Hydrogen-Electric Transport Aircraft System Technologies

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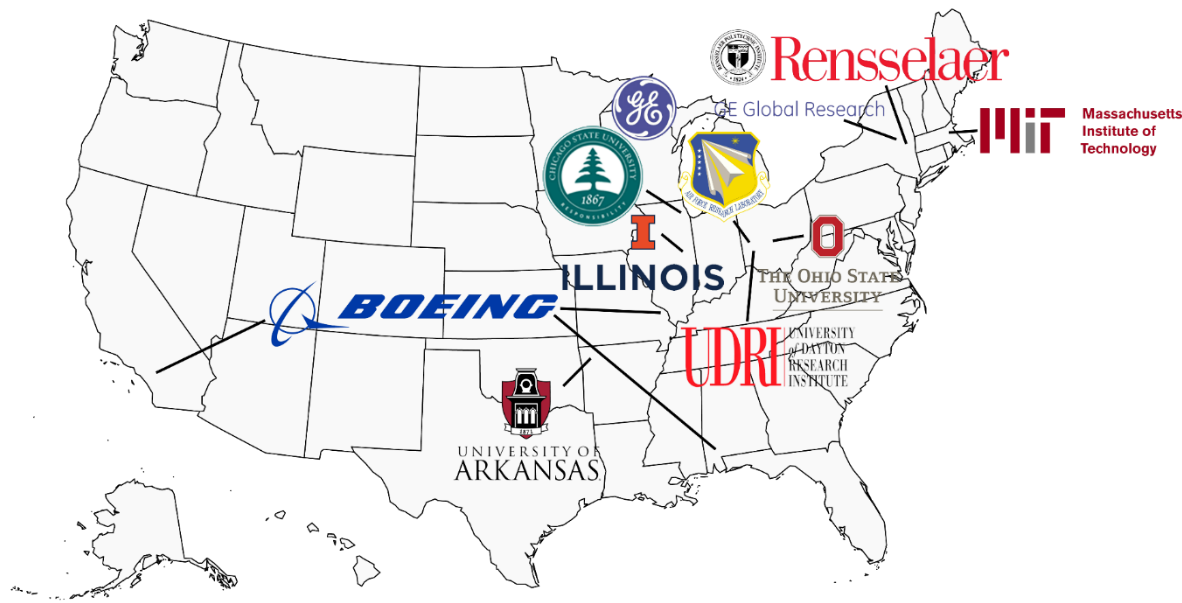
CHEETA
Center for High-Efficiency Electrical Technologies for Aircraft

Introductions

Our Team

- CHEETA
  - Established in 2019 under a $6M NASA ULI program
  - Led by the University of Illinois at Urbana-Champaign
- Bringing together world experts in
  - Aeronautics
  - Electrical Systems
  - Material Science
- Multi-institutional
  - 7 Universities
  - 2 Industry groups
  - Government research collaboration



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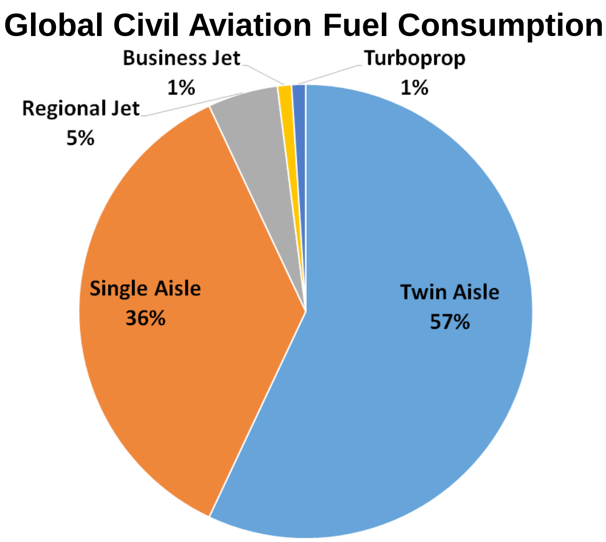
CHEETA Goals

