A Note on Glider Electric Propulsion

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Abstract

This work presents the aerodynamic effects of installing a non-retractable electric regenerative propulsion system in a typical Standard Class glider. The propulsion system, including the weight for batteries and power available are estimated using a comparison with existing electric propelled gliders. The thrust available, the additional drag during free-wind milling, and the possible power extraction are estimated. This data is used to determine the performance of a glider during gliding flight, powered flight, and while regenerating electrical power. The conclusion is that a Standard Class glider with a 1.9 meter diameter two-bladed variable pitch propeller that is driven by an electrical 25 kW motor mounted in a fixed pylon, leads to a quite interesting, safe and reliable electric motor glider that is suitable for club and cross country flight training.

Nomenclature

b	Wing span
c	Airfoil chord
C_{D_0}	Parasite drag coefficient
C_{D_n}	Frontal area drag coefficient
C_P	Power coefficient
C_T	Trust coefficient
D	Drag, Propeller diameter
e	Oswald factor
f	Equivalent flat-plate drag area
g	Gravity acceleration
L/D	Max. gliding ratio
n	Motor or propeller rotation in rps
P	Motor power
Q	Motor torque
Q_f	Electric motor idle torque
P_u	Propeller useful power
PI	Power index
RC	Rate of climb
Re	Reynolds Number
S	Wing area
S_p	Pylon lateral area
S	Frontal area
t	Thickness
T	Propeller traction
V	Glider flight speed
$V_{L/D}$	gliding ratio flight speed
x_m	Maximum thickness ordinate
w	Glider sinking speed
W	Maximum glider weight
W_e	Empty glider weight
β	Propeller blade pitch angle
δ	Variable increment
ρ	Air density

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Introduction

The use of battery fed electric propulsion in gliders, either for take-off assistance or for flight sustaining is increasing due to some advantages that electrical motors have in comparison to the internal combustion engines (ICE) represented by their lower noise, lower direct operational costs, higher reliability, and higher confidence levels in out landings.

Otherwise, their lower electric motor weight and cost are offset by the present battery weight and cost, and their alleged low CO_2 emission may be unreal if "well to wheel" emissions are taken into account, anywhere thermal generation electric sources are used.

The late American gliding pioneer Dr. Paul MacCready, was one of the first to point to the regenerative possibilities of electrical propelled gliders that by reducing their propeller pitch can use them as wind turbines in order to charge their batteries, while flying in rising air currents [1].

An additional advantage of electrical propulsion is that, unlike ICE engines, the electrical motors offer near zero torque resistance when running idle, and in this condition, as it will be shown in this paper, a propeller set at the right pitch may present quite small "wind milling" drag values.

Another thing to be considered is that a great number of single place gliders manufactured to this date are of the FAI Standard Class type, and that many of them are no longer used for competition flying, have selling prices that are a fraction of that of a brand new electric glider.

The above considerations led to the writing of this paper that investigates the possibility of obtaining inexpensive and highly reliable, electric propelled touring and training club motor gliders, just by equipping used standard-class gliders with fixed regenerative electric propulsion systems and using their wing water ballast structural weight margins and supporting structure to install the batteries. Such a battery installation will reduce the non-lifting parts weight increase that will be restricted to the engine, propeller, controller and cabling weights, and also to allow the use of less efficient, but also cheaper batteries, such as the MeH (Metal Hydride) type used in some hybrid automobiles.

The following discussion is based on the assumption of a typical Standard Class glider similar to those that have been fabricated in large numbers but are no longer in production or used in Standard Class world gliding championships.

Basic Data

Gliders and Motors

Table 1 shows some of the available data of three current electric-propelled gliders as well as of the adopted baseline Standard Class glider and of its proposed electric version. The motor power of the electric version was chosen so that its power index PI, defined by Eq. 1 below, falls into the range of the other three electric gliders power index values.

$$PI = \frac{W(\mathrm{RC} + V_{L/D}/(L/D))}{P} \tag{1}$$

Table 1 Comparison of glider characteristics. Mass properties in parentheses include ballast.

