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
  - CO₂ 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

A Global fossil fuel & industry emissions, 2014 (33.9 Gt CO₂)

Downloaded from http://science.sciencemag.org/ on March 20, 2019
Narrow-body aircraft segment is ultimate target

Most trips are 1500-2000 km in range

Commercial Aircraft Demand (2009-2029), units*

* 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
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

ASCEND  
Thermal Management System (TMS)

Electronic Drive & Protections

All Electric Powertrain

Heat Rejection

Cables & Wires (Pending)

REEACH

Fuel-to-Electric Power Conversion Device

Energy Storage Device

Energy Storage & Power Generation

High power batteries?

Decrees 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

Theoretical – yes, realistically – NO (500 Wh/kg seems to be practical limit)

Additional problems: charging time and infrastructure

## Fuel selection

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

* - 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
Fuel and efficiency effects on aircraft payload and range

**Payload sensitivity**

Increased Payload

**Range sensitivity**

Increased Range
Hybrid aircraft with direct liquid fuel cell (MTOW & tank size constant)

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

**Fuel cell/battery ATR72 HEAV flying range**
1480 gal tank, 700 kW FC, 350 kWh battery

**ATR72**
70 passengers

Hydrogen is **not** of FOA interest:
- Duplicative effort to FCTO
- Infrastructure prohibitively expensive
- Requires full aircraft redesign
Freight cost for different aircrafts

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

Energy Storage and Power Generation System (ESPG) for aircrafts

<table>
<thead>
<tr>
<th>Metric</th>
<th>Program target</th>
<th>SOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Carbon neutral/renewable liquid fuels</td>
<td>Fossil derived jet fuel</td>
</tr>
<tr>
<td>Fuel cost (per delivered power)</td>
<td>&lt; $0.15/kWh</td>
<td>$0.15/kWh</td>
</tr>
<tr>
<td>System energy density</td>
<td>&gt; 3000 kWh/kg</td>
<td>3400 Wh/kg</td>
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<tr>
<td>System (incl. fuel) power density</td>
<td>&gt; 0.75 kW/kg</td>
<td>0.84 kW/kg</td>
</tr>
<tr>
<td>System cost</td>
<td>&lt;$1000/kW</td>
<td>$1000/kW</td>
</tr>
</tbody>
</table>

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

→ to provide range
→ to assure takeoff
→ cost parity with incumbent technology

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

NH₃
bio-LNG
EtOH
synfuel

CNLF

Raytheon
United Technologies

FucelTech
SBIR

Technology

Anode supported
Metal supported
Ceramic

GT/scT
Tubular FC
Planar FC
SOFC/GT
Monopolar FC
PEMFC

arpa.e
CHANGING WHAT'S POSSIBLE