SOME THOUGHTS ON THE FEASIBILITY OF A SOLAR-POWERED PLANE

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ABSTRACT

Energy and environmental problems, as well as basic training and weekend pilot requirements, are stressing the need for a silent, economical powered sailplane that doesn't contribute to air pollution. Solar power would be the ideal answer. Basic power requirements seen to come within the state of the art in a decade or so.

Engine types to be considered are the direct current electric motor or, perhaps, some kind of special heat engine. For the electric drive, battery and engine weight problems give cause for concern, while present heat cycles may not meet efficiency requirements.

For better utilization of atmospheric energy, a CCV design, perhaps of tail-first layout, might be preferable. An acceptable price level and new air traffic control procedures (for cross-country work) will also be needed for the SPP to become a success.

NOTATION:

b	wing span	m
c_x	drag coefficient	
c_y	lift coefficient	
c_W	weight factor for wing	
w	rate of climb	m/s
B	solar radiation power	kW/m^2
B*	utilizable solar radiation	kW/m^2
D	drag	N
H	altitude	m, km
L	lift	N
P	power	kW
S	wing area	m^2
V	airspeed	m/s
W	airplane mass	kg
ε	glide ratio	
η	efficiency	
λ	wing aspect ratio	
ζ	air density	kg/m^3
γ	angle of incidence/solar rays	o
μ	angle of bank	o

SUBSCRIPTS:

o	basic/straight and level
μ	steady turn in level flight
c	for the solar cell
w	for climb

SUPERSCRIPT:

$\overline{}$	total

1. INTRODUCTION

"Flying has to be useful and popular."

Economics is now the dominant aspect in our society and an ever increasing emphasis is laid on environmental problems. If gliding is to remain popular, it has to earn its keep, i.e., it has to meet real demands in a way that doesn't violate others.

Considering the services provided that have put gliding in its present position, we may list, among others:

- pilot selection and elementary training;
- development of efficient aerodynamic forms and structures for airplanes;
- meteorological and atmospheric energy research;
- sport and joy riding.

A demand not presently fulfilled would be to provide really cheap personal air transport for medium distances, if only at moderate speeds and in fair weather conditions.

While working towards this goal:

- heavy demands on energy, e.g., on oil resources;
- high noise levels;
- and air pollution,

are to be avoided as far as possible.

To control our continued success, or failure, in compliance with these demands, it may be advisable to observe some trends now manifesting themselves in the gliding movement. In the 'good old bungee days' of ridge soaring flight instructing, joy riding and sport flying existed intermingled in flight operations, as well as in persons. Now, we are flying mission-oriented glider trips and, in too many cases, we observe specialist gliding types as well. From among them, the purist competition pilot may find a good assortment of types to choose from; perhaps not so the conscientious instructor, or the humble but comfort-loving weekend pilot. The former is trying to speed up the instruction timetable by giving his pupil some more flying time per launch in calm air [1-4],while the latter may not object to some mechanical help in getting home from a cross-country flight the same day without a retrieve car. Both of them are keeping an eye on the motorglider, but, despite some success, the growing weight of environmental problems may prevent a real breakthrough in this area. On the other hand, current forms of launching aids, especially air towing, are also conspicuous for their noise, high energy consumption, and exhaust gases.

In short, there is a need for a silent, economical powered sailplane working without air pollution. On the other hand, the rapidly growing popularity of our Rogallo friends reminds us that many people are willing to trade some performance for a cheap, uncomplicated and natural form of flying. Most of these demands would be met by a fully, or at least partially, solar-powered one or two-seater plane. At this moment, we cannot think of initiating the construction, or even the direct development of such a motorglider, but a situation report in the form of a short feasibility study may perhaps induce detail developments speeding up the whole process.

2. POWER AND ENERGY BALANCE

2.1 Energy and Power Concentration

Presently, we are accustomed to using fossil fuels, i.e., highly concentrated forms of geological solar energy for transportation. Soaring, on the other hand, can be enjoyed utilizing mainly atmospheric kinetic energy, converted solar energy radiated recently to the Earth. Of course, solar energy cannot match hydrocarbon fuels in energy concentration or constant availability. One may even wonder at the seriousness of planning a gross power input of some 1 kW/m^2 for whatever kind of conveyance. Current engine power levels of land, sea, and air vehicles are substantially above this, even without allowing for the thermal and mechanical losses in the engine. On the other hand, man-powered aircraft have done some flying on a much lower specific power [5]. Between balloon and jet powered supersonic flight, there should be a gap wide enough to wedge solar powered flying in.

