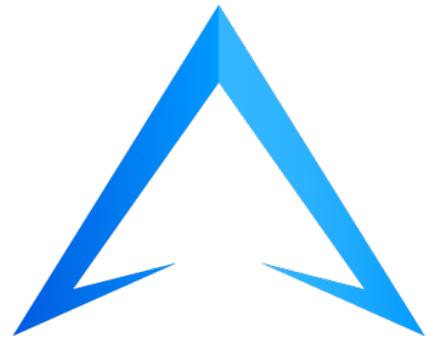


Overview of the NASA University Leadership Initiative (ULI) Program

Tools, Technologies, and Design for Future, Hydrogen-Powered, Fully-Electric Commercial Transport Aircraft

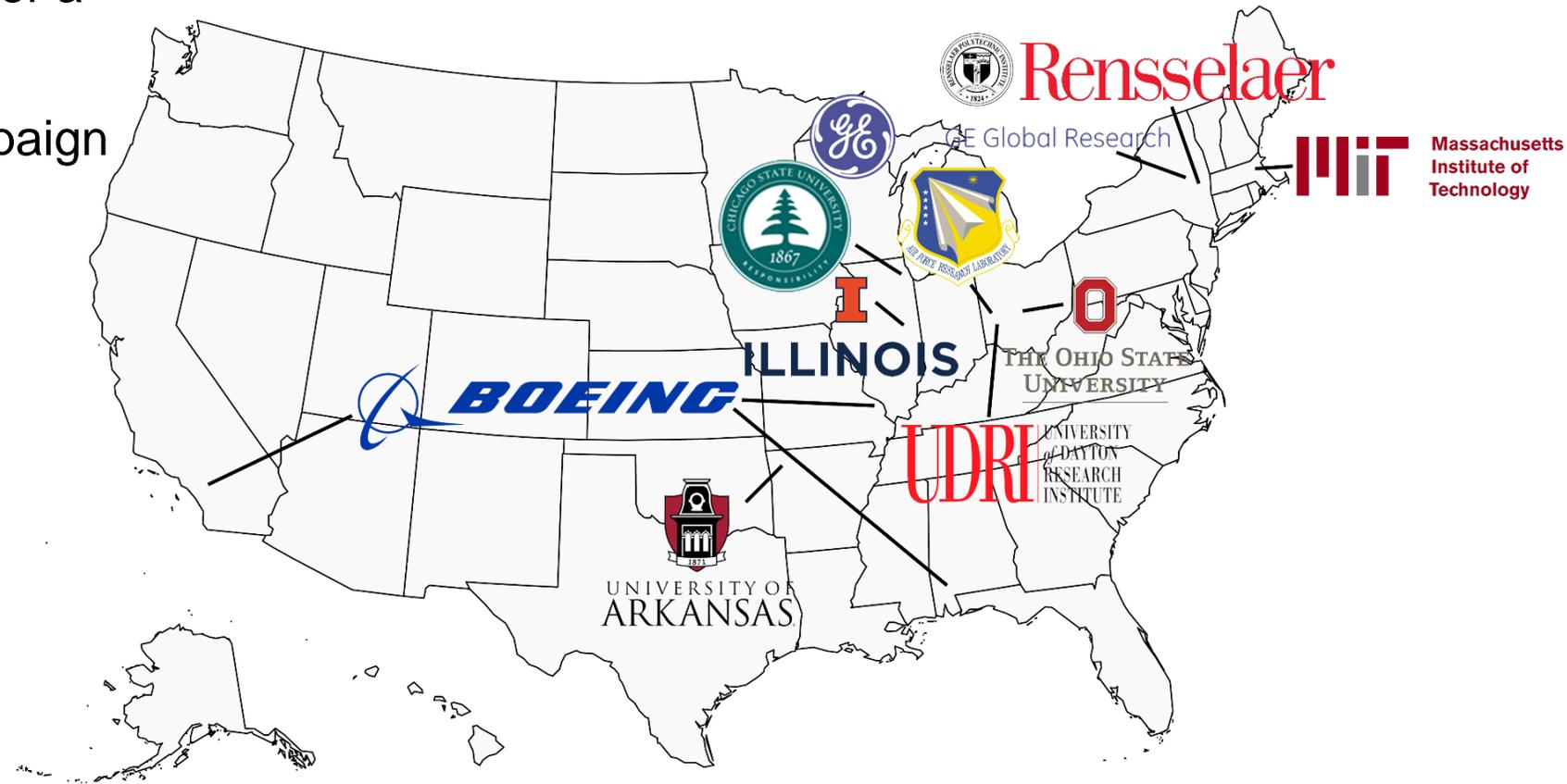


CHEETA

Center for High-Efficiency Electrical
