# SPORT AVIATION OF THE FUTURE. POSSIBLE CONCEPTS FOR FUTURE SPORT AIRCRFT USING DIFFERENT ENVIRONMENTAL FRIENDLY PROPULSION CONCEPTS

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## Abstract

*The goal of this study is to investigate how different green propulsion systems affect design, layout and performance of future sport aircraft. The study will present possible aircraft concepts using different propulsion systems and how performance requirements affect the design and choice of propulsion system. Limitations and comparisons with conventional combustion types will be addressed along with listing of potential risks with the use of different propulsion systems. This study is based and explores on the result of the student project made in the 2009 Aircraft Project Course at Linköping University.*

## 1 Introduction

This study focuses on the design of a new generation of eco-friendly electric powered sport aircraft.
All concepts presented are clean sheet designs This approach makes it possible to tailor the designs in order to minimize weight and drag. Electric power is produced by either batteries, fuel cells, solar cells or hybrids thereof.
It's commonly known that all known green propulsion systems of today deliver lower power-to weight ratios and less overall efficiencies than a comparable combustion engine, which implies that the only certification category applicable will probably be the category of powered gliders.
For the general aviation community, used to more powerful power plants, this might seem as a no-go solution for future aviation. The alternative for those who still would like to fly faster is to use bio fuels with existing combustion engine types.

## 2 Background

Previous human- and solar powered aircraft are the inspiration sources for this study.
Paul MacCready´s Gossamer Condor and Gossamer Albatross paved the way for how low powered flight could be achieved [1].
One of the most important ingredients for success in low powered flight is low weight. To design light is maybe not that difficult but to achieve simultaneous stiffness to be able to pick up loads is another question
Typical for these designs is that the structure accounts for a very large proportion of the empty weight.
Paul MacCready recognized this and borrowed inspiration from hang gliders for his designs.
He accomplished structural stiffness by means of external wire bracing. This affects drag, but in his case flight speed was limited anyway, so the choice was easy.
All previous contenders to the Kremer prize failed due to much too complicated structural designs based on then time gliders, which apparently became too heavy.

With the introduction of composites, overall stiffness became less of a problem and structural designs could be tailored.
Other inspiration sources worth mentioning, are Stuttgart University`s Icaré 2, which won a German contest for solar powered aircraft and Gunter Rochelt`s Solair II, which participated in the same contest.
Gunter Rochelt designed the first successful human powered aircraft in Europe (Muscleair II). The structural design of this aircraft inspired Eric Raymond (USA) to design the Sunseeker. The Sunseeker was a breakthrough in solar powered aircraft design when first introduced.

## 3 Solar powered aircraft

### 3.1 Sun power and user constraints

The sun peaks at 1000 W/m2, i.e. at noon on a clear day in the summer time. In the middle of Europe one might expect an average of 800 W/m2 under the same circumstances and in Sweden even less.
This means the use of such an aircraft is geographically limited as well as user period limited, so basically the period we are talking about is the glider season.
If you happen to fly a glider or a sun powered aircraft there's sun energy in both cases, either energy supplied by thermals or solar cell produced electricity.
Solar cells have no doubt an edge over thermals since solar cell produced electricity provides endurance and non-interrupted flight. Pilots will be able to stay up longer in the air without having to worry about the possible presence of thermal activity.
Assume we design an aircraft for an average of 800 W/m2 solar radiation. We then might be able stay up for nearly 7 hours. If simultaneously excess solar power is used to recharge batteries, 9-10 hour could be reached.

### 3.2 Market

Who would then be the obvious target group? Glider pilots no doubt. Such an aircraft could be marketed as a next generation motor glider, with self-launch capability.
It will bring more flexibility to gliding no doubt. Time in the air is extended while soaring in thermals is still made possible.

### 3.3 Basic assumptions

Efficiencies of solar cells ranges between 10 % to + 20%. There are solar cells with even higher efficiencies, but the higher the efficiency, the higher the cost.
For this study we used solar cells with an efficiency of 20% [2].This means total propulsion efficiency for our designs ends up around 15% including propeller efficiency.
Other assumptions:

- Designs are based on an average solar radiation of 800 W/m2
- Max. sink rate in glider configuration should be less than 0.7 m/s
- Min. cruise speed, i.e. solar powered cruise speed, 20% above stall speed
- Min. climb speed: 2 m/s.

- Hybrid design, i.e. battery power for take-off and climb, solar power for cruise.
- Structure sized in accordance with JAR 22 (motor gliders).
- Structure made in monolithic carbon and carbon/nomex sandwich to minimize weight and maximize stiffness.

