Aerospace Electrification-
Integrated Powertrain Development and Testing For More Electrified Aircraft

June 18th, 2025

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ITEC-Electric Aircraft Technology Symposium 2025

Why Aerospace Electrification

1

Energy Efficiency

- Finding pathways to electrified flight could lead to significant energy and disruptive improvements in Cost per Average Seat Mile (CASM), and lower operational expenses

2

Mission Flexibility

- Potential for purpose-built, “mission-optimized” EAP to meet operational demands of specific routes, markets, and policy goals

3

Regional Market Sector Growth

- Significant market exists for EAPs if the performance, operational and infrastructure requirements can be achieved[1]
- Hybrid vehicle can cover 73% of the existing mid-sized cargo network within the range of 750 miles[1]
- Conceptual Hybrid Electric Commercial Freighter ”closes” at 750 miles range[2]

Energy Efficiency

1

Individual Power Component Miniaturization

- 2 to 4x lower electrical losses
- 3 to 5x lower power system weight

2

MW Class Integrated Powertrain Development

- Thermal Management
- High Voltage Operations at Altitude
- System Integration

3

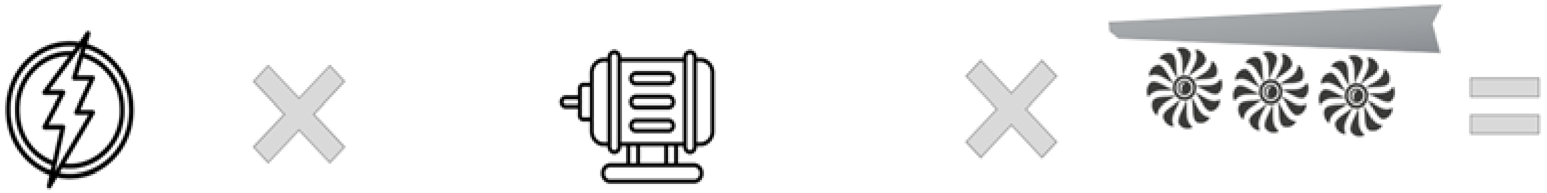
Energy Storage System Performance

- Battery System Performance Shortfalls

Source:Ralph Jansen, Peter Debock, Erik J. Stalcup, Timothy Dever, Jarred M. Wilhite, Dahlia Pham and Jacob M. Wishart AIAA 2025-1642
https://doi.org/10.2514/6.2025-1642

Motivation for the Electrification of the Propulsion System

- Example: Wide-body a/c converts chemical energy to thrust at approximately 40% efficiency.
- A fully electric powertrain with approaches like distributed electric propulsion can lead to an overall conversion efficiency greater than 75%.



Energy Carrier	Powertrain Efficiency	Propulsion Efficiency	Overall Efficiency
	55 – 57 %	70%	38-40 %
	90 – 95 %	85 %	76-81 %

Finding pathways to electrified flight could lead to significant energy and disruptive improvements in Cost per Average Seat Mile (CASM), and lower operational expenses

Integrated Powertrain Development

Barrier Risk

High Voltage Operation and Altitude

- MW-Class
- Power Stability
- Partial Discharge
- Performance

Risk Statement

Given that arcing, *partial discharge and corona of high power/ voltage transmission cables* can occur at cruise altitudes. Or, due to life effects, there is a possibility that the demonstrator could have **power system failures, resulting in potential loss of aircraft.**

What is the EAP A/C State of the Art

- 10-100KW
- Low Altitude
- Short range

Future Work

- High altitude
- Near-term: 800-1000V; Long-term: > 10kV

Integrated Powertrain Development

Barrier Risk

Powertrain System Integration

Risk Statement

Given that this powertrain system is novel, there is a possibility that it will not meet *stability, EMI compatibility, or performance requirements which will require redesign*, resulting in an **increase in cost and delay in schedule for Vision Vehicle development.**

Power Stability

EMI/EMC Compatibility

Performance

What is the EAP A/C State of the Art

- Small electric aircraft have demonstrated power system integration and operation
- Fault protection and stabilizing approaches based on ground or other transportation systems
- Power levels are typically less than 1MW

Future Work

- Light weight, low loss fault protection and power system stability components
- Certifiable approaches with high safety and reliability

Integrated Powertrain Development

Barrier Risk

Thermal Management

Risk Statement

Given that the amount of electrical power required for the demonstration is unprecedented in flight and generates *significant low quality/low grade heat*, there is a possibility that there will be **unforeseen challenges in designing a low parasitic power thermal management system.**

Low Grade Waste Heat

Design Low Parasitic Power TMS

Cryogenic Cooling

What is the EAP A/C State of the Art

- 20% end-to-end losses
- Liquid cooling electric engines is not the design penalty originally imagined compared to the design benefit

Future Work

- 5 to 10% end-to-end losses
- Liquid cooled systems with advance heat exchangers (leveraging additive manufacturing)

Integrated Powertrain Development

Barrier Risk

Battery System Performance Shortfall

Risk Statement

Given that the battery pack requirement exceeds current technology, there is a possibility that *the battery system design does not meet performance requirements*, resulting in **a higher battery weight and decrease Vision Vehicle performance.**

Aviation Grade

SoC Performance across Mission

Recharging in Flight

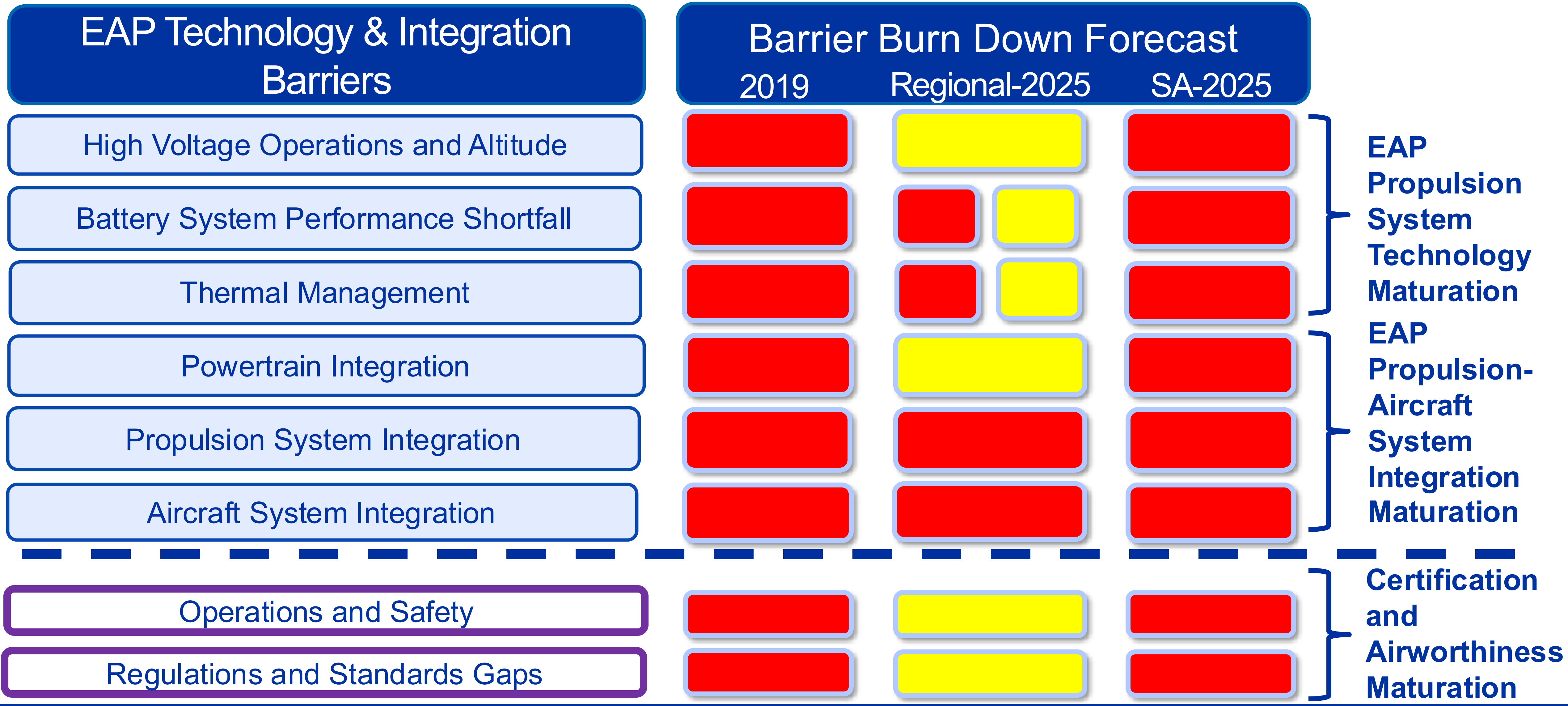
What is the EAP A/C State of the Art

- Significant volume and weight for Thermal Runaway (TR) protection required
- Regulatory legacy fuel reserve restricts novel concepts
- Regulatory Refueling turnaround limits range

