Electrified Powertrain Flight Demonstration (EPFD) Overview and Future

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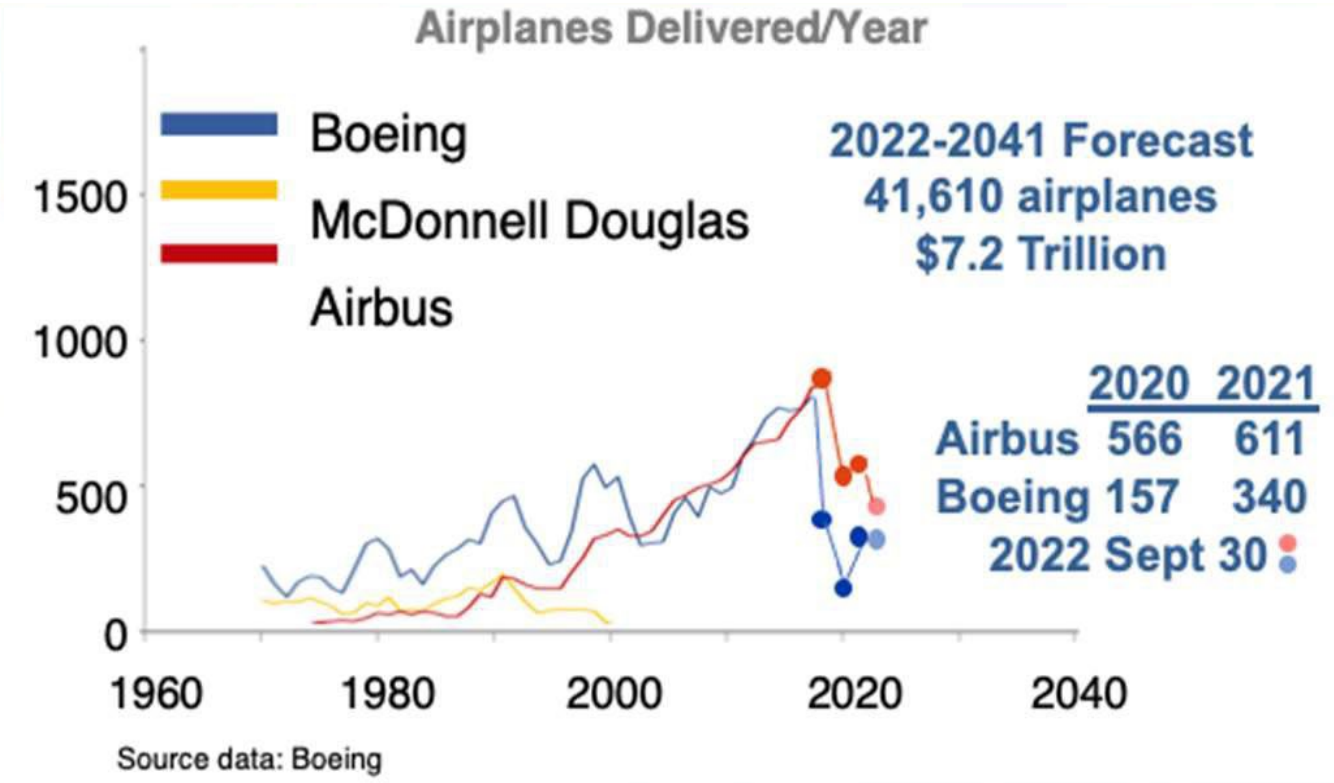
Sustainable Aviation Outlook

Subsonic Transport Market - Global competition expanding

- $78B positive trade balance; $1.8T total U.S. economic activity
- 10.9M direct/indirect jobs
- 21.3B tons of freight transported by U.S. airlines in 2019



Environmental Standards Landscape

Fleet Level – airplane, energy, & operations dependent

CORSIA Market-Based Measure (2020)

FAA Population Impacted by 65 (& 55) dB DNL

ATAG Goal for Net-Zero Carbon by 2050

Airplane & Engine Level

CO_2 standard
Airplane-level
CAEP/10

New for 2020

nvPM standards
Engine-level
CAEP/10 (/11 in 2023)

