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CHANGING WHAT'S POSSIBLE

Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)

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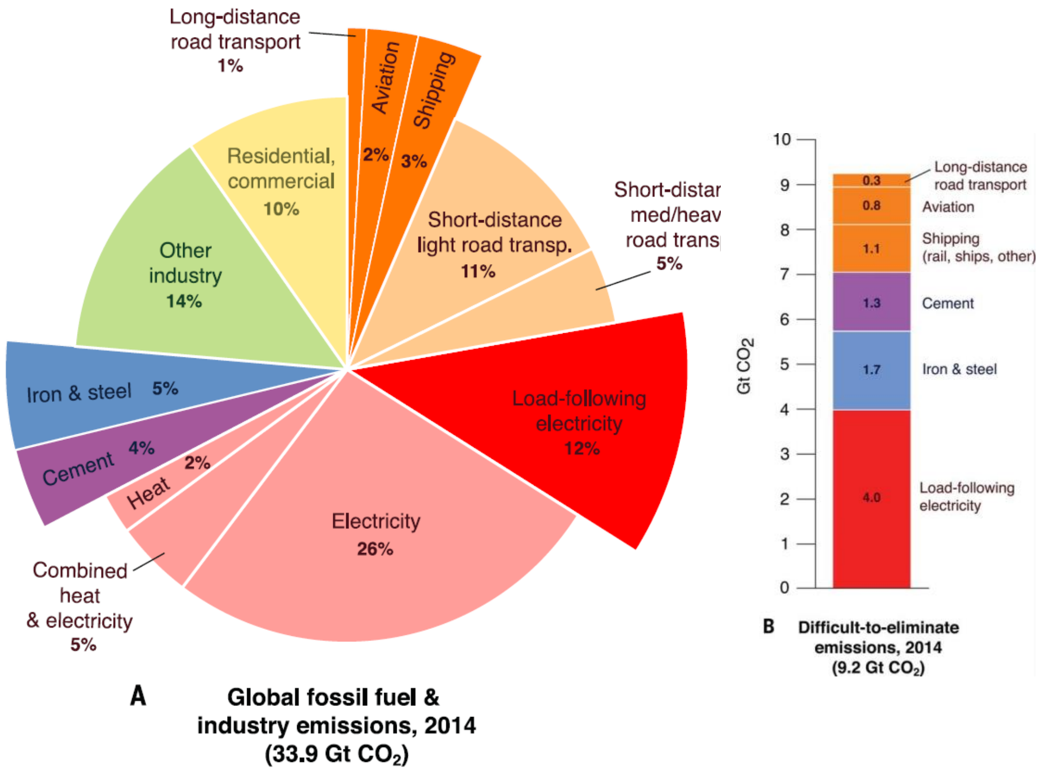
Global trends



- Increasing mobility/population
  - Aviation traffic to increase 3-4 times by 2050
  - Covid-19 effect unknown
- Increasing cost of fuel
  - Fuel constitutes about 1/3 of total aviation expenditures
- Growing pressure to reduce emissions
  - CO_2 emissions from aviation will triple by 2050 by ICAO estimate
  - Search for alternative fuels
- Intra-regional routes will continue to dominate the air travel market
  - Smaller aircraft are key to unlocking new route potential

