National Aeronautics and Space Administration

Overview of Electrified Aircraft Propulsion at NASA

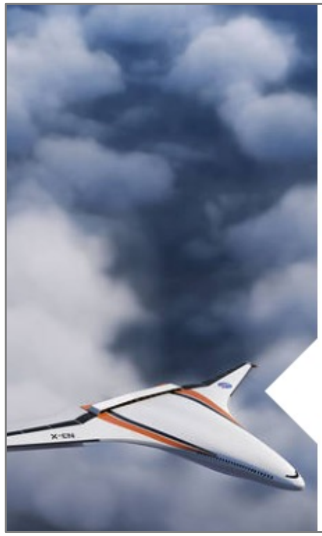
Dr. Jesse Quinlan
Strategic Technical Advisor, Advanced Air Vehicles Program (AAVP)

April 19, 2024

Power and Energy Conference at Illinois 2024

My NASA story …

Sandia National Laboratories



Advanced Air Transport Technology (AATT) Project

NASA's vision for advanced fixed wing transport aircraft is revolutionary energy efficiency and environmental compatibility. The overarching goal of the AATT Project is to explore and develop technologies and concepts to enable this vision.

Return Ticket for Aero Alum

Top NASA aerospace engineer is teaching aircraft design course for UVA's Department of Mechanical and Aerospace Engineering

NASA senior aerospace engineer Jesse Quinlan, who received his Bachelor of Science in aerospace engineering in 2009 and his Ph.D. in mechanical and aerospace engineering in 2015,...

READ MORE

The Sustainability Challenge

Revolutionizing Aviation through EAP

Systems-Level EAP Assessment

Aviation is Vital to our Nation’s Economy

- 8.97 million flights by U.S. carriers worldwide in 2022
- 24 million tons of freight transported by U.S. airlines in 2022
- $1.9 trillion total U.S. economic activity in 2019
- $51.5 billion positive manufacturing trade balance in 2021
- 2.1 million aerospace/defense jobs; 575,000 in aeronautics/aircraft in 2021

The Aviation Carbon Reduction Challenge

- By 2050, an estimated 10 billion passengers will fly each year a distance of 22 trillion revenue passenger kilometers.
- With today's fleet and operational efficiency, this activity would require over 620 megatonnes (Mt) of fuel and generate close to 2000 Mt of CO_2.
- Imagine enabling the same level of demand while reducing net CO_2 emissions to zero by 2050.

Meeting the challenge is the opportunity for the United States to lead the world in innovation and reductions in CO_2 aviation emissions, and to maintain economic competitiveness in a critical export industry ($6 trillion-plus market over the next 20 years).

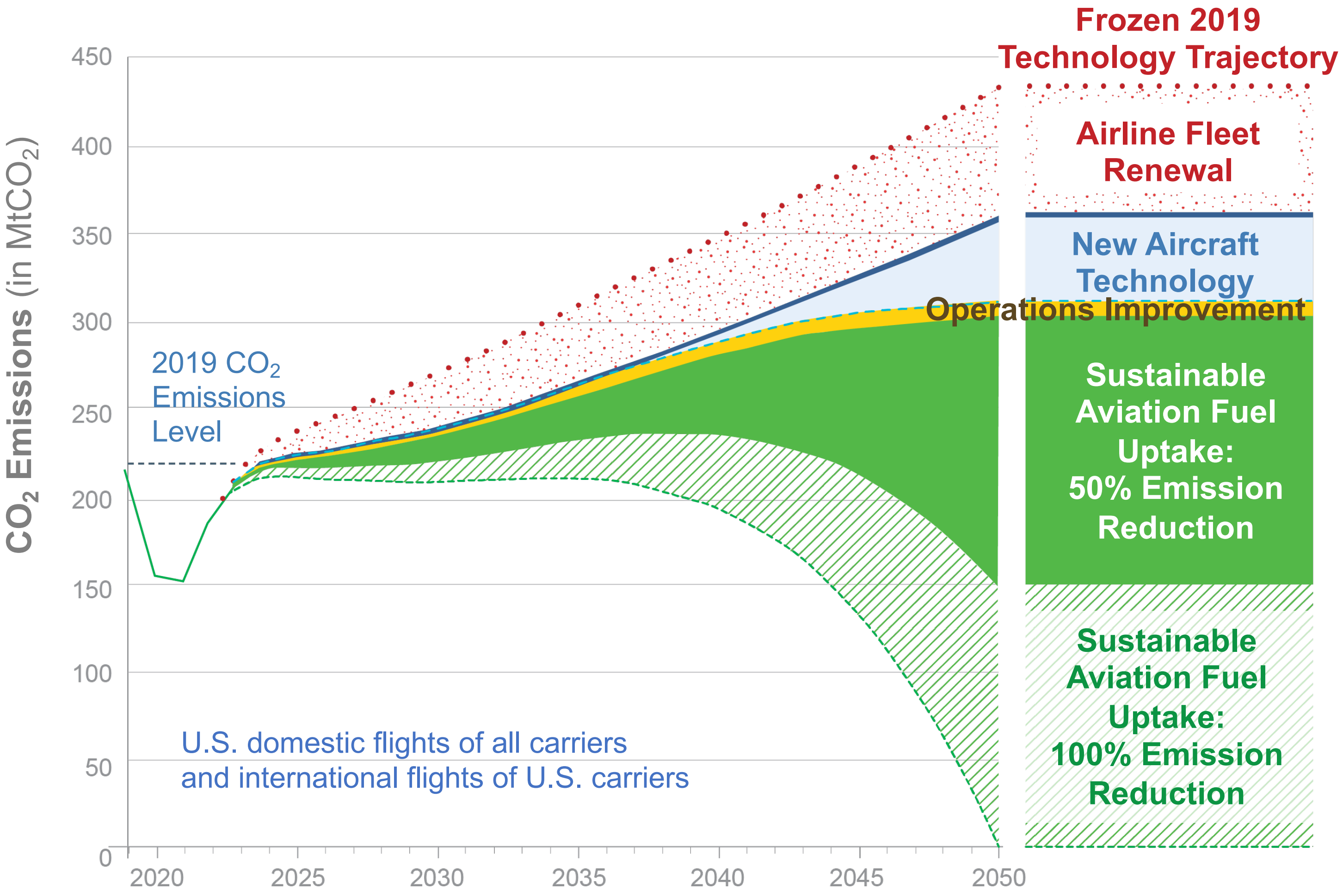
U.S. Aviation Climate Action Plan

Global Context for Sustainable Aviation

U.S. aviation goal is to achieve
net-zero greenhouse gas emissions by 2050.

U.S. Aviation Climate Action Plan is aligned with

- U.S. economy-wide goal
- International Civil Aviation Organization
- Air Transport Action Group



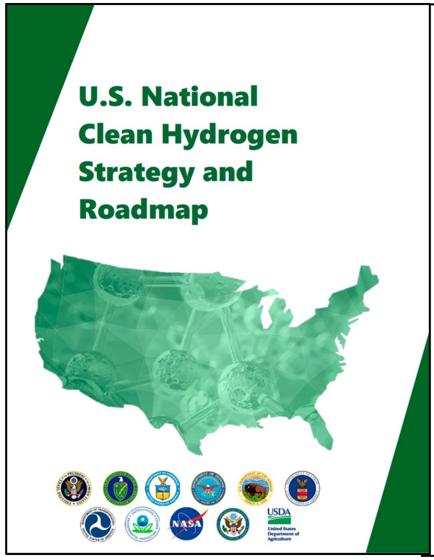
The U.S. is working with the global community to achieve net-zero greenhouse gas emissions by 2050 using a common basket of measures.

US Government Sustainability Strategies

FAA

Net-Zero GHG emissions from aviation by 2050

Assumption of SAF-dominated aviation fuels landscape



DOC/DOD/DOE/DOI/DOL/ DOT/EPA/NASA/USDA+

National clean H2 production and infrastructure strategy

National H2 production goals:

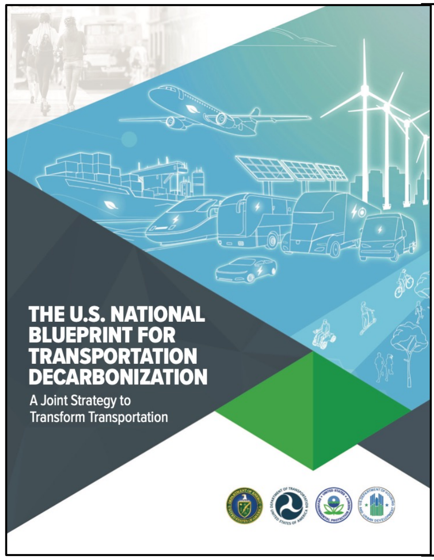
- 10MMT/year by 2030
- 20MMT/year by 2040
- 35MMT/year by 2050

DOE/DOT/FAA/USDA/EPA

References US Aviation Climate Action Plan goals

Establishes national goals for SAF production of:

- 3B gal/year by 2030
- 35B gal/year by 2050



DOE/DOT/EPA/DOH

Transportation sector wide decarbonization strategy

Three strategic pillars:

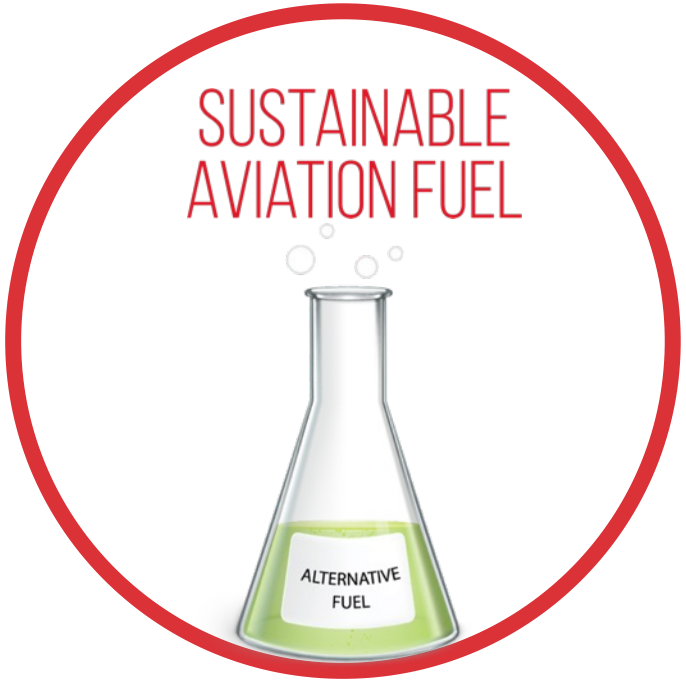
1. Community redesign
2. Improved efficiency
3. Transition to clean fuels

Solving the environmental sustainability challenge will require a whole-of-government strategy. NASA ARMD plays an important role in solving the aviation sustainability problem.