GLIDER	Antares	Apis E	Silent E	Baseline	Stand. E
Max. weight (kg)	480	350	300	349 (460)	460
Empty weight (kg)	233	200	275	350	
Span (m)	18	15	13	15	15
Wing area (m2)	11.9	12.2	10.3	10.7	10.7
PERFORMANCE					
Max. glide ratio	52	40	39	36.3	32.9
@ V (km/h)	110	90	90	95 (110)	105
Min. sink (m/s)	0.51	0.58	0.6	0.65 (0.75)	0.78
@ V (km/h)	71	60	85	75 (80)	80
Rate of climb (m/s)	4.6	2	2.5	–	2.7
ENGINE					
Power (kW)	42	15	13	–	25
Rotation (rpm)		6000	3400	–	–
Weight (kg)	22.5		8.5	–	15
Power Index	0.582	0.601	0.711	–	0.521
PROPELLER					
Diameter (m)	2.0	1.7	1.9	–	1.8–1.9
Rotation (rpm)	1500		1300	–	1800
Number of blades	2	2	1	–	2
Pitch control	fixed	fixed	fixed	–	variable
BATERY PACK					
Type	Li-ion	Li-poly	NiCd	–	MeH
Quantity	72	21		–	40
Weight (Kg)	76	40	36	–	42
Total charge (Kw.h)		5	4.1	–	5.4

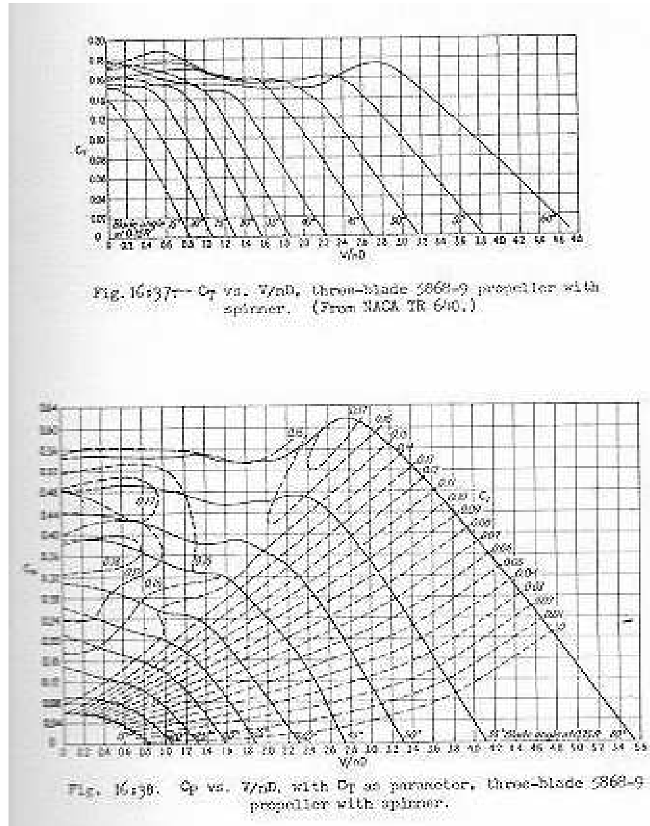

Figure 1 C_T and C_P vs. V/nD, and β from 15 to 60 deg. for three bladed propeller, with spinner [2].

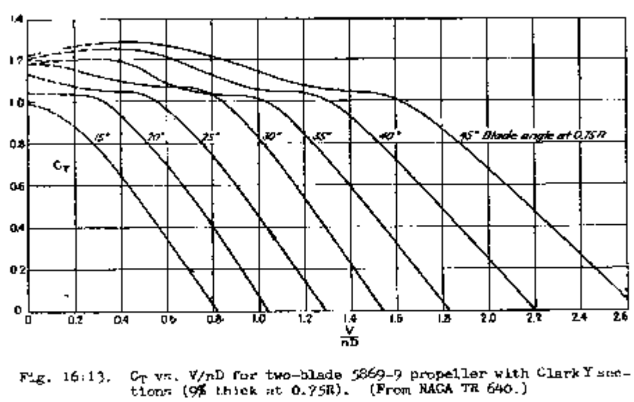

Figure 2 C_T vs. V/nD and β from 15 to 45 deg. for two bladed propeller [3].

Propellers

Figures 1, 2, and 3 show typical propeller power and thrust coefficients C_P and C_T for two and three bladed propellers with spinner [2,3] as a function of the V/nD advance ratio parameter.

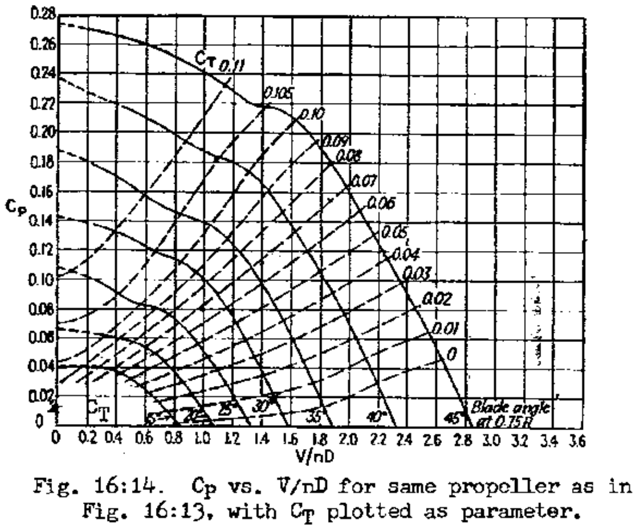

Figure 3 C_P vs. V/nD and β from 15 to 45 deg. for two bladed propeller [3].

