ICRERA 2023

12th INTERNATIONAL CONFERENCE ON RENEWABLE ENERGY RESEARCH AND APPLICATIONS

August 29 - September 1, 2023, Oshawa, Canada

Electric Aircraft – Recent Technology Developments in US

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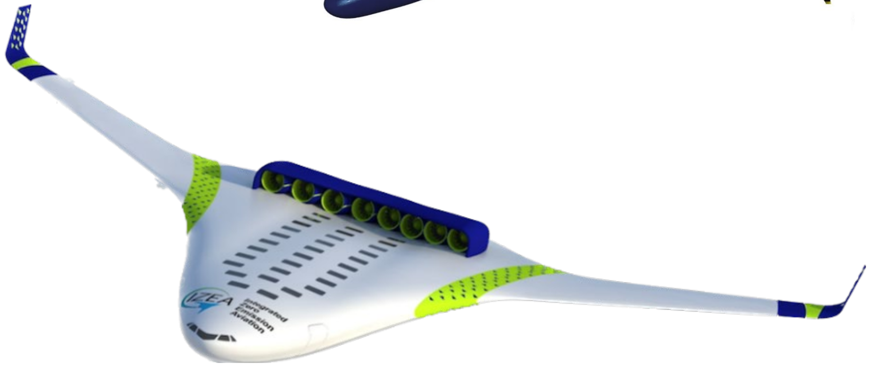
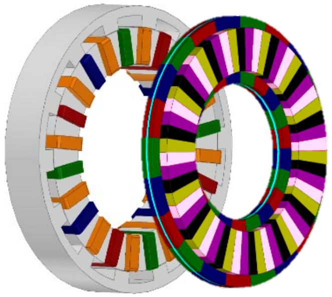
Outline

Ongoing Research for Large Electric Aircraft Components and Systems

- Introduction
- Major technical concepts and initiatives
- Optimal design of electric aircraft systems
- Battery-powered electric aircraft, NASA X-57
- Hydrogen-fueled electric aircraft, NASA ULI IZEA
- Electric aircraft propulsion motor drive
  - Review
  - Innovative concept
- Conclusion.



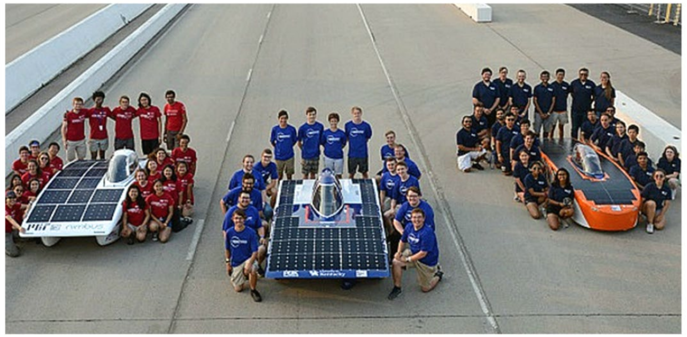


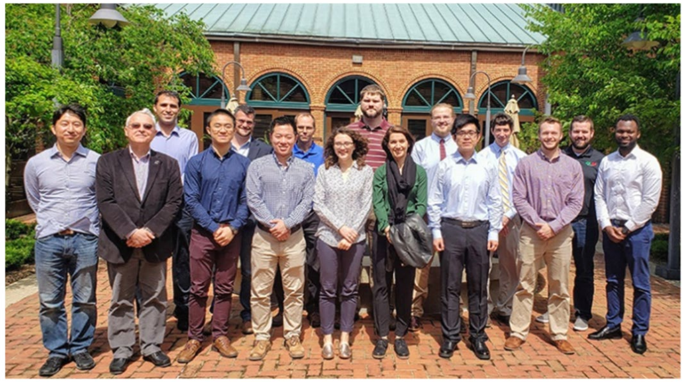
PEIK and SPARK at University of Kentucky (UK)

- Power and Energy Institute of Kentucky (PEIK), launched with DOE grant in 2010 at UK; 15 affiliated faculty; very large undergraduate and graduate certificate programs; https://www.engr.uky.edu/power

- SPARK Lab, established in 2015 with support from the L. Stanley Pigman Chair Endowment; one of the PEIK and ECE affiliated faculty-led research groups with approx. 10 researchers; http://sparklab.engr.uky.edu/

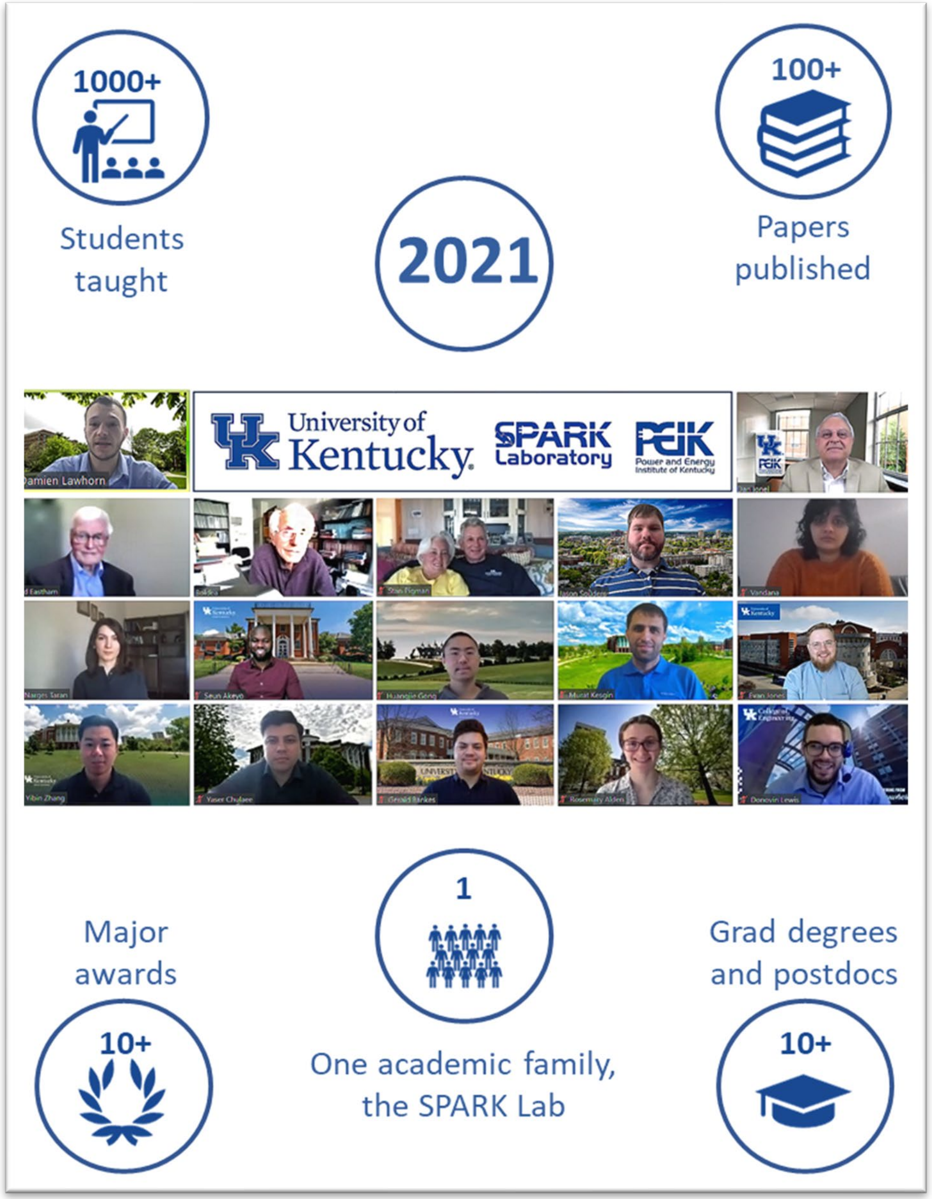
- Research sponsored by industry and utility, and by federal funded projects and grants from NASA, DOE, NSF, DoD, and DoEd on topics of electrification of transportation, renewable and distributed energy resources, smart homes and grids, electric machines and drives.





Examples of Electric Transportation Projects and SPARK Lab

- First generation Tesla Roadster (PC-IMD late 90’s)
- …
- ANSYS (2010-present)
- GM Research (2012-2015)
- First generation Formula E (2015-2016)
- UK Gato del Sol cars (2016-present)
- DOE electric traction challenge (2019-2023)
- NASA electric aircraft (2017-present).


1000+ Students taught

2021

100+ Papers published

University of Kentucky SPARK Laboratory PEIK Power and Energy Institute of Kentucky

Major awards 10+

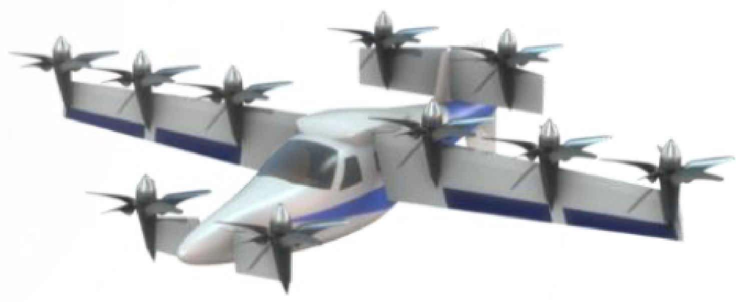
1 One academic family, the SPARK Lab

Grad degrees and postdocs 10+

NASA and US Electric Airplane Efforts

Market: National/International

Impact: Fuel Burn/Emission Reduction



Market: On demand mobility

Impact: New mobility capability

Market: Regional

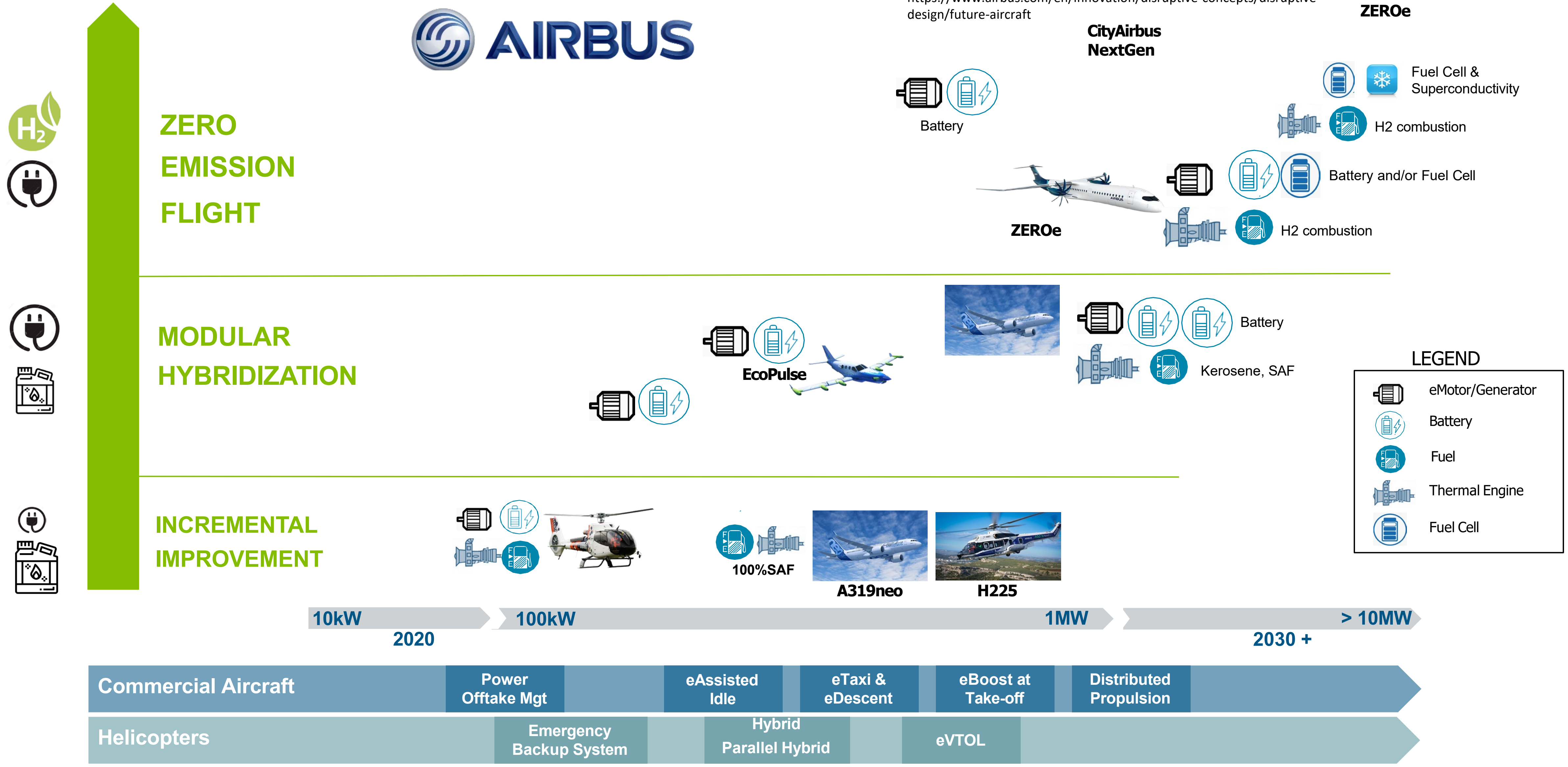
Impact: Revitalization of smaller routes

See also, for example

- https://www1.grc.nasa.gov/aeronautics/eap/Websites
- https://www.ampaire.com/
- https://www.jobyaviation.com/

Airbus Plans for Electric Aircraft

Source: Airbus Future aircraft
https://www.airbus.com/en/innovation/disruptive-concepts/disruptive-design/future-aircraft



AIRBUS

ZERO EMISSION FLIGHT

MODULAR HYBRIDIZATION

INCREMENTAL IMPROVEMENT

CityAirbus NextGen

Battery

ZEROe

Fuel Cell & Superconductivity

H2 combustion

ZEROe

Battery and/or Fuel Cell

H2 combustion

EcoPulse

Battery

Kerosene, SAF

100%SAF

A319neo

H225

LEGEND

	eMotor/Generator
	Battery
	Fuel
	Thermal Engine
	Fuel Cell

10kW — 100kW — 1MW — > 10MW

2020 — 2030 +

Commercial Aircraft: Power Offtake Mgt | eAssisted Idle | eTaxi & eDescent | eBoost at Take-off | Distributed Propulsion

Helicopters: Emergency Backup System | Hybrid Parallel Hybrid | eVTOL

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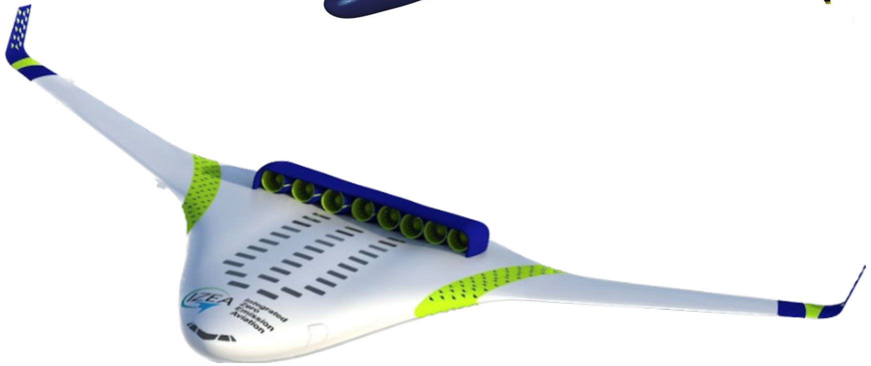
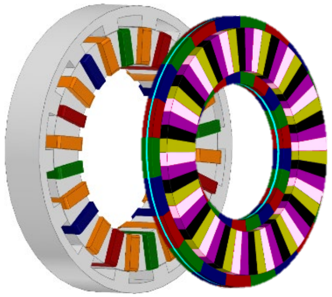
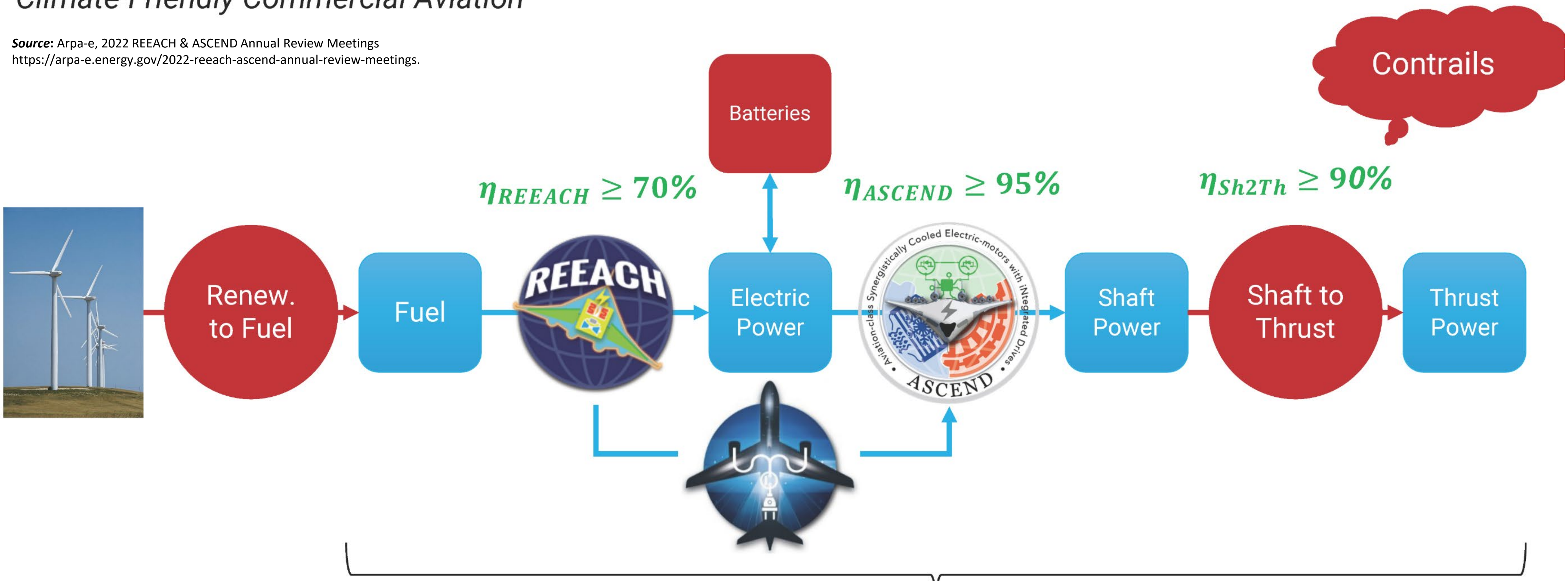




DOE ARPA-E Programs for Aviation

Climate-Friendly Commercial Aviation

Source: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings
https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.



Contrails

Batteries

$\eta_{REEACH} \geq 70\%$

$\eta_{ASCEND} \geq 95\%$

$\eta_{Sh2Th} \geq 90\%$

Renew. to Fuel

Fuel

Electric Power

Shaft Power

Shaft to Thrust

Thrust Power

$\eta_{aircraft} \geq 60\%$

Systems must also have acceptable weight, volume & cost

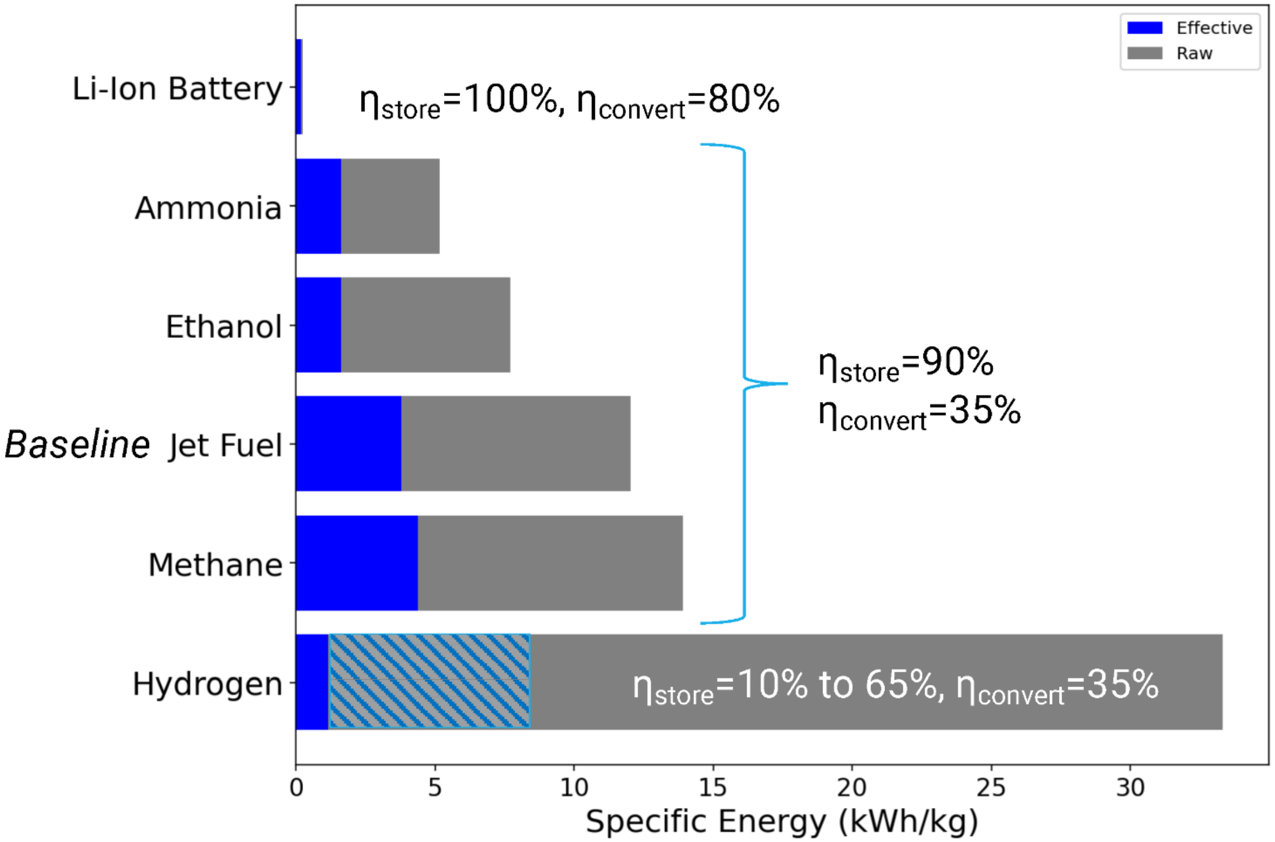
arpa·e CHANGING WHAT'S POSSIBLE

August 5, 2022

Aircraft Fuel and Energy Storage Options

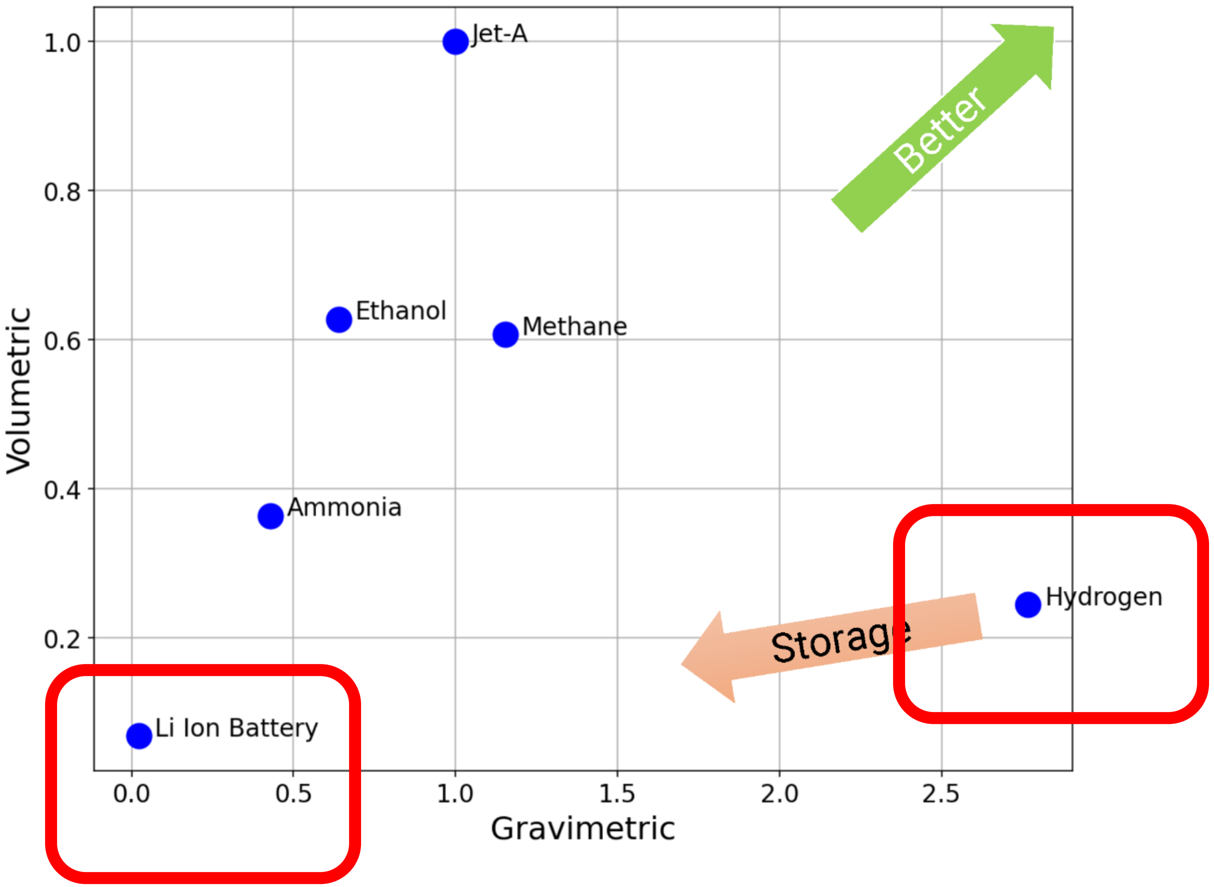
Source: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings
https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

