SIZING & PERFORMANCE ANALYSIS OF A MEGAWATT-CLASS ELECTRIFIED AIRCRAFT PROPULSION (EAP) SYSTEM FOR A PARALLEL HYBRID TURBOPROP CONCEPT

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INTRODUCTION & BACKGROUND

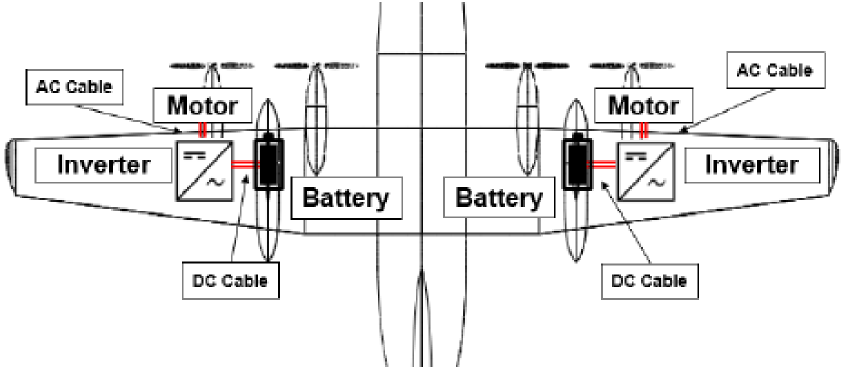
- Electrified Powertrain Flight Demonstration (EPFD) project
  - Collaboration between NASA & U.S. industry partners to integrate, test, and demonstrate Megawatt-class Electrified Aircraft Propulsion (EAP) systems

- With rapid emergence of novel, multi-MW hybrid-electric aircraft systems and concepts being developed:
  - How can we evaluate the impacts of aircraft electrification on vehicle-level performance?
  - What are the mission capabilities for a multi-MW, true parallel hybrid concept assuming near-term EAP technology performance levels?

CONCEPT OVERVIEW

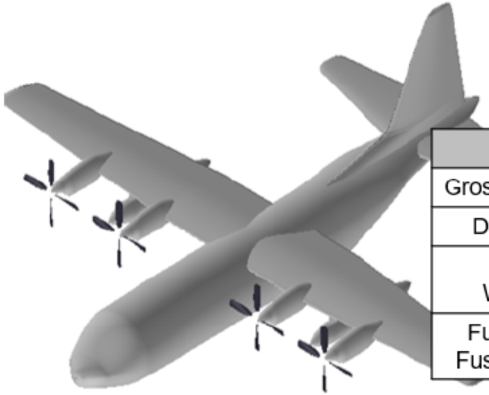
True Parallel Hybrid (TPH) Architecture

- Dual-sided, hybrid-electric powertrain with separately maintained EAP system alongside conventional gas turbine engines
- Featured on magniX EPFD Demonstrator



TPH Large Turboprop Freighter (LTF) Concept

- Four-engine turboprop concept featuring dual-sided, multi-MW, hybridized EAP system with parallel turbine and electric motor drive system



True Parallel Hybrid LTF	
Gross Takeoff Weight	150,000 lb
Design Payload	25,000 lb
Wing Area Wing Loading	86.4 psf 1,735.7 ft^2
Fuselage Length Fuselage Diameter	97.75 ft 14.07 ft