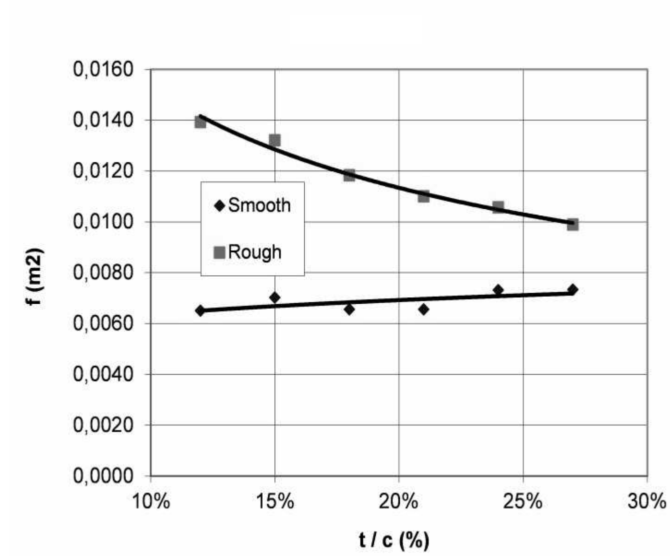

Figure 4 Pylon drag.

Table 2 Pylon drag for various thickness ratios (V= 90 km/h)

t/c	12%	15%	18%	21%	24%	27%
c (m)	1.250	1.000	0.833	0.714	0.625	0.556
xm/c	45%	40%	35%	30%	25%	20%
S_p (m^2)	1.250	1.000	0.833	0.714	0.625	0.556
Re (10^6)	2.25	1.80	1.50	1.29	1.13	1.00
Smooth C_{D_n}	0.0052	0.0070	0.0079	0.0092	0.0117	0.0132
Smooth f	0.0065	0.0070	0.0066	0.0066	0.0073	0.0073
Rough C_{D_n}	0.0111	0.0132	0.0142	0.0154	0.0169	0.0178
Rough f	0.0139	0.0132	0.0118	0.0110	0.0106	0.0099

Power and thrust are defined by :

$$P = C_P \rho n^3 D^5 \qquad (2)$$

$$T = C_T \rho n^2 D^4 \qquad (3)$$

Gliding Performance

The estimated gliding performance of the baseline glider was adjusted in order to account for the additional drag due to the pylon, the motor nacelle, as well as the two- or three- bladed propellers under wind-milling conditions.

Pylon Drag

Using a simplified method [4] to estimate the smooth and rough airfoil drag coefficients, the smooth and rough equivalent parasite areas “f” for 15 cm wide and one meter high pylons were computed in Table 2 and plotted in Fig. 4, for various pylon cross section thickness ratios.

$$f = C_D SP$$

Adopting $f \approx 0.0090\,\mathrm{m}^2$ corresponding to a 24% thick, and 50% smooth pylon, the glider drag coefficient increase due to the pylon is:

$$\delta C_{D_0} = \frac{f}{S} = \frac{0.009}{10.7} \approx 0.00084$$

This is a relatively conservative value when compared to the C_{D_n} computed using an optimum frontal area pylon drag coefficient $C_{D_n} \approx 0.055$, given in Ref. 5 (pp. 6–9, Fig. 10) that for the 0.15 m^2 pylon frontal area will result in:

$$\delta C_{D_0} = \frac{0.050 \cdot 0.15}{10.66} = 0.00077$$

Motor Nacelle Drag

The drag of an optimal 3:1 fineness ratio streamlined motor nacelle with a maximum diameter of 40 cm and a frontal area $S_n = 0.126\,\mathrm{m}^2$, can be also conservatively estimated using a turbulent $C_{D_n} = 0.050$, given in Ref. 5 (pp. 6–19, Fig 25):

$$\delta C_{D_0} = \frac{0.050 \cdot 0.126}{10.66} \approx 0.00059$$

Drag of Wind Milling Three-Bladed Propeller

Since electric motors running at idle have negligible torque values, the wind milling propeller drag for various blade pitch angles will be equal to the negative thrust computed with the C_T extrapolated in the C_T vs. V/nD plot of Fig. 1 for the β and V/nD values for which $C_P = 0$ in the C_P vs. V/nD plot of the same figure.

Using these values, the resulting propeller drag and the glider drag coefficient C_{D_n}increases are computed in Table 3 for blade pitch angles from 35 to 55 degree, and for speeds of 90 (see Fig. 5), 120 and 180 km/h, showing the same minimum value $C_{D_n} \approx 0.00098$, when the blade pitch is 45 degrees.

