A Roadmap to Our Sustainable Aviation Future:

Challenges and Opportunities of Aircraft Electrification

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PM, Electrified Powertrain Flight Demonstration Project

NASA ARMD Integrated Aviation Systems Program

Michigan Initiative for Sustainable Aviation (MISA)

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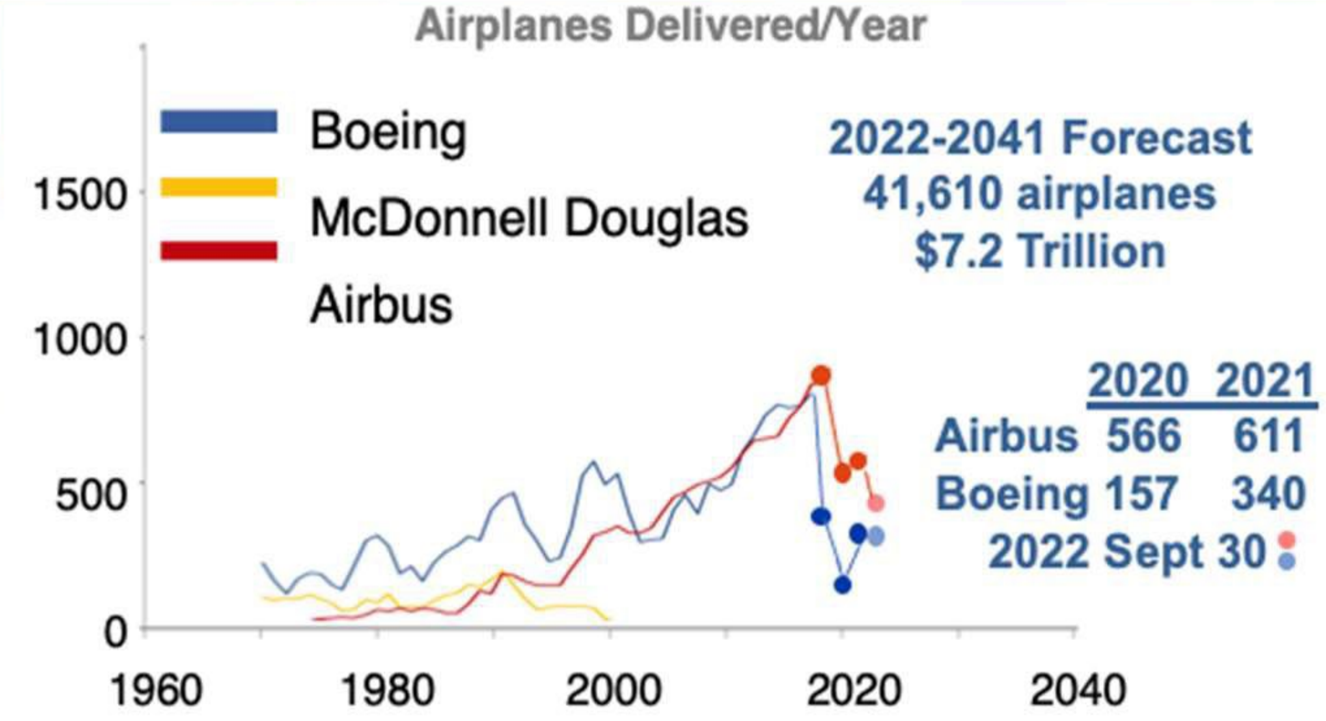
Subsonic Transport Market - Global competition expanding

- $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



Source data: Boeing

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)

Subsonic Transport faces growing environmental pressure

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

2030-2035 Entry-Into-Service Targets for EAP:

Thin haul, regional and next generation Sustainable Aviation markets

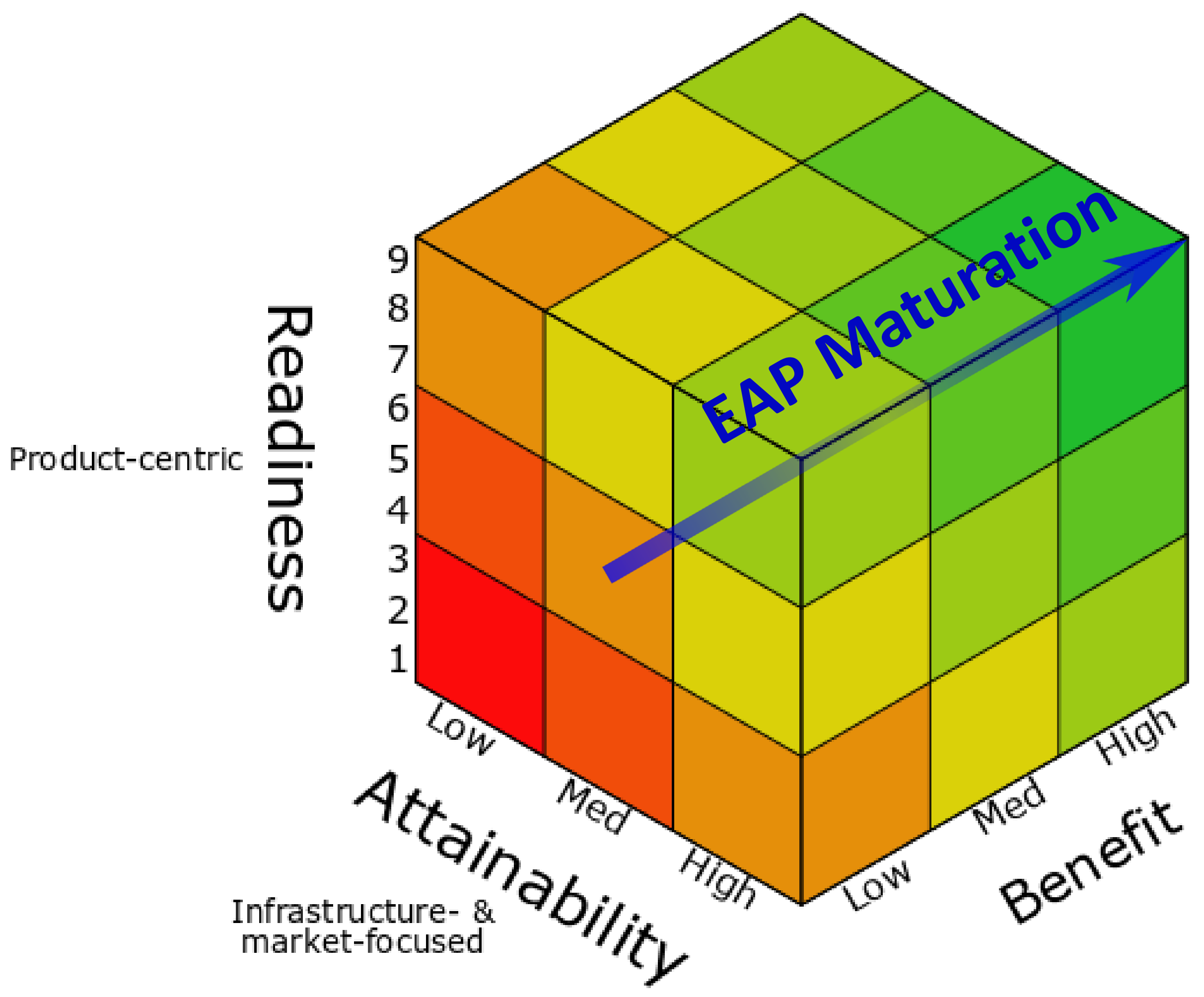
Market	Regional Air Mobility	Regional Turboprops & Turbofans	Single Aisle
Passengers	*1-19*	*20-150*	*150-more*
Speed	*≈150-250 mph*	*≈300-400 mph*	*≈500-700 mph*
Range	*≈100-500 miles*	*500-1500 miles*	*1500-3500 miles*
Power	*≈1MW*	*1 to 5 MW*	*3 to 30MW*
Heat	***≈200 kW waste heat***	***200kw to 1MW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

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.