Technologies for Aircraft

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

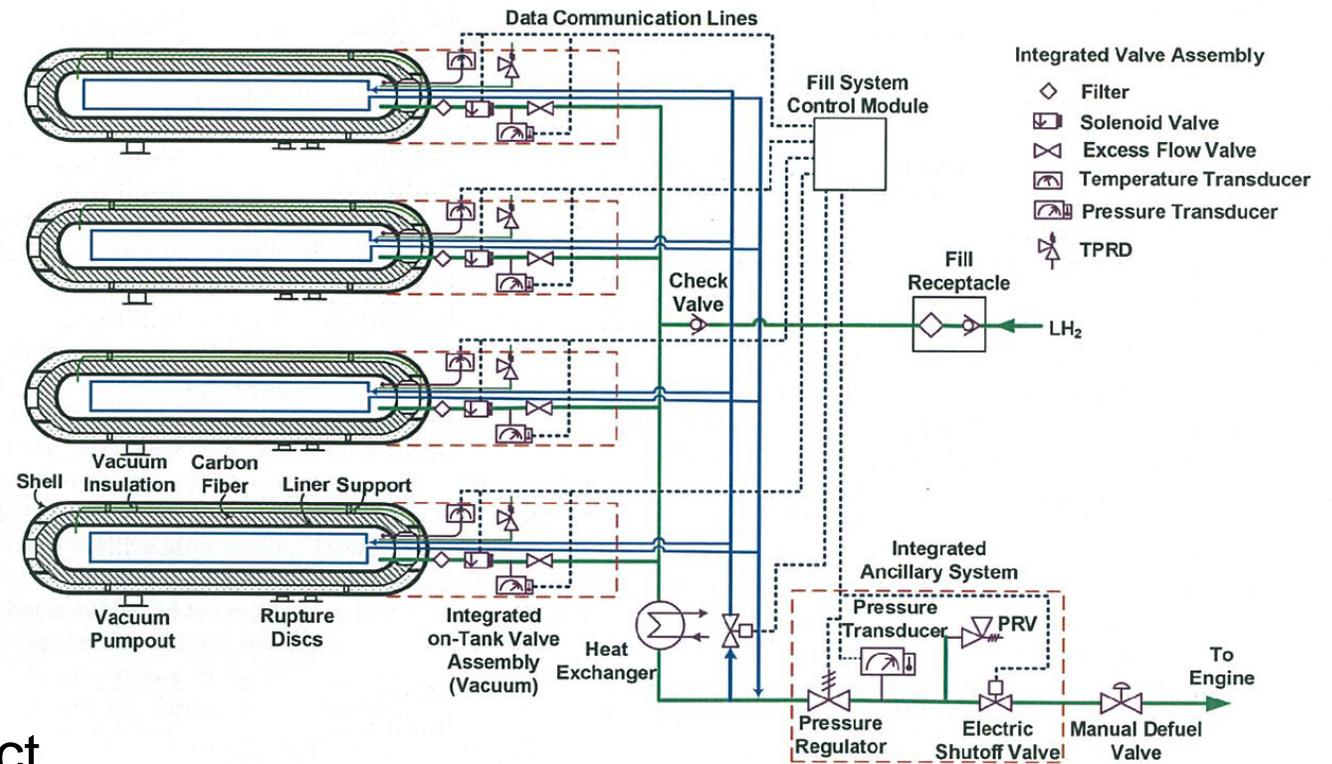


CHEETA Goals

- 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

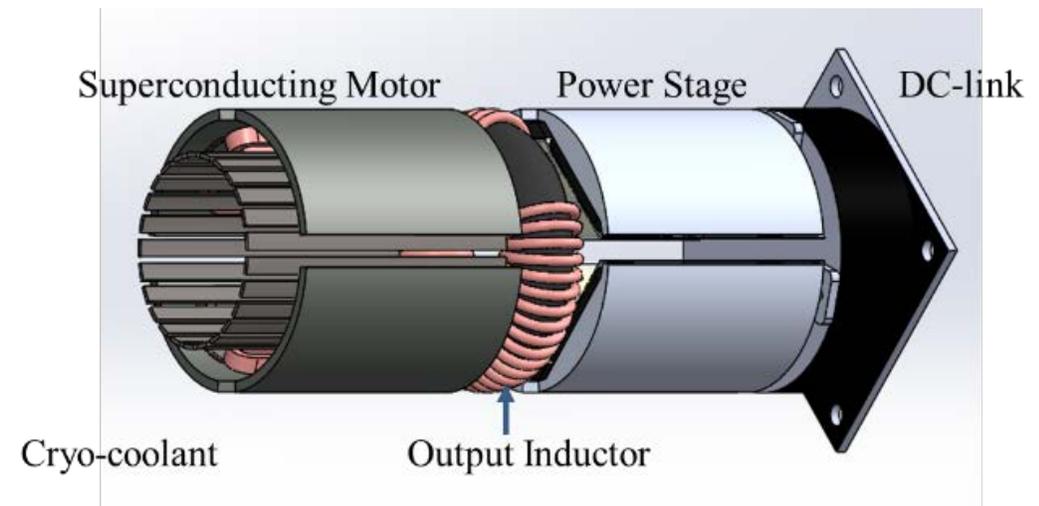
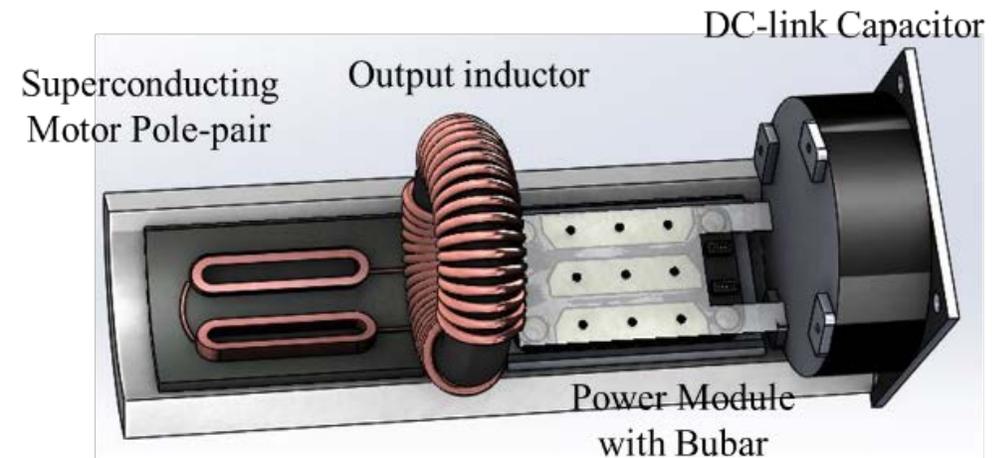
Technical Challenge: Energy Storage