Table 3 Free ($C_P = 0$) wind milling drag of a 1.8 m diameter three-bladed propeller

	CP = 0		V =	25,0	m/s	V =	33,3	m/s	V =	50,0	m/s
Beta	V / nD	CT	n (rps)	n (rpm)	T (DaN)	n (rps)	n (rpm)	T (DaN)	n (rps)	n (rpm)	T (DaN)
35	1,87	-0,009	7,43	446	-0,64	9,90	594	-1,14	14,85	891	-2,55
40	2,30	-0,009	6,04	362	-0,42	8,05	483	-0,75	12,08	725	-1,69
45	2,73	-0,012	5,09	305	-0,40	6,78	407	-0,71	10,18	611	-1,60
50	3,30	-0,020	4,21	253	-0,46	5,61	337	-0,81	8,42	505	-1,82
55	4,10	-0,035	3,39	203	-0,52	4,52	271	-0,92	6,78	407	-2,07
				δ Cdo =	0,00098		δ Cdo =	0,00098		δ Cdo =	0,00098

Table 4 Free ($CP = 0$) wind milling drag of a 1.9 m diameter two-bladed propeller

S (m2)	CP = 0		V =	25,0	m/s	V =	33,3	m/s	V =	50,0	m/s
Beta	V / nD	CT	n (rps)	n (rpm)	T (DaN)	n (rps)	n (rpm)	T (DaN)	n (rps)	n (rpm)	T (DaN)
20	1,07	-0,0025	12,30	738	-0,60	16,40	984	-1,07	24,59	1476	-2,42
25	1,32	-0,0030	9,97	598	-0,48	13,29	797	-0,85	19,94	1196	-1,90
30	1,58	-0,0030	8,33	500	-0,33	11,10	666	-0,59	16,66	999	-1,33
35	1,88	-0,0060	7,00	420	-0,47	9,33	560	-0,83	14,00	840	-1,88
40	2,32	-0,0120	5,67	340	-0,62	7,56	454	-1,10	11,34	681	-2,47
				δ Cdo =	**0,00081**		δ Cdo =	**0,00081**		δ Cdo =	**0,00081**

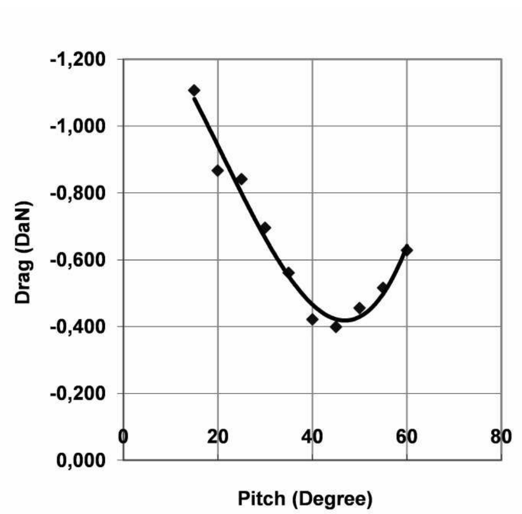

Figure 5 Estimated drag at 90 km/h of a free (CP = 0) wind milling three bladed 1.8 m diameter propeller

Drag of Wind Milling Two-Bladed Propeller

In Table 4 the same procedure is applied using Fig. 2 extrapolated negative C_T values for the β and V/nD values corresponding to $C_P = 0$ in Fig. 3, and the minimum glider δC_{D_n} due to the wind milling drag of a two blade propeller with 1.9 m diameter is estimated to be $\delta C_{D_n} \approx 0.00081$, for $\beta = 30$ degrees.

A more accurate assessment of the wind milling propeller drag would require the knowledge of the idle electric motor torque Q_f (small but not zero) due basically to the axle friction and magnetic hysteresis, both probably proportional to n. For $Q_f = k \cdot n$, the idle motor power would be $\delta P = -k \cdot n^2$, and δC_P proportional to V/nD.

Polars

Assuming the usual quadratic drag variation with speed (parasite drag proportional to V^2 and induced drag to $1/V^2$) [6], the glider sinking speed as function of flight speed or its "polar" curve, can be approached by:

$$w = \frac{C_{D_0}(1/2)\rho S V^3}{W} + \frac{W}{e\pi(1/2)\rho V b^2}$$

Fitting the above expression to the flight test measured polar points of the Jantar 2 Standard glider [7] will define a baseline polar curve with:

$$C_{D_0} = 0.010 \qquad e = 0.80 \qquad W = 349\text{kg}$$

In Table 5, and in Fig. 6 are shown the computed w and V for this baseline glider with 349 kg, for it with 460 Kg (partial ballast), and for its 460 kg electrical powered version equipped with an 1.9 m diameter two blade propeller.

