Hybridizing Light Aircraft

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The reason cars are hybridized is to increase their fuel efficiency (and thereby reduce CO2 emissions).

Gasoline engines are VERY inefficient at low throttle settings; Diesels, somewhat less so.

What hybridization effectively does is bring average ICE efficiency up toward peak.

Why Hybridize Light Aircraft?

Improved fuel efficiency?

- The reason cars are hybridized is to increase their fuel efficiency (and thereby reduce CO2 emissions).
- Gasoline engines are VERY inefficient at low throttle settings; Diesels, somewhat less so.
- What hybridization effectively does is bring average ICE efficiency up toward peak.
### Hybridizing Light Aircraft

<table>
<thead>
<tr>
<th>Effective ICE Efficiencies</th>
<th>Average auto</th>
<th>Hybrid auto (Prius)</th>
<th>Gasoline aircraft (Rotax 912S)</th>
<th>Diesel aircraft (DeltaHawk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>30%</td>
<td>38% (Toyota’s number)</td>
<td>29% @ 0.43 lb/hp-hr</td>
<td>36% est.</td>
</tr>
<tr>
<td>Average (aircraft climb, cruise)</td>
<td>14% @ 25 mpg</td>
<td>25% @ 45 mpg</td>
<td>27% @ 0.45 lb/hp-hr</td>
<td>34% @ 0.35 lb/hp-hr</td>
</tr>
<tr>
<td>Ratio of average/peak</td>
<td>0.47:1</td>
<td>0.66:1</td>
<td>0.93:1</td>
<td>0.94:1</td>
</tr>
<tr>
<td>ICE improvement available</td>
<td>27%</td>
<td>0%</td>
<td>31%</td>
<td>25%</td>
</tr>
<tr>
<td>Hybridization improvement available</td>
<td>40%</td>
<td>0%</td>
<td>NONE</td>
<td>NONE</td>
</tr>
</tbody>
</table>

- Unlike cars, aircraft ICEs run at near peak efficiency most of the time.
- Therefore, hybridization can do little to improve piston aircraft fuel efficiency.
  - Note: turbines could be different, as they are incredibly inefficient at both low power settings and low aircraft speeds.

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Other advantages to hybridizing a light aircraft

• Quiet electric operation around neighborhood airports
  – Via pure electric propulsion up to 3000’ AGL
  – After engine noise is eliminated, propeller noise is dominant. It too, can be greatly reduced.
    • Quiet propellers operate at much slower speeds than engines or electric motors
    • A PSRU, ideally a CVT, is needed to match optimum speeds

• Reliability of electric or dual power during the most dangerous time: takeoff

• Backup power always available in case of engine failure
  – Even when “fully” discharged, a last 20% of battery energy always available for emergency power at the cost of slightly shortened battery life

• Full takeoff power available at any altitude

• More benefits yet from strong (vs. mild) hybrids (discussed below)

• A pure electric airplane would need electric reserve, reducing already-very-limited endurance by 30 or 45 minutes
  – 1 hr no-reserve endurance may be maximum state-of-the-art with Li-ion
Hybridizing Light Aircraft

Basic calculations, conversions, and values used throughout

- 1 m = 3.28 ft
- 1 kWh = 1 joule (W-sec) * 3600 sec = 3600 joules = 3.6 Joules
- 1 hp = 550 ft-lb/sec = 746 W

\[
\begin{align*}
1 \text{ hp-hr} &= 0.746 \text{ kWh} = 550 \text{ ft-lb/sec} \times 3600 \text{ sec} = 1,980,000 \text{ ft-lb} \\
1 \text{ kWh} &= 1,980,000 \text{ ft-lb} / 0.746 = 2,654,000 \text{ ft-lb}
\end{align*}
\]

Therefore, from basic physics, the energy required to lift an airplane is:

- 1,000,000 ft-lb (1000 lb elevated by 1000’ or 455 kg by 305m) = 1/2.654 kWh = 0.377 kWh

If done via a 90% efficient electric motor/controller driving a 75% efficient propeller:

- **1000 lb elevated by 1000’ requires** 0.377/(.9 * .75) = 0.56 kWh of electricity

- Gasoline averages 131 MJ/gallon = 36.4 kWh/gal and 6.0 lb/gal
- Diesel averages 145 MJ/gallon = 40.4 kWh/gal and 6.6 lb/gal

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### Estimated LSA energy requirements

(more depth & accuracy by other speakers, but needed here to evaluate hybrid configurations)

