Are Practical Electric and Hybrid Airplanes Just Around the Corner?

(post-presentation slides;
more detail in accompanying outline)

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There are good reasons for electric airplanes ASAP

- **Cost**
  - At the shaft, electricity is less than 1/5 the cost avgas
  - Though batteries are hugely expensive, so are the aircraft engines they can replace
- **Noise – an increasing problem at GA airports**
- **Aircraft engines pollute**
  - Aircraft piston engines have not been cleaned up at all. In contrast, new auto engines are around 200x cleaner than before, making each piston aircraft a 'gross polluter' in comparison
  - 100LL is now actually on its way out, due to airborne lead near GA airports
  - Particulates, hydrocarbons, oxides of nitrogen, etc, must eventually be regulated
  - Studies show that electric power is cleaner than the best of today's auto engines
- **Electric airplanes will immediately be lower carbon**
  - Because 2-3 times as efficient as ICE
  - Average U.S. electricity now higher CO_2 per kWh than gasoline, but not for long
    - CA already twice as low
    - Many states have renewable portfolio standards – soon the U.S?
  - Plenty of electric capacity available
  - Hangars could be covered with solar panels
  - Low carbon biofuels will have limited availability for the foreseeable future
- **Reliability – potentially much higher, though not yet proven**
  - Potential to be safer than twins, which don't actually have a better engine-out safety record than singles (due to loss of control from sudden off-axis thrust)

What minimum performance is needed for a practical electric airplane?

- **My guesses as a GA pilot & former C-172 owner**
  - For some, not all pilots
  - Not what's competitive without fuel & environment considerations
  - Endurance bladder-limited to 3 hours anyway
  - Cruise speed and endurance rated at sea level (SL)
    - Endurance rated at the same cruise speed
  - Refueling will depend upon
    - As-yet-nonexistent charge stations, or
    - A high-power electrical outlet available via pre-arrangement

Recreational Flying

- **Local flying – near C-150 or LSA performance**
  - 1-2-place, 200 lb/person (200-400 lb) payload (no baggage)
  - 100 mph/87 kt cruise, 8k ft ceiling
  - 1.5 hours endurance at cruise + VFR reserve
  - Overnight refueling, except <1 hr for rentals
- **Day trips – near C-172 or LSA performance**
  - 2-4-place, 225 lb/person (450-900 lb) payload
  - 100+ kt cruise, 10k+ ceiling (12k+ in the West)
  - 2-3 hours endurance (230-345 mi) + VFR or IFR reserve
  - 4 hours maximum to refuel
- **Long distance cross-country flying – C-172++**
  - 2-4-place, 250 lb/person payload (500-1000 lb)
  - 100-200 kt cruise, 12k+ ceiling
  - 2.5-3 hours endurance (288-690 mi) + VFR or IFR reserve
  - 1 hour max to refuel (time for a meal)

- **Business Travel**
  - **Single-person travel, a stop after each leg**
    - **Like recreational day trips, except**
      - 1-place, 250-500 lb payload (may include equipment)
      - 1-2 hours maximum refuel time due to multiple legs
      - More speed is highly desirable, as time is money
  - **Carrying clients or associates, a stop after each leg**
    - **Like single-person business, except**
    - 3-4-place, 250 lb/person (750-1000 lb) payload
  - **Long distance cross-country flying**
    - **Like recreational, except IFR reserve and 150+ kt cruise**
- **Commuting**
  - 1-2-place, 225 lb/person payload (225-450 lb), 100-150 kt cruise
  - 2-2.5 hours (more is too long a commute) at cruise (230-375 mi) + IFR reserve
  - 6-8 hours to refuel during work

What can hybridizing an airplane accomplish?