Fuels necessary for long-distance (>200 miles) flights

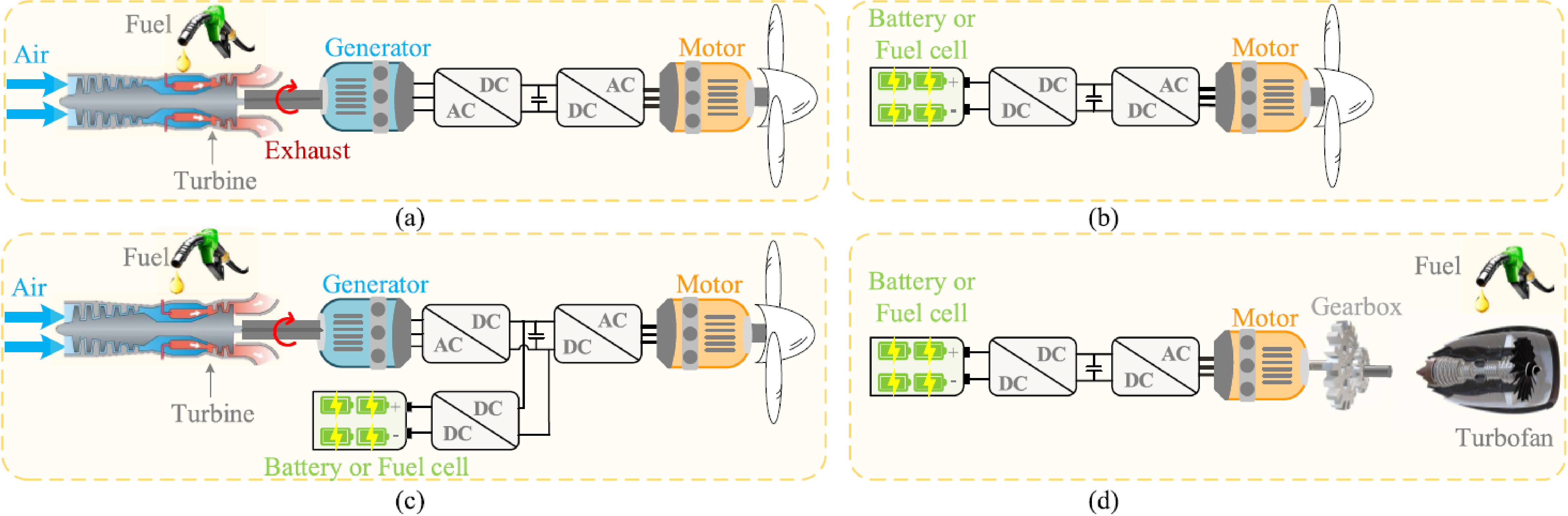


*Effective not inclusive of fuel to electric energy conversion systems

Fuel/Jet-A Volumetric vs Gravimetric Specific Energy



Electric Aircraft Propulsion Systems (EAPS)



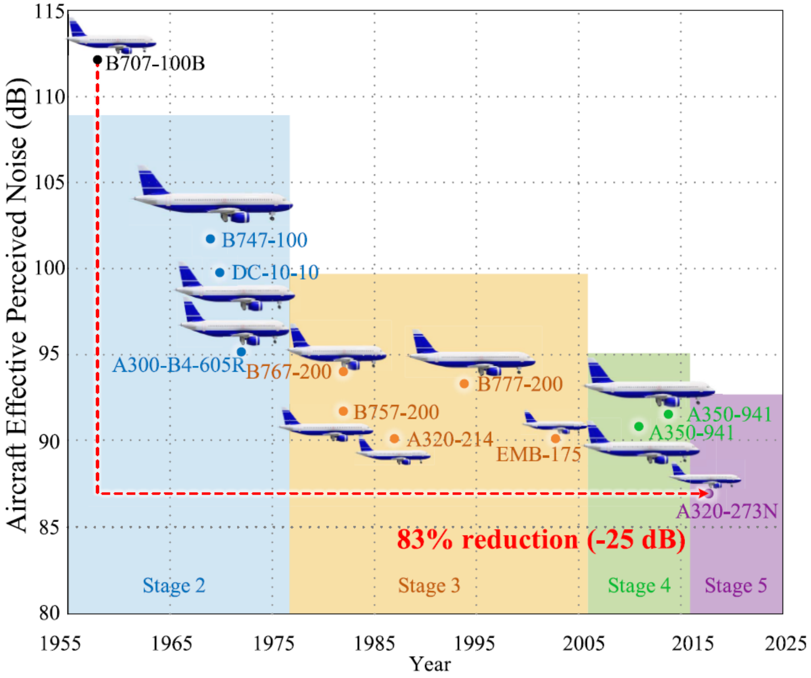
(a) (b) (c) (d)

Fig. 2. Aircraft propulsion based on various powertrain structures: (a) turboelectric, (b) all-electric, (c) series hybrid-electric, and (d) parallel hybrid-electric.

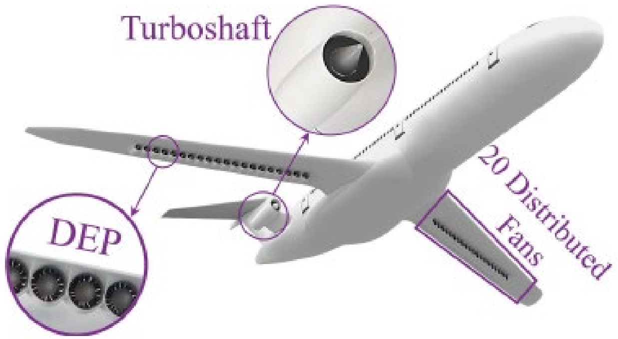
Source: **University of Kentucky**, M. T. Fard *et al*, "Aircraft Distributed Electric Propulsion Technologies—A Review," in *IEEE Transactions on Transportation Electrification*, vol. 8, no. 4, pp. 4067-4090, Dec. 2022, doi: 10.1109/TTE.2022.3197332.

- Hybrid and distributed propulsion options to be discussed
- Multiple propulsors, each with their own electric motor.

Electric Aircraft Main Advantages



- Emission reduction
- Noise reduction
- Distributed propulsion
  - Boundary layer ingestion – increased efficiency
  - Fault tolerance and redundancy
- Blended wing body (BWB) aerodynamics – increased efficiency.



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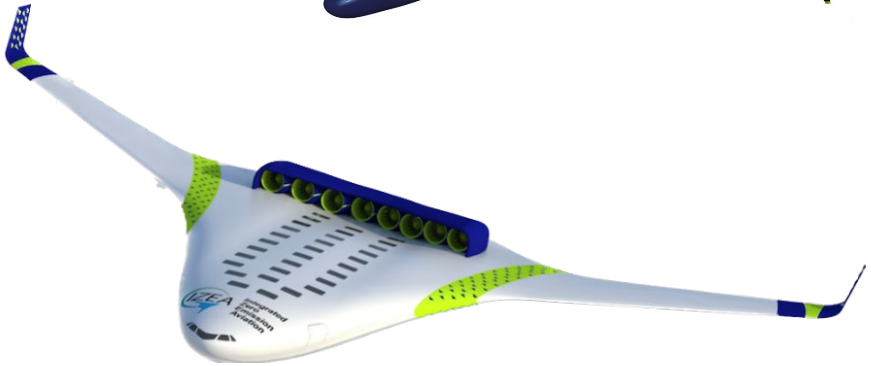
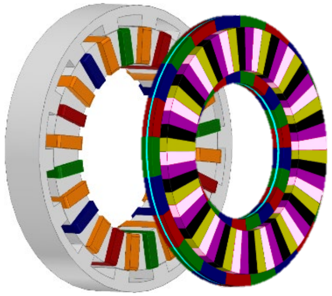
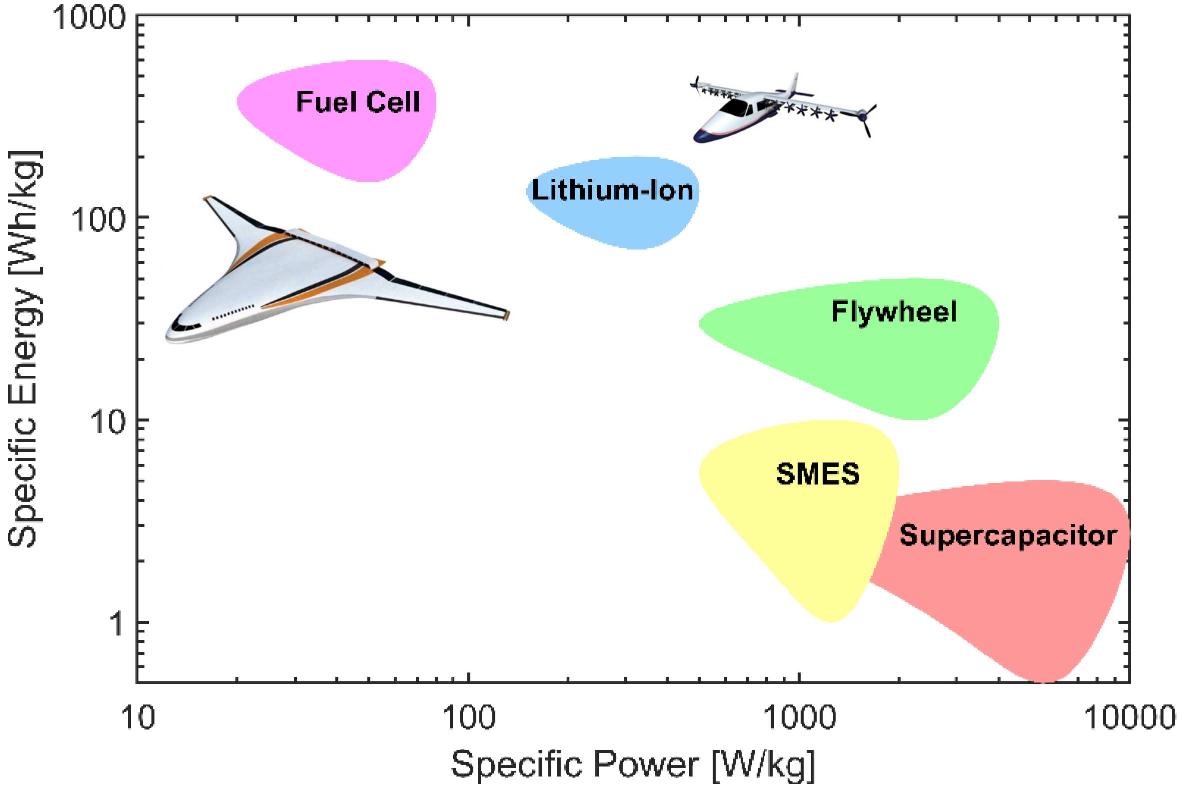
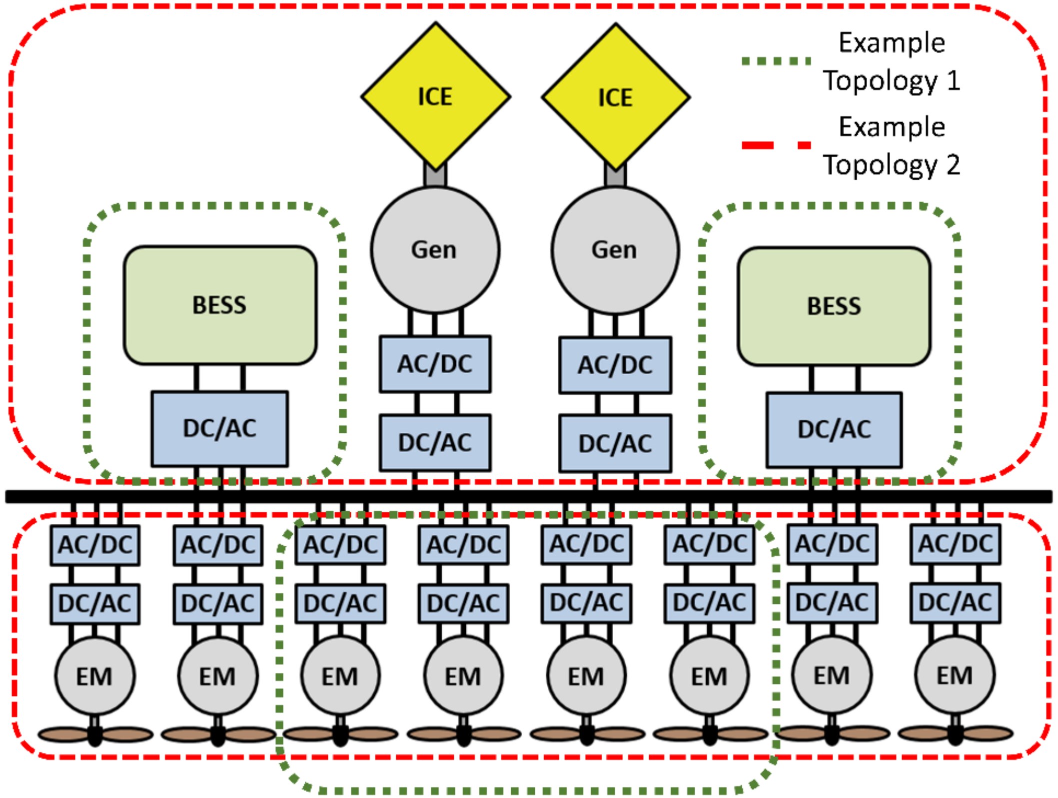




Optimal EAPS Design



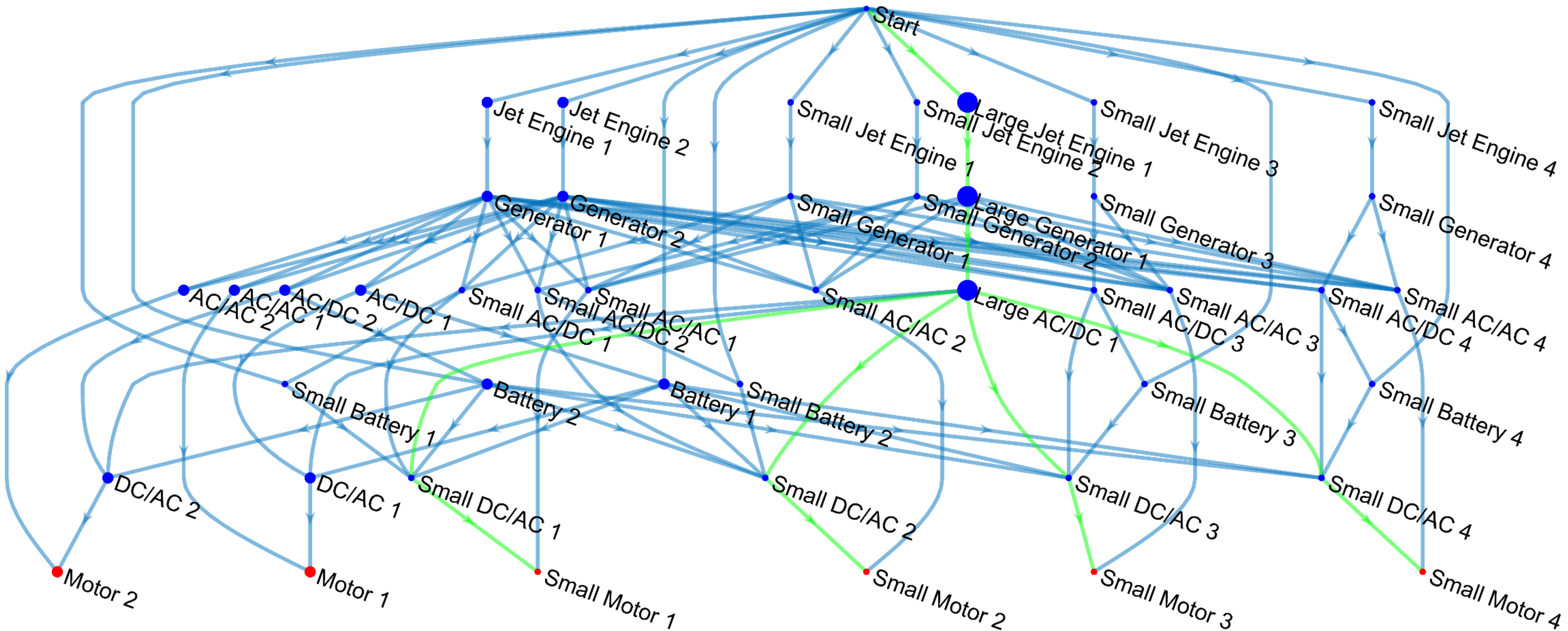


- Derivation of optimal topologies and component ratings based on an automated process
- Systematic literature survey to establish available technology and characteristics at component and subsystem level
- Multi-objective study with interpretation of pareto front design candidates.

***Source:* University of Kentucky**, Lawhorn, D. *et al.*, "Multi-objective Optimization for Aircraft Power Systems using a Network Graph Representation," IEEE Transactions on Transportation Electrification, Vol. 7, No. 4, doi: 10.1109/TTE.2021.3066123., pp. 3021-3031 (2021)

EAPS Optimization based on Graph Network

- Network flow optimization problem with a single objective or multiple/concurrent objective functions: losses (efficiency), mass, reliability
- Approaches:
  - Minimal cut sets have been used to evaluate reliability in several studies
  - Dijkstra’s type algorithms offer ways to find minimal cost paths between source and sink nodes.



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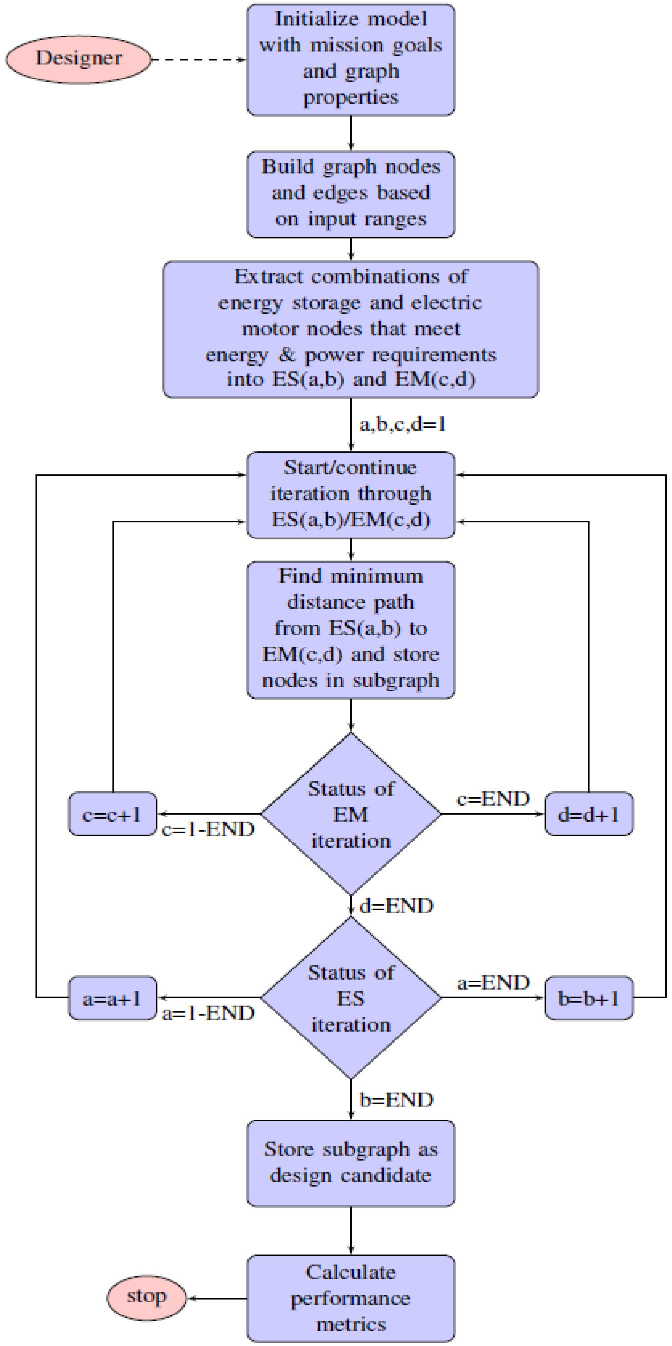


Designer

Initialize model with mission goals and graph properties

Build graph nodes and edges based on input ranges

Extract combinations of energy storage and electric motor nodes that meet energy & power requirements into ES(a,b) and EM(c,d)

a,b,c,d=1

Start/continue iteration through ES(a,b)/EM(c,d)

Find minimum distance path from ES(a,b) to EM(c,d) and store nodes in subgraph

Status of EM iteration

c=c+1

c=1-END

c=END

d=d+1

d=END

Status of ES iteration

a=a+1

a=1-END

a=END

b=b+1

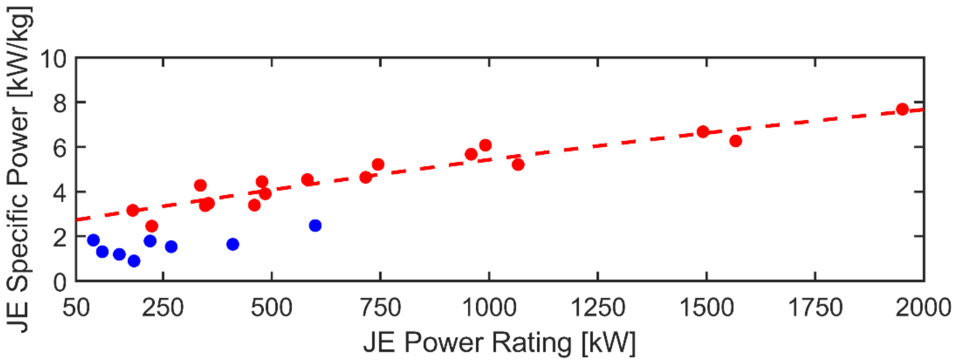
b=END

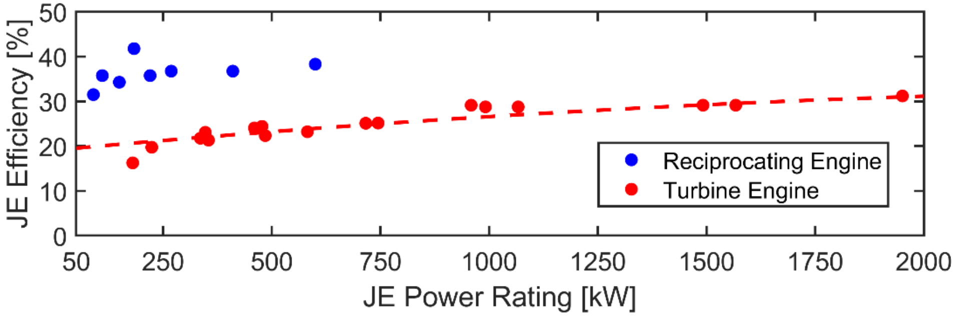
Store subgraph as design candidate

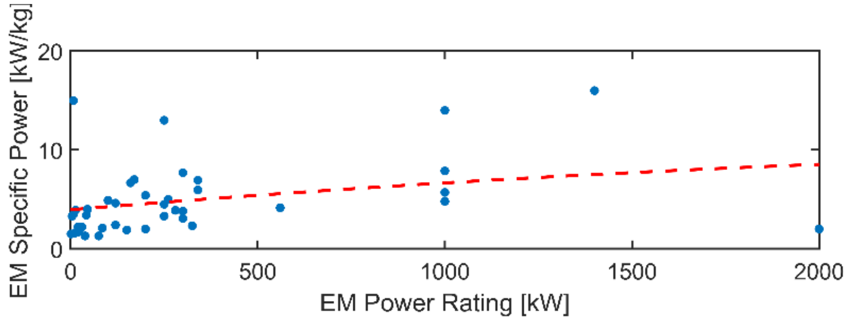
Calculate performance metrics

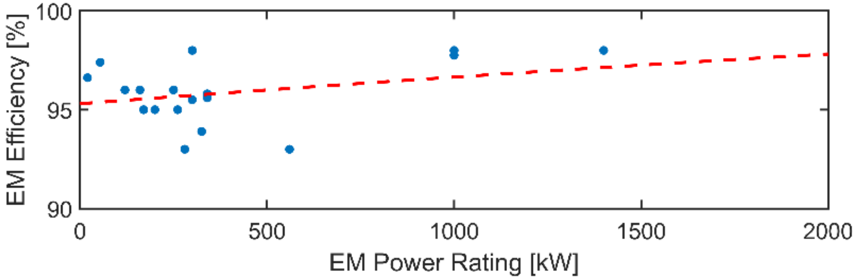
stop

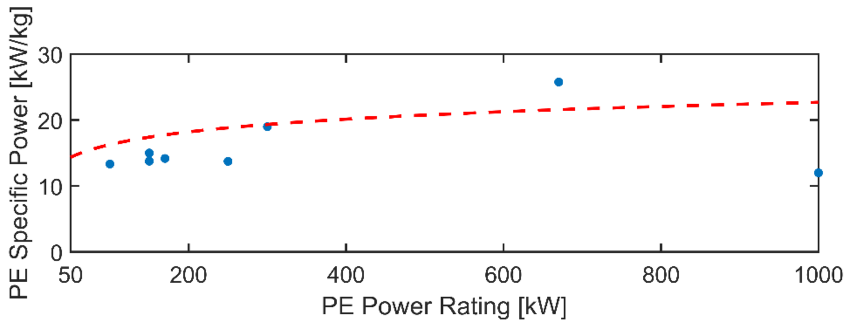
Performance of Aircraft Components

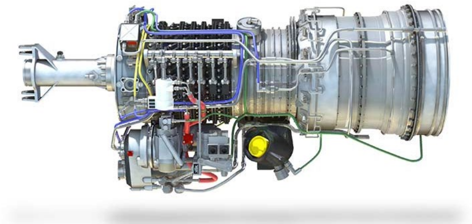












- Systematic literature search for jet engines, electric machines, and power electronics (PE)
- Efficiency of PE is typically very high.

