The Electric Aircraft EcoSystem: Performance Potential, Economics and Societal Impact in the Age of Sustainable Air Travel

Gaudy Bezos-O'Connor

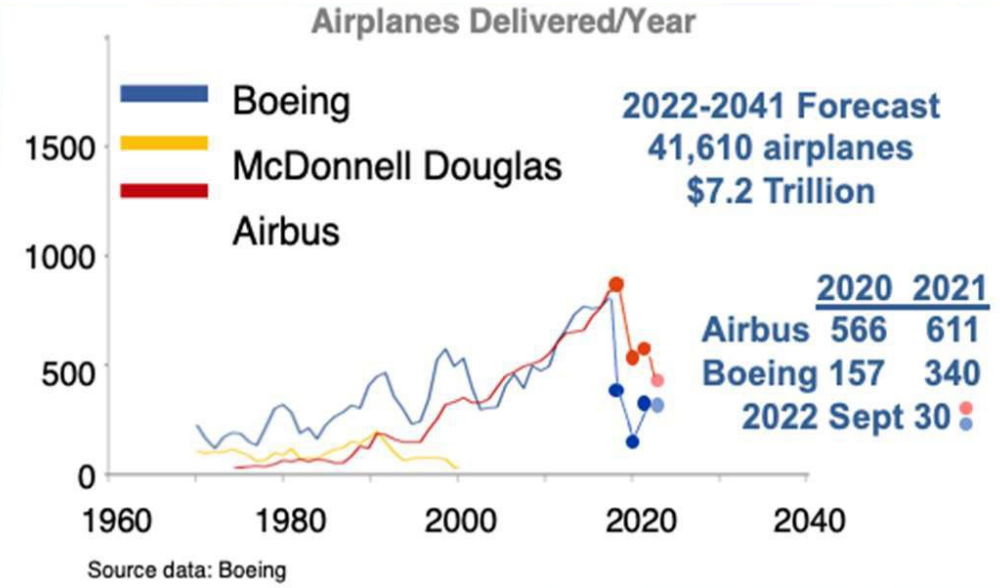
PM, Electrified Powertrain Flight Demonstration Project

AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), June 12-16, 2023

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



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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		Noise regulation Airplane-level Chapter 14/Stage 5
New for 2020		**Existing periodic updates**
nvPM standards Engine-level CAEP/10 (/11 in 2023)		LTO NOx regulation Engine-level CAEP/8

Flight shaming,
new standards, noise-limited capacity

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

How to define Electric Aircraft Propulsion (EAP)?

- Use of electric power system in the propulsion function of the aircraft
- Includes
  - Fully Electric
  - Hybrid Electric
  - Turbo Electric
- Energy Sources include
  - Batteries
  - Fuel Cells
  - Turbo-generators

To reduce the amount of energy used per passenger mile innovations are required in advancing electrification, energy sources and storage solutions

The EAP Opportunity

Truly Zero Emissions

- Zero Contrails! other GHG – NOx, Ozone, soot
- Sustainable Aviation Fuels will be needed to de-carbonize mid to long range, but emit carbon that has to be captured by plants, DAC or DOC and are not 100% Carbon neutral in production.

Reduce Noise Pollution

- Anecdotally -20 dBa noise reduction, could enable quiet night flights

Energy infrastructure already in-place globally (Electricity)*

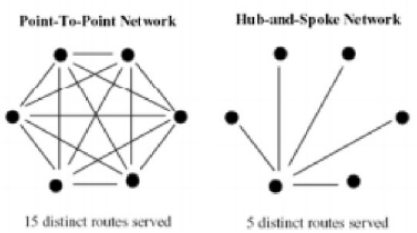
- Although charging ~~might~~ ***will*** be challenging for larger aircraft

Economical

- Electricity cheaper than fuels and more price stability (1/3rd cost), less maintenance?