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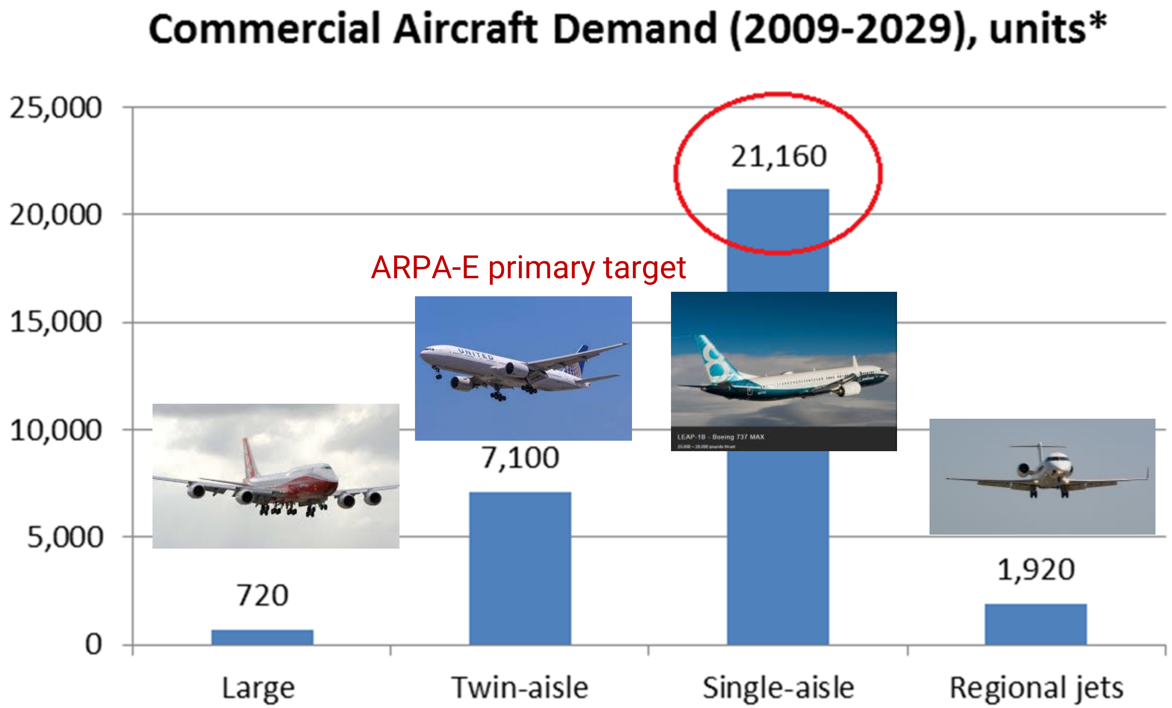
Narrow-body aircraft segment is ultimate target



* The corresponding dollar market value is as follows: Large ($220 billion); Twin-aisle ($1.63 trillion); Single-aisle ($1.68 trillion); and Regional jets ($60 billion).

Source: Boeing

Most trips are 1500-2000 km in range

ARPA-E Aviation Programs

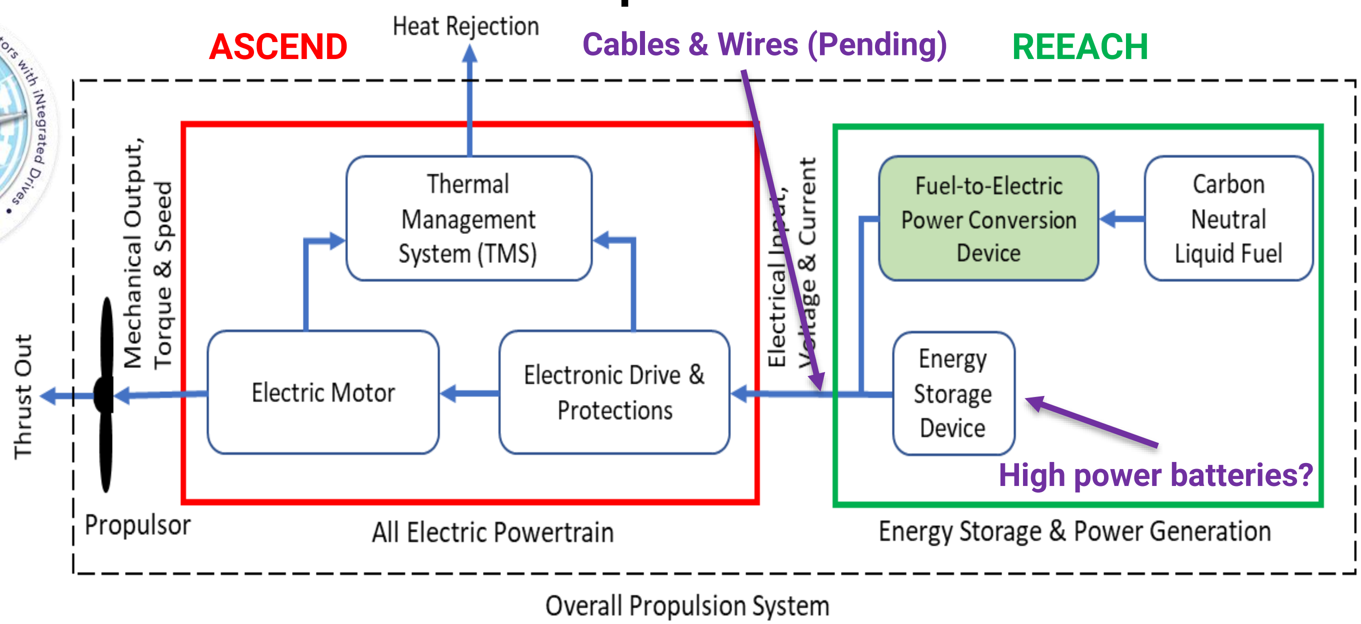
ARPA-E Announces 17 Projects for Carbon Neutral Hybrid Electric Aviation