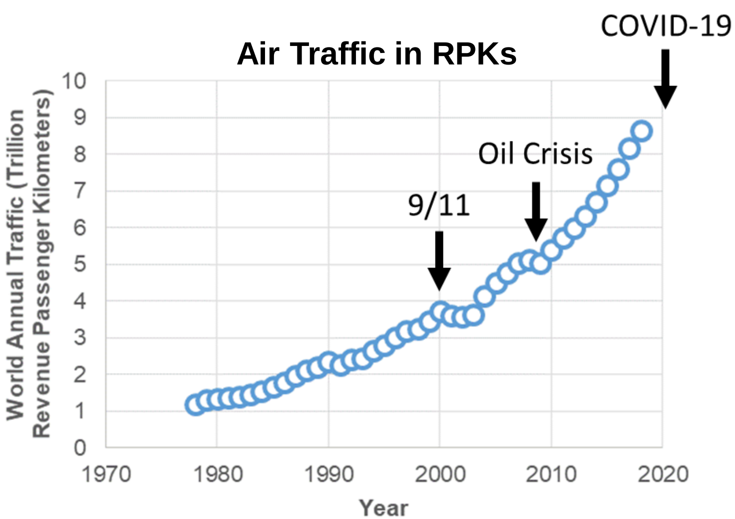
- Develop, mature, and design disruptive technologies for electric commercial aviation
  - Distributed propulsion and high-efficiency electrical power conversion
  - High-power, flight-weight cryogenic electric machines and power electronics
  - Materials and systems for superconducting high-power transmission and large current density
  - Integration and optimization of unconventional and complex aircraft systems
- Motivate and train the next-generation of professional engineers through engaging outreach

Why Electric Aircraft?

- Global aviation industry produces over 900 million metric tons of CO_2 per year[1]
- Forecasted 4-5% growth rate in air travel per year[2]
- Transportation is the leading source of greenhouse gas emissions in the US[3]
  - Aircraft make up ~10% of this contribution
- Technology improvements in flight efficiency lag growth (net 64% increase in aviation CO_2 by 2050)



Yutko and Hansman (2011)



Ansell and Haran (2020)

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[1] Air Transport Action Group
[2] US Department of Transportation
[3] US Environmental Protection Agency

Implementation Challenges: Components

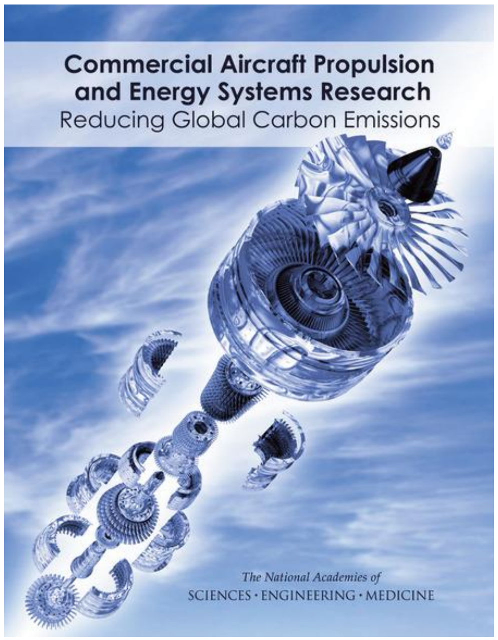

TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

	Electric System[a]		Battery[b]
Aircraft Requirements	Power Capability (MW)	Specific Power (kW/kg)[c]	Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator <1	>6.5	n/a
Regional and single-aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric[b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for large aircraft	Generator 0.5-1	>3	Not studied

[a] Includes power electronics.
[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.
[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

Current (non-cryo): 0.25 MW [B787 Generator]

Current: 250 Wh/kg [Tesla Li-Ion]

National Academies (2016)