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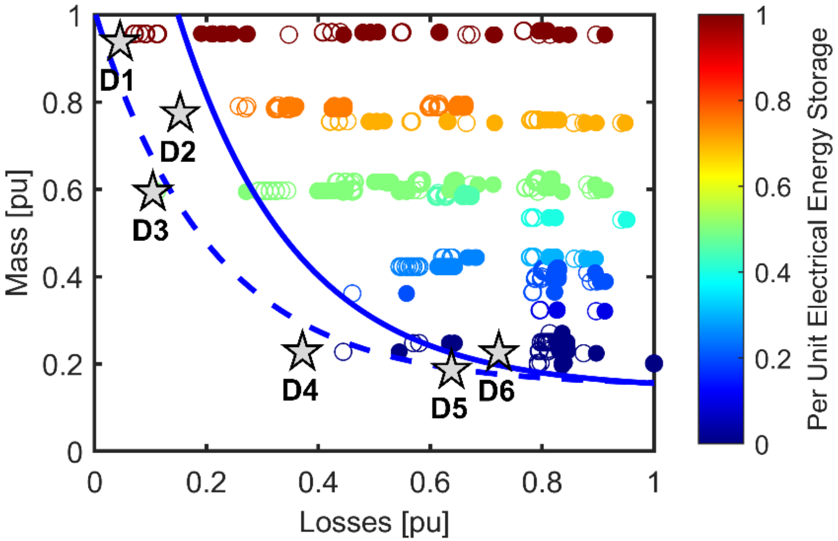
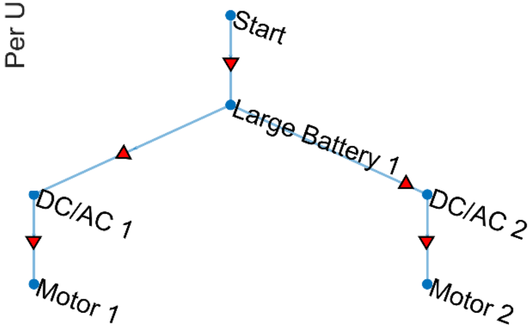
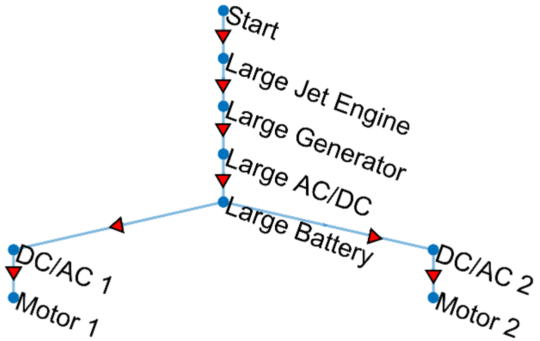
Pareto Front Designs, incl. All-electric, Hybrid, and Turbo

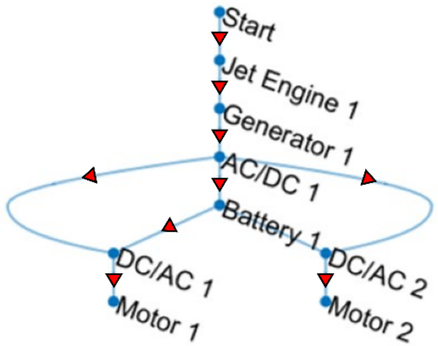




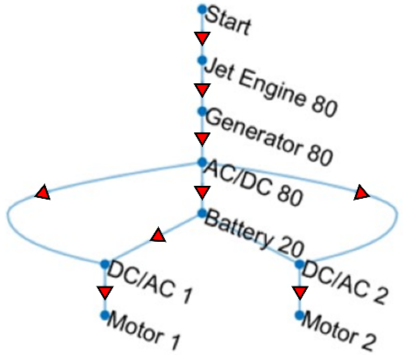
D1: All-electric



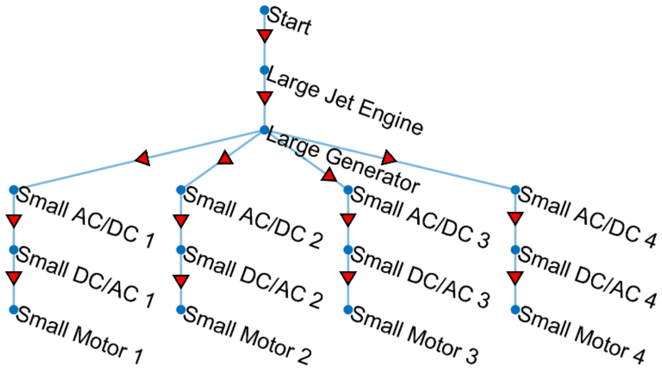
D2: Series Hybrid-electric



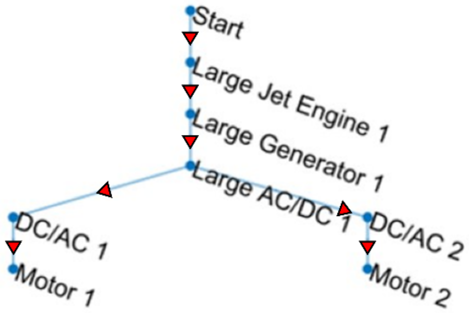
D3: Parallel Hybrid-electric



D4: Parallel Hybrid-electric



D5: Turbo-electric



D6: Turbo-electric

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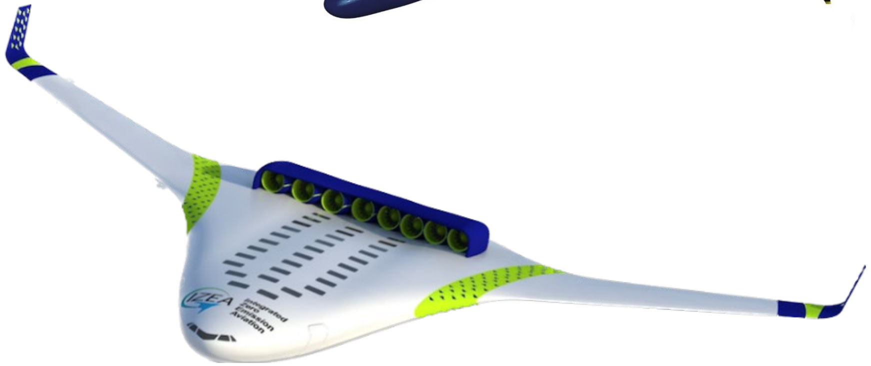
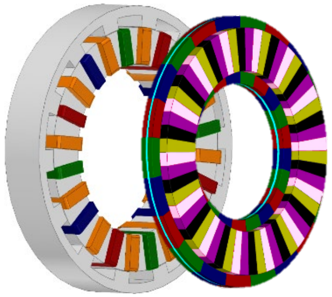
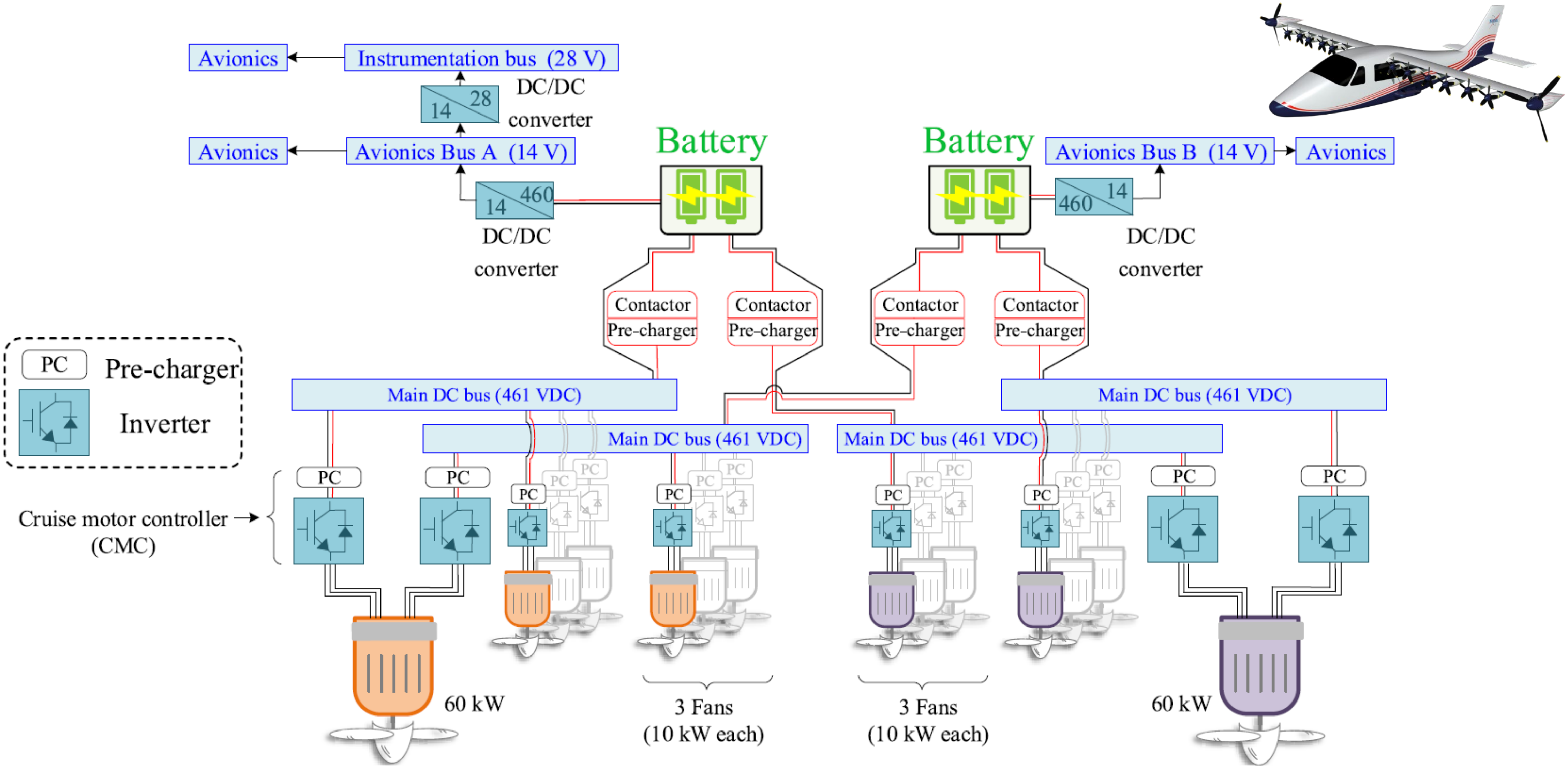




NASA X-57 (Mod IV) Battery Operated Aircraft – EAPS



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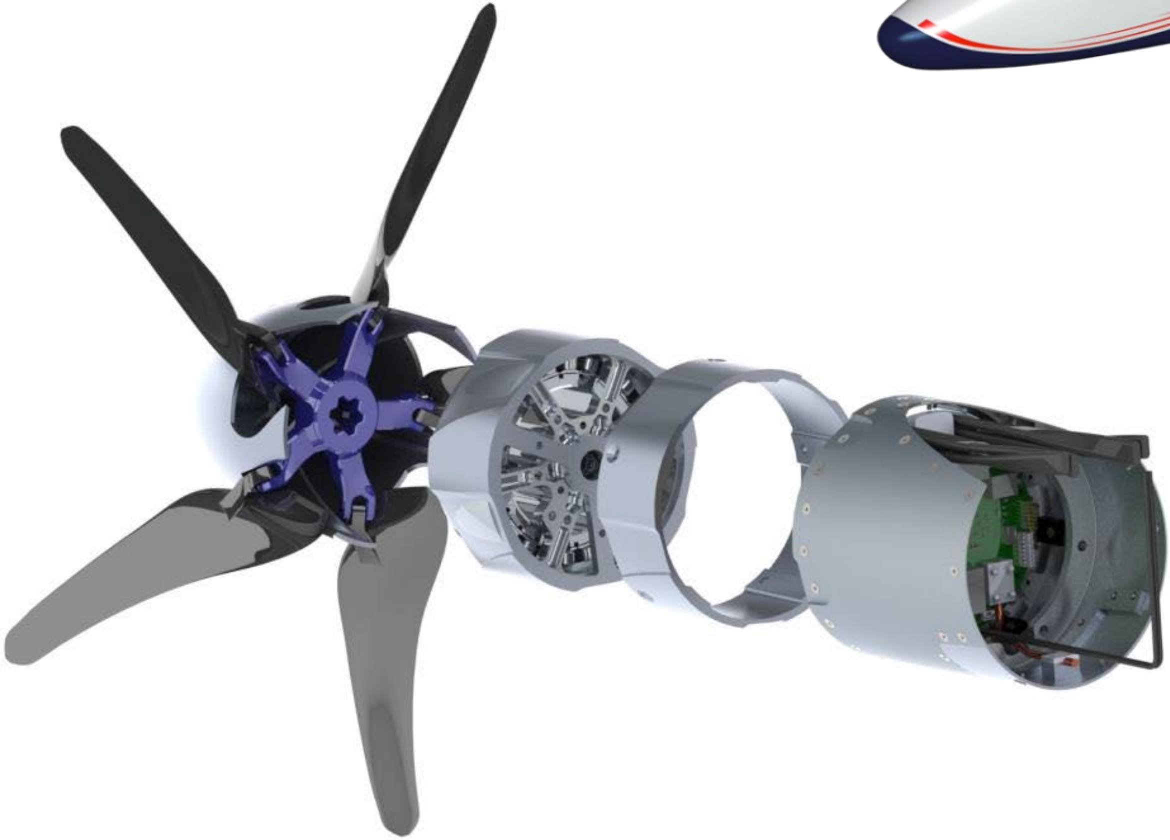
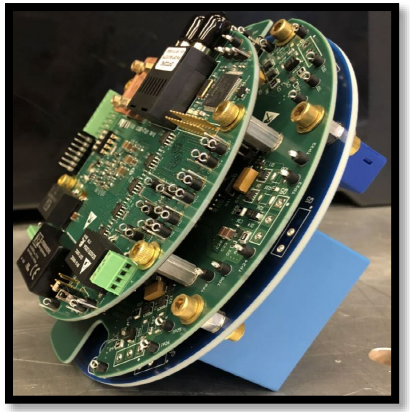
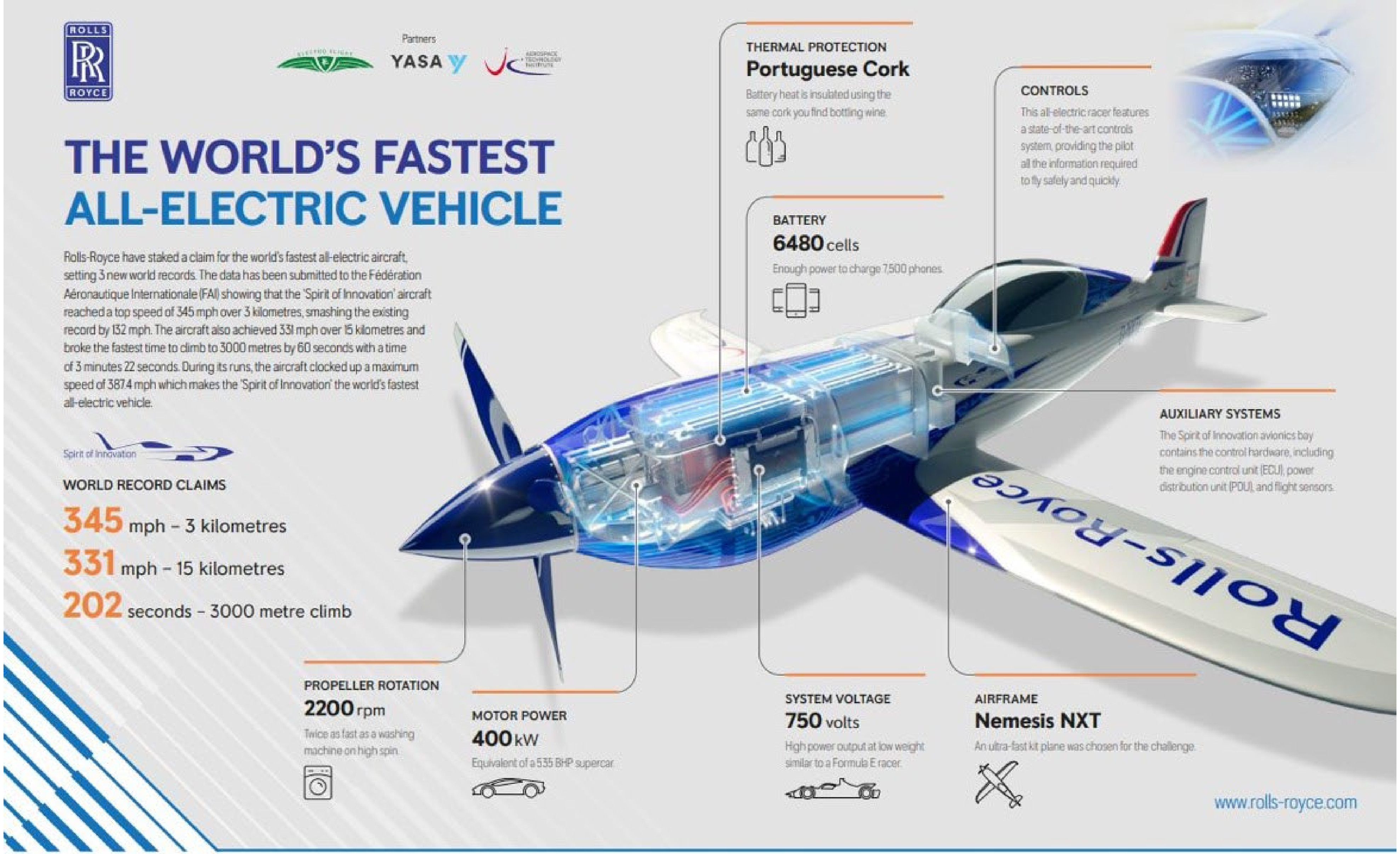
NASA X-57 – Example Electric Propulsion Components





Rolls-Royce Experimental Battery-Operated Aircraft



THE WORLD'S FASTEST ALL-ELECTRIC VEHICLE

Rolls-Royce have staked a claim for the world's fastest all-electric aircraft, setting 3 new world records. The data has been submitted to the Fédération Aéronautique Internationale (FAI) showing that the 'Spirit of Innovation' aircraft reached a top speed of 345 mph over 3 kilometres, smashing the existing record by 132 mph. The aircraft also achieved 331 mph over 15 kilometres and broke the fastest time to climb to 3000 metres by 60 seconds with a time of 3 minutes 22 seconds. During its runs, the aircraft clocked up a maximum speed of 387.4 mph which makes the 'Spirit of Innovation' the world's fastest all-electric vehicle.

WORLD RECORD CLAIMS

345 mph – 3 kilometres

331 mph – 15 kilometres

202 seconds – 3000 metre climb

THERMAL PROTECTION

Portuguese Cork

Battery heat is insulated using the same cork you find bottling wine.

CONTROLS

This all-electric racer features a state-of-the-art controls system, providing the pilot all the information required to fly safely and quickly.

BATTERY

6480 cells

Enough power to charge 7,500 phones.

AUXILIARY SYSTEMS

The Spirit of Innovation avionics bay contains the control hardware, including the engine control unit (ECU), power distribution unit (PDU), and flight sensors.

PROPELLER ROTATION

2200 rpm

Twice as fast as a washing machine on high spin.

MOTOR POWER

400 kW

Equivalent of a 535 BHP supercar.

SYSTEM VOLTAGE

750 volts

High power output at low weight similar to a Formula E racer.

AIRFRAME

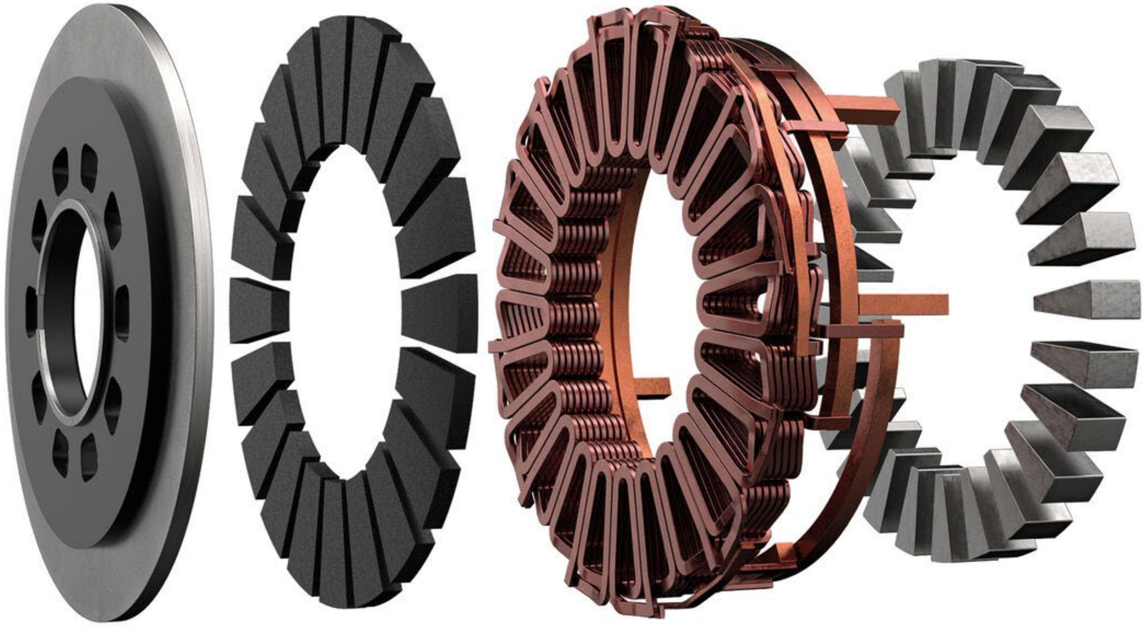
Nemesis NXT

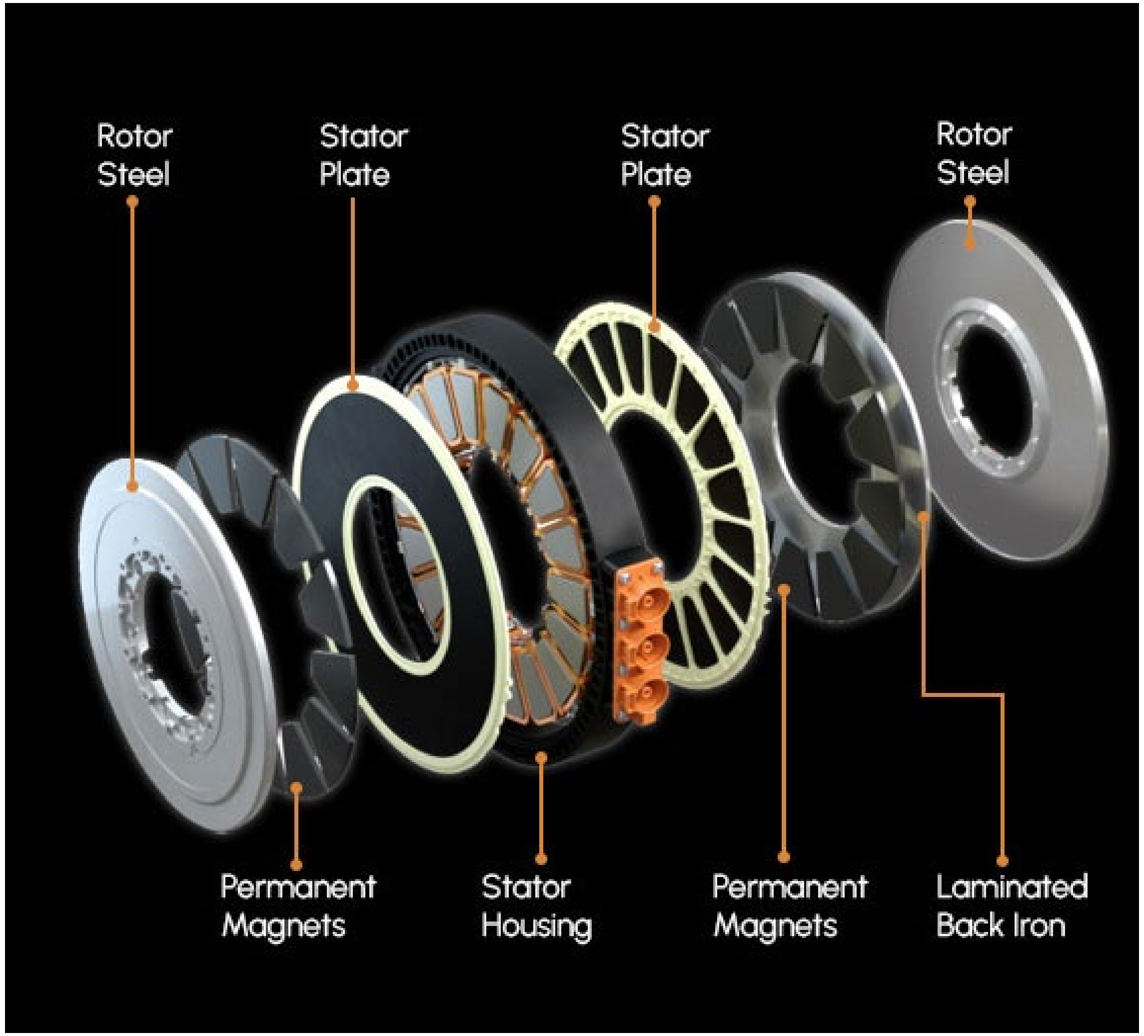
An ultra-fast kit plane was chosen for the challenge.