Flight shaming, new standards, noise-limited capacity

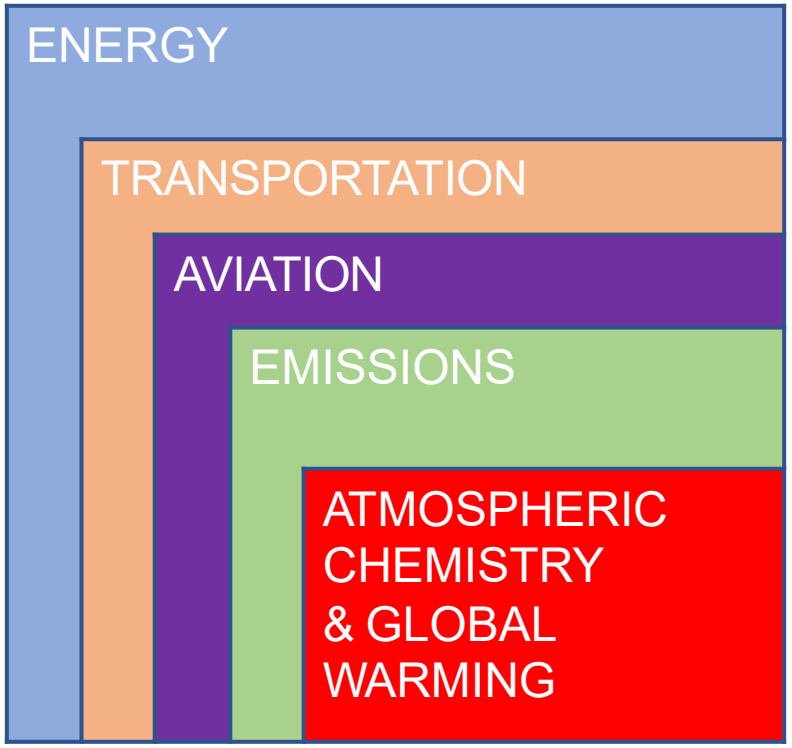
Noise regulation
Airplane-level
Chapter 14/Stage 5

Existing periodic updates

LTO NOx regulation
Engine-level CAEP/8

ICAO CAEP exploring the feasibility of a "long-term aspirational goal" for carbon

Aviation in Context of Energy, Transportation, and Climate



Reducing dependence on fossil fuel is the underlying challenge driving change across the entire energy sector

Aviation sector is hard to decarbonize and has unique altitude-based impacts and sensitivity to weight

Subsonic commercial airliner operations dominate aviation's climate impact

Lifecycle impact considerations – "source-to-tank" and "tank-to-wake" plus disposal and local air quality

Aviation will need to achieve BOTH net-zero CO_2 emissions and non-CO_2 radiative forcing IN-SECTOR to halt aviation's contribution to global warming. Non-CO_2 impacts comprise two-thirds of the net radiative forcing from aviation.

<u>Motivation (relative to climate change)</u>

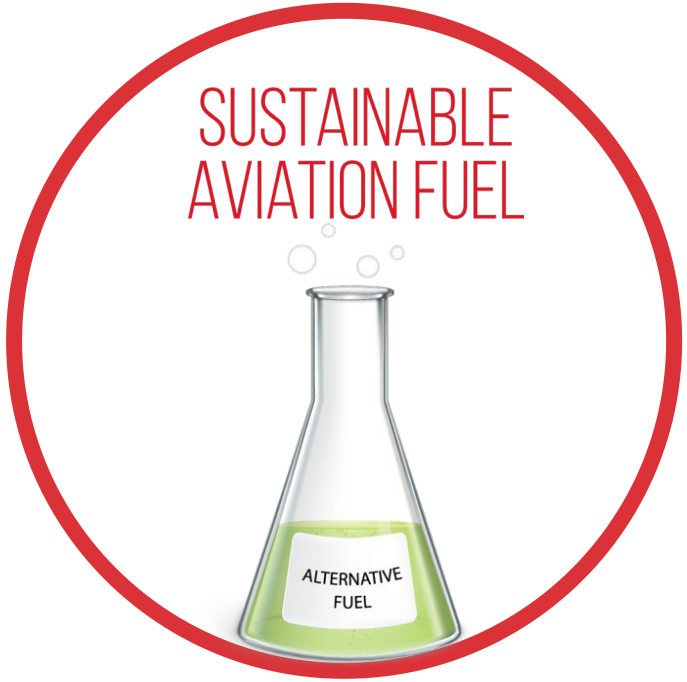
Halt aviation's contribution to global warming
without suppressing flight demand and without out-of-sector offsets
while remaining a viable and valued cornerstone of transportation