ARPA-E announced $33 million in funding for 17 projects as part of the Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) and Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH) programs.

REEACH and ASCEND teams will work to decrease energy usage and associated carbon emissions for commercial aircraft propulsion systems. Click to learn more.

White space – carbon neutral aviation

ARPA-E aviation powertrain focus areas



Decreases propulsion system weight and enables distributed propulsion (enabler)

Provides target flight range and payload (show stopper)

Complementary programs to make zero-carbon aviation economical

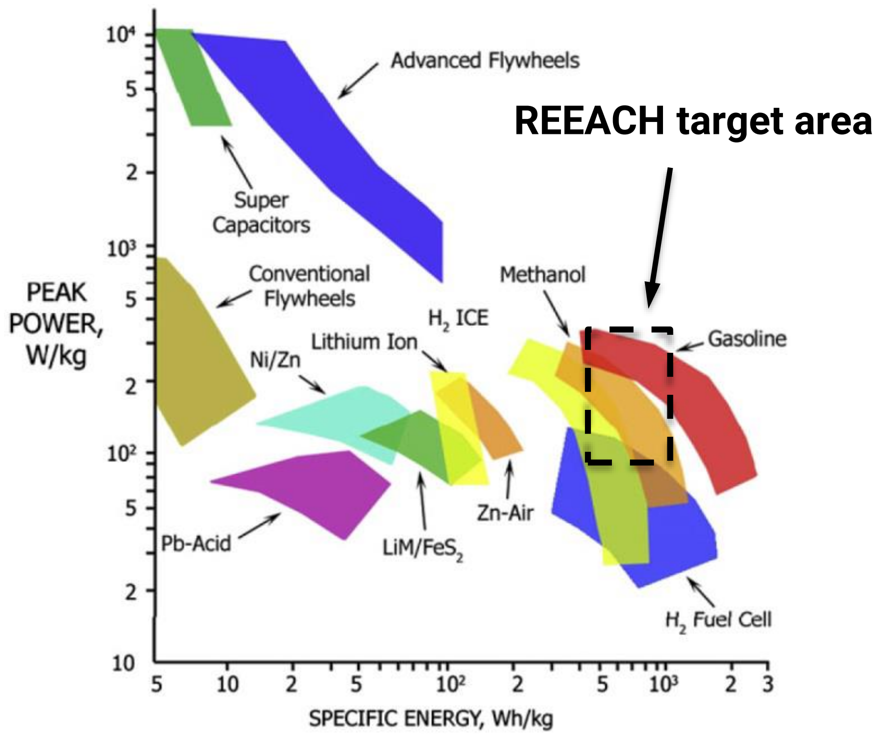
REEACH program objectives

Develop *high efficiency hybrid* energy storage and power generation (ESPG) system that uses energy dense renewable liquid fuels

- Utilize carbon neutral fuels in a *high efficiency* conversion device to provide long flight range (effective delivered specific energy $E_E = E_P*\eta$)
  - chemical energy converted to electric power directly in fuel cells or indirectly in advanced thermal engines with generators
- Integrate the fuel conversion device with a *high power* device (e.g. a battery) to support takeoff and climb
  - the battery to be recharged during the flight for safety