Gross solar radiation power without cloud shadowing is about

$$B = 1.8\,\mathrm{cal/cm^2\,min} = 1.256\ \mathrm{kW/m^2} \qquad (1)$$

Non-perpendicular incidence and solar cell/engine losses diminish this value to

$$B^* = B\cos\varphi\,\bar{\eta} \qquad (2)$$

as shown in Fig. 1. Power levels are not too impressive, I'm afraid.

2.2 Specific Power Required

Power available being proportional to airplane wing (plus fuselage and tailplane) area, the power required for sustained flying will also be computed for a unit area. In straight and level flight, equilibrium of vertical forces can be written as

$$W = \frac{\varrho}{2} V^2 S c_y \qquad (3)$$

giving for the airspeed

$$V = \sqrt{\frac{2}{\varrho}\frac{W}{S}\frac{1}{c_y}} \qquad (4)$$

Basic power requirement for straight and level flight is

$$\frac{P_0}{S} = \varepsilon V \frac{W}{S} \qquad (5)$$

and substitution of Equ. (4) in (5) gives

$$\frac{P_0}{S} = \sqrt{\frac{2}{\varrho}}\,\varepsilon\left(\frac{W}{S}\right)^{\frac{3}{2}}\sqrt{\frac{1}{c_y}} \qquad (6)$$

Numerical examples have been worked out using aerodynamical parameters representative of present and future technology levels (Table 1).

Basic specific power requirements as a function of wing loading are plotted on the upper left part of Fig. 2. As an example: A motorglider of present day standards ($\varepsilon = 1/28$ at $c_y = 0.9$), having a wing loading of 28 kg/m^2 (point A to point B), requires about 0.219 kW/m^2 basic power at sea level. For flying at H=2 km height, the power required is increased by slightly over 10% to 0.241 kW/m^2 (point C).

For level turns without sideslip

$$\frac{P_\mu}{S} = \frac{P_0}{S}\,\frac{1}{\cos^{3/2}\mu} \quad . \tag{7}$$

(points D-E in Fig. 2). Power required for climb is

$$\frac{P_w}{S} = \frac{W}{S}\,\frac{w}{102} \qquad \mathrm{kW/m^2} \tag{8}$$

(see lower left chart in Fig. 2).

While comparing power available and required values, it seems that:

a. a low wing loading, well below present sailplane values, will be essential;
b. a high overall efficiency for the powerplant and the drive system will also be needed;
c. the problem can only be solved with some form of energy storage and/or an auxiliary petrol engine for climb, downdraft, overcast, etc.

3. POWER PLANT AND ENERGY STORAGE

3.1 Electric Motor and Storage Batteries

The first step in solar power conversion techniques of today is either a solar cell array or some sort of optical focusing device. This latter method is out of the question for airplanes because of form and frontal area restrictions, so solar power for flying will be converted first into electrical energy.

In view of this, one may wonder if some sort of direct electric drive, like an EGD pump, would not be ideal for the SPP. Dust particles, passing near the wing surface, may be charged at the leading edge and accelerated by passing a voltage gradient. Sorry to say, calculations done by the author on the feasibility of EGD pumps have given essentially negative results: basic dimensions and efficiencies turned out equally unpromising.

Efficiency is one of the keywords for electric SPP realizations. Current solar cells are achieving about η_c=0.13-0.18, or something like 0.16-0.22 kW/m^2 (see e.g.[6]). In the coming years, improvements, but no breakthroughs, are to be expected. Considering the power available/required ratios arrived at in the preceeding paragraphs, further losses are to be kept to very low rates. Good efficiency and operational characteristics speak strongly for the direct current electric motor. Specific weights in the 1 kg/kW range seem to be required and attainable by going to the 10,000-30,000 RPM range.