Aviation Pillars for a Sustainable Future

Global Aviation GOAL: net-zero carbon emissions by 2050

NASA = Primary Role



NASA = Supporting Role

NASA = Primary Role

The Sustainability Challenge

Revolutionizing Aviation through EAP

Systems-Level EAP Assessment

Four Transformations for Sustainability, Greater Mobility, and Economic Growth.

NASA Sustainable Aviation Strategy

2008-2013 | 2014-2019 | 2020-2025 | 2025-2030 | 2030+

Subsonic Concept/Technology Studies
Electrified Aircraft Propulsion
Transonic Truss-Braced Wing
Blended Wing Body

Environmentally Responsible Aviation Project

Flight Demonstrator Studies

Advanced Composites Project

SUSTAINABLE FLIGHT NATIONAL PARTNERSHIP

Sustainable Flight National Partnership to mature and integrate key technologies for next-generation subsonic airliners (2030s)

TODAY

ACCELERATING TOWARD NET-ZERO CARBON

Cast a wide net for zero-emission concepts and technologies

Select and develop promising concepts in partnership with universities, industry

Create a credible mission, architecture, and technologies for beyond next-generation subsonic transports for 2050 horizon

POWERING AVIATION TO NET-ZERO CARBON AND BEYOND

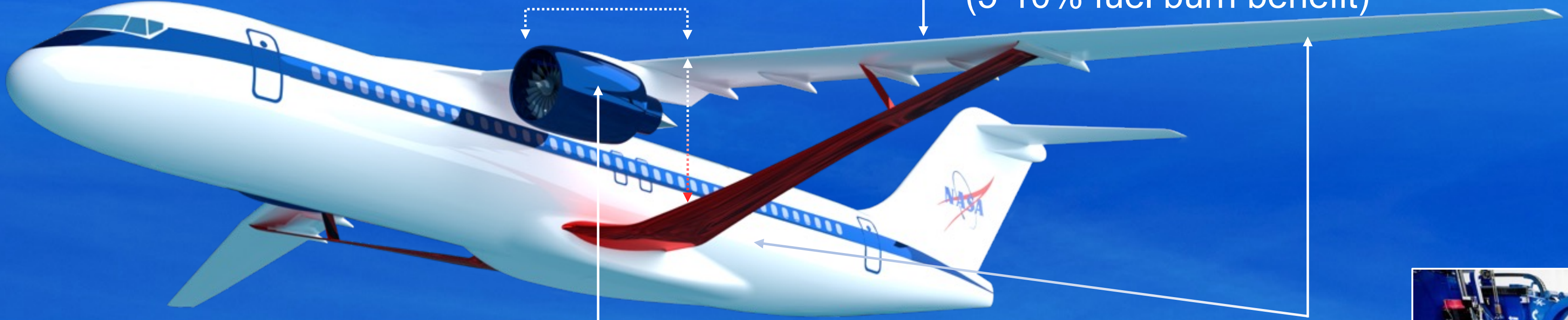
Investment in innovation today paves the way to a net-zero carbon and beyond aviation future.

Sustainable Flight National Partnership

Ensure U.S. industry is the first to establish the new “S Curve” for the next 50 years of airliners

Integrated Aircraft System Efficiency
Propulsion Airframe Integration Opportunity

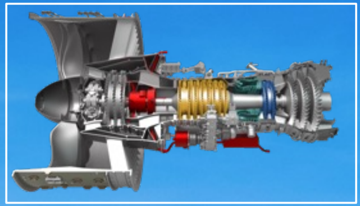
Aerodynamic Efficiency
Transonic Truss-Braced Wing
(5-10% fuel burn benefit)



Weight
High-Rate Composites
(4-6x manufacturing increase)

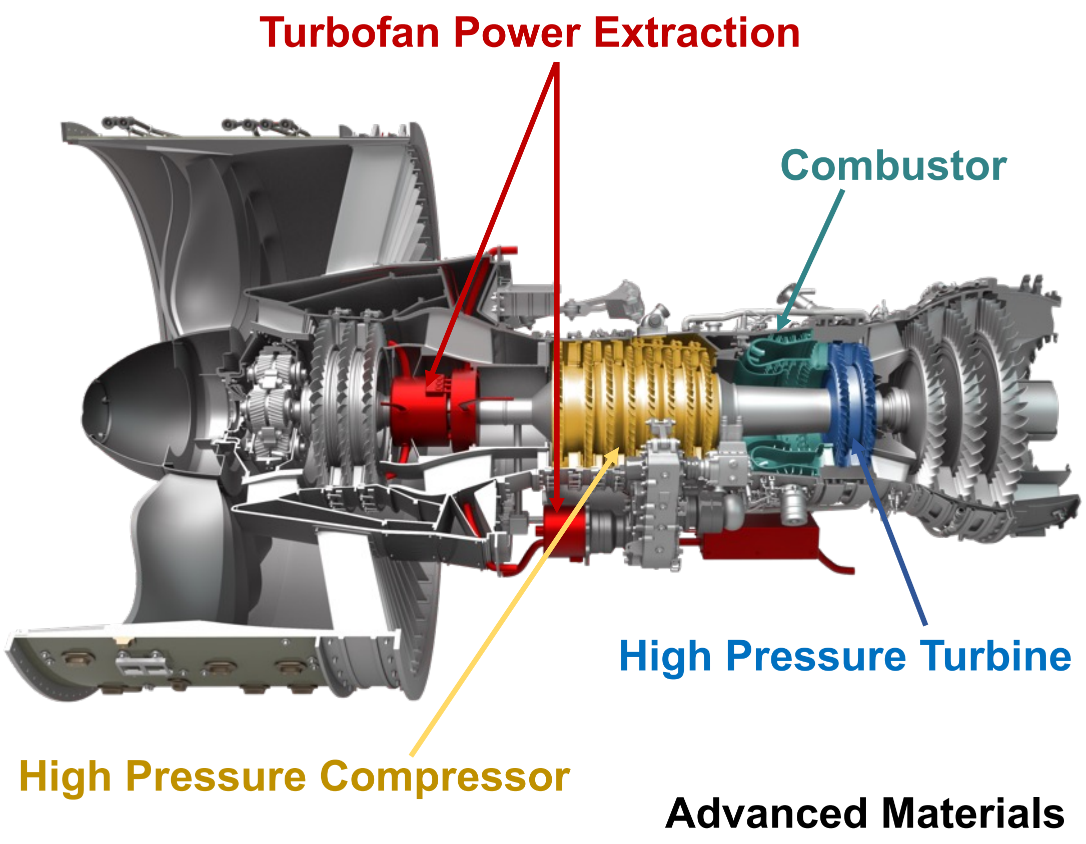
Electrified Aircraft Propulsion
~5% fuel burn and maintenance benefit

Engine Efficiency
Small Core Gas Turbine
(5-10% fuel burn benefit)



Hybrid Thermally Efficient Core

Accelerate development and demonstration of advanced turbine engine technologies



Scope

- Develop and demonstrate in integrated ground tests engine core technologies to Increase thermal efficiency, reduce engine core size and facilitate hybridization

Benefit

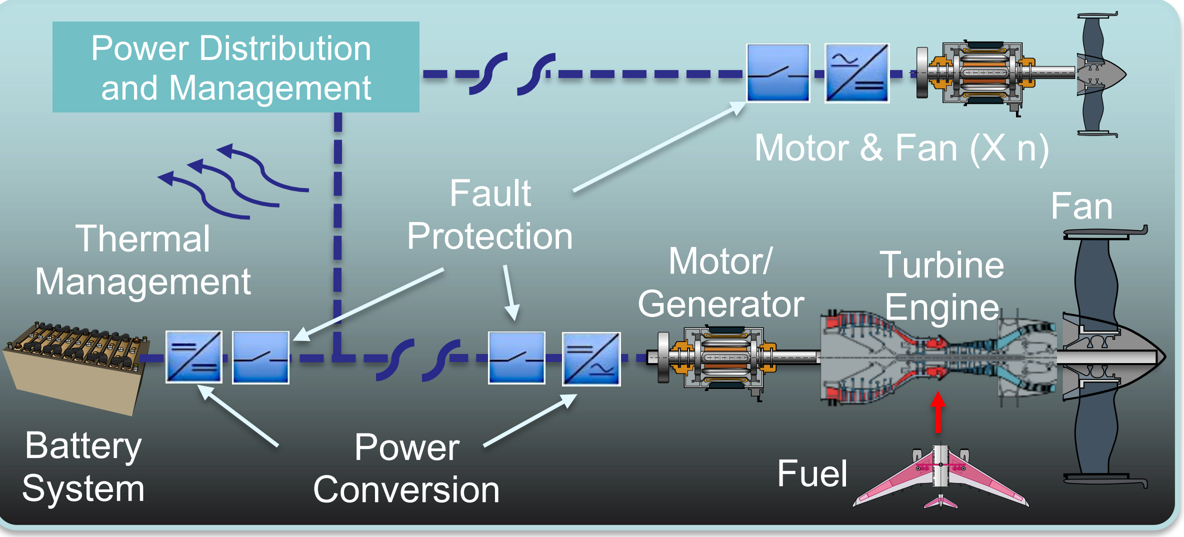
- Achieve **5-10% fuel burn reduction** versus 2020 best in class
- Achieve **up to 20% power extraction** (4 times current state of the art) at altitude to optimize propulsion system performance and enable hybridization