- Cryogenic circuit design
 - Cryo-compressed, single-phase hydrogen multitank system
- Thermal budget
 - LH₂ boil off
 - Venting and safety systems
- LH₂ distribution and maintenance
 - Material selection
- Lifecycle analysis
 - Cost and environmental impact



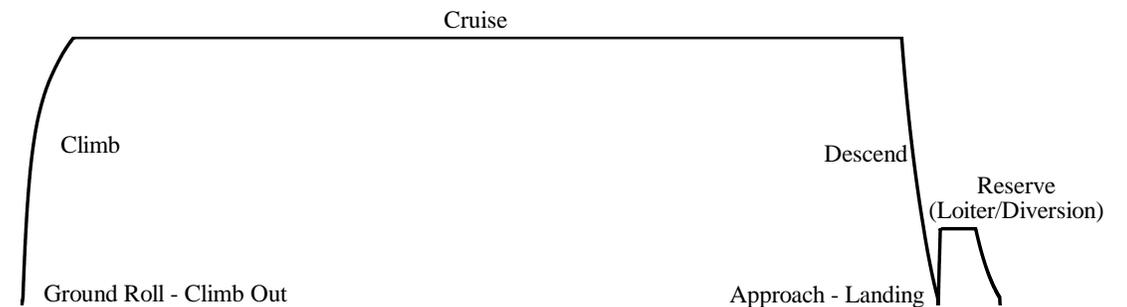
Technical Challenge: Integrated Electronics

- Power system operating conditions
 - High-level trades
 - AC losses
- Cryoelectronics
 - Semiconductor devices and passive components at extremely low temperatures
- Fully-integrated electrical machine
 - Reduced connection complexity, weight, reflected waves, and radiated EMI
- High-current pole pair testing
- Quench protection



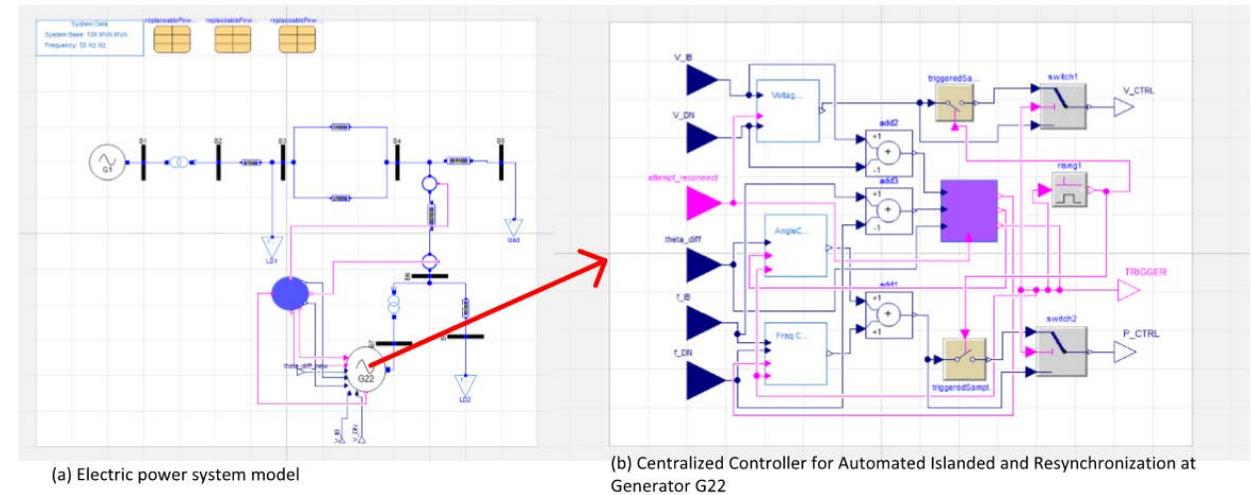
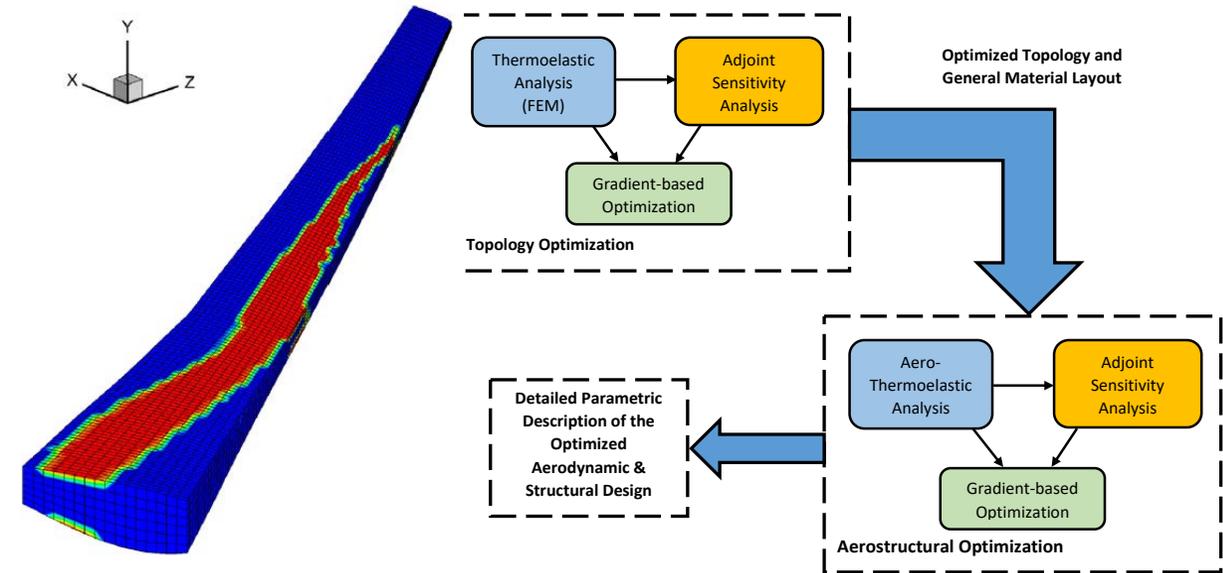
Technical Challenge: Vehicle Design