The weakest point in this arrangement is perhaps energy storage required for peak power or overcast periods. Table 2 gives approximate specific weight data for electric batteries with respect to fuel cells. Types presently commercially available would weigh in at about 100-150 kg for a 3000 m climb. Even the best experimental fuel cells stand at about 25 kg for this purpose. Light and cheap battery power is one of the essential conditions for SPP development.

3.2 Closed Cycle Hydrogen-Oxygen Engine

In view of battery weight limitations, one may be inclined to look for chemical forms of energy storage, e.g., by water decomposition. All the same, no complete solution is known to the author. If the hydrogen is burned in oxygen, with suitable inert gas dilution in a closed cycle heat engine, no substantial weight reduction is indicated and poor thermal efficiency may diminish the net power output below the value required for sustained flight.

For the moment, the combination solar-electric-heat engine does not seem promising, but at this initial stage it is not to be discarded completely, either.

3.3 Propulsion and Drive

In order to convert engine power into propulsive thrust, part of the air flowing past the plane has to be accelerated backwards. In principle, several ways can be thought out for doing this. From among these, direct electrostatic acceleration is, as spoken of in point 3.1, not promising. Flapping wings do beautiful work on birds, and sometimes on models, too, but there is as yet no successful full scale application of them known to the author. It may be due to the size effect, or to poor understanding of basic laws. Anyway, it does not work properly. For the time being, the third concept, the airscrew propeller, must be recommended.

Adapting it to the peculiar needs of low-powered slow flying will present some not insolvable problems. For good efficiency, low disk loading is to be preferred, while noise problems may be eased by going to high solidity/low-rpm combinations. For elementary trainers, shrouded propellers may have some advantages [10] , especially in preventing ground accidents.

Propeller drives will be characterized by high gear ratios, probably necessitating a double reduction. The occasional auxiliary petrol engine could be conveniently freecoupled to the intermediate shaft. From among current drive systems, the toothed belt type seems to offer the most promise.

3.4 Takeoff and Taxiing

The SPP should have enough takeoff power - at least with the auxiliary engine on - to make unaided starts from grass fields. For normal airfield work, especially for instruction, a reduced cable length winch launch will be, nevertheless, a most welcome aid in battery charge conservation.

Taxiing even airliners on rugged nosewheel type landing gears has something of an abnormality to it, and more so for a motorglider. Unless some sort of direct wheel drive can be found, it will always involve energy waste and poor handling qualities. In the landing roll, the wheel drive motor could then double as a recuperative brake.

4. STRUCTURES

4.1 Weight Restrictions

Considering the power required/available ratio, SPP wing loadings may be restricted to something under 20 kg/m^2, even for the later designs. Preliminary weight analysis indicates this is a major design problem. First of all, wing weights will have to be reduced well below current values. For an acceptable useful load capacity, wing weight factors [11] under c_W=0.004 are to be achieved.

Fuselage and tailplane weight management may be a little easier. However, much attention should be paid to such seemingly minor items as propeller and drive, landing gear, etc., since excess weight in these parts can account for several tens of kilograms.

In striving after near-ultimate weight reductions, material thicknesses will decrease accordingly, and novel methods of stiffening against local buckling will also be required. In general, the amount of weight reduction necessary will not be realizable without radical innovations.

4.2 Integral Wiring and Semi-rigid Structures

The elaborate wiring, connecting wing-surface solar cells to the batteries, would add considerable weight. Couldn't this wiring net double as reinforcing for the wing skin? Of course it could, but only after finding a material equally suitable for both, and after developing a mat-laying technology that will provide good electrical connections on the right places.

Sailplane development has lead the way for flying in many ways. The requirement for a very light, strong structure of exact form and high surface finish may create an entirely new class of flexible structures. First of all, flaps and control surfaces would be primary candidates for it.

Another interesting possibility would be to use the propeller (in steep glides) for recuperative braking, by driving the motor as a generator. This can be done by blade rotation beyond feathering. In this case, motor polarity, too, is to be reversed. A more elegant and faster way of doing this would be by propeller blade chamber reversal, a very nice problem for flexible structure development.