New technologies have to be developed

Energy storage/delivery requirements

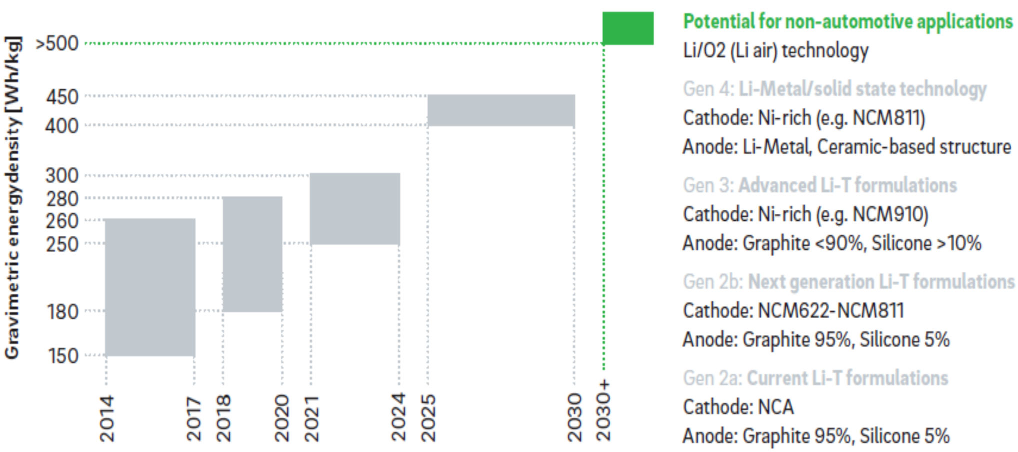


- **Take-off power is about 3x of cruise power**
- **High energy density is needed for long haul**
- **Requirement of high power AND high energy supports hybridization**
- **NASA minimum goal for full electric aircraft 1000 Wh/kg**
  https://ntrs.nasa.gov

Could batteries reach NASA target specific energy?

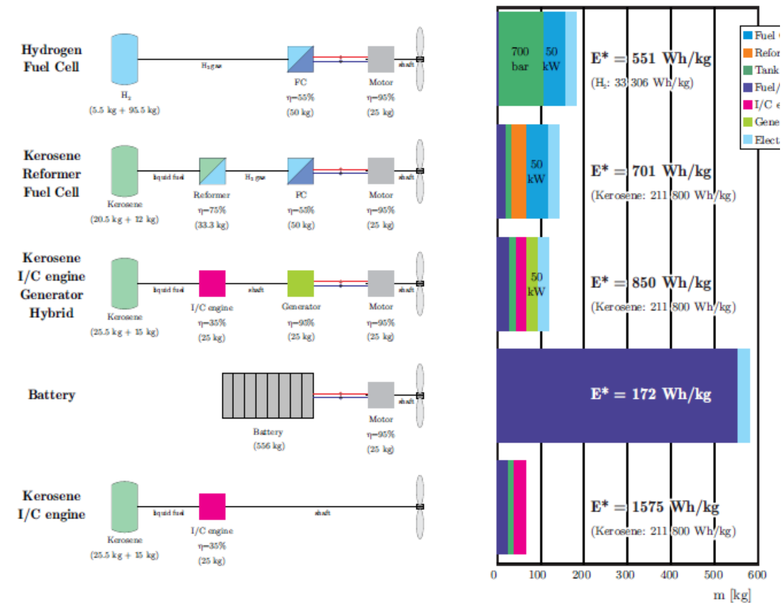
NASA target specific energy 1000 Wh/kg

Projected automotive roadmaps indicate batteries will only reach the 500 Wh/kg level required for aerospace after 2025.



Source: Roland Berger

Mass and equivalent energy density of electric power generation systems delivering an electric power of 50 kW for 2 hours



M. Hepperle "Electric Flight – Potential and Limitations" (2012)

- **Theoretically – yes, realistically – NO (500 Wh/kg seems to be practical limit)**
- **Additional problems: charging time and infrastructure**