For all these three gliders the same Oswald efficiency factor was used and for the E version the already computed pylon, engine fairing and wind milling 1.9 m two blade propeller C_{D_n} were added to the baseline glider C_{D_n} resulting in:

$$C_{D_0} = 0.01000 + 0.00085 + 0.00059 + 0.00081 \approx 0.0122$$

In comparison to the base aircraft the fixed electric propulsion system results only in a small increase in minimum sink of about 0.13 m/s and a reduction of the maximum glide from 1/36.3 to 1/32.8. At high speeds the performance loss due to the additional drag of the propulsion system is compensated by the higher wing loading of the electric version, as shown in Fig. 6.

Table 5 Computed flight polars.

g (m/s2)	9,807	Baseline			Baseline w/ ballast (460 kg)			E - Standard		
S (m2)	10,7	M (kg)	348,6		M (kg)	460		M (kg)	460	
b (m)	15	Cdo	0,0100		Cdo	0,0100		Cdo	0,0122	
ρ (Kg/m3)	1,226	e	0,80		e	0,80		e	0,80	
V	q	D	L/D	w	D	L/D	w	D	L/D	w
Km/h	DaN/m2	DaN	-	(m/s)	DaN	-	(m/s)	DaN	-	(m/s)
75	26,6	10,6	32,2	-0,65						
80	30,3	10,1	34,0	**-0,65**	15,1	29,8	**-0,75**	15,9	28,5	**-0,78**
85,0	34,2	9,7	35,2	-0,67	14,2	31,8	-0,74	15,0	30,1	-0,79
90,0	38,3	9,5	36,0	-0,69	13,5	33,4	-0,75	14,4	31,3	-0,80
95,0	42,7	9,4	**36,3**	-0,73	13,0	34,7	-0,76	14,0	32,2	-0,82
105,0	52,1	9,5	35,8	-0,81	12,5	36,1	-0,81	13,7	**32,9**	-0,89
110,0	57,2	9,7	35,1	-0,87	12,4	**36,3**	-0,84	13,8	32,7	-0,93
125,0	73,9	10,7	31,9	-1,09	12,8	35,3	-0,98	14,5	31,0	-1,12
130,0	79,9	11,1	30,7	-1,18	13,1	34,6	-1,04	15,0	30,1	-1,20
140,0	92,7	12,1	28,1	-1,38	13,8	32,7	-1,19	16,0	28,2	-1,38
150,0	106,4	13,3	25,7	-1,62	14,8	30,6	-1,36	17,3	26,1	-1,60
160,0	121,0	14,7	23,3	-1,91	15,9	28,3	-1,57	18,8	24,0	-1,85
170,0	136,6	16,1	21,2	-2,23	17,3	26,1	-1,81	20,5	22,0	-2,15
180,0	153,2	17,7	19,3	-2,59	18,7	24,1	-2,08	22,4	20,1	-2,48
190,0	170,7	19,5	17,6	-3,01	20,4	22,1	-2,38	24,5	18,4	-2,86
200,0	189,1	21,3	16,0	-3,47	22,1	20,4	-2,73			

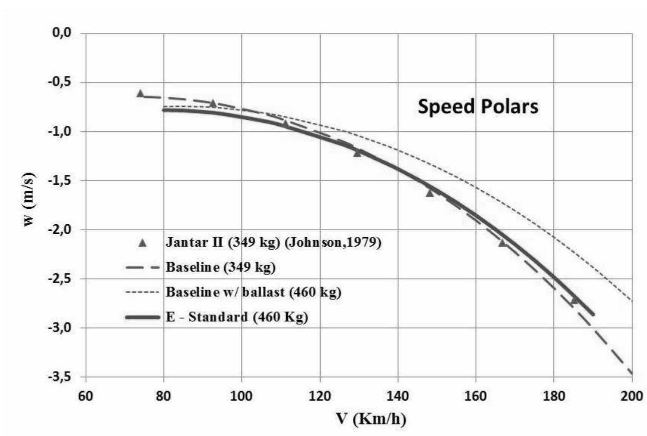

Figure 6

Powered Climb Performance

The powered rate of climb of the electric E glider at 95 km/h is estimated using Eq. 7:

$$\mathrm{RC} = \frac{(T-D)\cdot V}{W}$$

where D is the drag at this speed of the E glider without the propeller that is $\approx$ 12 daN ($C_{D_n} \approx 0.0114$).

Two- and Three-Bladed Propeller

Table 6 presents the computation of the thrust, useful power, and the corresponding efficiency for a 1.8 meter diameter three-bladed propeller driven by a 25 kW electric motor. At 95 km/h, the maximum thrust is 70.3 DaN at 1900 rpm and the resultant climb speed 3.35 m/s.

