Hybridizing Light Aircraft

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Why Hybridize Light Aircraft?

Improved fuel efficiency?

- The reason cars are hybridized is to increase their fuel efficiency (and thereby reduce CO_2 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

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

- 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

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

Basic calculations, conversions, and values used throughout

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

- **1 hp-hr** = 0.746 kWh = 550 ft-lb/sec * 3600 sec **= 1,980,000 ft-lb**
- **1 kWh** = 1,980,000 ft-lb / 0.746 **= 2,654,000 ft-lb**

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

Estimated LSA energy requirements

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

LSA (e.g. AGA Lafayette 3)	**Scaled to 1320 lb/600 kg gross (max. LSA)**
Empty wt w/912	N/A
Empty wt w/o ICE	435 lb/ 198 kg
Req'd payload	**500 lb**/ 227 kg
Avail. for propulsion	**385 lb/ 175 kg**
Rotax 912 (60 kW / 80 hp)	121 lb/ 55 kg
Vs	56 mph
Vapproach	80-85 mph
Max. L/D ratio, incl. unfeathered prop. drag*	16.5:1
Est. Vglide = speed at max L/D	**85 mph**/ 136 kph = 7480 ft/min
Vglide sink rate	453 ft/min
Energy loss at Vglide Note: unfeathered propeller drag is estimated to approximately match propeller inefficiency during cruise. Therefore propeller inefficiency will be ignored for cruise energy calculations.	Vglide energy loss = cruise power (shaft)598,000 ft-lb/min = 0.225 kWh/min **= 13.5 kW** (kWh/hr) **= 18.1 hp**
Shaft energy/distance	159 Wh/mi = 99 Wh/km
Fuel@Vglide (at sea level)	8.16 lb/hr = 1.36 gph
Gasoline mileage	63 mpg
Electric cruise w/90% eff. motor/controller	15.0 kW @ 85 mph/ 136 kph
Electric energy per distance	**176 Wh/mi** = 110 Wh/km
30 min (42 mi) VFR reserve	7.5 kWh (to 100% DOD)
1000' (305m) electric climb, incl. cruise energy	0.74 + 0.26 kWh = **1.0 kWh**
Electric climb, 1000'/min, incl. cruise energy	44.4 + 15 kW = **60 kW = 80 hp**
Electric go-around (est. 10 mi)	1.6 + 0.9 = **2.5 kWh**

Possible hybrid LSA components

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

	Specific power	Specific energy	Efficiency	Estimated Cost
Gasoline engine (e.g. Rotax 912S)	1.15 kW/kg	N/A	27% (0.45 lb/hp-hr)	$500/kW
Gasoline	N/A	13.3 kWh/kg (3.60 Wh/kg after 27% ICE efficiency)	Price @ 27% =>	$0.51/kWh @ $5.00/gal
Diesel engine (e.g. DeltaHawk DH200V4)	0.84 kW/kg	N/A	34% (0.35 lb/hp-hr; 26% better than gasoline)	$500/kW
Diesel (& bio-)	N/A	13.5 Wh/kg (4.6 Wh/kg after 34% ICE efficiency)	Price @ 34% =>	$0.36/kWh @ $5.00/gal
Electric motor/ generator (AC brushless)	3 kW/kg est.	N/A	95%	$100/kW
Electronics	6 kW/kg est.	N/A	95%	$100/kW
Electricity	N/A	N/A	@ 70% from grid	$0.17/kWh @ $0.12/kWh
Li-ion power battery (A123 ANR26650 cell + est. 20% added module weight)	2.5 kW/kg (~30C or 2 min rate)	97 Wh/kg; 78 Wh/kg to 80% DOD	80-90%	$1500/kWh; $60+/kW
Li-ion energy battery (Electrovaya MN module)	1.0 kW/kg (est. 5C or 12 min rate)	168 Wh/kg; 135 Wh/kg to 80% DOD	90-95%	1200/kWh; $240/kW
Supercapacitor (Maxwell BMOD0165)	7.9 kW/kg (~2000C or 2 sec rate!)	3.8 Wh/kg	95-99%	$148/kg => $39,000/kWh; $18.7/kW
Pie-in-the-sky ultracapacitor* (eeStor's claims)	2.8 kW/kg (10C or 6 min rate)	278 Wh/kg; 250 Wh/kg to 33% voltage	95-99%	$61/kWh; $6/kW

* 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**

Hybridizing Light Aircraft

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

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

Parallel Hybrid Architectures

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

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 CO_2 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!**