Could enable new flight platforms, enhanced maneuvers

- Automation, Safety, "unlock" smaller airports, reduce hub and spoke, higher altitude(less friction)



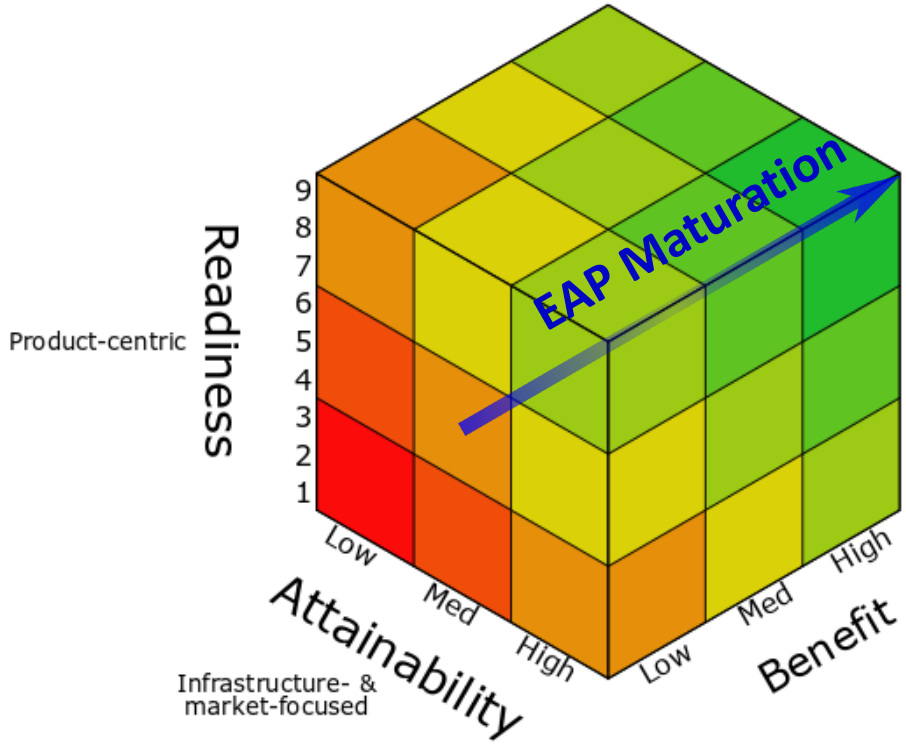
Source: ARPA-e 2023

EAP Readiness

- 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

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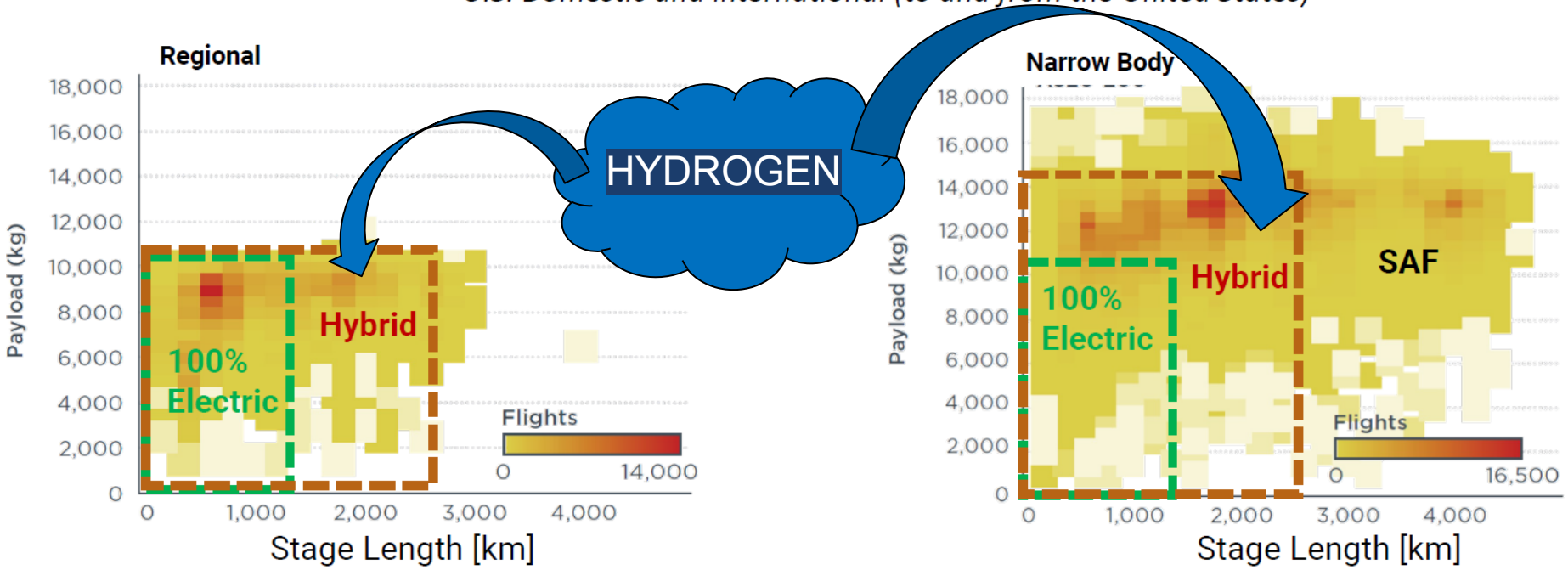
Addressable Markets