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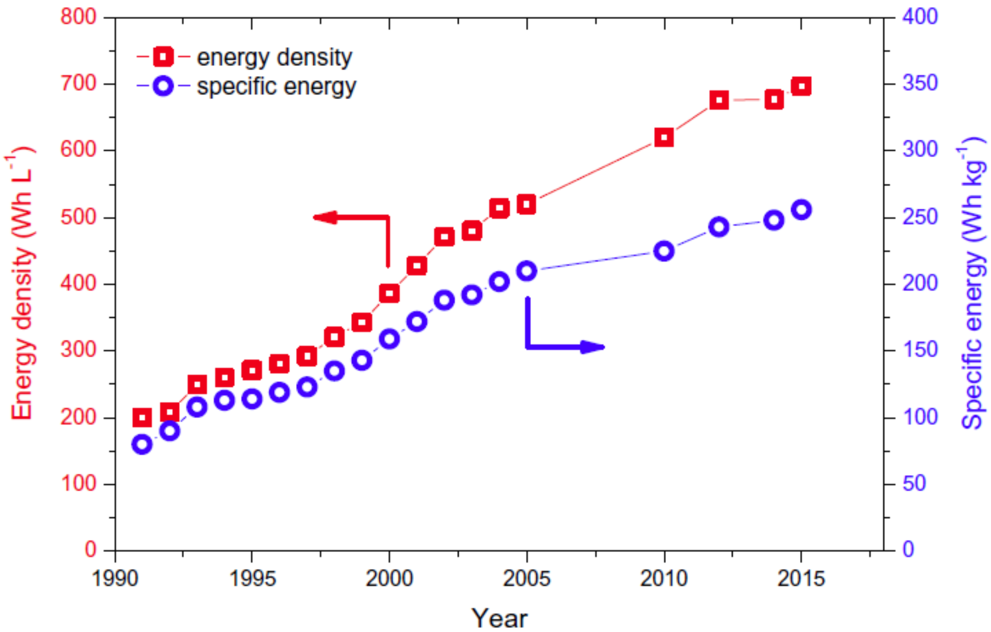
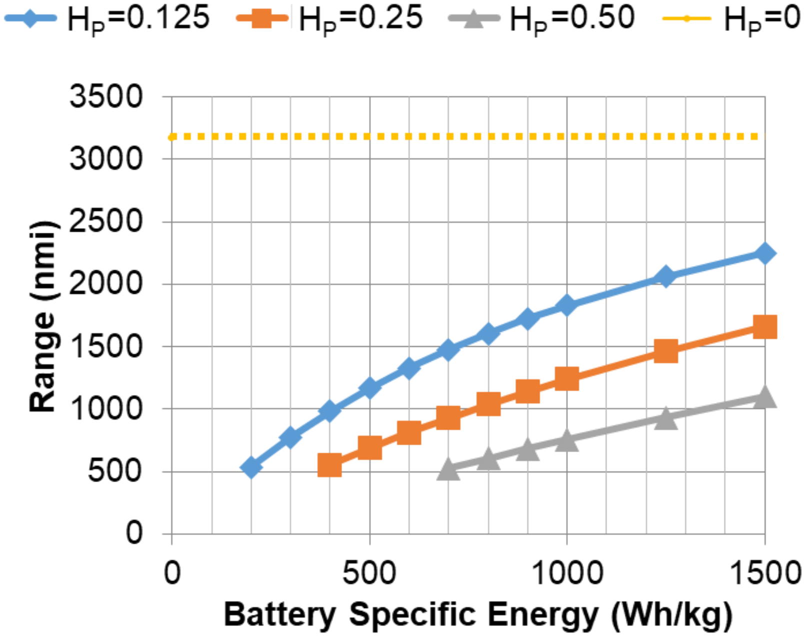
Implementation Challenges: Energy Storage

Battery Specific Energy Development (Cell Level)



Placke et al. (2017)

Boeing 737-700 Hybrid-Electric Range



Wroblewski and Ansell (2018)

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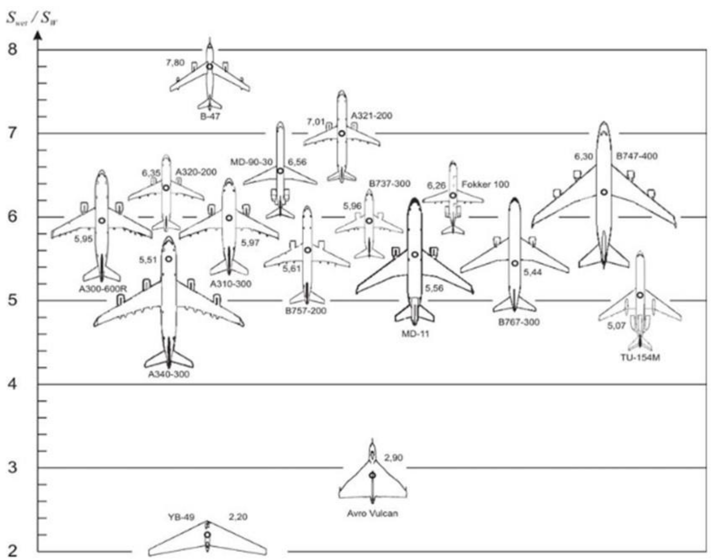
Implementation Challenges: Configuration



