Meeting #4, Rochester (UK), July 2002

Design of Solar Powered UAV

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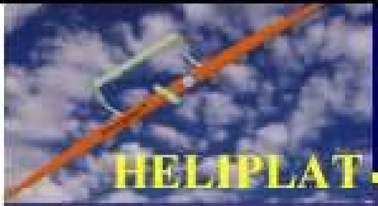
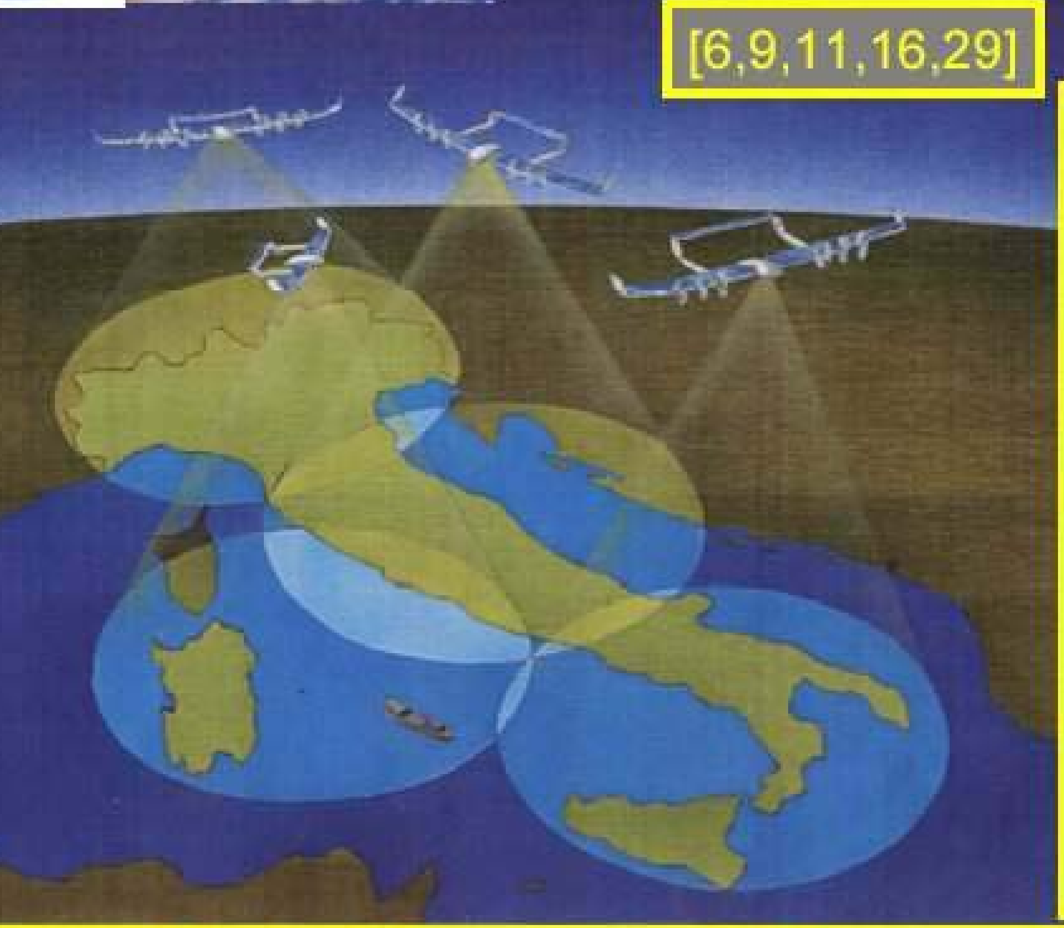


A.S.I. (1995-2000)

EC-5FP (2000-2002)

HELINET

[6,9,11,16,29]



- High Altitude (15-30 km) Very long Endurance (HAVE) UAV capable of remaining aloft for very long period of time by a solar-power & fuel cells system
- Artificial satellites, with the advantage of being much cheaper, closer to the ground and more flexible.

Self-launched and easily recovered for maintenance.

- More detailed land vision due to their relative closeness to the land and at cost much less than a real satellite.

ergy is derived from sun radiation by means of solar cells; excess energy pumped back into a fuel cells energy storage system; during the night, e platform would maintain the altitude by the stored (solar) energy.

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Applications

- **The missions of such platforms would cover a very large spread of applications:**

- atmospherical pollution control and meteorological monitoring,
- real-time monitoring of seismic-risk areas, coastal surveillance,
- telecommunications services such as cellular - telephones networks,
- video-surveillance, photogrammetry, hydrographic monitoring system
- agriculture monitoring, fire detection and so on.

- **From a flying altitude of 17 km, an area of about 300-400 km in diameter would be covered for communication transmission if the onboard antenna irradiation diagram is properly chosen.**

- **Just 4-5 platforms would cover the whole of Italy from North to South.**

- **7-8 platforms would cover the entire south Mediterranean Sea, from Spain to Israel.**

Solar-powered airplane

- 1st proposal of solar-powered airplane: by A. Raspet (USA) in 1954, after new photovoltaic solar cells were developed. Because of their very high cost and very low efficiencies, he didn't succeed.
- In 1974, the UAV Sunrise II, designed by R. Boucher, made the 1st solar powered flight after a launch from a catapult.
- At the end of '70, new new solar powered aeroplanes were designed by Paul MacCready:The Gossamer Penguin and Solar Challenger (1980) [17].

Gossamer Penguin

1st vehicle flying for 14 min. directly by solar power; wingspan of 21.5m, empty weight=31kg; pilot=44kg; Power 541 W.

Derived by the human-powered airplane Gossamer Albatross, it showed the criticality of the power balance mainly during the take-off phase, and the flight stability under gust.

Solar-powered airplane

Solar Challenger

- **Wingspan 14m; empty weight=98kg; pilot 62kg; Power 2.5kW; Vc=20m/s.**
- **Designed strong enough to flight under gust, it had a huge horizontal stabilizer and 22 sq.m. of solar cells. On July 1981, it flew 262 km from Paris to near London across the English Channel, staying aloft 5h 23m; maximum altitude 3.5 km.**

Solar-powered airplane

SUNSEEKER

Powered sailplane designed in 1986 by E. Raymond using 8 sq.m of thin flexible, low efficiency solar cells. On 1990, he flew 3967km coast-to-coast after 125 hours of flight made in one month. [22].

(Wingspan 17m; empty weight=90kg; pilot 70kg; Power 300W; V_C=38m/s)

ICARE' 2

Powered sailplane designed by the University of Stuttgart (D), it can takeoff by using rechargeable batteries (Span 15m; TOGW = 250kg) [23].


SUNSEEKER


ICARE' 2

Solar-powered UAV

1994:NASA ERAST (Environmental Research Aircraft & Sensor Technology) program. Four different aircrafts were initially developed for covering different altitude, duration and payload capabilities, but each one operating at a cost of no more $5000 per flight hour. Each of the four demonstrator is piloted from a ground station. A budget of $125 million was invested by NASA, from 1994 to 2000, for the ERAST program [24].


Altus


Pathfinder

4287-2. Photographed 28AUG1997
. (NASA/Nick Galante)


Perseus B

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC98-44585-3 Date: June 5, 1998 Photo by: Jim Ross

Aurora Flight Sciences' Perseus B Remotely Piloted Aircraft in Flight


Raptor

Solar-powered UAV

NASA ERAST Projects

Altus (General Atomics): high altitude UAV; Span 16.8 m; TOGW: 7.4kN; payload weight 1.4kN. Endurance: 4h @ 18.2 km or 36 h @ 12.1 km;

Main efforts: engine integration, flight operations techniques and procedures, light weight structures, payload integration, science mission demonstration.

Raptor/Demonstrator 2 (Scaled Composites): high altitude UAV; Endurance:48h@20km; Span 20m;TOGW: 9500 N,, payload weight 750 N

Main efforts: engine development, light weight structures, science payload integration, flight control systems, including over-the-horizon communication capabilities.

Perseus B (Aurora Flight Sciences): High altitude UAV; Span 17.8 m; Endurance: 48h @ 20 km; TOGW: 10.5 kN; Payload weight 2.3kN. double turbocharged engine.

Main efforts: engine concept, light weight structures, science payload integration, fault-tolerant flight control system.

Pathfinder (AeroVironment): solar-powered, ultra light- weight composite flying wing; Span 30 m; Altitude: 21.8 km; TOGW: 2210 N; Payload weight: 300 N.

Main efforts: solar cell (15% efficiency), battery and electric motor technology; flight operations techniques and procedures, structures, science mission demonstration; extremely long-duration flights.

Solar-powered UAV

Four solar-powered platforms (Pathfinder, Pathfinder+, Centurion, Helios) have been designed and manufactured by AeroVironment, under NASA contract: about $75 million have been financed by NASA to obtain the goal of a demonstrator that in year 2003 could continuously fly for 3-4 days.

In 1998 PathfinderPlus exceeded 24 km of altitude in a 15 hours flight.

In summer 2001, HELIOS (AeroVironment) solar-powered platform sets a new world record of 29350 metres (96863 ft) [17].

Pathfinder

Solar-powered UAV

Centurion (Empty mass 530 kg, Span 61.8 m, solar cells efficiency 18.5%, electric motors efficiency 93%) made successful first flight at low altitude on Nov 98.

Platform was designed by ultra-light structure: Kevlar and Carbon fibres.

UAV is being subjected, during the flight, to very large wing deflections, especially when gust load are applied to the platform. Detrimental effects on the aeroelastic behaviour of the wing in a very long endurance flight.

www.dfrc.nasa.gov/

Dryden Flight Research Center EC98-44803-127 Photographed NOV 1998
The Centurion solar-electric flying wing, one of several remotely piloted aircraft being developed under NASA's ERAST program, settles towards a landing on Rogers Dry Lake. NASA Dryden/Carla Thomas

Centurion

Helios Solar-powered UAV

www.dfrc.nasa.gov/
Erast Projects

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC00-0283-4 Date: September 16, 2000 Photo by: Tom Ts

Technician Marshall MacCready installs solar cells on the Helios Prototyp

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
ASA Photo: ED01-0140-2 Date: April 28, 2001 Photo by: Nick Galante
rewmen maneuver the Helios Prototype flying wing on its ground support dolly during
functional checkouts prior to its first flights under solar power.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ED01-0140-6 Date: April 28, 2001 Photo by: Nick Galante
Ground crewmen maneuver the Helios Prototype flying wing on its ground support dolly during functional checkouts prior to its first flights under solar power.

Helios Solar-powered UAV

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ED01-0209-7 Date: July 14, 2001 Photo by: Nick Galante/PMRF
The Helios Prototype flying wing is shown near the Hawaiian island of Niihau during its first test flight on solar power from the U.S. Navy's Pacific Missile Range Facility.

