Solar Powered Aircraft

Part -1

Roger Bentley, Whitfield Solar Ltd.
&
Tony Gee, Independent & RAeS
Introduction

Many ways to fly using solar energy:
- Conventional aircraft – fossilised sunshine!
- Biofuel.
- Terrestrial solar beaming μwave energy to the aircraft.
- Double-skinned hot air balloon: inner, black, outer transparent.
- Airship: solar cells on upper surface, powering propellers.

But here:
- Heavier-than-air a/c powered by solar cells on wings & other empennages.
- Useful payload (surveillance, telecoms relay, or ~>100kg to carry one or more people).
- Need high efficiency: Look at sailplane technology (~80 years), and man-powered a/c (~30 years).
The Presentation

Part-1
- Availability of solar power
- Solar cells and their efficiencies
- Can solar cells make an aircraft fly?

Part-2
- Technical choices
- Aircraft & aircraft
- The future

(Not much on batteries, controllers, propellers etc., as covered in the ‘Electric Flight’ talk.)

First:
Look at man-powered a/c as efficient lightweight pre-cursors;
Then at solar-powered planes that have flown.
### RAeS: Solar Powered Aircraft

## Some Man-powered Flights

<table>
<thead>
<tr>
<th>Date</th>
<th>Plane / Origin</th>
<th>W’span (m)</th>
<th>W’area (m²)</th>
<th>Weight (kg)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>Puffin / Wimpenny</td>
<td>28.4</td>
<td>36.5</td>
<td>129.6</td>
<td>Straight: 0.8 km</td>
</tr>
<tr>
<td>1977</td>
<td>G’ Condor / MacCready</td>
<td>29.3</td>
<td>-</td>
<td>31.8</td>
<td>Kremer ‘8’ course</td>
</tr>
<tr>
<td>1979</td>
<td>G’ Albatross / “</td>
<td>29.8</td>
<td>-</td>
<td>32</td>
<td>English Channel</td>
</tr>
<tr>
<td>1988</td>
<td>Daedalus / MIT</td>
<td>43</td>
<td>-</td>
<td>31.3</td>
<td>Crete - Santorini</td>
</tr>
</tbody>
</table>

### Other Relevant Flights

(Will see later why these are significant for solar flight.)

<table>
<thead>
<tr>
<th>Date</th>
<th>Plane / Origin</th>
<th>W’span (m)</th>
<th>Weight (kg)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Voyager / Rutan</td>
<td>33</td>
<td>1020 empty</td>
<td>RtW non-stop</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4400 full</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>WhiteKnight 2</td>
<td>43</td>
<td>30,000 payload</td>
<td></td>
</tr>
</tbody>
</table>