<table>
<thead>
<tr>
<th><strong>LSA (e.g. AGA Lafayette 3)</strong></th>
<th><strong>Scaled to 1320 lb/600 kg gross (max. LSA)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty wt w/912</td>
<td>N/A</td>
</tr>
<tr>
<td>Empty wt w/o ICE</td>
<td>435 lb / 198 kg</td>
</tr>
<tr>
<td>Req’d payload</td>
<td>500 lb / 227 kg</td>
</tr>
<tr>
<td><strong>Avail. for propulsion</strong></td>
<td></td>
</tr>
<tr>
<td>Rotax 912 (60 kW / 80 hp)</td>
<td></td>
</tr>
<tr>
<td>Vs</td>
<td>121 lb / 55 kg</td>
</tr>
<tr>
<td>Vapproach</td>
<td>56 mph</td>
</tr>
<tr>
<td>Max. L/D ratio, incl. unfeathered prop. drag*</td>
<td>80-85 mph</td>
</tr>
<tr>
<td><strong>Est. Vglide = speed at max L/D</strong></td>
<td>85 mph / 136 kph = 7480 ft/min</td>
</tr>
<tr>
<td>Vglide sink rate</td>
<td>453 ft/min</td>
</tr>
<tr>
<td><strong>Energy loss at Vglide</strong></td>
<td></td>
</tr>
<tr>
<td>Note: unfeathered propeller drag is estimated to approximately match propeller inefficiency during cruise. Therefore propeller inefficiency will be ignored for cruise energy calculations.</td>
<td>Vglide energy loss</td>
</tr>
<tr>
<td>Shaft energy/distance</td>
<td>159 Wh/mi = 99 Wh/km</td>
</tr>
<tr>
<td>Fuel@Vglide (at sea level)</td>
<td>8.16 lb/hr = 1.36 gph</td>
</tr>
<tr>
<td>Gasoline mileage</td>
<td>63 mpg</td>
</tr>
<tr>
<td>Electric cruise w/90% eff. motor/controller</td>
<td>15.0 kW @ 85 mph / 136 kph</td>
</tr>
<tr>
<td>Electric energy per distance</td>
<td>176 Wh/mi = 110 Wh/km</td>
</tr>
<tr>
<td>30 min (42 mi) VFR reserve</td>
<td>7.5 kWh (to 100% DOD)</td>
</tr>
<tr>
<td><strong>1000’ (305m) electric climb, incl. cruise energy</strong></td>
<td>0.74 + 0.26 kWh = 1.0 kWh</td>
</tr>
<tr>
<td>Electric climb, 1000’/min, incl. cruise energy</td>
<td>44.4 + 15 kW = 60 kW = 80 hp</td>
</tr>
<tr>
<td>Electric go-around (est. 10 mi)</td>
<td>1.6 + 0.9 = 2.5 kWh</td>
</tr>
</tbody>
</table>
## Hybridizing Light Aircraft

### Possible hybrid LSA components

(more depth & accuracy by other speakers, but needed here to evaluate hybrid configurations)

<table>
<thead>
<tr>
<th>Component</th>
<th>Specific power</th>
<th>Specific energy</th>
<th>Efficiency</th>
<th>Estimated Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline engine</strong> (e.g. Rotax 912S)</td>
<td>1.15 kW/kg</td>
<td>N/A</td>
<td>27% (0.45 lb/hp-hr)</td>
<td>$500/kW</td>
</tr>
<tr>
<td><strong>Gasoline</strong></td>
<td>N/A</td>
<td>13.3 kWh/kg (3.60 Wh/kg after 27% ICE efficiency)</td>
<td>Price @ 27% =&gt; $0.51/kWh @ $5.00/gal</td>
<td></td>
</tr>
<tr>
<td><strong>Diesel engine</strong> (e.g. DeltaHawk DH200V4)</td>
<td>0.84 kW/kg</td>
<td>N/A</td>
<td>34% (0.35 lb/hp-hr; 26% better than gasoline)</td>
<td>$500/kW</td>
</tr>
<tr>
<td><strong>Diesel (&amp; bio-)</strong></td>
<td>N/A</td>
<td>13.5 Wh/kg (4.6 Wh/kg after 34% ICE efficiency)</td>
<td>Price @ 34% =&gt; $0.36/kWh @ $5.00/gal</td>
<td></td>
</tr>
<tr>
<td><strong>Electric motor/ generator</strong> (AC brushless)</td>
<td>3 kW/kg est.</td>
<td>N/A</td>
<td>95%</td>
<td>$100/kW</td>
</tr>
<tr>
<td><strong>Electronics</strong></td>
<td>6 kW/kg est.</td>
<td>N/A</td>
<td>95%</td>
<td>$100/kW</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>@ 70% from grid</td>
<td>$0.17/kWh @ $0.12/kW</td>
</tr>
<tr>
<td><strong>Li-ion power battery</strong></td>
<td>2.5 kW/kg (~30C or 2 min rate)</td>
<td>97 Wh/kg; 78 Wh/kg to 80% DOD</td>
<td>80-90%</td>
<td>$1500/kWh; $60+/kW</td>
</tr>
<tr>
<td><strong>Li-ion energy battery</strong></td>
<td>1.0 kW/kg (est. 5C or 12 min rate)</td>
<td>168 Wh/kg; 135 Wh/kg to 80% DOD</td>
<td>90-95%</td>
<td>1200/kWh; $240/kW</td>
</tr>
<tr>
<td><strong>Supercapacitor</strong> (Maxwell BMOD0165)</td>
<td>7.9 kW/kg (~2000C or 2 sec rate!)</td>
<td>3.8 Wh/kg</td>
<td>95-99%</td>
<td>$148/kg =&gt; $39,000/kWh; $18.7/kW</td>
</tr>
<tr>
<td><strong>Pie-in-the-sky ultracapacitor</strong></td>
<td>2.8 kW/kg (10C or 6 min rate)</td>
<td>278 Wh/kg; 250 Wh/kg to 33% voltage</td>
<td>95-99%</td>
<td>$61/kWh; $6/kW</td>
</tr>
</tbody>
</table>