Sustainable Aviation Pillars & NASA Roles

- Use less energy
  - reduces energy cost
  - reduces required fuel volume
  - airplane & propulsion technology
  - efficient operations
- Use cleaner energy
  - drop-in
  - non-drop-in

  …requires major change to airplane & infrastructure

NASA = Primary Role



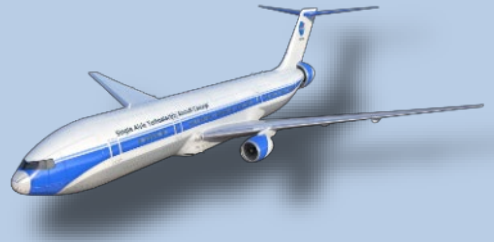
NASA = Supporting Role

NASA = Primary Role

Why is Electrified Aircraft Propulsion (EAP) Important? Why Mega Watt (MW)-Class?

- NASA and industry system studies show that EAP has the potential to reduce energy use, carbon and nitrogen oxide emissions
- EAP systems enable favorable direct operating costs (total energy and maintenance) resulting in benefits for both the public and the airline operators and is synergistic with low emission airport infrastructure changes
- EAP opens the design space and adds flexibility
  - Distributed architectures
  - Reduced turbofan core sizes
- EAP coupled with advanced airframe architectures may enable functionally silent and ultra-low emission flight

2030-2035 Entry-Into-Service Targets for EAP:
Thin haul, regional and next generation Sustainable Aviation markets



Market	Regional Air Mobility	Regional Turboprops & Turbofans	Single Aisle
Passengers	*1-19*	*20-150*	*150-more*
Speed	*≈150-250 mph*	*≈300-400 mph*	*≈500-700 mph*
Range	*≈100-500 miles*	*500-1500 miles*	*1500-3500 miles*
Power	*≈1MW*	*1 to 5 MW*	*3 to 30MW*
Heat	***≈200 kW waste heat***	***200kw to 1MW waste heat***	***600kW to 6MW waste heat***

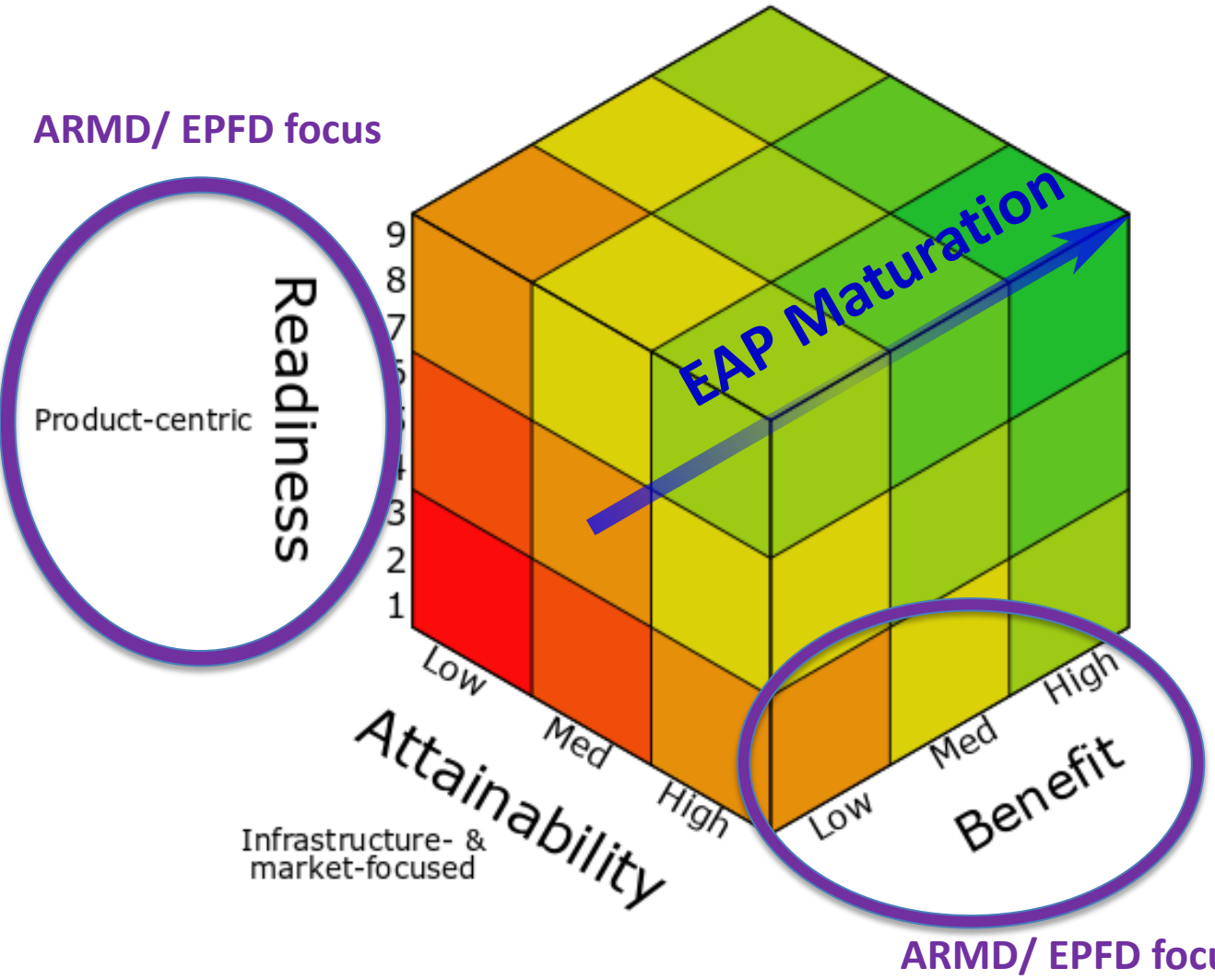
1 MW Class Electrified Powertrain System is an inflection point to a new aircraft electrification S-curve