Future Work

- Light weight safety measures to address TR
- Adopting mission-tailored reserves
- Incorporating recharging in addition to refueling

EAP Part 25 Transport Category
EIS Barrier Risks Burndown as of 2025



Mission Flexibility

1

Flexible Payload and Range

For the same aircraft, improvements in Battery Specific Energy expand maximum range performance, allowing for improved market coverage

Electrified aircraft propulsion unlocks the potential for purpose-built aircraft with flexible payload and range performance for energy-efficient regional air cargo and passenger operations

2

Efficient Power Splits

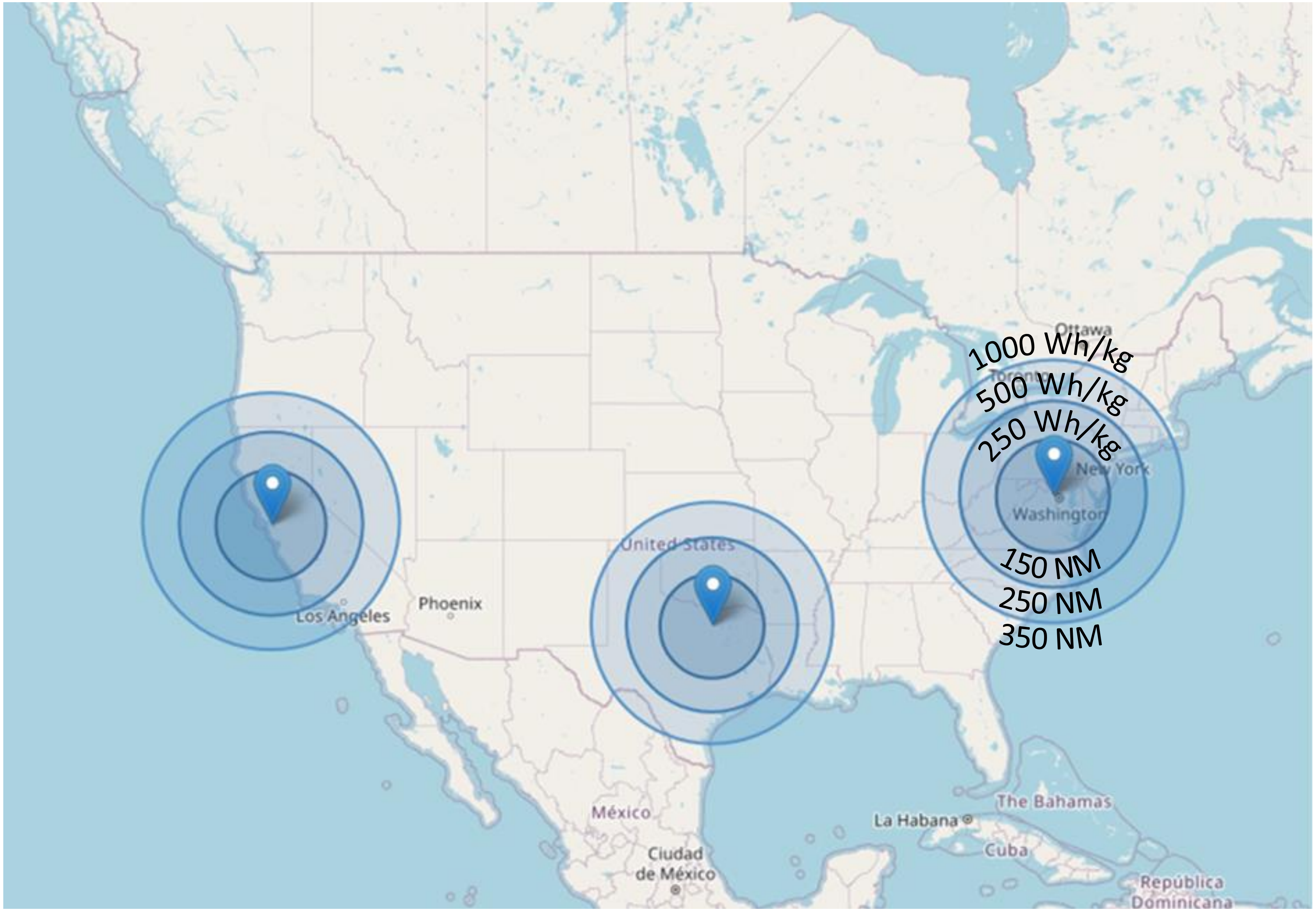
Parallel-hybrid architecture enables flexibility in efficient power-split throughout flight to achieve target ranges at optimal fuel savings

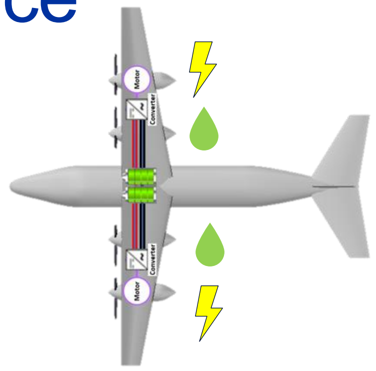
3

Battery Technology Performance

Payload capacity and range performance expands with improvements to battery technologies

