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
- Fuel-cell
- Battery/Energy Storage
- 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.

![Graph showing specific energy and density of different battery types with labels](image)

- **Ni-H\(_2\)**: 50,000 cycles
- **Li-ion**: ~100-15,000 cycles
- **Li-S**: ~300 - ? cycles

**Battery Energy Storage**

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 H₂, 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

**Technology Readiness Level (TRL)**

<table>
<thead>
<tr>
<th>Stack Power Density (kW/kg)</th>
<th>2.0</th>
<th>1.6</th>
<th>1.2</th>
<th>0.8</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 kW/kg at system level</td>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25 kW/kg at system level</td>
<td></td>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial PEM Fuel Cell</td>
<td></td>
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</table>

**Developmental SOFC**

Balance of Plant Contributes Significant Weight (~50%)
Hydrogen Storage

Extensive Research Underway on Solid State Hydrogen Storage

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

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

Gravimetric Density (% weight Hydrogen)

Volumetric Density (kg/m³)

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

Complex hydrides

Microspheres

Nanotubes

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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
- Reformer
  - \( C_nH_{2(n+1)} - H_2 \)
- Fuel-cell (PEM)
  - Chem - Elect
- PM/D
  - Elect - Elect
- Electric Motor
  - Elect - Mech
- Electric Motor
  - Elect - Mech

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, \( H_2 \), 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
  \[
  E_R = \sum_{n}^{m} (P_n)(t_n)
  \]
  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>Mission</th>
<th>( E_R )</th>
<th>( P_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Utility GA</td>
<td>800 kW*hr</td>
<td>225 kW</td>
</tr>
<tr>
<td>Light Trainer</td>
<td>60 kW*hr</td>
<td>50 kW</td>
</tr>
</tbody>
</table>
Power-system Weight Model

- $W_S$: Total system weight
- $W_{ES}$: Sum of energy storage component weights
- $W_{EC}$: Sum of energy conversion component weights

\[ W_S = W_{ES} + W_{EC} \]

\[ W_{ES} = \sum_n (E_S)(\gamma_n) \]

\[ W_{EC} = \sum_n^{m} (P_{\text{max}})(\theta_n) \]

Where:
- $P_{\text{max}}$ 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 ($\text{H}_2$) $33.5$ kW*hr/kg
  - Kerosene ($\text{C}_{12}\text{H}_{26}$) $14.3$ kW*hr/kg

- **Batteries ($\eta = .98$)**
  - Li-S (2010) $0.25$ kW*hr/kg
  - Li-ion/Li-S (2015) $0.65$ kW*hr/kg

- **Tanks**
  - Liquid HC $10.0$
  - $\text{H}_2(\text{gas})$ (2010) $0.06$
  - $\text{H}_2(\text{gas})$ (2015) $0.10$
Chemical and Electrical Energy Conversion
Typical and Projected Performance Parameters

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

- **Fuel-cells ($\eta = 50\%$)**
  - Proton Exchange Membrane (PEM)
    - 2010: Automotive systems
    - 2015
    - **Proton Exchange Membrane (PEM)**
    - 2010: Automotive systems
    - 2015
  - Solid Oxide Fuel-Cell (SOFC)
    - 2010
    - 2015
    - **Solid Oxide Fuel-Cell (SOFC)**
    - 2010
    - 2015

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

### Typical Performance Parameters

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

Power-systems weight comparison

- GTOW: 3564 kg
- 1600 kg ~ 3525 lb
- 315 km/hr ~ 170 knts
- 225 kW ~ 300 HP
- 4.75 hr

Bar chart showing electrical power systems weight for different engines and fuel cells.
Light Primary Trainer
Power-systems weight comparison

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

Electrical Power Systems Weight (kg)

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel

## Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

### PEM
- Efficiency; $\eta$  
  - Current: 50%  
  - Piston Equivalent: 60%  
- Power density; $\theta$  
  - Current: 0.9 kW/kg  
  - Piston Equivalent: 2.5 kW/kg  
- Battery energy density; $\gamma$  
  - Current: 0.25 kW*hr/kg  
  - Piston Equivalent: 0.75 kW*hr/kg  
- Fuel/Tank weight ratio; $\rho$  
  - Current: 0.06  
  - Piston Equivalent: 0.20

### SOFC
- Efficiency; $\eta$  
  - Current: 50%  
  - Piston Equivalent: 65%  
- Power density; $\theta$  
  - Current: 0.25 kW/kg  
  - Piston Equivalent: 0.90 kW/kg  
- Battery energy density; $\gamma$  
  - Current: 0.25 kW*hr/kg  
  - Piston Equivalent: 0.75 kW*hr/kg

### Pure Battery
- Battery energy density; $\gamma$  
  - Current: 0.25 kW*hr/kg  
  - Piston Equivalent: 2.35 kW*hr/kg
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.