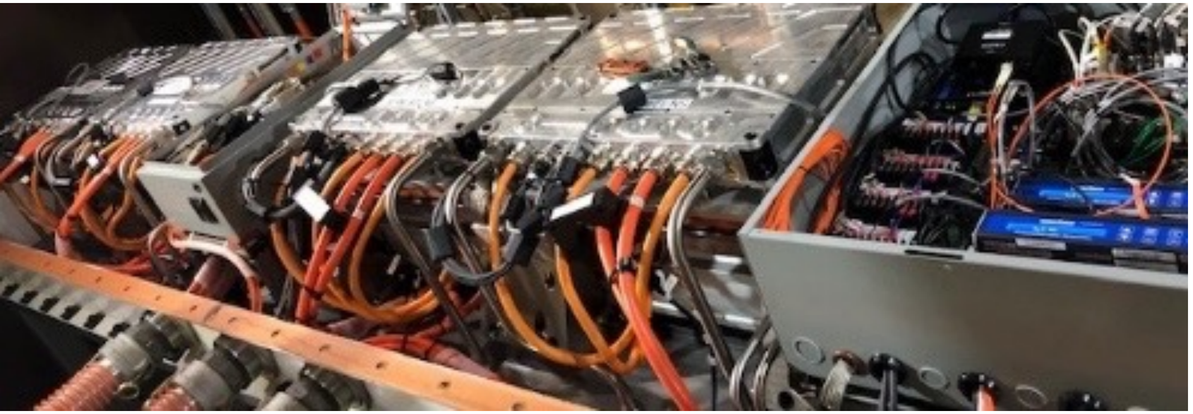
Approach

- Partner with industry to mature and demonstrate promising technologies

Focused Technologies for Electrified Aircraft Propulsion

Retire barrier technical and integration risks for megawatt-class electrified aircraft propulsion systems





Scope

- Address critical challenges for electrified aircraft propulsion by maturing and reducing risk for Electrified Aircraft Propulsion (EAP) technology, focused on:
  - Mass and weight reduction
  - Electrical losses
  - Reliability
  - EMI, power quality, dynamic stability
  - Limits on DC voltage levels
  - System design and integration

Benefit

- Accelerate U.S. industry readiness to transition to EAP-based commercial transport aircraft.
- Reduce key risks for a range of future applications and help enable new standards that are needed for EAP-based aircraft certification

Approach

- Conduct technology-focused integrated ground tests
- Partner with industry on testing of electrified propulsion architectures and component technologies
- Leverage prior electric aircraft propulsion advances (TRL ~4)

NASA Electrified Powertrain Flight Demonstration

Electrified Powertrain Flight Demonstration (EPFD) project:

- Partnership with U.S. industry to establish and demonstrate integrated megawatt-class powertrain systems.

EPFD Goals:

- Accelerate US industry technology readiness and competitiveness
- Facilitate new aviation industry S – Curve for electrification
- 2030-2035 Entry Into Service: Next generation thin haul, regional and Single-Aisle markets

Regulations and Standards will play a large role:

- NASA is partnering with industry to identify the regulatory and standards gaps that may exist for the highest priority electric technologies and gather data to support future regulations and standards development.

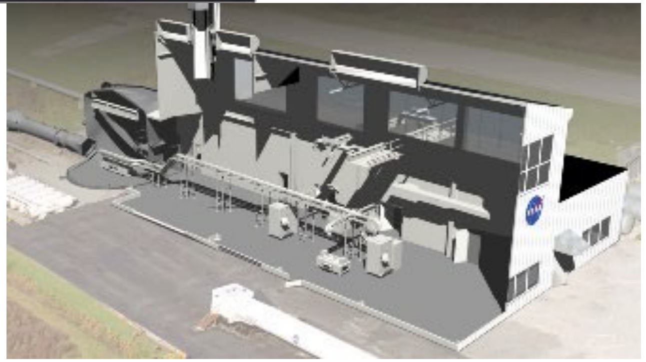
Technology Development and Barrier Challenges

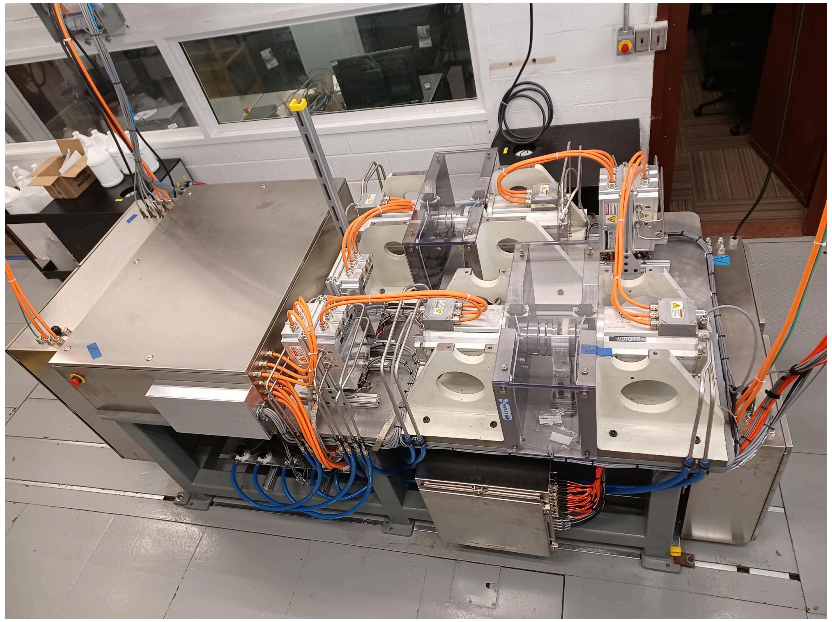
Technical Performance	Technical Performance Description	Target Performance
KPP/TPM-1	Total Power level of the Integrated MW-Class Powertrain System	1.5MW
KPP/TPM-2	Power level of individual electrical components	1MW
KPP/TPM-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V
KPP/TPM-4	Altitude Capability of the Integrated MW-Class Powertrain System	30,000 ft.
KPP/TPM-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg
KPP/TPM-6	End to End loss of the Integrated MW-Class Powertrain System	20%
KPP-7	Mission Fuel Burn/Energy Reduction	4%

Integrated Ground Testing

- Control systems will play a vital role in ensuring the realization of electric powertrain technologies
  - Hardware-In-the-Loop (HIL) testing is a means to bridge the gap between conceptual simulations and full-scale system testing

NASA Electric Aircraft Testbed (NEAT) facility
- Test integrated powertrains in MW-class
- Simulated Altitude



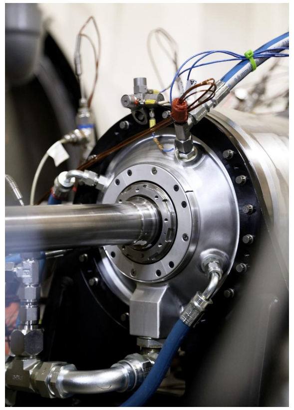


Hybrid Performance Emulation Rig (HyPER)
- <100 kW facility with energy storage

EPFD Industry Partners

NASA selected two U.S. companies to that will rapidly mature Electrified Aircraft Propulsion technologies through ground and flight demonstrations.

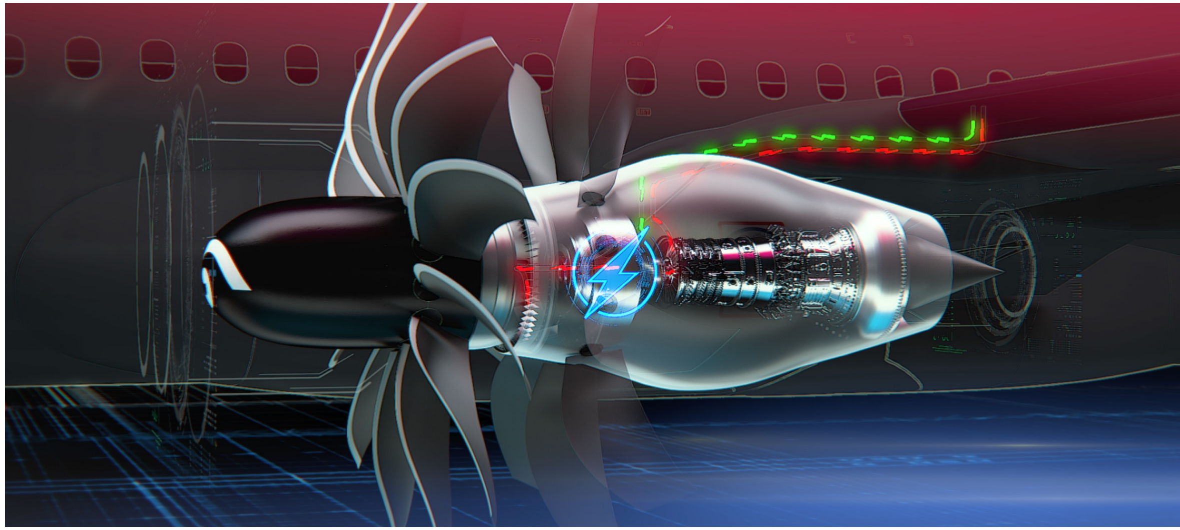
GE Aviation, $179 million.



- Partnered with Boeing to modify Saab 340B powered by GE CT7-9B turboprop engines
- Megawatt-class and multi-kilovolt hybrid-electric propulsion system tested in simulated altitude conditions at NASA NEAT facility

Future Engine Designs

- Hybrid electric compatible with Sustainable Aviation Fuel and hydrogen
- Demonstrator informs future GE engine product designs with hybrid electric capability



EPFD Industry Partners

NASA has selected two U.S. companies to that will rapidly mature Electrified Aircraft Propulsion technologies through ground and flight demonstrations.