U.S. Domestic and international (to and from the United States)



Data from U.S. Department of Transportation, BTS Form 41 Traffic (2014). Extracted from ICCT - cost assessment of near and mid-term technologies to improve new aircraft fuel efficiency. 2016 International Council on Clean Transportation

A Retrospective: How Far We have Come…

- A Look Back to the Past
- The Recent Past
- The Present State
- The Future

A Look Back to the Past

Photo: Air-e

Militky MB-E1
1st Crewed Electric Aircraft
(1973, First Flight)

Photo: NASA/Bill Ingalls

Pipistrel Taurus G4
1st 4-Seat Electric A/C
(2011, First Flight)

Photo: Wikimedia

Tupolev Tu-155
1st H2 Passenger Demo.
(1988, First Flight)

E-Fan 1
All Electric- 2 seat
Monoplane
(2014, First Flight)

Photos: Airbus

E-Fan X
2-MW Class
Serial Hybrid Electric
(2017 Rolls Royce-Airbus)

The Recent Past

Photo: magniX

Harbour Air eBeaver

First All-Electric Commercial Plane

(Dec 10, 2019 - First Flight)

Photo: magniX

magniX eCaravan

Largest All-Electric At Time

(May 28, 2020 - First Flight)

Photo: Ampaire

Ampaire

Hybrid Electric, 6-Seat Cessna 337 Skymaster

(Nov 22, 2020, First Hawaiian Commercial Route)

The Present State

Photo: Eviation

Eviation
Alice
All-Electric Aircraft
(Sept. 27, 2022 – First Flight)

Photo: Ampaire

Ampaire
Eco Caravan
Hybrid-Electric Aircraft
(Nov. 18, 2022 – First Flight)

Photo: ZeroAvia

ZeroAvia
HyFlyer II
Hydrogen-Electric Aircraft
(Jan. 19, 2023 – First Flight)

Photo: Universal Hydrogen

Universal Hydrogen
“Lightning McClean”
H2 Regional Airliner
(Mar. 2, 2023 - First Flight)

The Future

Heart Aerospace
Electric Aircraft

Pratt & Whitney, Collins Aerospace
Hybrid-Electric Aircraft

EPFD / NASA, GE Aerospace, magniX
Hybrid-Electric Aircraft

Wright Electric
Electric Aircraft

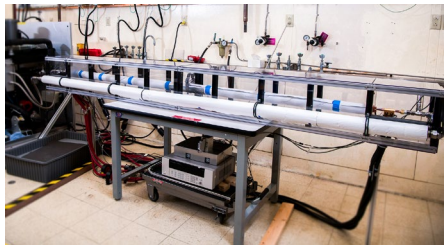
Airbus
ZEROe Hydrogen Aircraft

magniX, Tier 1
Electric Helicopter

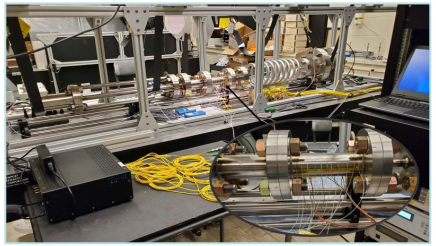
Wisk Aero
e-VTOL Air Tax- 4-seat

Current State: NASA Assessment of MW-Class EAP Barrier Technical and Integration Risks

