

## REGENERATIVE BATTERY-AUGMENTED SOARING

Paul B. MacCready, AeroVironment Inc.

*For presentation at the Self-Launching Sailplane Symposium  
National Soaring Museum, Elmira, New York  
July 16, 1998*

### Summary

Some auxiliary powered sailplanes take off with a propeller turned by a battery-powered motor. During flight, using technologies developed for regenerative braking of battery-powered cars, the propeller can be operated as a windmill and the motor be employed as a generator to recharge the battery. Some altitude is sacrificed during the charging, which is usually done in upcurrents; a portion (probably less than one half) of this "altitude energy" can then be utilized as desired later in the flight. Thus the pilot has an additional variable to incorporate into flight strategy, and the capability of extending the search for a safe landing site.

### Introduction

Several factors in combination support the concept that Regenerative Battery-Augmented Soaring (RBAS) may be an attractive aspect of future soaring:

**1. Battery power is clean and quiet.** The desire for clean and quiet self launching puts priority on exploring battery power for auxiliary powered sailplanes. Batteries are limited in the energy per kilogram they can store, but are adequate as an energy source to power the sailplane to heights where atmospheric energy sources can be utilized safely.

**2. Strong upcurrents provide a high power resource.** During thermal soaring, and to some extent in waves and slope currents, energy is conventionally stored as the potential energy of weight times height, for later conversion to speed and distance. In moderate and strong conditions, the rate of energy supply, the power, is large. Consider an ultralight sailplane with a gross weight of 400 lbs, having a minimum sinking speed of 1.5 ft/sec and thus capable of flying on a minimum of 600 ft lbs/sec or 1.09 HP (814 watts) of thrust power. In a strong upcurrent netting a climb of 1000 ft/min., or 16.7 ft/sec, it stores potential energy at a rate of 12.1 HP (9042 watts)—a huge power compared to that used in still air at minimum sink or best L/D speeds. A heavy two-place sailplane climbing at the same rate, grossing 1200 lbs including ballast, accumulates energy at triple the rate of the ultralight. Incidentally, all sailplanes will typically dash at high speed to the next thermal while consuming energy at rates 30 to 100% of the rate of power gain in the

thermal.

**3. Solar cells provide only low power.** Direct solar power, in bright sunlight, on an area of 2/3 of a 120 ft<sup>2</sup> wing, will provide about 1000 watts from high grade photovoltaic cells. The sunshine on the cells and the rising thermal both represent a use of solar energy. In strong convective conditions the thermal as a much stronger power source is especially appealing, and some of its power can be used for battery charging. Supplementary charging from solar cells is still an attractive option at all times during the flight, depending on sun availability.