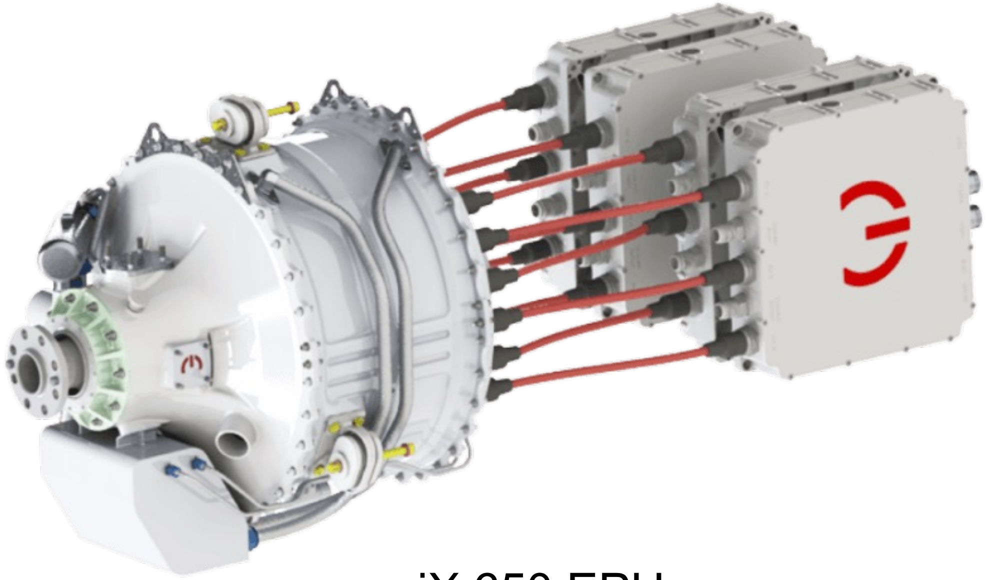
magniX, $74.3 million.

- Aims to demonstrate electric propulsion technology to power a hybrid De Havilland Canada Dash 7 aircraft, with first flight planned for mid-2020's

- The retrofitted aircraft will be powered by two PT6 engines and two magni650 electric propulsion units (EPUs)

Electric Propulsion Unit

- Advances the regional turboprop market



magniX 650 EPU

Long-Term Transport Technology and Innovation

Generational studies to inform future technology investments

2008-2019	2020-2029	2030 - 2039	2040 - 2050

Subsonic Fixed Wing

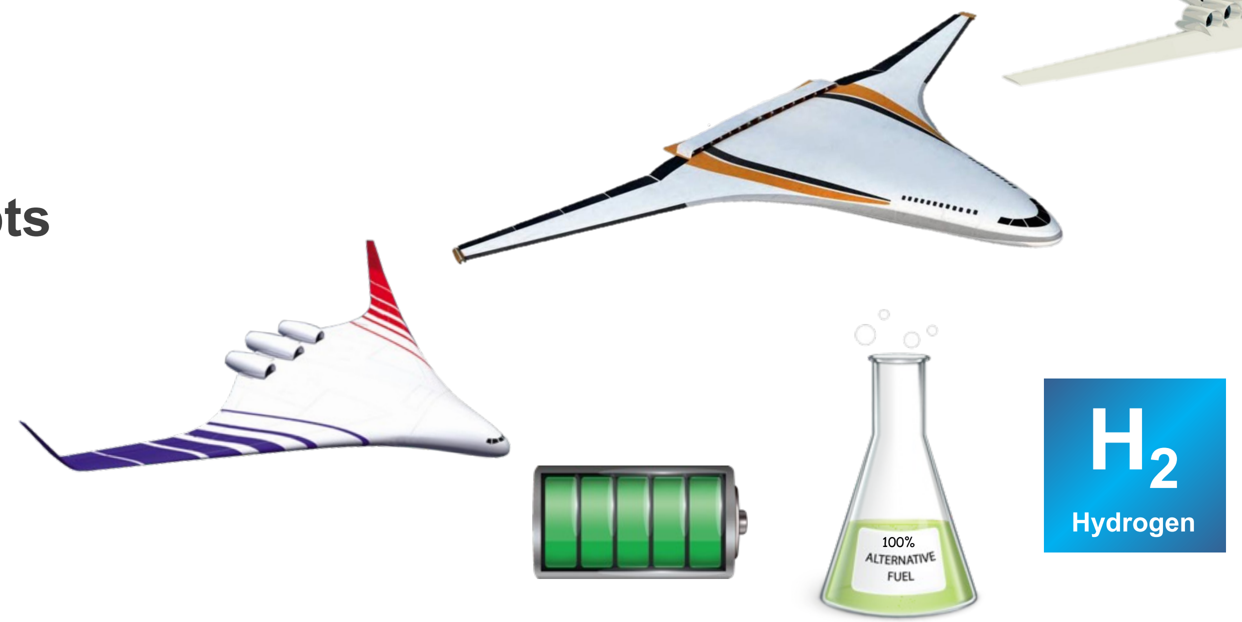
N+2 Studies, ERA for the 2020s Impact

N+3 Advanced Concept Studies SFNP for 2030s Impact

Concept Studies and Technology Development Needed for 2040s Impact

Opportunities to Define
Future Aviation Systems and Concepts

- Advanced Concept Studies for 2040+ EIS
- Net-Zero Emissions Concepts
- Promising Technologies and Architectures
- Support Aviation Community with NASA-unique Contributions



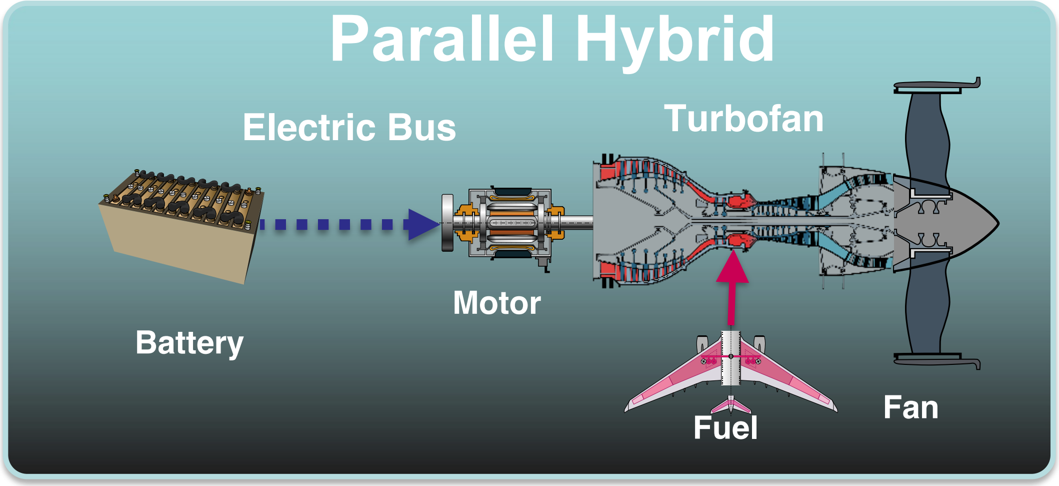
Innovations for 2040s and Beyond.