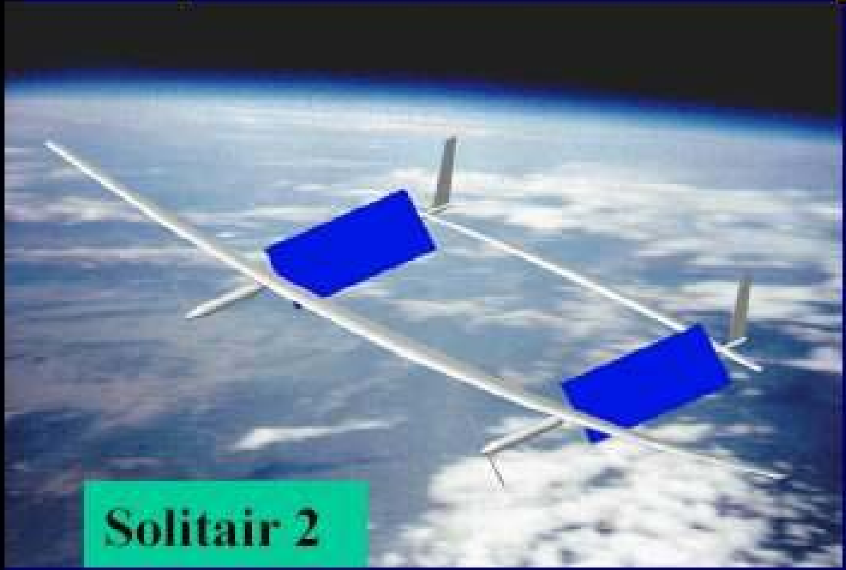
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ED01-0209-2 Date: July 14, 2001 Photo by: Nick Galante/PMRF
The Helios Prototype flying wing is shown over the Pacific Ocean during its first test flight on solar power from the U.S. Navy's Pacific Missile Range Facility in Hawaii.

Helios (AeroVironment): solar-powered platform; wingspan 76m; TOGW: 7300 N; Payload weight: 1000N, Payload power 1kW. Altitude: 29.5 km Endurance: several months.

www.dfrc.nasa.gov

Solar-powered UAV

SOLITAIR (DLR): wingspan 65 m;
Endurance: months also at lat >45°N;
TOGW: 7000 N; Altitude: 15-25 km
Payload weight: 1000 N.



Solitair 2

Solitair 1 – 5.2m wing span model

SOLITAIR configuration developed to demonstrate the long endurance operation at high European latitudes (45-55°N) [25].

Two solar panels, each of about 60m² of surface are rotate with respect to the sun radiation in order to collect an higher solar power.

Very high stability control program should be necessary when high speed wind (up to 35m/s) would be active.

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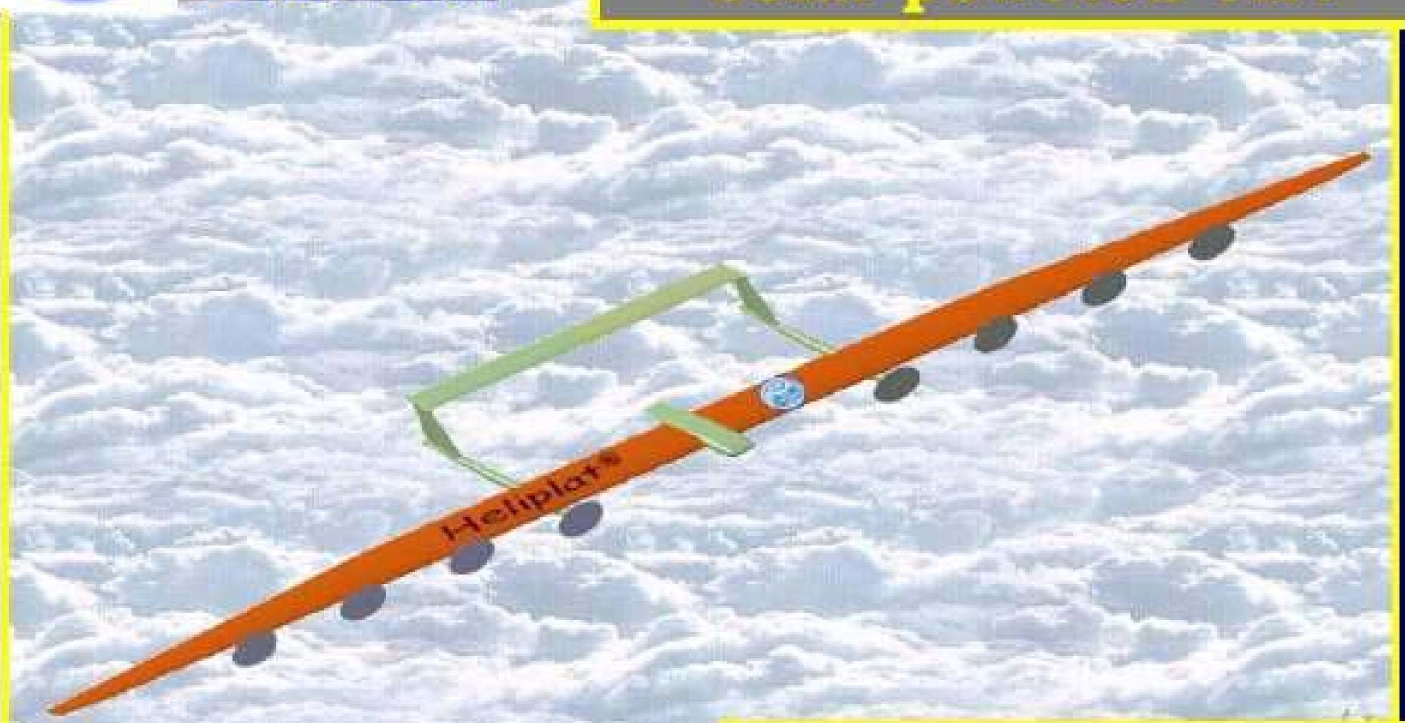
Solar-powered UAV



[6,9,11,16,29]

HeliPlat®: Span 73m; TOGW: 7500 N; Payload weight: 1kN, Payload power 1kW; solar cell effic.20%; fuel cell efficiency 60%. Endurance: 6-9 months. Altitude: 17-20 km

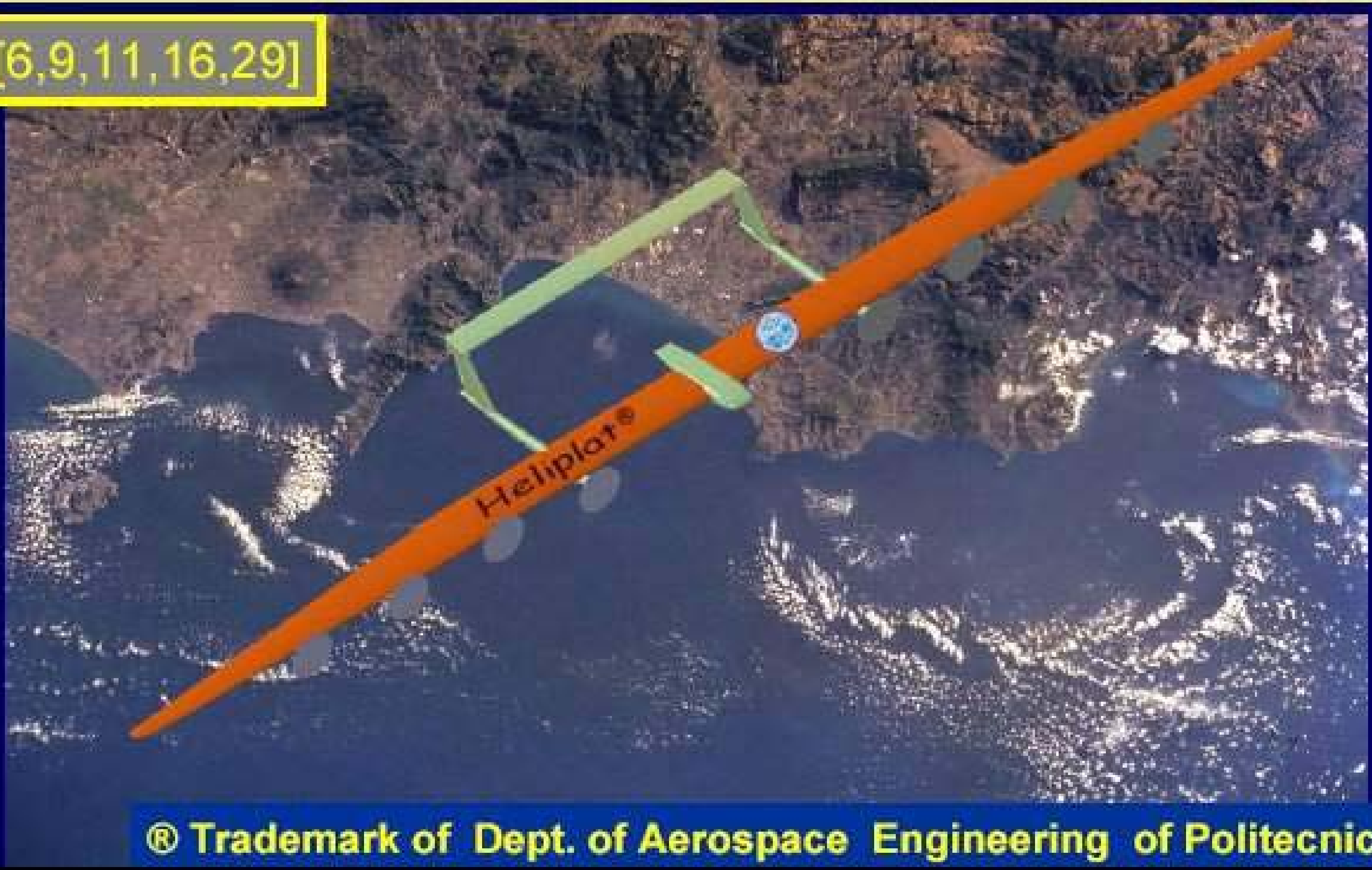
®Trademark Dept Aerosp. Eng. POLITO

HELIPLAT® (*HELIos PLATform*)

P req=6kW; Vc=71 km/h (TAS); n max=3.1

Sw=176.5m2; b=73m; ARw=30.2; Croot=2.97m; taper r=0.32
S ht=28m2; b=17.5m; AR ht=11; C ht = 1.6m.