www.rolls-royce.com

YASA and EvoLito

Source: YASA and EvoLito
https://evolito.aero/about/





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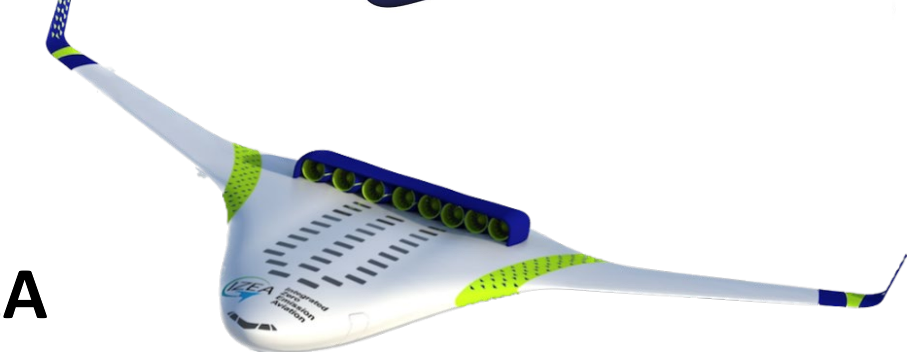
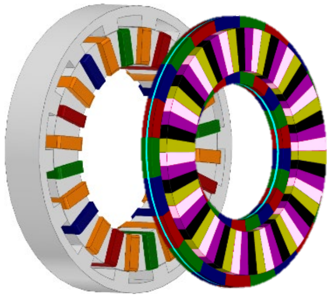
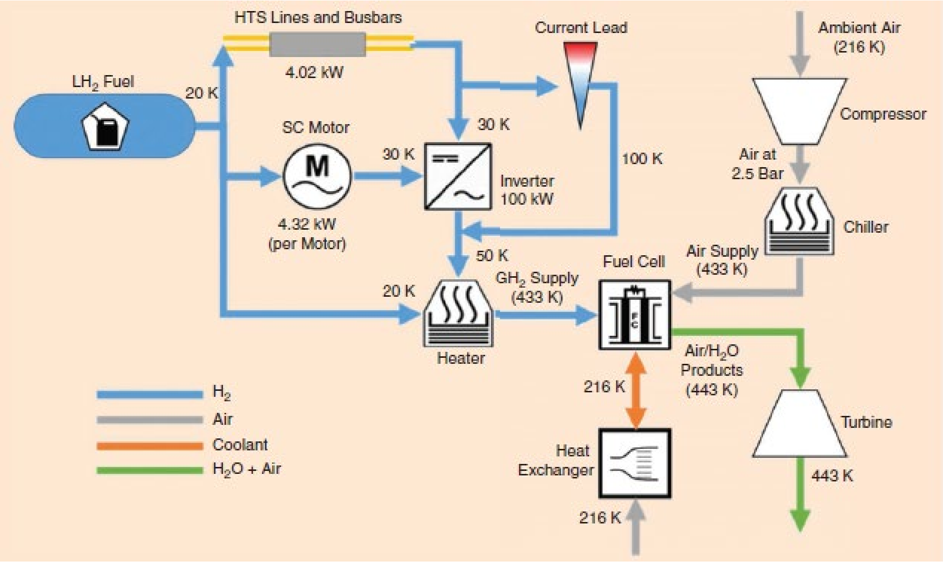
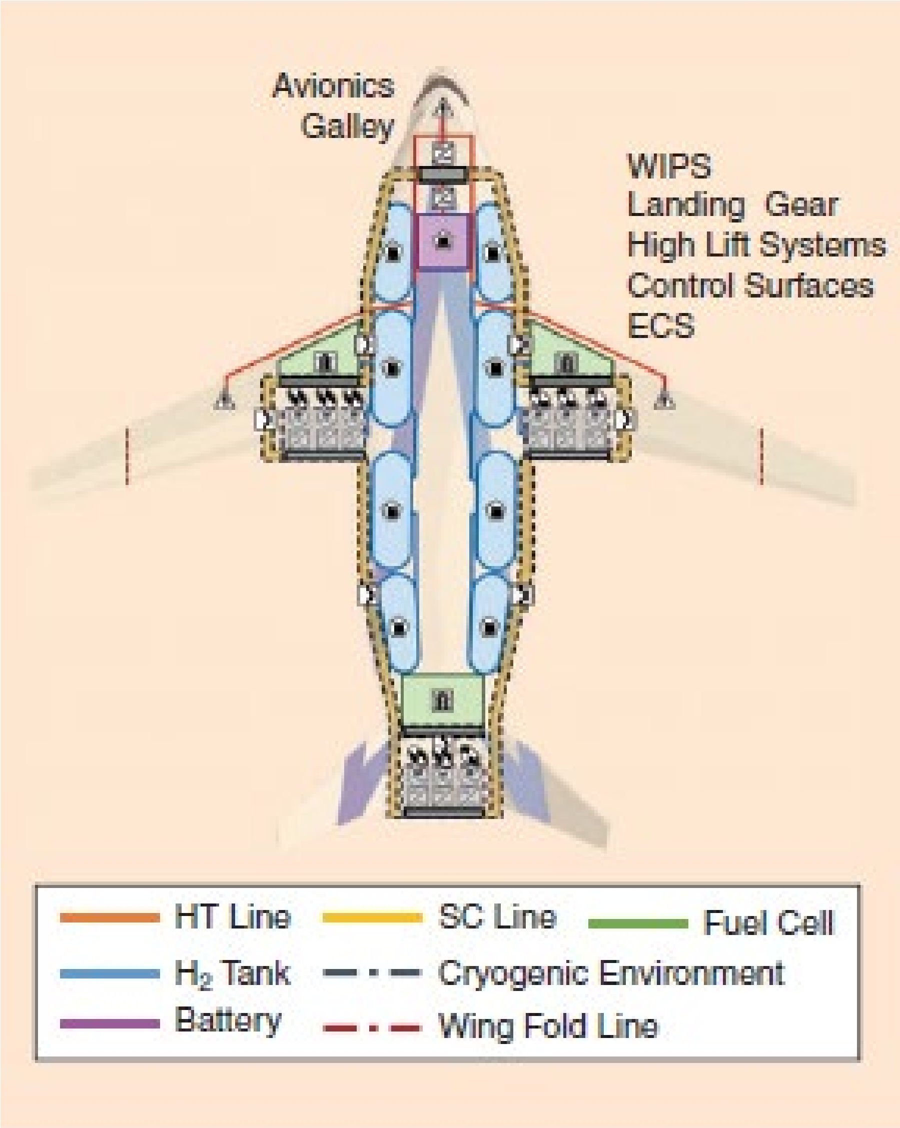




Example NASA ULI Project – CHEETA Led by UIC

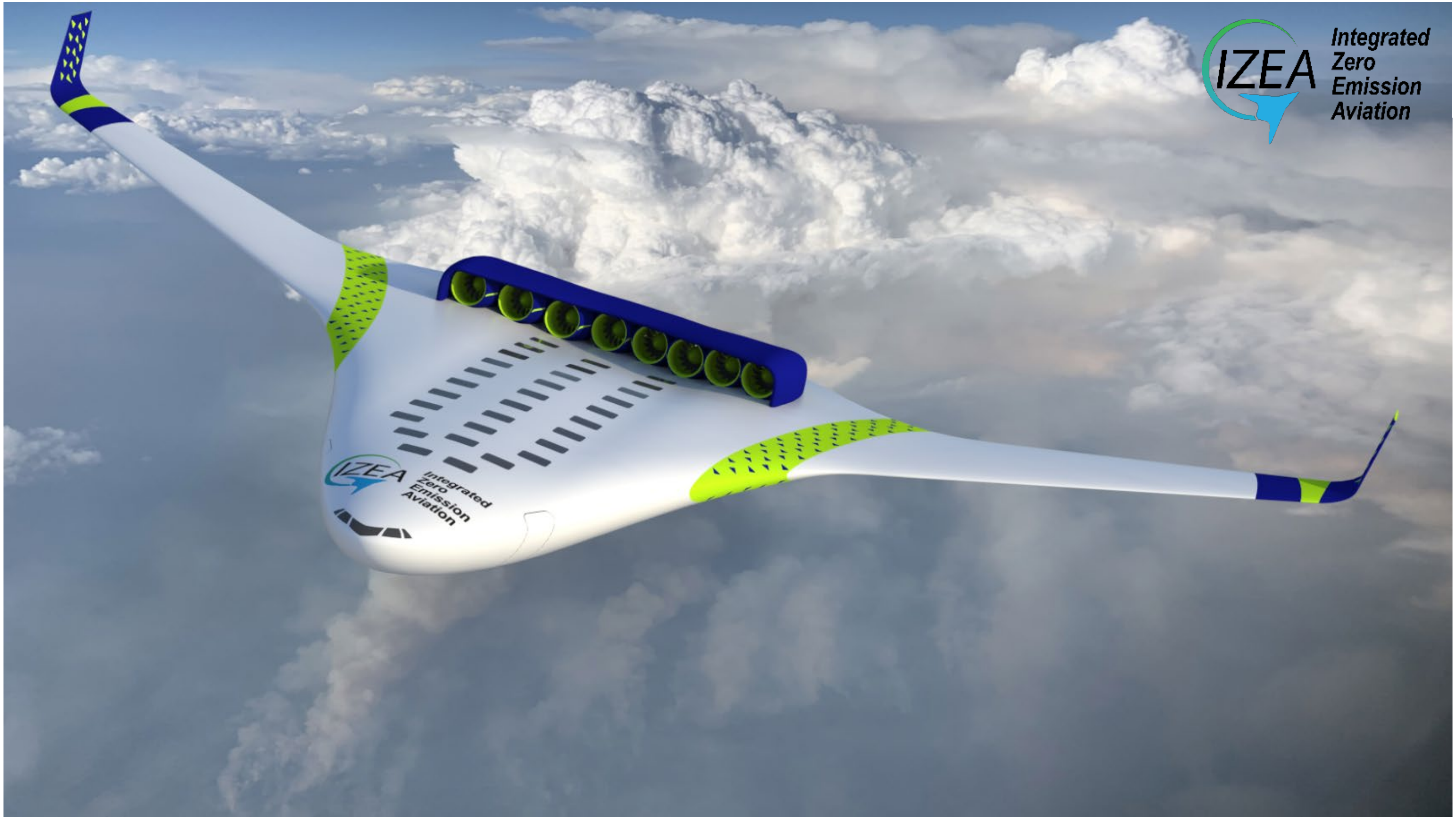




- NASA University Leadership Initiative (ULI)
- Circa 2017 - 2022
- Integrated liquid hydrogen and cryogenic superconducting machines: generators and motors
- Also superconducting HTS lines and busbars
- Liquid flow to cryogenic inverters and power electronic components heatsinked to run at their nominal operating temperature.

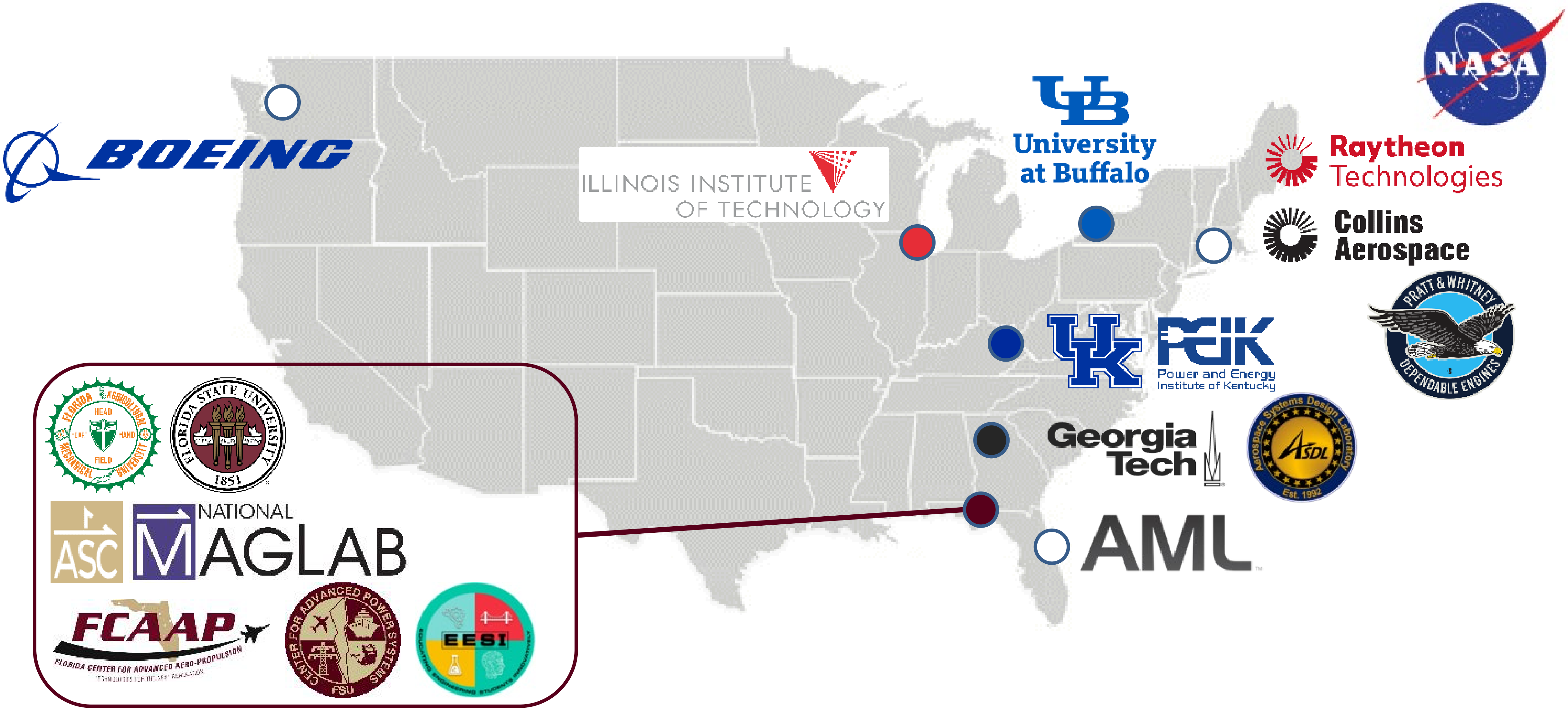
Source: P. J. Ansell, "Hydrogen-Electric Aircraft Technologies and Integration: Enabling an environmentally sustainable aviation future," in IEEE Electrification Magazine, vol. 10, no. 2, pp. 6-16, June 2022, doi: 10.1109/MELE.2022.3165721.

NASA ULI IZEA – Integrated Zero Emission Aviation



Source: NASA IZEA Annual Review 2023.

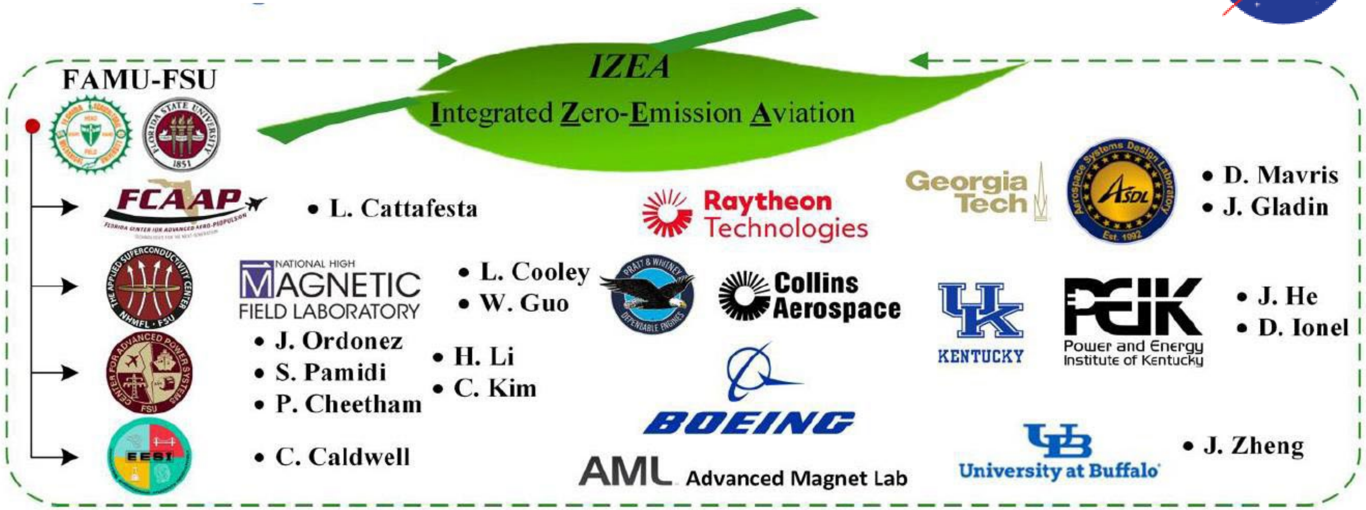
NASA ULI IZEA – Integrated Zero Emission Aviation



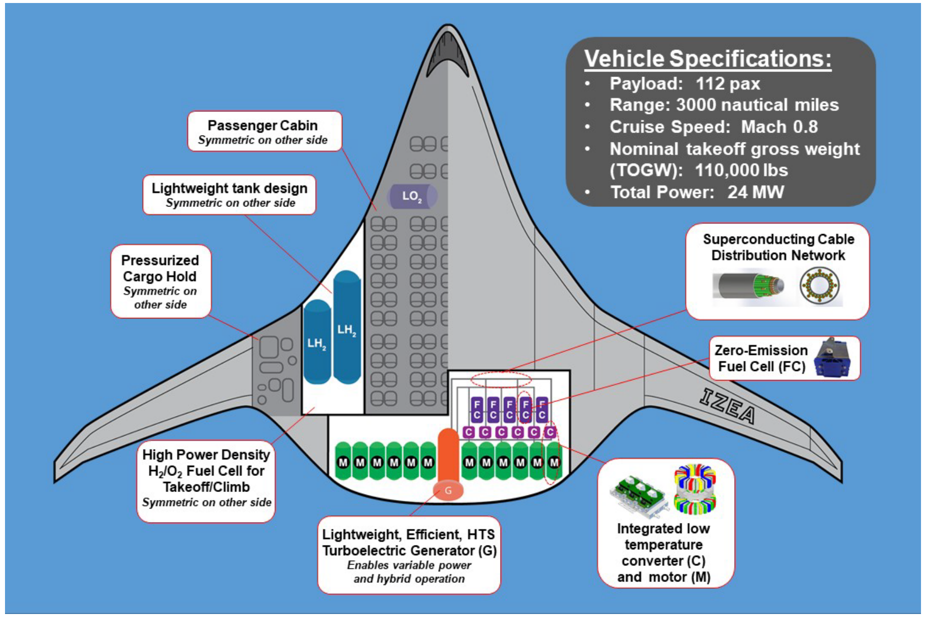
Source: NASA IZEA Annual Review 2023.

NASA ULI Project IZEA – Framework and Concept

- NASA ULI program was established in 2017 and includes multiple projects
- Our project: Integrated Zero-Emission Aviation using a Robust Hybrid Architecture (**IZEA)**
- Five (5) years: 2022 - 2027
- Team members: 4 universities and 5 companies
- Lead, Florida State University
- At UK, electric machines and drives.

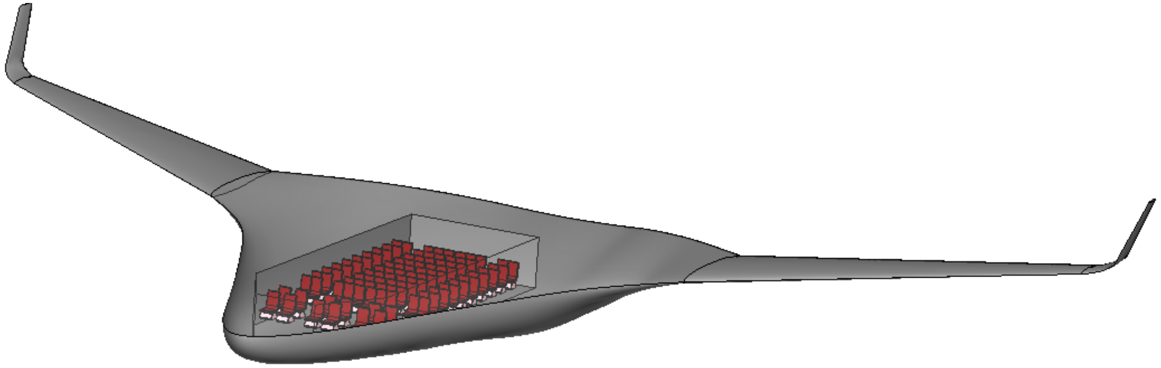


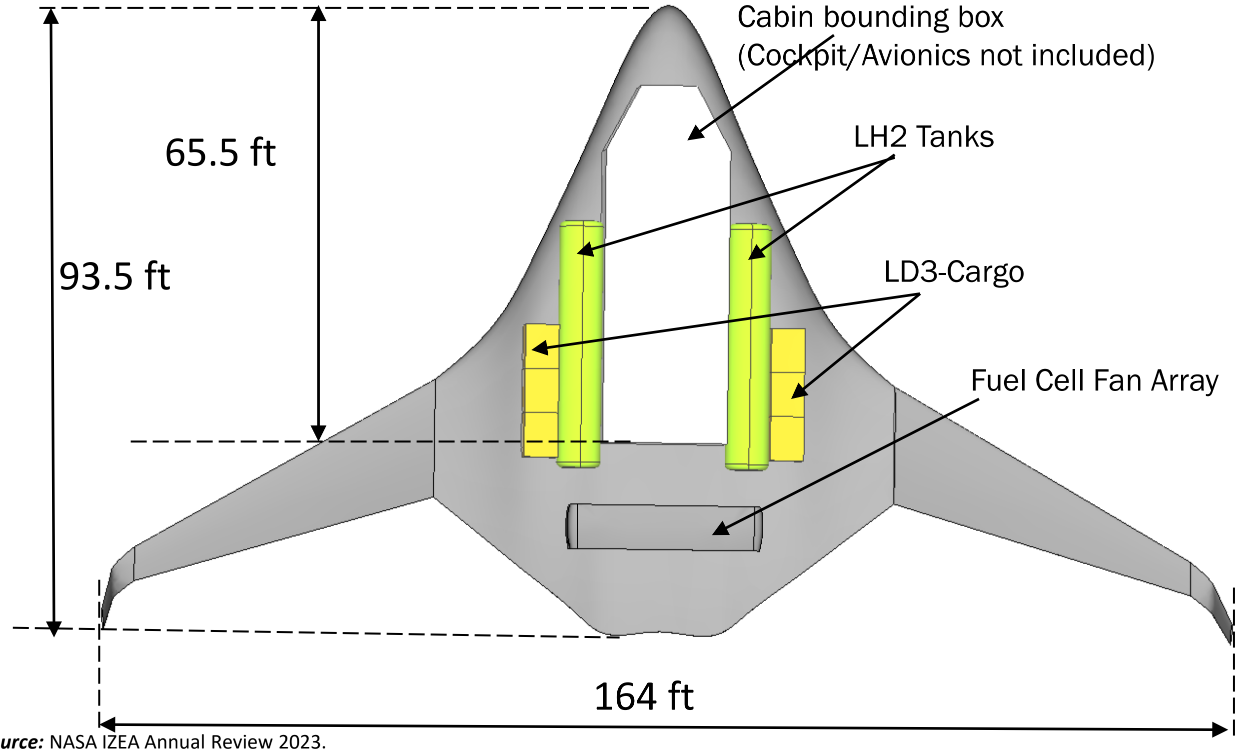
Source: NASA IZEA Annual Review 2023.