Fuel selection

Fuel	Specific energy, kW/kg	Conversion engine	Conversion efficiency, %	Delivered specific energy, kW/kg	Cost, $/kWh**
Jet fuel	12.04	Turbofan	34	4.1	0.149
Biojet fuel*	10.6	Turbofan	34	3.6	0.192
Ethanol	8.33	Hybrid FC	60	5.0	0.103
LH2* (incl. tank)	33.3 (19.3)	Hybrid FC	60	11.6	0.200
Ammonia	5.17	Hybrid FC	60	3.1	0.145
Biojet fuel*	10.6	FC+reformer	47	5.0	0.143
bio-BuOH*	9.17	FC+reformer	48	4.4	0.151
LNG (incl. tank)	14 (10.5)	FC+reformer	47	4.9	0.150
Synfuel*	12.04	ICE hybrid	44	5.3	0.162

* - projected cost, ** - cost of delivered (propulsion) energy

- Bio jet fuel is not economical as drop-in solution
- Variety of renewable fuels could be economical if high efficiency technologies will be developed

Lower energy density requires higher conversion efficiency

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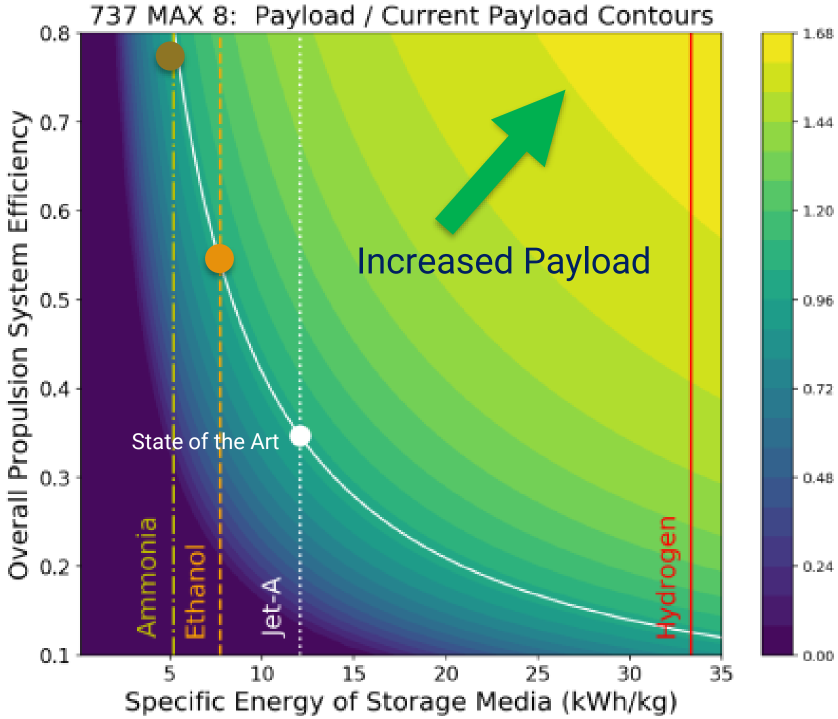
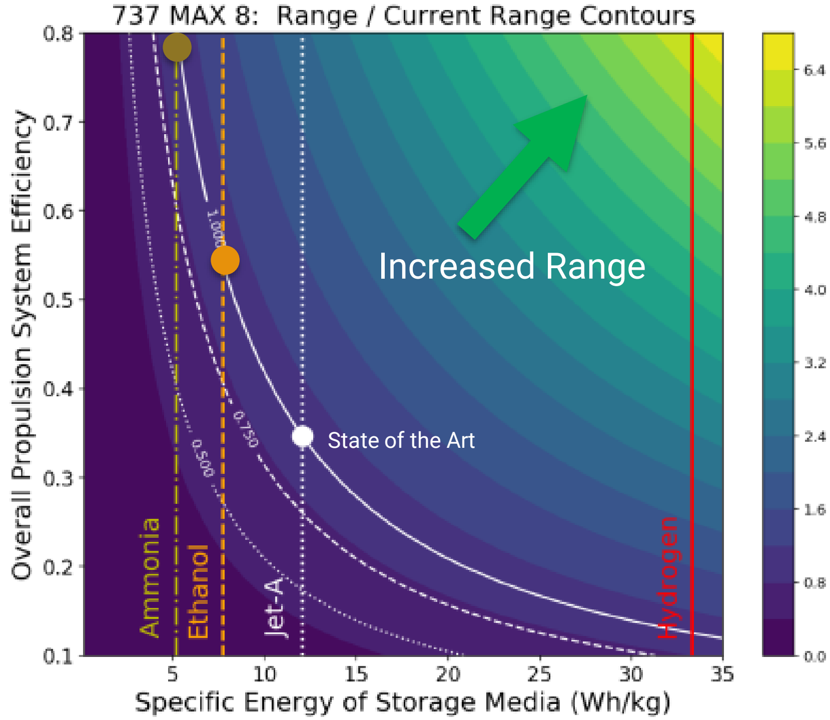
Fuel and efficiency effects on aircraft payload and range

