Promising Electric Aircraft Drive Systems

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Outline

• Background
• Critical Technologies for Electric Aircraft
• Power-system configuration options
• Comparing Electric Aircraft Power-systems
• Analytical approach
• Typical component subsystem performance
  – Energy Storage
  – Energy Conversion
• Power-system weight comparisons
• Electric power systems performance targets
• Summary
Background

• The idea to power aircraft with electric motors has been around a long time
  – Patents filed in 1943 for both battery and piston-engine hybrid electric airplanes
  – Progress limited by key technology barriers
    > A source of electricity with power and energy densities suitable for aircraft
    > Electric motors with high power/weight ratios

• What has changed
  – Environmental concerns are accelerating development of electric power-system technologies that have the potential to overcome the historical barriers
Worldwide Interest in Piloted Electric Aircraft

Pipistrel Taurus – 2007
Li-Polymer battery
65 mph 1.0 hr

Boeing Dimona – 2008
PEM fuel cell + Li-ion battery
62 mph for 20 min

Antares DLR-H2 – 2008
PEM fuel cell + battery
106 mph, 10 min flight, 465 mi range

DigiSky SkySpark – 2009
Li-Polymer battery
155 mph, 8 minute flight

Yuneec E430 – 2009
Li-ion battery
~1.5-2 hr with 60 mph cruise
Why Now

• Increasing public awareness of environmental and climate concerns

• Maturation and accelerated development of key enabling technologies

• Possible near term market opportunities with reasonable paths for growth
Critical Technologies for Electric Aircraft

Electric Motor

Battery/Energy Storage

Fuel-cell

Hydrogen Storage
Non-Cryogenic Electric Motors

- Power density of non-cryogenic motor will continuously increase with the growth in electric car market (> 6 kW/kg motors can be expected in future).

- > 20 kW/kg power density can be achieved for cryogenic motors.
Battery technologies in development have the potential for 10X increase in storage capacity over currently available Li-ion batteries.

Specific Energy (kW•h/kg)

- Ni-H₂ 50,000 cycles
- Li-ion ~100-15,000 cycles
- Li-S ~300 - ? cycles
- Advanced Li-S
- Li-ion nano-Si
- Li-Polymer

Specific Density (kW•h/m³)

- 1000
- 800
- 600
- 400
- 200
- 0.8
- 0.6
- 0.4
- 0.2
- 1.0

Fuel-cell power-systems will require some battery storage to balance power demands.
Fuel Cell Systems - Advantages / Disadvantages

- **Proton Exchange Membrane (PEM) Fuel-cell:**
  - More mature, operational in cars, high power density demonstrated
  - Need pure H\(_2\), availability and storage challenge
  - Lower operating temperature (low quality heat released) needs larger heavier heat exchanger

- **Solid Oxide Fuel-Cell (SOFC):**
  - Less mature, currently low power density systems
  - 30-45 minute startup warm-up
    - Battery startup operations could reduce impact
  - Can use hydrocarbon fuels
  - Efficiencies greater than 60 % for hybrid system
    - Fuel-cell with gas turbine bottoming cycle
  - Higher power density needed for mobile systems
    - Pathway exists to achieve higher power density but will require significant technology development
State of Fuel-cell Technology

- Significant opportunity exists to reduce weight of balance of plant through use of lightweight materials and composite materials (~50% weight reduction possible) – 1 kW/kg stack would correspond to 0.66 kW/kg at system level
- Effective system integration may yield further weight reductions
Hydrogen Storage

Extensive Research Underway on Solid State Hydrogen Storage

- Complex hydrides
- Microspheres
- Nanotubes

H₂ content of Reformed kerosene
- Volumetric Density: 320 kg/m³
- Gravimetric Density: 33%

Volumetric Density (kg/m³)

Gravimetric Density (% weight Hydrogen)

- Current available: 3-6 wt%
- Potential for > 15 wt % based on theoretical limits

DOE 2010 Goal
2 kW•h/kg

DOE 2015 Goal
3 kW•h/kg

Low Temp Hydrides

Compressed H₂ (with container)

Liquid/Cryogenic H₂ (with container)