50 PAX Near-Term Regional Turboprop Operations Tradespace

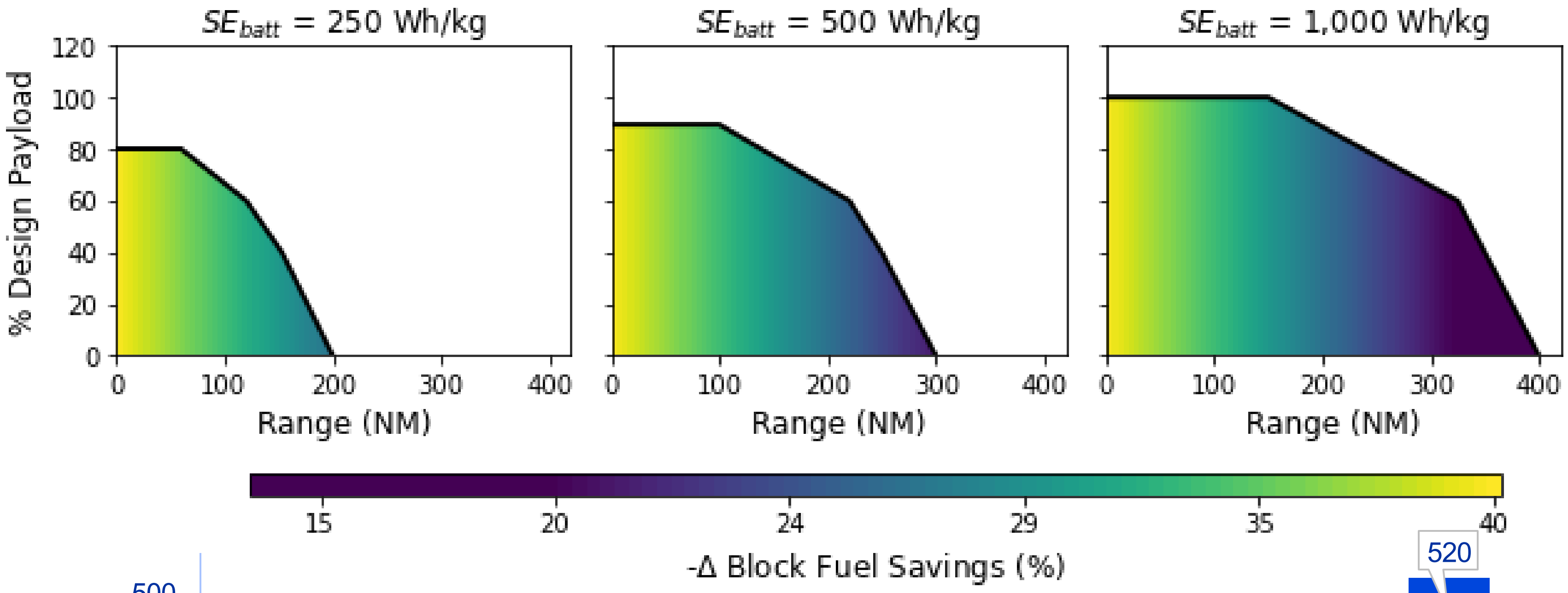


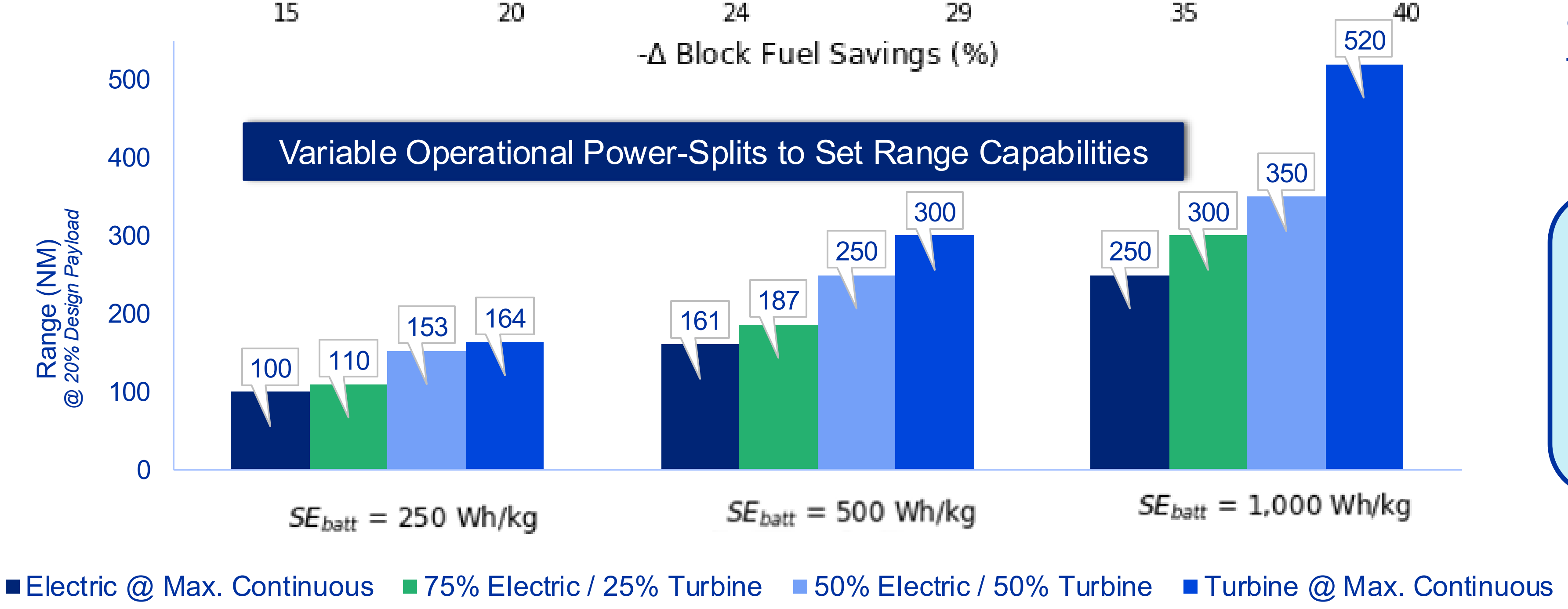


50/50 Cruise Power Split
At 20% of Design Payload

For the same aircraft, improvements in Battery Specific Energy expand maximum range performance, allowing for improved market coverage

Hybrid-Electric 50 PAX Regional Turboprop Payload-Range (50/50 Power-Split)



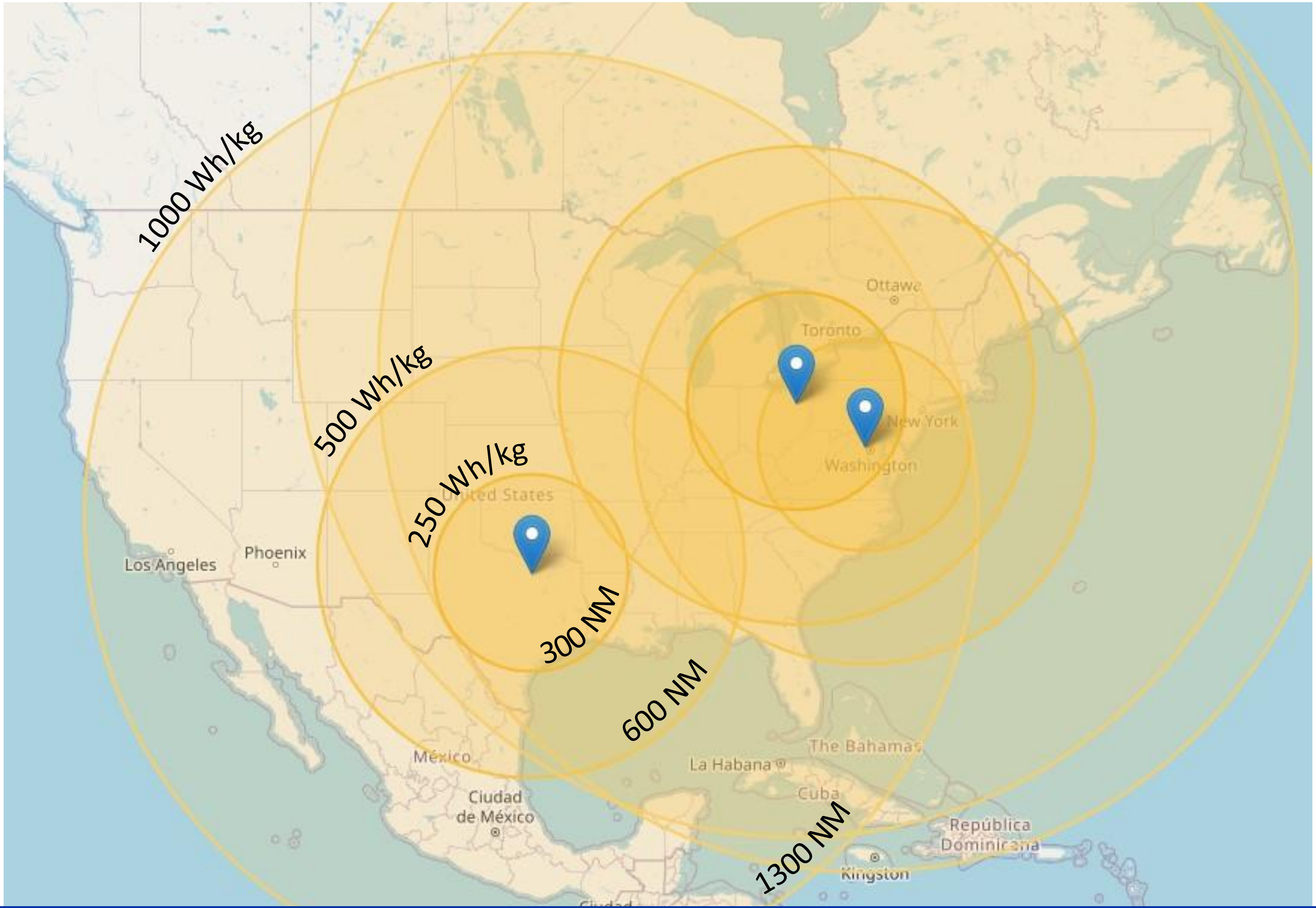


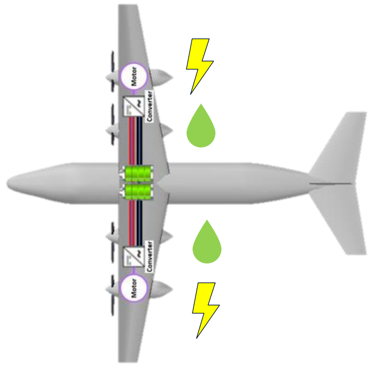
- Payload capacity and range performance expands with improvements to battery technologies

- Parallel-hybrid architecture enables flexibility in efficient power-split throughout flight to achieve target ranges at optimal fuel savings