for Virgin Galactic / Rutan
## RAeS: Solar Powered Aircraft

### Some Solar-Powered Flights (~100 a/c)

<table>
<thead>
<tr>
<th>Date</th>
<th>Plane / Origin</th>
<th>W’span/Area</th>
<th>Wt: Empty/Pay/AU</th>
<th>Notes (blue = person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>Sunrise I / R. Boucher</td>
<td>9.7 8.4</td>
<td>12.3 - -</td>
<td>First solar flight 11/74</td>
</tr>
<tr>
<td>1975</td>
<td>Sunrise II / - ditto -</td>
<td>9.8 8.4</td>
<td>10.2 - -</td>
<td>For several hrs</td>
</tr>
<tr>
<td>1978</td>
<td>Solar One / F. To, UK</td>
<td>20.5 24.2</td>
<td>104.3 P -</td>
<td>'Brief flight'</td>
</tr>
<tr>
<td>1979</td>
<td>Solar Riser / L. Mauro</td>
<td>9.1 9.5</td>
<td>55.8 - 125</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>Solair 1/ G. Rochelet</td>
<td>16.0 22.0</td>
<td>120 - 200</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>G’ Penguin / MacCr’dy</td>
<td>20.7 57.0</td>
<td>30.8 67.7 -</td>
<td>Lift-off &amp; flight</td>
</tr>
<tr>
<td>1990</td>
<td>Sunseeker / Raymond</td>
<td>- -</td>
<td>- P -</td>
<td>Across US in steps</td>
</tr>
<tr>
<td>1994</td>
<td>Pathfinder/NASA-M’Cr.</td>
<td>29.5 70.8</td>
<td>207 45 -</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Centurion/NASA-M’Cr.</td>
<td>61.8 148.3</td>
<td>533 329 862</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>Icare II</td>
<td>25.0 25.7</td>
<td>270 90 360</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>Helios / NASA-MacCr.</td>
<td>75.3 186.6</td>
<td>600 330 930</td>
<td>reached 96,800 ft</td>
</tr>
<tr>
<td>2003</td>
<td>Zephyr-3 / QinetiQ</td>
<td>12 -</td>
<td>14 - -</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>So Long / AC Inc.</td>
<td>4.8 1.5</td>
<td>12.6 - -</td>
<td>48 hrs, some soaring</td>
</tr>
<tr>
<td>2005</td>
<td>Sky Sailor /ETH, Swz.</td>
<td>3.2 0.8</td>
<td>2.5 - -</td>
<td>for Mars</td>
</tr>
<tr>
<td>2008</td>
<td>Zephyr-6 / Qinetiq</td>
<td>18 27.9</td>
<td>~32 2.0 -</td>
<td>82.5 hrs; 60,000 ft.</td>
</tr>
</tbody>
</table>
Gossamer Penguin
Solar Pathfinder
Helios
Helios
Sun Sailor – wing (with Si cells)

Sunrise 1
RAeS: Solar Powered Aircraft

Power from Sun: How much is there?

Above Earth’s atmosphere, facing the sun, power = ~1300 W/m².
Atmosphere attenuates - even on clear blue day - to ~1000 W/m²

Does not matter much where on earth you are:

• On a bright winter’s day in the UK at ~ noon, get the same amount of power - facing sun - as Timbuktu in Summer!

• So a solar plane in UK - flying with its wings banked to face the sun - would do OK.

• Problem with the UK winter is simply that not very much sunlight falls on a horizontal surface (wings) in level flight, and sun is not up for long.

• Need to consider distribution of sunlight energy vs wavelength.
Solar Cells & their Efficiencies - History

- Electricity from light (photovoltaic, PV effect) 1839 by Becquerel.
- First PV crystalline Si cells from Bell Labs, 1954, 4% efficient.
- By 1960 efficiencies were ~14%.
- Great hopes for terrestrial power. But, need large pure crystals, so too expensive for most uses. Used in space-satellites.
- Price of PV cells fell, and from 1970 specialist terrestrial applications - marine lights, mountain-top relays, etc. - ‘expensive’ power cheapest.
- Other types of cell developed: poly-crystalline silicon, amorphous silicon, cadmium telluride, copper indium di-selenide, and gallium arsenide.
- Japan’s ‘Project Sunshine’, and later Germany’s innovative feed-in tariff led to 10,000’s, of houses with PV roofs in the 1980s and 90s.
- Further fall in the price, coupled with widespread subsidies, now sees PV used for power stations of 100 kW - 50 MW, and global production of PV cells >4,000 MW p.a.
- Currently, commercial cells for terrestrial use cost ~£2 per watt; with efficiencies 14-20%.

Today’s most efficient cells use gallium arsenide, GaAs (in 30+% range). Too expensive for terrestrial use, but workhorse for satellites. Maybe they too will come back to earth!
Solar Cells & their Efficiencies

Two major aspects of solar cell efficiency:

- **Type of light absorption**
  If direct absorption (amorphous silicon, α-Si), gallium arsenide, GaAs) absorbs sunlight very well, and needs be only a few µm thick. Important for aircraft (less weight).
  If indirect (e.g., Si); typically needs 300 µm thick for good absorption, though 100 µm is acceptable.

- **No of semi-conductor junctions (band-gaps)**
  In a single-junction cell, photons in sunlight with energy below band-gap energy level cannot be used; while the more blue photons with energy above the band-gap are used inefficiently. The efficiency of single-junction cells in sunlight is theoretically limited to ~33%.