- Unconventional aircraft configuration
 - LH₂ storage volume challenge
 - Aero-propulsive coupling and resulting impact on vehicle system
- Propulsor design
 - Electrically-driven
 - Tolerant to inlet distortion and complex internal flow
- Flight characteristics
 - Vehicle mission modeling



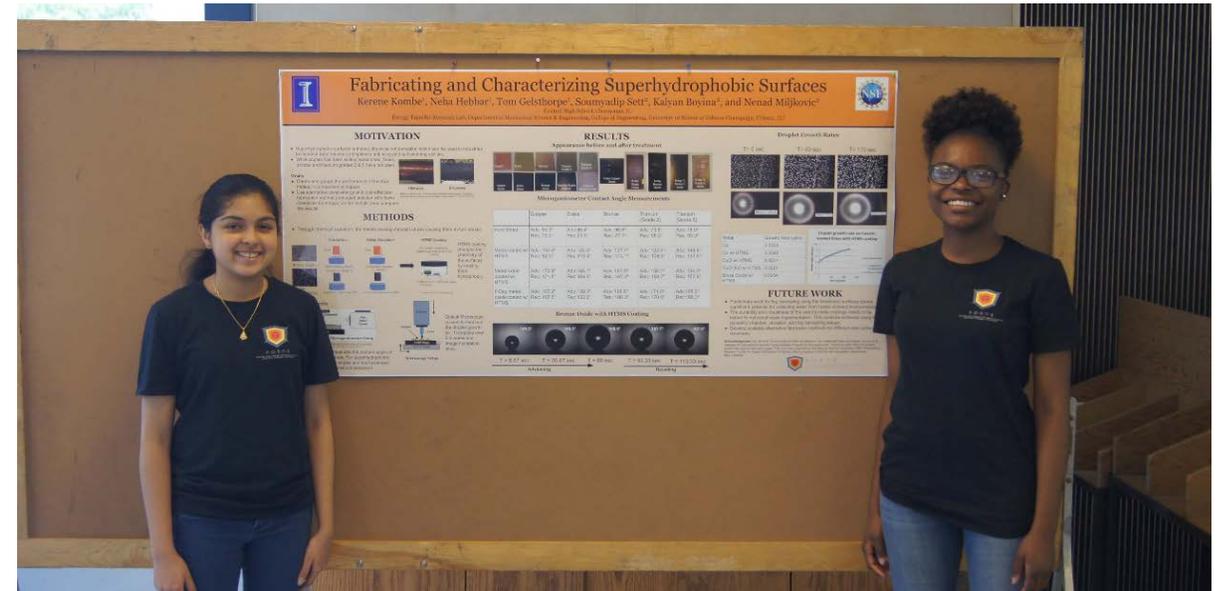
Technical Challenge: System Integration

- Multi-domain modeling
 - High-level, low-level trades
 - Control and protection of systems
 - Grid reconfiguration
- Multi-disciplinary design optimization
 - Aero-structural-thermal airframe definition
- Vehicle safety assessment
- Future production feasibility



Technical Challenge: Outreach

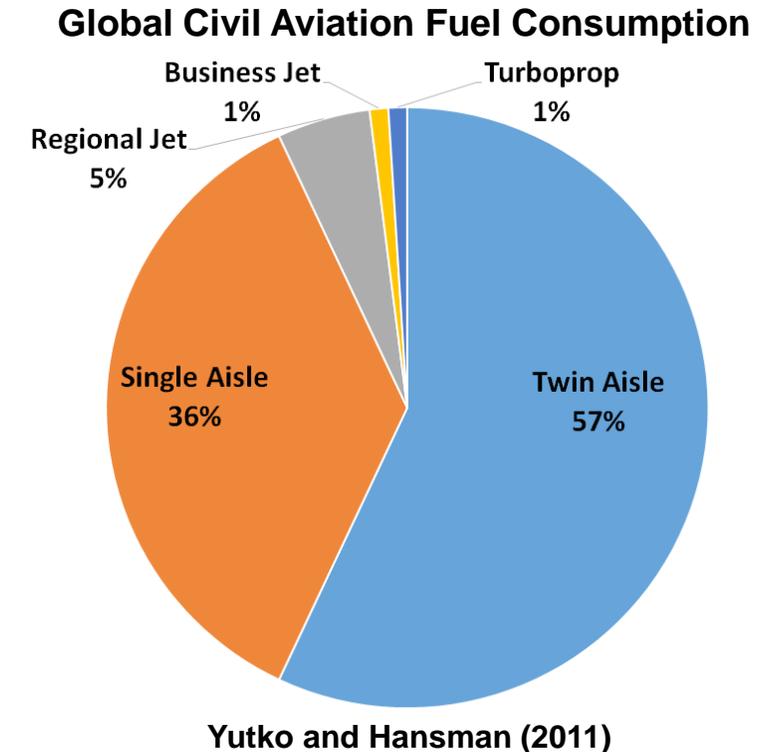
- Training future leaders of aerospace
 - Illinois Young Scholars Program
 - Inclusive team development and partnerships
- Graduate career exploration
- Educating broad research community
 - AIAA/IEEE Electric Aircraft Technologies Symposium



Backup Slides

Why Electric Aircraft?