Potential for purpose-built, "mission-optimized" EAP to meet operational demands of specific routes, markets, and policy goals

Mid-Term (2035) EAP Turboprop Freighter Operations Tradespace





50/50 Cruise Power Split
25,000 lb Design Payload

- Fuel savings of 24% to 52% across 250-1,500 NM missions translate directly to reductions in CO_2 emissions compared to conventional cargo aircraft

Ranges up to 1,300 NM capture 95% of total annual U.S. narrowbody cargo operations

Source: Wishart, Jacob & Jansen, Ralph & Mahavier, Kendall & Coppinger, Kaitlin. (2025). Hybrid Electric Turboprop Commercial Freighter (HETCOF) Market Study. 10.2514/6.2025-1641

Regional Market Sector Growth- Entry Into Service

1

EAP Regulatory Tradespace

- Acceleration of EAP standards being actively worked to enable electric engines, wiring and connectors, energy storage and airplane integration

2

EAP NAS Operations Tradespace

- Growth of Point to Point Networks
- Reduction of community noise impacts
- Reduction of ground-based emission impacts

3

EAP Ground Infrastructure Tradespace

- Enable small and regional airports to be economically competitive with large airportsns
- Emerging investments are occurring across the U.S. embracing electrified aircraft operations

Entry Into Service

Mature EAP A/C Technology Is a Necessary, but Not Sufficient, Condition for EIS

- Entry Into Service (EIS) is predicated on two key items:
  - A Mature Electrified Aircraft Propulsion (EAP) Technology that is Manufacturable
  - A Certifiable Airplane and Electric Engines
    - Traditional engine certification programs take 3-5 years
    - For EAP, there are no regulations, and special conditions are required, which can take 5-7 years
    - Special conditions require the development of acceptable means of compliance (MOC), which can take 3-5 years, supporting the special condition

To enable EIS by 2035, the standards to build Means Of Compliance (MOC) for special conditions must start in 2025

EAP A/C Regulations Tradespace

Both Operational and Aircraft Certification Must Be Addressed

Operational Certification

- Parts 91, General Operating and Flight Rules
- Part 135, Operating Requirements: Commuter and on Demand Operations (Regional)
- Part 121, Operating Requirements: Domestic, Flag, and Supplemental Operations (Single Aisle)

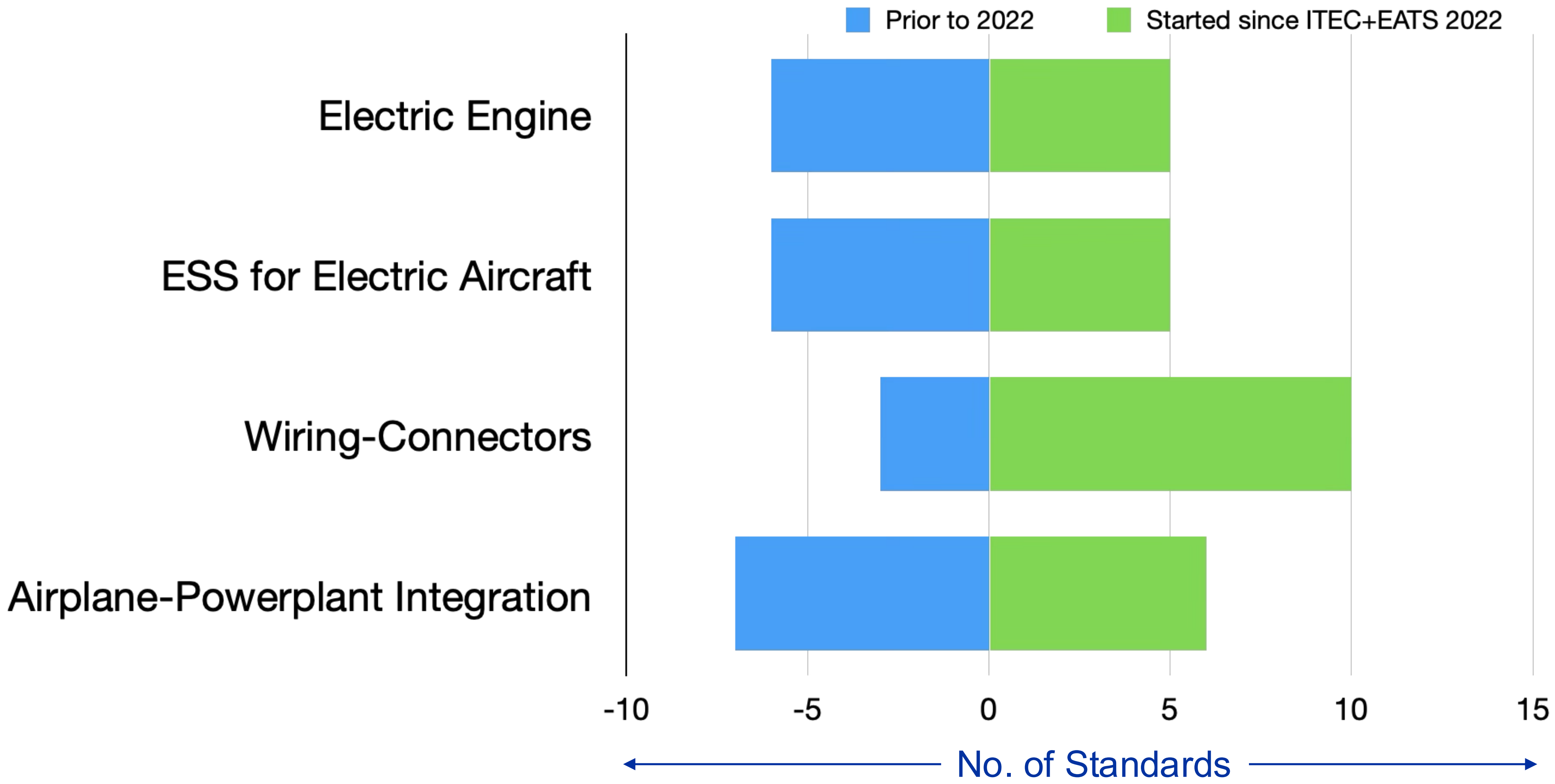
Aircraft Certification

- Part 25, Transport Category Airplanes
- Part 33, Aircraft Engines
- Part 35, Propellers

Highest Priority EAP A/C Standards Development Areas

Electric Engines		ASTM F39.05 SAE E-40 IEC 60439-4	• PMM Tests supporting HV cable loads • ASTM F3338 Standard Specification for Design of Electric Engines
Energy Storage Systems		ASTM F39.05 SAE AE-10 RTCA DO-311	• AS7499, Power Quality for HV systems (SAE AE-10) • New Guide for Design and Production of Energy Storage Systems to Power Aircraft Propulsion (ASTM F39)
Wiring & Connectors		SAE AE-10 SAE AE-7	• Cable tests for HV standards for AE-10 High Voltage Committee and AE-7 Aerospace Electrical Power and Equipment Committee (SAE) • Arc fault detection requirements and technology (SAE)
Airplane Integration		SAE E-40 ASTM F44 RTCA DO-160	• ARP8677, Safety Considerations for Electrified Propulsion Aircraft (SAE) • Installation of propellers for electric engines, • ASTM Development of Powerplant Displays for electric engines

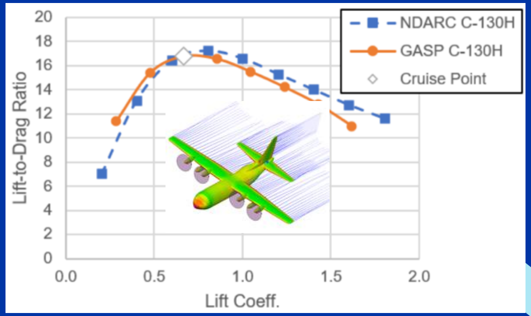
Number of Current Standards In Development by Highest Priority Technology Gap



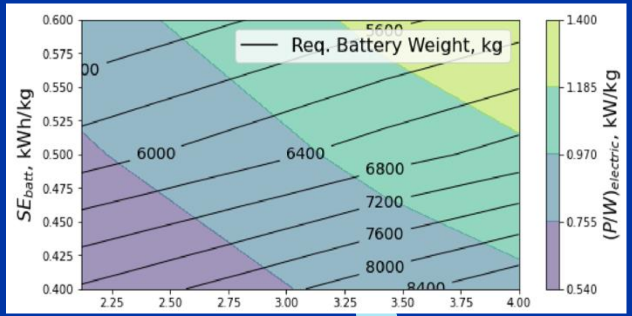
Over 35 standards began development since 2019. *Twenty-six since ITEC+EATS 2022!*