Payload sensitivity



Range sensitivity



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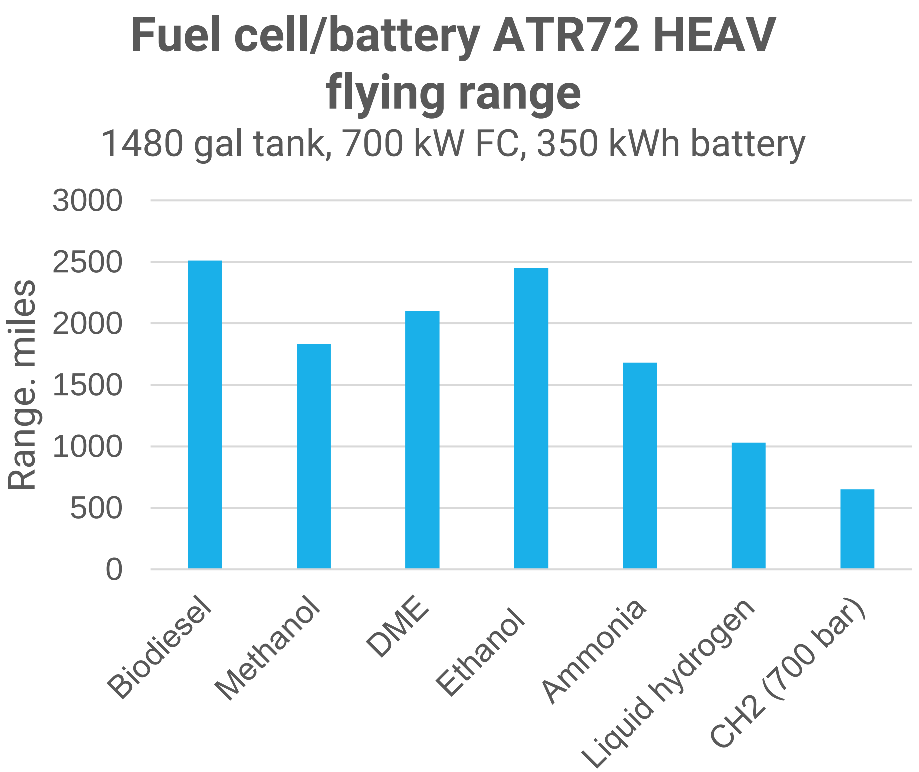
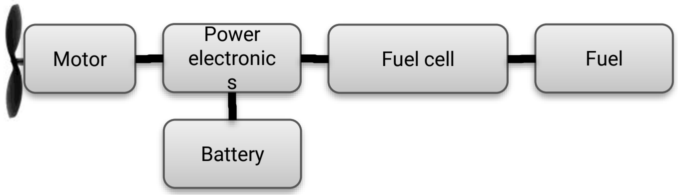
Hybrid aircraft with direct liquid fuel cell

(MTOW & tank size constant)



ATR72
70 passengers



Hydrogen is **not** of FOA interest:

- Duplicative effort to FCTO
- Infrastructure prohibitively expensive
- Requires full aircraft redesign

* - Fuel cell efficiency 55%, battery round trip efficiency 90%, energy consumption 4.6 kWh/mile for regional aircraft