An example of a simple sizing diagram, used for initial sizing, is shown in Fig. 1.

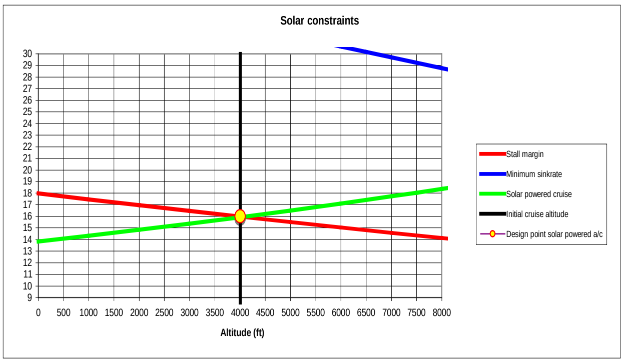


**Fig. 1. Sizing diagram solar powered flight. Wing loading (kg/m2) versus cruise altitude (ft)**

## 3.3 Conventional configurations

The conventional configurations are designed as pushers. An inverted fin shields the propeller on ground and during take-off and landing. The propeller is foldable, which minimizes drag while soaring. The horizontal stabilizer is positioned on the top of the inverted fin and can be used for extra solar cell area if needed. The fin doubles as landing gear, i.e. includes the tail wheel. The landing gear arrangement is a bicycle arrangement, with the main gear positioned centrally in the fuselage.
Incidence of the wing is set at 5 degrees, since the aircraft can't rotate on take-off; the aircraft lifts off by itself. This simple gear arrangement minimises landing gear weight and drag.
In plan view the wing and horizontal stabilizer are designed squared to maximize solar cell area.
The aircraft can either be a single-seater (Fig.2) or a two-seater (Fig.3). In the two-seater version pilots are seated side by side to minimize C of G travel. Main dimensions and properties are displayed in Table 1.

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.1 | 7.5 |
| Span (m) | 16.8 | 26.8 |
| A | 23 | 23 |
| S (m2) | 19.6 | 31.2 |
| Empty weight (kg) | 135 | 270 |
| Battery weight (kg) | 36 | 66 |
| Pilot+parachute (kg) | 90+7 | 194 |
| MTOW (kg) | 268 | 530 |
| Max. shaft power (kW) | 8 | 16 |
| Solar shaft power (kW) | 2.2 | 4.1 |
| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 77 | 76 |
| (L/D)max | 33 | 33 |
| Endurance (h) | 6.9 | 6.9 |
| Climb rate (m/s) | 1.8 | 1.7 |
| | | |

**Table 1. Conventional configurations**

**Fig. 2. Single-seater**

**Fig. 3. Two-seater**

## 3.4 Canard configurations

In the canard version the canard doubles as main gear and trim surface. As in the conventional configurations the canard aircraft would be configured as a pusher with foldable propeller for soaring purposes. In this case the motor and propeller is mounted at the top of a T-tailed fin to give sufficient ground clearance. The T-tail acts as an additional longitudinal control surface, but its main object is to help the aircraft to rotate on take-off. The rotation problem refers to the landing gear arrangement. The aircraft can be configured as a single-seater (Fig.4) or as a two-seater (Fig.5). In the two-seater version the pilots are seated side by side to minimize C of G travel. Main dimensions and properties are shown in Table 2.

**Fig. 4. Single-seater**

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.4 | 8 |
| Span (m) | 16.7 | 21.8 |
| A | 18 | 18 |
| S (m2) | 15.4 | 26.5 |
| Empty weight (kg) | 114 | 218 |
| Battery weight (kg) | 36 | 66 |
| Pilot+parachute (kg) | 97 | 194 |
| MTOW (kg) | 247 | 478 |
| Max. shaft power (kW) | 8 | 16 |
| Solar shaft power (kW) | 2.2 | 3.7 |
| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 80 | 76 |
| (L/D)max | 33 | 35 |
| Endurance (h) | 6.9 | 6.9 |
| Climb rate (m/s) | 2 | 1.8 |

