VEHICLE ASSESSMENT AND SYSTEM-WIDE BENEFIT ANALYSES OF HYBRID-ELECTRIC COMMERCIAL AIRCRAFT – ELECTRIFIED POWERTRAIN FLIGHT DEMONSTRATION PROJECT (EPFD)

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Abstract

NASA is committed to aiding the aviation community to realize revolutionary improvements in environmental performance of subsonic transports using alternative propulsion approaches. One such approach to improving 2030-2035 subsonic transport system-level metrics of emissions and conventional fuel consumption is the use of hybrid electric propulsion. Partnering with U.S. industry, the Electrified Powertrain Flight Demonstration (EPFD) project was created to focus on turning megawatt-class hybrid electric powertrain flight into a reality. A goal of EPFD is integrating megawatt-class propulsion into commercial aircraft. This is a multi-disciplinary system integration effort and vehicle assessment, where the benefits are understood, and the limiting factors (technical and operational) addressed. System-wide benefits analyses are necessary to ensure that the goal is achievable. This paper outlines EPFD efforts in parametric sizing of megawatt-class propulsion applied to state-of-the-art single-aisle turbofan and turboprop aircraft using projected 2030-2035 technologies and their projected system-wide impact on emissions and fuel use.

Keywords: electrified aircraft propulsion, green aviation, aircraft performance

1. Introduction

As part of the Aeronautics Research Mission Directorate's (ARMD’s) 2019 Strategic Implementation Plan (SIP), NASA conducts research to identify the risks with incorporating promising technologies into future subsonic commercial transport aircraft. In particular, NASA is pursuing technologies that can help to reduce operating costs, lower mission fuel burn, and reduce community noise. The Subsonic Transport System Level Metrics, from the NASA ARMD SIP (2019) are shown in Table 1 [1].

Table 1 Subsonic Transport System Level Metrics [1]

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near term 2015-2025	Mid term 2025-2035	Far term Beyond 2035
Noise (cumulative below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NO_x Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NO_x Emissions (relative to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (relative to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

Vision system studies have shown that electrified aircraft propulsion (EAP) concepts, under development by NASA and U.S. industry for well over a decade, are rapidly emerging as a path to meeting the mid-term metrics for subsonic transport vision systems.

NASA, through the Electrified Powertrain Flight Demonstration (EPFD) project [2], is investigating the utilization of ground and flight demonstrations to rapidly accelerate megawatt-class (MW-class) powertrain system maturation, identify and retire technical and integration risks, identify and address gaps in associated regulations and standards, and advance relevant design and modelling tools used to validate technical performance measures of the vision system studies.

According to Zilliac, et al. [3], a MW-class, open-rotor, all-electric single-aisle 150-passenger aircraft, based on the 737MAX, with a mission range of 840 nm (Fig. 1) could service nearly 50% of all U.S. departures and would lead to a reduction of 29% in aviation fuel consumed annually based on 2019-level demand, with potentially more assuming air-traffic-control modifications in the U.S. National Airspace System (NAS). However, the battery cell-level specific energy required would be on the order of 1620 Wh/kg. While this level of specific-energy is well beyond the 2030-35 timeframe; EPFD's vehicle assessment has shown that advantages and benefits can be realized with proper optimization and capturing available synergies of hybrid-electric propulsion even at lower specific energy levels.

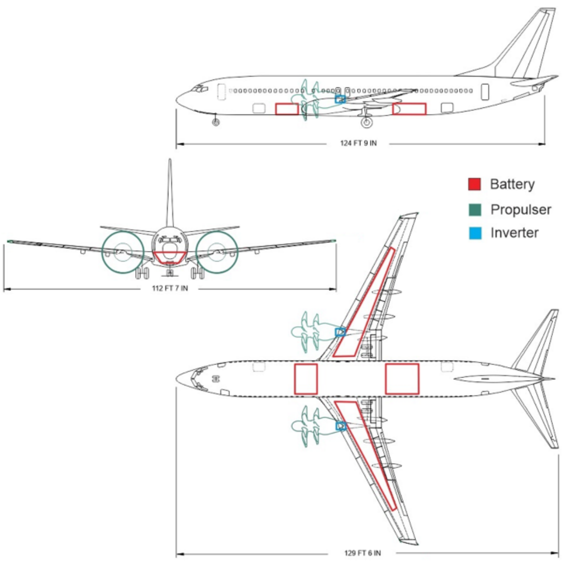

Figure 1. Notional 150-pax all-electric aircraft [3].