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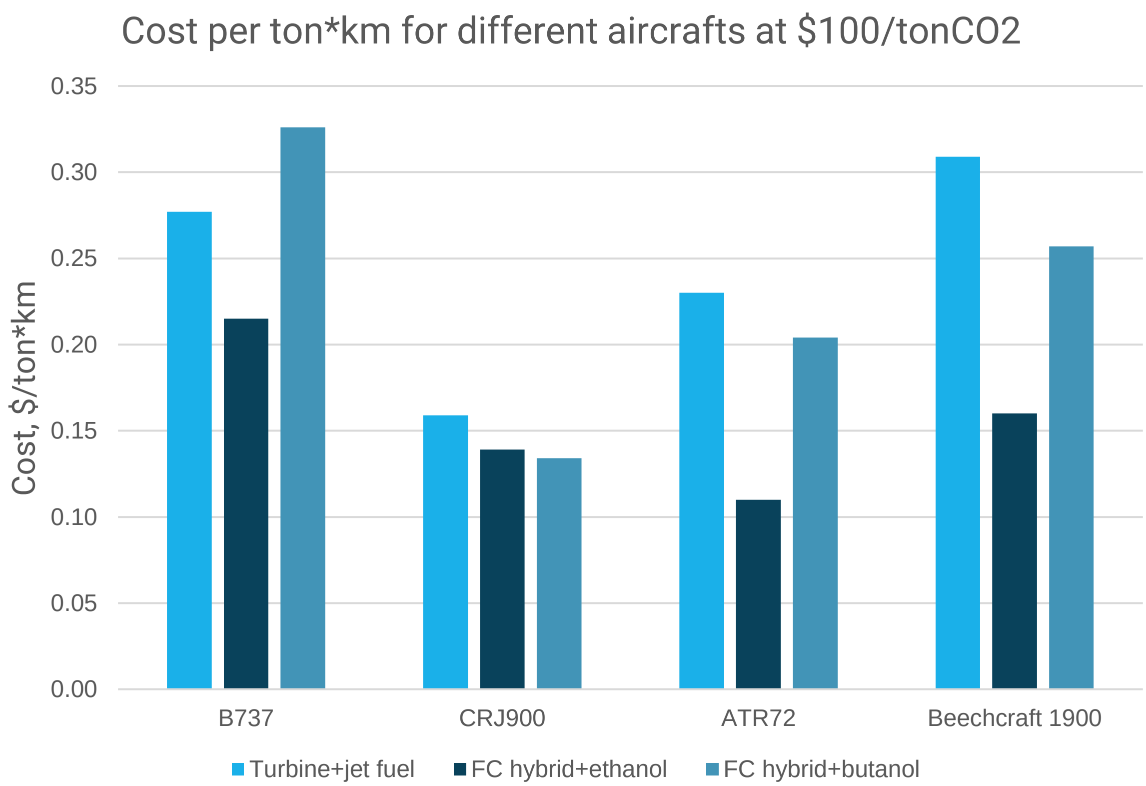
Freight cost for different aircrafts



Conclusion: commercial electric aviation can compete with conventional turbofans and turboprops on cost and performance

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Program metrics

Energy Storage and Power Generation System (ESPG) for aircrafts

Metric	Program target	SOA
Fuel	Carbon neutral/renewable liquid fuels	Fossil derived jet fuel
Fuel cost (per delivered power)	< \$0.15/kWh	\$0.15/kWh
System energy density	> 3000 kWh/kg	3400 Wh/kg
System (incl. fuel) power density	> 0.75 kW/kg	0.84 kW/kg
System cost	<\$1000/kW	\$1000/kW

→ to provide range

→ to assure takeoff

→ cost parity with incumbent technology

Deliverable: demonstrate a kW-scale ESPG system and perform flight imitation test

Wide open design space (fuel in – electric power out) limited only by system level targets

