

Are Practical Electric and Hybrid Airplanes Just Around the Corner?

(what I added to my model early this morning
surprised me when I awoke)

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Change of Title and Focus

- I delayed writing this talk until yesterday, as Aviation Green Prize rules were continuing to change
 - Conversion factor changed from 50 kWh/gallon to 33.7 kWh/gallon, making electricity's mpge less advantageous
 - The race has been delayed from Sept 2010 to June 2011
 - Better batteries should be available, making electric *range* -- which is what my modeling focused on -- much easier
 - Instead of pure speed, the race formula is now $1/(2/\text{passenger-mpge} + 1/\text{mph})$
 - Strongly biased toward fuel efficiency, since drag increases as the cube of speed
 - This is true during the design process even if not at best glide speed
 - I believe the winner will
 - Fly an LSA-sized airframe at just above 100 mph
 - By powered by a high-efficiency turbo-Diesel engine
 - » Diesel engine exhaust has especially toxic emissions that are difficult to clean up
 - Employ a glider-like long-wing design
 - The electric airplanes I modeled, though quiet, fuel efficient, and low carbon, will no longer meet the AGP's minimum mpge.



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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 CO₂ 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)



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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



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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)



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• 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



Are Practical Electric and Hybrid Airplanes Just Around the Corner?

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



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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?



Are Practical Electric and Hybrid Airplanes Just Around the Corner?

	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/CAFE 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	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	Lancair IV Electric, opt. for slower flight with a longer folding wing	Vans RV-10	Vans RV-10 Diesel Hybrid	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	(needs higher power batteries)	OEM turbo piston version							OEM	(needs higher power batteries)		OEM LSA	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 (CAFE mats=44), ft	31	31	35.5	51	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	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	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	300	1000		168	168				168	168	300	300	1000 N/A
18	Projected battery cost at	Today				>2012				>2012				>2012				>2012			
19	\$700k/Wh 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	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	0	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	4	2	2	2	2	1	1	2	2	4
28	Engine Mfr	Lycoming	DeltaHawk	Continental	AC Propul.	AC Propul.	AC Propul.	AC Propul.	AC Propul.		Thielert	AC Propul.	Rotax	Rotax	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Lycoming
29	Engine	ID650N	DH200V4	TSIO550	3-ph	3-ph	3-ph	3-ph	3-ph		2.0 (135 hp)	3-ph									O-320-E2D
30	Engine + motor shp hp	310	400	350	201	201	201	201	201	260	335	201	80	912	1/4 DeltaHawk	1/4 AC Prop.	1/4 AC Prop.	1/4 AC Prop.	1/4 AC Prop.	50	150
33	Climb rate, calc ft/min	2574	3073	1987	1037	1037	1037	1037	769	2172	2707	1130	1608	2040	1199	833	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:	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	28%	35%	N/A	27%	27%	35%	N/A	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	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	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	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	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/FR 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, emp@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	\$24	\$23	\$9	\$19	\$8	\$4	\$3	\$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	\$3	\$6	\$31
62	At best glide speed (Yg: Vg:	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	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	Local	Local	Local	DayTrips	DayTrips	DayTrips	LongDist	LongDist	
90	Desired charge time, hr		1		1	1	1	1	1	1	1	12				4	4	4	1	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	480	240	240	240	44			240	240	240	480		
93	Current required A	107		107	293	293	507	507	1173	107	107	44			15	79	53	213			
94	Useful for	Long Dist	Long Dist		Commute	BusClient	BusLDist	BusLDist	BusLDist		LocalRent	LocalRent	LocalRent	LocalRent	LocalRent	SingleBus	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	480	240	240	480				240	240	240	480		
98	Current required A	107		107	69	147	507	507	1173	107	107	267				176	157	107	107		