[6,9,11,16,29]



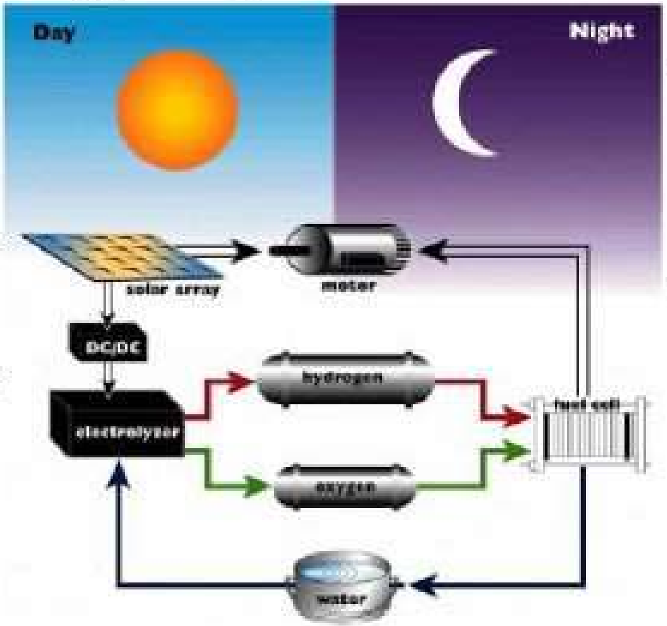
® Trademark of Dept. of Aerospace Engineering of Politecnico di Torino

Solar-powered UAV

Regenerative Fuel Cell Energy Storage System Summary

Day Cycle

- Sun energy converted to electricity by Solar Cells
- Half of electricity goes to Motor to propel plane
- Other Half of electricity goes to Electrolyzer to convert water into Hydrogen and Oxygen fuel

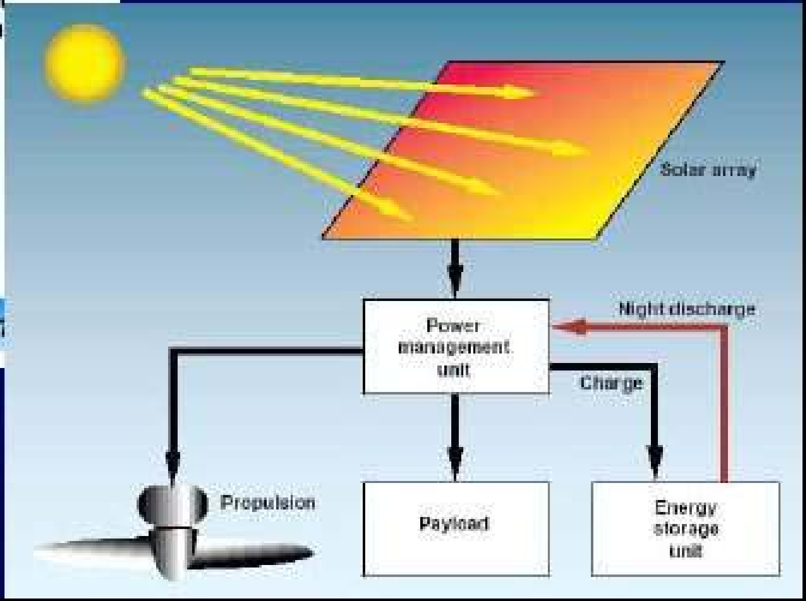


Night Cycle

- Oxygen and Hydrogen combine in Fuel Cell to produce electricity to propel plane
- Water from Oxygen and Hydrogen stored un next day

Fuel cell energy storage system enables continuos flight through n

www.dfrc.nasa.gov/
Erast Projects



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Solar-powered UAV

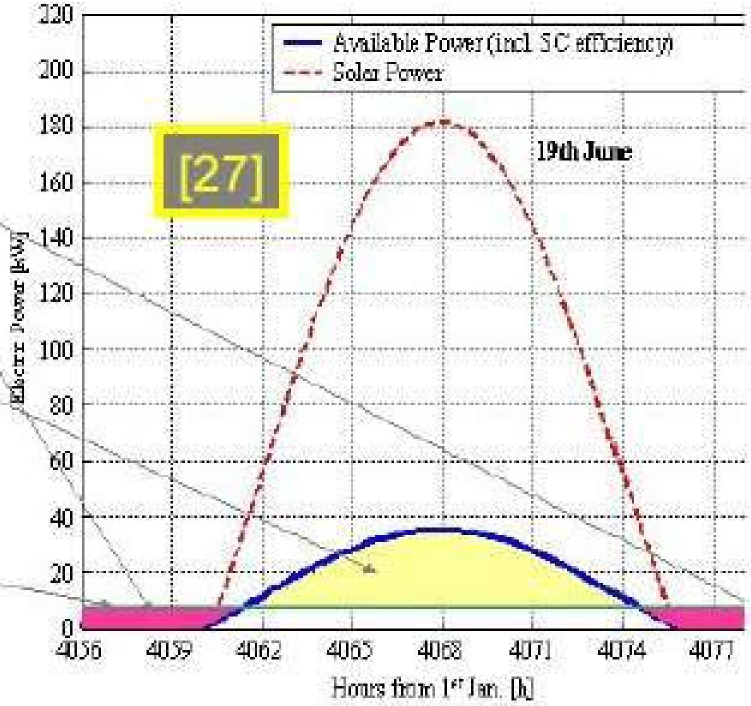
SOLAR CELLS

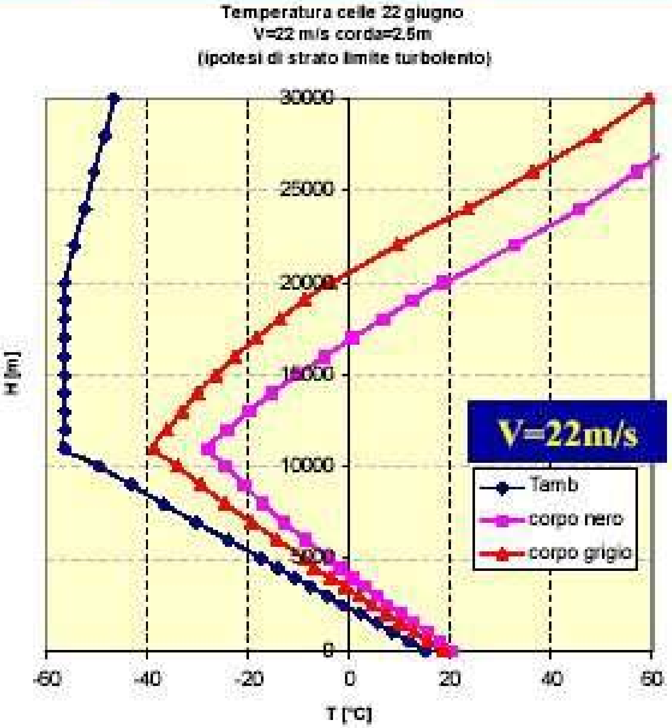
- •Low effectiveness of to-date solar cells still heavily affect the development rate of solar-powered platform.
- •High efficiency (14-15%) thin (2-300 microns) single-crystal silicon cells are to-day available at low price (about 800 Euro/m2) .
- •Higher efficiencies (up to 22%) very thin (50-70 microns) single-crystal silicon cells are also available, although at higher price (about 40.000 Euro/m2).
- •The Solar cells efficiency strictly depends on the surface temperature of the array .

Energy provided by fuel cells

Extra energy to the electrolyser

Power demanded by the motors





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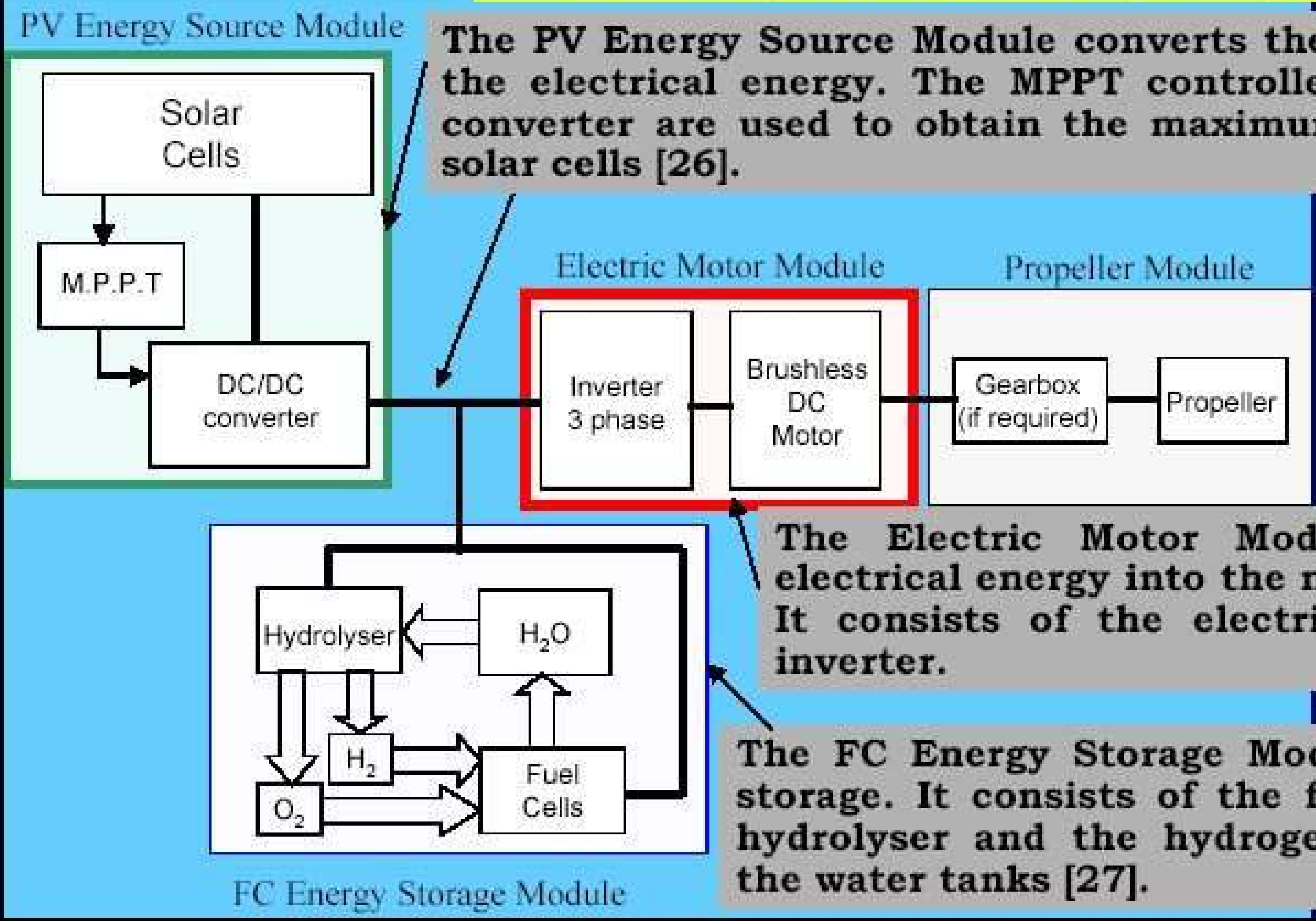
The electric energy system elementary bricks.