**Table 2. Canard configurations**

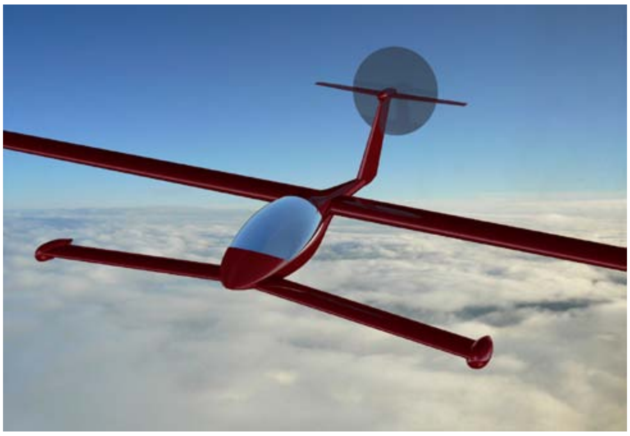

**Fig. 5. Two-seater**

The resulting tables indicate that the canard configurations seem to be more favourable, showing lesser empty weights. This is mostly due to lower bending moment on the fuselage thanks to the canard combined with a lower aspect ratio on the wing while aiming at approximately the same L/D max for all configurations.
All configurations have the same thickness-to chord percentage on the wing (t/c=20%).
Only one configuration actually manages the stipulated climb rate requirement of 2 m/s, but the others are pretty close and can probably, with some fine-tuning, be made to meet that requirement. All configurations cruise at fairly low speed in sun-power mode. The difficulties in handling such an aircraft in cruise becomes apparent by studying Fig. 6, which shows a V-n diagram typical for all configurations.

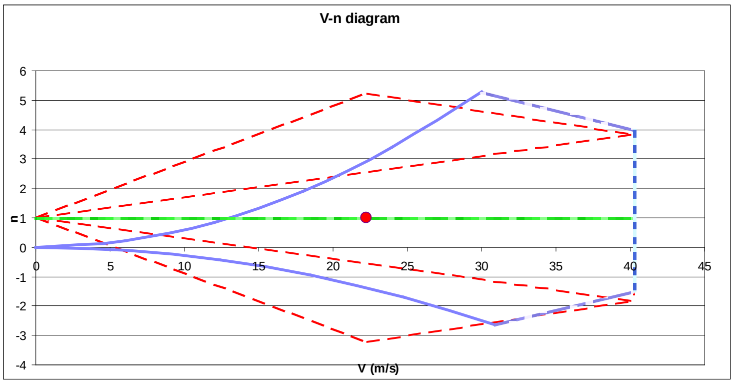


**Fig. 6. Typical V-n diagram**

In Fig.6 the blue curves and lines mark the manoeuvre envelope, while the red dashed lines mark the gust envelope. By design sun-powered aircraft will always be close to the stall limit in cruise.

This means a sudden gust or a too sharp turn might bring the aircraft into a stalled condition and since there's no additional power available, it requires a skilled pilot to manoeuvre the aircraft.
In a canard configuration the canard will have to stall first due to stability, which means maximum lift of the wing can never be fully explored. Thus special attention needs to be put in into the aerodynamic design of the canard in order to avoid premature stalling; otherwise it will be a limiting factor for the whole design.
The canard configurations can taxi around and take-off unsupported thanks to the tri-pod landing gear configuration. The conventional configurations on the other hand require assistance on ground in their present form.

## 4 Battery powered aircraft

### 4.1 Battery power and constraints

Studies of battery-powered aircraft have been going on for quite a while. Most "electric" aircraft are pure derivatives of existing combustion engine designs, but there are new designs emerging as well. The Chinese Yeneec E430 [3] and German PC-Aero´s Electra One [4] are some late arrivals, which look promising.
The batteries we are using for this study are Li-ion batteries. The internal resistance of Li-ion batteries is 320 mΩ which is relatively higher compared to other battery types which limits the discharge rate. However the requirement of less power for motor gliders makes it acceptable for the designs. The performance of Li-ion batteries degrades at higher temperatures but for motor gliders cruising at relatively low altitudes make it possible to operate close to ambient temperature. The individual battery packs can be connected in parallel to simply increase the endurance time. Moreover Li-ion batteries proved to have much safer track record in recent years.
The reduced cost, increased life cycle, and improved safety of Li-ion batteries have provoked interest for its application to next generation electric aircraft. As the energy density of these batteries is improving over time with wide operating temperature range, expected market for powered gliders is no doubt huge enough.
To date the energy density of Li-ion battery varies between 150 and 250 Wh/kg. For this study the capacity of a Li-ion cell used is 40 Ah and energy density of 240 Wh/kg. The designs are based on max. continuous current of 40 A (1C) and the number of cells in series and parallel is determined based on design and required power.