- Global aviation industry produced 859 million tons of CO₂ in 2017^[1]
- Forecasted 90% growth in US air travel within next 20 years^[2]
- Transportation is the leading source of greenhouse gas emissions in the US^[3]
 - Aircraft make up ~10% of this contribution
- Forecasted shortage in oil as early as 2020's^[4]



Clean and abundant energy source needed for future of aviation

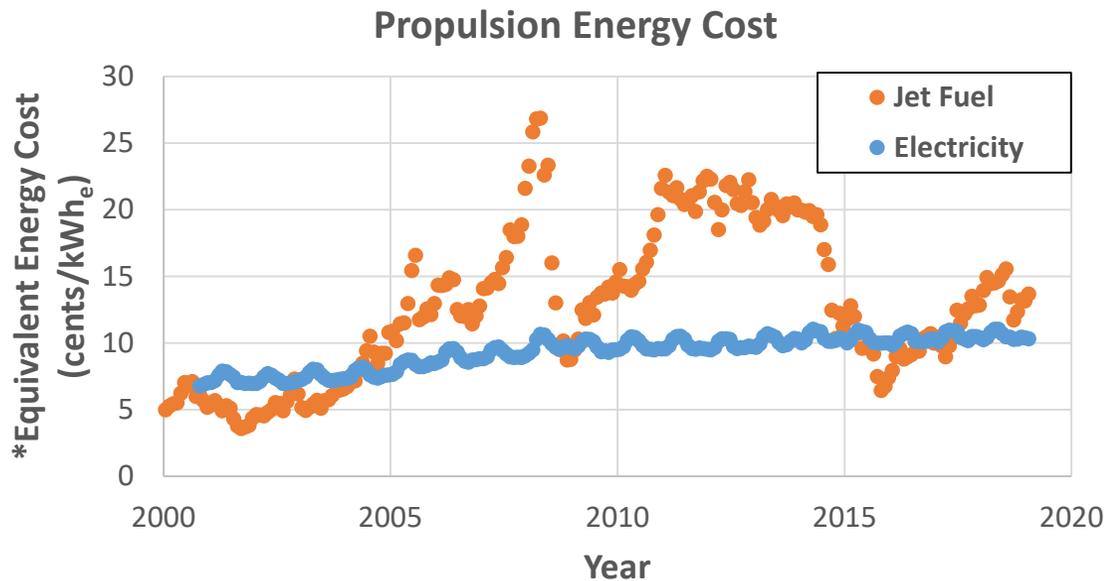
^[1] Air Transport Action Group

^[2] Huerta (2012)

^[3] US Environmental Protection Agency

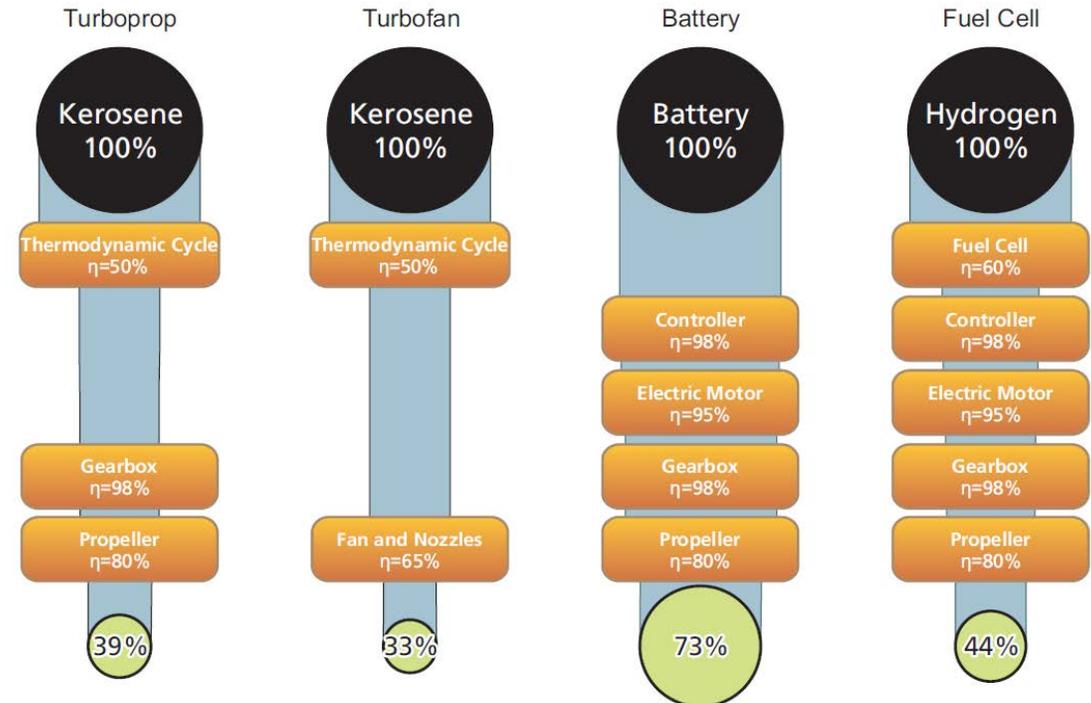
^[4] Goldman Sachs EMEA Natural Resources Research (2018)

Why Electric Aircraft?