* 336 lb (152 kg), 2005 cu.in. (33 L), 52 kWh (187 MJ), 31 Farad, 3500V
Hybridizing Light Aircraft

Mild hybridization: 3 kWh usable electric storage (0.3 gal/ 0.8 kg of gas equiv)

- **Propulsion system**
  - Electric system & ICE each rated for full climb power: 60 kW
  - 55 kg, $30k, 60 kW/ 80 hp ICE (e.g. Rotax 912)
  - ~68 kg, $16.5k hybrid components
    - ~38 kg, $4.5k, battery pack using A123 cells
    - ~30 kg, $12k, motor/controller
  - ~123 kg, 52 kg below max; room for gasoline & instruments
  - **Hybridization added ~68 kg (11% of LSA weight), $16.5k**

- **Capabilities/Regimes:** EV take-off and climb to 3000’ AGL, then
  - ICE takes over
  - Battery should automatically recharge from ICE immediately upon cruise or cruise-climb
    - Full charge provides energy for one EV go-around
    - Full charge can occur in 4 min during cruise
  - Touch-and-goes require ICE operation in pattern
    - Recharge from ICE can provide for EV climb
  - Emergency power: normally-unused last 20% of battery
    - 0.6 kWh, enough for 600’ climb or 3.5 mi cruise
Hybridizing Light Aircraft

Strong hybridization: 10.3 kWh usable electric storage (1.0 gal/ 2.9 kg of gas equiv)

• Propulsion system
  – Electric system rated for full climb power: 60 kW/ 80 hp
    • ~106 kg, $24.3k hybrid components
      – 76 kg, $12.3k actual Electrovaya battery (8 modules)
      – ~30 kg, $12k motor/controller
    – ICE rated to supply cruise power plus charging
      – 13.5 + 6.5 kW charging = 20 kW
        » 13.5 kW @ 10,000’ (no charging)
      – ~17 kg, $10k (-35 kg, -$20k vs. 3 kWh hybrid)
      – Can provide enough charge for go-arounds
        » 1 pure electric go-around after each 30 min
        » Continuous ICE-assisted go-arounds
    – ~126 kg, 49 kg below max; room for gas & instruments
  • Hybridization added ~71 kg (12% of LSA weight), $4.3k
Strong hybridization: 10.3 kWh usable electric storage (continued)

- **Capabilities/Regimes:** EV take-off and climb to 3000’ AGL, then
  - If ICE unused and battery grid-charged (**PHEV airplane!**)
    - EV climb to 10,000’ AGL (10 min/ 8.5 mi) —or—
    - 50+ mi (35 min) EV range
      - no wind, to same altitude airport
      - 1 gal unused gas provides 45-min reserve
      - Short trips can be purely electric!
      - $1.75 vs. $4.00 for fuel
  
  - If ICE used
    - 3 pure EV go-arounds available w/o recharge (4 with recharge)
    - ICE can charge battery as desired during cruise
      - Fast enough for continuous go-arounds
      - 30 min to full after initial electric 3000’
      - 100 minutes to full from empty
    - 10 gal gas provides 600+ mi range beyond EV
  
    - ICE operation in pattern required for >3 touch-and-goes
    - Emergency power: normally-unused last 20% of battery
      - 2 kWh, enough for 2000’ climb, 11 mi cruise, or abbreviated go-around
## Hybrid Architectures