EAP COMPONENT-LEVEL PERFORMANCE PARAMETERS

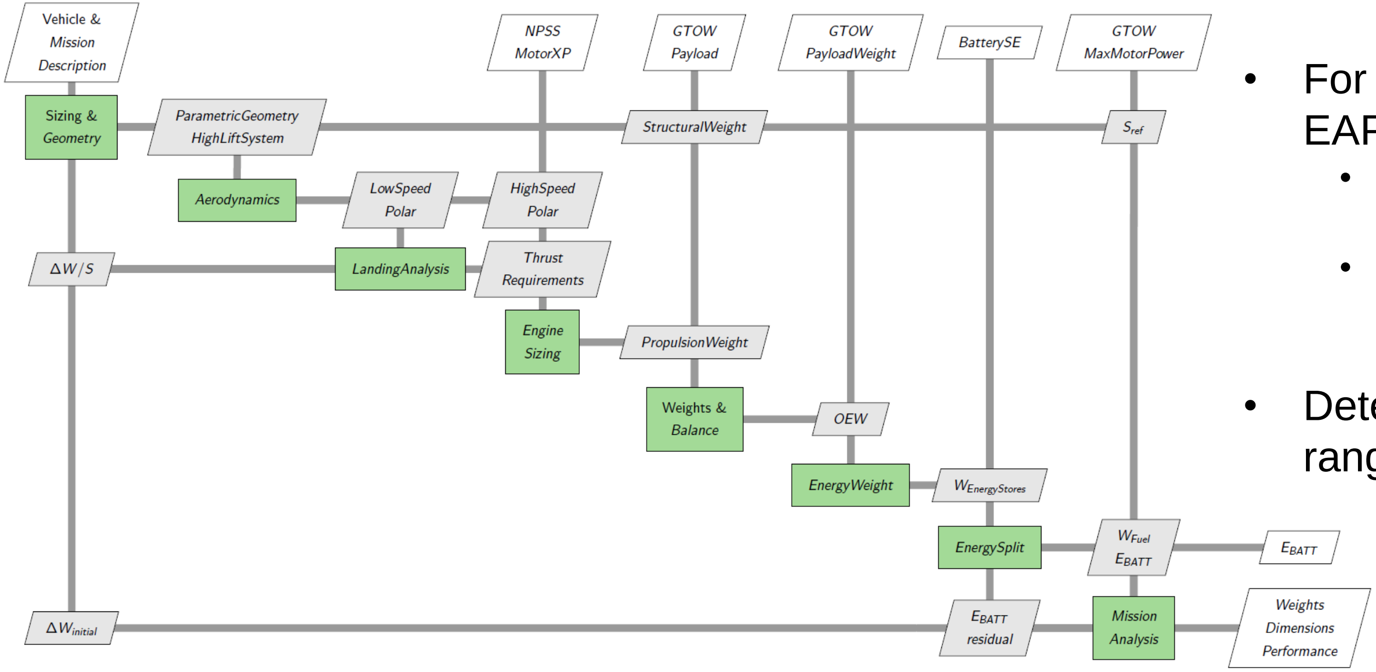
- Near-term EAP technology levels informed by power/energy requirements for freighter mission carrying normal design payload & literature review:

	Specific Power				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	5.2	3.9	3.4	kg/m/MW	0.08%	0.04%	0.02%	% loss/m

- Total weight for EAP system includes battery, AC/DC cabling, thermal management systems (TMS), gearbox, and inverter weight