Source: US Energy Information Administration

*Equivalent energy cost = energy cost / total drivetrain efficiency



Hepperle (2012)

Operating cost reduction potential for electrical aircraft systems

Implementation Challenges

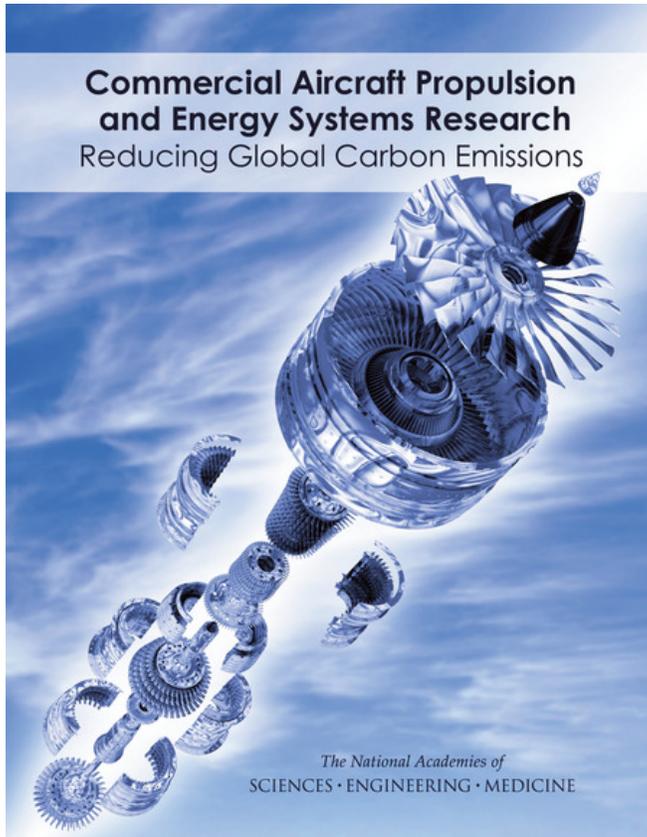


TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

| Aircraft Requirements | Electric System ^a | | Battery ^b |
|--------------------------------------|------------------------------|-------------------------------------|-------------------------|
| | 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 |

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

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

^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.

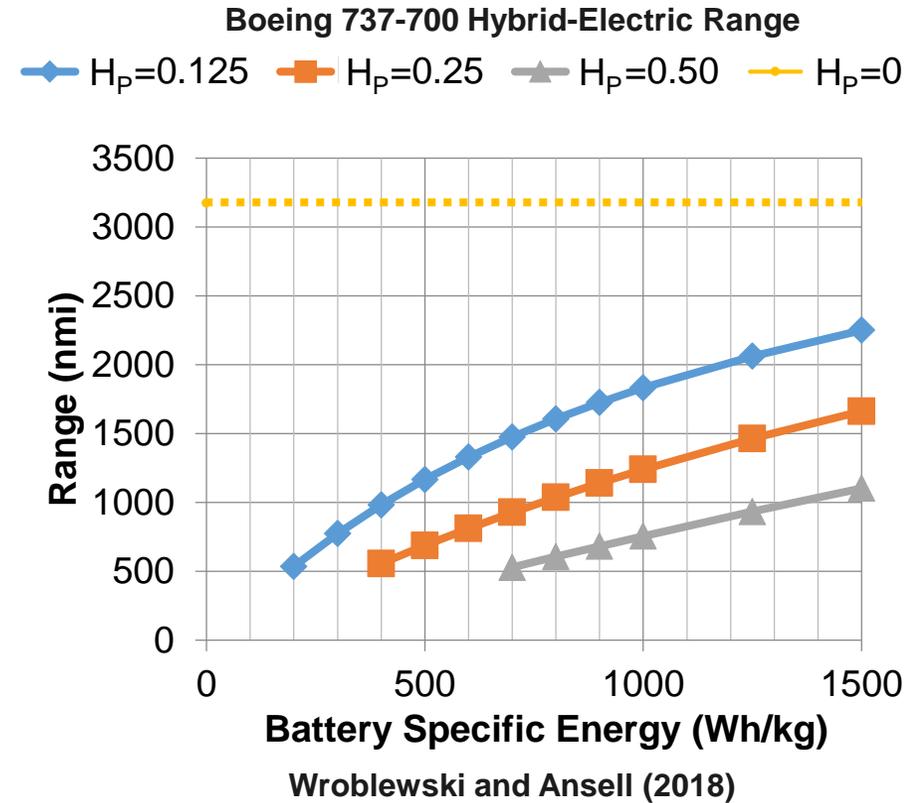
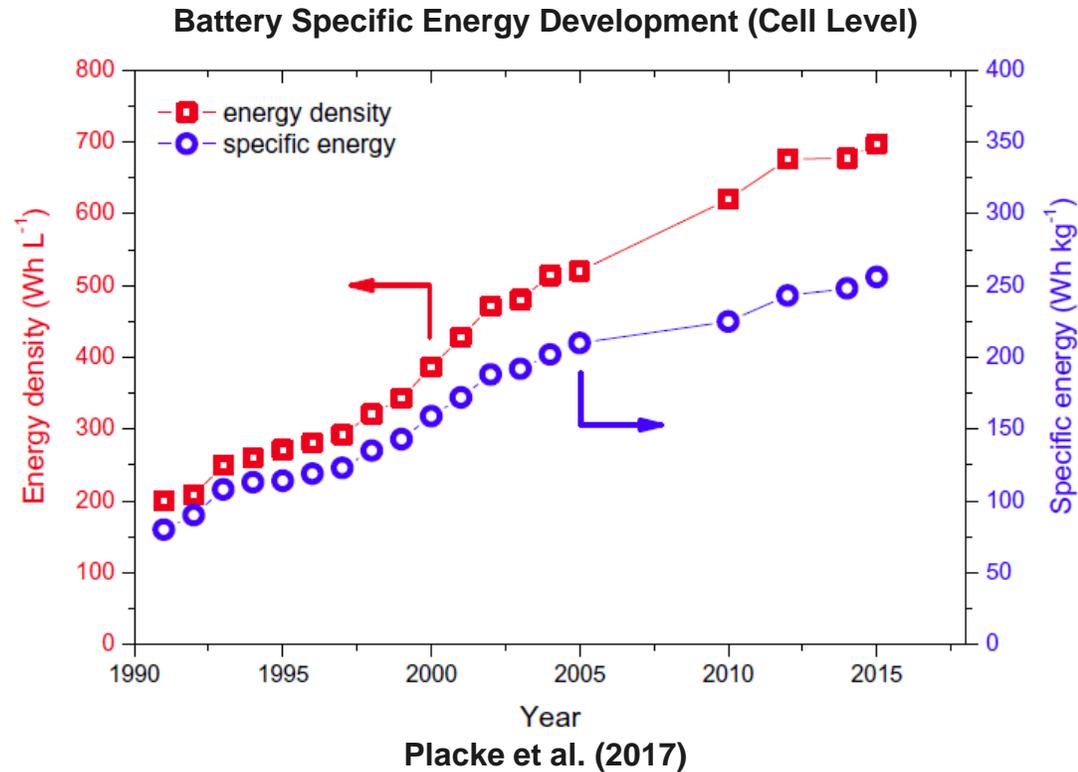
^c Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