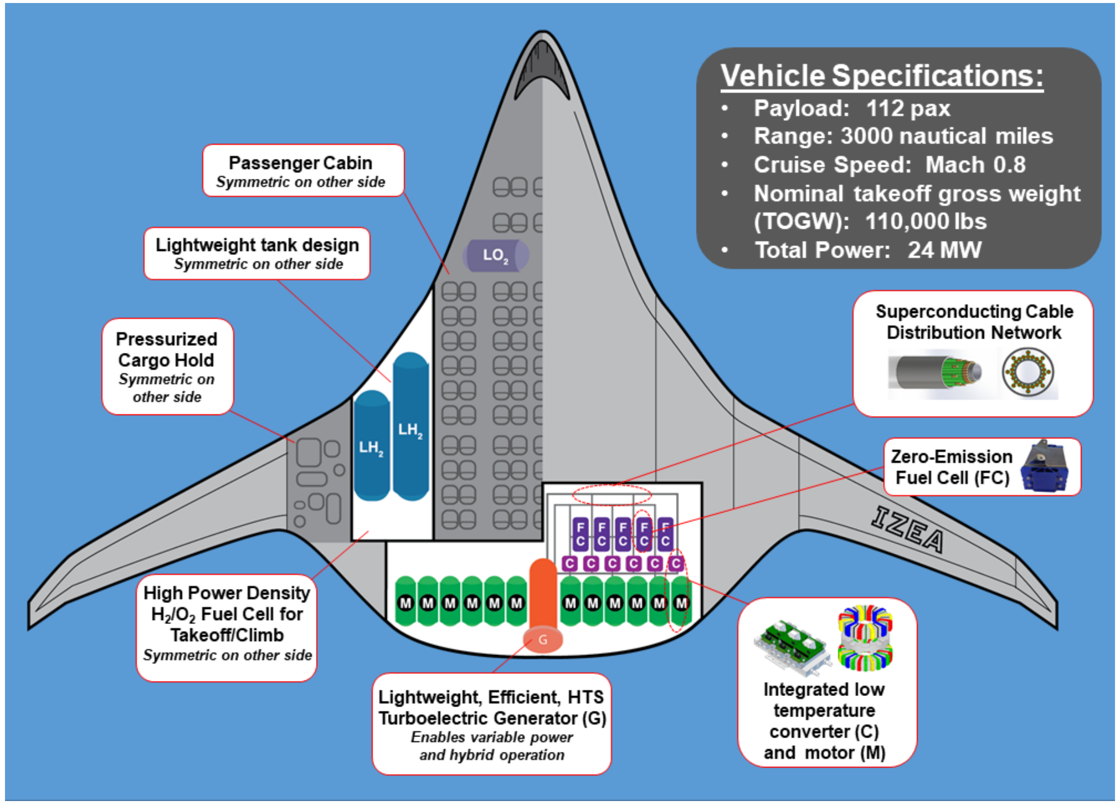


Vehicle Specifications:
- Payload: 112 pax
- Range: 3000 nautical miles
- Cruise Speed: Mach 0.8
- Nominal takeoff gross weight (TOGW): 110,000 lbs
- Total Power: 24 MW

IZEA Concept Aircraft







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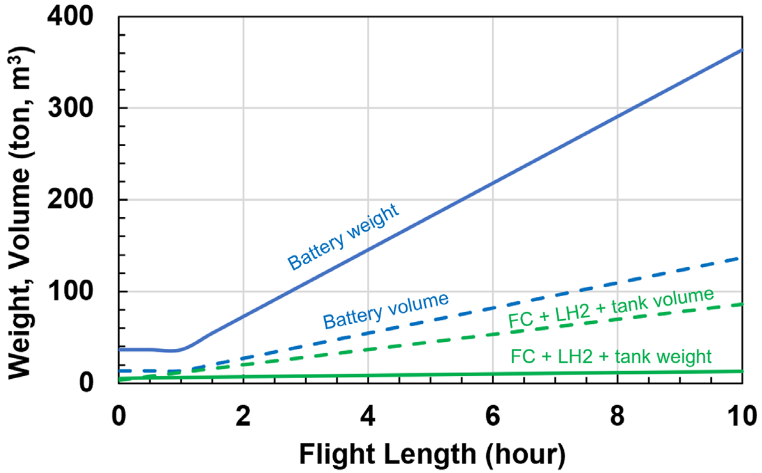
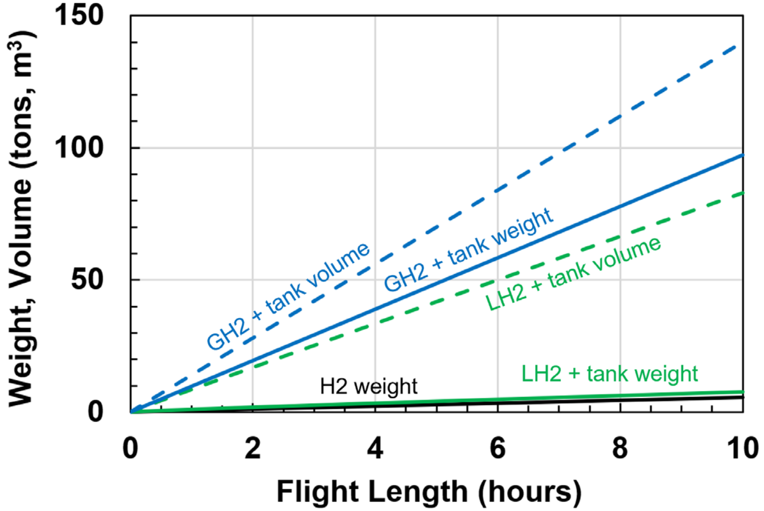
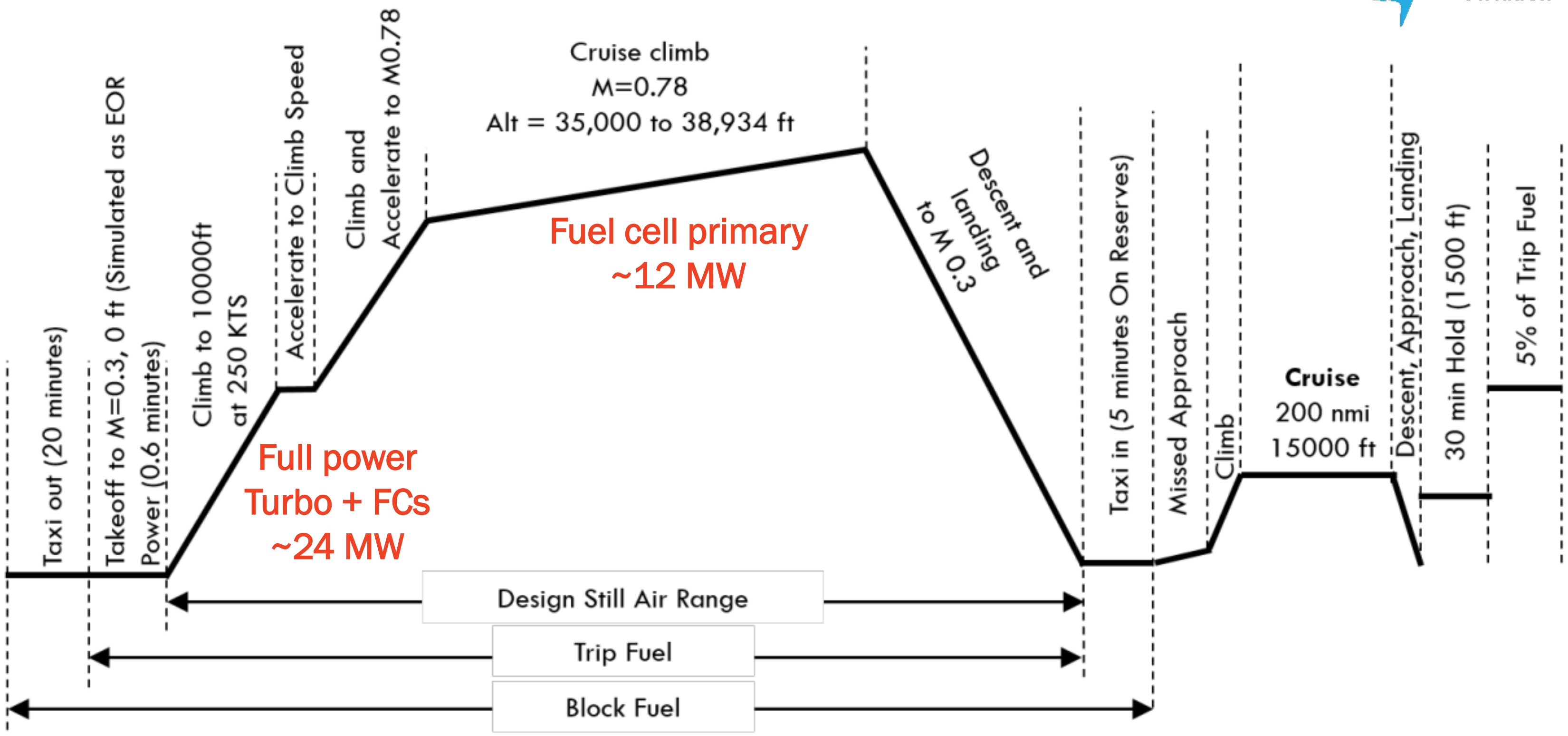
- Total Power: 24 MW

Source: NASA IZEA Annual Review 2023.

Fuel and Typical Mission Profile







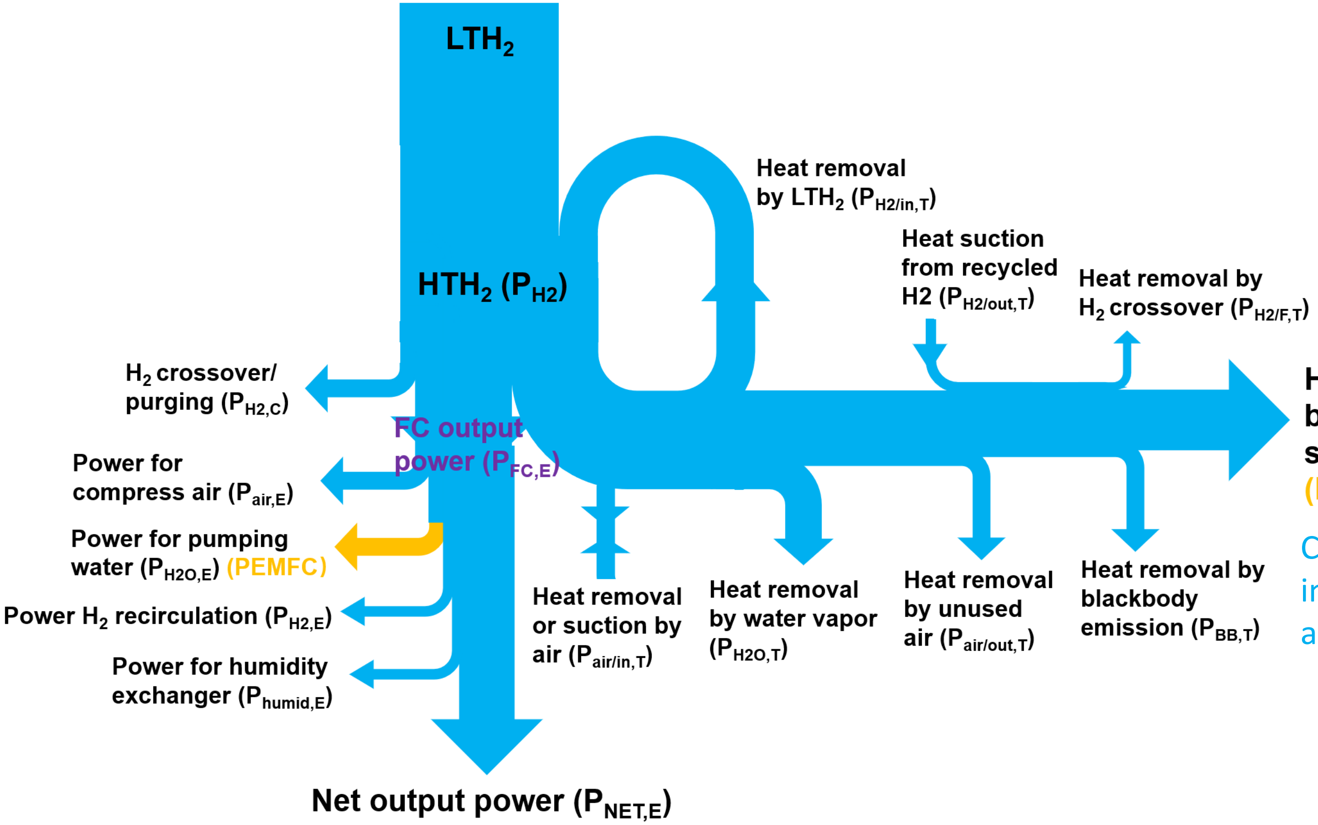
Fuel cell primary
~12 MW

Full power
Turbo + FCs
~24 MW

The liquid hydrogen significant advantage in gravimetric energy density vs. rechargeable batteries and compressed hydrogen. Example left graphs for a reference 10MW output power.

Source: NASA IZEA Annual Review 2023.

Fuel Cell, Energy Conversion Efficiency, and Cooling



LTH_2

HTH_2 (P_{H2})

Heat removal by LTH_2 ($P_{H2/in,T}$)

Heat suction from recycled H2 ($P_{H2/out,T}$)

Heat removal by H_2 crossover ($P_{H2/F,T}$)

Heat removal by cooling system ($P_{CS,T}$) (PEMFC)

H_2 crossover/ purging ($P_{H2,C}$)

FC output power ($P_{FC,E}$)

Power for compress air ($P_{air,E}$)

Power for pumping water ($P_{H2O,E}$) (PEMFC)

Power H_2 recirculation ($P_{H2,E}$)

Power for humidity exchanger ($P_{humid,E}$)

Heat removal or suction by air ($P_{air/in,T}$)

Heat removal by water vapor ($P_{H2O,T}$)

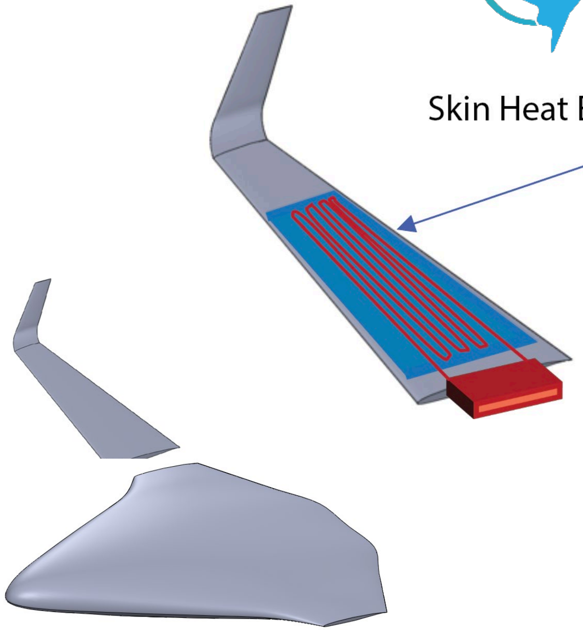
Heat removal by unused air ($P_{air/out,T}$)

Heat removal by blackbody emission ($P_{BB,T}$)

Net output power ($P_{NET,E}$)

Cooling system includes ram air and aircraft skin

Integrated Zero Emission Aviation



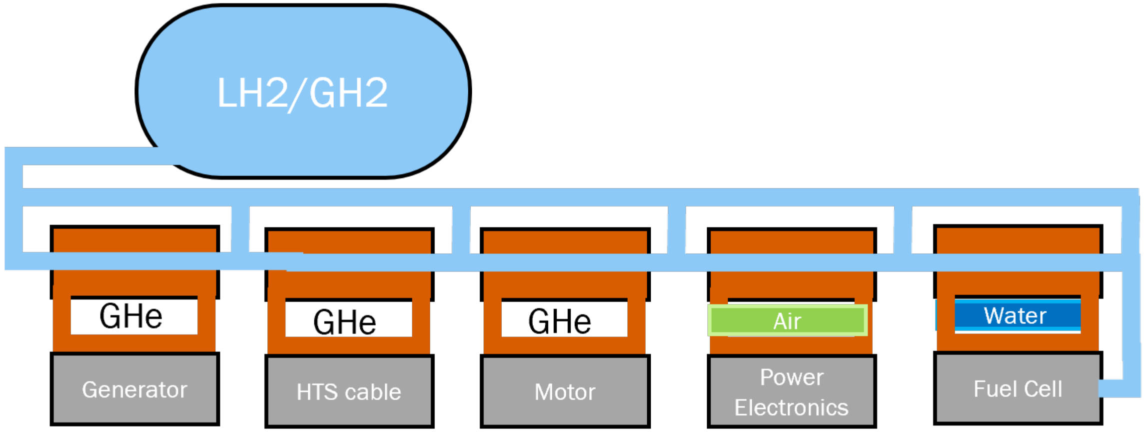
Skin Heat Exchanger

- Fuel Cells (FC), Proton Exchange Membrane (PEMFC), Solid Oxid Fuel Cells (SOFC)
- Energy conversion overall efficiency approx. 50%
- Substantial losses and hence cooling required, approx. 2/3 through radiator and the rest through skin heat exchanger.

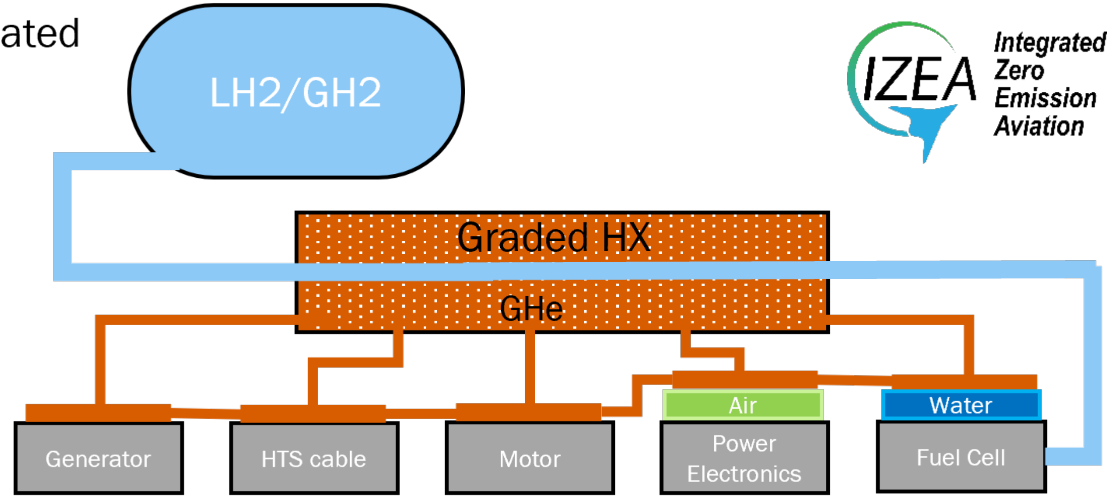
Source: NASA IZEA Annual Review 2023.

Integrated Thermal Management System

Individual

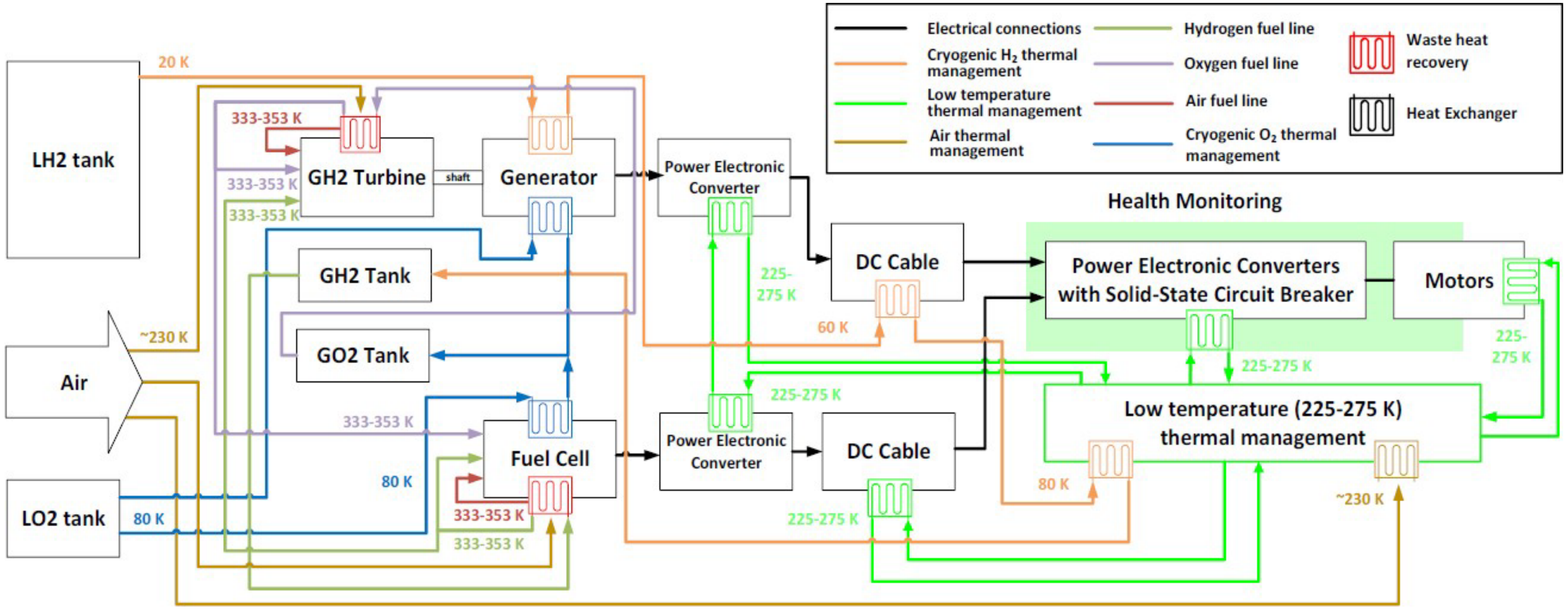


Integrated



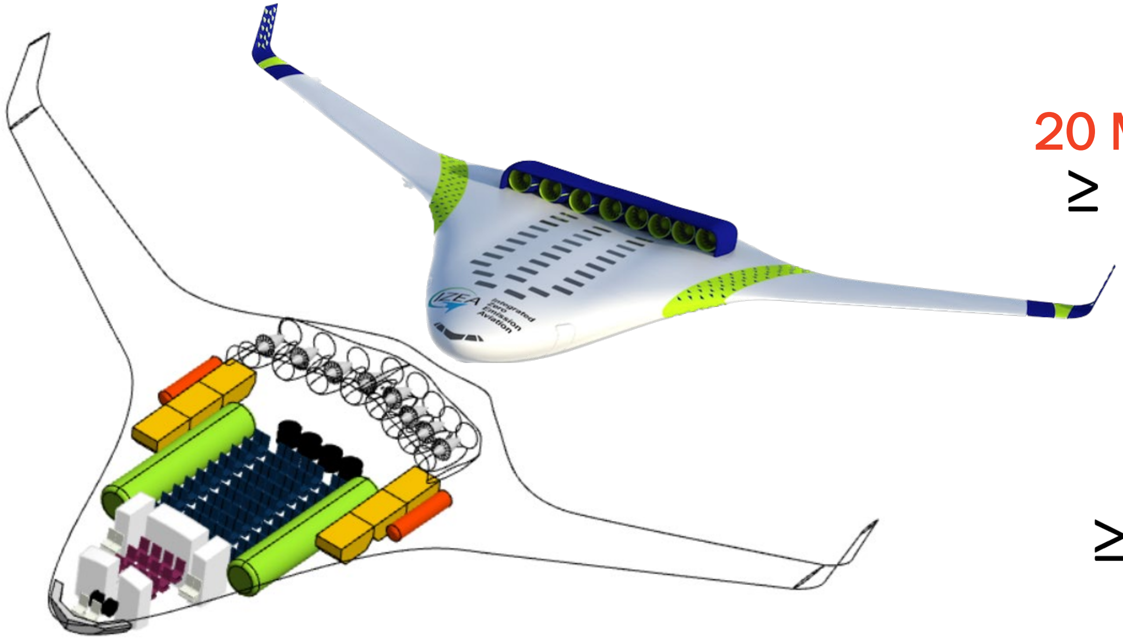
Integration advantages

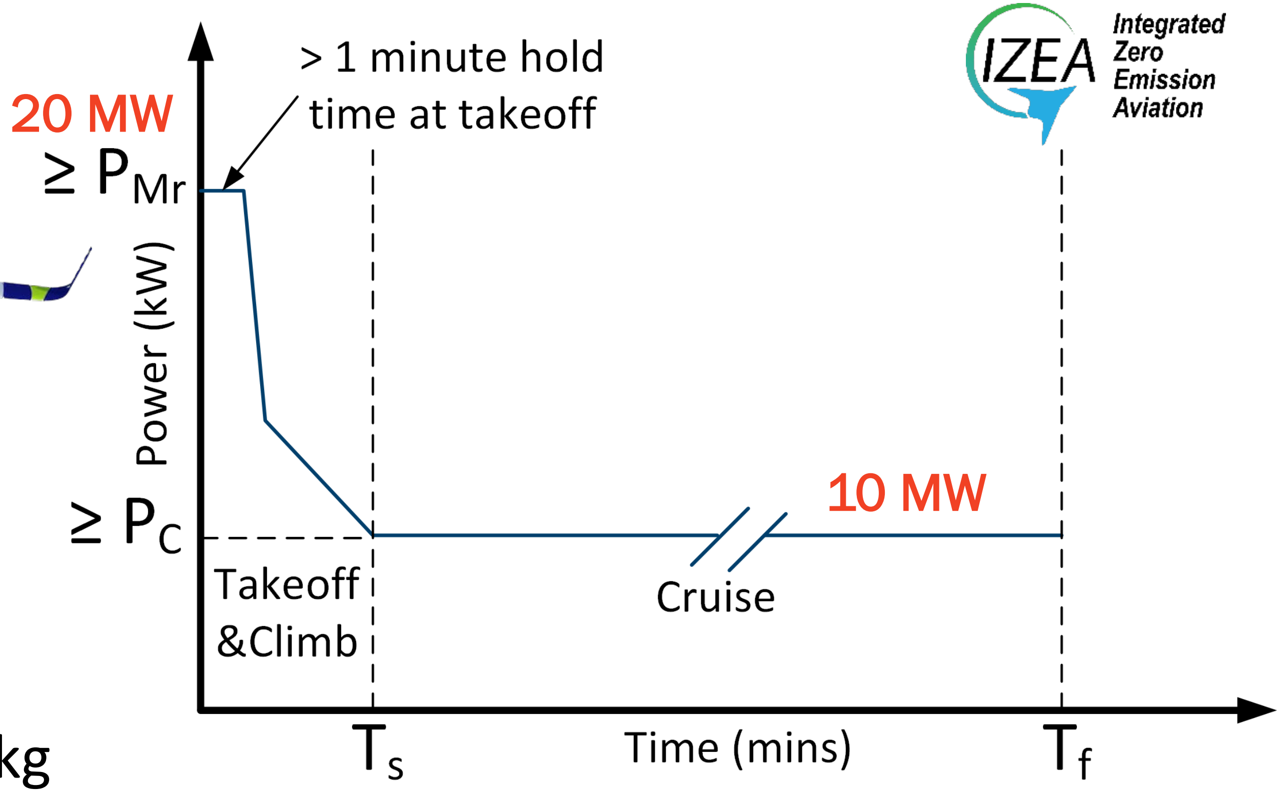
- Minimize heat leaks in HXs
- Simpler plumbing for LH2
- Versatile cooling on each component/subsystems
- Independent flow controls for resilient cooling.