INTEGRATED MODELING & SIMULATION ENVIRONMENT

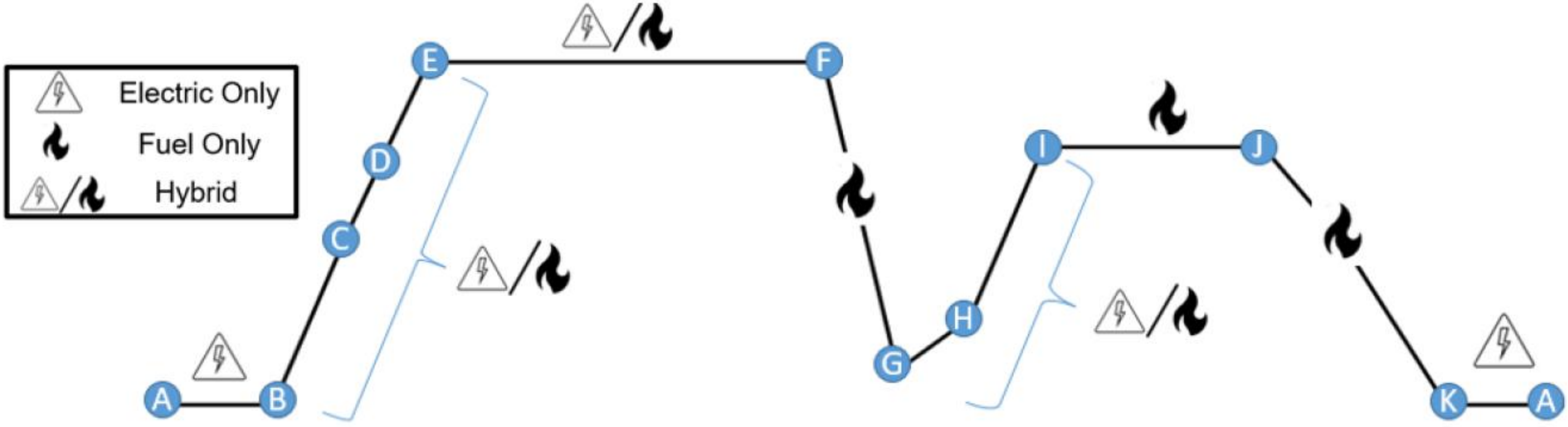
- Integrated M&S environment for parametric modeling & mission analysis for conventional and hybrid-electric powertrain and vehicle concept



- For fixed vehicle, payload & EAP system specifications:
  - Max. motor power (EHPMAX)
  - Battery specific energy (SE_{BATT})
- Determine battery sizing & range performance

HYBRID-ELECTRIC MISSION PROFILE FOR TPH LTF STUDY

- Concept of Operations (ConOps) for hybrid-electric aircraft includes power/energy management assuming 20% min. state-of-charge & compliance with FAA Part 25/121 airworthiness and reserve mission requirements



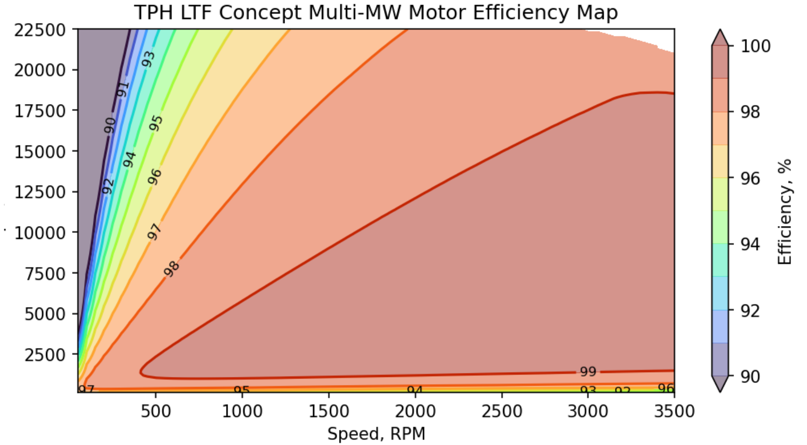
Segment definitions provided in paper.

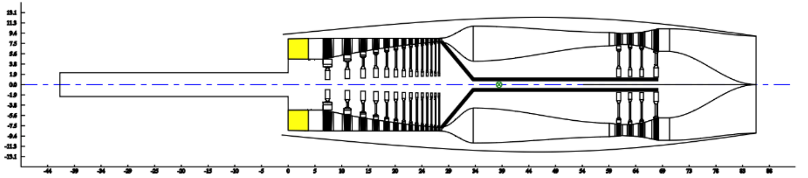
PROPULSION SYSTEM MODELING (BASELINE & HYBRID-ELECTRIC)

- Electric motor model developed using MotorXP while conventional gas turbine engine weight & performance synthesized using NPSS & WATE++

Electric Motor Parameter (Per Motor)	Value
Base Speed, RPM	1,350
Max. Torque, N-m	22,500
Max. Input Power, MW	3.33
Max. Current, A-rms	1,964
Percent Power @ NRP, %	92.8