Better
Power-system configuration options

Energy Storage (Chemical)
- Hydrocarbon
- Hydrogen
- Electrochemical

Energy Conversion (Mechanical Final Output)
- Baseline
  - IC Engine
    - Chem - Mech
- Fuel-cell (SOFC)
  - Chem - Elect
- PM/D
  - Elect - Elect
  - Electric Motor
    - Elect - Mech
- Fuel-cell (PEM)
  - Chem - Elect
- PM/D
  - Elect - Elect
  - Electric Motor
    - Elect - Mech

Reformer
- $C_nH_{2(n+1)} \rightarrow H_2$

Chem - Elect
- Electric Motor
- PM/D
- Electric Motor

Systems boundary

IC: Internal (Intermittent) Combustion
PEM: Proton Exchange Membrane
SOFC: Solid Oxide Fuel-Cell
PM/D: Power Management/Distribution
Comparing Electric Aircraft Power-systems

- Power-systems are normalized by maximum power and total available energy
- System weight is used as a figure of merit
- Two reference mission used as a basis for comparison
  - **Light Utility General Aviation (GA)**
    > 3525 lb GTOW
    > 170 Knts
    > 300 HP
    > 4.75 hr endurance
  - **Light Primary Trainer**
    > 1100 lb GTOW
    > 85 Knts
    > 67 HP
    > 1.5 hr endurance
- Electric aircraft synergistic advantages not considered
Analytical Approach

- Vehicle Power-systems are decomposed into energy storage and energy conversion subsystem components
  - **Energy storage components**
    > Fuel: Hydrocarbons, H₂, electrochemical…
    > Containers: tanks, pressure vessels, batteries…
  - **Energy conversions components**
    > Chemical to mechanical: Combustion Engines
    > Chemical to electric: Fuel-cells, Batteries
    > Electric to electric: Power Management
    > Electric to mechanical: Electric Motors

- Storage component weights scale to energy requirement
- Conversion component weights scale to power requirement
- Weight of Power-systems providing equivalent mechanical energy (Power delivered over time) is the primary figure of merit
Power-system Energy Model

• $E_R$: Energy Requirement

\[
E_R = \sum_{n=1}^{m} (P_n)(t_n)
\]

Where:
- $P_n$ is power level for interval $n$
- $t_n$ is time at interval $n$

• $E_S$: Total stored energy

\[
E_S = \frac{E_R}{\eta_1(\eta_2)(\eta_3)(\eta_4)}
\]

Where:
- $\eta_n$ is efficiency of energy conversion component $n$

Reference Missions:

<table>
<thead>
<tr>
<th>Light Utility GA</th>
<th>$E_R = 800$ kW*hr</th>
<th>$P_{\text{max}} = 225$ kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Trainer</td>
<td>$E_R = 60$ kW*hr</td>
<td>$P_{\text{max}} = 50$ kW</td>
</tr>
</tbody>
</table>
Power-system Weight Model

- $W_S$: Total system weight
  \[ W_S = W_{ES} + W_{EC} \]

- $W_{ES}$: Sum of energy storage component weights
  \[ W_{ES} = \sum_n (E_S)(\gamma_n) \]

- $W_{EC}$: Sum of energy conversion component weights
  \[ W_{EC} = \sum_n^m (P_{max})(\theta_n) \]

Where:
- $P_{max}$ is Maximum power
- $\gamma_n$ is the weight scaling factor for energy storage component $n$
- $\theta_n$ is weight scaling factor for energy conversion component $n$
Energy Storage
Typical and Projected Performance Parameters

Energy Storage weight factors: $\gamma$ (energy density)

- **Fuels**
  - Hydrogen ($H_2$)
  - Kerosene ($C_{12}H_{26}$)

- **Batteries ($\eta = .98$)**
  - Li-S (2010)
  - Li-ion/Li-S (2015)

- **Tanks**
  - Liquid HC
  - $H_2$ (gas) (2010)
  - $H_2$ (gas) (2015)