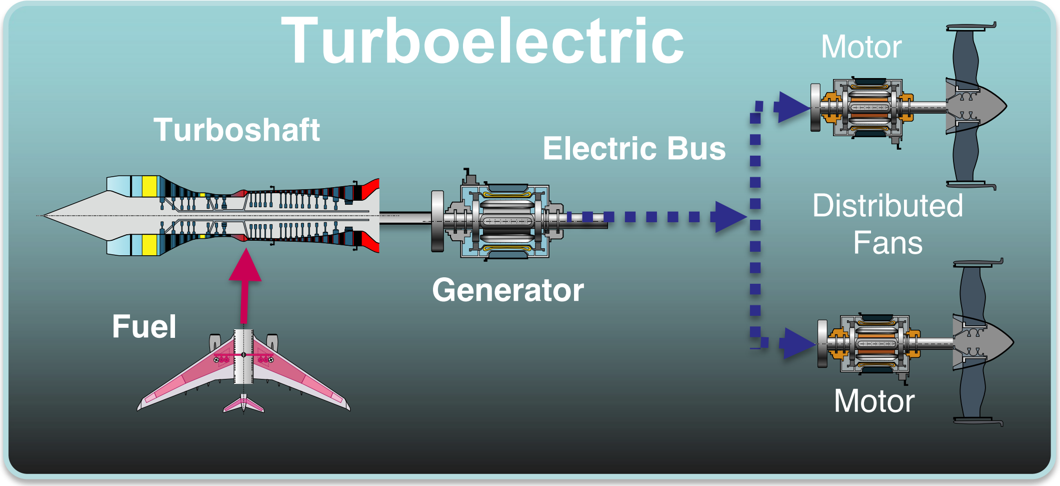
The Sustainability Challenge

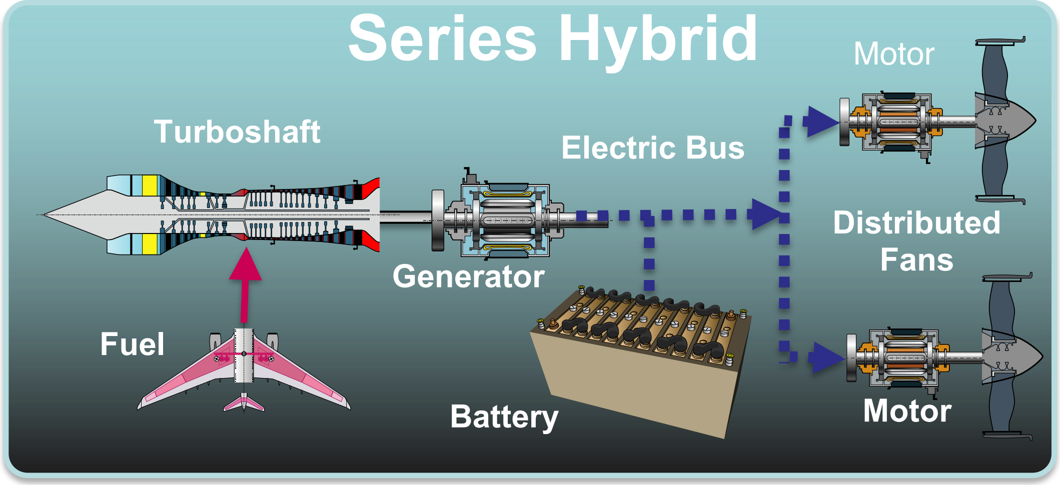
Revolutionizing Aviation through EAP

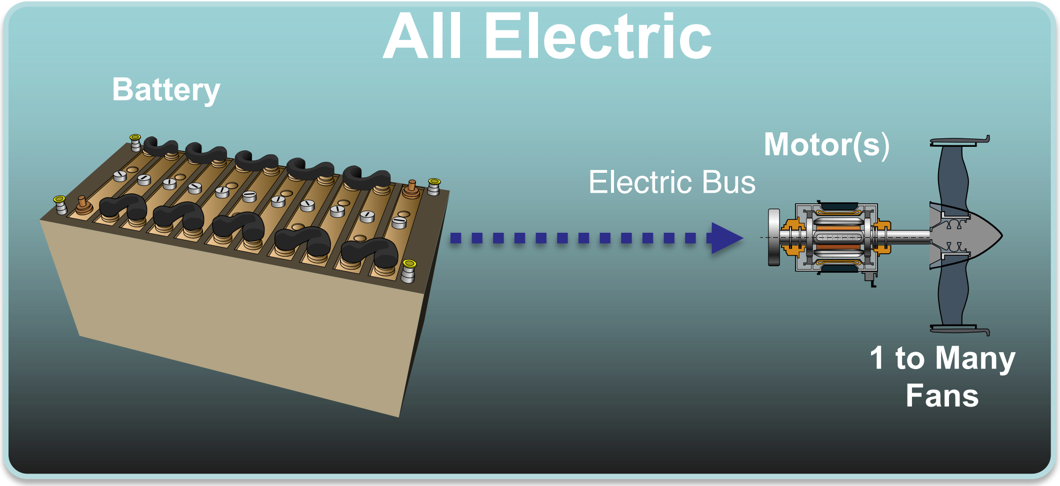
Systems-Level EAP Assessment

Fundamental EAP Architectures









The Breguet Range Equation

$$\boxed{R = \frac{V}{g \cdot SFC}\left(\frac{L}{D}\right)\ln\left(\frac{W_{\text{initial}}}{W_{\text{final}}}\right)}$$

'Range'

How far an airplane can fly

'Specific Fuel Consumption'

How efficiently an airplane turns fuel into thrust

'Lift-to-Drag'

How efficiently an airplane generates lift

'Mission Weight Fraction'

The takeoff weight divided by the landing weight

Understanding EAP Impact on Aircraft Performance

The [Electric] Breguet Range Equation

$$\boxed{R_{elec} = \frac{c_b}{g}\left(\frac{L}{D}\right)\ln\left(\frac{\mathrm{W}_{batt}}{\mathrm{W}_{\mathrm{TO}}}\right)\eta_i\eta_m\eta_p}$$

‘Range’

How far an airplane can fly

‘Battery Energy Density’

How efficiently a battery stores energy

‘Lift-to-Drag’

How efficiently an airplane generates lift

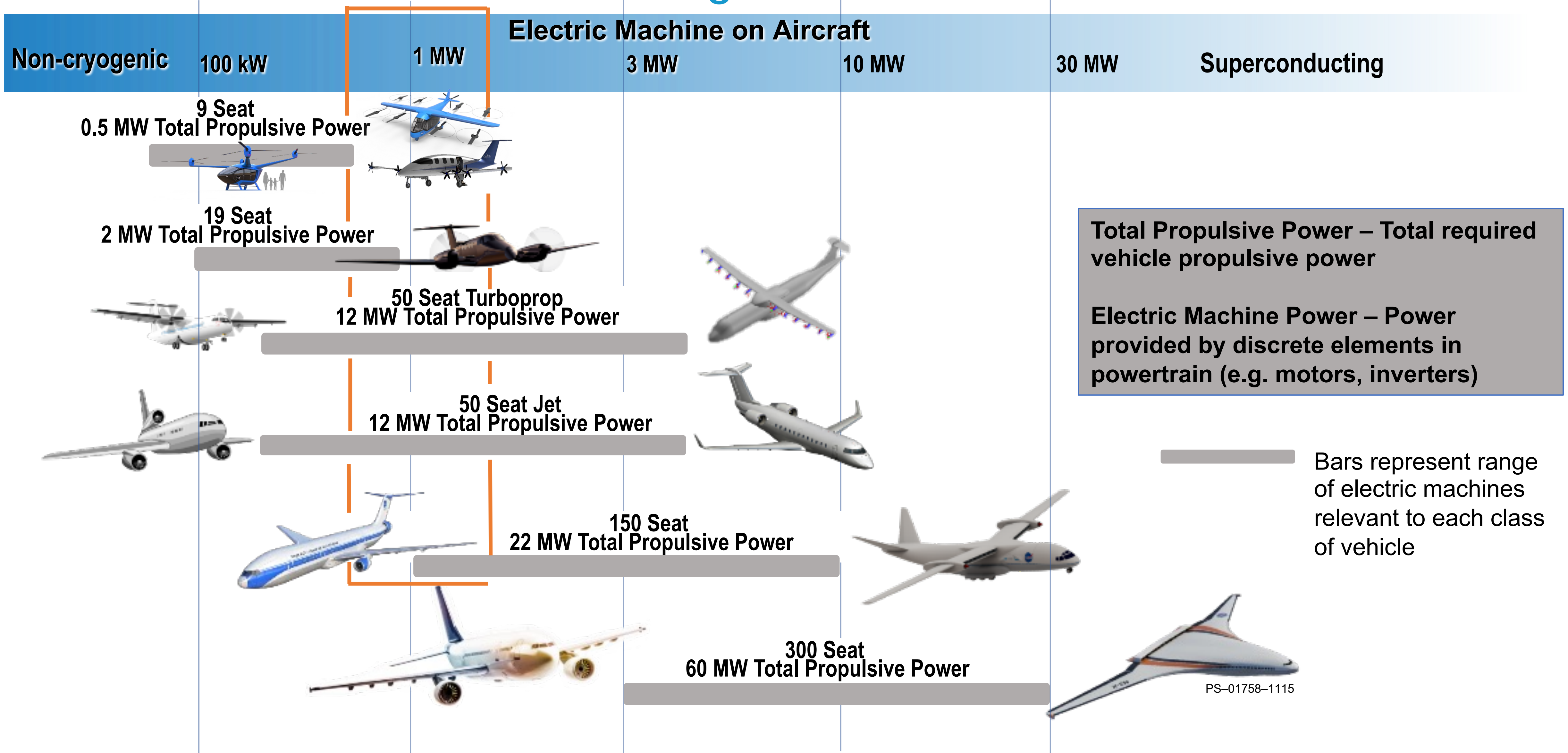
‘Battery Weight Fraction’

The battery weight divided by the takeoff weight

‘Powertrain Efficiency’

Inverter, motor, propulsive efficiencies

Electric Machine Power as a Strategic Parametric



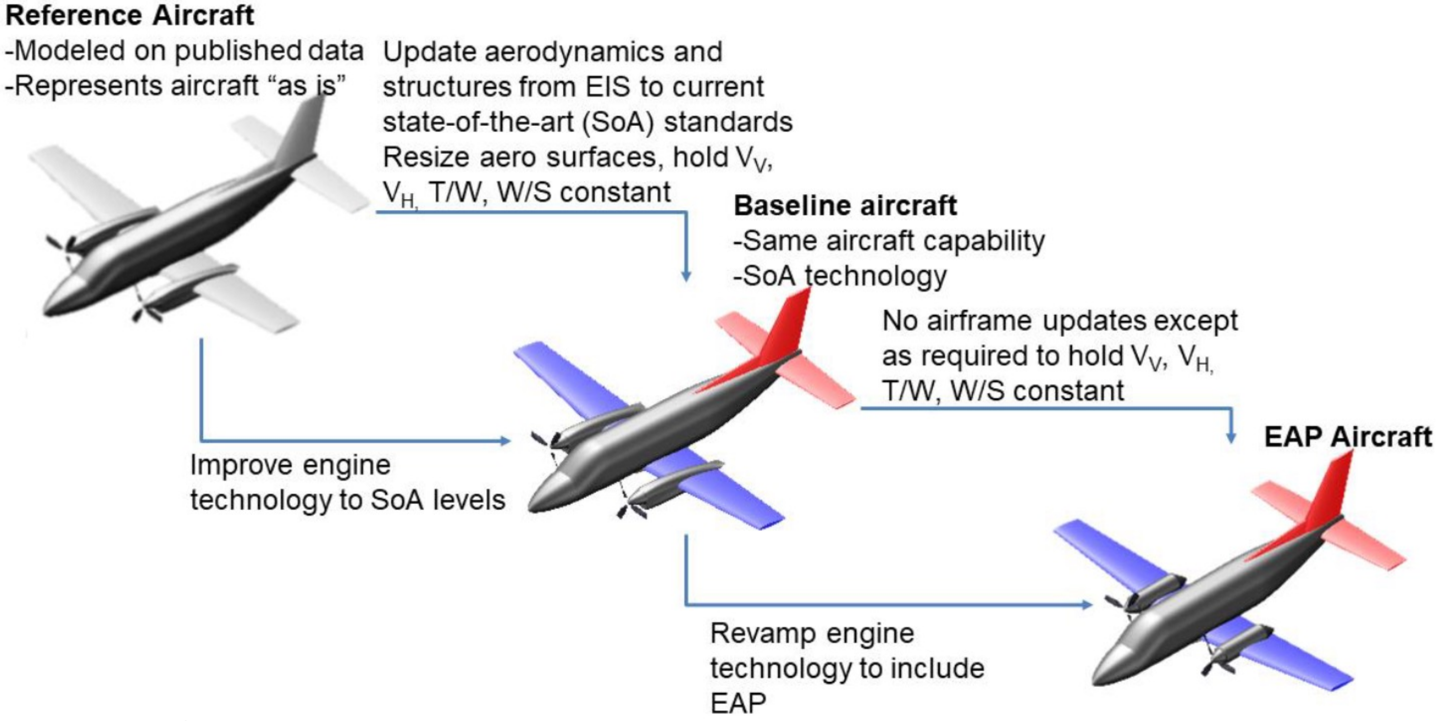
Broad application of MW-Class can revitalize existing short/thin haul and/or open new small aircraft markets.