The purpose of this paper is to provide a publicly available overview of EPFD's vehicle assessment and system-wide benefit analyses (VASBA) of EAP vision vehicles using technology potentially available within the 2030-35 timeframe that can prove to be viable for integration into commercial vehicles, both turboprops and single-aisle turbofans. Vehicle assessment is also used to determine if EAP enhanced vehicle performance can meet or exceed the mid-term Subsonic Transport Vision System Level Metrics of Table 1. Fleet-wide benefits and operational considerations related to the use of EAP aircraft to perform regional flights are also evaluated by EPFD. Operational considerations include supporting ground infrastructure requirements, electric grid considerations, electric energy production, and electric energy storage considerations to support all-weather operations.

2. ANALYSES

2.1 TOOLS AND BASELINE AIRCRAFT

The VASBA effort in the EPFD project is a result of successful collaboration of members of multiple NASA centers and academic partners from Georgia Tech and the University of Michigan. Assessment and analysis tools include numerical modeling of aerodynamics, aircraft sizing, propulsion, acoustics, emissions, and uncertainty analysis.

Establishment of a state-of-the-art baseline single-aisle turbofan and turboprop aircraft is crucial to calibrate our tools and to assess the performance impacts from EAP system integration on vehicles representing EAP market opportunities. The comparison single-aisle, 150-passenger, turbofan powered baseline aircraft is based the Airbus A320neo [4], using the PW1133G engine. The criteria for EAP technology integration are a technology readiness level (TRL) of 9 by 2030 and no precluding incompatibilities with other required existing or potential technologies. The aircraft sizing mission was conducted using a standard day with energy storage sizing conducted for a windless hot day. Trajectories include sea level electric taxi (e-taxi), takeoff boost, climb boost, cruising with or without in-flight recharging, descent, and taxi for five minutes on reserves. The baseline 50-pax, turboprop powered aircraft include the DHC-7 [5] using the PT6A-50 engine, and a four-engine passenger/cargo vehicle [6] using the T56-A-15 engine. Trajectories are similar to the turbofan aircraft but include a reserve mission flown at 15,000 ft for 150 nm. Electric powertrain models consist of parametric loss-based electric motor models, power converters, parametric surrogate batteries, and electric cables.

2.2 HYBRIDIZED TURBOPROP AIRCRAFT

Assessment of proposed advanced technology turboprops under EPFD have included 19 to 50 passenger regional turboprops such as in Refs. [7, 8]. In the exploration of the potential for multi-MW-class EAP systems, Pham, et al. [9] considered a generic large turboprop transport/freighter (LTF) concept developed for vehicle assessment purposes only, where key features of the baseline aircraft include:

- Four conventional turboprop engines rated at 3.32 MW per engine.
- Ability to mount external wing pods that can be used for battery storage to provide inertial wing bending relief for over-sized payloads.

Figure 2 illustrates the proposed hybridized version of the LTF that Pham, et al. refer to as true parallel hybrid (TPH) or the TPH LTF. For the TPH LTF, the two outboard turbines are replaced with electric motors (including inverter, cabling, and thermal management system) of 1.645 MW each. The motors are powered by Li-ion batteries with a specific energy of 300 Wh/kg.

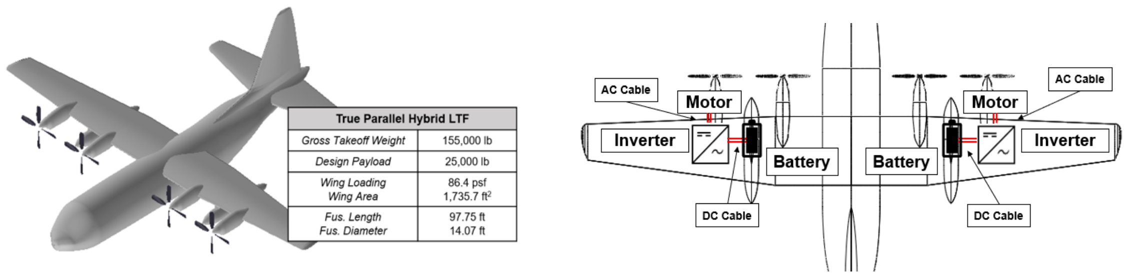

Figure 2. Configuration overview of the parallel hybrid LTF (TPH LTF) concept [9]

The hybrid-electric aircraft modeling and sizing were accomplished using the updated NASA tool, General Aviation Synthesis Program (GASP). GASP, a maintained and updated legacy FORTRAN-based aircraft synthesis and mission analysis code developed at NASA Ames Research Center [10], consists of several modules pertaining to aircraft subsystems that are integrated to allow for mission specification and performance estimation at the conceptual design and sizing phase. Conventional engine and electric motors were modeled in the Numerical Propulsion System Simulation (NPSS) program developed by NASA Glenn Research Center [11] that allows for the analysis and design of propulsion systems. Engine and motor performance parameters are provided in each model. Their analysis was conducted with fixed geometry where both the LTF and TPH LTF vehicle models were initialized with a maximum gross takeoff weight of 150,000 lb, a design payload of 25,000 lb, vehicle structural weight of approximately 45,000 lb and takeoff wing loading of 86.4 psf. Table 2 gives the configuration values of both the LTF and TPH LTF using nominal EAP technology.