NAS Level Assessment of EAP Operations

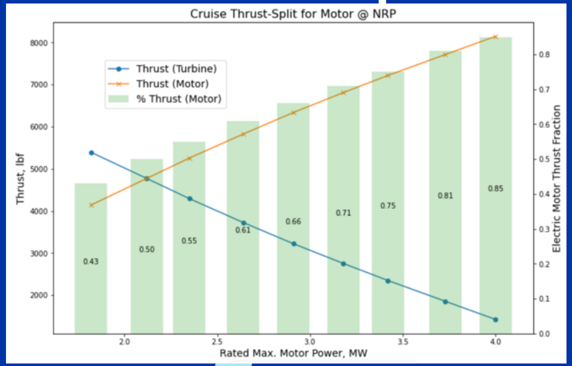
Aerodynamics



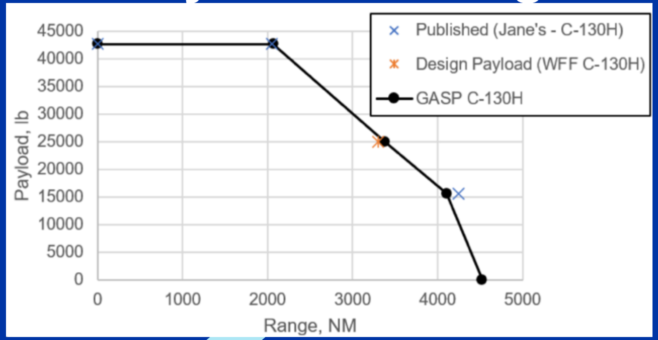
Required Battery Weight



Thrust Split

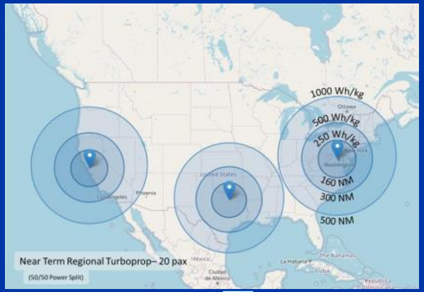


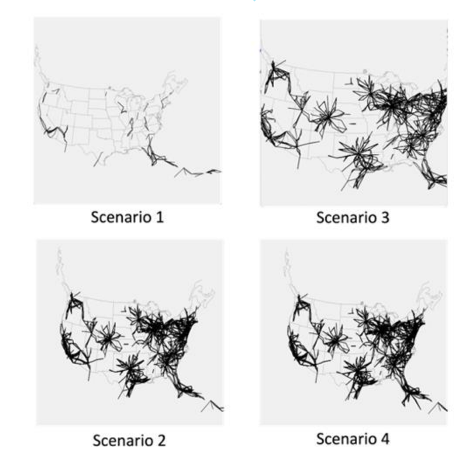
Payload vs Range



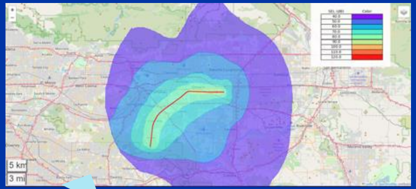
Modeled EAP Hybrid PAX Aircraft

NAS Level Assessment of EAP Operations

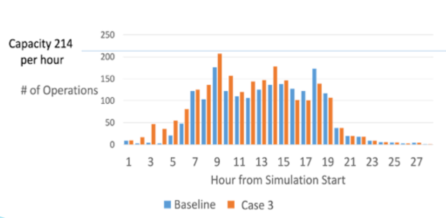




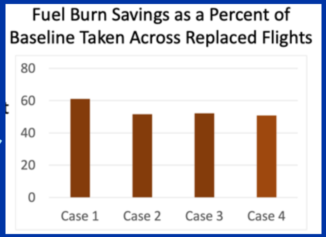
Community Noise Impact



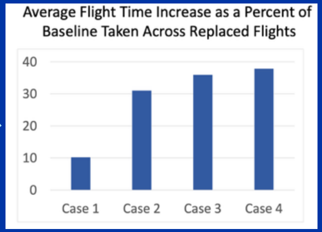
National Airspace System Simulator



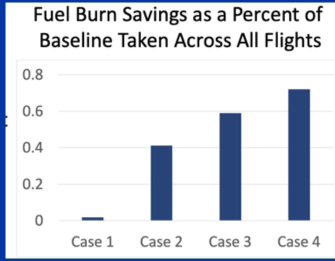
Airport Capacity



Fuel Savings Percent of Replaced Flights



Flight Time Increase



Fuel Savings Percent of Baseline

Replacement opportunities for flights within 300 miles.

- 1 vehicle for 1 EAP Hybrid
- 1 vehicle for up to 2 EAP Hybrid
- Etc

- Simulate proposed operational changes that can provide a pathway to introduce electrified vehicles to the NAS

- Obtain relevant metrics to assess Cost and Benefit of proposed operational changes

EAP Ground Infrastructure Tradespace

ENERGY PRICES

Assumption of stable future energy prices or adherence to user-defined escalation rates

TECHNOLOGY PERFORMANCE

Reliance on standard models and historical data for performance expectations of technologies (solar, wind, storage, etc.)

GRID RELIABILITY

Assumption of constant grid availability unless outage scenarios are specifically modeled

FINANCIAL PARAMETERS

Use of average financial metrics such as discount rates, incentives, and depreciation unless customized by the user

National Renewable Energy Lab (NREL): REopt Tool → **Determines power supply options and estimates associated capital expenditures for airports**

Source: NREL REopt https://reopt.nrel.gov/tool

EAP Infrastructure Parameters

Inputs

Drivers

Energy Costs and Revenue, Economics, Resilience, and Environment Goals

Technology Options

Renewable Generation, Conventional Supply, and Energy Storage

Loads

Electric Loads, Heating and Cooling, and Dispatchable Loads

Outputs

Technologies

Energy Mix and Size

Operations

Optimal Dispatch Strategy

Project Economics

Capital Costs, Operating Costs, and Net Present Value

Source: GaTech ASDL Grand Challenge Research: Customizable Hybrid Aviation & Renewable Grid Expansion Scenarios Dashboard

Customizable Hybrid Aviation Renewable Grid Evaluation Scenarios Dashboard

Optimize Airport Infrastructure

- Gap between existing and required airport infrastructure
- Infrastructure capital expenditure
- Asset sizing: solar, wind, and battery

Reduce Emissions

- Airport and grid projected emissions reduction
- GSE emissions reduction
- Power demand to reduce peak loads and optimize renewable energy sources

Maintain Schedule Integrity

- Flight schedule sensitivity to increased flights
- Flight and airport operations integrity

Quantify Energy Expenditure

- Airport electricity consumption: baseline vs required load
- GSE fuel savings

Why Aerospace Electrification?
In Summary

1

Energy Efficiency

Finding pathways to electrified flight could lead to significant energy and disruptive improvements in Cost per Average Seat Mile (CASM), and lower operational expenses

2

Mission Flexibility

For the same aircraft, passenger or freight, improvements in Battery Specific Energy expand maximum range performance, allowing for improved market coverage

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Regional Market Sector Growth

Significant market exists for EAPs if the performance, operational and infrastructure requirements can be achieved

EIS is predicated on a Mature EAP Technology that is Manufacturable, and Certifiable - Airplane and Electric Engines **AND** Infrastructure Ready

Acknowledgments

- NASA EPFD Project Team
- NASA EPFD Regulations and Standards Working Group
- NASA GRC EAP Technology Community
- NASA AAVP Advance Air Transport Technology Team
- NASA Ames EAP Systems Analysis Team
- Georgia Tech ASDL EPFD Grand Challenges Systems Analysis Team
- NASA Ames NAS Digital Twin Team
- DOT VOLPE
- ARPA-e: ASCEND, PROPEL-1K
- University of Michigan EAP Systems Analysis Team

We are Closer to an Electrified Future, *Fully Charged and Ready to Go!*

Thank you!

References

Title 14 Code of Federal Regulations, https://www.ecfr.gov/current/title-14 (see Parts 25, 33, 35, 91, 135, and 121).