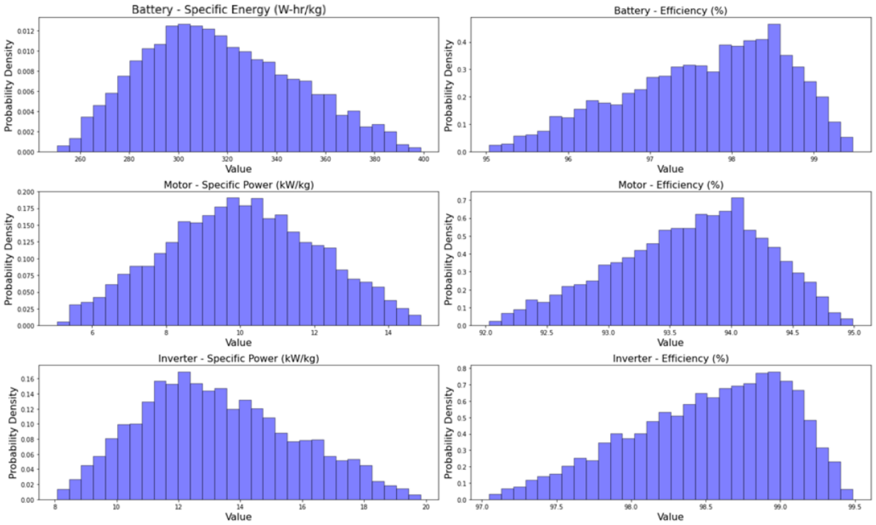
Engine Parameter (Per Engine)	Value
SLS Takeoff Rating, shp	4,465
SLS TO Tailpipe Thrust, lbf	800
Reference Gear Ratio	0.0738
Ambient Conditions	ISA
Constant Turbine Speed, RPM	13,820
Constant Shaft Speed, RPM	1,020





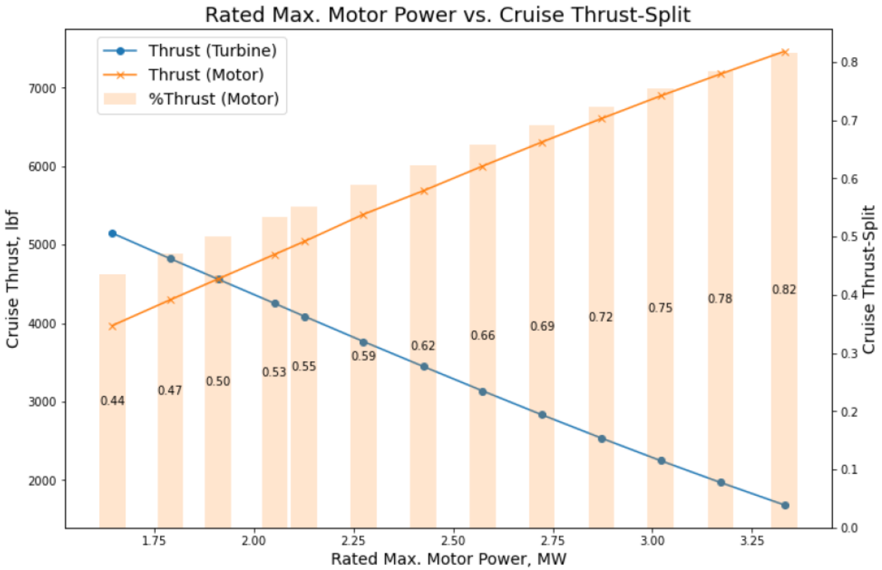
Monte Carlo (MC) Simulations

- Variations in EAP component-level parameters captured stochastically



Motor Sizing Impacts on Cruise Thrust-Split

- Cross-over point at 1.910 MW where thrust contributions from both powertrains equal