POLITO: Dept. Of Electrical Eng. – Dept. Of Energy



The PV Energy Source Module converts the solar energy into the electrical energy. The MPPT controller and the DC/DC converter are used to obtain the maximum power from the solar cells [26].

The Electric Motor Module converts the electrical energy into the mechanical energy. It consists of the electric motor and the inverter.

The FC Energy Storage Module acts as energy storage. It consists of the fuel cells array, the hydrolyser and the hydrogen, the oxygen and the water tanks [27].

POLITO, Dept. of Electric Eng. Brushless electric motor [28].

Good efficiencies are obtainable for other elements of the propulsive system; this would be obtained by a low mass and high reliability proper design of the rare-earth-magnet electric brushless motor (>95%) and proper design of the propellers (>80%) for high altitude flight with high diameter and speed of less than thousand rpm.

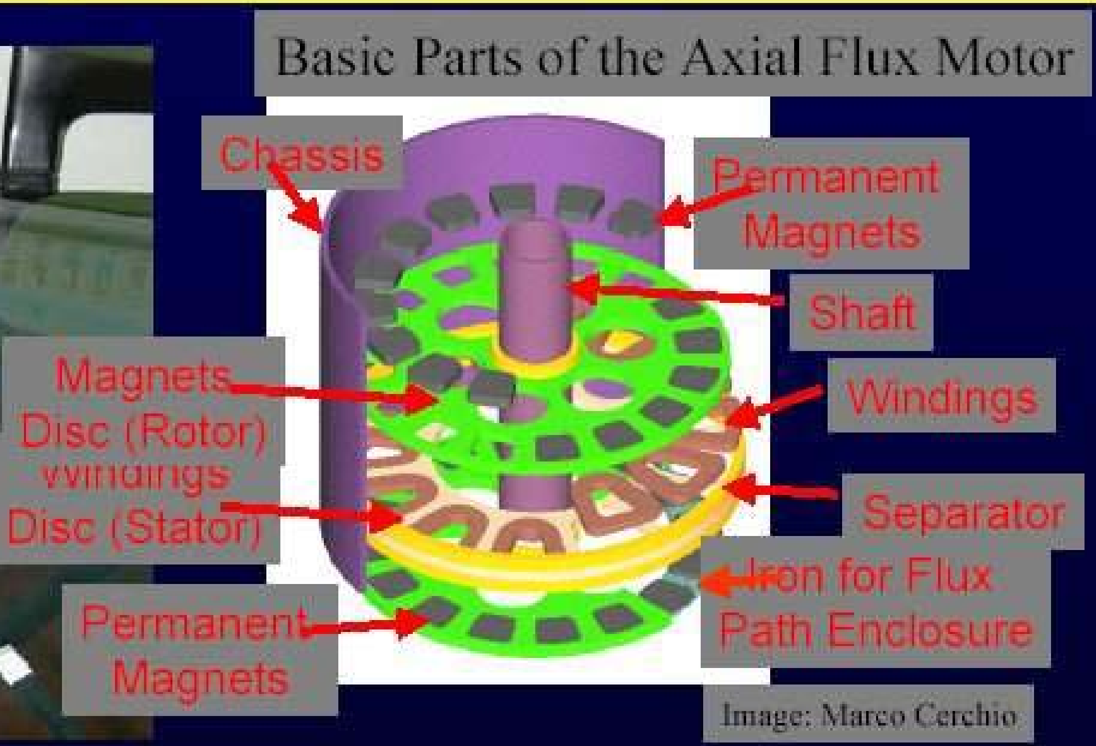


Image: Marco Cerchio

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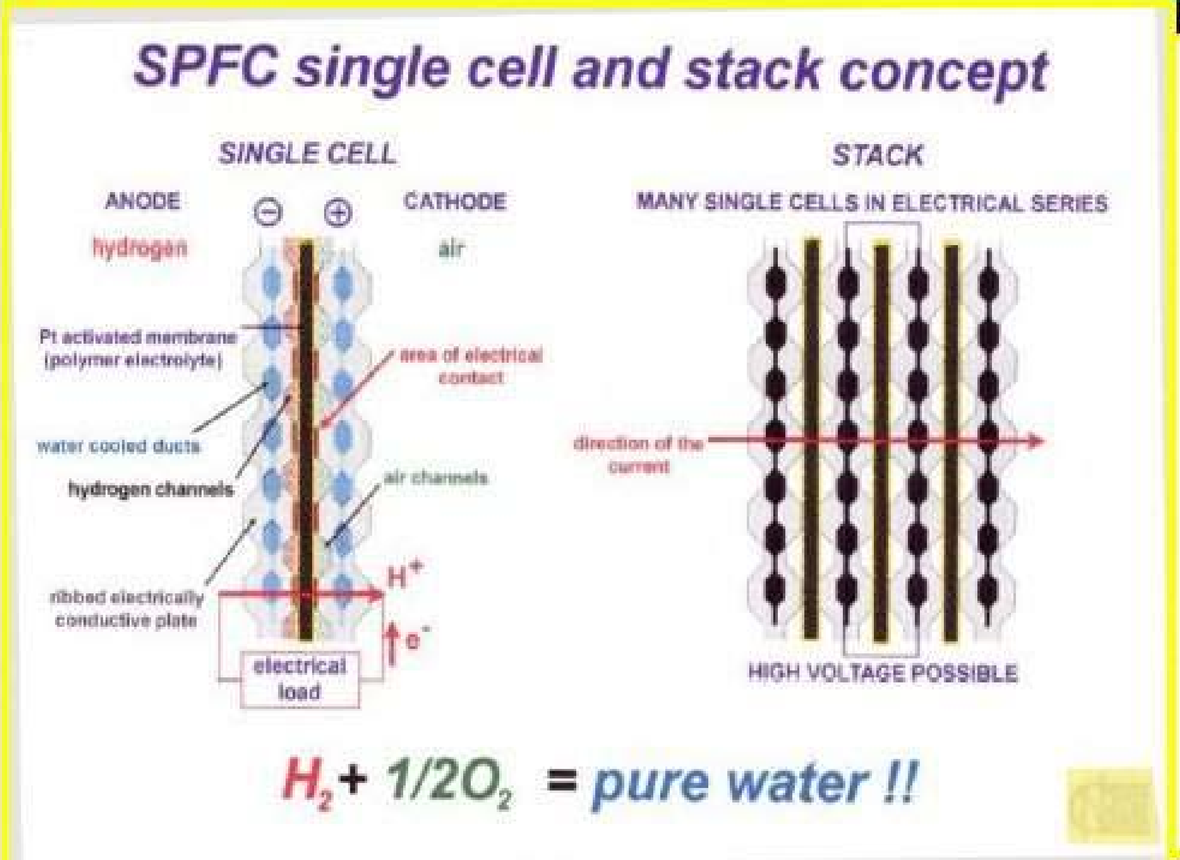
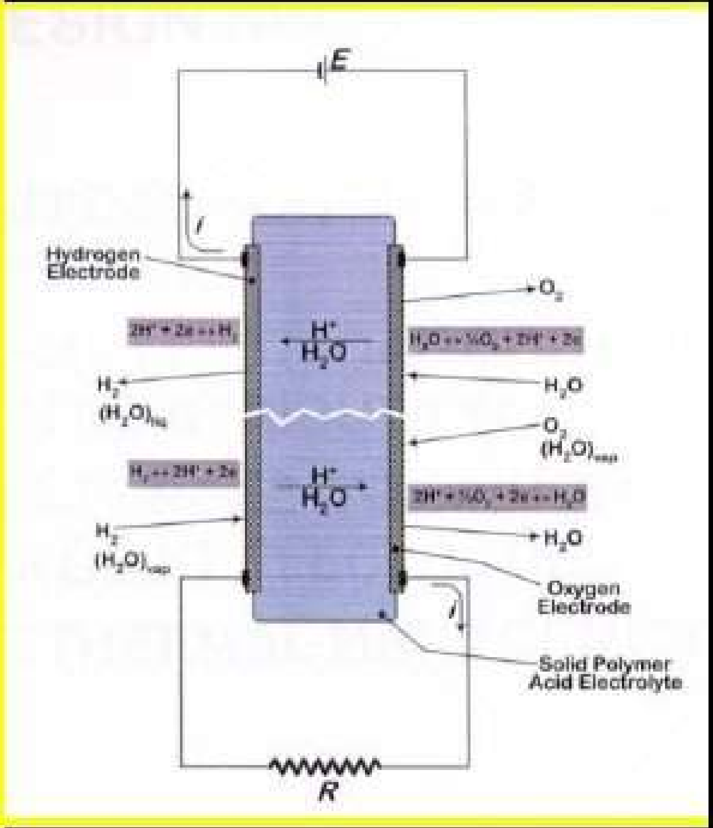
Solar-powered UAV: Fuel cells

- Very efficient storage energy systems based on the electrolysis of water, storage of hydrogen and oxygen, and the following recombination to water in a fuel cell during the power production.



SPFC single cell and stack concept

$H_2 + 1/2 O_2$ = pure water !!