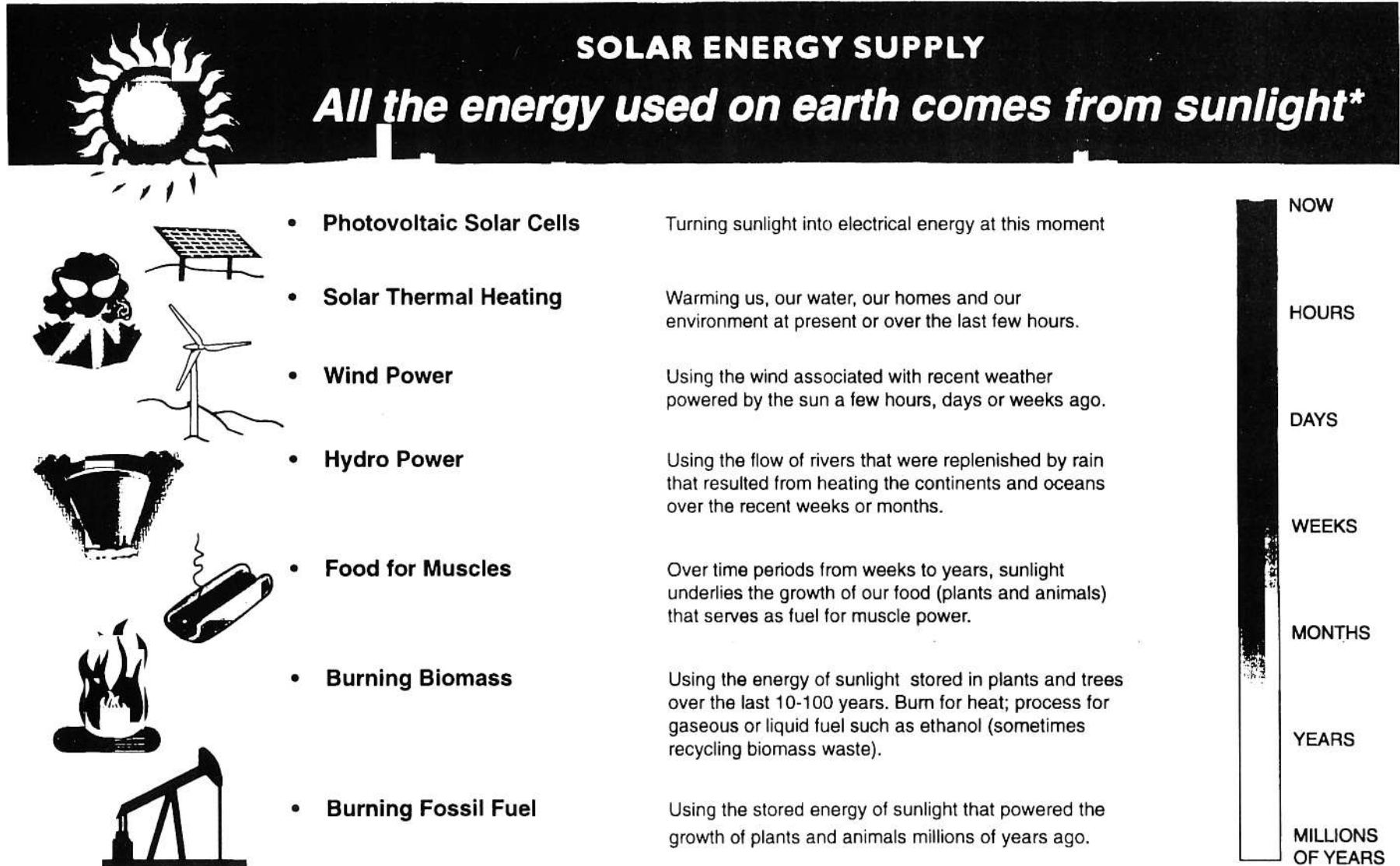
**4. A role model for battery replenishment is the regenerative braking of cars.** Recently, with the attention put on battery-powered cars, there has been considerable development on regenerative braking: putting the kinetic energy of braking into recharging the battery rather than heating the brake linings. Thus technologies have become well advanced for charging batteries with rapidly-changing inputs, and the technologies are improving rapidly.

**5. Recharge when the altitude penalty is small.** While you are being given large amounts of power in thermals, and also in many wave and slope current situations, you can conveniently take some of that power and recharge the battery you used for takeoff. Use the propeller in a windmill mode, extracting power as you sink relative to the surrounding ascending air, turning your electric motor into a generator. Charging is especially attractive on occasions when the sailplane is in a strong upcurrent but precluded from climbing (limited by cloud base, an inversion lid, Air Traffic Control, or oxygen requirements, or by the small vertical extent of a slope current).

**6. Spend the energy when it buys you a lot.** You can do such recharging on occasions throughout the flight, and use the energy to speed to the next thermal, or hunt for lift, or propel you to a safe landing spot—and perhaps still have enough energy in the battery for a takeoff the next day.

### What is Soaring?

RBAS opens up consideration of some philosophical questions about soaring. Virtually all soaring exploits solar energy; there is almost no other source of energy that powers our atmosphere and biosphere (see Figure 1). Soaring utilizes air motion of thermals, winds against



***All these energies are renewable, but on a human time scale we find it inconvenient to wait millions of years for fossil fuels to be regenerated. Hydro, wind, solar, and food are truly renewable on our human time scale. Burning wood (and other biomass) is renewable energy on our time scale - but only if we don't consume it too fast and run out.***

slopes, waves, perhaps even wind shear and turbulence; launching by bungee, foot, or horse (drawing on the solar energy in food), or by winch (using electricity from various sources such as nuclear\*, hydro, or fossil fuels), or auto or airplane using fossil fuels (the stored energy of sunlight of millions of years ago) or more recently created biomass fuels. A few sailplanes have battery-powered electric motors, primarily for takeoff. Some charge the batteries by solar cells – usually on the ground before flight. The 1980-81 solar powered Solar Challenger was initially tested with battery power, but its major flights utilized only photovoltaic cell power (plus sometimes thermals).