National Academies (2016)

Disruptive improvements in technology needed for electrification



Implementation Challenges



Batteries provide limited viability for fully-electric transport aircraft

Hydrogen as an Energy Carrier

- Fuel Cells

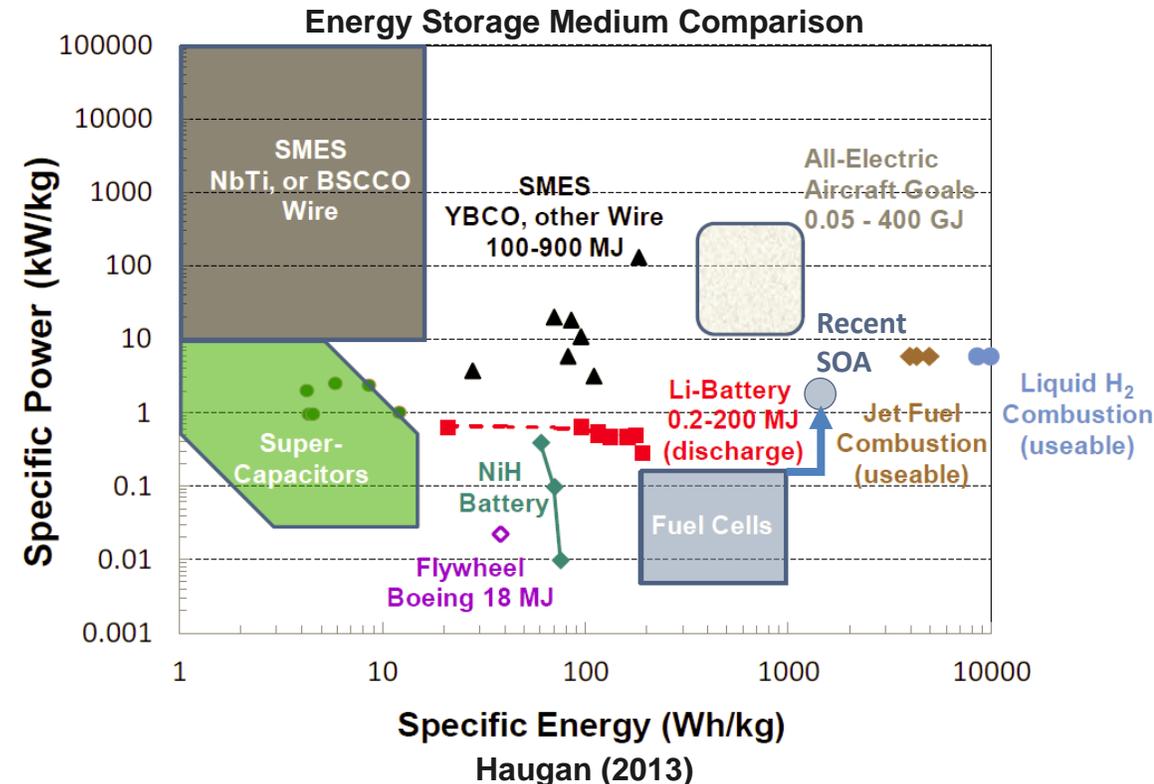
- Specific power increase from 0.3 kW/kg to 2 kW/kg over previous 15 years
- Projected increase to 10 kW/kg stack-level^[5]

- Liquid Hydrogen (LH₂)