Solar-powered UAV: Fuel cells

Requirements obtainable:

a) Long lifetime (40.000 hours);

b) Reliability of components (≥ 2 years)

c) Increasing Efficiencies (total efficiency >55-60%);

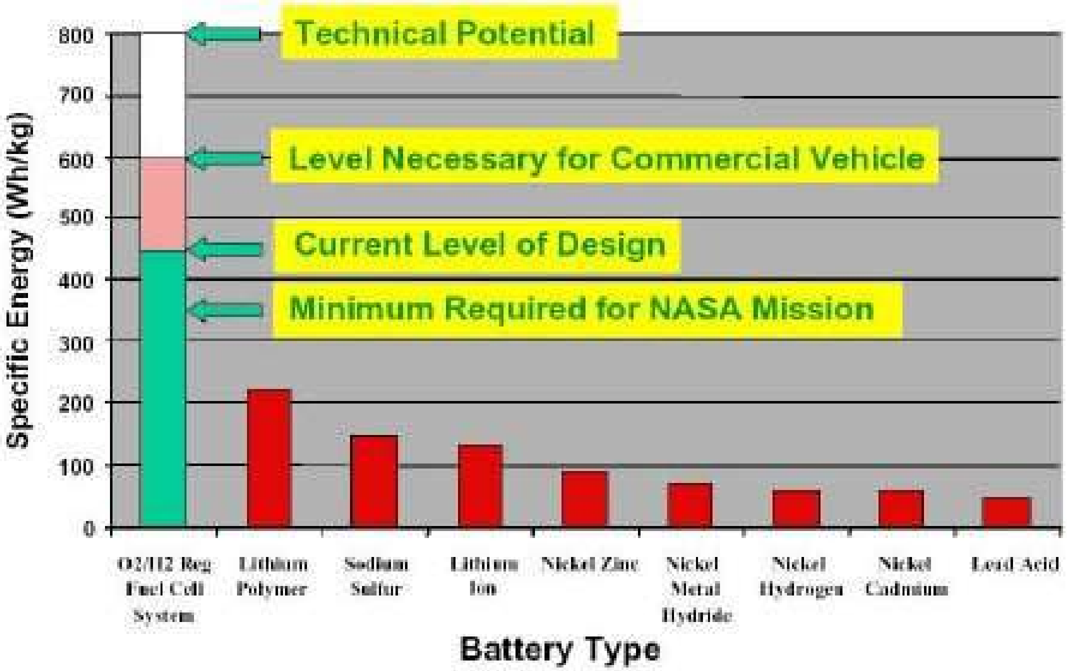
d) Voltage stability; e) Simple system.

- Production Cost: 200.000 - 400.000€.
- Main problems:

Reliability and feasibility of the whole system. In particular: service pressure and temperature under different environmental conditions should have to be deeply evaluated.

- Main goals: high efficiency and minimum mass of the whole fuel cells system.

Comparison of Rechargeable Energy Storage Systems



Solar-powered UAV: Fuel cells

Typical Fuel cell Stack

POLITO, Energy Dept.,
Electrolyser Laboratory Tests [27]

HeliPlat® Design

Multi-disciplinary optimization computer program

- A computer program has been developed to design the platform, by taking into account [6,9,11,16, 29]:

1) Solar radiation change over one year 2) Altitude 3) Wind speed

4-5) Masses and efficiencies of solar cells and fuel cells

6) Aerodynamic performances 7) Structural mass

- Highest structural and aerodynamics efficiencies are obtained by:

- Wide use of ultra-high modulus graphite/epoxy material to obtain a very light - high stiffened structure.
- Numerical aerodynamic analysis (propeller and profile models and CFD analysis of complete airplane): XFOIL and VSAERO codes.
- Advanced design tools (such as CATIA)
- Numerical structural analysis (MSC/PATRAN/NASTRAN).

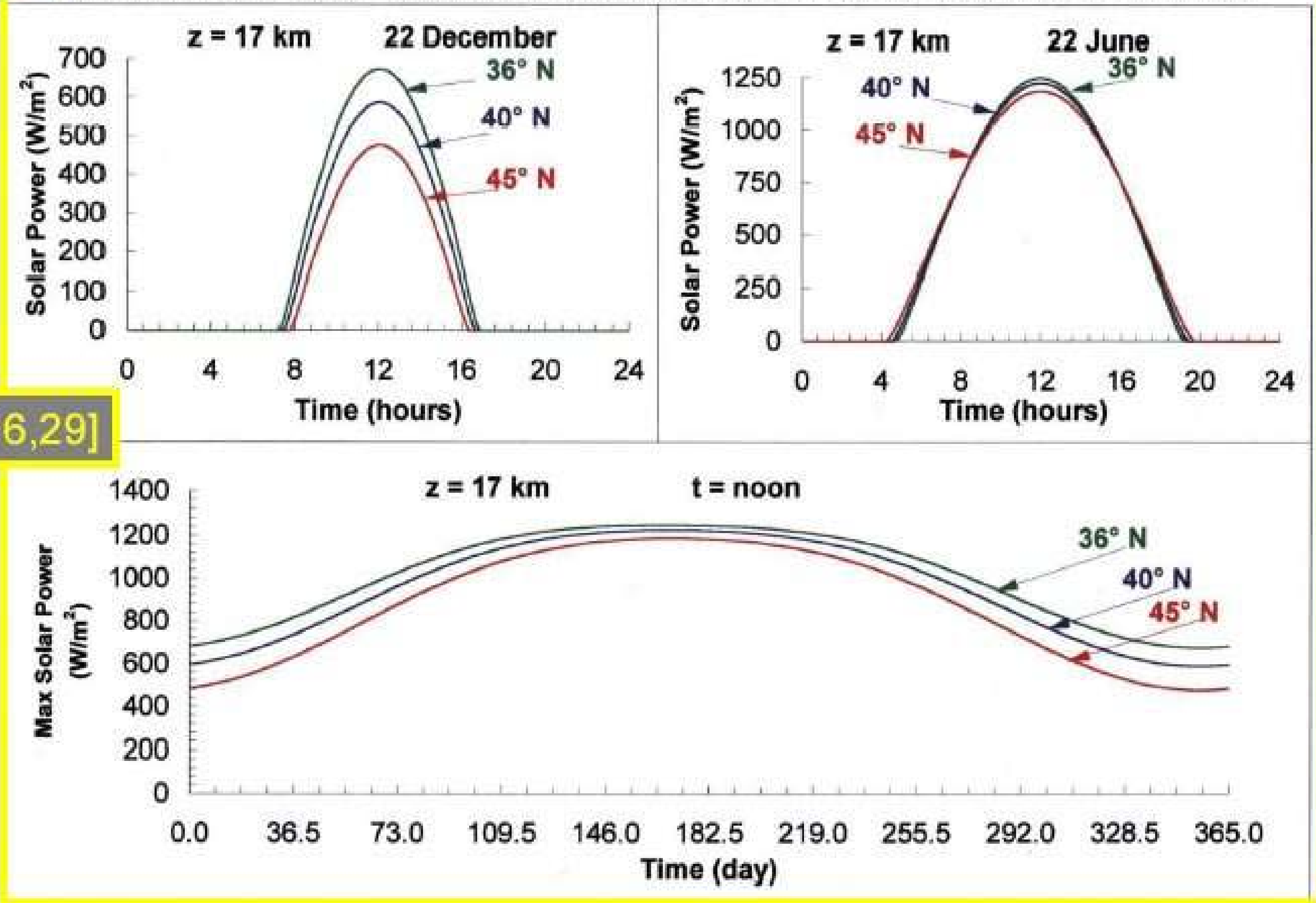
Design and Parametric Analysis

The design procedure to follow in the analysis is based on the energy balance equilibrium between the available solar power and the required power; the former being dependent from the solar cell area installed on wing and stabilizer, the latter depending from the velocity and total drag of the platform. In particular, the endurance parameter has to be fulfilled to minimise the power required for an horizontal flight; this means to minimise the parameter $C_D/C_L^{3/2}$; it is preferable to reduce also the drag coefficient C_D instead of only increase the lift coefficient C_L, also because of the lower structural load [6, 9, 11, 16].

$$\boxed{P = W \cdot \left(C_D/C_L^{\,1.5}\right) \cdot \sqrt{(2/\rho)\cdot(W/S)}}$$

A parametric study has been carried out for the platform design, taking into account the wind speed up to 27 km, the solar radiation change over one year, altitude, latitude, solar cells efficiency and weight, fuel cells efficiency and energy density, aerodynamic profile drag, etc. The results obtained give very important indication of which parameters has to be improved in order to reduce weight and dimensions of the platform or in alternative to increase the payload mass.

DAILY AND YEARLY SOLAR POWER DISTRIBUTION AT SEVERAL LATITUDE



[6,9,11,16,29]

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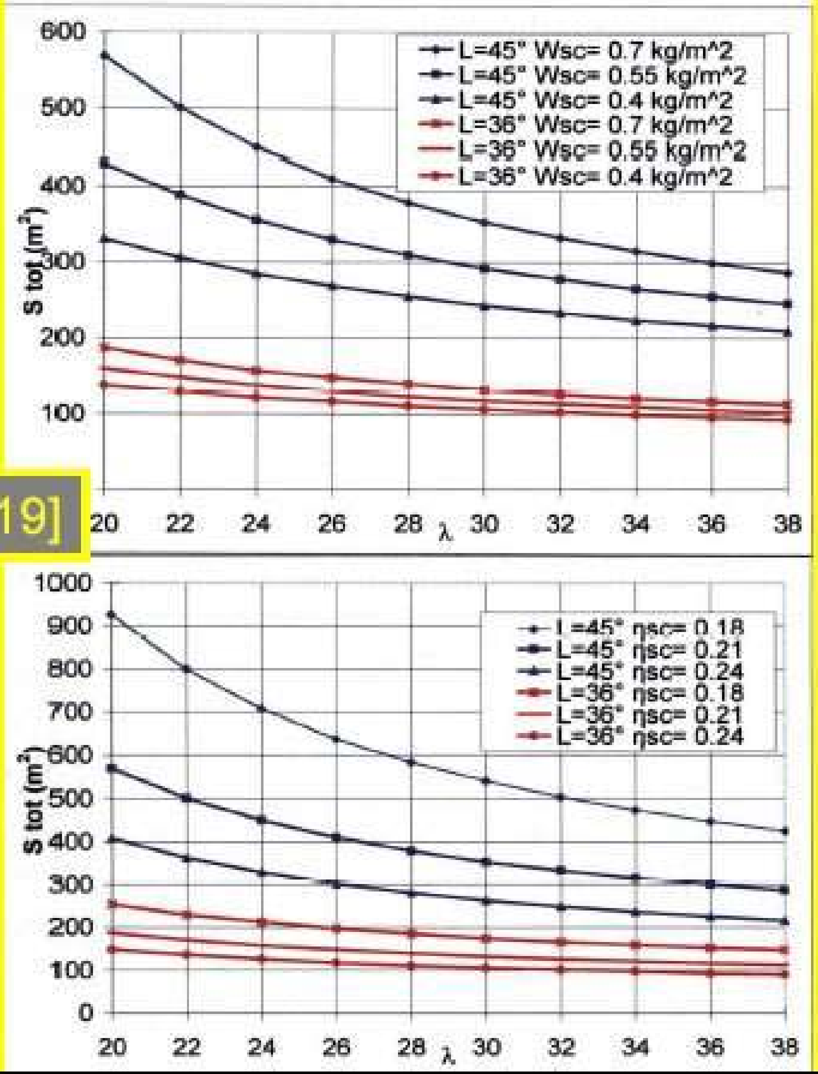
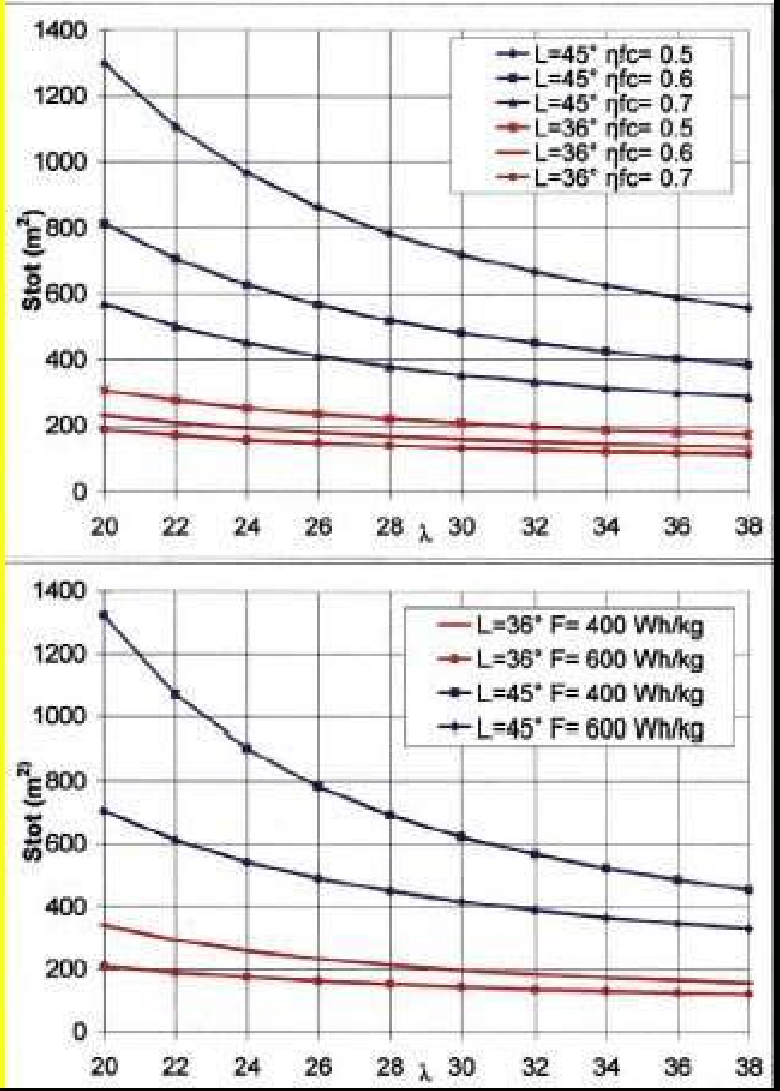
REQUIRED TOTAL PLANFORM AREA AS FUNCTION OF SOLAR CELLS