Evolution of All-Electric Aircraft with Advances in Battery Technology

- Pack specific energy
  - Have improved > 250% since the 90s
- Advanced chemistries needed to reach higher values
- Pack factors need reduction from 32% to 10-20%

25-50 miles

20 PAX
commuter

100 miles

Current, 170-200 Wh/kg

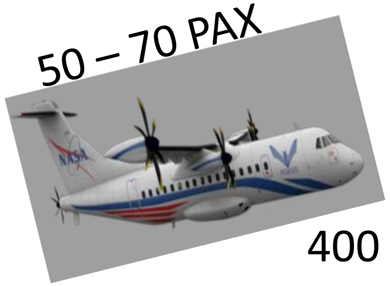
100 miles

20 PAX
commuter

200 -250
miles

300 – 350 Wh/kg

50 – 70 PAX



400 Wh/kg

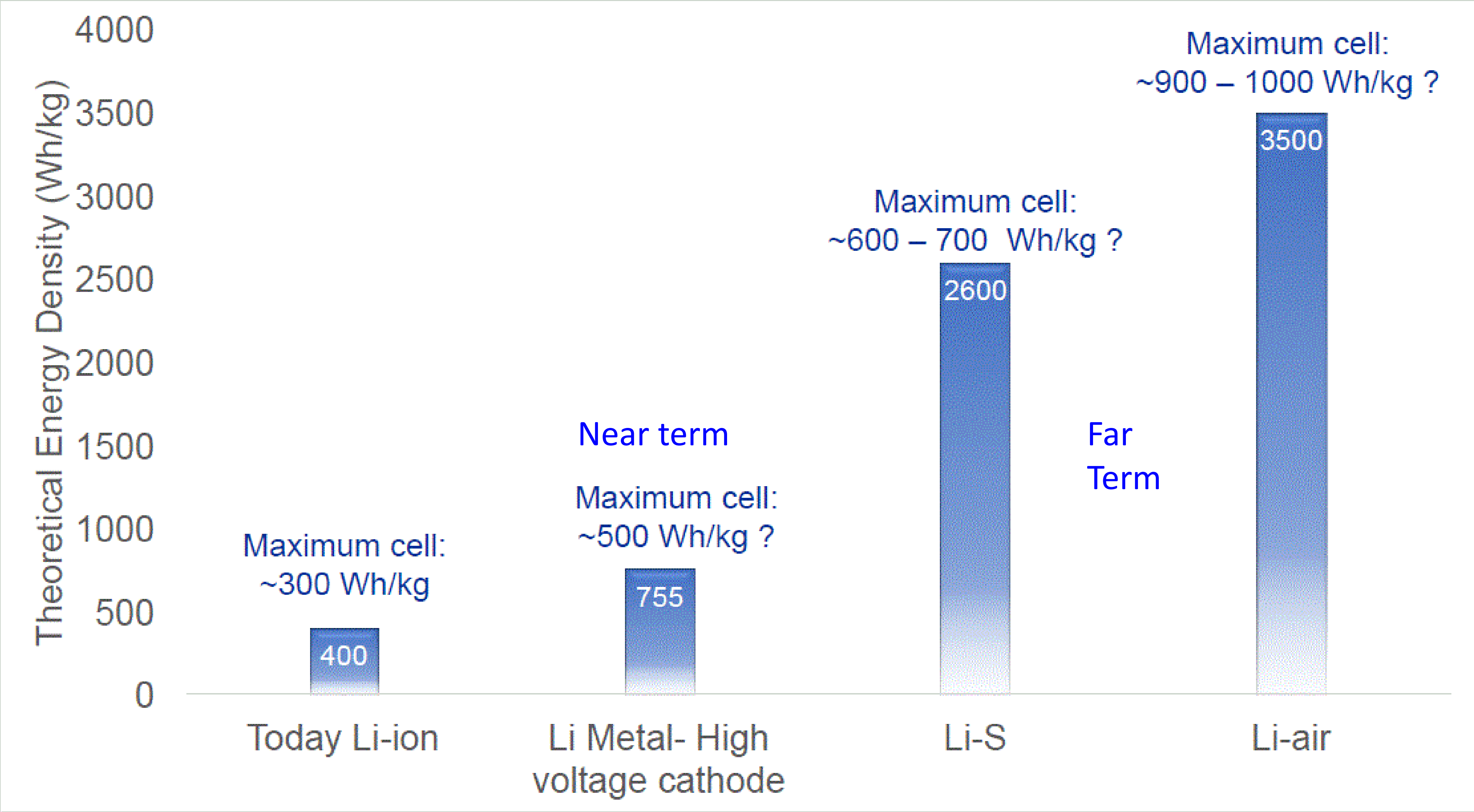
Regional

500 Wh/kg

Single-aisle, 737 class

1000 Wh/kg

Beyond Li-Ion



Evolution of Hydrogen Electric Aircraft with Advanced Technology

- Fuel cells and turbofans are two paths for integrating hydrogen solutions
- Hydrogen offers very low emissions and relatively high efficiency