So what is pure soaring, and what is future soaring?

Setting up new categories stimulates competitions that help to motivate pioneers and to advance soaring. However, rules can stifle innovation, especially in the early stages of a field when the potentials, even the categories, are unclear\*\*. Consider paragliders; hang gliders; ultralight sailplanes; Standard, 15 Meter, and Open Class sailplanes; auxiliary power for various categories; and sometimes age or experience criteria. Will another category help or hurt? The topic deserves discussion.

I suggest that RBAS aircraft be used for fun, without competition or any categorization. As experience grows, perhaps competitions with logical rules will emerge. In any case, RBAS represents a new variable in the soaring equation, an additional factor to optimize as you continually re-strategize your flight. You would have as much as an extra 2500 feet of altitude at your disposal, borrowed from some 6000 feet of possible altitude gain earlier in the flight.

A brief look at natural flight helps illuminate some of the deeper issues of what defines soaring. True flight has evolved in nature by four different routes; insects first, and then three types of vertebrates: pterosaurs, birds, and bats. As with humans, all four types of natural fliers derive energy from food – vegetation, or other creatures that consume vegetation. However, in contrast to surface-bound creatures, many of these natural fliers evolved to use another energy source – the aforementioned slope currents, thermals, waves, etc. that benefit sailplanes. For some super soarers such as vultures, the atmosphere typically contributes far more than the food. Most insects fly, and their ancestors have been flying for over 200 million years. Some make use of upcurrents, but the real soarers came later. Pterosaurs survived over 100 million years before their extinction with the dinosaurs 65 million years ago. Birds, that coexisted with the pterosaurs and survived the dinosaur extinction, now demonstrate many excellent soaring techniques (and sometimes share tasks of hunting and using thermals with sailplanes). Bats, being nocturnal, rarely take advantage of soaring. Some giant pterodactyls,

\*The only non-solar source in this list.

\*\*This subject is explored, with regard to bicycling, in my article "Goals, Roles, and Technological Innovation", Medical and Scientific Aspects of Cycling, 1988; reprinted in The Technical Journal of the IHPVA, Vol. 6 No. 2, Summer, 1987.

the 11m span Quetzalcoatlus Northropi from over 65 million years ago, and a giant Teratorn, a condor-like bird from 6 million years ago, weighed over 200 pounds, perhaps over 300 pounds, and so fit the size and weight range of modern hang gliders and ultralight sailplanes.

With RBAS, sailplanes now are one up on birds. Natural creatures cannot internally store kinetic or potential energy; the RBAS vehicle can. And a plane that incorporates solar cells has another energy source unavailable to natural fliers. Perhaps our envy of the magnificent soaring techniques of birds will change to them envying us because we have several energy sources unavailable to them.

### **Mechanisms**

A propeller optimized for thrust is not optimized for serving the windmill function, and a propeller of any sort idling in the airstream will create drag. There are several approaches to handling these issues. One is for the propeller design to be a compromise yielding good, but not ideal, effectiveness in both charging and power delivery modes. A "true pitch" twist with a symmetrical airfoil might be a good starting point, providing minimum drag when free to rotate. When neither charging nor powering is taking place, this propeller, even with no drag from the motor/generator, is still a source of drag. However, the magnitude of the drag is very small compared to the total vehicle drag (say only a few percent at the best L/D flight mode.) The motor/generator drag can be eliminated by a clutch. Another method is to use a low RPM induction motor; no gearing is required, and there is no drag from permanent magnets. However, such a motor will be relatively heavy.