- A clever trick is to make the cell of many different layers, giving two or three band-gaps. This splits the solar spectrum into parts, and uses each part more effectively, raising theoretical limit of a 3-junction cell to ~55% (~35% achieved in practice).
Infra-red wavelengths - about 1/2 total energy
Ultra violet (uv): little energy, but destructive, each ‘photon’ packs punch. This spectrum is important for solar cell efficiency.
### Solar Cells & their Efficiencies

<table>
<thead>
<tr>
<th>Thickness (microns)</th>
<th>Efficcy. (%)</th>
<th>Output* (W/m²)</th>
<th>Density (kg/l)</th>
<th>Specific Power (W/kg)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Si</td>
<td>300</td>
<td>23</td>
<td>230</td>
<td>2.3</td>
</tr>
<tr>
<td>ditto</td>
<td>100</td>
<td>23</td>
<td>230</td>
<td>2.3</td>
</tr>
<tr>
<td>Amorph. (α-Si)</td>
<td>5</td>
<td>5</td>
<td>50</td>
<td>~2.3</td>
</tr>
<tr>
<td>3-jnct. α-Si</td>
<td>10</td>
<td>12</td>
<td>120</td>
<td>~2.3</td>
</tr>
<tr>
<td>CIGS</td>
<td>10</td>
<td>18</td>
<td>180</td>
<td>~6</td>
</tr>
<tr>
<td>CdTe</td>
<td>10</td>
<td>15</td>
<td>150</td>
<td>~7</td>
</tr>
<tr>
<td>GaAs (Ge sb.)</td>
<td>210</td>
<td>30</td>
<td>300</td>
<td>~5.3</td>
</tr>
<tr>
<td>GaAs (inv mt)</td>
<td>15</td>
<td>30</td>
<td>300</td>
<td>~6</td>
</tr>
</tbody>
</table>

* At 1000W/m² incident. ** Excludes substrate, mounting & encapsulation.

(Numbers in red are approximate.)

**PV cells are only a small part of weight of aircraft; so higher power can be important.**
Calculations for Solar-Powered Flight - 1

Level flight: ‘Compensate’ (counteract) glide descent:

Energy/sec. to balance sink = power = mgh = m * 9.81 * (v/n) [W]

(Where: aircraft mass: m [kg]; glide ratio, 1:n; forward speed: v [m/s], vertical sink in 1 sec., h = v/n [m])

Can solar cells give enough power to fly their own weight (level flight)?
(Assume glide ratio = 40 at 20 m/s)

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>Wt./m2 (kg)</th>
<th>Power req'd (W)</th>
<th>Output (at 1000 w/m2) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sq. m of cells:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 300μx-tal Si</td>
<td>23</td>
<td>0.7</td>
<td>3.4</td>
</tr>
<tr>
<td>- 3-junct. α-Si</td>
<td>12</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>- GaAs inv.mphc.</td>
<td>30</td>
<td>0.09</td>
<td>0.05</td>
</tr>
</tbody>
</table>

So plenty of power!
Calculations for Solar-Powered Flight - 2

Real aircraft

Zephyr-6

UAV, wt. ~30kg, assume glide ratio = 30 at 10 m/s

Power for level flight = 110 W.

Power from 3-junct. α-Si cells on wings: 1700 W

Sailplane: Jonker JS1

at min. wt. 350 kg +motors etc.; glide ratio ~50 at 21 m/s

Power for level flight = ~2000 W.

Power from 300μx-tal Si cells on wings: 2500 W

Conclusions: Normal PV on wings OK for UAV

But not OK for state-of-art sailplane;

Marginally OK for lightweight sailplane?
Approaches to PV Cell Efficiency

Source: Martin Green, University New South Whales
Solar Powered Aircraft

Part -2

Roger Bentley, Whitfield Solar Ltd.