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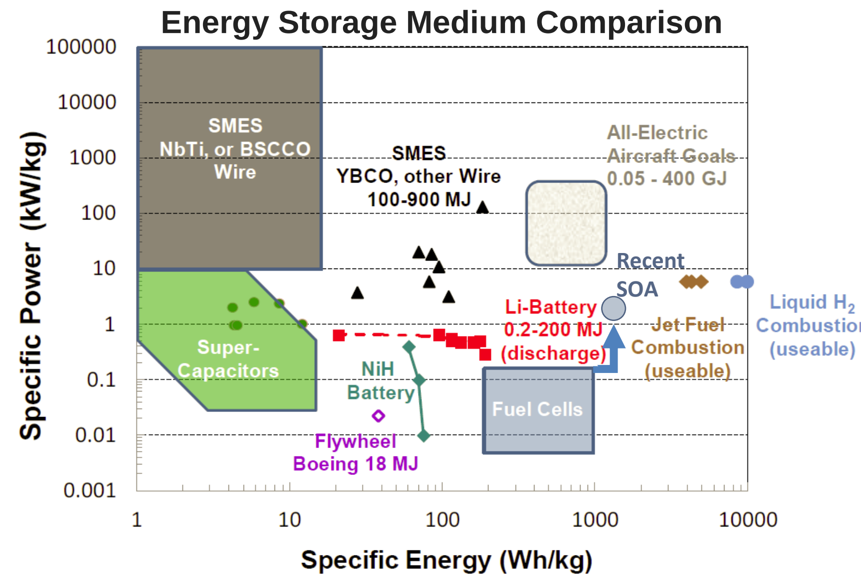
Hydrogen as an Energy Carrier

- Liquid Hydrogen (LH_2)
  - Specific energy 700× that of batteries (3× Jet A)
  - Liquid state ~20K, with 1/4 energy density of Jet A
  - Abundance of H_2, improvements in economic viability with time
  - Ability to produce/supply on-site
- Fuel Cells
  - Specific power increase from 0.3 kW/kg to 3.73 kW/kg[4] over previous 15 years
  - Large improvements in specific power forecast at fuel cell stack-level[5]
- Environmental
  - Zero CO_2, CO, NO_X, SO_x, partially-combusted hydrocarbons, particulate matter



Haugan (2013)

Table 1. Rated Power Performance of FCS with SOA Alloy Catalysts

Stack Parameters	2018 FCS with d-PtCo/C Catalyst	2017 FCS with d-PtNi/C Catalyst
Membrane	Ionomer: 850 EW PFSA with chemical additive Substrate: Mechanical reinforcement Thickness: 14 μm	Ionomer: 850 EW PFSA with chemical additive Substrate: Mechanical reinforcement Thickness: 14 μm
Cathode Catalyst	d-Pt_3Co/C (0.1 mg_{Pt}/cm^2), EW=950, I/C=1.0	Electrode: d-$PtNi_3$ (0.1 mg_{Pt}/cm^2), acid washed Ink: organic, EW=850, I/C=1.0
Anode Catalyst	Pt/C (0.025 mg_{Pt}/cm^2)	Pt/C (0.025 mg_{Pt}/cm^2)
Stack Gross Power	88.5 kW	88.1 kW
Stack Voltage (Rated)	250 V	250 V
Number of Active Cells	380 cells (also 381 cooling cells)	377 cells (also 376cooling cells)
Stack Gross Power Density	3.07 kW/L	2.84 kW/L
Stack Gross Specific Power	3.73 kW/kg	3.45 kW/kg
Stack Inlet Pressure	2.5 bar	2.5 bar

DOE/GO-102019-5156 (2019)