Source: NASA IZEA Annual Review 2023.

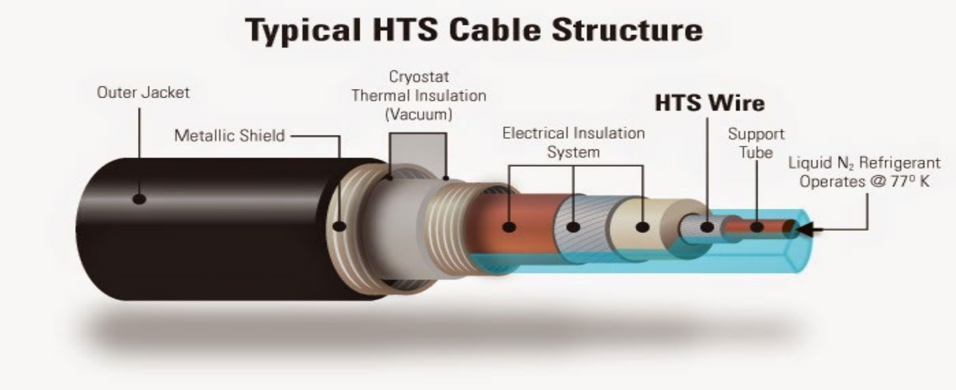
H2, Tanks, Motors and Drives, Cables, and Mass Estimates





Integrated Zero Emission Aviation

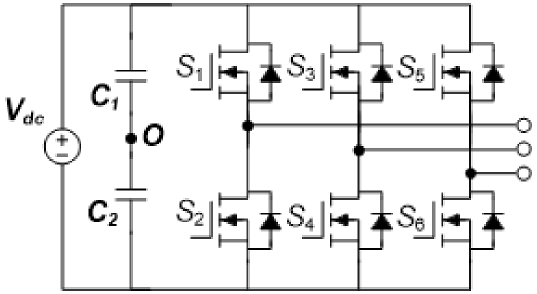
- Discussion; example ratings and estimates
- Tank mass incl. wall and insulation 2 x 500 kg
- Required hydrogen 2,000 kg for short mission (100min) incl. take off
- Consider 10 kW/kg for motor and PE drive
- IZEA plans to use HTS superconducting cables.



Source: NASA IZEA Annual Review 2023.

IZEA Motor Drive Power Electronics – Topologies

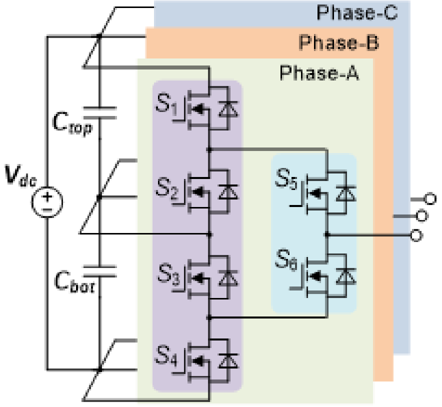
(1) SiC 2-Level



Wolfspeed

Half-Bridge SiC
1200V/480A

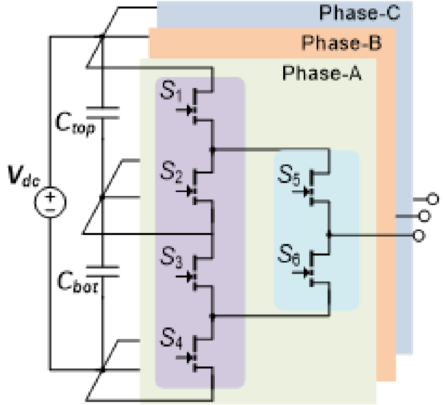
(2) SiC 3-Level



Wolfspeed

SiC discrete
650V/49A

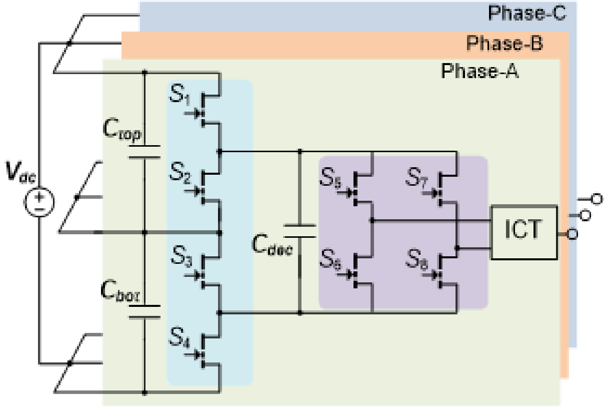
(3) Cryogenic GaN 3-Level



GaN Systems

GaN HEMT discrete
650V/30A

(4) Proposed cryogenic
GaN 5-Level



GaN Systems

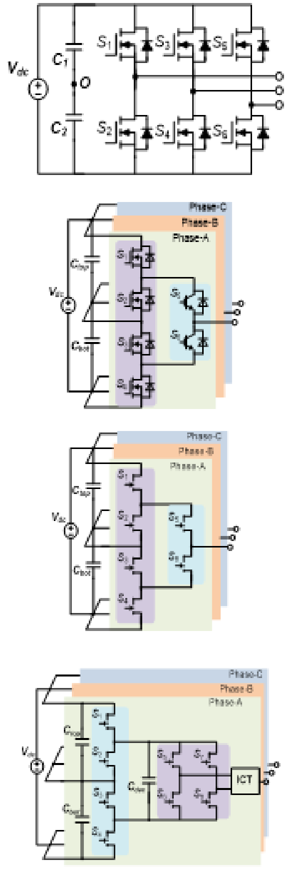
GaN HEMT discrete
650V/30A

- Constant DC-link voltage of 800V and selected switching frequency (by given rms phase current ripple percentage <3%) for each topology’s simulation
- Losses calculated using Eon/Eoff(Isw), Rdson(Tj) curves, based on experimental data at cryogenic temperatures for GaN.

IZEA Integrated Zero Emission Aviation

Source: NASA IZEA Annual Review 2023.

IZEA Motor Drive Power Electronics – Losses and Efficiency

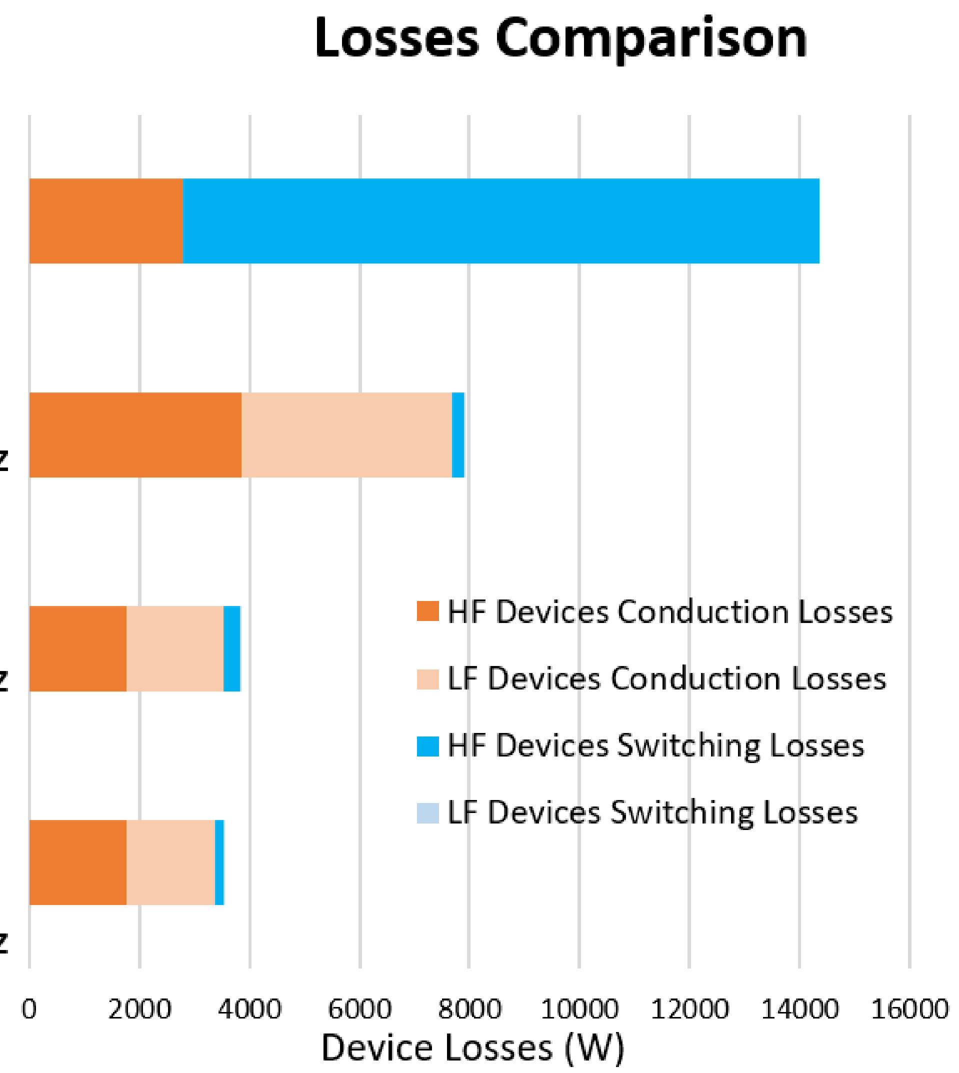


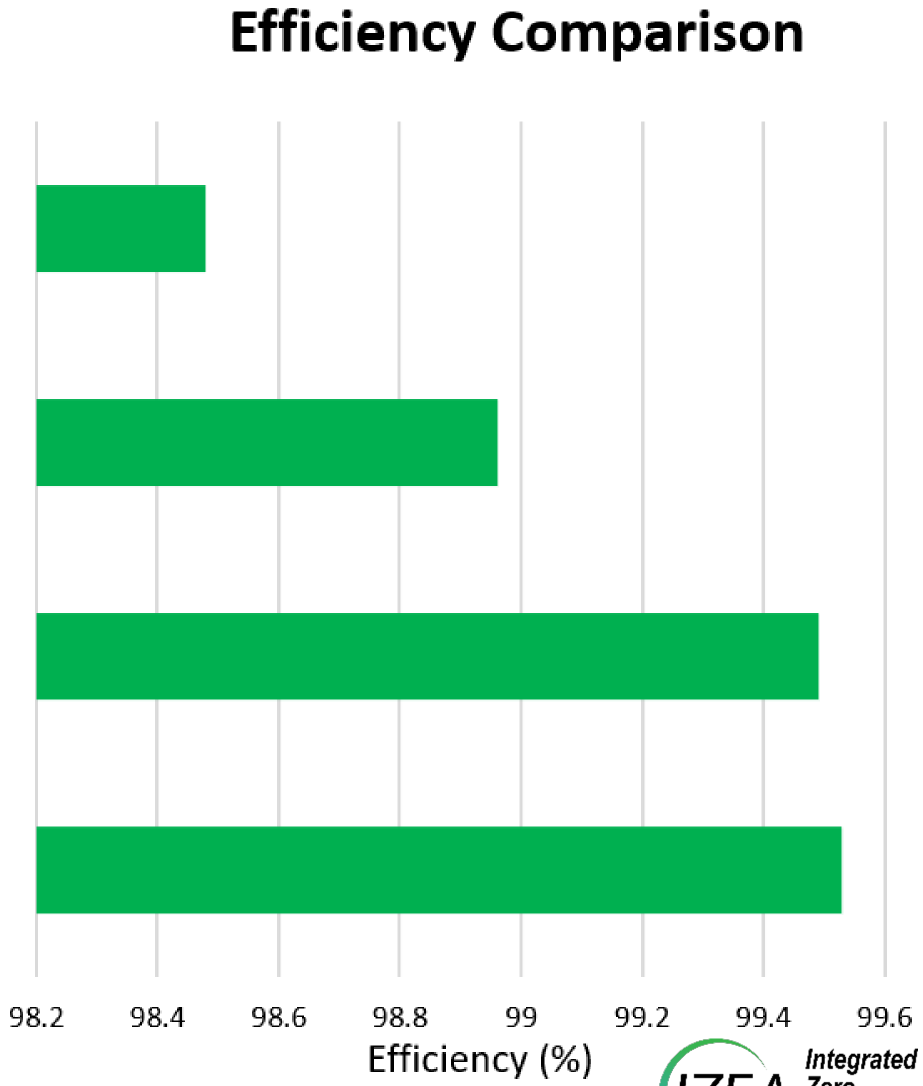
SiC 2-Level
f_{sw}= 77kHz

SiC 3-Level
f_{sw}= 38.5kHz

Cryogenic
GaN 3-Level
f_{sw}= 38.5kHz

Proposed
Cryogenic
GaN 5-Level
f_{sw}= 17.5kHz





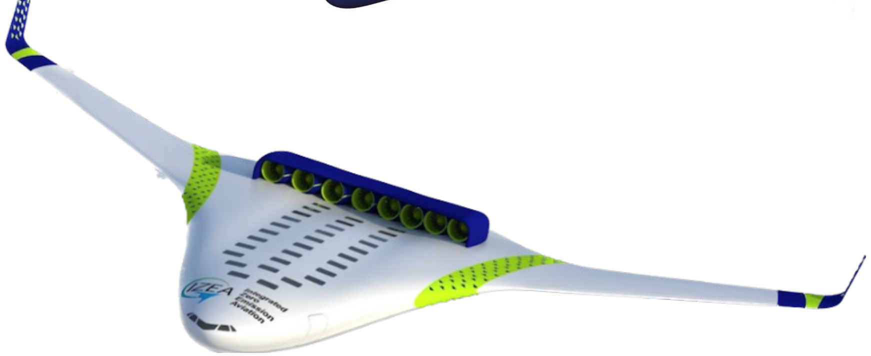
IZEA Integrated Zero Emission Aviation

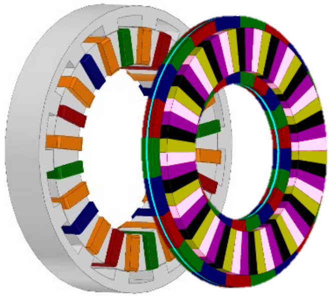
Source: NASA IZEA Annual Review 2023.

Outline

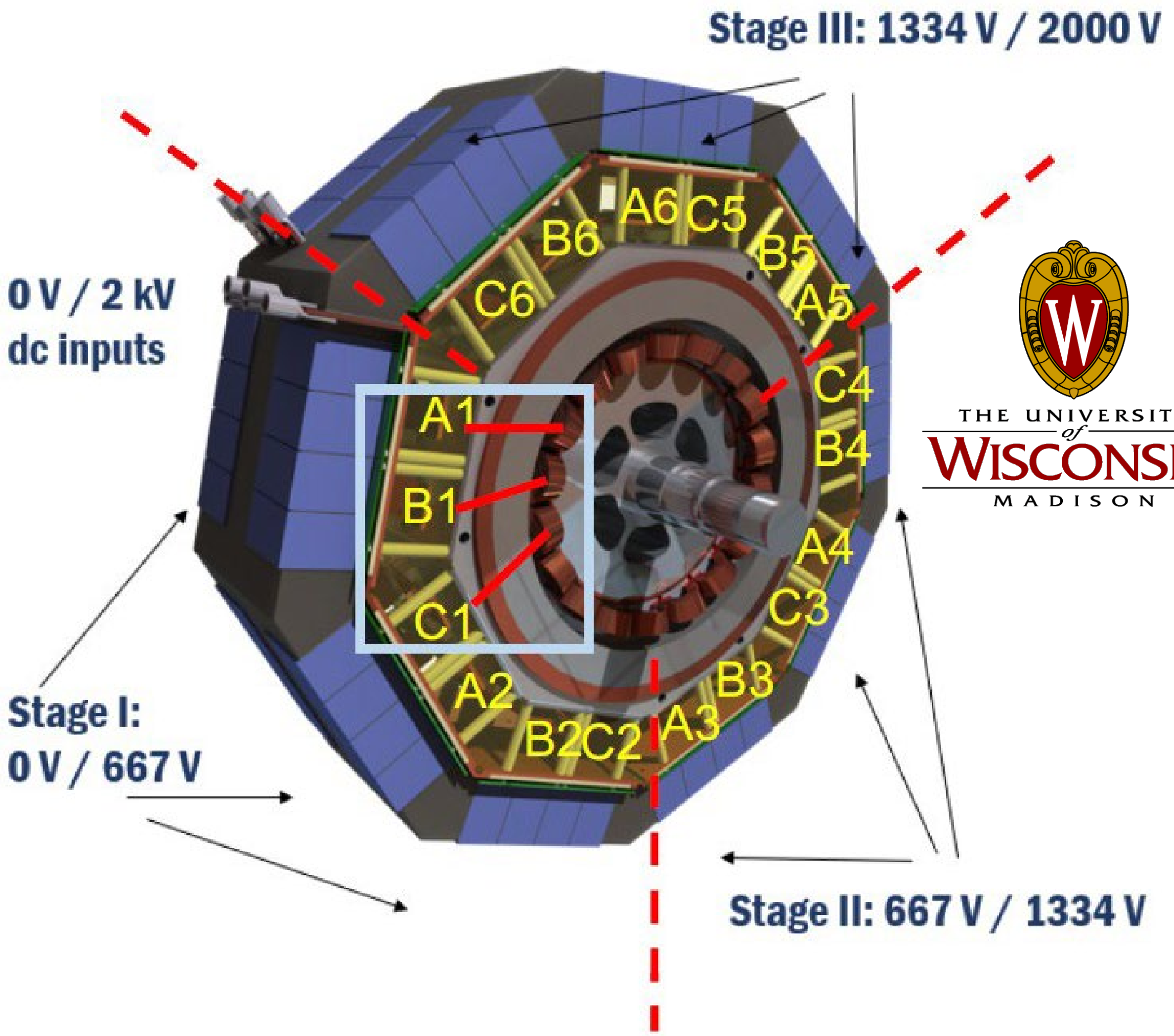
Ongoing Research for Large Electric Aircraft Components and Systems

- Introduction
- Major technical concepts and initiatives
- Optimal design of electric aircraft systems
- Battery-powered electric aircraft, NASA X-57
- Hydrogen-fueled electric aircraft, NASA ULI IZEA
- **Electric aircraft propulsion motor drive**
  - **Review**
  - **Innovative concept**
- Conclusion.

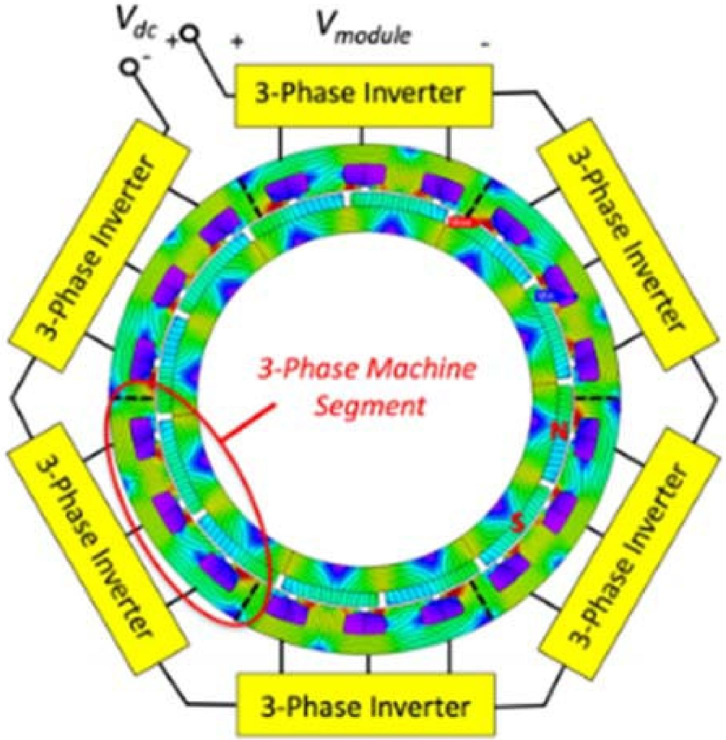


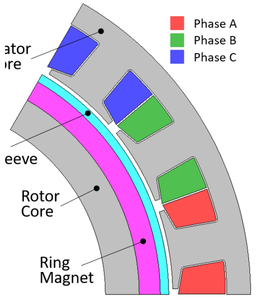


Example Previous NASA ULI Sponsored Project - Wisconsin



THE UNIVERSITY of WISCONSIN
MADISON

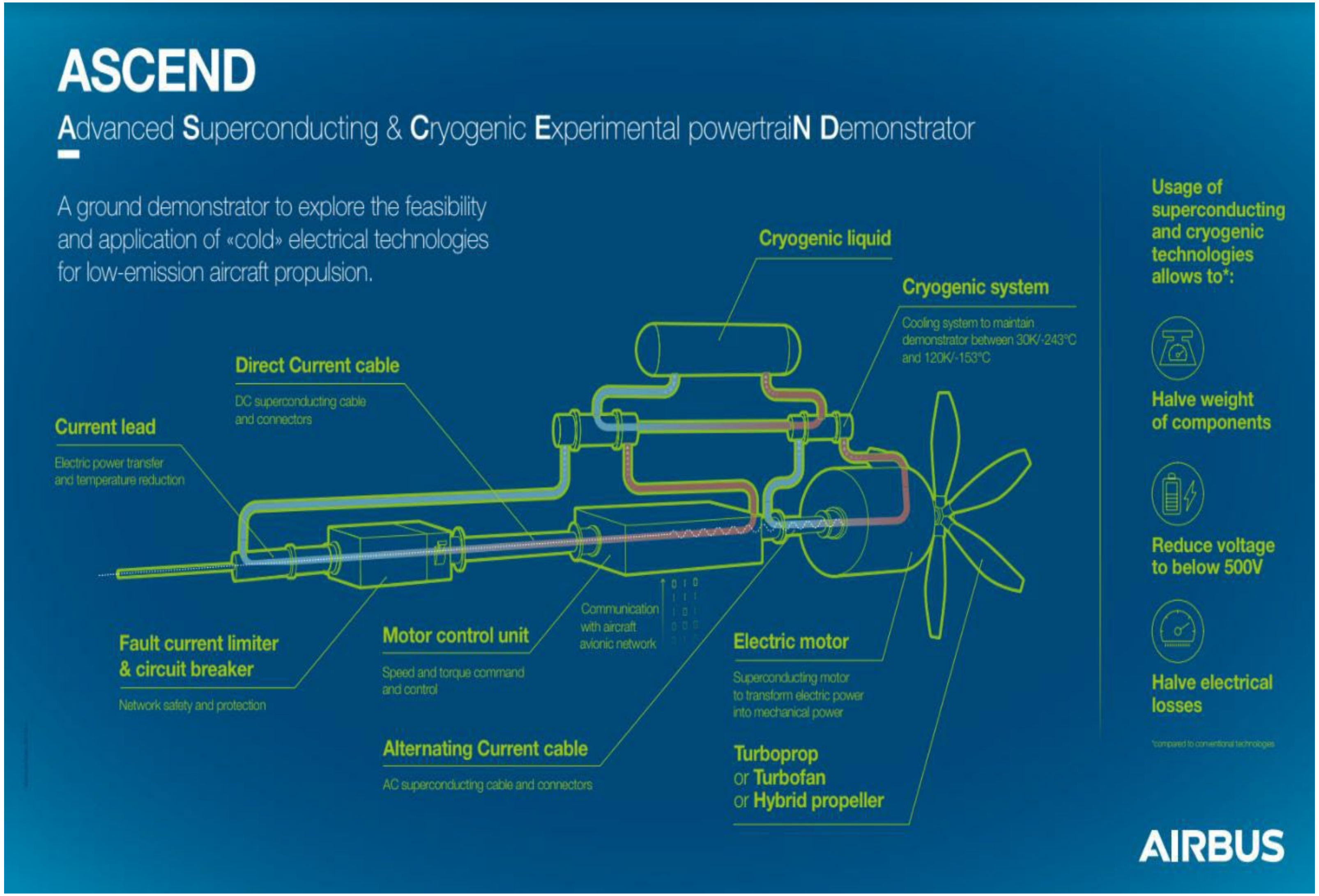




- Integrated Motor Drive (IMD)
- Rated 1MW @ 20,000rpm
- Voltage 2kV, SiC
- Multiple stages/modules
- Special materials and technology.