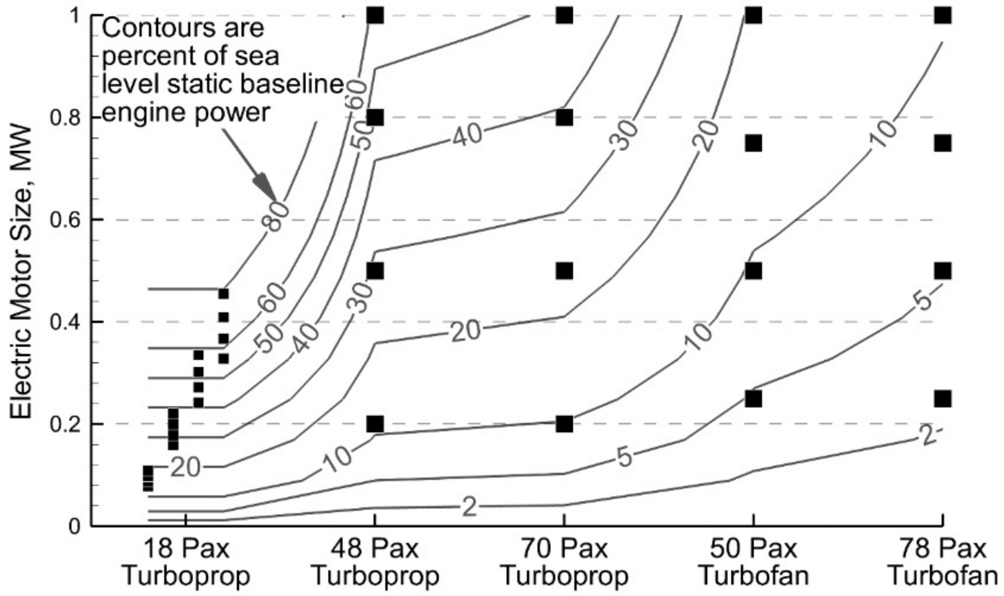
Aeronautics Systems Analysis for EAP

- Making sound investment decisions requires an understanding of both vision vehicle opportunities and challenges
- While EAP offers significant promise for vehicle-level emissions reductions, the realized benefits are sensitive to vehicle-integration, technology, and sizing assumptions
- Numerous studies have been conducted internally and with external partners to elucidate the challenges and implications on the vehicle system
- Results from a few recent studies will be summarized here, emphasizing the important of parametrics, metrics of interest, and assessment of cost and benefits

Parallel Hybrid Design Space Exploration Study (Marien et al.)

Aircraft	Passengers	Entry-Into-Service	Engine	Propulsion Architecture
Embraer EMB 110P	18	1968	PT6A-34	Turboprop
ATR 42-500	48	1995	PW127E	
ATR 72-600	70	2010	PW127F	
Embraer ERJ 145	50	1997	AE3007A1	Turbofan
Embraer E175	78	2002	CF34-8E	





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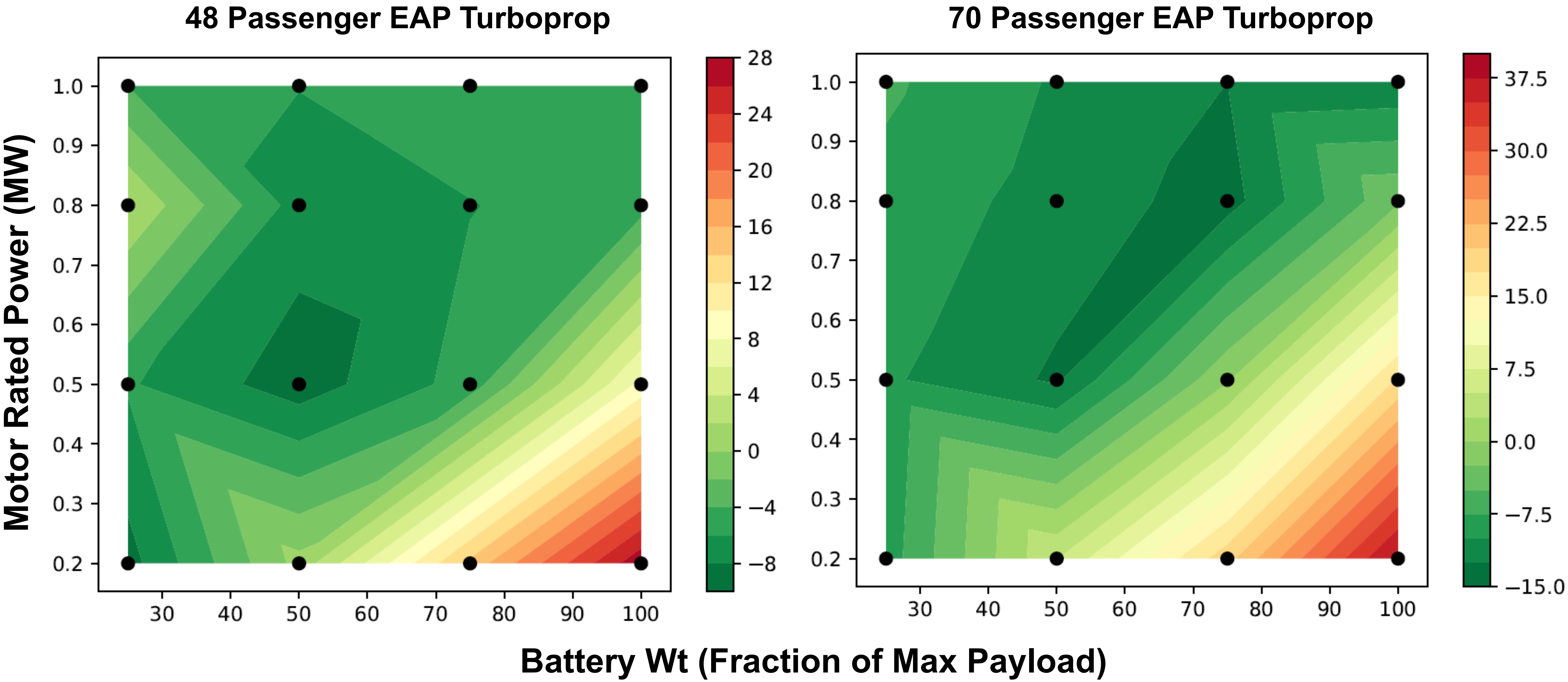
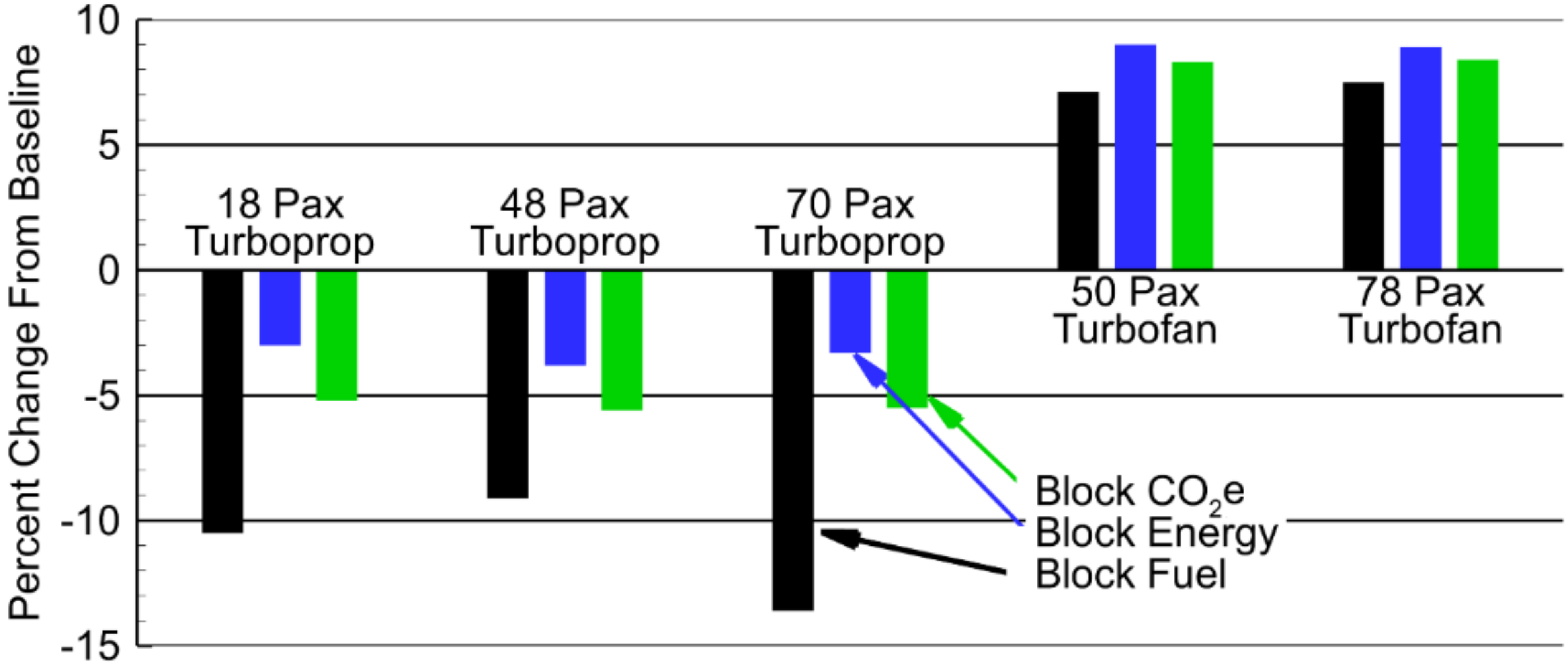
Parallel Hybrid Design Space Exploration Study (Marien et al.)