Table 2. LTF and TPH LTF Configuration Values Given Nominal EAP Technology Levels [9]

	LTF	TPH LTF (Nominal)	Δ%
Gross Takeoff Weight (GTOW), lb	150,000	150,000	-
Operating Empty Weight (OEW), lb	80,000	116,200	+45.3
Design Payload (W_{PL}), lb	25,000	25,000	-
Max. Payload ($W_{PL,max}$), lb	42,000	26,810	-36.2
Design Range for W_{PL}, nm	2,528	314	-87.6
Loaded Fuel for Design W_{PL} (WFA), lb Battery Capacity, kWh	45,000 0	8,800 5,715.4	-80.4 -
Block Fuel Used for 300 nm mission, lb	5,622	3,220	-42.7
Number of Engines, # Turbine Motor	 4 0	 2 2	 - -
Max. Rated Power, hp Turbine Motor	 4,465 0	 4,465 2,560	 - -
Takeoff T/W, hp/lb Turbine Motor	 0.2458 0	 0.1229 0.1020	 -50 -
AEO Takeoff Field Length, ft	4,445	5,310	+19.5
OEI Takeoff Field Length, ft	4,832	6,315	+30.7
2nd Segment OEI Rate-of-Climb, fpm	1,050	512	-51.2
Top-of-Climb Rate-of-Climb, fpm	1,238	814	-34.3
BSFC, lb/hr/lb	0.5678	0.5695	+0.3
Specific Range, nm/lb	0.07502	0.12955	+72.7

For a 300 nm economic mission, where the total cruise thrust is split equally between the conventional turboprops and electric motors, Pham, et al. [9] found that the nominal TPH LTF configuration showed a 42% improvement in block fuel. To estimate the range in block fuel improvement, Pham, et al. also varied the near-term EAP technology levels of the component parameters (Table 3).

Table 3. Near-term EAP technology levels in terms of power, specific power, specific energy, and efficiency [9]

	Values				Efficiency			
	Min.	Nom.	Max.	Unit	Min.	Nom.	Max.	Unit
Battery	250	300	400	W-hr/kg	95%	98.5%	99.5%	%
Motor	5	10	15	kW/kg	92%	94%	95%	%
	1.65	1.91	3.33	MW				
Inverter	8	12	20	kW/kg	97%	99%	99.5%	%
Cabling					95%	97.5%	98%	%

Under the same flight conditions, improvement in block fuel varied between 42% and 63%. However, all cases came with reduced payload capacity and design range performance.

2.3 HYBRIDIZED SINGLE-AISLE TURBOFAN AIRCRAFT

Previously, Milios, et al. [12] and Gladin, et al. [13] assessed the performance of a dual-motor mild hybrid turbofan propulsion system and its resulting system-level impacts on a single-aisle, 150-passenger class, 2030 technology reference aircraft based on the Airbus A320neo with PW1127G-JM turbofan. This was compared to an appropriate 150-passenger Large Single-Aisle (LSA) non-electric advanced aircraft model developed by Gladin, et al. using 2018 technology and the methodology of Harish, et al. [14]. Gladin, et al. showed nearly 5% improvement in block fuel for a 900 nm economic mission range, with an approximately 10% block fuel reduction for a 500 nm economic mission.

In their latest work, Gladin, et al. [15] modeled both a non-electric 2030 technology reference aircraft based on the Airbus A320neo with PW1127G-JM turbofan and a similar but clean sheet Parallel Hybrid (PLH) vehicle. Hybrid operational modes included e-taxi, takeoff boost (TKO Boost) and engine core downsizing, climb boost, electric power transfer in sub-idle descent, and turbine electrified energy management (TEEM) [16,17]. The energy storage system included batteries with a specific energy of 391 Wh/kg and supercapacitors.

The results of their recent study found that for the design mission of 3400 nm there is an increase in block fuel burn compared to the non-electric 2030 technology reference aircraft. However, for the shorter range economic off-design missions of 500 nm and 900 nm there is a reduction in block fuel of up to 6% and 4%, respectively (Fig. 3).