19 PAX commuter
< 400 miles

Photo: ZeroAvia

< 1 MW, SOA Specific power

50-80 PAX commuter

Photo: Universal Hydrogen

100 miles

200 -250 miles

4-6 MW, 2 kW/kg
(60% improvement)

112-150 PAX
Hybrid Regional and Single Aisles

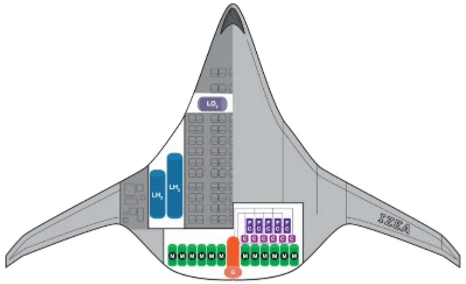


Photo: ***NASA*** IZEA ULI

8-10 MW, 2.5 kW/kg
(2x improvement)

Single-aisle 180 PAX, 737 class

Photo: ***NASA*** Cheeta ULI

40 MW, > 4 kW/kg
(3-4x improvement)

Challenges:
- Energy storage
- Volume
- fuel cell specific power / thermal, durability
- H2 as an energy source

H2 Key Barrier Risks

Fuel Cell Energy Density	LH2 Storage Technologies	LH2 Crashworthiness	Transfer, Disconnects, Purging & Venting
Electrical Design Considerations	Grounding and Bonding	Embrittlement and Material Compatibility	Managing Boil Off
Integrated Thermal Management	Insulation – Tanks, Plumbing, Fittings, etc.	Fire and Safety	Plumbing, Valves & Sealing

Attainability

- The ability to realize a commercially viable product overcoming <u>non-technical barriers</u>
  - Operability/System-of-systems infrastructure
    - ***Is this aircraft concept consistent with the air transportation infrastructure and operational environment?***
  - Stakeholder acceptability
    - ***Will the world accept this aircraft?***
  - Economics
    - ***Can creating the aircraft concept and bringing it into cost-effective service attract infrastructure investment and an end-user base?***

U.S. & International Regulatory Engagement for EAP

- Key Gaps: Electric Engines (Part 33); Powerplant & Energy Storage (Part 23, 25, 27)
- Means of Compliance to address key gaps: Test Methodologies
  - TRL advancement through Flight Demonstrations

EAP operability, acceptability and investment

NGOs/Associations Commitments:

- Air Transport Action Group (ATAG) - Fly Net Zero and Waypoint 2050
  - Supported by International Federation of Air Line Pilots' Associations (IFALPA)
  - Supported by Civil Air Navigation Services Organization (CANSO)
- International Air Transport Association (IATA) - Fly Net Zero
- International Coordinating Council of Aerospace Industries Associations (ICCAIA)
- International Business Aviation Council (IBAC)
- Airports Council International (ACI)
- Internation Energy Agency – Aviation Tracking Report
- Royal Aeronautical Society - Publicly reaffirmed commitment to RAE 2050 NetZero campaign
- Royal Academy of Engineers - National Engineering Policy Centre (NEPC)
- ASME, ASCE, AIChE, SAE, AIAA, IEEE, ASTM, EuroCAE...

Source: ICAO LTAG Tech SG/ 2023

The Challenge AND the Opportunity for MISA

Goal: Develop simultaneously three roadmaps that address Sustainable Aviation from the perspective of:

- Technologies, Aircraft integration, Operability, Reliability and Maintenance Roadmap
  - Electrification Architectures:
    - All Electric
    - Hybrid Electric
      - Electric Machines plus Gas Turbine Engines
      - Hybrid Propulsion Systems: SAF, Battery… Hydrogen, Ammonia …

- Infrastructure/Logistics Value Chain Roadmap
  - For Energy Sources/Recharging/Storage
  - For Operations and Maintenance

- Regulatory and Standards Engagement Rpadmap
  - Local
  - State
  - Federal
  - International

Potential Demonstration Pilots?