<table>
<thead>
<tr>
<th>Description</th>
<th>Power-split or Series/Parallel (like Toyota HSD)</th>
<th>Series (like Chevy Volt)</th>
<th>Parallel (like Honda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>A planetary gear system connects the ICE, motor/gen, and a 2\textsuperscript{nd} motor/gen used to regulate EV/ICE speeds &amp; power split.</td>
<td>An electric motor drives the prop. The ICE only charges the battery via a separate generator.</td>
<td>The ICE and motor are both attached to the prop. A clutch may be provided to allow the ICE to stop.</td>
</tr>
<tr>
<td>ICE power xfer efficiency</td>
<td>80%</td>
<td>85%</td>
<td>100%</td>
</tr>
<tr>
<td>Extra weight (other than battery)</td>
<td>2 motor/generators + planetary gear</td>
<td>1 motor + 1 generator</td>
<td>1 motor/generator</td>
</tr>
<tr>
<td>Issues</td>
<td>ICE efficiency too low</td>
<td>ICE efficiency too low</td>
<td><strong>Best for airplanes.</strong> (see next slide)</td>
</tr>
</tbody>
</table>
## Hybridizing Light Aircraft

### Parallel Hybrid Architectures

<table>
<thead>
<tr>
<th>Parallel Hybrid Architectures</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No clutch</strong></td>
<td>Fewer components and stress, ICE reliability from always spinning</td>
<td>Inefficiency &amp; wear of ICE spinning on electric power. Power failure if ICE seizes.</td>
<td>Inefficiency of e.g. 10% if valves are opened may be worth it for mild hybrid.</td>
</tr>
<tr>
<td><strong>Clutch</strong> (optimum for strong hybrids)</td>
<td>Efficiency &amp; reliability from ICE not spinning during electric-only power. Power available even if ICE seizes.</td>
<td>Possible unreliability &amp; added strains from inflight engine starts</td>
<td>Added stress &amp; failure modes worthwhile only for strong hybrid</td>
</tr>
<tr>
<td><strong>No PSRU</strong></td>
<td>Simple, reliable</td>
<td>Engine &amp; motor speed too fast for quiet prop (e.g. 2700 vs. 1000 rpm) &amp; must be too slow for weight minimization</td>
<td>Possible only if using heavier low-speed electric ‘hub’ motor, and if prop speed is higher during ICE operation.</td>
</tr>
<tr>
<td><strong>Fixed PSRU</strong> (desirable if reliable)</td>
<td>Allows static speed optimization for ICE or for motor; ICE &amp; motor can be smaller and lighter</td>
<td>PSRU reliability is often lower than that of ICE, let alone electric motor</td>
<td>Basically necessary to reduce ICE &amp; motor weight for 1000 rpm prop</td>
</tr>
<tr>
<td><strong>CVT PSRU</strong> (optimum if reliable)</td>
<td>Allows dynamic ICE and motor speed optimization otherwise unavailable for LSA aircraft that can’t have variable-pitch props.</td>
<td>Dr. Andy Frank has best known implementation, but untested reliability in aircraft</td>
<td>Could allow use of a high-speed ICE &amp; even higher speed electric motor (especially when combined with a clutch) for minimum weight and loses.</td>
</tr>
</tbody>
</table>
Conclusions

• Aircraft hybridization is valuable for very different reasons than for autos
  – Quiet and reliability, not increased ICE efficiency
  – Modern technology, though, could improve ICE efficiency by ~25%
• Hybridization, mild or strong, adds around 11% to the weight of an LSA
• For aircraft, parallel hybridization is optimum
  – A PSRU and clutch are highly desirable
  – If proven reliable, a CVT PSRU can provide significant advantages
• Strong hybridization (vs. mild, capable only of EV climb to 3000’)
  – Due to ICE downsizing and lower battery power requirements
    • Adds about the same weight, ~11%, to an LSA
    • Adds 1/4 the cost: $4.3k vs. $16.5k
  – Adds significant safety and mission capabilities
  – If grid-charged, becomes a PHEV, allowing 50 mi pure EV trips!
    • An automatic advantage of strong hybridization!
    • Quiet, 1/3 fuel cost, much lower CO2 and criteria emissions!
      – No smog controls yet on aviation engines
    • Vs. a pure electric airplane
      – The ICE + 1 gal of gas provides the required 30-min reserve, doubling the effective EV range
        vs. replacing the ICE with an equivalent weight of batteries
      – Longer distance trips can be flown using gasoline

• PHEVs rule, for airplanes as well as for automobiles!