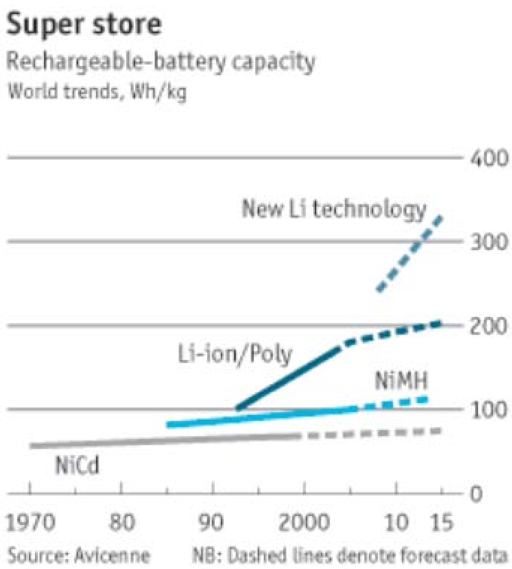


**Fig. 7. Energy density trends for Li technology batteries [5]**

In order to get endurance or range at least comparable to that of combustion engine designs we have to carry a lot of batteries, which means lots of weight.
To reach endurance or range cruise speed must be low to save energy, i.e. similar to the solar powered aircraft situation. The great difference is that with a solar powered aircraft, in the cruise case, we have zero excess power, while with battery powered flight there´s plenty of power margin. This makes it a lot easier for the pilot to control the aircraft while maneuvering or handling a gust situation. In addition, having a larger power margin, means higher cruise speeds are possible but on the expense of endurance or range of course.

## 4.2 Configurations

The battery-powered configurations are based on the sun powered, i.e. both conventional (Fig.9 and 10, Table 3) as well as canard layouts and single- as well as two-seaters are presented. The basic assumptions are the same as those for the sun powered aircraft (3.3).
The difference between the sun powered versions and the battery powered is that wing loading can be increased since we don´t have to care about the limiting sun power anymore (compare Fig.1 with Fig.7). Increased wing loading means higher stall speeds, so we need to increase our cruise speed to keep the 1.2 stall speed margin. Since battery weight will be a dominant factor, we need to decrease structure weight wherever we can and the major portion of structural weight is in the wing itself.
So the solution is to reduce aspect ratio and taper ratio (since a squared plan form is not needed anymore), which means L/D will suffer and so will soaring performance.

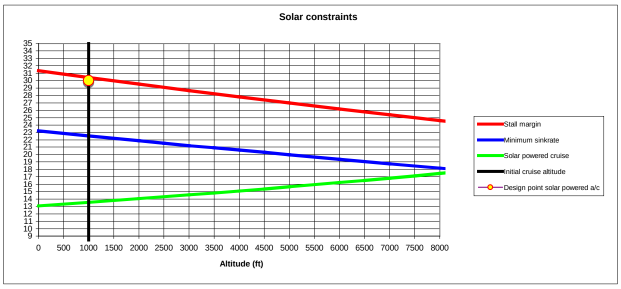


**Fig.8. Sizing diagram, battery powered aircraft. Wing loading (kg/m2) versus cruise altitude (ft)**

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.6 | 8 |
| Span (m) | 11.7 | 16.4 |
| A | 15 | 15 |
| S (m2) | 9.1 | 17.9 |
| Empty weight (kg) | 101 | 189 |
| Battery weight (kg) | 76 | 155 |
| Pilot+parachute (kg) | 97 | 194 |
| MTOW (kg) | 274 | 538 |
| Max. shaft power (kW) | 12 | 25 |
| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 84 | 84 |
| (L/D)max | 26 | 27 |
| Endurance (h) | 3 | 2.8 |
| Climb rate (m/s) | 2.7 | 2.7 |
| Max cruise speed (km/h) | 160 | 160 |

**Table 3. Conventional configurations**

**Fig. 9. Conventional two-seater**

**Fig.10. Conventional single-seater**

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.6 | 8 |
| Span (m) | 10.8 | 15.2 |
| A | 13 | 13 |
| S (m2) | 9 | 17.7 |
| Empty weight (kg) | 97 | 183 |
| Battery weight (kg) | 76 | 155 |
| Pilot+parachute (kg) | 97 | 194 |
| MTOW (kg) | 270 | 532 |
| Max. shaft power (kW) | 12 | 25 |
| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 92 | 92 |
| (L/D)max | 28 | 30 |
| Endurance (h) | 2.9 | 2.9 |
| Climb rate (m/s) | 2.7 | 2.6 |
| Max cruise speed (km/h) | 160 | 160 |

**Table 4. Canard configurations**

## 5 Fuel cell powered aircraft

### 4.1 Basic assumptions and constraints

The German DLR Antares is a derivate of an existing high performance glider. The Antares carries two external wing pods; one is the hydrogen tank while the other is the fuel cell itself.