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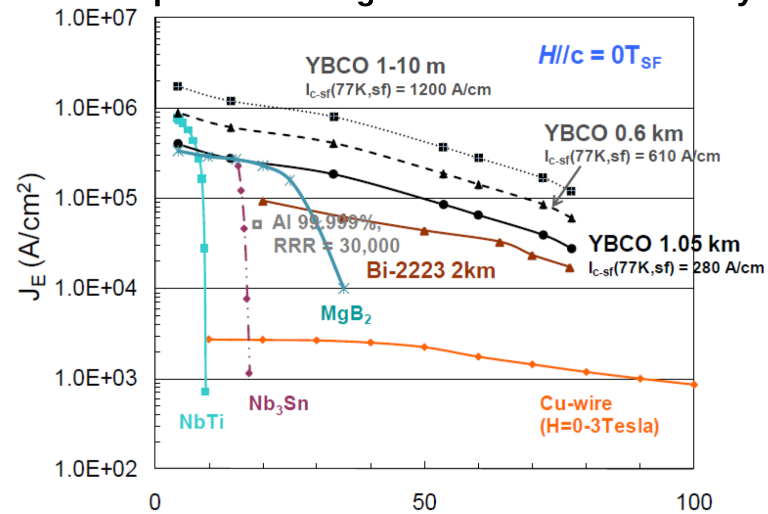
[4] 2018 FCS with d-PtCo/C Catalyst, DOE/GO-102019-5156
[5] Kadyk et al. (2018)

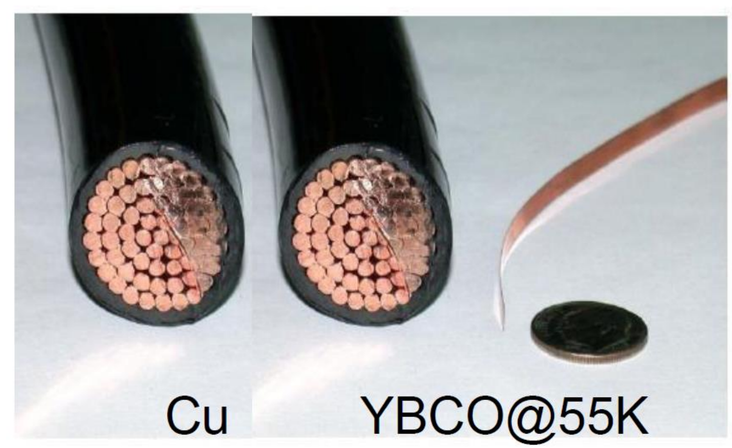
LH_2 Superconducting Power System

- Dual-Use H_2 Configuration
  - Hydrogen as an energy carrier *and* as a cryogen, enabling superconducting system
- Superconducting Power Transmission
  - No ohmic losses
  - Lower transmission voltage (mitigates breakdown/partial discharge challenges)
  - Smaller, lightweight conductors
- Cryogenic machines
  - Ultra-high efficiency (superconducting wire)
  - Large current density and small conductor size for very high rated and specific power

Superconducting Material Current Density



Haugan (2013)



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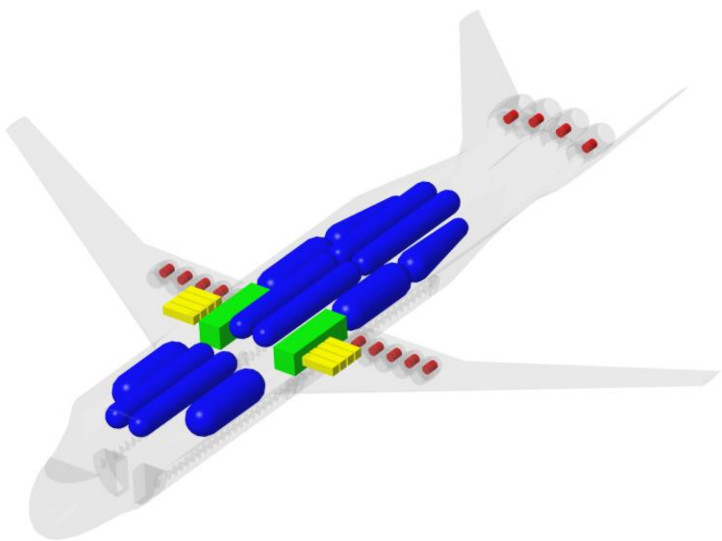
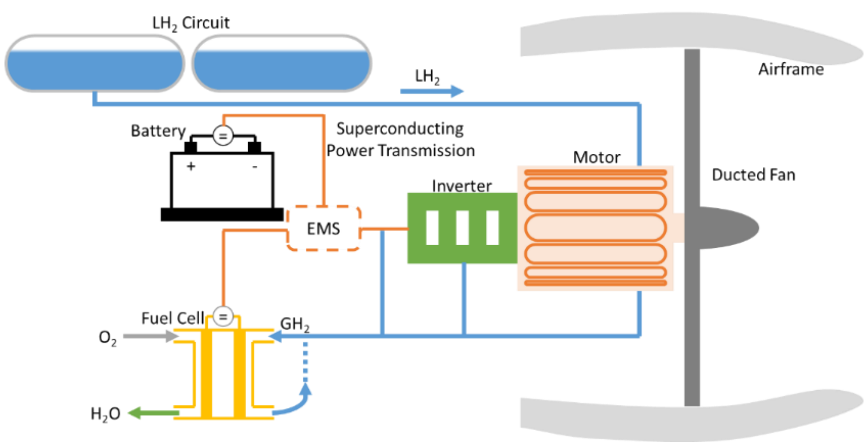
Hydrogen-Electric Aircraft Configuration