REQUIRED TOTAL PLANFORM AREA AS FUNCTION OF FUEL CELLS

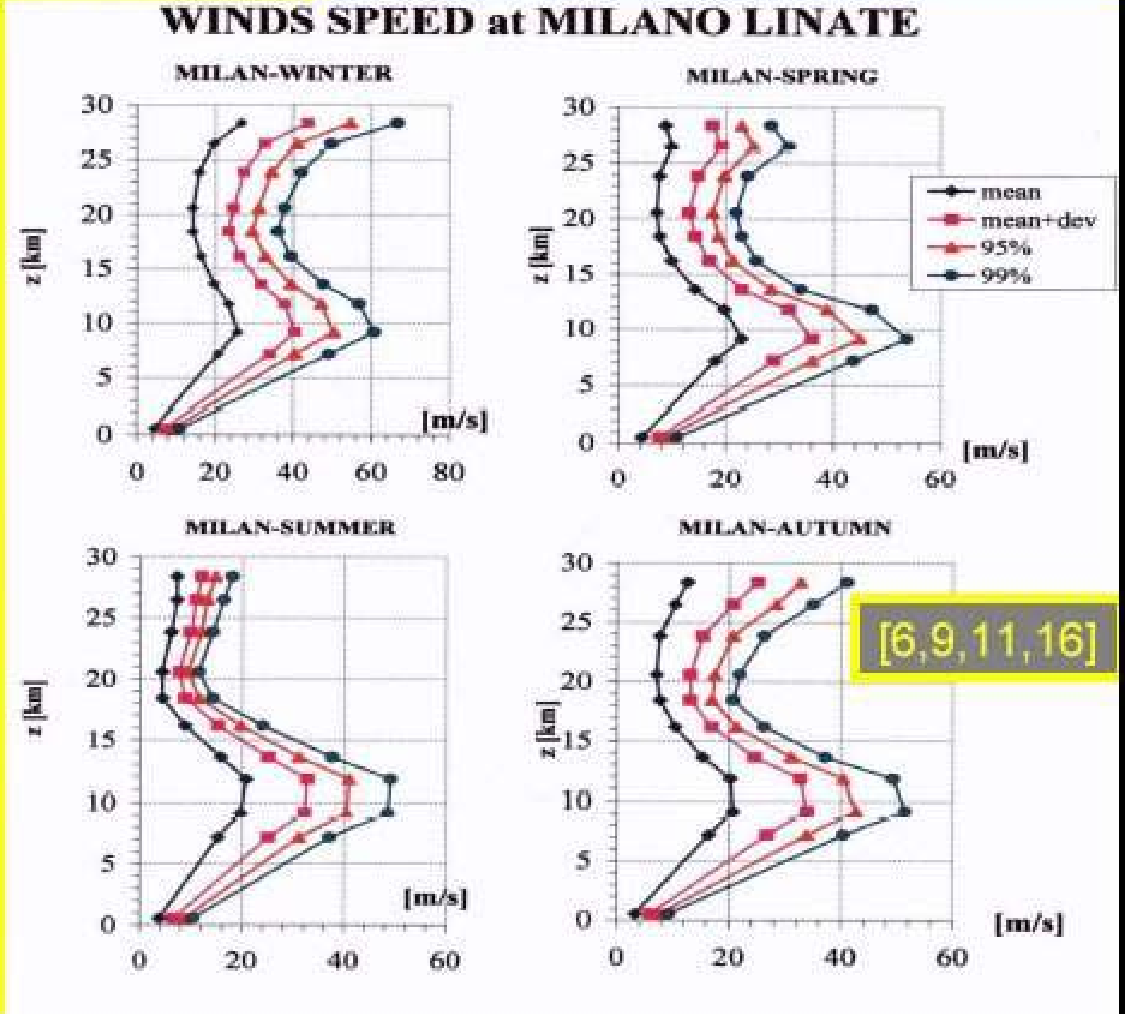


[6,9,11,16,19]

WIND SPEED STATISTICAL DATA

Elaboration from Italian Air Force Record Data

A wind study has been performed at several locations to examine the operating speed of the platform over the whole year. The upper air data climatic tables recorded by the Italian Air Force have been elaborated to obtain the wind profiles as function of the altitude [from 1,000 hPa (111m) to 10 hPa (31055m)] for several latitudes. The data were taken from 1963 to 1997. Along the many data reported there, the wind speed has been elaborated and plotted as a function of the altitude; it has been very clear from these picture, that winds are at a minimum between the altitudes of 18 and 22 km, depending from the time of year.


WINDS SPEED at MILANO LINATE

[6,9,11,16]

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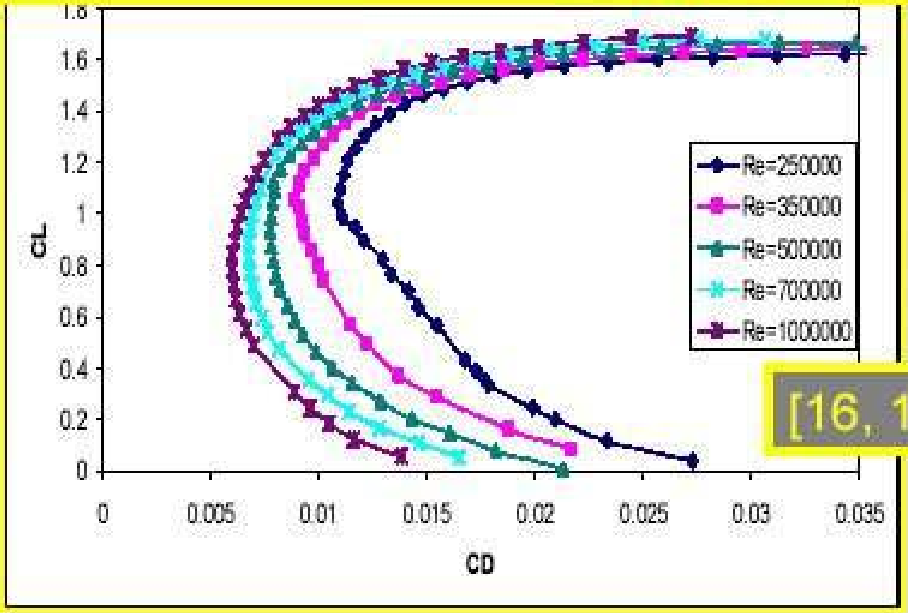
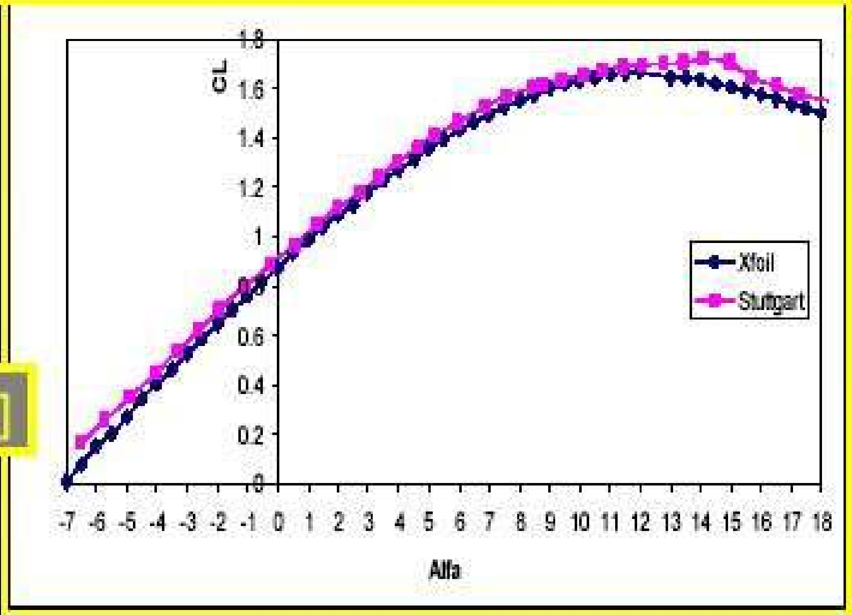
AIRFOIL HPF-118 - XFOIL CFD Analysis & Wind Tunnel Test

