk of operating outside the relight envelope of the turboprop engine which is required for descent based on the Concept of Operations defined in Ref. [5], the turbine engines are set to idle for the mission flown by the TRL 1-2 HETCOF configuration.

Table 7. 750 NM Design Mission Fuel Savings

Performance	TRL 5+ HETCOF	TRL 3-4 HETCOF	TRL 1-2 HETCOF
Block Fuel Savings	23.8%	34.0%	38.2%
Total Fuel Savings	24.7%	32.8%	35.2%

Table 7 details the fuel savings for the 750 NM design mission where the mission fuel savings of 38.2% is within the 30 to 50% breakeven point for the market study in Ref. [3] for the full-electric mission, where updated results from optimization of the propeller design and power-split will increase the realized savings in the final study. The preliminary results provide the performance realized by the parameterized vehicle and EAP system sizes presented in the initial HETCOF study, where further improvements in the vehicle design, trajectory, and power scheduling throughout the mission will be presented in the updated results.

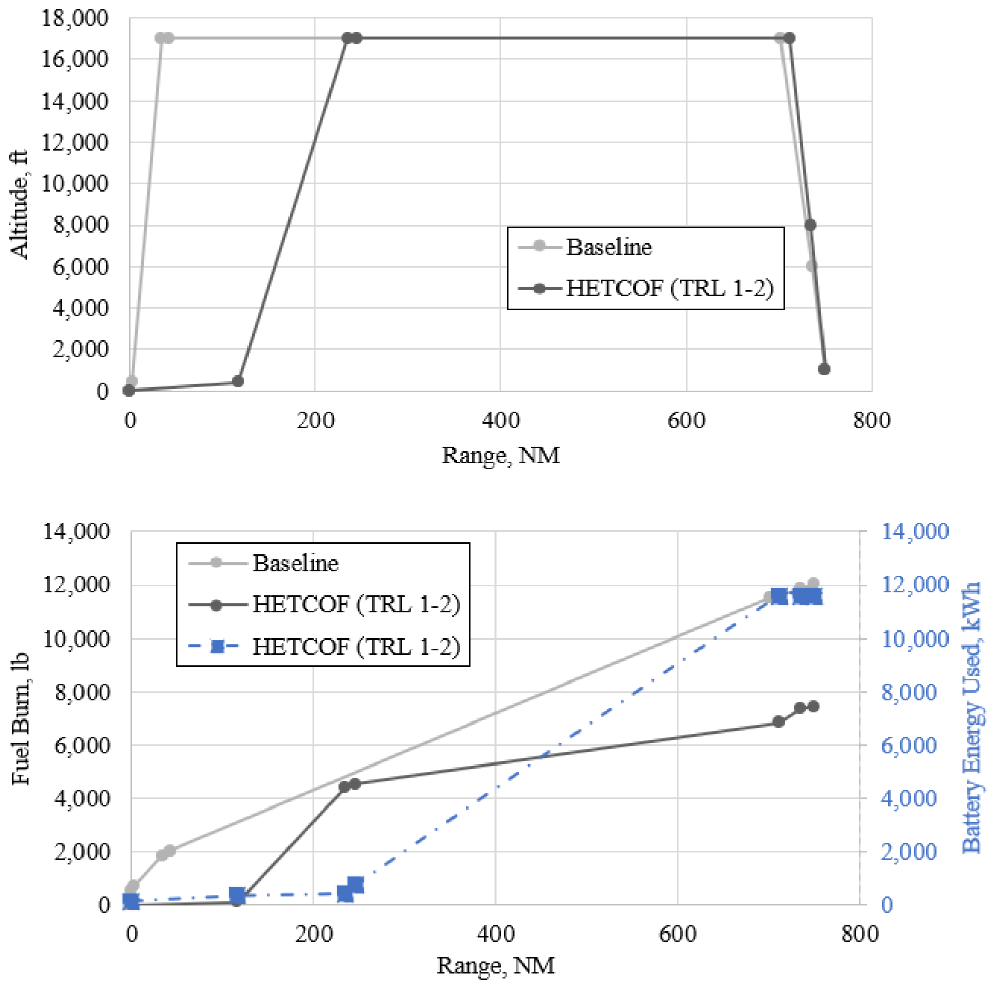


Figure 5. HETCOF TRL 1-2 All-Electric 750 NM Mission Trajectory and Energy Profile

Figure 5 presents the preliminary results from optimization of the all-electric 750 NM cruise mission to meet the minimum climb gradient where for minimization of fuel burn, electric motor assist during climb was reduced to allow for full-electric cruise with the available battery capacity. As future results will remove the constrained battery weight, the TRL 1-2 configuration may opt for higher allocation toward electric energy storage systems. Further improvement of the operating line for the electric motor and optimization of the propeller design may lead to improved efficiencies and therefore fuel savings and range capabilities.

V. Conclusion

This draft manuscript provides the detailed preliminary sizing and mission concept of operations using the initial HETCOF system specifications in Ref. [4] to achieve the 2,400 NM and 750 NM mission with significant fuel savings that align with the breakeven analysis from Wishart et al [3]. The final paper will demonstrate how optimization of the vehicle design, mission, and powertrain controls throughout operation can result in greater realized fuel savings while improving maximum payload retention. Fuel savings of 11-13% can be realized with improvements in technology levels for the 2,400 NM mission with hybrid-electric takeoff and climb, but turbine-only cruise and for the hybrid-electric 750 NM mission (with all-electric cruise for the TRL 1-2 configuration), fuel savings ranging between 25% to 38% are achieved with notable alignment with the breakeven fuel reduction provided in Ref. [4].

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