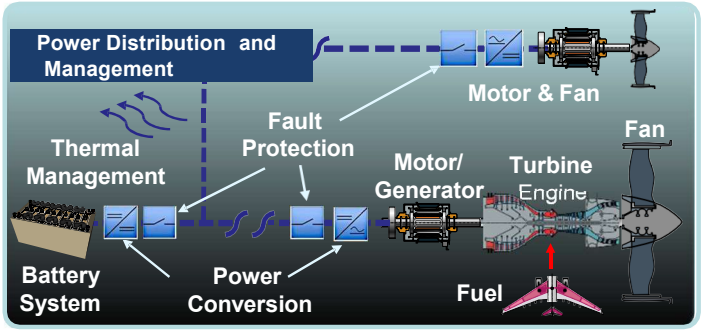
Barrier Risk	FY19	FY20	FY21	FY22	FY23	FY24	FY25
High Voltage Operation at Altitude	5x5	4x5	3x5	3x5	2x5	2x5	1x5
Thermal Management	5x4	4x4	3x4	3x4	3x4	3x4	2x4
Propulsion System Integration	4x4	3x4	2x4	2x4	2x4	1x4	1x4
Battery System Performance Shortfall	5x3	4x3	4x3	2x3	2x3	2x3	1x3
Powertrain System Integration	3x4	3x4	2x4	2x4	1x4	1x4	1x4
Aircraft System Integration	4x5	4x5	2x5	1x5	1x5	1x5	1x5



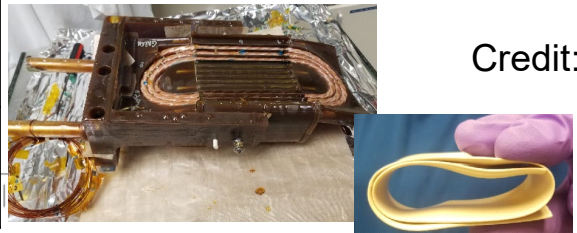
The High-Power Advanced Cable Technology



Thermal Recovery Energy Efficient System



Electric Machine Insulation



Credit: NASA

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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

100 miles

Current, 170-200 Wh/kg

100 miles

200 -250 miles

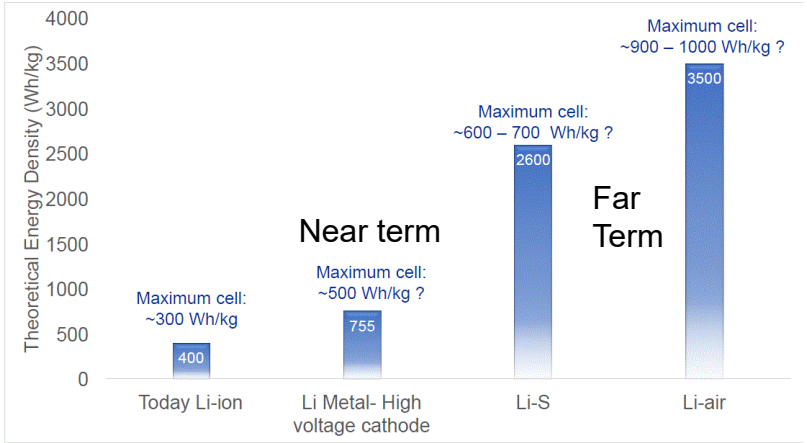
300 – 350 Wh/kg

400 Wh/kg

500 Wh/kg

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
- **Challenges**: energy storage, volume, usual hydrogen issues, fuel cell specific power / thermal, durability