5. ATMOSPHERIC ENERGY UTILIZATION

In view of the poor concentration of solar energy, alternate sources of power should not be ignored. Every kind of updraft can give additional height that will translate into distance or speed. Sailplane-like thermalling and ridge soaring present no special problems, except that of determining optimal power settings and glide speeds.

For fast cross-country flying with auxiliary power, dolphin-style traversing of thermals comes into its own. Specialization and refinement of flight tactics may provide an extra bonus here, also.

Energy may also be extracted from horizontal or vertical wind gradients and from wind speed oscillations. Dynamic soaring is practised by several bird species and, after an early but slow beginning, the number of publications on sailplane dynamic soaring is now growing rapidly (see e.g. [12-16]).

Dolphin flight and dynamic soaring require good maneuverability. In longitudinal motions and in yaw, conventional (tail-behind-the-wing) layout airplanes use a normal force opposite to the desired change of direction for generating the necessary change of moment. Because of this, there is a lag in response, and longitudinal stability and maneuverability are interacting [17]. For advanced fighter-type designs, these restrictions are eliminated by additional movable surfaces. The drag penalty, due to these, is unacceptable for a SPP. Even the complication of a retractable foreplane would be too much for it. In all likelihood, the only way of combining unrestricted agility with really high lift to drag ratio, is by going to the canard design. This arrangement also gives much less sink in tight circling [18], an extra bonus worth striving for. Sorry to say, tail-first configurationsalso possess fundamental foreplane-wing interaction problems. These may sometimes lead to substantial losses in performance and to dangerous flight characteristics. Bad forward visibility and safety problems in winch launching could also prevent making use of the idea. Nevertheless, this configuration deserves serious investigation because of possible advantages.

6. ECONOMICS AND FLIGHT OPERATIONS

Up to now, no mention has been made of the probable research/development costs, of tooling and manpower calculations, and market research. By present-day standards, the SPP would be economically doomed to failure because of very high price levels many people could not afford. But we have only recently witnessed the birth of the pocket calculator industry, an economic miracle nobody dreamed of a few years ago. May it repeat itself...and in flying!

After somebody acquires a plane, he or she wants to fly and utilize it for air travel. After complying with basic laws of aerodynamics and mechanics, flight safety depends on the ability to see and to be seen. Present day sailplane avionics are very deficient in this respect. In instrument flight, there is practically no obstacle and collision warning. Air control centers cannot take the burden of individually monitoring all private flying. Regionally coded automatic transponders placed on mountain tops, etc., could form some sort of self-service precision navigation network based on lightweight airborne computers. Theoretically, collision warning should also not be outside the scope of the system, but this problem looks more suitable for automatic central data processing.

Current ATC procedures are very serious on sailplane-type flying in compelling practically all controlled flights to prescribed route and altitude holding. In this respect, some more freedom in controlled airspace is needed for making the course and altitude deviations necessary for atmospheric energy utilization.

7. SUMMARY

Solar-powered flight is not impossible, but it depends on several improvements being achieved. Some of these necessary improvements are:

- an overall efficiency of $\bar{\eta}=0.5$ or more;
- DC motor weight of less than 1 kg/kW;
- battery specific power of about 200 W/kg;
- structural efficiency giving a weight factor for the wing of $c_W=0.004$ or less
- integral wiring;
- flexible structures;
- a CCV configuration of very good L/D ratio;
- light and cheap IFR avionics;
- improved ATC procedures, etc.

These problems can only be solved by far sighted, long-term research and international cooperation.