- **Suggested/modeled hybrid**
  - Parallel, powered by the electric motor and/or the engine
  - Motor always turns, direct or via a PSRU
  - Engine, attached via a centrifugal clutch, can start & stop
  - Enough electric energy to climb to e.g. 10k ft
    - Ground (PHEV) charging enables some fuel displacement
  - A reversing propeller can capture energy during descents
- **Quiet airport operations**
  - Except when full power needed for short field or high altitude takeoffs
- **Smaller, lighter, efficient Diesel engine**
  - Sized only for cruise power (especially DeltaHawk)
  - Higher efficiency also means less weight for fuel
- **Some electric energy is always held in reserve for an emergency**
  - **For long life, normal discharge is by only 80%**
  - Fewer engine-failure-induced fatal crashes
  - Electric power is more reliable, and dual-power is more reliable yet

My modeling (live spreadsheet to follow)

- **For both electric and hybrid, I started with the fastest 4-place piston kit airframes**
  - **Kit airplanes get registered as amateur-built experimental**
    - Modifiable and can be flown most anywhere
  - **Must be efficient to be fast**
  - **Maximum L/D occurs at usefully fast speeds**
  - **2 places and associated payload can be sacrificed for sufficient range with today's batteries**
  - **As batteries improve, will the airframe remain near optimum for increasing either…**
    - Cruise speed and range, or
    - Payload?