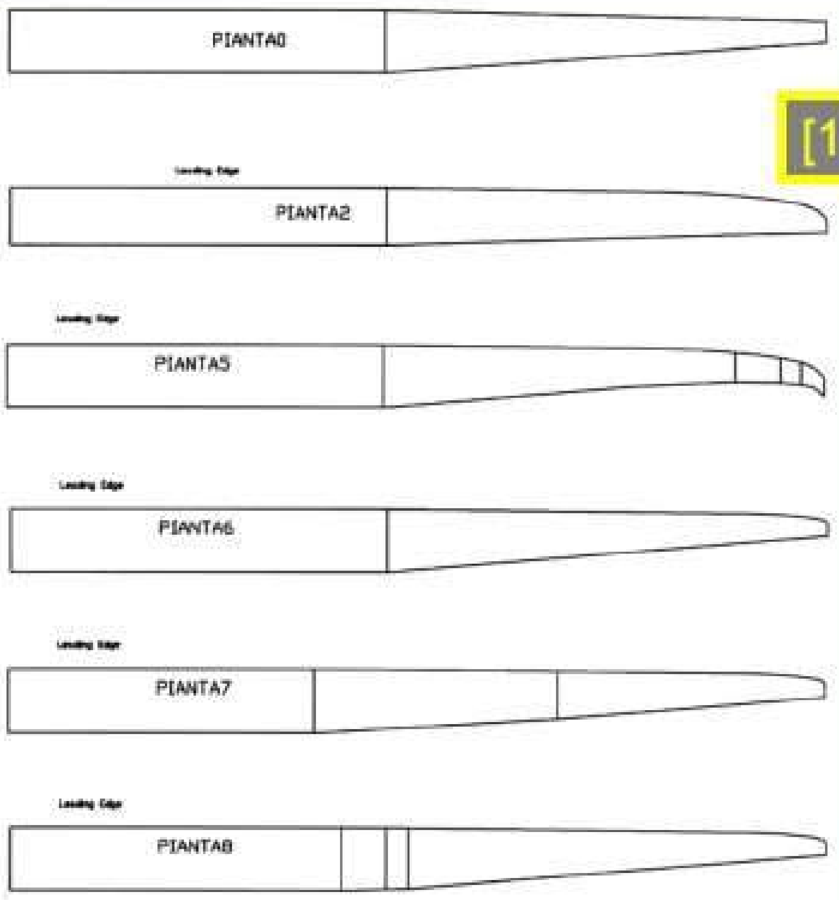
- New airfoils with high aerodynamic performances for low Reynolds numbers have to be developed in order to reduce the power required for the flight. Theoretical methods are able to predict, with a good accuracy, the lift coefficient as a function of the incidence angle, maximum lift coefficients and stalling behaviour, profile polars, etc.
- Wind-tunnel tests are however necessary to obtain an accurate behaviour of the profile. The production of a highly accurate wind-tunnel model, including several static pressure tabs for pressure distribution measurements, would be necessary for wind tunnel tests in a Low-Speed-Low-Turbulence Wind-tunnel. A good correlation between theoretical and experimental results would be possible.



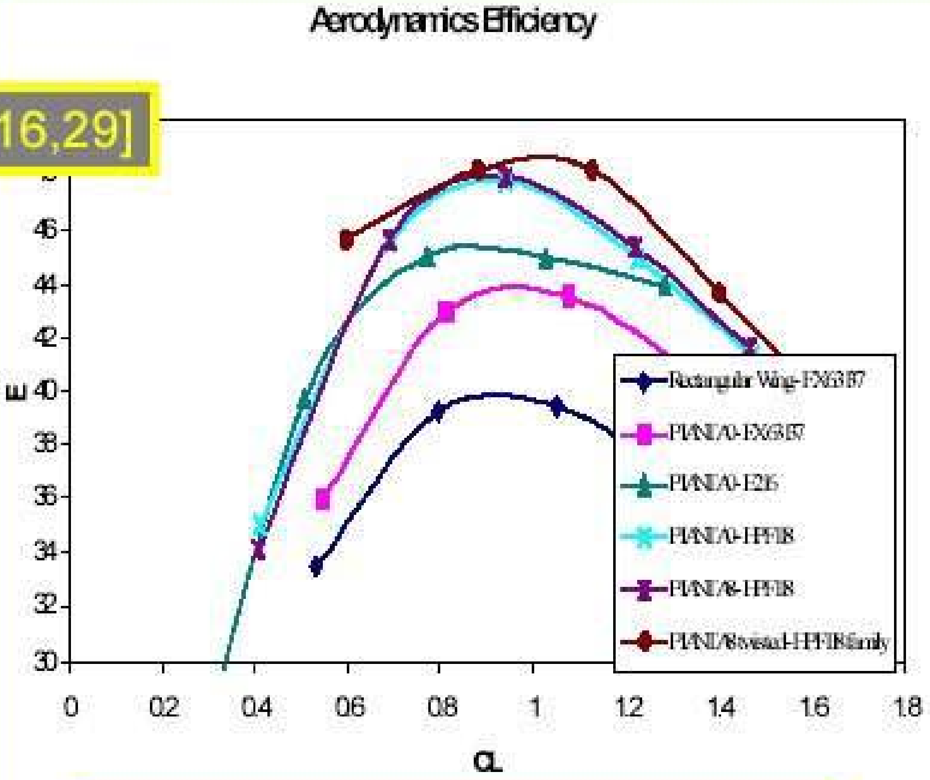
[16, 19]



Several Wing plan form have to be taken into consideration in order to increase the efficiency by reducing the induced drag.



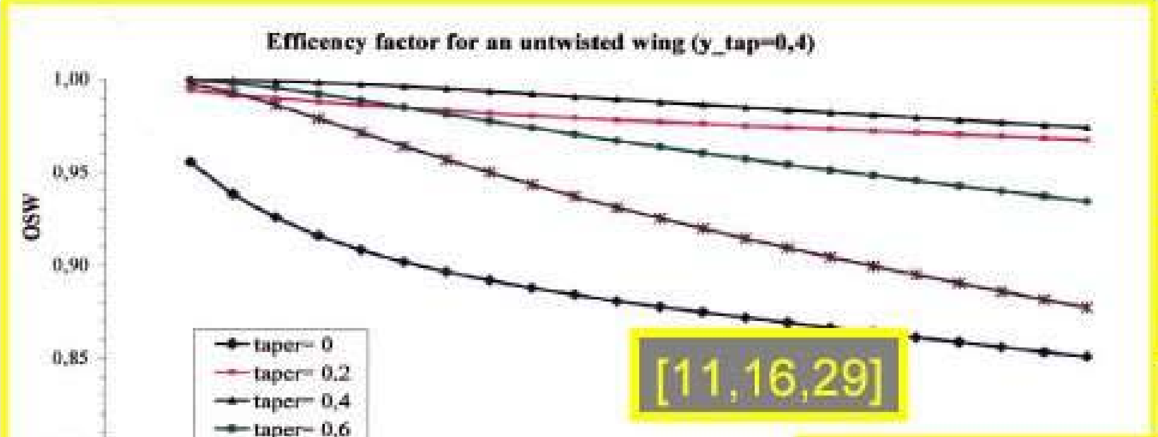
[11,16,29]



Example of Effect of wing shape on the Aerodynamic Efficiency

OSWALD Efficiency Factor (e) as function of Aspect Ratio (λ) and taper ratio.

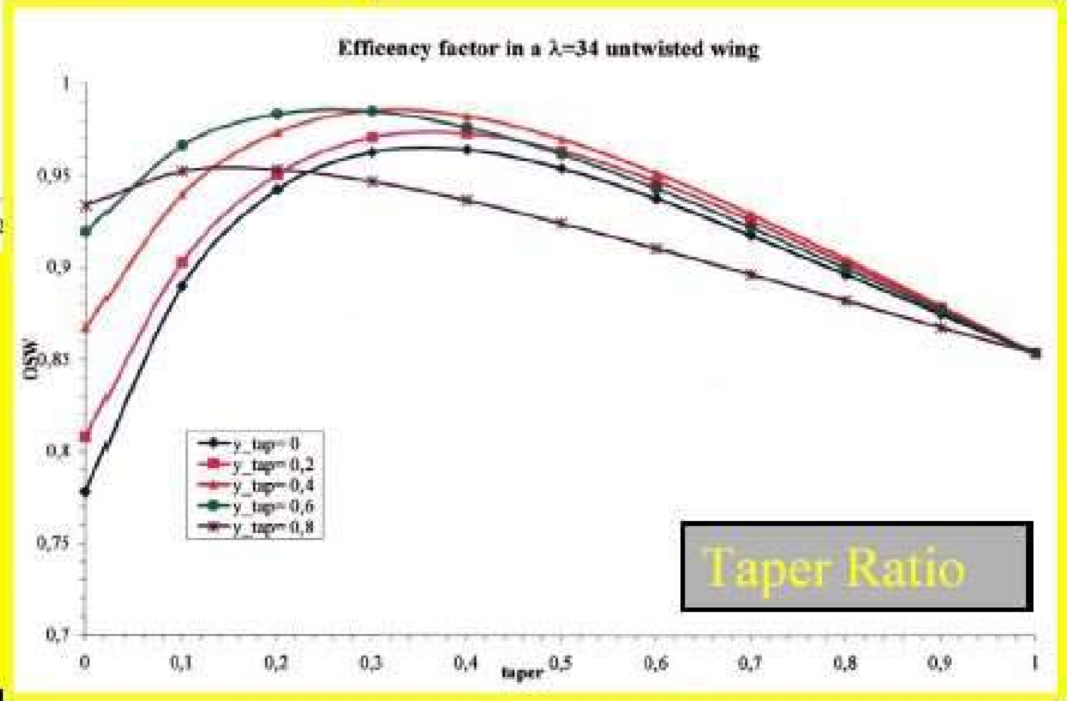
$C_{di} = C_L^2/e \pi \lambda$


Efficency factor for an untwisted wing (y_tap=0,4)

[11,16,29]