&

Tony Gee, RAeS G.A. Cttee
Revisit Objectives

To sustain:

Least power/energy for tasks ranged between:

(i) stay local (UAV platforms for telecoms/survey);

(ii) go far/fast (efficient tourer).

Existing technology:

(i) 1902 ~ 1950: first viable controlled a/c-glider (Wright No2) to ‘downwind drifters’ with L/D ~30;

(ii) modern FRP sailplane (L/D ~50 - 65 for 15-25m (~50–80ft) spans i.e. readily-available technology (1970): go long way on ‘minimal’ energy.
Energy Storage

HALE* UAV** platforms: Climb to ~20+km; store solar p/energy (*High Altitude Long Endurance  **Unmanned Aerial Vehicle)

Batteries: technology driven by road vehicles with similar requirements for energy capacity/unit weight + ‘chemistry’ Nano-fibres for increased surface-area/unit-volume?

Super Capacitors: electric field and precision manufacture issues

Fuel Cells: chemistry

Anticipate improvements.
Design-breaks

1. Sustain level flight + marginal climb-rate: power $P_s$

2. ‘Reliable’ climb - $2P_s$?

3. Take-off capable - $3P_s$?

Cases 1 & 2 need assisted take-off *i.e.* as present i.c. sustainer gliders: winch or aero-tow launched and use retractable ~20kW ‘turbo’ motor *(when?)*.

Case 3 uses ~40-60 kW motor.

(1 bhp = 746W ~0.75kW; 1kW ~1.33 bhp)
**Units, Masses etc**

(back-of-envelope, ball-park)

60mph \(\sim 88\text{ft/s}\); \(60\text{kt} \sim 100\text{ft/s} \sim 30\text{m/s}\); \(2\text{kts} \sim 1\text{m/s}\)

1kt \(\sim 6000\text{ft/hr} \sim 100\text{ft/min} \sim 30\text{m/min} \sim 0.5\text{m/s} \sim 1.6\text{ft/s}\)

Mass \(M\) kilograms (kg); work \(w\) Joules (J); force \(F\) Newtons (N) to inc. lift \(L\) & drag \(D\); distance \(x\) metres (m); time \(t\) seconds (s), velocity \(v\) (m/s); power \(P\) Watts (W).

**Mechanical Work/Power Required**

a/c mass \(M\) requires support force \(F = Mg\) (where \(g = 9.81 \text{ m/s}^2 \sim 10 \text{ m/s}^2\))

Choices: Best glide (L/D) or minimum sink? Fast tourer, “platform”, UAV, HALE or what?

Example: assume \(M = 500\) kg \(\Rightarrow\) lift \(L \sim 5000\text{N}\)
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‘POLAR’ CURVE

\( v_{ms} \quad v_b \quad a/\text{speed } V_i \rightarrow \)

Sink
rate
\( V_s \)

min sink

best glide (L/D)
(for zero wind)
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Best Glide Case: ‘Fast Cruiser

Say L/D 50; M = 500kg so L ~ 5000N

It follows that drag D = L/50 = ~100N (~10 kg) = force required along flight path (to sustain flight).

Work \( w = FD \), power \( P = FD/t = Fv_b \)

Where, say, \( v_b = 60\text{kts} \sim 30\text{m/s} \)

So \( P = Fv_b \sim (100 \times 30) \text{ W} = 3\text{kW} \)

(Alternate reality check: \( P/\text{Energy loss rate} \), with 50:1 glide @ 30m/s a/speed

Sink-rate \( v_s = 30/50 = 0.6 \text{ m/s} \ i.e. \text{ vertical velocity of 5000N force} \)

Thence, power \( P = Fv_s \sim (5000 \times 0.6) \text{ W} = 3\text{kW} \)
Minimum Sink Case: ‘platform-drifter’

Min Sink $v_{ms} \sim 0.6$ sink-rate at best glide, say 0.4m/s @ 40kts (~20m/s) in round Nos.

So (vertical) work-rate of 500kg a/c reduces to

$$P = Fv_{ms} \sim Mg v_{ms} \sim 5000 \times 0.4 = 2000 \text{ W} = 2 \text{ kW}$$

i.e. reduces minimum energy scenario for same a/c.