- Assume entry-into-service ~2050
  - Technology development concept
- Aircraft Platform
  - High-volume energy storage requirement
- Distributed Electric Propulsion
  - Flexibility in placement and configuration of propulsors enables
    - Boundary-layer ingestion (improves in system efficiency)
    - Improved high-lift performance
    - Resilience against propulor-out scenarios (OEI)
- System Integration
  - Electrical, thermal system architecture and control
  - Design optimization of aircraft





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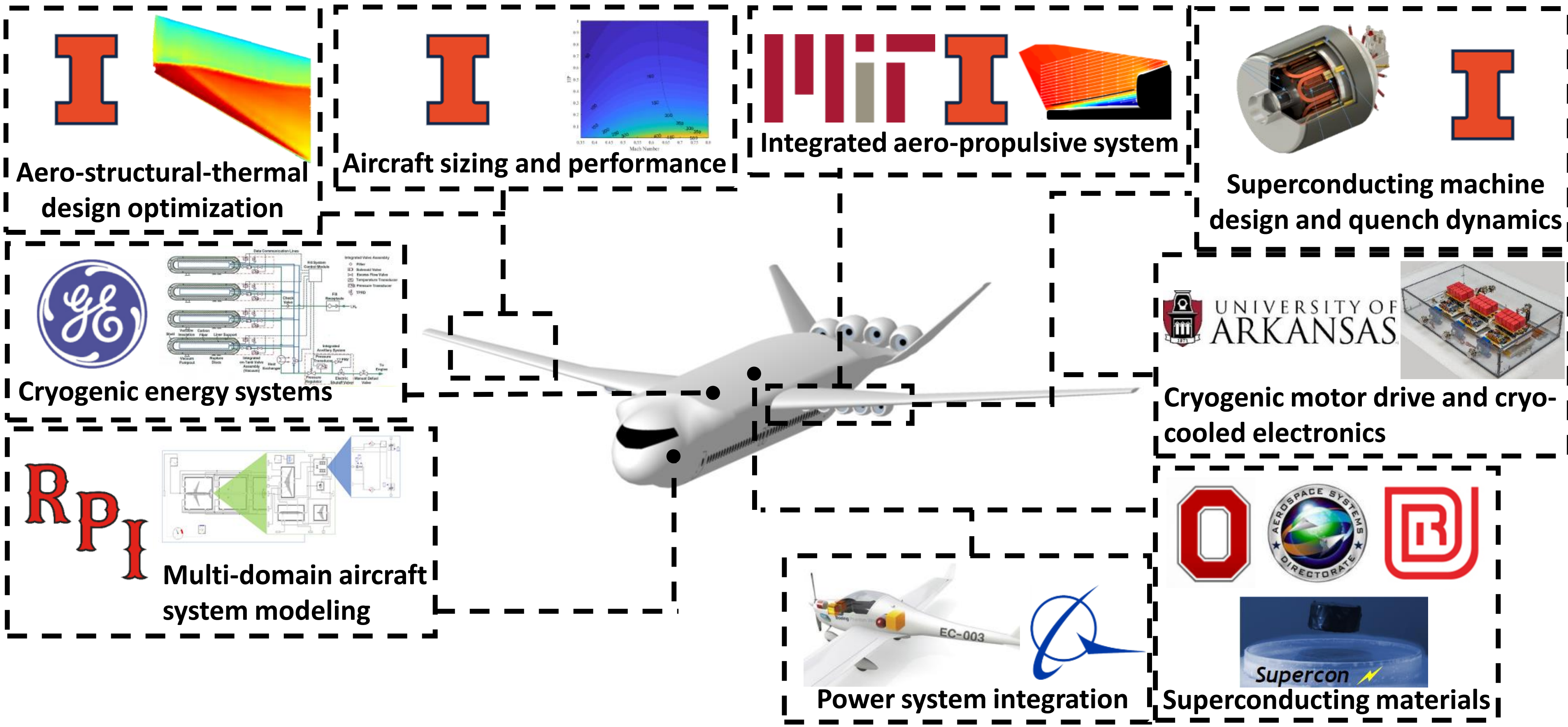
ULI Study Components