- Specific energy 700x that of batteries (3x Jet A)
- Liquid state ~20K, with 1/4 energy density of Jet A

- Superconducting Power

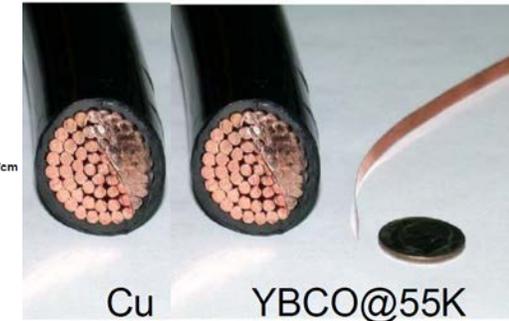
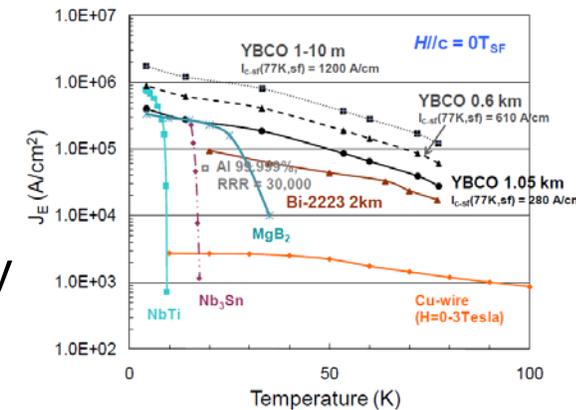
- No ohmic losses, high current density
- Ultra-efficient power transmission, compact high-power machines



Additional Benefits of Hydrogen-Electric

- Environmental
 - Zero CO₂, CO, NO_x, SO_x, partially-combusted hydrocarbons, particulate matter
- Distributed Electric Propulsion
 - Aero-propulsive coupling for improved efficiency
 - Improved resilience to propulsor-out scenarios
 - Noise shielding and quiet operation
- Lower Transmission Voltage
 - Smaller, lightweight conductors for transmission
 - Mitigates breakdown or partial discharge
- Availability
 - Abundance of H₂, improvements in economic viability with time
 - Ability to produce/supply on-site

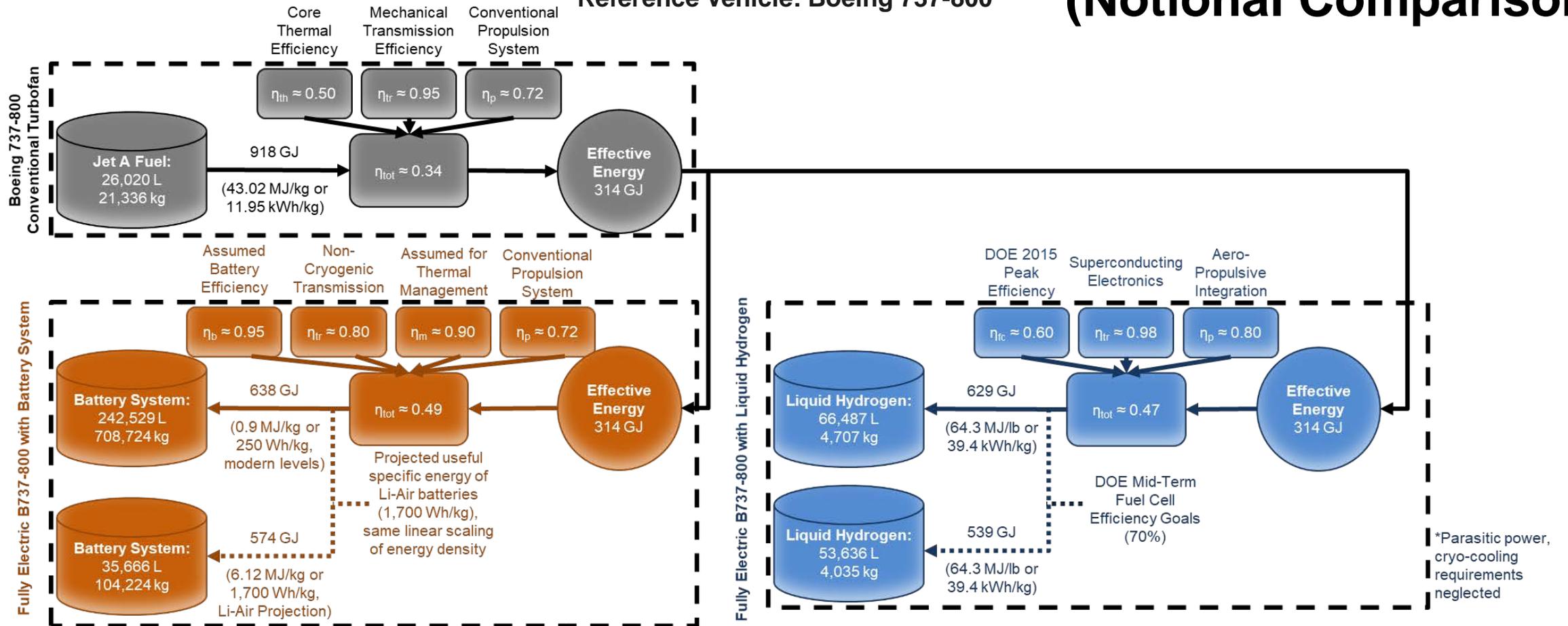
Haugan (2013)



Electrified Aircraft Weight and Volume

Reference Vehicle: Boeing 737-800

(Notional Comparison)



Hydrogen/Fuel Cell Integrated Aircraft