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

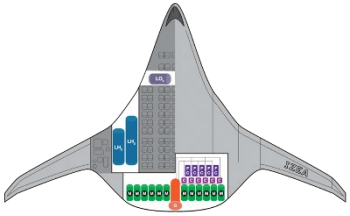


Photo: ***NASA*** IZEA ULI

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)

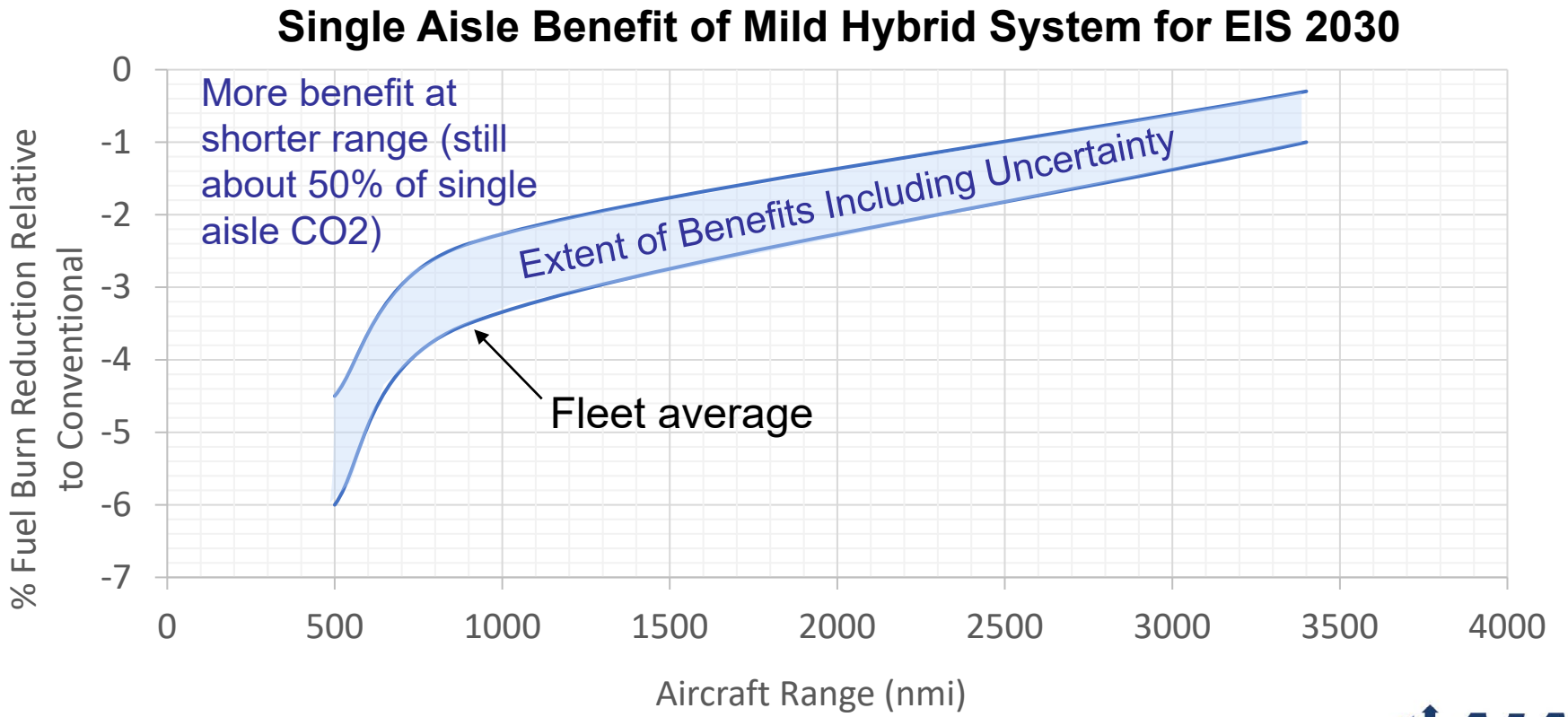
H2 Key Barrier Risks

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

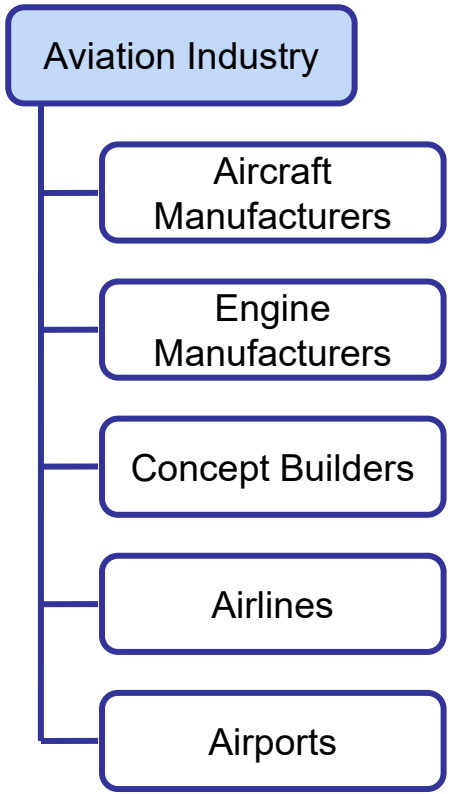
- The ability to realize a commercially viable product overcoming non-technical barriers
  - Operability/System-of-systems infrastructure
    - *Is this aircraft concept consistent with the air transportation infrastructure and operational environment?*
  - Stakeholder acceptability
    - *Will the world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

Studies Show Significant Potential Benefit



Source: NASA studies

Aviation Industry Commitment



Boeing, Airbus, Bombardier, Embraer, Gulfstream, ATR, de Havilland Canada
GE Aerospace, Rolls Royce, Pratt & Whitney, SAFRAN, CFM International
ZeroAvia, Universal Hydrogen, Archer, Joby Aviation, Lilium
Fly Net Zero: IATA ~290 airlines, 120 countries, 83% of world's air traffic
Heathrow - New Aviation Propulsion Knowledge and Innovation Network (NAPKIN),
Munich Airport Advanced Air Mobility, Airbus – Hydrogen Hub at Airports

- Support the commercial aviation industry's ambition to achieve net-zero carbon emissions for global civil aviation
- Further improve fuel efficiency of current fleet
- Utilize SAF as the short-term solution
  - Boeing and Airbus aim to achieve certification of 100% SAF by 2030
- Provide advanced concept solutions
  - Propulsion > Hybrid-electric, electric, hydrogen-electric, hydrogen combustion