PERFORMANCE IMPACTS FOR NOMINAL EAP TECHNOLOGY LEVELS

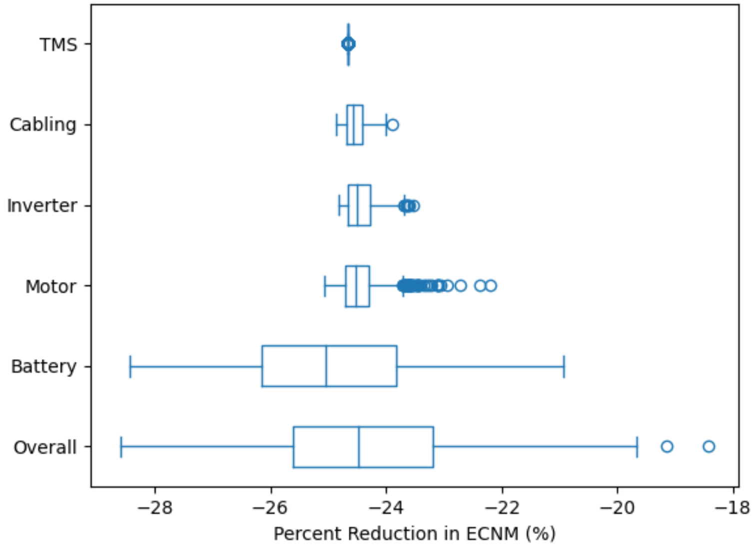
- For 300 NM mission, nominal TPH LTF configuration results in 42.7% block fuel savings with increased takeoff distance & reduced rate-of-climb

Performance Parameter	Baseline 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	-
Loaded Fuel for Design W_{PL} (WFA), lb	45,000	8,800	-80.4
Battery Capacity, kW-hrs	0	5,715.4	-
Block Fuel Used for 300 NM mission, lb	5,622	3,220	-42.7
Max. Rated Power, hp			
Turbine	4,465	4,465	-
Motor	0	2,560	-
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

RESULTS OF VEHICLE-LEVEL SENSITIVITY STUDIES

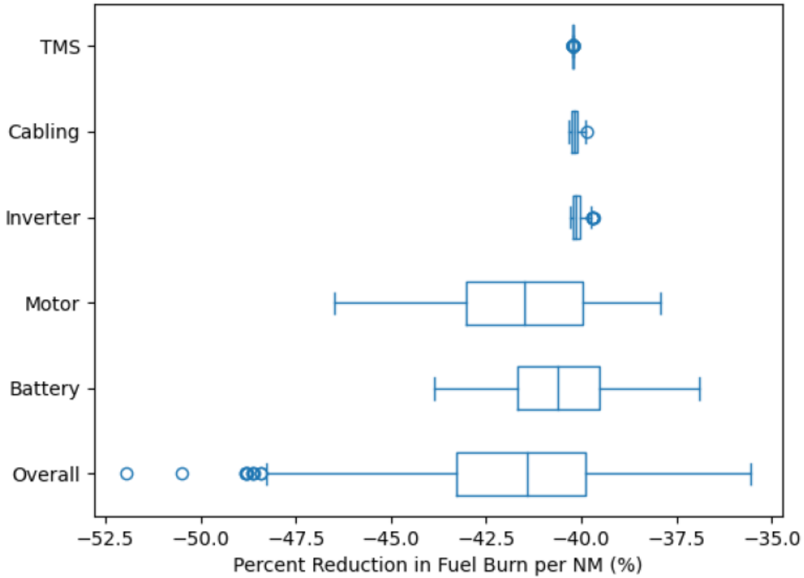
Energy Consumption per Nautical Mile (ECNM)

- Battery specific energy density has highest impact and variability in ECNM reduction 22.3-27.4%