In the Antares the carriage is external and no doubt this is a good approach if your design is based on a derivative, but the resulting configuration creates excessive drag. In a blank paper design you would probably take a different approach trying to integrate more by making use of the existing hull of the fuselage or wing.

One big problem is that large, high-pressurised volumes are needed for the tank to reach endurance and the tank itself tends to get voluminous as well as heavy. Thus it needs to be housed close to the centre of gravity, i.e. the same problem as in the case of the batteries in the solar powered and battery powered versions. Another complication is that the fuel cell tends to get quite hot and this requires good ventilation.

The designs for the fuel cell powered aircraft are based on the battery-powered configurations, i.e. battery weight is exchanged for fuel cell plus tank weight, which means MTOW will be the same. External geometry will be the same as for the battery powered aircraft (Table 3 and 4). The main difference is that endurance will improve (Table 5 and 6).

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.6 | 8 |
| Span (m) | 11.7 | 16.4 |
| A | 15 | 15 |
| S (m2) | 9.1 | 17.9 |
| Empty weight (kg) | 101 | 189 |
| Battery weight (kg) | 76 | 155 |
| Pilot+parachute (kg) | 97 | 194 |
| MTOW (kg) | 274 | 538 |
| Max. shaft power (kW) | 12 | 25 |
| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 84 | 84 |
| (L/D)max | 26 | 27 |
| Endurance (h) | 3.5 | 3.2 |
| Climb rate (m/s) | 2.7 | 2.7 |
| Max cruise speed (km/h) | 160 | 160 |

**Table 5. Conventional configurations**

| Type | Single-seater | Two-seater |
|---|---|---|
| Overall length (m) | 7.6 | 8 |
| Span (m) | 10.8 | 15.2 |
| A | 13 | 13 |
| S (m2) | 9 | 17.7 |
| Empty weight (kg) | 97 | 183 |
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| Propeller dia. (m) | 2 | 2 |
| Cruise speed (km/h) | 92 | 92 |
| (L/D)max | 28 | 30 |
| Endurance (h) | 3.5 | 3.2 |
| Climb rate (m/s) | 2.7 | 2.6 |
| Max cruise speed (km/h) | 160 | 160 |

**Table 6. Canard configurations**

### 4.2 Fuel cell

The fuel cell used for the design is of the proton exchange membrane (PEMFC) type and is based on the specifications given in Table 7 [6]. The hydrogen flow rate (consumption) is estimated to be 0.024 kg/min. and 0.047 kg/min. for single- and two-seater respectively. The air supply counts for 2.034 kg/min. and 4.067 kg/min. respectively.

| | | |
|---|---|---|
| Voltage per cell (V) | | 0.686 |
| Total output voltage (V) | 1-seater | 115 |
| | 2-seater | 464 |
| Max. output current (A) | 1-seater | 113 |
| | 2-seater | 56 |
| Hydrogen utilization (%) | | 50 |
| Oxygen utilization (%) | | 20 |
| Current density (mA/cm$^2$) | | 200 |
| Platinum density (mg/cm$^2$) | | 0.2 |

**Table 7. Fuel cell specification**

The estimated weight of fuel cell stack and hydrogen cylinder [7] given in Table 8 counts for a total weight of 68 kg and 128 kg for single- and two-seater respectively which includes cell balancer (1 kg), power cables (3 kg) and air pump (3 kg) with a hydrogen capacity of 2.03 kg and 4.55 kg respectively. The dimension of cell stack comes out to be 0.11×0.71×0.24 m and 0.45×0.5×0.17 m for single- and two-seater respectively.

| | | |
|---|---|---|
| Fuel cell stack weight (kg) | 1-seater | 23 |
| | 2-seater | 42 |
| Hydrogen tank weight (kg) | 1-seater | 45 |
| | 2-seater | 86 |

**Table 8. Weights**

Therefore the total power supplied by fuel cell system for the single-seater version is 13 kW for a capacity of 21 kWh. The diameter and length of hydrogen tank (cylinder) is found to be 0.16 m (16 % for chord) and 5 m respectively for a volume of 0.101 m$^3$. For the two-seater the total power is 26 kW for a capacity of 41.2 kWh. The diameter and length of tank is found to be 0.185 m and 7.4 m respectively for a volume of 0.2 m$^3$. The maximum tank pressure is assumed to be 45 MPa.