Table 7 presents the computation of the thrust, useful power, and corresponding efficiency for a 1.9 meter diameter two-bladed propeller driven by a 25 kW electric motor. At 95 km/h the maximum thrust is 63.2 DaN at 1800 rpm and the resultant climb speed 2.69 m/s.

Power Regeneration

The power regeneration [1, 8] is computed assuming the E-glider flying in up currents at 95 km/h, and that the drag increase D due to its propeller acting as a wind turbine, will not cause an increase in its sink speed w larger than 1.5 m/s. Since

$$\delta D \cdot V = W \cdot \delta W$$

then for V = 26.4 m/s, M = 460 kg, and w = 1.5m/s we need to have:

$$\delta D \leq 25.7 \text{ daN}$$

Three-Bladed Propeller

In Table 8, using D as a negative traction, V/nD, C_T and P (both negative) are computed for different rpm by extrapolation of Fig. 1 curves and using the β found in the C_T vs. V/nD plot to find the C_P in the C_P vs. V/nD plot.

It is found that about 7 kW can be harvested by the 1.8 meter diameter propeller set at a low 7 degree pitch, but this value shall be taken with caution due to the extrapolation employed to compute both C_P and C_T.

Table 6 Traction and efficiency of the 1.8 m three bladed propeller at 95 km/h

Climb			M =	460	Kg			
ρ =	1,226	Kg/m3	D =	1,8	m			
P =	25000	watt	V =	95	Km/h	26,4	m/s	
n	n	V/nD	CP	β	CT	T	Pu	η
rpm	rps	-	-	degree	-	DaN	watt	-
1500	25,0	0,586	0,069	20,0	0,090	72,4	19096	0,764
1600	26,7	0,550	0,057	17,5	0,080	73,2	19313	0,773
1700	28,3	0,517	0,047	16,5	0,070	72,3	19077	0,763
1800	30,0	0,489	0,040	15,2	0,065	75,3	19860	0,794
1900	**31,7**	**0,463**	**0,034**	**14,0**	**0,061**	**78,7**	**20766**	**0,831**
2000	33,3	0,440	0,029	13,0	0,055	78,6	20746	0,830

Table 7 Traction and efficiency of the 1.9 m two-bladed propeller at 95 km/h

ρ =	1,226	m	D =	1,9	m	74,8	pol	
P =	25000	watts	V =	95	Km/h	25,000	m/s	
rpm	rps	V/nD	CP	β	CT	T (DaN)	Pu (watt)	eta
1500	25,00	0,526	0,0527	17,0	0,059	58,9	14723	0,589
1600	26,67	0,493	0,0434	15,5	0,054	61,3	15332	0,613
1700	28,33	0,464	0,0362	13,5	0,049	62,8	15706	0,628
1800	**30,00**	**0,439**	**0,0305**	**12,1**	**0,044**	**63,2**	**15811**	**0,632**
1900	31,67	0,416	0,0259	11,0	0,039	62,5	15615	0,625

Table 8 Generated power, and drag of 1.8 m diameter three-bladed propeller used as wind turbine at 95 km/h

M =	460	Kg	a =	1,5	m/s	
δ D =	-25,7	DaN				
n	n	V / nD	CT	β	CP	P
rpm	rps	-	-	deg.	-	watt
1100	18,33	0,800	-0,0593	7,0	-0,045	-6421
1150	19,17	0,765	-0,0543	7,0	-0,043	-7011
1200	20,00	0,733	-0,0498	7,0	-0,040	-7410

Table 9 Generated power, and drag of 1.9 m diameter two-bladed propeller used as wind turbine at 95 km/h.

M =	460	Kg	a =	1,5	m/s	
δD =	-25,7	DaN				
n	n	V / nD	CT	β	CP	P
rpm	rps	-	-	deg.	-	watt
1300	21,67	0,641	-0,0342	5	-0,021	-6482
1400	23,33	0,595	-0,0295	5	-0,020	-7710
1500	25,00	0,556	-0,0257	5	-0,019	-9009

Two-Bladed Propeller

Table 9, using negative C_T and C_P extrapolated values from Figs. 2 and 3, shows that a similar power can be obtained with a 1.9 m diameter two bladed propeller set a 5 degree pitch.

Propellers and Wind Turbines

In the Appendix, it is shown that a 1.8 m diameter three bladed wind turbine or a 1.9 m diameter two bladed one, operating in a 95 km/h wind, generates twice the power at the expense of nearly only one third of the drag needed by the propellers.

Propeller airfoils are usually slightly positively cambered in order to provide thrust with low drag. When operating as wind turbines at low pitch they operate at negative angles of attack. As a result their power conversion efficiencies are low, especial in comparison to wind turbines, which use negatively cambered airfoils in order to better harvest wind power.