Due to marginality, ‘Floaters’ likely to lead technology with lower sink rate and $v_{ms}$
Efficiency Issues

‘photon’ energy -> ‘electron’ energy -> mechanical:

1. ‘Diurnal’ solar availability winter/summer? latitude?
2. Sun azimuth angle? latitude?
3. Solar Panels
4. Batteries
5. Controller/converter
6. Motor(s)
7. Transmission
8. Propeller
Obliquity
(energy/area - cosine effect)
Solar Declination and Bearing Angles
(sun-tracking)

With horizontal solar panels, heading has no effect.

Tilting solar arrays improve solar angle: but must then fly 'cross-sun' and 'go about' onto reciprocal course with tilt reversal. Asymmetric handling problems? Possibly OK for UAV platform, but for 'cruiser'?

Smart Materials: surface tangential diffraction/absorption effects? Minimise scatter/reflection: stealth technology?
Increase Aspect Ratio => Efficiency

Man-powered a/c: long, narrow wings.

MacCready realised highest efficiency required higher forward speed at limit of human effort. Better to go with slower less efficient wing, further within ‘human viability’ range.

Applies equally to ‘Solar Viability’ range.
Swiss (ESA) HALE and other projects:

Design studies by ETH Zurich and EPFL Lausanne


From: Design of Solar Powered Airplanes for Continuous Flight - ETH Zurich (‘mono-cantilever’)

Fig. 9. Mass distribution with respect to wingspan assuming AR = 12
Motor and Propeller Efficiencies (ε)

A. Cocconi, AcPropulsion Inc, CA designer of ‘SoLong UAV’ which First achieved 24+hr solar flight (June ’05) From his presentation ‘Optimized Electric Drive Systems’ April 2008

Integral ‘DC’ motor + electro-magnetic/optic commutation. Variations: many coils (switched) or few (analogue sine prop)? P/magnet rotor (brushless) or ‘ironless’ [requiring slip rings?: liquid (Hg)??]

<table>
<thead>
<tr>
<th>rev/min</th>
<th>ε (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>89%</td>
</tr>
<tr>
<td>300</td>
<td>91%</td>
</tr>
<tr>
<td>450</td>
<td>93%</td>
</tr>
<tr>
<td>Cruise motor</td>
<td>89%</td>
</tr>
<tr>
<td>Cruise prop</td>
<td>85%</td>
</tr>
<tr>
<td>Combined</td>
<td>76%</td>
</tr>
</tbody>
</table>
Propeller Technology

Feathering – electric drive (from machine tool technology) already used for TSLMG upgrades eg Grob 109 and Schiebe SF-27 Super Falke with 105bhp engine for glider towing. (NB 140kW launches 2 a/c)

Fully feathering prop. enables ‘regenerative’ descent

Stemme S-10 2-seat 22m span SLMG uses centrally-mounted engine driving long prop shaft. Buried prop blades centrifugally deploy from (axially moveable) spinner/nose-cone. L/D 50 as glider.
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**Existing Technology: Schleicher ASW 28M**
*(single seat SLMG)*
Existing Technology: Schempp-Hirth Janus CT 2-seat ‘turbo’ (sustainer)

retrofitted to 20 yr old design
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Lange Antares
Antares Motor (stator)