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REFERENCES

1. Pigott, D.:"Glider Pilot Training & the Role of the Powered Glider," (OSTIV Publication VIII, Part I, 1965).
2. Ledermann, W.: "Erfahrungsbericht über die Verwendung des Moterseglers für die Grundschulung von Segelfliegern," (Aero Revue, April, 1970, #4, pp. 183-184).
3. Pigott, D.: "The Role of the Motor Glider for Gliding Training," (Aero Revue, August, 1975, #8, pp. 461-463).
4. Held, H.: "Possible Uses for Powered Gliders in Modern Glider Training," (Aero Revue, Sept., 1979, #9, pp. 528-529 and Oct., #10, pp. 589).
5. Shenstone, B.S.: "Manpowered Aircraft," (OSTIV Publication VIII, Part I, 1965).
6. "Aeronautics and Astronautics," Nov. 1975, pp. 28-29.
7. de Hoffmann, F.: "Energie-Speicherung und Methoden des Energie-Transports," (Naturwissenschaften 64, Jg. Heft 4, 1977, April, pp. 166-173).
8. Scherrer, H.: "Stromquellen für den Elektroflug," (Aero Revue, Aug. 1976, pp. 468-471).
9. Communications Satellite Corporation ad.
10. Wattson, R.K., Hoehne, V.O.: "Shrouded Propellers & Their Application," (Aerospace Engineering, July, 1959, pp. 58-62
11. Stender, W.: "Sailplane Weight Estimation," (OSTIV, 1969).
12. Klemperer, W.B.: "A Review of the Theor of Dynamic Soaring," (OSTIV Publication V, 1958).

13. Fritsch, E.: "Zum Dynamischen Segelflug," (OSTIV Publication XI, 1970).

14. Tromsdorff, W.: "Flugmechanische und Technische Voraussetzungen für den Dynamischen Segelflug mit Bemanntem Fluggerat," (OSTIV Publication XIII, 1974).

15. Gorisch, W.: "Energy Exchange Between a Sailplane & Moving Air Masses Under Instationary Flight Conditions with Respect to Dolphin Flight & Dynamic Soaring," (Aero Revue, Nov., 1976, #11, pp. 691-692; #12, Dec., pp. 751-752).

16. Utgoff, V.V., Johnson, F.G.: "Dynamic Soaring in the Atmospheric Boundary Layer: An Experimental Investigation," Aero Revue, May, 1978, #5, pp. 293-298).

17. Gedeon, J.: "Statistical Aspects of Handling Criteria Research," (OSTIV Publication X, 1968).

18. Kovacs, Gy.: "Kacsák Vagy Repülőgépek? 6 Rész.," - Canards or Flying Machines? Part 6; in Hungarian - (Repülés, Vol. XXX, #12, 1977,dez., p. 17).

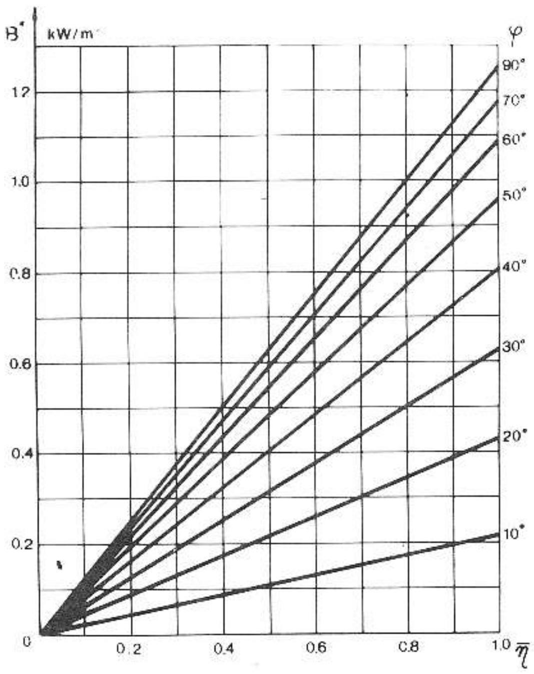

Fig. 1. Specific power available from solar radiation.

Period:	Lift Coefficient for c_y	Glide Ratio ε = D/L	Sign:	Line:
Present	Max. L/D 0.7	1/30	1a	Full
	Min. Power 0.9	1/28	1b	Dotted
Near Future	Max. L/D 0.7	1/35	2a	Full
	Min. Power 1.0	1/32.5	2b	Dotted
Far Future	Max. L/D 0.7	1/40	3a	Full
	Min. Power 1.1	1/37	3b	Dotted

Table 1. Present and expectable aerodynamic parameters.