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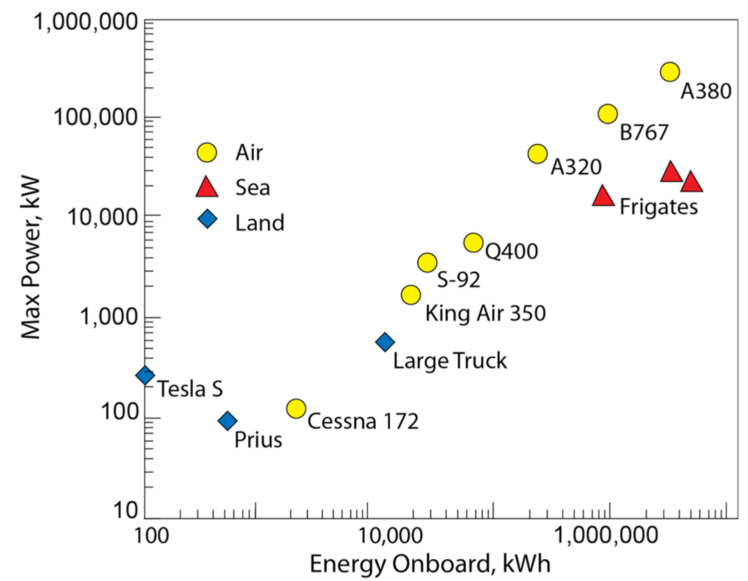
Research Needs

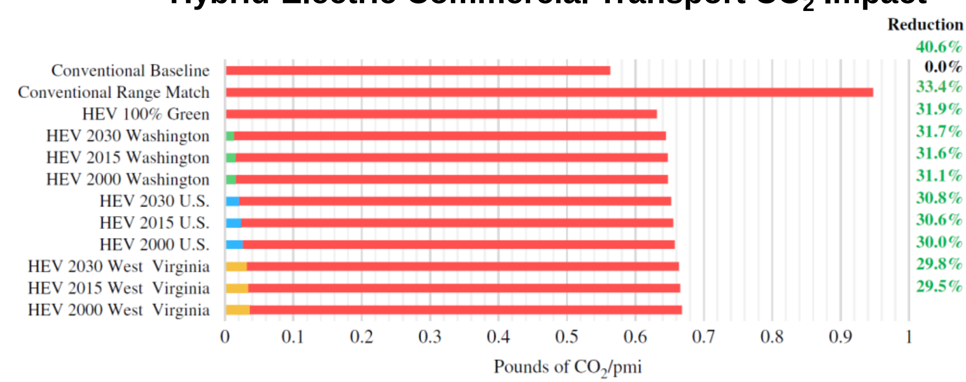
- Fuel cell specific power
  - Not yet competitive with gas turbines at system level
  - Further hindered by thermal management (PEM) and other BOP
- Stack gross power
  - 10's to 100's of MW power required
- Lightweight tanks
- High-temperature PEM and other lower-TRL systems
  - Attractive means for thermal challenges of LT-PEM
  - Increase current density and specific power
- System integration impacts
  - Close loop between hydrogen and fuel cell advances and aircraft system performance
- Support infrastructure
  - Even if aircraft system is viable, what else does it take?

Transportation Power and Energy Required



Epstein and O'Flarity (2019)

Hybrid-Electric Commercial Transport CO_2 Impact



Wroblewski and Ansell (2018)

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