Program structure

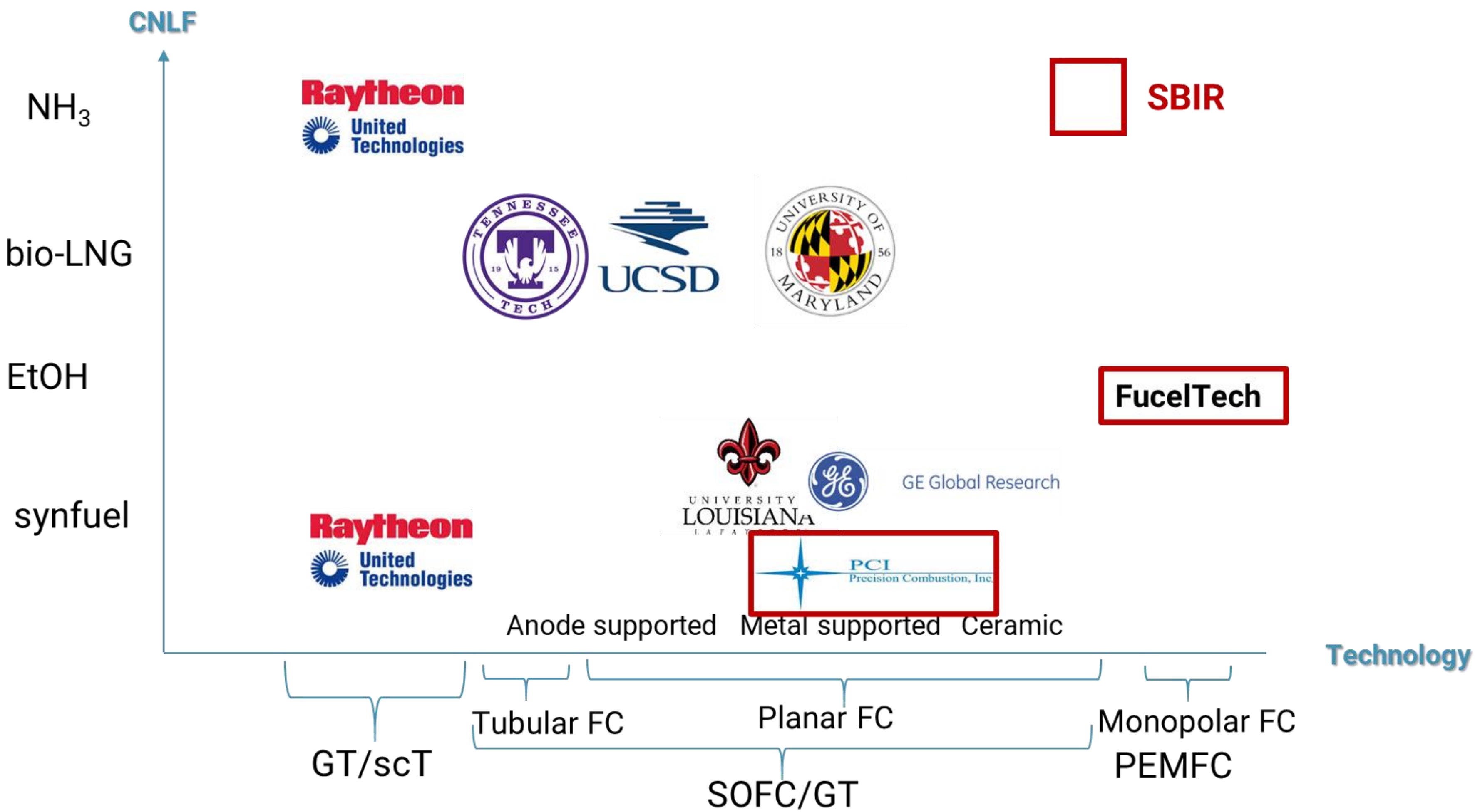
Phased approach:

- Phase I – component development ($20M)
- Phase II – system prototype demonstration (TBD)
- Project cost $4-6M

Deliverables:

- Demonstration of at least 5 kW takeoff/1.75 kW cruise ESPG fuel cell breadboard system
- Demonstration of at least 100 kW takeoff/35 kW cruise ESPG combustion engine breadboard system
- The prototype to be tested at conditions simulating flight

REEACH Technology Map



REEACH Partnership Map

Raytheon United Technologies | Collins Aerospace | gti | Oregon State University

GE Global Research | Georgia Tech | PCI Precision Combustion, Inc. | NREL National Renewable Energy Laboratory

UCSD | Honeywell Aerospace

University of Louisiana | Raytheon United Technologies | FuelCell Energy Ultra-Clean, Efficient, Reliable Power | INL Idaho National Laboratory

University of Maryland | Raytheon United Technologies | Colorado School of Mines 1874 | ion Storage Systems

Tennessee Tech | Boeing | Special Power Sources | Oak Ridge National Laboratory | Raytheon United Technologies

PCI Precision Combustion, Inc. | UCONN

FucelTech | University of Delaware

SBIR

https://arpa-e.energy.gov