The use of propellers with symmetrical airfoils have been proposed in order to improve the power regeneration [8]. As a result of their lower efficiency, however, they require more powerful and heavier motors to attain the same take-off and climbing performance.

Results

A sketch of the modified glider is shown in Fig. 7. The added propulsion system consists of a 1.9-meter variable pitch propeller and the 25 kW electric motor are mounted on a fixed pylon. The streamlined pylon has a height of one meter high and is 15 cm wide.

In gliding flight, the addition of a free-milling propulsion system results in a 3.4-point reduction in maximum glide ratio and a 0.13 m/s increase in minimum sink in comparison to the base glider as visible in Fig. 6. Due to the engine and battery added weight the high speed performance of the modified glider is relatively similar to that of the baseline glider without ballast.

The resulting powered rate of climb is 2.7 m/s. The energy needed for takeoff and climb to 600 m (approx. 5 min.) can be recharged using the propeller as a wind turbine and by flying at 95 km/h for about 20 minutes in an up current of at least 1.5 m/s.

The use of a three-bladed propeller increases the powered climb performance and reduces the necessary recharging flight time. It is, however, less suitable for an higher performance version with a retractable propulsion system. In addition, it is more awkward to be dismounted and stowed in a trailer.

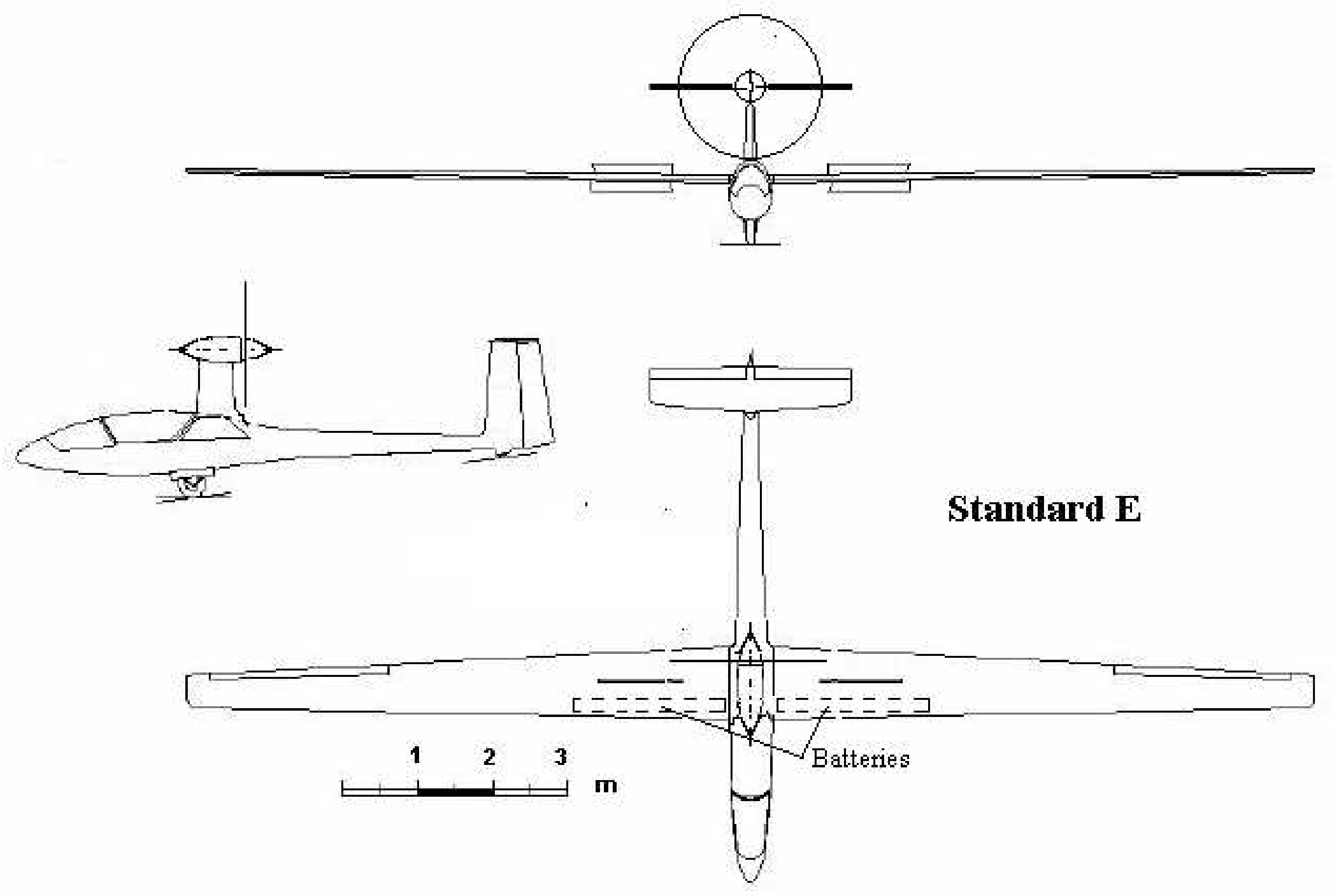

Figure 7 Three view of the baseline Standard Class glider including electric motor conversion.