***Source:* University of Wisconsin**, J. Swanke *et al.*, "Comparison of Modular PM Propulsion Machines for High Power Density," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019, pp. 1-7, doi: 10.1109/ITEC.2019.8790587.

Airbus ASCEND Project



ASCEND

Advanced **S**uperconducting & **C**ryogenic **E**xperimental powertrai**N** **D**emonstrator

A ground demonstrator to explore the feasibility and application of «cold» electrical technologies for low-emission aircraft propulsion.

Cryogenic liquid

Cryogenic system

Cooling system to maintain demonstrator between 30K/-243°C and 120K/-153°C

Direct Current cable

DC superconducting cable and connectors

Current lead

Electric power transfer and temperature reduction

Fault current limiter & circuit breaker

Network safety and protection

Motor control unit

Speed and torque command and control

Communication with aircraft avionic network

Electric motor

Superconducting motor to transform electric power into mechanical power

Alternating Current cable

AC superconducting cable and connectors

Turboprop
or **Turbofan**
or **Hybrid propeller**

Usage of superconducting and cryogenic technologies allows to*:

Halve weight of components

Reduce voltage to below 500V

Halve electrical losses

*compared to conventional technologies

AIRBUS

AIRBUS

Breakthrough high power electric systems

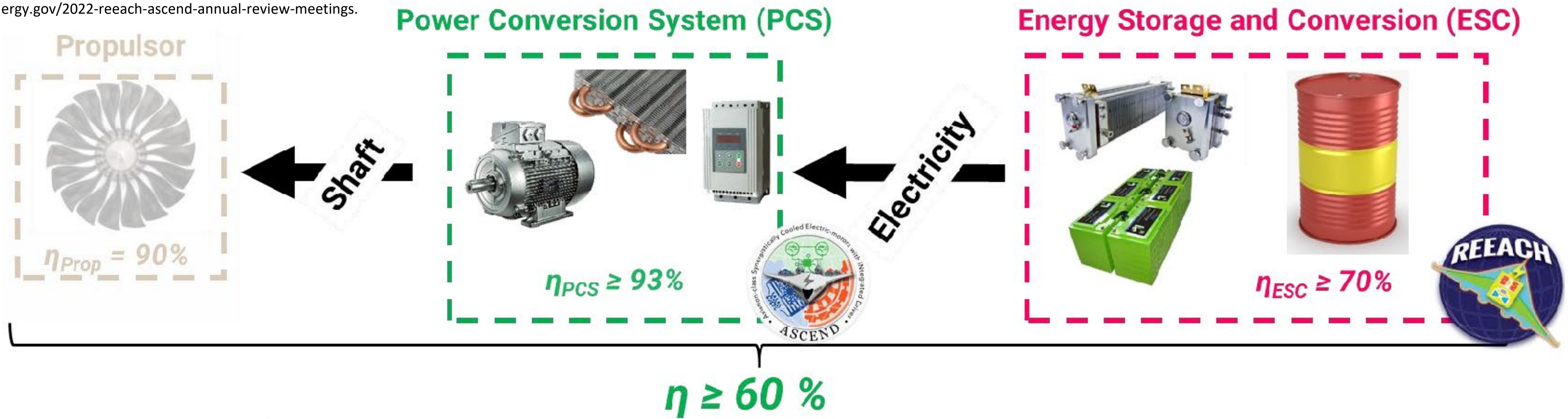
- Low voltage (< 500V)
- Reduce weight and volume
- Increase efficiency (+ 5-10%)
- Enable high torque motors, fault current limiters

Cryogenic and Superconductivity

Source: Airbus ASCEND Project 2021
https://www.airbus.com/en/newsroom/stories/2021-03-cryogenics-and-superconductivity-for-aircraft-explained

ARPA- E ASCEND Specific Objectives

Source: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings
https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.



- Motor + PE + TMS system
- Electric aircrafts with high propulsive power during the takeoff and climb phases
- A fraction (25-35%) of the peak propulsive power during the cruise phase
- Typical demonstrator ratings
  - 250kW at 5,000rpm
  - All-electric propulsion: ≥ 12 kW/kg
  - All-electric propulsion cruise nominal eff: ≥ 93%
  - Power electronics PE (including TMS): 30kW/kg and 98% eff
  - Electric motor: 5kW/kg.

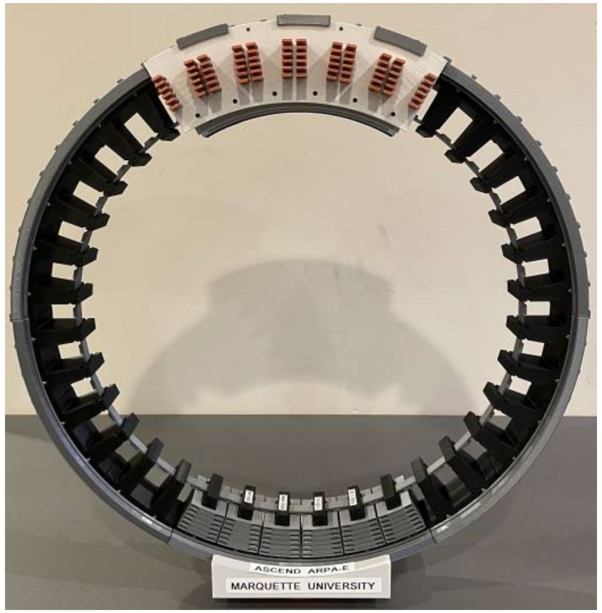
ARPA-E ASCEND Technology Chart

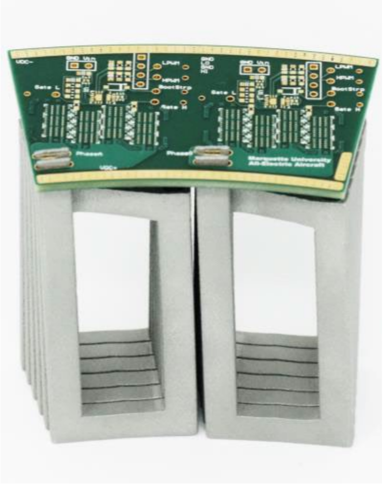
Source: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings
https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

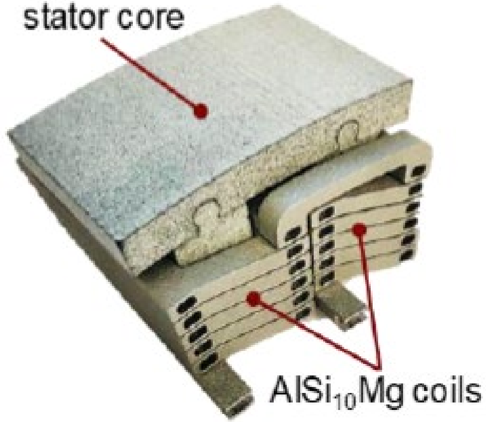
CHANGING WHAT'S POSSIBLE

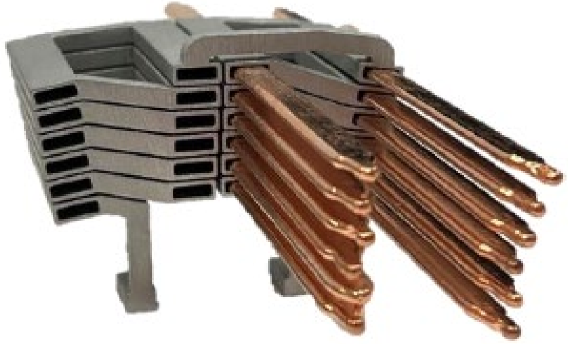
… Note the equivalent search for the one-best topology …

Halbach Array and Integrated Cooling Examples

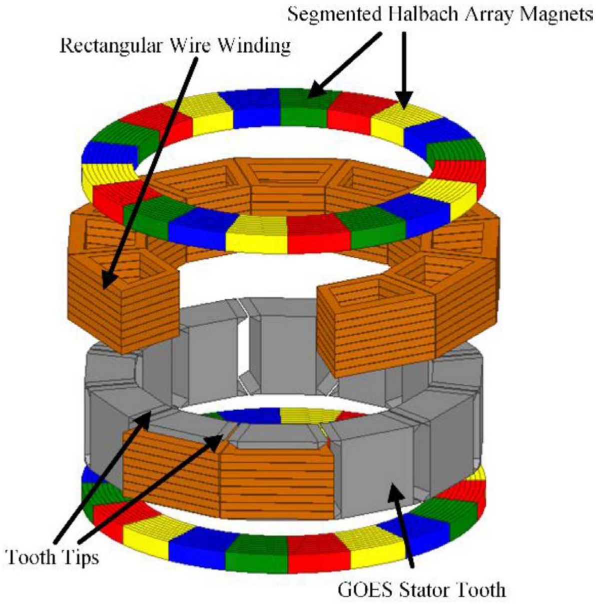


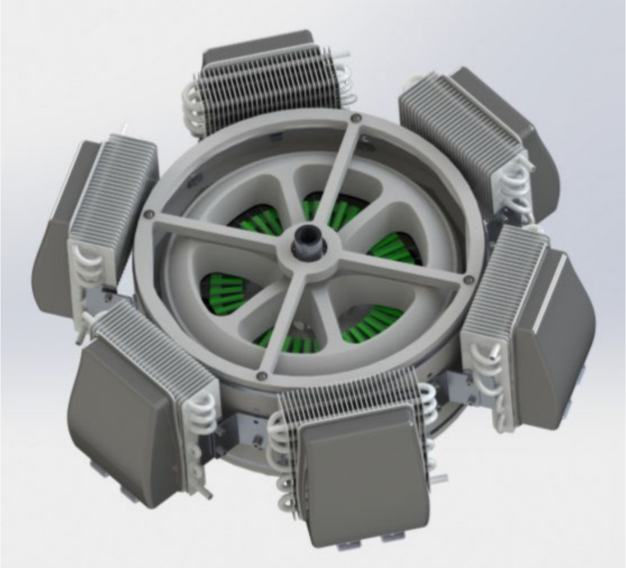


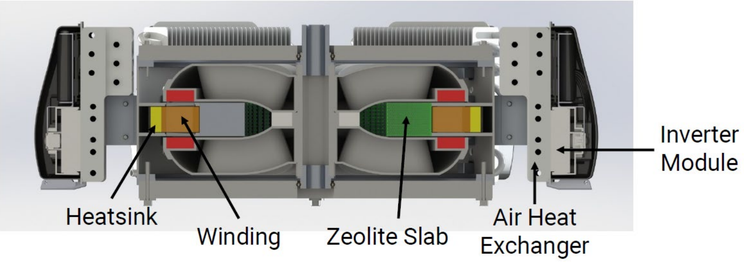




Source: **Marquette University**, Al-Qarni, Ali *et al.* "Design and analysis of a high specific power outer rotor surface mounted permanent magnet machine equipped with additively manufactured windings." 2021 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, 2021
See also: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.





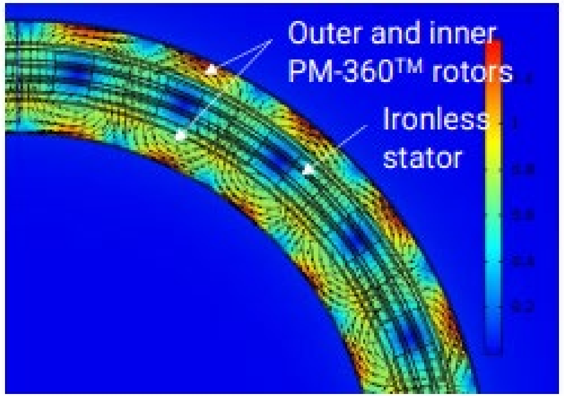


Source: **Texas A&M**, Talebi, Dorsa, et al. "Electromagnetic design characterization of a dual rotor axial flux motor for electric aircraft." IEEE Transactions on Industry Applications 58.6 (2022): 7088-7098
See also: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

Main source: ARPA-E 2022 annual review public presentations
Credits: Left – Marquette University *et al*, Right – Texas A&M *et al.*

Halbach Arrays and Multiple Airgaps Examples

Source: **AML, Inc.**, Luongo, Cesar A. *et al.* "Next generation more-electric aircraft: A potential application for HTS superconductors." IEEE Transactions on applied superconductivity 19.3 (2009): 1055-1068
See also: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

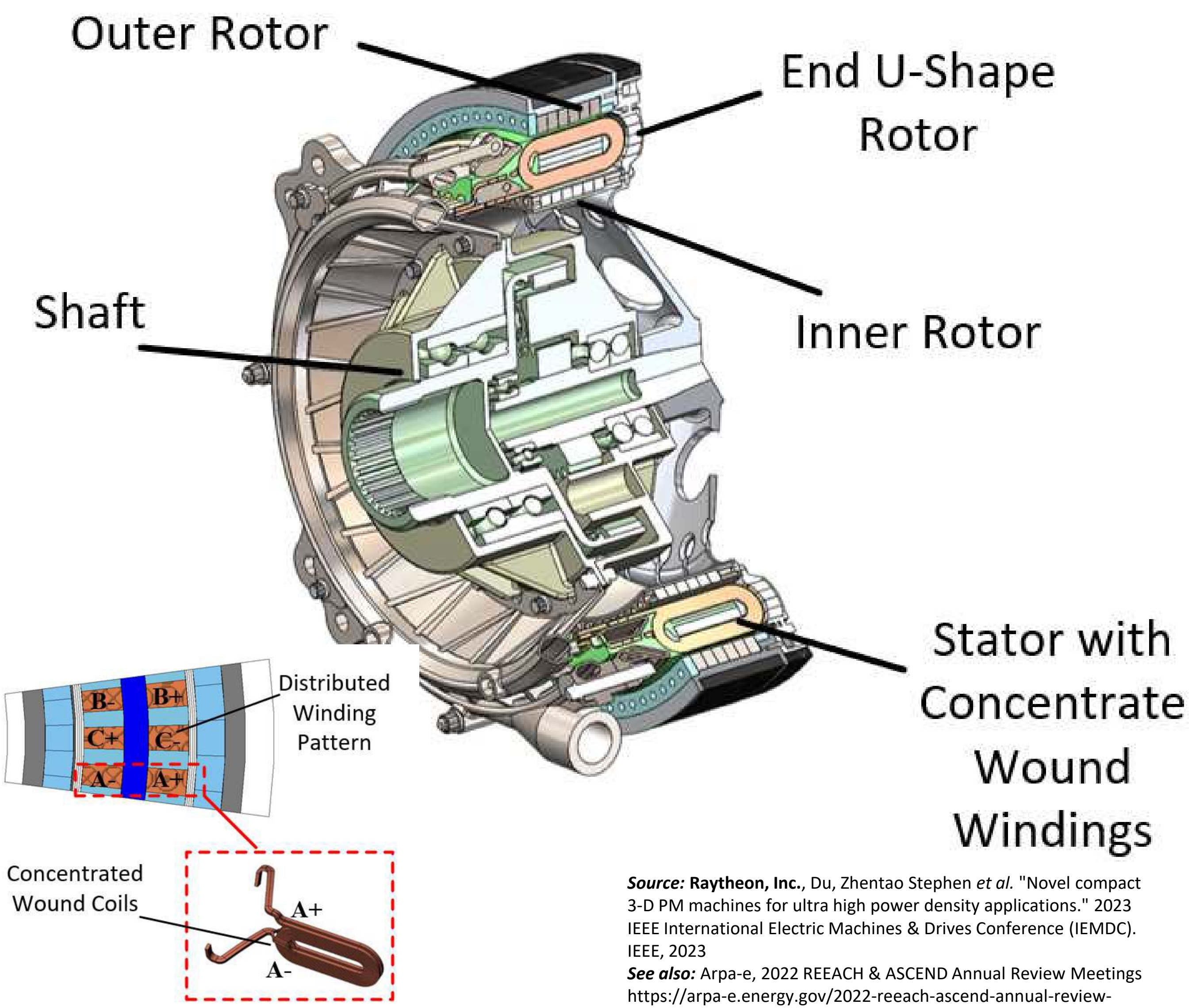


Outer and inner PM-360™ rotors

Ironless stator

PM-360™

Main source: ARPA-E 2022 annual review public presentations
Credits: Left – AML, Inc. *et al*, Right – Raytheon, Inc. *et al.*



Outer Rotor

End U-Shape Rotor

Shaft

Inner Rotor

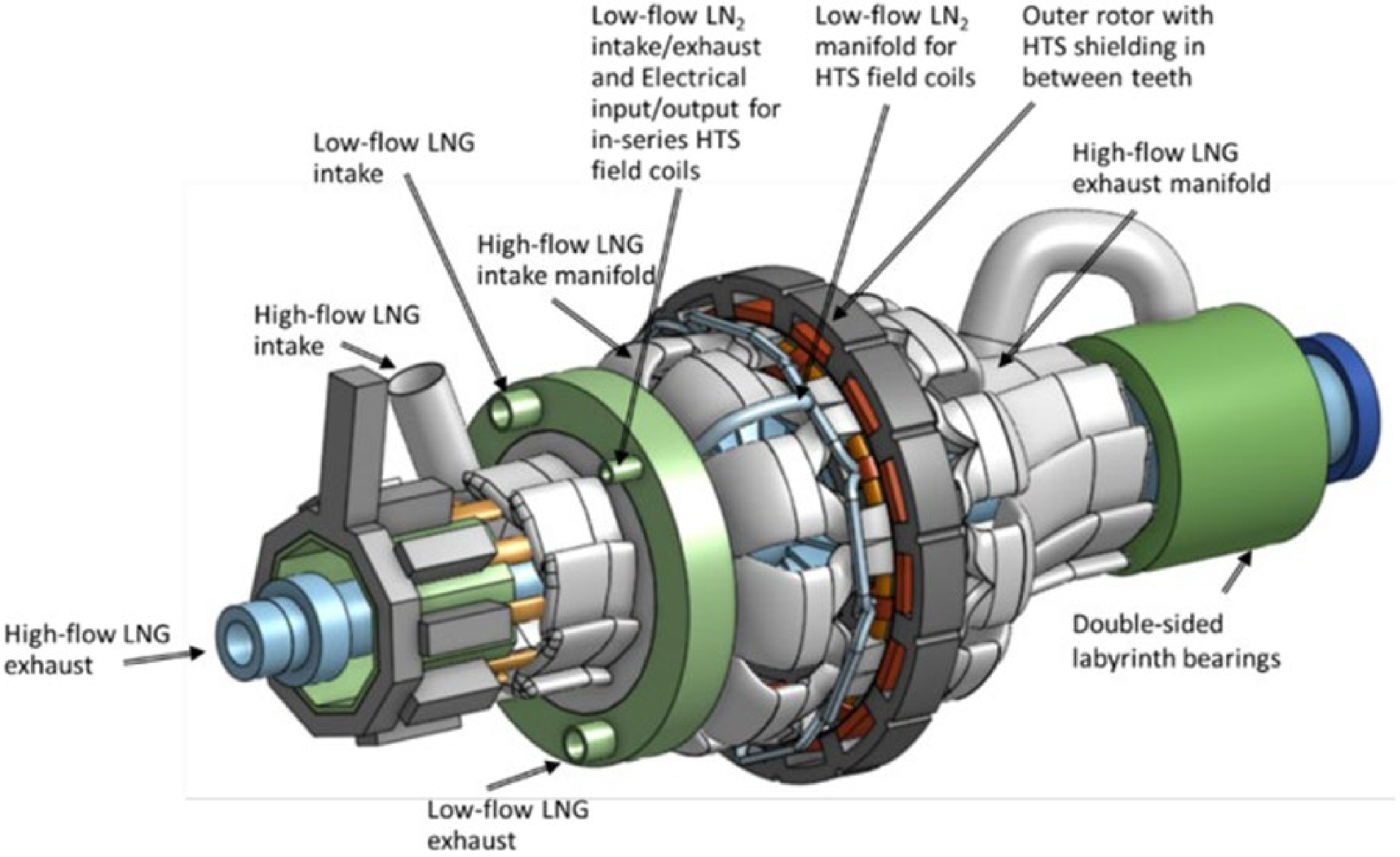
Stator with Concentrate Wound Windings

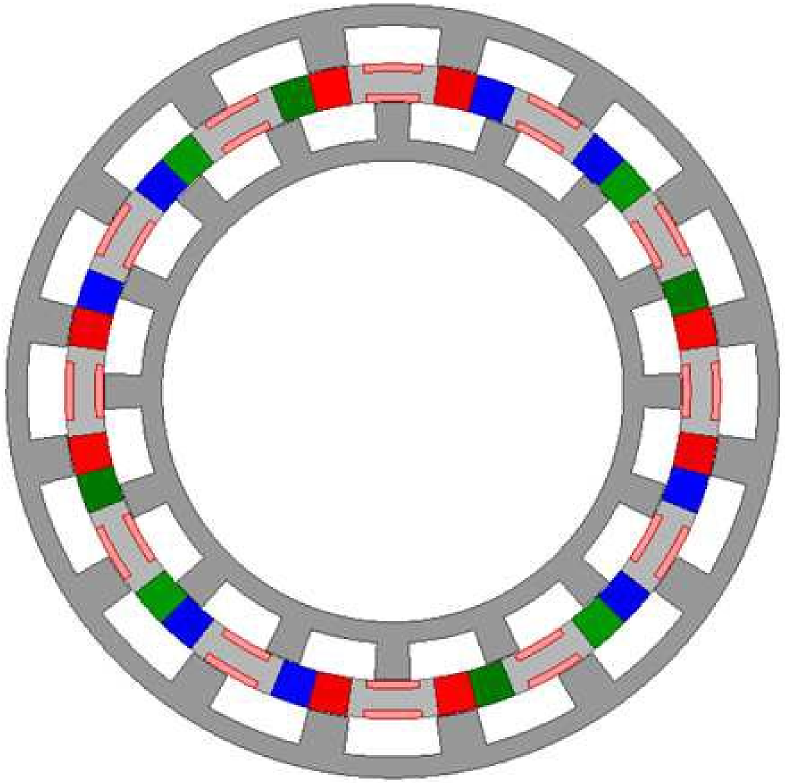
Distributed Winding Pattern

Concentrated Wound Coils

Source: **Raytheon, Inc.**, Du, Zhentao Stephen *et al.* "Novel compact 3-D PM machines for ultra high power density applications." 2023 IEEE International Electric Machines & Drives Conference (IEMDC). IEEE, 2023
See also: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