EAP Readiness: Challenges and Opportunities

- Some questions need to be answered before electric aircraft flights are widespread
  - Has the **technology** improved enough?
    - Battery technology, thermal management, …
  - How much **storage** is needed for reserves?
  - How would the **diversion** due to bad weather be handled?
  - How can an electric aircraft be **certified**?
    - Safety (fire)
  - Would **NAS operations** be affected by electric aircraft?
    - Takeoff, climb, cruise performance
    - Turnaround time
  - How much **infrastructure** change would be required?

EAP Readiness, Attainability and Benefit

Source: ICAO LTAG Tech SG/ 2023



For EAP aircraft to become real, three roadmaps are needed:

- Technology (& ilities)
- Regulatory

  AND
- Infrastructure

WHAT ARE THE BARRIERS THAT MUST BE TACKLED FOR EACH ROADMAP?

MW-Class Powertrain Barrier Technical Risks

Barrier Risk	Risk Statement
High Voltage Operation at Altitude	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 the possibility that the demonstrator could have power system failures, resulting in potential loss of aircraft.
Thermal Management	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.
Battery System Performance Shortfall	Given that the battery pack requirement exceeds current state of the art 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.

MW-Class Powertrain Barrier Integration Risks

Barrier Risk	Risk Statement
Propulsion System Integration	Given that this electrified aircraft propulsion system is novel, there is a possibility that there are unforeseen conflicts in the turbomachinery integration with electric machines, resulting in, but not limited to, reduced operability and larger system weight that decreases overall Vision Vehicle performance.
Powertrain System Integration	Given that this powertrain system is novel, there is a possibility that there it will not meet stability, EMI compatibility, or performance requirements which will require a redesign, resulting in an increase in cost and delay in schedule for Vision Vehicle development.
Aircraft System Integration	Given that MW EAP has never been deployed on an aircraft before, there is a possibility that there are unforeseen conflicts integrating EAP system into the aircraft, resulting in an increase in cost and a delay in schedule and an inefficient aircraft.