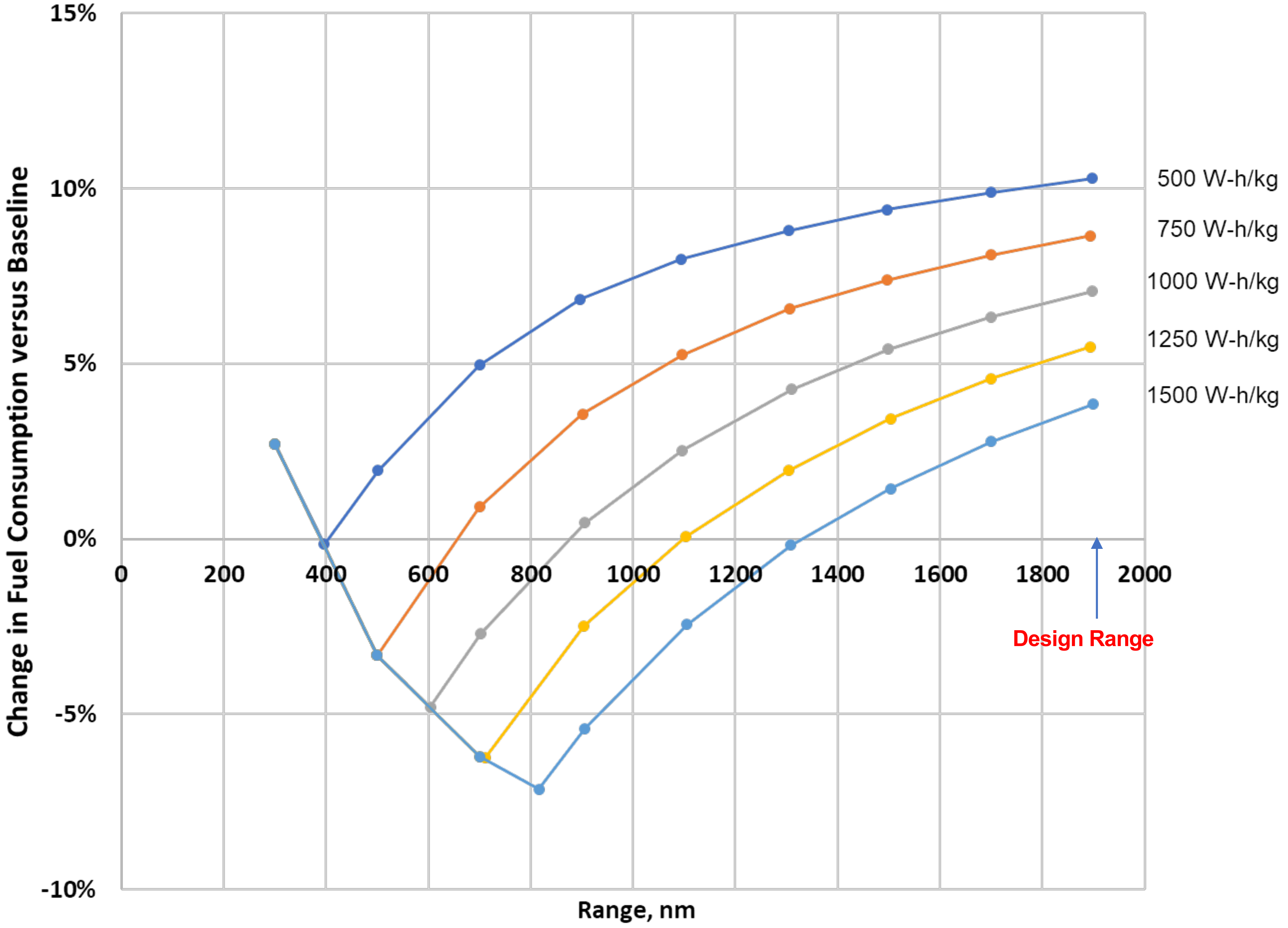


Summary of Block Fuel, Block Energy, Lifecycle CO2 Results



With an assumed BSE of 500 W-h/kg, lifecycle CO2e benefits are predicted for several of the configurations studied.

Relative Fuel Consumption as Function of Range (78 PAX Turbofan)



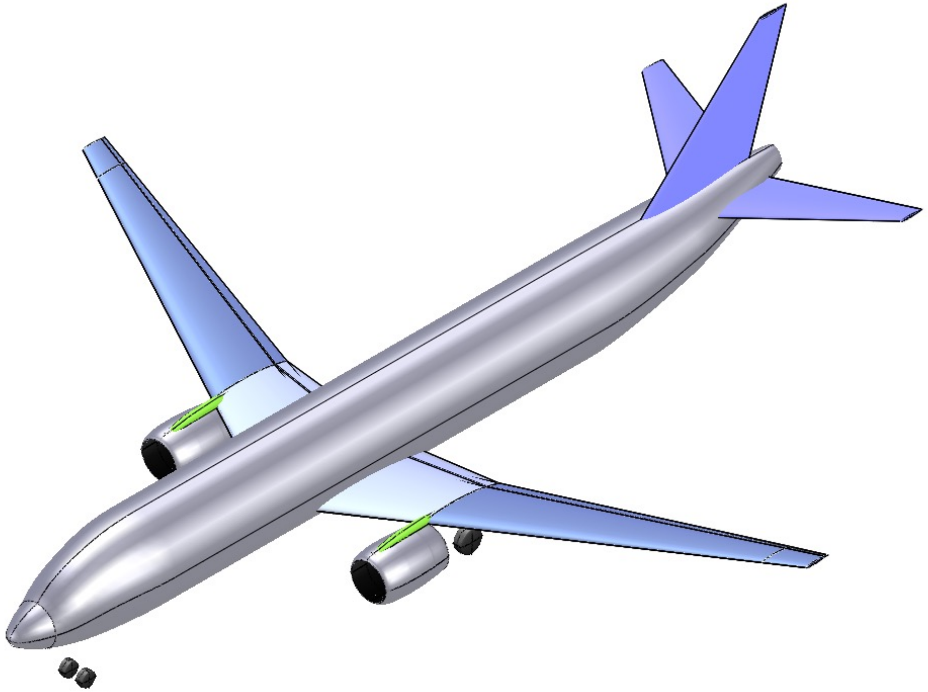
EAP Aircraft Cost Results Summary

	18 Passenger Turboprops		48 Passenger Turboprops		70 Passenger Turboprops		50 Passenger Turbofans		78 Passenger Turbofans	
	Baseline	EAP	Baseline	EAP	Baseline	EAP	Baseline	EAP	Baseline	EAP
Economic Mission Range (nm)	250	250	459	459	488	488	500	500	500	500
Empty Weight, less EAP hardware (lb)	6,412	6,817	21,617	22,765	26,135	28,585	23,876	25,553	43,844	46,916
EAP hardware (lb)	--	964	--	3,290	--	8,947	--	4,257	--	7,596
Block Fuel (lb)	484	440	1,834	1,673	1,949	1,698	2,212	2,185	3,645	3,524
Block Electricity (kW-h)	--	157	--	496	--	1,358	--	1,045	--	1,531
DOC+I ($ /seat-mile)	0.491	0.531	0.199	0.218	0.081	0.097	0.131	0.150	0.112	0.130
% Change in DOC+I Compared to Baseline	--	8.1%	--	9.5%	--	19.8%	--	14.5%	--	16.1%

Despite reduced block fuel burn, added vehicle weight results in increased direct operating costs of parallel hybrid EAP vehicle concepts.

Mild Hybrid Electric Concept Study (Frederick et al.)

- Design exploration of 2035 mild hybrid electric single-aisle aircraft including e-Taxi and e-Climb
- Propulsion system architecture based on NASA Turbine Electrified Energy Management (TEEM)
- Alternative energy storage technologies considered – batteries, supercapacitors, flywheels



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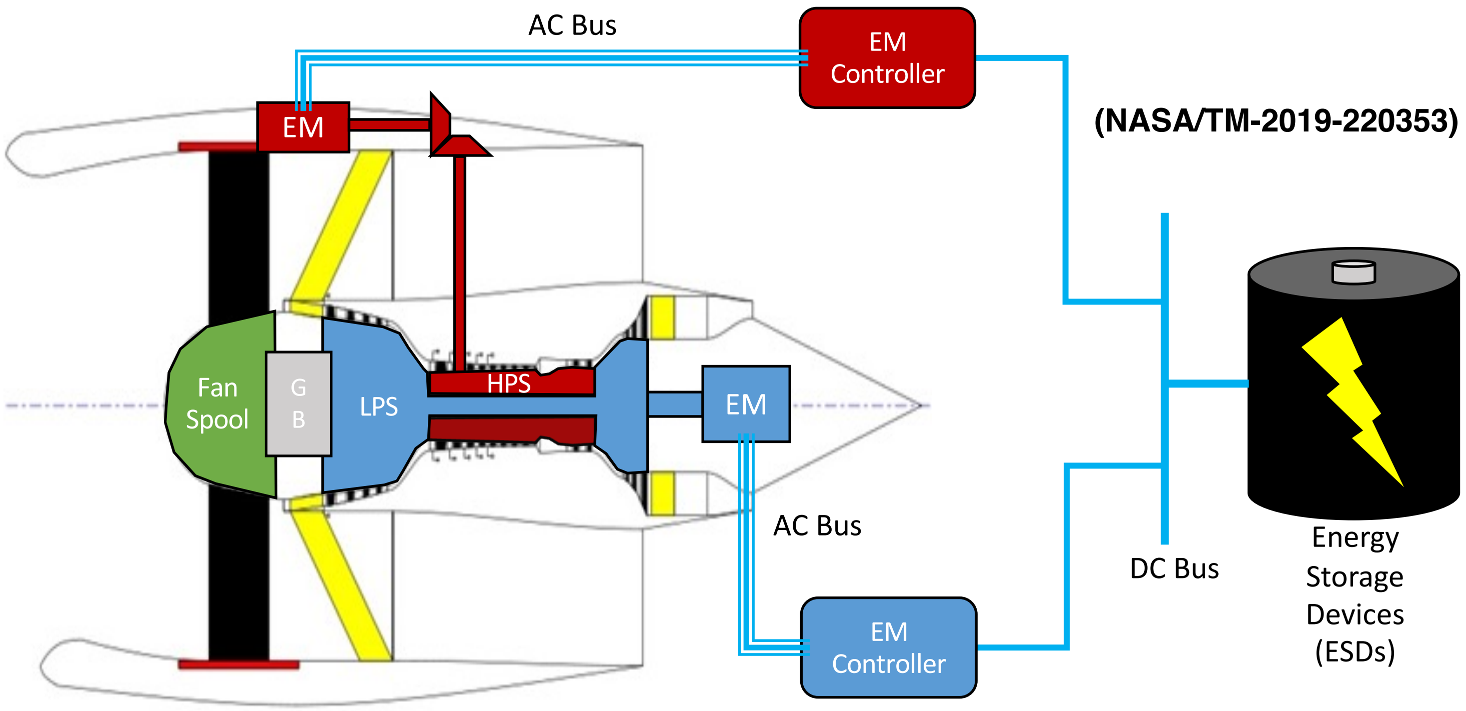


EM – Electric Machine
GB – Gearbox
HPS – High Pressure Spool
LPS – Low Pressure Spool
DC – Direct Current
AC – Alternating Current

Mild Hybrid Electric Concept Study (Frederick et al.)