These are references info from ARPA-E that might be useful to talk end to end losses and battery related stuff. They are part of the reference in the HETCOF paper that speak to the motivation graphic that Gaudy showed in our first meeting. That is from the HETCOF technical paper jointly written between NASA and ARPA-E.

[1] ARPA-E, "Ultrahigh Temperature Impervious Materials Advancing Turbine Efficiency (ULTIMATE)", DE-FOA-0002337, 5 June 2020, https://arpa-e.energy.gov/technologies/programs/ultimate

[2] Kirk, K, "Electrifying transportation reduces emissions AND saves massive amounts of energy", Yale Connections, 7 August, 2022.

[3] Borlaug, B., Salisbury, S., Gerdes, M. and Muratori, M., "Levelized cost of charging electric vehicles in the United States." Joule 4, no. 7 (2020): 1470-1485.

[4] ARPA-E, "Grid-free Renewable Energy Enabling New Ways to Economical Liquids and Long-term Storage (GREENWELLS)", DE-FOA-0003234, 25 January 2024, https://arpa-e.energy.gov/technologies/programs/greenwells

[5] ARPA-E, "Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)", DE-FOA-0002240, 31 January 2020, https://arpa-e.energy.gov/technologies/programs/reeach

[6] de Bock, H.P., Tew, D.E., Rahman, Z., Lecoustre, V. and Cox-Galhotra, R.A., 2023, June. Progress Toward Climate-Friendly Aviation in the ARPA-E ASCEND and REEACH Programs. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 86939, p. V001T01A039). American Society of Mechanical Engineers

[7] Wishart, Jacob & Jansen, Ralph & Mahavier, Kendall & Coppinger, Kaitlin. (2025). Hybrid Electric Turboprop Commercial Freighter (HETCOF) Market Study. 10.2514/6.2025-1641

[8] Ralph Jansen, Peter Debock, Erik J. Stalcup, Timothy Dever, Jarred M. Wilhite, Dahlia Pham and Jacob M. Wishart AIAA 2025-1642 https://doi.org/10.2514/6.2025-1642

This one specifically gives the big picture reasons energy and cost are saved, but it is written in the context of a car:

https://yaleclimateconnections.org/2022/08/electrifying-transportation-reduces-emissions-and-saves-massive-amounts-of-energy/

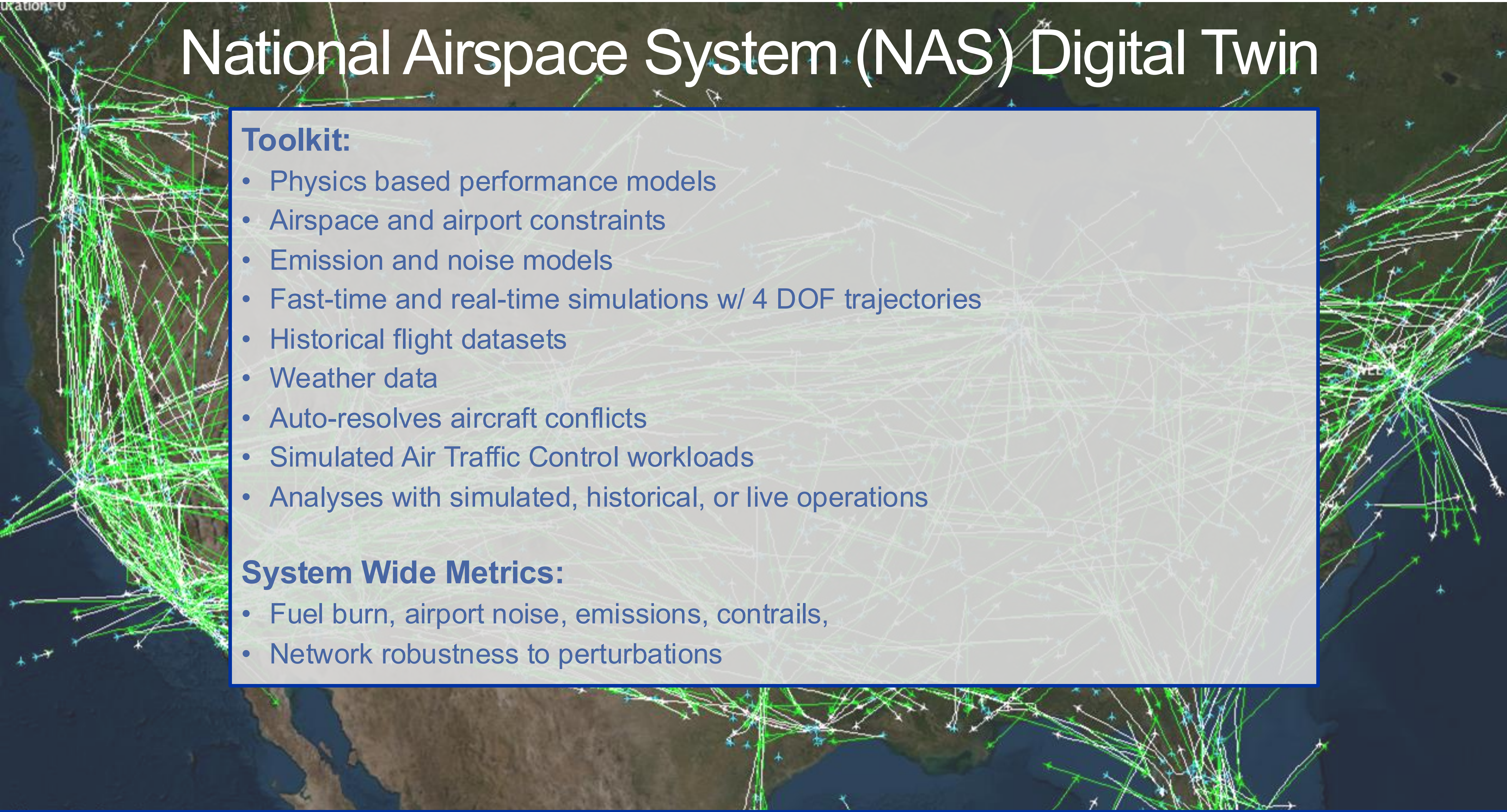
Hybrid Electric Turboprop Commercial Freighter (HETCOF)

- Hybrid turboprop intended for regional cargo operations.
- Range: Economic – 750nm, Design 2400 nm
- Electric Power level – up to ≈ 8 MW total in two ≈ 4MW electric engines
- Significant portion of total mission energy for economic mission stored in batteries
- Study done at a range of technology assumptions to determine key performance parameters for components and subsystems like power, energy storage, thermal, ect.
- Market – domestic freight operations

Publications:

- Hybrid Electric Turboprop Commercial Freighter Opportunity, AIAA Scitech 2026
- Hybrid Electric Turboprop Commercial Freighter (HETCOF) Market Study, AIAA Scitech 2026

National Airspace System (NAS) Digital Twin



Toolkit:

- Physics based performance models
- Airspace and airport constraints
- Emission and noise models
- Fast-time and real-time simulations w/ 4 DOF trajectories
- Historical flight datasets
- Weather data
- Auto-resolves aircraft conflicts
- Simulated Air Traffic Control workloads
- Analyses with simulated, historical, or live operations

System Wide Metrics:

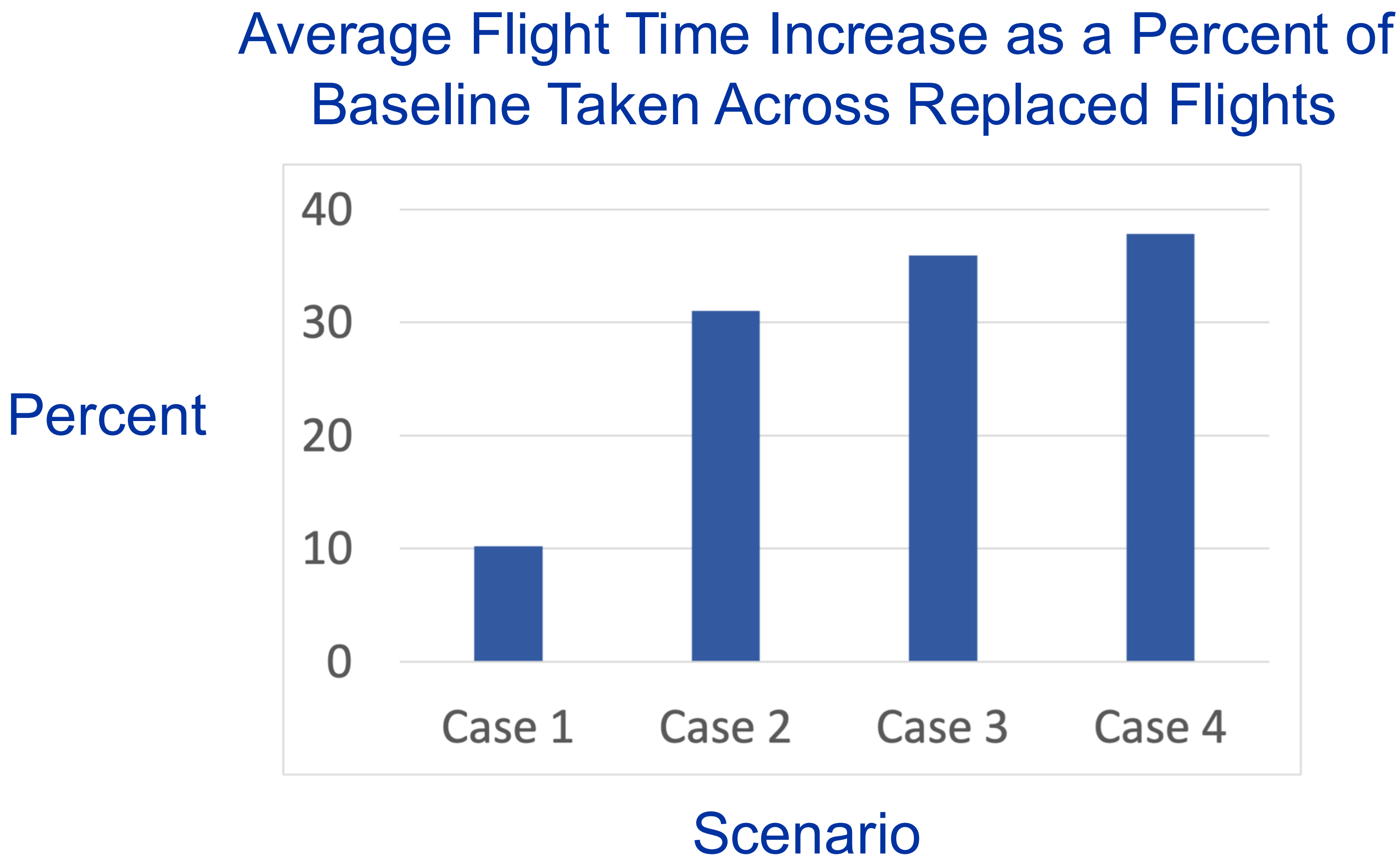
- Fuel burn, airport noise, emissions, contrails,
- Network robustness to perturbations

Source: NASA ARC NAS Digital Twin Modeling Tool

NAS Level Assessment Of EAP Operations

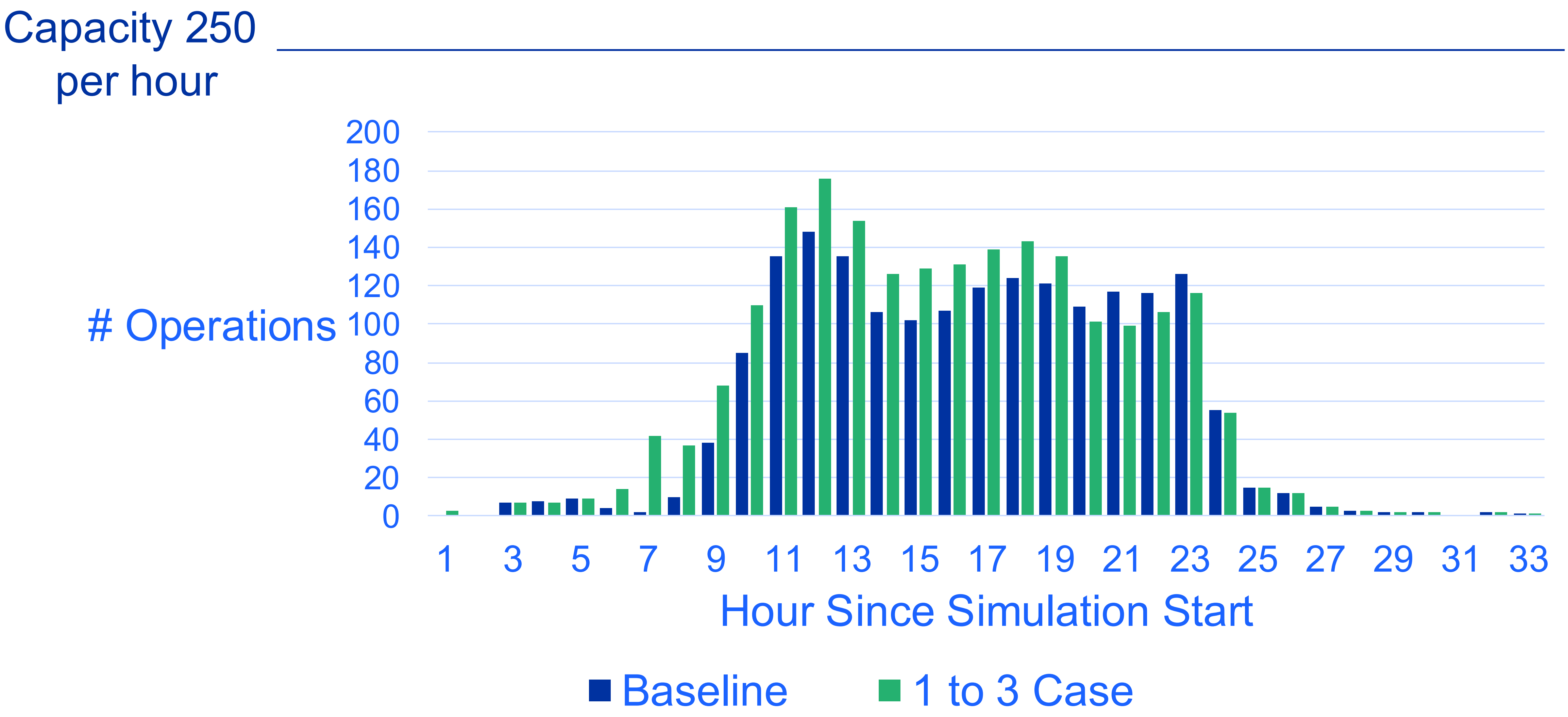
Data driven methodology for introducing EAP into the NAS which considers airport capacity, fuel savings, flight time increases, noise…

Average Flight Time Increase (Passenger Perspective)