  - Airframe > Blended wing body, truss-braced wing, etc.
- Research into infrastructure requirements of advanced concepts

Source: ICAO LTAG Tech SG/ 2023

Governments Commitment

- United Nations Framework Convention on Climate Change (UNFCCC) has 194 Nationally Determined Contributions
- US aims to achieve net-zero GHG emission from the U.S. aviation sector by 2050
- UK targets net-zero aviation by 2050
  - Policy measures: existing aviation system efficiency improvements, supporting SAF and having a SAF mandate, legislation for CORSIA, addressing non-CO2 impacts
- Germany aims to become GHG neutral by 2050
  - The National Hydrogen Strategy, National Innovation Programme on Hydrogen Fuel Cell Technology
  - PtL Kerosene Roadmap > minimum of 200,000 tons of PtL kerosene in German aviation by 2030
- Sweden aims to have zero net GHG emissions by 2045
  - at least 27% for aviation fuel by 2030; ~90 million EUR
- SAF feasibility studies in India and United Arab Emirates

Source: ICAO LTAG Tech SG/ 2023

NASA 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 for *next-generation subsonic transports (2030s)*

Today

Accelerating toward Net-Zero Carbon

Cast a wide net for zero-emission concepts and technologies

Powering Aviation to Net-Zero Carbon and Beyond

NGOs/Associations Commitments

Proactive engagement and advocacy of EAP operability, acceptability and investment:

- 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

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

Societal – Public Awareness & Acceptance

PBS NEWS HOUR

Menu Full Episodes Podcasts Newsletters Live

Could electric airplanes propel a third revolution in aviation?