NASA's Aviation Sustainability Strategy

2008-2013 | 2014-2019 | 2020-2025 | 2026-2030 | 2030+

Subsonic Concept/Technology Studies
Electric Aircraft Propulsion, Transonic Truss-Braced Wing

Environmentally Responsible Aviation (ERA) Project

Flight Demonstrator Studies

Advanced Composites (ACP)

Sustainable Flight National Partnership

Sustainable Flight National Partnership (SFNP) to mature and integrate key technologies **(TRL 6)** for *next-generation subsonic transports (2030s)*

- MBSE/SA
- SFD Project
- HiCAM
- HyTEC
- EPFD & AATT

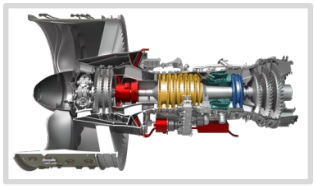
Today

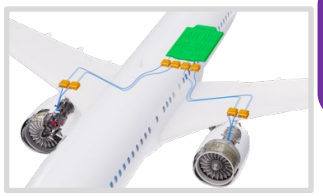
Accelerating toward Net-Zero Carbon

Cast a wide net for zero-emission concepts and technologies

Powering Aviation to Net-Zero Carbon and Beyond

ARMD's Sustainable Flight National Partnership: Integrated Technology Development





FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29

Technology Readiness Target

Model Based Systems Analysis & Engineering → "Digital Flight Test"

Sustainable Flight Demonstrator (SFD) → Flight Test

Leverage the Asset – Future Spirals

Transonic Truss Braced Wing (AATT) → TC Completion

Hi-Rate Composite Aircraft Manufacturing (HiCAM) → Mfg & Structural Demonstration

Hybrid Thermally Efficient Core (HyTEC) → Core Demonstration

Electrified Powertrain Flight Demonstration (EPFD) → Flight Tests

Electrified Aircraft Propulsion Technologies (AATT) → TC Completion

Achieve TRL 6 in time for industry product decision making

ARMD Electric Aircraft Propulsion (EAP) Portfolio

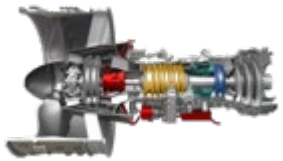
ARMD Critical Commitment (CC) 3.1:
Demonstrate practical vehicle-level integration of MW-class electrified aircraft propulsion systems, leveraging advanced airframe systems to reinvigorate the regional and emerging smaller aircraft markets and strengthen the single aisle aircraft market.

AATT FOCUS - improving performance, lifetime, reliability and cost that will be required for entry into service

- Working on electrical and materials solutions which enables high performance and high efficiency machines and power electronics to operate at high voltage at altitude

EPFD FOCUS - providing real-world application thereby reducing EIS technology and integration barriers for emerging technologies through the flight demonstrations (magniX, GE)

- Tackling safety and integration at the powertrain, propulsion, and aircraft systems levels
- Exploring test methodologies for means of compliance and flight test data to inform regulations and standards



HyTEC FOCUS - reducing risk for electric powertrain integration in Single Aisle turbofan architecture

- Demonstrating power insertion/extraction on a modern commercial turbofan
- Maturing controls and energy management across dual spool turbofan engine

The current ARMD EAP Portfolio is synergistic and complimentary to achieving CC 3.1 through mid-TRL technology development and integrated ground and flight demonstrations.

Electrified Powertrain Flight Demonstration Project

Accelerate Transition of MW class powertrain systems to US transport aircraft fleet

Scope

- Demonstrate practical vehicle-level integration of megawatt-class electrified aircraft propulsion systems, leveraging advanced airframe systems to reinvigorate the regional and emerging smaller aircraft markets and strengthen the single aisle aircraft market.
- Assess gaps in regulations/standards to support future Electrified Aircraft Propulsion (EAP) certification requirements.

Benefit

- Accelerate U.S. industry readiness to transition to EAP-based commercial transport aircraft.
- Enable new standards that are needed for EAP-based aircraft certification.

Approach

- Engage with U.S. industry to integrate and demonstrate megawatt-class EAP machines in flight.
- Engage with the FAA, SAE, ASTM, etc. to contribute data that inform EAP standards and regulations.

Industry Partners selected on September 30th, 2021:

- GE Aerospace, Cincinnati, OH: Single Aisle Market
- magniX , Everett WA: Regional Turboprop Market

FY21	FY22	FY23	FY24	FY25-FY26

Test 1 Prel/ detail design, fab & integration

First flight — Test 1

Test 2 Prel / detail design, fab & integration

First flight — Test 2