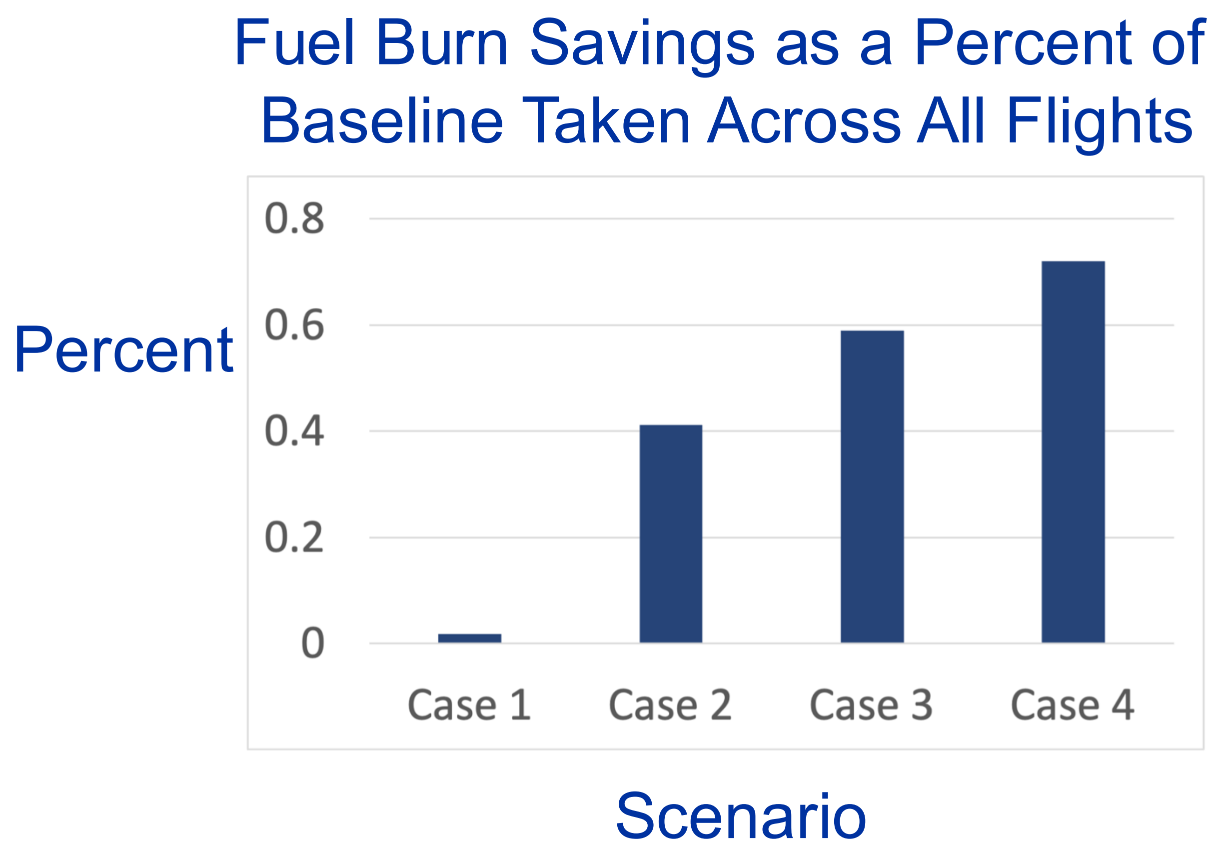
Case - replaced / added flights
Case 1 – 157 / 0; Case 2 – 2139 / 1982; Case 3 – 2618 / 2940; Case 4 – 2997 / 4077

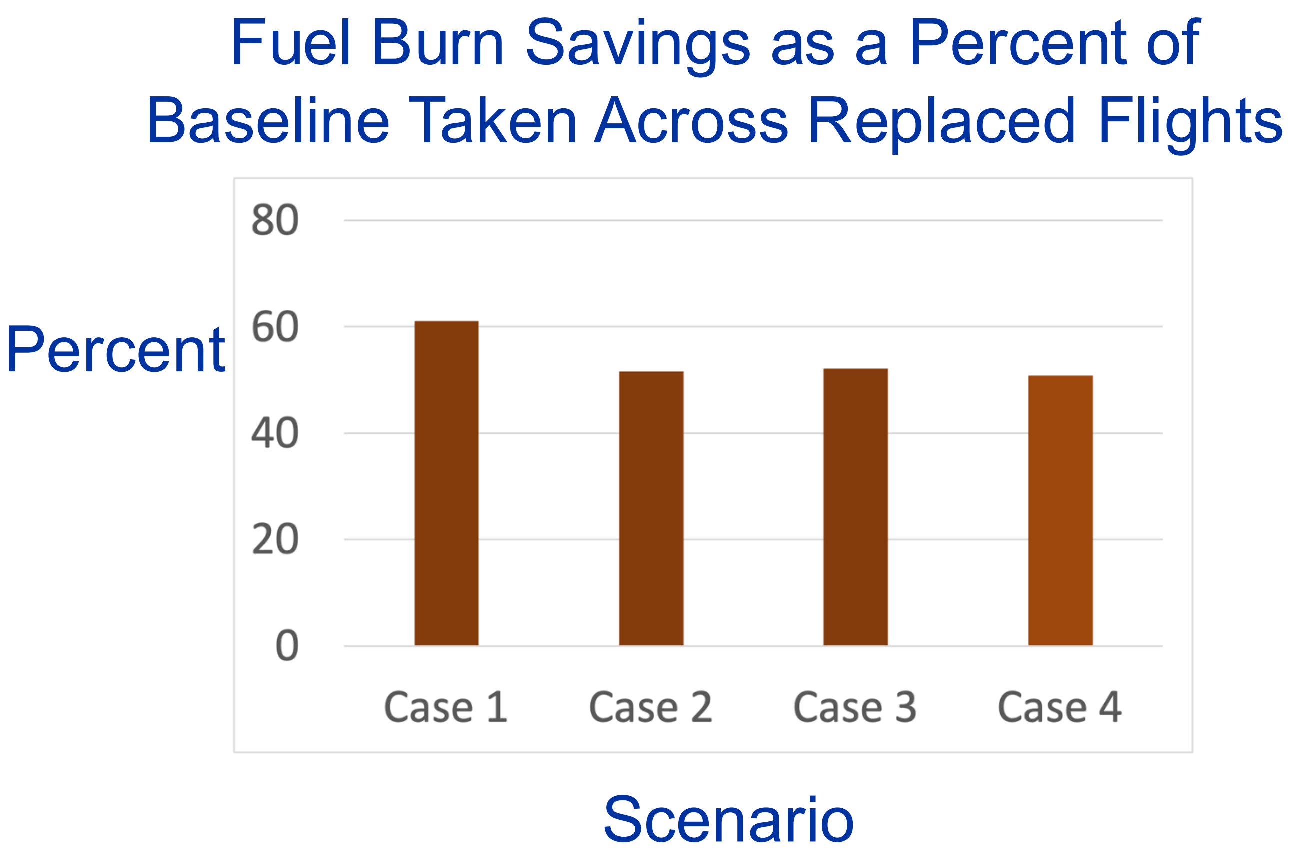
Source: NASA ARC NAS Digital Twin Modeling Tool



Source: NASA ARC NAS Digital Twin Modeling Tool

Fuel Burn Savings





Case - replaced / added flights
Case 1 – 157 / 0; Case 2 – 2139 / 1982; Case 3 – 2618 / 2940; Case 4 – 2997 / 4077

Source: NASA ARC NAS Digital Twin Modeling Tool

Customizable Hybrid Aviation Renewable Grid Evaluation Scenarios (CHARGES) Dashboard

Inputs

Upload flight schedule data for 24-hour period

Drag and drop file here
Limit 200MB per file • CSV
Browse files

MCI Inputs.csv 0.9KB ×

Aircraft Performance

- [x] EPFD Hybrid DHC-7
- [ ] Other Aircraft

Power Load Scenarios

- [x] Ideal Power Load
- [ ] Maximum Power Load

Input average baseline power consumption (kW):

1000000.00 − +

Maximum baseline power growth from electrification (%):

5

0 100

Airport Information

Main Airport Code: MCI

Airport Location: Kansas City International Airport, Missouri

Longitude: -94.7139

Latitude: 39.2976

Add Electric Flight

Origin Airport (3-letter code): 0/3

Destination Airport (3-letter code): 0/3

Arrival Time: MM/DD/YY HH:MM

Departure Time: MM/DD/YY HH:MM

Add Flight

Flight Schedule

Origin Airport	Arrival Time	Main Airport	Departure Time	Destination Airport
ORD	2024-01-21 07:	MCI	2024-01-21 08:37	ORD
ORD	2024-01-21 10:	MCI	2024-01-21 11:30	ORD
DFW	2024-01-21 11:	MCI	2024-01-21 13:35	DFW
ORD	2024-01-21 12:	MCI	2024-01-21 13:06	ORD
DFW	2024-01-21 13:	MCI	2024-01-21 14:53	DFW
ORD	2024-01-21 13:	MCI	2024-01-21 14:34	ORD
MSP	2024-01-21 14:	MCI	2024-01-21 15:23	MSP
ORD	2024-01-21 15:	MCI	2024-01-21 18:37	ORD
ORD	2024-01-21 16:	MCI	2024-01-21 17:29	ORD
ORD	2024-01-21 16:	MCI	2024-01-21 18:12	ORD

Flight Routes Map

Aircraft Performance Data

Initial SoC vs Range Plot ⌄ | Block Electricity vs Range Plot ⌄ | Flight Time vs Range Plot ⌄

Range (nmi)	Initial SoC (%)	Block Electricity (kWh)	Flight Time (min)
50	44	293	25
80	48	370	35
110	52	450	44
140	56	545	53
170	64	698	62
200	71	850	70
250	84	1,104	85
300	96	1,358	100
350	100	1,437	114

Source: GaTech ASDL Grand Challenge Research: Customizable Hybrid Aviation & Renewable Grid Expansion Scenarios Dashboard