Conclusions

The main aerodynamic aspects of installing a non- retractable regenerative electric propulsion system in a typical Standard Class glider have been analyzed. It is concluded that a quite reliable and safe cross country and training club motor glider is obtainable by installing such a system in existing and less competitive Standard Class gliders.

References

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Appendix

Wind Turbines

R	Wind turbine tip radius
Ω	Wind turbine rotation speed (rad/s)
V	Wind Speed

Figures I-1 and I-2 show wind turbine power and thrust coefficients C_P and C_T for one to five blade turbines as function of the blade tip speed factor = R/V, which is inversely proportional to the V/nD propeller advance ratio parameter [9].

Also unlike for propellers, the wind turbine traction T is a windward oriented force, so corresponding to the propeller drag, and instead of the definitions presented by Eqs. 2 and 3 in the main text, the wind turbine C_P power and C_T thrust coefficients are defined in such a way that:

$$P = C_P \frac{1}{2} \rho \pi R^2 V^3 \quad \text{(I-1)}$$

$$T = C_T \frac{1}{2} \rho \pi R^2 V^2 \quad \text{(I-2)}$$

Using these coefficients the power and drag of a 1.8 m diameter three-bladed wind turbine, and of a 1.9 m diameter two-bladed wind turbine, computed for a 95 km/h wind are presented in Tables I-1 and I-2.

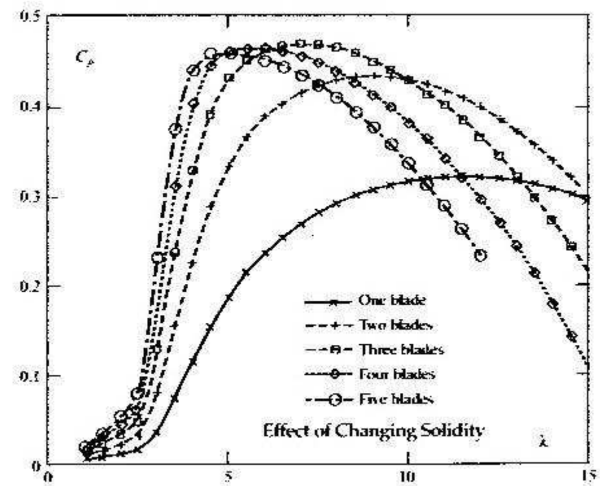

Figure I-1 Wind turbine power coefficients

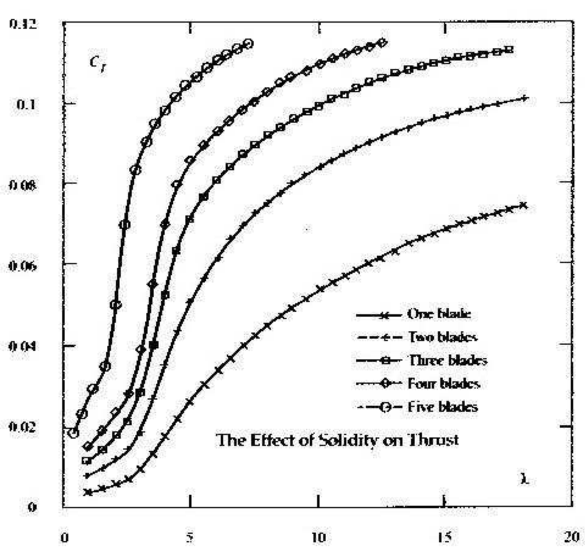

Figure I-2 Wind turbine traction (drag) coefficients

Table I-1 1.8 m diameter three bladed wind turbine power and drag.

V =	95,0	Km/h	26,4	m/s		
Cp	n	λ	β	P	CT	T
-	rpm	-	deg.	watt	-	DaN
0,236	1000	3,57	20,5	6769	0,040	4,3
0,470	1960	7,00	10,8	13467	0,088	9,6

Table I-2 1.9 m diameter two bladed wind turbine power and drag.

V =	95,0	Km/h	26,4	m/s		
Cp	n	λ	β	P	CT	T
-	rpm	-	deg.	watt	-	DaN
-0,212	2000	7,54	10,0	6769	0,071	8,6
-0,440	2387	9,00	8,4	14047	0,080	9,7