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	A	B	C	D	I	K	L	M	N	O	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	**Worksheet for possible electric aircraft to enter the NASA/CAFÉ high-efficiency 2-place airplane contest**																				
2	By Ronald Gremban; latest version, 4/24/2009																				
3	Copyright 2008, 2009 by ForSites Corp. All rights reserved.																				
4																					
5	**Template**		**Velocity XL-RG**	**Velocity XL-RG Diesel Hybrid** (needs higher power batteries)	**Lancair IV**	**Lancair IV Electric**, opt. for slower flight with a longer folding wing	**Lancair IV Electric**, opt. for slower flight with a longer folding wing	**Lancair IV Electric**, opt. for slower flight with a longer folding wing	**Lancair IV Electric**, opt. for slower flight with a longer folding wing	**Lancair IV Electric**, opt. for slower flight with a longer folding wing	**Vans RV-10**	**Vans RV-10 Diesel Hybrid** (needs higher power batteries)	**Vans RV-10 Electric**, optimized for slower flight with a longer wing	**Pipistrel Sinus**	**Pipistrel Sinus**	**Pipistrel Sinus**	**Pipistrel Sinus**	**Pipistrel Sinus**	**Pipistrel Sinus**	**Pipistrel Sinus**	**Cessna C-172M**
6	**Aircraft characteristics**		OEM non-turbo piston version	OEM non-turbo piston version	OEM turbo piston version	Sinus at low weight, 100 mph cruise	At 100 mph cruise, shorter wings & **Diesel**	**Electric** Sinus at 100 mph cruise, shorter wings	**Electric** Sinus at 100 mph cruise, shorter wings	**Electric** Sinus at 100 mph cruise, shorter wings	**Electric** Sinus at 100 mph cruise, shorter wings	For comparison. Note: calc. climb too high due to fixed prop
7	Wingspan (CAFÉ max=44), ft		31	31	35.5	51	51	51	35.5	35.5	32	32	35	49	49	35	35	35	35	35	36
11	**Gross weight**	**lb**	**2,900**	**3,200**	**3,550**	**3,550**	**3,550**	**3,550**	**3,550**	**3,550**	**2,700**	**2,900**	**3,320**	**1,290**	**1,050**	**1,010**	**1,320**	**1,320**	**1,320**	**1,320**	**2,300**
14	Fuel capacity	gal	70	40	90	0	0	0	0	0	60	35	0	15.1	3.0	3	0	0	0	0	38
17	Battery sp-energy	Wh/kg		**168**		**168**	**300**	**300**	**300**	**1000**		**168**	**168**			**168**	**168**	**300**	**300**	**1000**	**N/A**
18	**Projected battery cost at**			**Today**		**Today**	**>2012**	**>2012**	**>2012**	**>2020**		**Today**	**>2012**				**Today**	**>2012**	**>2012**	**>2020**	
19	$700/kWh today, $500 in 2012		700	**$17,920**	500	**$80,640**	**$70,400**	**$121,600**	**$121,600**	**$140,800**		**$17,920**	**$64,000**				**$29,568**	**$37,760**	**$25,600**	**$25,600**	
20	**Battery capacity**	**kWh**	**0**	**26**	**0**	**115**	**141**	**243**	**243**	**563**	**0**	**26**	**128**	**0**	**0**	**0**	**42**	**76**	**51**	**102**	**0**
22	**Batt. weight**	**lb**	**0**	**334**	**0**	**1,505**	**1,033**	**1,783**	**1,783**	**1,239**	**0**	**334**	**1,676**	**0**	**N/A**	**N/A**	**552**	**554**	**375**	**225**	**0**
23	**Payload**	**lb**	**780**	**784**	**1,010**	**554**	**1,026**	**476**	**476**	**1,020**	**820**	**752**	**400**	**574**	**406**	**401**	**226**	**224**	**402**	**552**	**686**
27	**Seats**		**4**	**4**	**4**	**2**	**4**	**2**	**2**	**4**	**4**	**4**	**2**	**2**	**2**	**2**	**1**	**1**	**2**	**2**	**4**
28	Engine Mfgr		Lycoming	DeltaHawk	Continental	AC Propul.	AC Propul.	AC Propul.	AC Propul.	AC Propul.		Thielert	AC Propul.	Rotax	Rotax	Unknown	Unknown	Unknown	Unknown	Unknown	Lycoming
29	Engine		IO550N	DH200V4	TSIO550	3-ph	3-ph	3-ph	3-ph	3-ph		2.0 (135 hp)	3-ph	912	912	1/4 DeltaHawk	1/4 AC Prop.	1/4 AC Prop.	1/4 AC Prop.	1/4 AC Prop.	O-320-E2D
30	Engine + motor shp	hp	310	400	350	201	201	201	201	201	260	335	201	80	80	50	50	50	50	50	150
33	Climb rate, calc	ft/min	2574	3073	1987	1037	1037	1037	769	769	2172	2707	1130	1609	2040	1199	833	833	833	833	1338
34	**Cruise (max. range if avail.)**		**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**	**Cruise:**