Cryogenically-cooled Superconducting Flux Switching



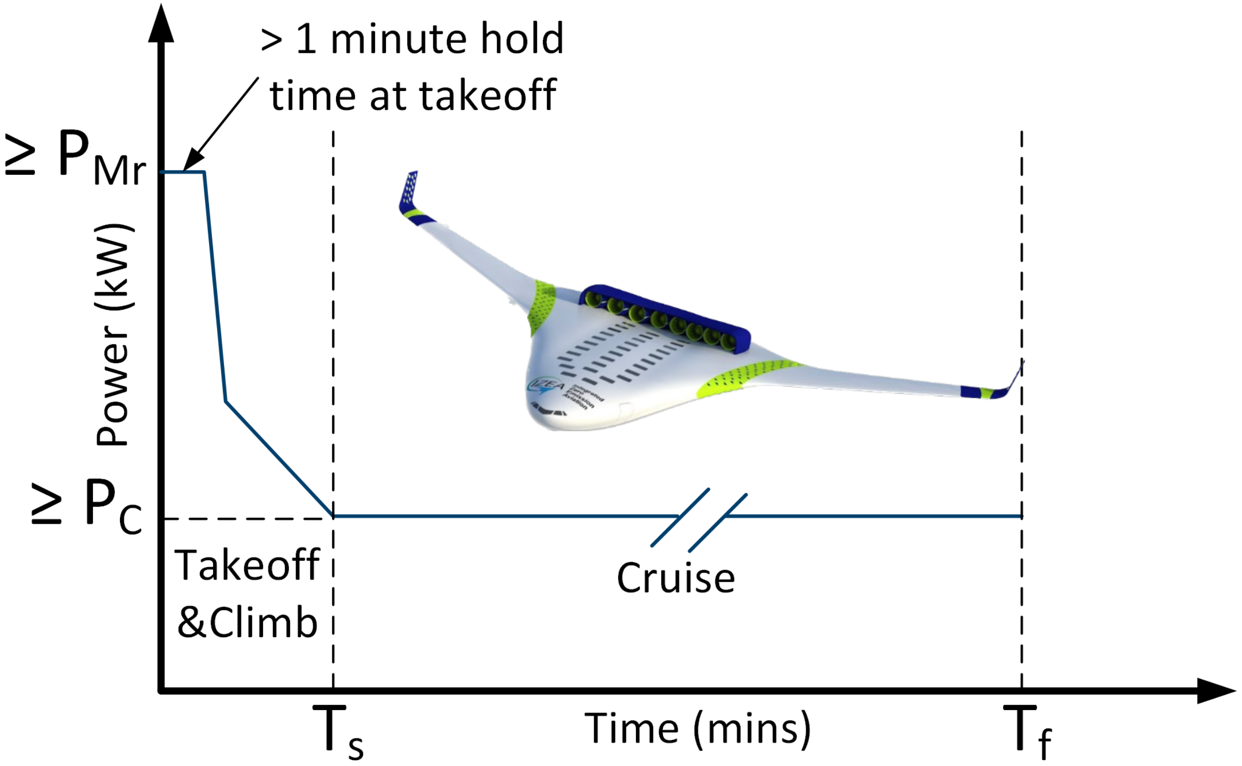


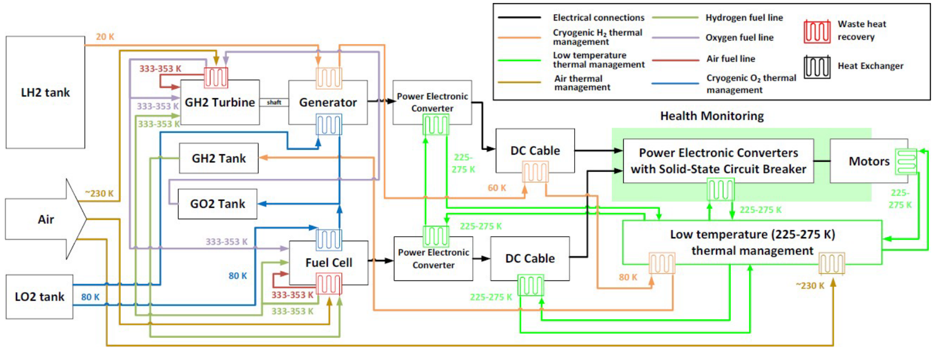
Main source: ARPA-E 2022 annual review public presentations
Credits: University of California Santa Cruz and AFRL

Source: **UC Santa Cruz**, Saeidabadi, Saeid, *et al.* "Flux switching machines-for all-electric aircraft applications." 2022 International Conference on Electrical Machines (ICEM). IEEE, 2022
See also: Arpa-e, 2022 REEACH & ASCEND Annual Review Meetings https://arpa-e.energy.gov/2022-reeach-ascend-annual-review-meetings.

IZEA - Electric Propulsion Motor Requirements

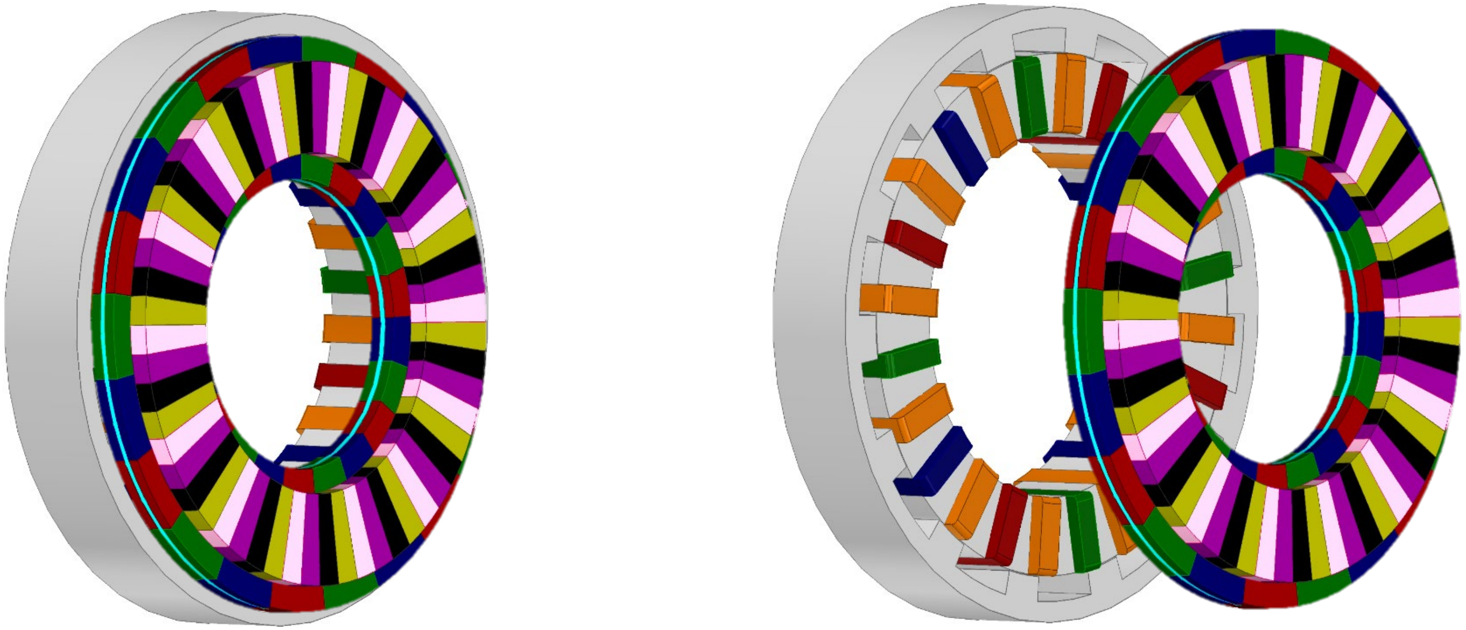
- Multiple (8) multi-MW motors
- Conflicting objectives
  - Ultra-high efficiency
  - Light and small, i.e. very high kW/kg
  - Best fault tolerance
  - Most reliable
- Note the high ratio between short and long-term power rating
- Cryogenically cooled, but not superconducting winding
- Considered voltage 800-1,100Vdc.





Source: NASA IZEA Annual Review 2023.

Innovative One-Motor Two-Stages Four-Modules Concept



- **Aim for best combination of fault tolerance, specific power, and efficiency.**
- Two stages / electromagnetic units, each with two stator modules and two inverters
- One special emag sync (no PM): radial flux with outer rotor, AC 3-phase, winding, DC stator excitation, concentrated non-overlapping toroidal coils, robust reluctance consequent-pole rotor, *operates only during take off and max power regime*
- One special PM sync: axial flux dual rotor, Halbach PM arrays, coreless stator(s); *operates at all times.*

Source: **University of Kentucky**, Lewis, D. D *et al.*, "Fault Tolerant Electric Machine Concept for Aircraft Propulsion with PM Rotor and DC Current Stator Dual-Stage Excitation", Proceedings, IEEE ICRERA, Oshawa, Ontario, CA (Aug 2023)

Innovative One-Motor Two-Stages Four-Modules Concept

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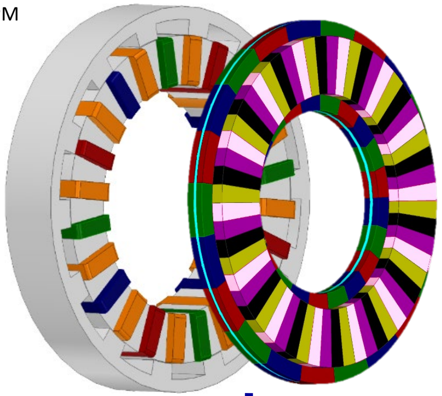
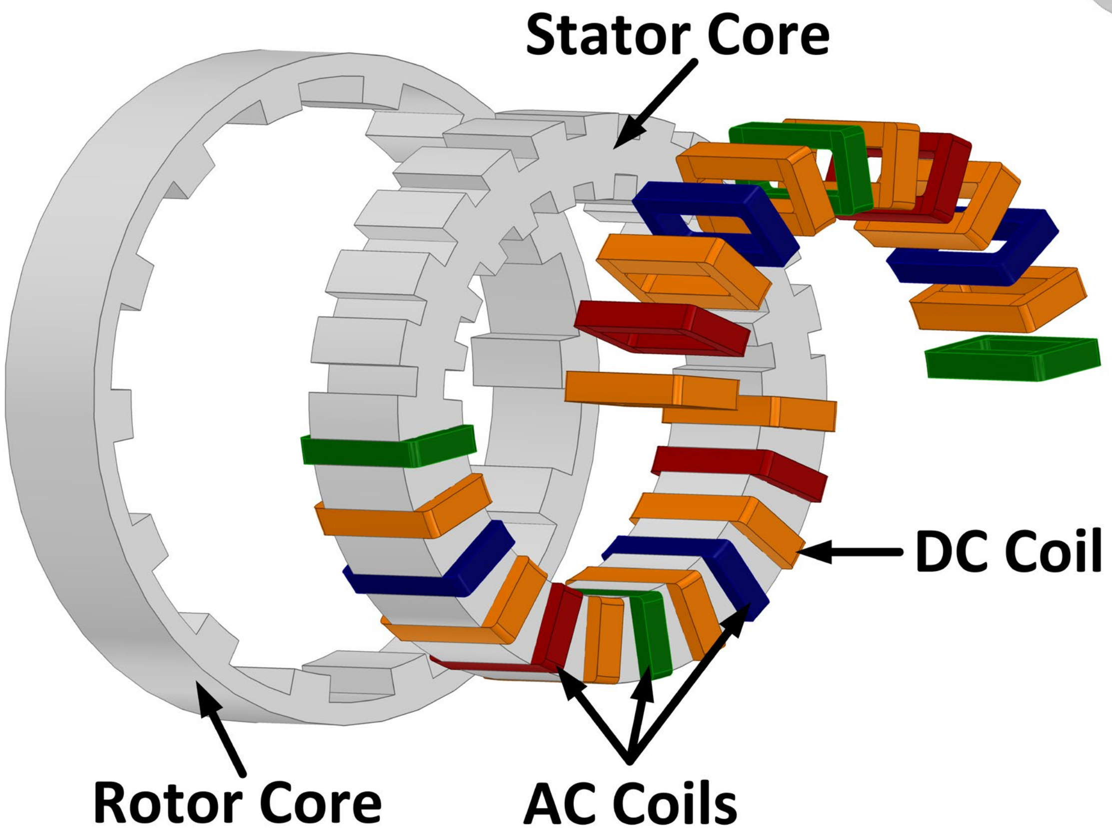
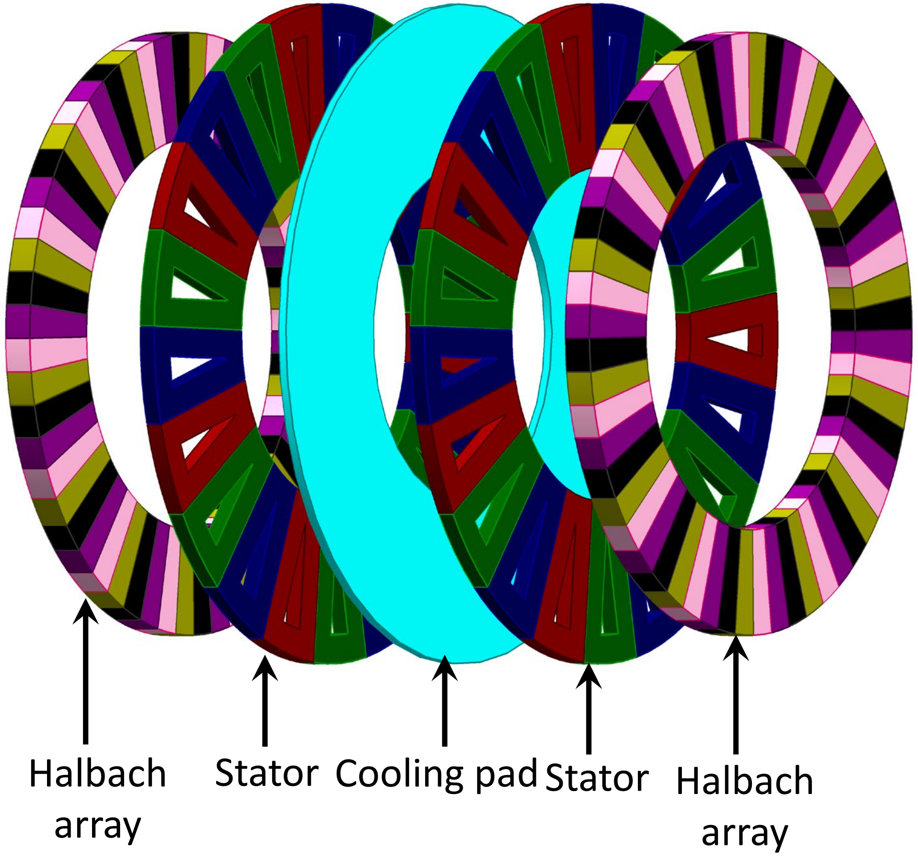
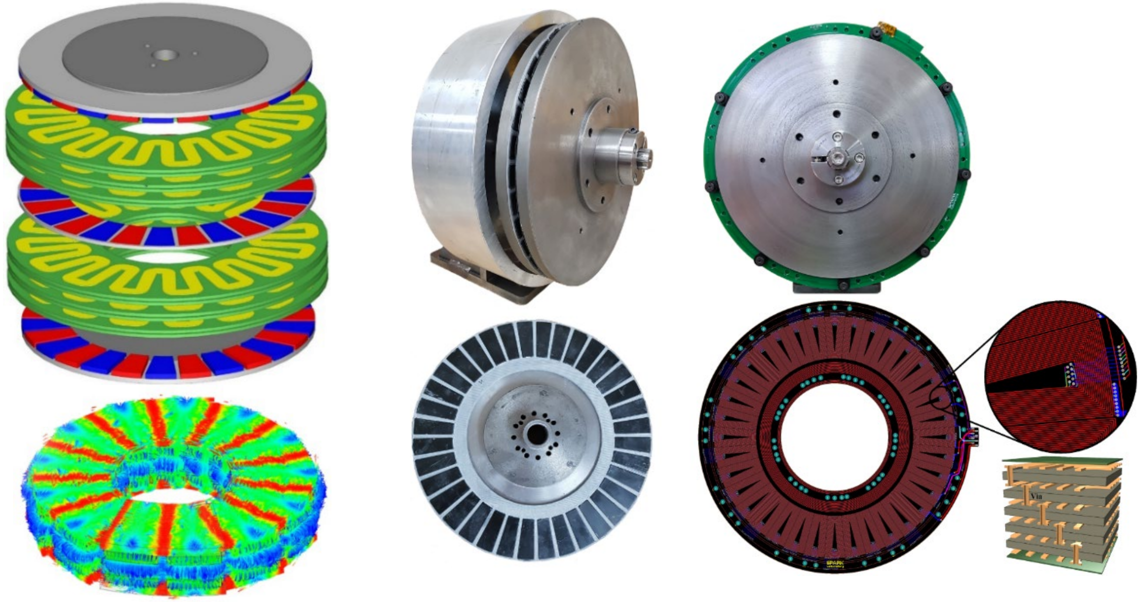
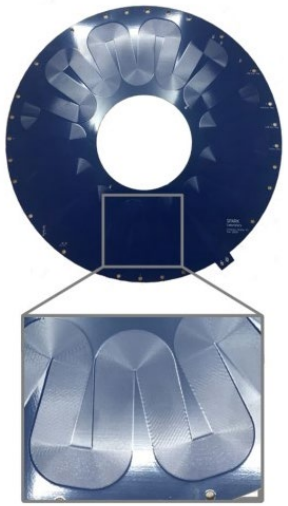


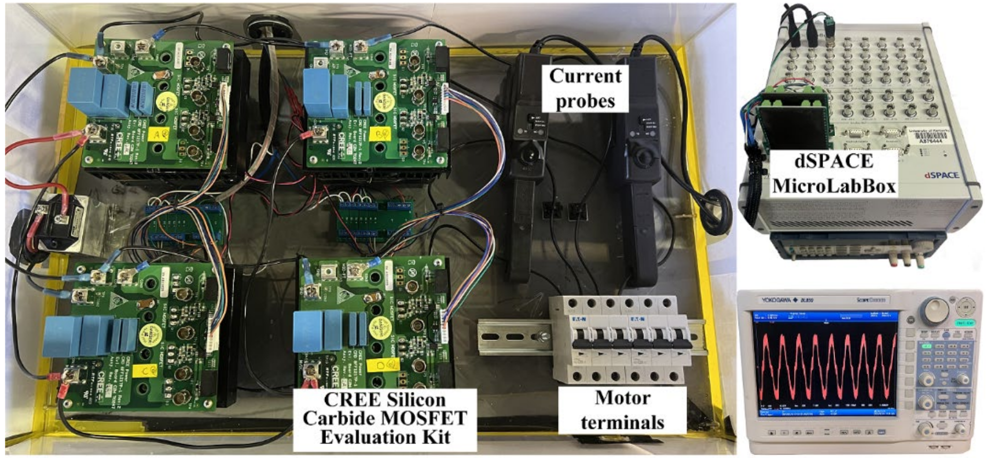


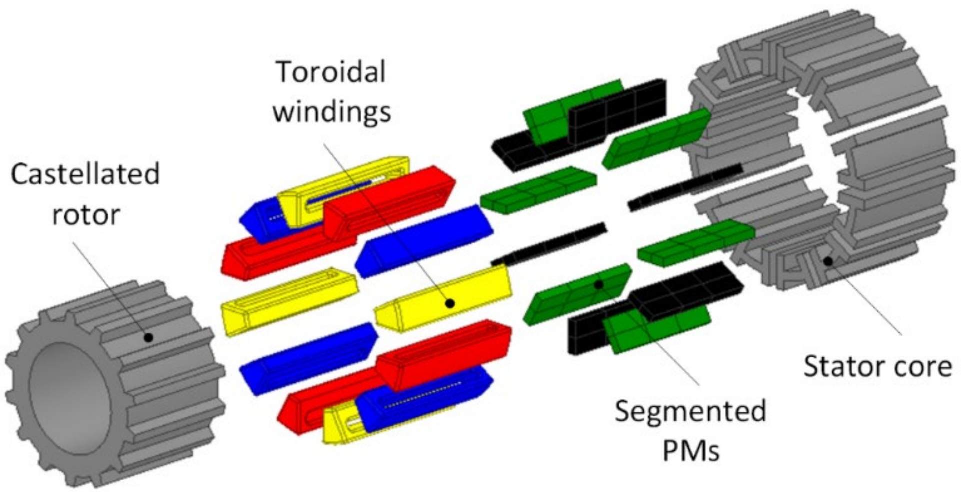


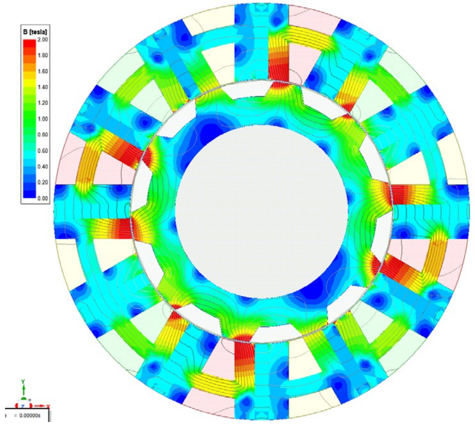
SPARK Laboratory Demonstrators

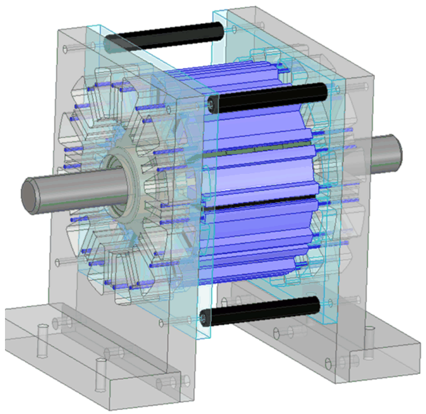








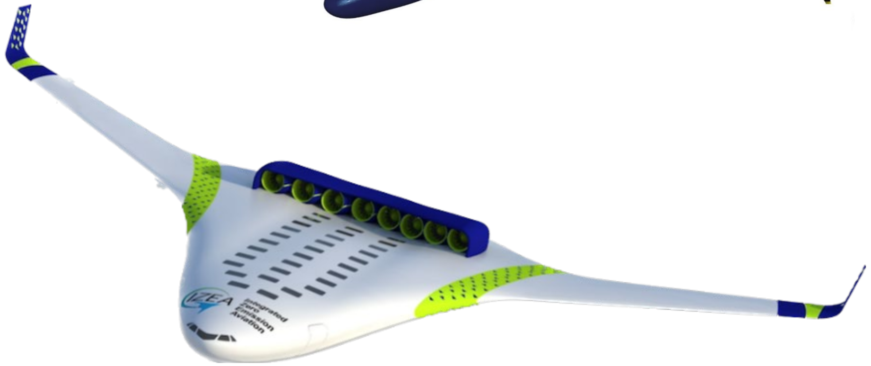


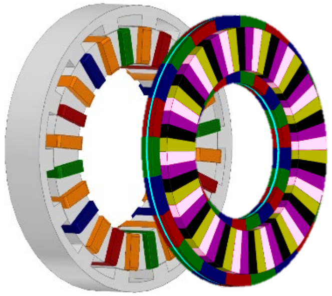


Outline

Ongoing Research for Large Electric Aircraft Components and Systems

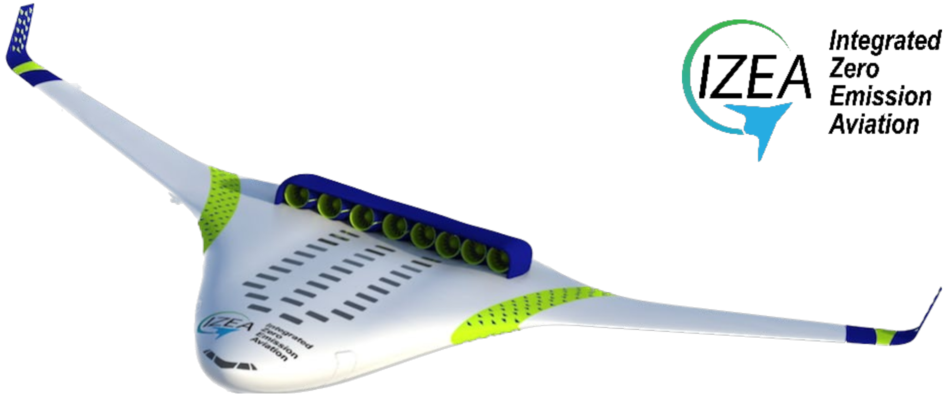
- Introduction
- Major technical concepts and initiatives
- Optimal design of electric aircraft systems
- Battery-powered electric aircraft, NASA X-57
- Hydrogen-fueled electric aircraft, NASA ULI IZEA
- Electric aircraft propulsion motor drive
  - Review
  - Innovative concept
- **Conclusion.**





Conclusion

- *Follow-up research paper on the innovative motor concept*
- Ongoing research for large electric aircraft components and systems – multi-disciplinary advanced engineering research
- Major public and private initiatives and programs
- Technical feasibility?
  - Hydrogen vs. battery
  - Superconducting vs. just cryogenic
- Economic feasibility?
- Industry transformation?
  - Development
  - Major investments and new infrastructure
- Large-scale field deployment?



IZEA Integrated Zero Emission Aviation

ICRERA 2023

12th INTERNATIONAL CONFERENCE ON RENEWABLE ENERGY RESEARCH AND APPLICATIONS

August 29 - September 1, 2023, Oshawa, Canada

Thank you!

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