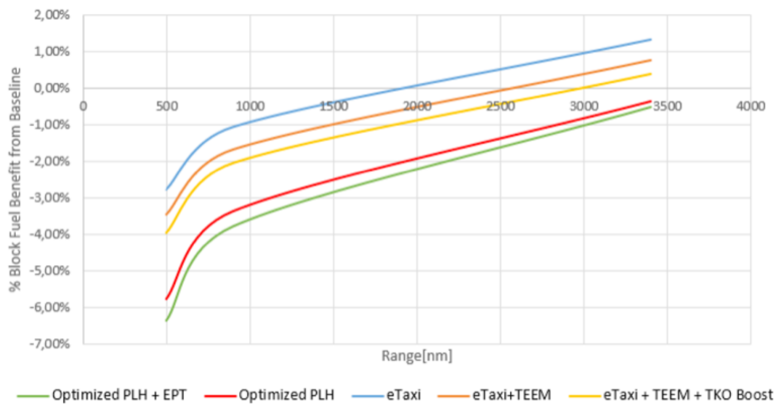

Figure 3. Block fuel burn delta w.r.t. baseline at off-design mission ranges [15]

2.4 EFFECT OF HYBRIDIZED AIRCRAFT IN THE U.S. NATIONAL AIRSPACE

Windhorst, et al. [18] investigated the fuel burn and flight time impacts of hybrid electric aircraft operating in the NAS. Their approach was to create future scenarios containing hybrid electric flights, supplying present capacity for transportation of passengers between city pairs and to simulate those scenarios in NASA's NAS Digital Twin [19]. Four scenarios were created, each containing progressively more flights that had their aircraft type replaced by hybrid electric aircraft. When a conventional aircraft with more seats than the hybrid electric aircraft was replaced, additional hybrid electric flights were added to the future scenario to keep its total number of seats equal or greater to those in the baseline scenario.

Depending on the scenario, results showed that hybrid electric operations saved between 50% to 60% of the fuel burned by the conventional aircraft replaced and between 0.01% to 0.7% of the total fuel burned in the airspace. The additional hybrid electric flights added to the scenarios did not cause any of the airports to exceed their operational capacity. However, hybrid electric operations did increase the flight time of the replaced conventional aircraft between 10% to 38% and the average flight time of aircraft in the airspace between 0.01% to 5.5%.

2.5 HYBRID AIRCRAFT FLEET REPLACEMENT

In an effort to demonstrate practical hybrid electric aircraft usage for regional airlines seeking to incorporate these new aircraft into their fleets, Chan, et al. [20] addressed barriers to airline operations of hybrid electric aircraft for short haul routes. This was done by developing realistic operating cost estimations along with an analytical fleet assignment optimization model. This easily adaptable model was able to generate optimal fleet assignments with environmental benefits for a mixed fleet of conventional and hybrid-electric aircraft.

Though their optimization model successfully accounts for physical and practical considerations, it does not consider the novel technological and operational constraints of hybrid-electric aircraft such as maintenance (e.g., maintenance of hybrid-electric aircraft may only be possible at specific airport stations) and aircraft range (which limits certain aircraft types to flying shorter routes). A more refined view of hybrid electric aircraft integration into existing commercial airline fleets will be made with the next iteration of the model after the incorporation of more refined constraints.

3. SUMMARY

Through the EPFD project, NASA is investigating the utilization of ground and flight demonstrations to rapidly accelerate megawatt-class (MW-class) powertrain system maturation, identify and retire technical and integration risks, identify and address gaps in associated regulations and standards, and advance relevant design and modelling tools used to validate technical performance measures of the vision system studies. This paper has shown results that indicate hybrid-electric aircraft in the MW-class are viable in the near term and have the potential to show fuel savings in off-design mission ranges (~300 nm for turboprops and ~500 to 900 nm for turbofans). EPFD sponsored efforts have also investigated the effect of these hybridized vehicles on the NAS and barriers to airline operations of hybrid electric aircraft for short haul routes. Central to all of these investigations is the need for industry to produce higher specific energy batteries and continue to advance component development. The higher the specific energy, the less the block fuel burned and the longer the design range.

Future analyses in EPFD should include, among other things, more extensive investigation of purpose-built hybrid-electric aircraft. For example, integration of battery storage and other EAP components into the vehicle's design will lead to better aerodynamic performance and energy requirements. Single-aisle vehicle operations at lower Mach numbers could also enable significant reductions in energy requirements since cruising at lower Mach numbers requires less wing sweep allowing for simpler structures and less weight. Future fleet analyses will include industry perspectives on introducing EAPs into NAS and formulating scenarios for network studies that are of greater utility to EAP stakeholders.

4. Contact Author Email Addresses

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5. Copyright Issues

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