<table>
<thead>
<tr>
<th>Fuel/Tank wt ratio</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Li-S</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Li-ion/Li-S</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Liquid HC</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>$H_2$ (gas)</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$H_2$ (gas)</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>
Energy Conversion weight factors; \( \theta \) (power density)

- **Fuel-cells (\( \eta = 50\% \))**
  - **Proton Exchange Membrane (PEM)**
    - 2010: Automotive systems: 0.9 kW/kg
    - 2015: 1.5 kW/kg
  - **Solid Oxide Fuel-Cell (SOFC)**
    - 2010: 0.25 kW/kg
    - 2015: 0.50 kW/kg

- **Power management/distribution (\( \eta = 97\% \))**
  - 2010: Automotive systems: 5.0 kW/kg
  - 2015: 8.0 kW/kg
### Mechanical Energy Conversion

#### Typical Performance Parameters

**Energy Conversion weight factors; \( \theta \) (power density)**

<table>
<thead>
<tr>
<th>Energy Conversion Type</th>
<th>Efficiency ( \eta )</th>
<th>Weight Factor ( \theta )</th>
<th>Power</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Combustion Engine</strong> ( \eta = 30% )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Continental IO-550 (300 HP)</td>
<td></td>
<td></td>
<td>1.0 kW/kg</td>
<td>0.984 kW/kg</td>
</tr>
<tr>
<td>&gt; Power = 224 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Weight = 227 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Rotax 912S (100HP)</td>
<td></td>
<td></td>
<td>1.10 kW/kg</td>
<td></td>
</tr>
<tr>
<td>&gt; Power = 74.6 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Weight = 68 kg</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Electric Motors</strong> ( \eta = 95% )</td>
<td></td>
<td></td>
<td>3.4 kW/kg</td>
<td>3.49 kW/kg</td>
</tr>
<tr>
<td>- Tesla Automobile (244 HP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Power = 182 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Weight = 52.2 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Honda FCX (134 HP)</td>
<td></td>
<td></td>
<td>2.96 kW/kg</td>
<td></td>
</tr>
<tr>
<td>&gt; Power = 100 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Weight = 33.8 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gas Turbine</strong> ( \eta = 34% )</td>
<td></td>
<td></td>
<td>5.1 kW/kg</td>
<td></td>
</tr>
<tr>
<td>- P&amp;W PT6A (1500 HP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Power = 1125 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; Weight = 220 kg</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Light Utility Aircraft
Power-systems weight comparison

1600 kg ~ 3525 lb GTOW
315 km/hr ~ 170 knots
225 kW ~ 300 HP
4.75 hr

GTOW
3564 kg

Electrical Power Systems Weight (kg)

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel


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Light Primary Trainer
Power-systems weight comparison

500 kg ~ 1100 lb GTOW
160 km/hr ~ 85 knts
50 kW ~ 67 HP
1.5 hr

![Bar chart showing electrical power systems weight comparison for different power sources: Piston Engine, Gas Turbine, PEM 2010, PEM 2015, SOFC 2010, SOFC 2015, Battery 2010, Battery 2015. The chart compares motor, power management, fuel cell, battery, tank, and fuel weights.]
## Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Piston Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; $\eta$</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td>Power density; $\theta$</td>
<td>0.9 kW/kg</td>
<td>2.5 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td>Fuel/Tank weight ratio; $\rho$</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>SOFC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; $\eta$</td>
<td>50%</td>
<td>65%</td>
</tr>
<tr>
<td>Power density; $\theta$</td>
<td>0.25 kW/kg</td>
<td>0.90 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td><strong>Pure Battery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>2.35 kW*hr/kg</td>
</tr>
</tbody>
</table>
Summary

- Available electric motor and power-management systems are adequate, however significant technology challenges remain in the development of batteries, fuel-cells, and light weight H₂ tanks.

- Battery powered aircraft will require a 10X energy density increase to match Light Utility GA piston performance, but looks like a viable option for Light Primary Trainer aircraft in the near future.

- Several potentially viable approaches exist for electric propulsion-systems and targets for component performance have been identified, but significant development work remains before the best solution is known.

- The rate Electric Aircraft Propulsion technologies are advancing is encouraging and holds the promise of new more capable aircraft in the near future.