38	Shaft power	hp	233	200	300	65.4	65.4	65.4	101.8	282.8	143	135	83.6	60.0	19.7	16.2	24.2	24.2	24.2	49.2	76.5
39	Fuel rate	gph or kW	17.1	11.5	22	57.1	57.1	57.1	88.8	246.7	10.6	7.2	72.9	4.6	1.5	0.9	21.1	21.1	21.1	42.9	6.2
41	ICE efficiency	%	28%	32%	28%	N/A	N/A	N/A	N/A	N/A	28%	35%	N/A	27%	27%	35%	N/A	N/A	N/A	N/A	25%
42	**Speed (input)**	**mph**	236	224	330	**120**	**120**	**120**	**150**	**230**	176	173	**115**	128	100	100	**100**	**100**	**100**	**128**	109
43	**Effective L/D**	**XX:1**	**7.9**	**9.6**	**8.0**	**17.4**	**17.4**	**17.4**	**13.9**	**7.7**	**8.9**	**9.9**	**12.2**	**8.1**	**14.2**	**16.6**	**14.6**	**14.6**	**14.6**	**9.2**	**9.5**
44	**Endurance, no reserve**, hr		**4.1**	**3.5**	**4.1**	**2.0**	**2.5**	**4.3**	**2.7**	**2.3**	**5.7**	**4.9**	**1.8**	**3.3**	**2.0**	**3.5**	**2.0**	**3.6**	**2.4**	**2.4**	**6.1**
47	**Speed @ SL**	**mph @ SL**	**209**	**198**	**224**	**120**	**120**	**120**	**150**	**230**	**156**	**153**	**115**	**124**	**100**	**100**	**100**	**100**	**100**	**128**	**104**
50	**Range**, no reserve, mi@SL		857	689	918	242	296	511	411	525	887	747	202	405	199	350	200	358	243	305	633
51	**w/VFR reserve**, mi@SL		**752**	**590**	**806**	**182**	**236**	**451**	**336**	**410**	**809**	**671**	**144**	**343**	**149**	**300**	**150**	**308**	**193**	**241**	**581**
54	**Fuel efficiency**, empg@SL		**12.2**	**17.2**	**10.2**	**71**	**71**	**71**	**57**	**31**	**14.8**	**21.3**	**53**	**26.9**	**66**	**117**	**160**	**160**	**160**	**100**	**16.7**
56	**Cost/100 mi @ $5/gal, $**		**$41**	**$29**	**$49**	**$7**	**$7**	**$7**	**$9**	**$16**	**$34**	**$23**	**$9**	**$19**	**$8**	**$4**	**$3**	**$3**	**$3**	**$5**	**$30**
57	**Cost/hr @ 45¢/gal, $**		**$85**	**$58**	**$110**	**$8**	**$8**	**$8**	**$13**	**$37**	**$53**	**$36**	**$11**	**$23**	**$8**	**$4**	**$3**	**$3**	**$3**	**$6**	**$31**
62	**At best glide speed (Vg):**		**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**	**Vg:**
63	**Best glide speed, mph**		**115**	**115**	**144**	**120**	**120**	**120**	**144**	**144**	**105**	**105**	**100**	**59**	**59**	**70**	**70**	**70**	**70**	**70**	**80**
66	**L/D** (from expected ratio)		**19.1**	**18.2**	**14.5**	**17.4**	**17.4**	**17.4**	**14.5**	**14.5**	**14.8**	**14.3**	**14.0**	**27.0**	**30.0**	**25.8**	**22.5**	**22.5**	**22.5**	**22.5**	**12.7**
81	**Strings of batteries**		**12**	**2**	**8**	**9**	**11**	**19**	**19**	**44**	**9**	**2**	**10**	**9**	**0**	**0**	**3.3**	**5.9**	**4.0**	**8.0**	**4**
88	**Chg time at max level 2, hr**		18.4	**1.4**		**6.3**	**7.7**	**13.2**	**13.2**	**30.6**		**1.4**	**7.0**				**2.3**	**4.1**	**2.8**	**5.6**	
89	**Useful for**		**LongDist**	**LongDist**	**LongDist**	**DayTrips**	**LongDist**	**LongDist**	**LongDist**	**LongDist**		**LongDist**	**Local**				**Local**	**DayTrips**	**DayTrips**	**LongDist**	
90	**Desired charge time, hr**			**1**		**1**	**1**	**1**	**1**	**1**		**1**	**12**				**12**	**4**	**4**	**1**	
91	**Required charge rate, kW**			**26**		**115**	**141**	**243**	**243**	**563**		**26**	**11**				**4**	**19**	**13**	**102**	
92	Voltage	V		240		240	480	480	480	480		240	240				240	240	240	480	
93	Current required	A		107		480	293	507	507	1,173		107	44				15	79	53	213	
94	**Useful for**		**Long Dist**	**Long Dist**		**Commute**	**BusClient**	**BusLDist**	**BusLDist**	**BusLDist**			**LocalRent**				**LocalRent**	**SingleBus**	**SingleBus**	**SingleBus**	
95	**Desired charge time, hr**			**1**		**7**	**2**	**1**	**1**	**1**		**1**	**1**				**1**	**2**	**2**	**2**	
96	**Required charge rate, kW**			**26**		**16**	**70**	**243**	**243**	**563**		**26**	**128**				**42**	**38**	**26**	**51**	
97	Voltage	V		240		240	480	480	480	480		240	480				240	240	240	480	
98	Current required	A		107		69	147	507	507	1,173		107	267				176	157	107	107	