Fuel Burn per Nautical Mile

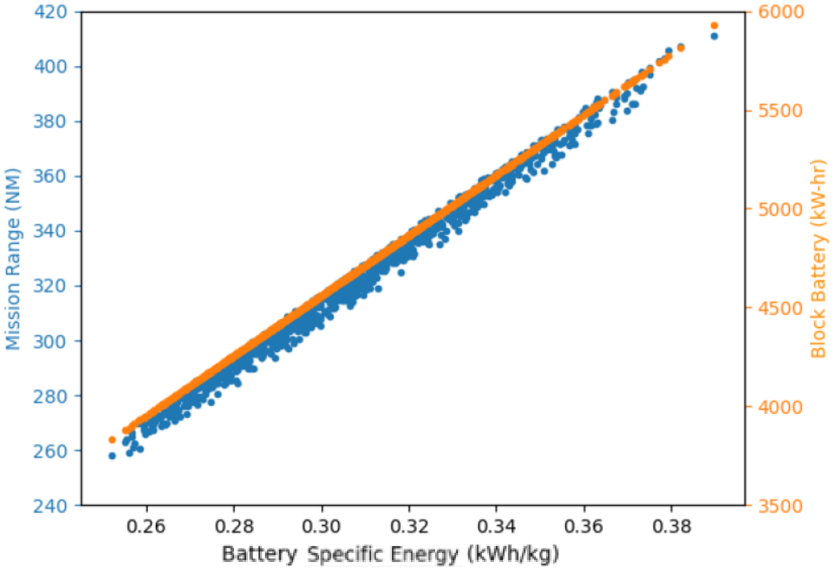
- Total block fuel savings for TPH LTF concept 42-63% for ~300 NM range & 25,000 lb payload



RESULTS OF VEHICLE-LEVEL SENSITIVITY STUDIES

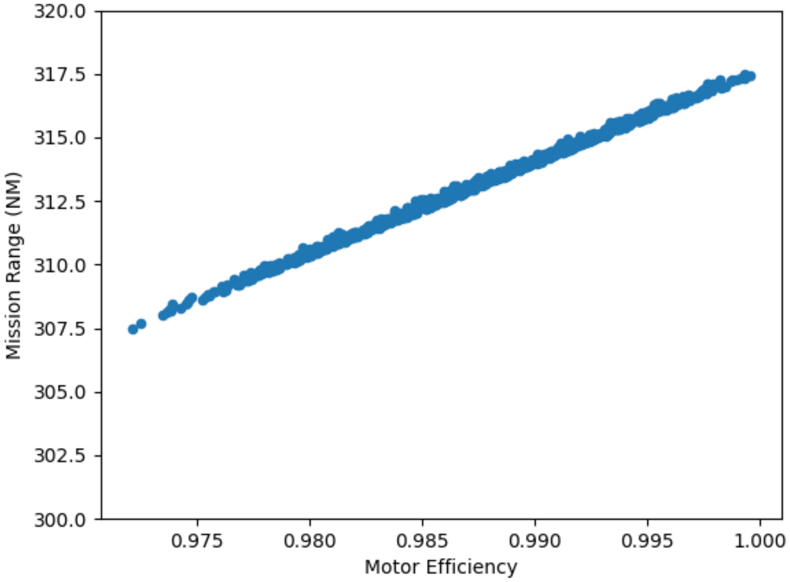
Battery Specific Energy (SE_{BATT})

- Battery technology improvement results in increased range performance & fuel savings



Motor Efficiency

- Improvements in motor efficiency result in improved range performance capabilities:



CONCLUSIONS

- Integrated approach to sizing & capturing vehicle-level performance sensitivities to variations in EAP technology levels in the 2020-2035 timeframe

- Key drivers for overall vehicle performance improvements:
  - Battery specific energy
  - Maximum EAP system power output
  - Motor efficiency

- Improving pack-level battery specific energy (SE_{BATT}) from 250 Wh/kg to 400 Wh/kg results in ~25% Energy Consumption per Nautical Mile (ECNM) reduction & 40-63% fuel savings for short-haul missions (300 NM)
  - Informing how focused improvements to EAP component-level specifications enhance mission performance capabilities for multi-MW freighter concept

Q&A Session