A more desirable approach would be to fold the propeller back into the fuselage when neither propulsion nor windmill generation is needed. From the efficiency standpoint, the most attractive approach is somehow to use two separate props, one optimized for propulsion and one for generation, both being folded back into the fuselage when they are not in use. A compromise would be to have a 4-blade prop, on a fore-aft generator/motor shaft, just behind the top of the fin. Design two blades for propulsion and two for windmilling; fold back and latch the unused pair along the rearward extended shaft, or fold back all four when none are needed. For good efficiency near the minimum sink (minimum power) speed at which the prop or windmill would often be operated, the diameter should be large. The fin location facilitates having a large diameter prop. All in all, there are many approaches to the electro-mechanical and aerodynamic compromises of RBAS.

The simplest electrical system is a direct drive to the motor/generator, plus a specific battery voltage. With this system the prop or windmill rpm can be altered by airspeed. Alternatively, the system can select for charge or power with the aid of a controllable pitch prop, or a continuously variable gear box, or a versatile power electronics module that can match battery, prop rpm, and charge/discharge or idling function as needed. The system management can be automatic or pilot-operated.

### **Examples of Powers and Energies**

The following example suggests that for a representative

system, for a foot of altitude sacrificed to charge the battery, 0.48 foot of altitude is available later in the flight. This calculation ignores the normal sink of the plane in a thermal or slope current, assuming we are interested in the additional descent rate caused by charging (a 1000 ft/min thermal assumes the plane, within charging drag, ascends at 1000 ft/minute). It also ignores the 1.5 ft/sec normal sink rate of the plane during the propeller powered climb. If the battery charge is used so slowly that it just covers the normal sink rate, there is no climb added although there is a duration and distance increase. If the battery, motor, and propeller systems are reasonably efficient and can provide high power and high climb rate, the effect of normal sink during the brief climb period will be relatively small. Putting all these factors together, one can generalize that the RBAS system will return to you in altitude equivalent when you want it some 1/3 to 1/2 of the altitude equivalent you "deposited" earlier in the flight.

If the aforementioned 400 lb sailplane extracts an additional 2.7 HP (2000 watts) from the air (its drag power, causing it to descend an extra 3.69 ft/sec while charging the battery), then with 75% efficiency (from the combination of windmill and generator inefficiencies) 1500 watts will reach the battery. Whatever the flight speed, the 2.7 HP represents an increase in sink rate of 3.69 ft/sec. With the battery later returning 85% of its extra charge, and motor efficiency and prop efficiency combined to total 75%, 63.8% of the 1500 watts from charging for a given period is available as propulsion power and can later permit 956 watts to provide later climb for the same time interval. 956 watts of thrust power during climb adds 1.76 ft/sec. Thus per second of charge and discharge you lose an extra 3.69 ft but than later have an extra 1.76 ft of altitude to spend. For every foot lost in charging, only 0.48 feet is later recovered. This 48% factor is not a good as obtained with an advanced regenerative braking system or a car because propeller and windmill inefficiency are not part of the car case, and the premium on weight for the airplane compromises motor/generator and battery efficiency

Lead acid and NiCad batteries typically deliver a maximum of 16-18 watt hours per pound. This is equivalent to raising the battery weight some 8-9 miles. If a battery weighs 10% of the gross weight, and propeller and motor system puts 50% of the energy withdrawn into climb, the battery would let the sailplane climb up nearly a half mile (for a machine flight duration of over 1/2 hour in calm conditions). New nickel metal hydride batteries can double the stored height potential, and lithium polymer batteries increase the height over 3-fold. The battery must be able to handle the occasionally-rapid charge and discharge rates. Batteries designed for high power can deliver in the range of 100-200 watts of power per pound. For motor weight, a reasonable factor for planning purposes is to assume 4 lbs per kilowatt. The systems designer will find complex interactions between the many design variables. For example, some batteries are inexpensive, some high energy, some high power, and some long life, but every real battery is a compromise because none score high for all

factors. Ditto for motors and for associated power electronics, and for the overall sailplane structural and aerodynamic design. As to motors, high power per pound motors are available, but operate at high rpm and require gear reductions that add weight, noise, and some inefficiency.