### 4.3 Integration

One idea is to integrate the tank into the load carrying structure and one such solution could be to make a tubular main spar, which doubles as main spar and tank (Fig.11)

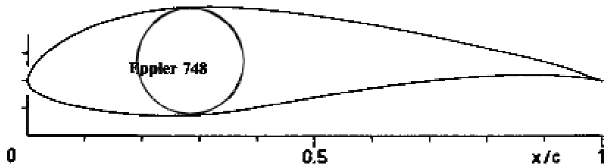


**Fig. 11. Available cross section of spar**

Since the pressure is high in the tank, tank pressure will probably size the spar, which normally would be sized by bending moment and thus might render a much too heavy wing. Even if such a spar could be made in carbon fibre with a liner as sealant, the ends of the pressure vessel would have to be made in metal to be able to integrate the necessary filling valves and that will make the design even heavier.

If this approach turns out to be too heavy, which one might suspect, an alternative solution could be to integrate a separate, non-load carrying hydrogen tank into the tubular spar and thus let the spar be sized by bending, as in normal cases. For this study we used the latter approach, since the former requires much deeper analysis than time have allowed, but nevertheless the integration question is no doubt interesting and should be considered in future studies.

## 6 Discussions

### 6.1 Solar powered aircraft

Since power by obvious reasons is limited solar powered aircraft will be sensitive to fly and will require skilled pilots, with regard to lack of excess power in critical situations (Fig.6).

Solar cell integration on the wing and in some cases also on the horizontal stabilizer requires much design work to get it right in terms of smooth integration of the solar cells relative to the upper surfaces to decrease drag as much as possible without having too much energy losses in the solar cell integration.

Also much effort has to be put into how maintenance of the solar cells should be done in an efficient way, i.e. not too laborious and not too costly, otherwise solar powered aircraft will be almost impossible to sell.

Current solar cells are quite brittle and therefore require stiff attachment. This puts additional requirements on the wing regarding torsional and bending stiffness and hence influences structural design.
The use of solar powered aircraft is limited and the type is essentially a self launched glider.

### 6.2 Battery powered aircraft

Battery powered aircraft seems to be the easiest way around to replace current combustion engine types. Battery powered aircraft have power to spare and thus require "normally" skilled pilots. Batteries can easily be charged wherever the aircraft lands since the infrastructure is well established.
Although the use of such aircraft is limited since batteries in general are known not to work that well in a cold environment, like a typical Swedish winter.

### 6.2 Fuel cell powered aircraft

It will probably take some time before fuel cell powered aircraft comes to the market. The technology seems promising but there's a basic problem with infrastructure; how would you charge such an airplane? Charging requires plenty of bottles with high-pressure hydrogen being stored at different airfields, which is non-existing today and how do you handle the explosion risk on filling?
Use will be limited by the same reason as for battery-powered aircraft; gas performance will degrade with lower temperatures.

## 7 How we made this study

This study was made using an in-house design program, which the students designed the baseline for in the Aircraft Project Course of 2009 at Linköping University. Some modifications were made to that baseline program in 2010, notably the electric motor model ant the structural weight assumptions. The design program basically relies on Torenbeek´s weight formulas [8], but they have been trimmed against real data (as built), i.e. Solair II weight data, which kindly has been published on the net [9]. The electric motor model used in this study is based on [10] and trimmed against published Solair II motor data [9].
The resulting design program has been tested against several applications; solar, battery as well as fuel cell powered aircraft and found to give comparatively good results.

## 8 Conclusions

The study has shown that it's quite possible to design electric aircraft with different power sources. The basic technology is available both in terms of material, electronics and electric motors.
For these kinds of aircraft light structures, light motors and systems as well as low drag is emphasised more than ever.
"Green" aircraft won't be any high-speed machines and can't compete with combustion-engined types since power is by design limited.
All alternative power sources described in this paper have limitations, but battery-powered aircraft seems most promising at least for the short term.
The concept is mature and has potential to materialise as a serial built product quite soon. The other power concepts differ in that matter. Solar powered aircraft have a basic problem with integration and maintenance of solar cells, which needs to be solved before the aircraft can be offered on the market. Fuel cells is still an evolving technology and needs more time to mature. It does look promising, but the major problem with fuel cells is infrastructure.

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