May 26, 2021 6:25 PM EDT

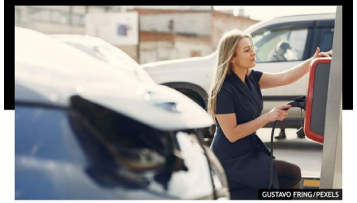
Union of Concerned Scientists

DONATE MENU

The EQUATION

Californians Embrace Zero-Emission Vehicles with Record Sales

May 3, 2023 | 12:51 pm

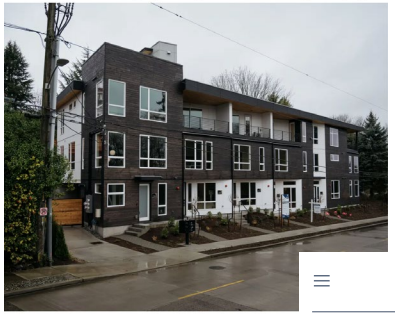


The New York Times

SQUARE FEET

'All-Electric' Movement Picks Up Speed, Catching Some Off Guard

As cities across the nation embrace electric power as a cleaner alternative to natural gas, developers are scrambling to keep up.



Five new, all-electric townhomes built by Green Canopy near the in Seattle. Some developers are establishing their own goals to r emissions. Grant Hindsley for The New York Times

By Jane Margolies
Feb. 4, 2020

salon

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How the "electrify everything" movement went mainstream

One in five Americans now lives in an area that's trying to move buildings off fossil fuels

By EMILY PONTECORVO

PUBLISHED FEBRUARY 19, 2023 8:29AM (EST)

nission towers on February 21, 2021 in
exans lost their power when winter storm Uri
coal, natural gas and nuclear plants that were
emperatures brought on by the storm. Wind
nated 24 percent of energy to the state
y froze. (Justin Sullivan/Getty Images)

Denverite

Denver plans to send large buildings into the warm embrace of renewable electricity

The City and County Building seen from atop the Denver Art Museum's newly opened Martin Building. Oct. 13, 2021. Kevin J. Beaty/Denverite

Sam Brasch
Nov. 24, 2021, 11:19 a.m.

coloradobiz
PEOPLE ISSUES BUSINESS STATEWIDE

All-Electric Houses On the Rise — Colorado Homebuilders Embrace Alternatives to Natural Gas

All-electric houses in Pueblo generally cost more upfront, but the investment can be recouped in six or seven years.

December 15, 2022 by Allen Best

yahoo!

Biden Administration Paying Americans Thousands of Dollars to Embrace EV's and Solar Homes

William Dahl
February 24, 2023 · 2 min read

AFAR

By Elissa Garay • March 03, 2022

Electric Planes Are Coming Sooner Than You Think

Electric aviation is no flight of fancy: Leading airlines like United and EasyJet are onboard as early adopters, with the first U.S. commercial routes slated for 2026.

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Societal - Next Gen of EAP Innovators

FAA Pod Casts:
Encourage curiosity about the wide world of aviation

NASA's SFNP Sustainable Aviation Ambassadors Internship Program

- Leverage engagement:
  - Aerospace Industry Professional societies
  - Federal and International Research Labs
  - Global academia
- Sponsor funded research and hands on demonstration challenges in EAP and Sustainable Aviation from High School to Post Graduate
  - STEAM for EAP

A sustainable aviation future requires a multi-disciplinary and diversified workforce that can translate electrification innovations into the aviation environment

In Summary

- Global investment in Electrified Aircraft Propulsion (EAP) is happening
- Electrification solutions are complementary with SAF and H2 strategies
- Cost share partnerships between governments, OEM, and entrepreneurial aviation industry leaders have created a viable path to product introduction for Aircraft and Rotorcraft (Part 23, 25 and 27) and Aircraft Engines (Part 33)
- Flight research is critical to demonstrating practical vehicle level integration of EAP systems solutions AND informing regulatory and certification processes
- Current efforts must be responsive to global societal drivers for economic and climate sustainability
- The next generation of EAP innovators are critical to realize our sustainable aviation future

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