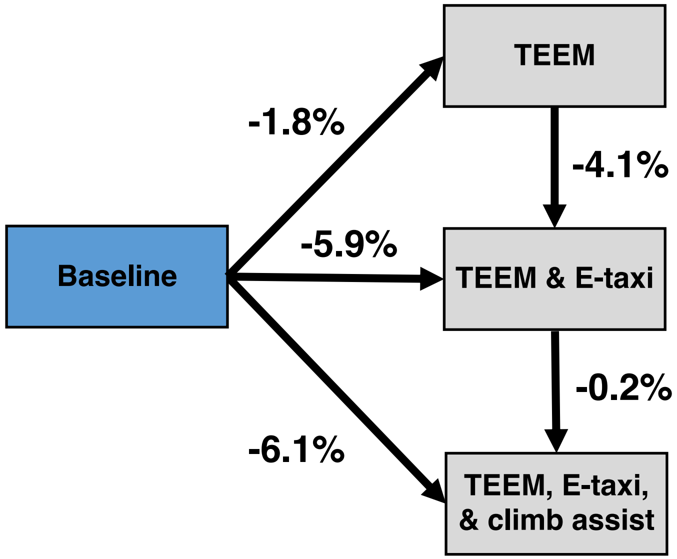
Energy storage system

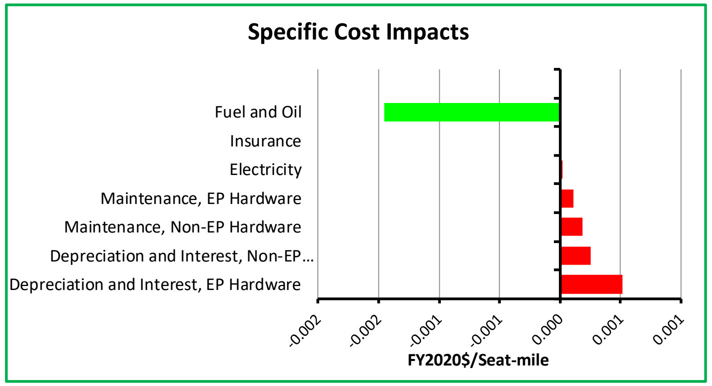
- Unusual requirements – high power, low energy capacity
- Peak power to meet requirements for TEEM and acceleration phases of E-taxi
- Continuous power for electric climb assist and constant speed E-taxi
- Best system is a combination – batteries for energy storage and supercapacitor for power output

	Specific Energy [W·h/kg]	Specific Power [W/kg]	
Configuration		Peak	Continuous
Battery	350	700	350
Supercapacitor	60	8,000	1,600
Flywheel*	150	500	500

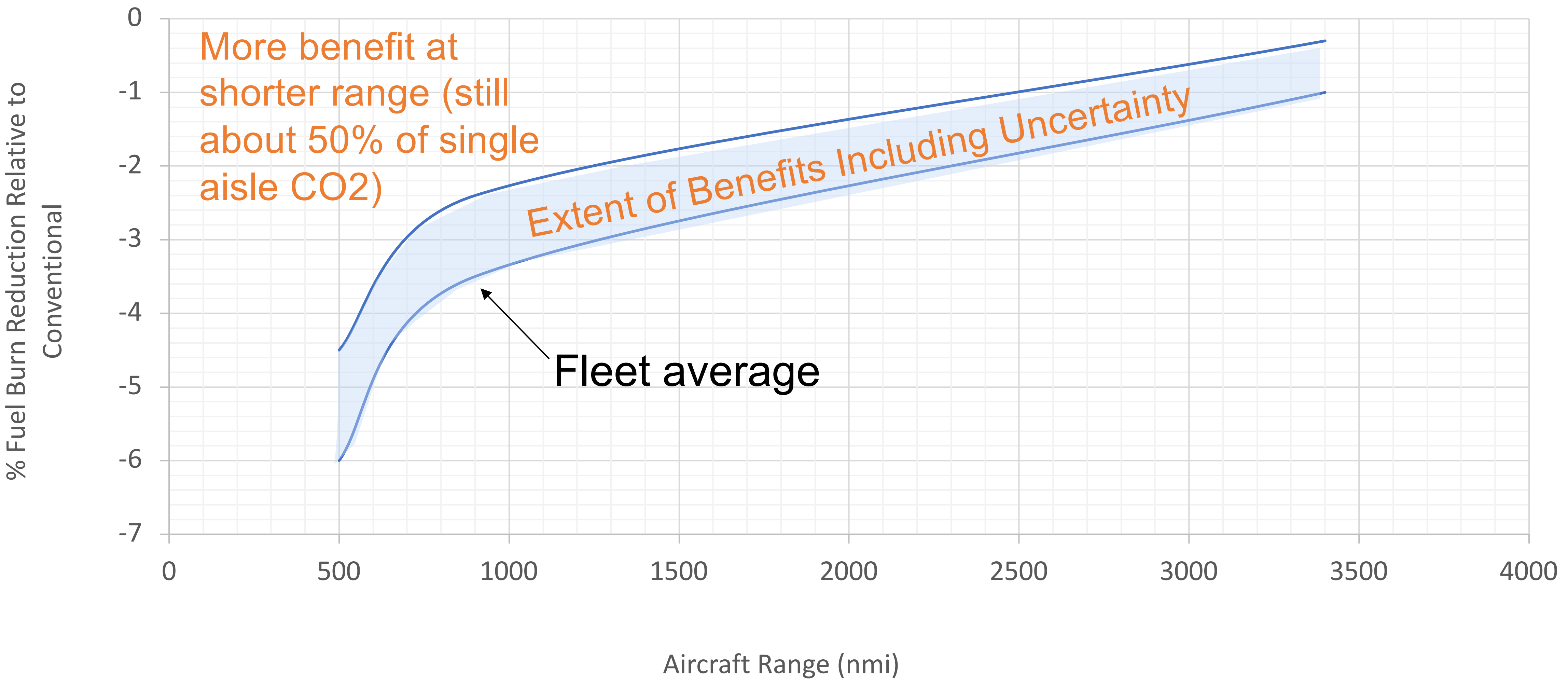
Integrated Performance Assessment

	Block fuel	
Configuration	Value [lbs]	wrt baseline
Baseline	6,900	-
TEEM* only	6,772	-1.8%
E-taxi only	6,638	-3.8%
TEEM* and E-taxi	6,491	-5.9%
TEEM*, E-taxi, and 400kW climb assist	6,478	-6.1%





Mild Hybrid Electric Concept Study for EIS 2030 (Gladin et al.)



https://arc.aiaa.org/doi/10.2514/6.2017-0338

Summary

- ARMD is making significant investment in EAP component and integrated system technologies and is leveraging expertise throughout industry and academia in this pursuit

- EAP is one critical element of the sustainable aviation solution; but it will take more

- EAP benefits at the integrated vehicle level are highly sensitive to a few key parametrics, including battery specific energy, motor specific power, and component efficiencies

Environmental sustainability may be the most significant aviation challenge we see in our lifetimes, and with your support, today's EAP research and technology development will help enable the revolutionary vehicle concepts needed to solve this problem.

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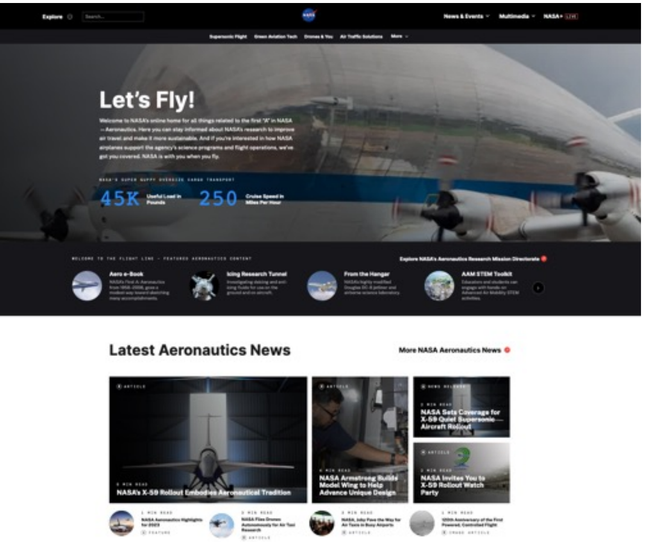

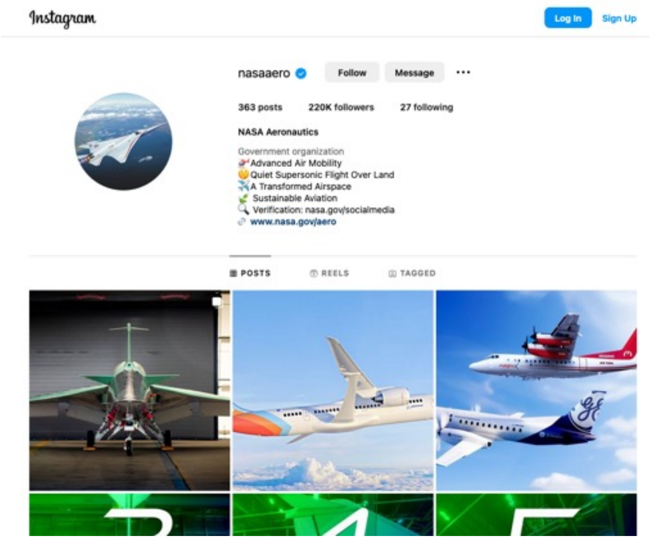

NASA