The pilot is also confronted with complex strategies for making most effective use of the battery system to improve the flight. Some batteries age rapidly if the maximum possible charge is taken from them.

This discussion has been hypothetical, not a report on a demonstrated concept, and so should be considered with caution. The regenerative braking system of a practical battery-powered car may deliver as mechanical energy less than 60% of the mechanical energy going into it. Regenerative braking with a typical electric-assist bicycle system may regenerate only 10-20% of the input energy, figures so low that incorporating regenerative braking is scarcely worth the complexity (unless there are dividends as an advertising gimmick). The bike system involves inefficiencies from the big rpm gear-up and gear-down ratios from motor to wheel, and a rather inefficient motor/generator because a more efficient one is too heavy and expensive. Compared to the car system, RBAS benefits from operating over a narrower rpm range, but there are the added propeller/windmill inefficiencies. Compared to the bike system, the gearup and gear-down ratios of RBAS are much smaller, and the large motor/generator can readily be more efficient. Considering everything, the 1/3 to 1/2 overall regeneration efficiency suggested here as obtainable with RBAS is not unreasonable, but achieving it is not a trivial task.

#### **A Flight Example**

The 400 lb gross weight of the ultralight sailplane discussed above is the sum of:

- 200 lb pilot, parachute, and some food and drink
- 40 lbs - lead acid or NiCad batteries
- 15 lbs-motor
- 155 lbs - airframe

With 10% of the gross weight invested in batteries, the fully charged battery can be used to climb nearly 2500 feet in still air.

Takeoff and climb to 1250 feet, leaving the battery 50% charged. Some weak early morning thermals let you stay aloft, barely, as you drift to a hill with a good slope current. You could just stay aloft at an altitude of 400 feet above the hill, but instead you choose to go back and forth at hill top level where your climb could be 5 ft/sec. You recharge the battery (10 minutes, 5 ft/sec, means 3000 feet, that can be converted to 50% of battery charge, later providing about 1200-1300 feet of climb capability). Now a thermal mingles with the slope lift and lifts you to 5000 feet. You dash toward where you suspect a thermal will be, but none is discovered, and after you descend to 1000 feet you use all of the battery to take you up to 3200 feet. Venturing further downwind you at last get good lift, but at 4500 feet you see that a stable layer at about 5000 feet puts a lid on what this thermal can do for you so you stay at 4500 feet, recharging

at a fast rate that is the maximum your system can handle, say 3000 watts, and taking only about 15 minutes for a full recharge.

After a 150 mile triangle, late in the day, with battery almost fully charged, you start a long last glide back to the destination, the airport where you took off 7 hours earlier. A headwind has increased, and you worry about falling short, but with the battery you climb up to 1200 feet over the airport. While descending to a landing you recharge the battery a bit while steepening your descent. You land with a 65% filled battery, enough for takeoff to lift the next day.

### **Some Final Considerations**

The high power available from the windmill-charging mode in strong upcurrents can be used for other applications than later climb. It can operate a heater for flight in cold conditions (or, in concept, an air conditioner for flight in hot weather). The electric power can also provide boundary layer control to improve glider efficiency, but in the practical case, at the Reynolds Numbers involved in the ducting and airfoil, and considering weight and complexity, converting stored energy to altitude can be expected to be more productive.

For a 2-place sailplane, lights and heat might permit multi-day flights on a slope current. A radio-controlled model airplane, with GPS navigation and a windmill charging system, could make an autonomous, long duration flight on a mountain slope in continuous wind conditions.

For a sailplane, the potential energy of height times vehicle weight is analogous to money in the bank. RBAS gives the pilot an additional "altitude bank account", money that can be withdrawn whenever the pilot wants – as long as enough deposits were made previously to keep the account from being overdrawn. The pilot has to deal with an unfriendly, greedy bank. The bank has a policy never to extend credit. It also charges a 50% (or more) service fee – consider it a tax – on every deposit. The pilot makes deposits when times are so good that the tax is deemed acceptable. Prudence dictates that the account never be completely depleted. The joy of flying will be increased if the pilot knows there is some "altitude" available in the account.

Electricity generating aloft, derived from upcurrents, can add a new dimension to soaring.