Stator integral with strut; rotor built onto short prop shaft
Stemme S-10 SLMG

- cruise 100kt+
- long range 650mls
S10 Features

Standard Cockpit

Prop-shaft tunnel

Folding Prop
(+ feathering option)
### Stemme S10 Details

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing span:</td>
<td>23.00 m (75 ft 5½ in)</td>
</tr>
<tr>
<td>Width, wings folded:</td>
<td>11.40 m (37 ft 4½ in)</td>
</tr>
<tr>
<td>Weight empty:</td>
<td>660 kg (1,455 lb)</td>
</tr>
<tr>
<td>Max. t/o &amp; landing wt:</td>
<td>850 kg (1,874 lb)</td>
</tr>
<tr>
<td>Max. wing loading:</td>
<td>45.5 kg/m² (9.31 lb/sq ft)</td>
</tr>
<tr>
<td>Power: T/Off (5 Min)</td>
<td>115hp, 87.7 kw @ 5800 rpm</td>
</tr>
<tr>
<td>Power: (cont.)</td>
<td>100hp, 74.5 kw @ 5500 rpm</td>
</tr>
<tr>
<td>Max. power loading:</td>
<td>10.06 kg/kW (16.53 lb/hp)</td>
</tr>
<tr>
<td>Max climb rate S/L and MTOW:</td>
<td>4.14 m/s (817 ft/min)</td>
</tr>
<tr>
<td>Service ceiling:</td>
<td>30,000 ft (9,140 m)</td>
</tr>
<tr>
<td>T/O-run (MSL, ISA, MTOW):</td>
<td>205 m (675 ft)</td>
</tr>
<tr>
<td>T/O-distance (MSL, ISA, MTOW):</td>
<td>447 m (1470 ft)</td>
</tr>
<tr>
<td>Max range std tanks (2x45 ltr):</td>
<td>697 nm (1,290 km)</td>
</tr>
<tr>
<td>Best glide ratio@57 kt 106 km/h:</td>
<td>50</td>
</tr>
<tr>
<td>Min sink rate (@45 kt 83 km/h):</td>
<td>112 ft/min (0.57 m/s)</td>
</tr>
</tbody>
</table>
Duty Cycle: possibilities, tactics, strategy

Sun out: Use convection or not? Is there choice?

Clear blue sky: solar power 100% available but (causal) temperature inversion => poor thermal convection (swings & roundabouts!).

Fine weather Cu Clouds: <~50% Cu, can fly in ‘blue’ clear of cloud; however, air there is sinking due to outflow from cloud-convection (what goes up…!). Cu clouds tend to form ‘Streets’ which may or may not be continuous.

Best of Both sources?: when sun makes significant azimuth angle and oblique elevation angle to cloud, can simultaneously use solar energy and convective lift by flying sufficiently below cloud-base, remaining in direct sun-light.

Decide ‘how’ to fly.
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Cumulus Cloud ‘Streets’

Plan-view

Solar rad’n

Section

Solar rad’n
Solar Radiation Incidence Angles on Terrain

[\rightarrow = \text{strongest}
\text{‘local solar vector’ \textit{i.e.} for } \theta = \text{zero}]

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Scaling Issues

Cantilever problem of distributed load conventionally supported at wing centre.

(u/grad example) Distributed Load => bending moment prop. to span-squared: next slide).

MacCready and Rutan realised that multiple fuselages/booms enable more-evenly distributed payload along wing.
Bending Moments (BM)

\[ w = \text{load-force/unit length} \]

\[ \text{B.M} = \ Fl + \frac{wl^2}{2} \quad : F(l-x) + \frac{1}{2}w(l-x)^2 \quad : 0 \]
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‘Big Wings’
The Future

- PV cells
- Battery developments (Zephyr uses Li-S: twice Li polymer energy density)
- Fuel cells
- ‘Ultra’-capacitors (static charge storage)
- Motors: ‘rare-earth’ magnet materials
- Structural design, wing-loading
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Aurora - Odysseus
Summary

Solar-cells: Semi-conductor technology - multiple developments

Energy storage: batteries: Li-ion, Li-S, developing technology (m/vehicles); super capacitors; fuel-cells: chemistry + prod^n

Controller: p.w.m power electronics – good + regen

Motor: direct (‘frameless’) on prop shaft* - regen., wt reduction)

Propeller: feathering*; regen,  [*existing m/c-tool technology]

UAV – low a/frame weight; ‘marginal’ structure possible.

HALE – efficient energy strorage => height/PE (30km)

‘Platform’ vs. cruiser: different specs - viability criterion presently between?

Piloted => structural ‘reliance’ + payload => pilot skills for optimum use of solar energy?
THE END

Thank you for attending.