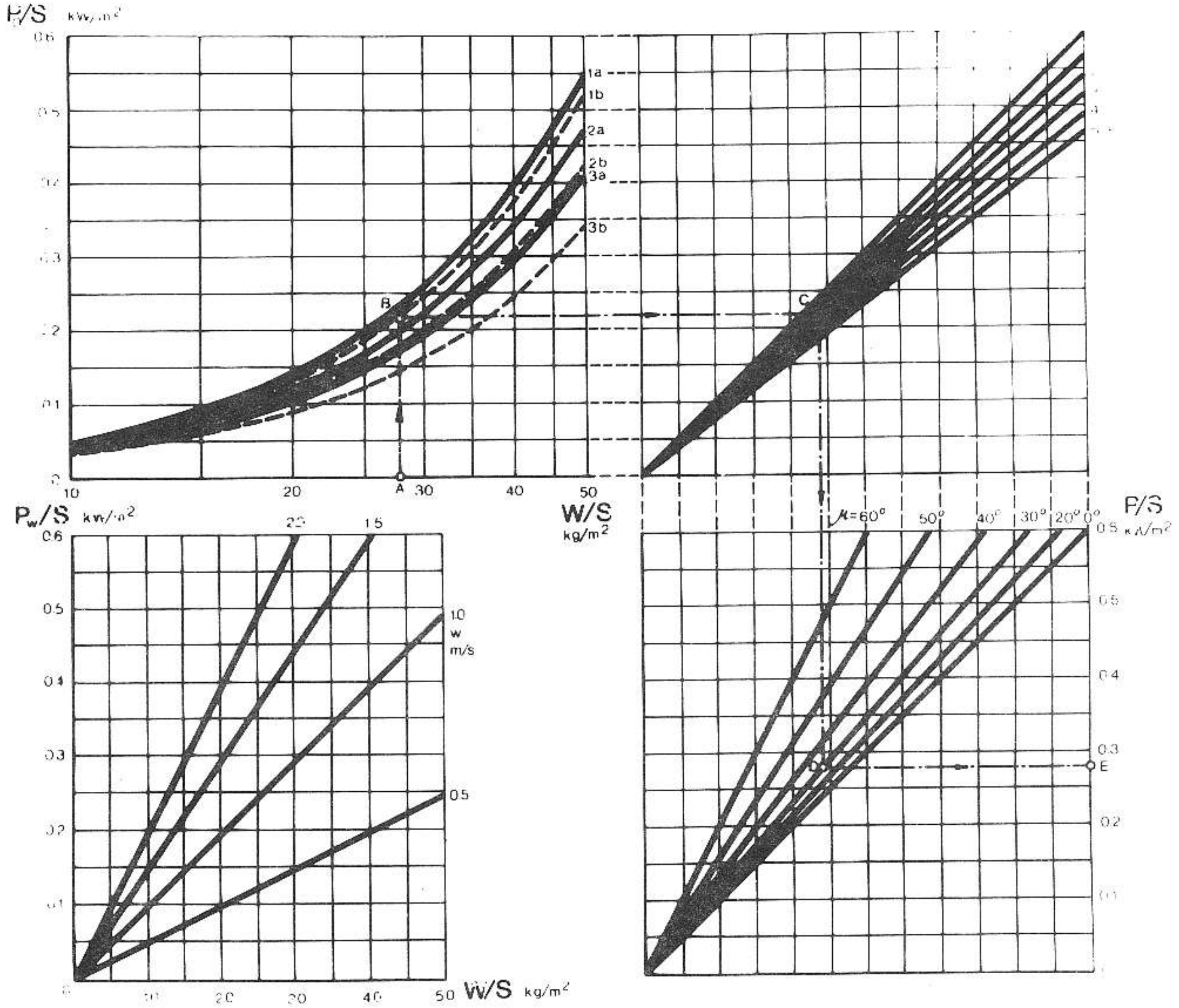

Fig. 2. Specific power required.

Battery Type:	Specific Capacity Wh/kg	Span of Life Cycles	Source:
Pb/PbO_2	40 - 50	∿1400	[7]
Ni/Cd	27	>500	[8]
Fe/NiOOH	48 - 65	∿2000	[7]
Ni/N_2	33 - 44	10 years	[9]
Na/S	120	∿1000	[7]
$Li(Al)/FeS_2$	120	150 - 1000	[7]
H_2/O_2	140 - 200		[7]

Table 2. Present and prospective battery/fuel cell parameters.