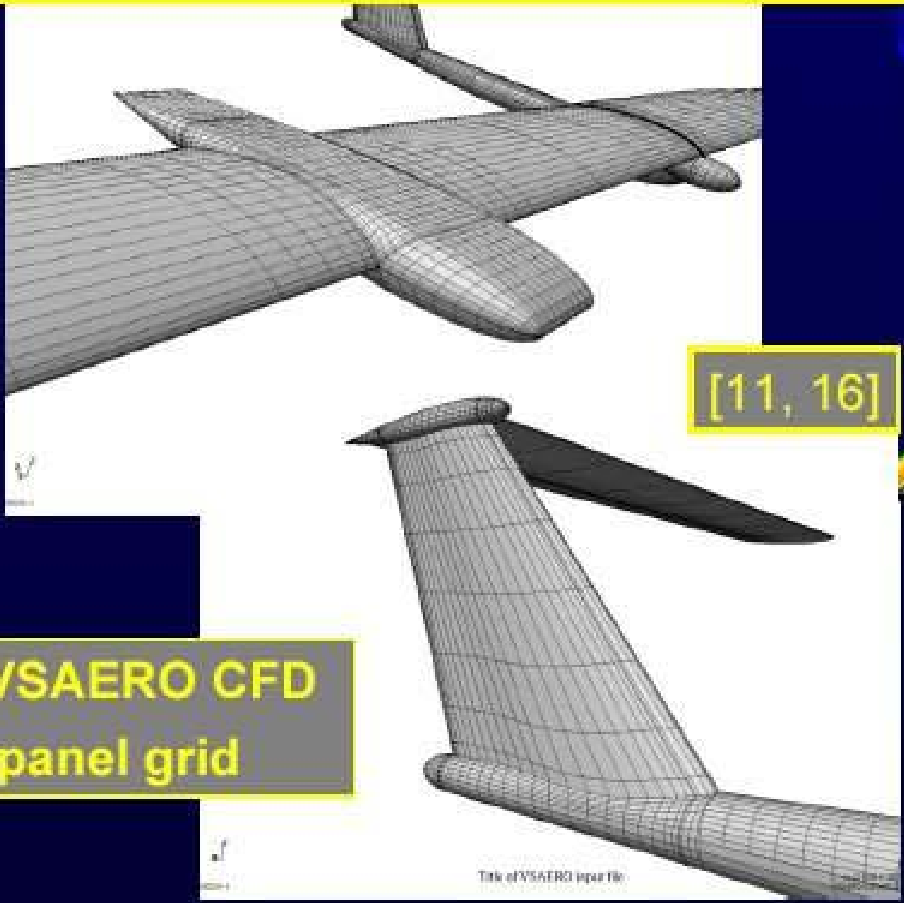
Aspect Ratio

The rectangular wing is not the best configuration in order to reduce the induced aerodynamic drag. The maximum efficiency factor (around 0.98) is reached for values of y_tap between 0.4 and 0.6 in a taper range comprised between 0.2 and 0.4. A proper rectangular/trapezoidal configuration would be adopted for obtain an optimum solution very similar to the elliptical performance.


Efficency factor in a λ=34 untwisted wing

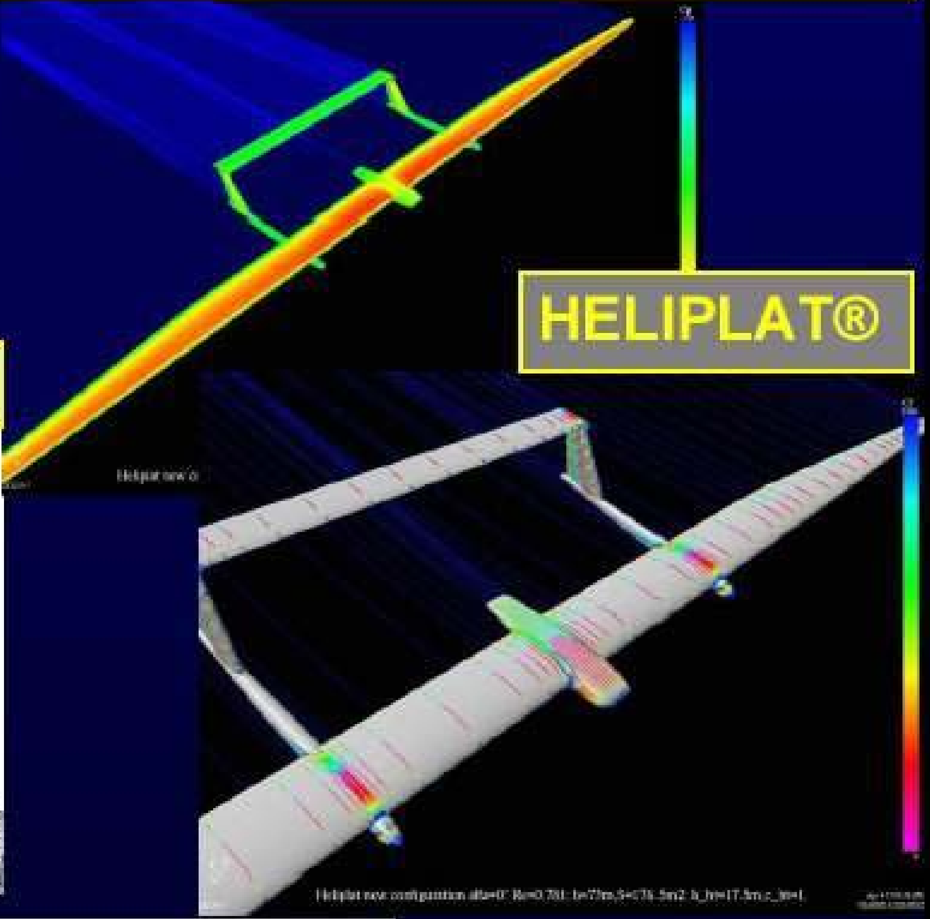
Taper Ratio

Calculation of the pressure distribution all over the wing is possible as long as a potential flow pressure distribution is concerned; this can be done with the panel method program. The platform and airfoil coordinates at the root and tip and positions of the taper ratio change have to be specified, as well as the angles of attack. A viscous flow pressure distribution would be possible by the VSAERO code [21] to obtain the performances of the whole wing and airplane.



[11, 16]

VSAERO CFD panel grid



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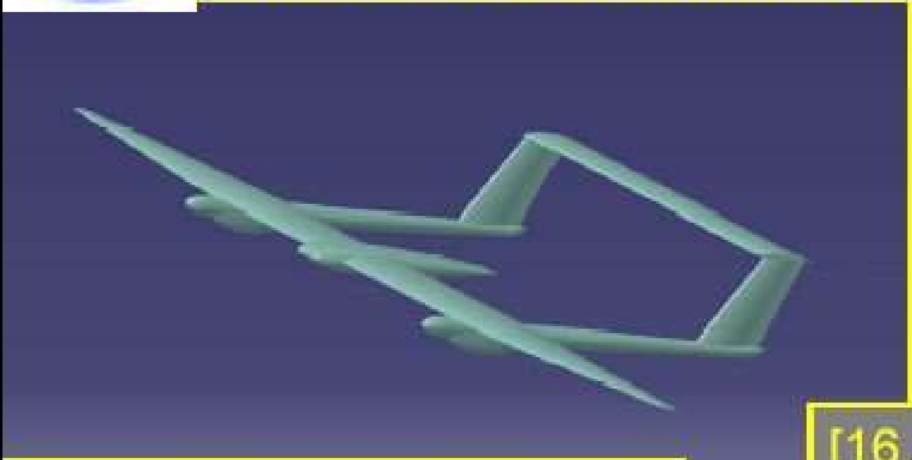
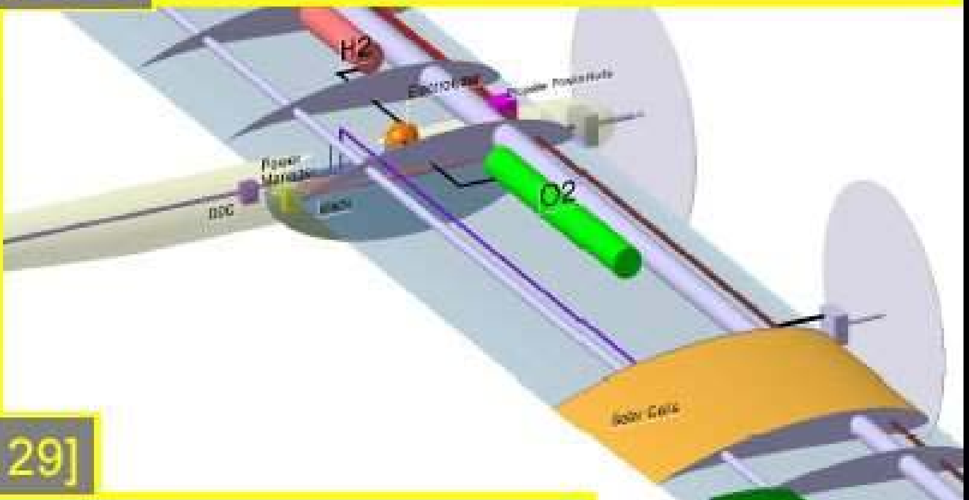
HELIPLAT® Preliminary layout

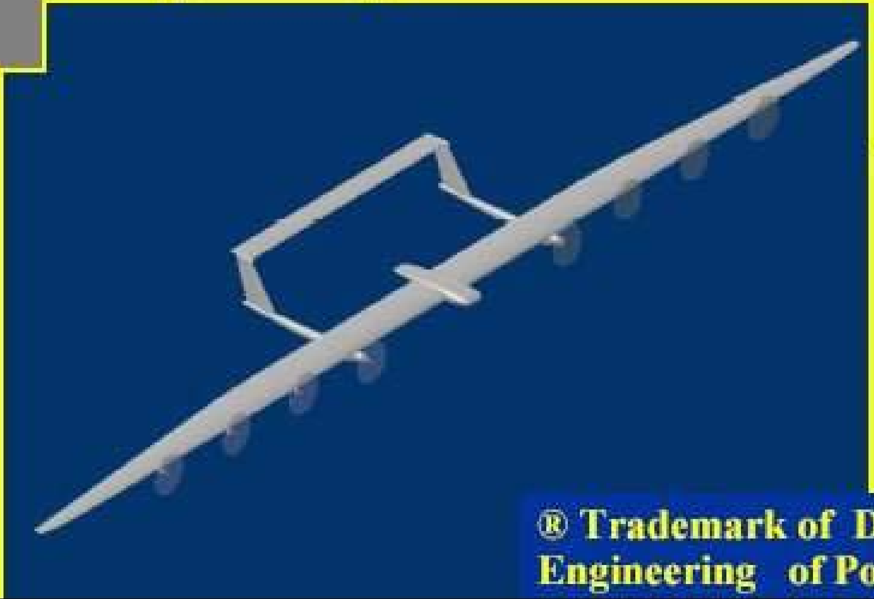




[16, 29]

CATIA CAD Drawing

The power system would be split into two groups. Each group is positioned inside of the boom structures in correspondence of the wing spar intersection. An electronic control unit has to be considered in order to manage the electric motors functioning to assure the assumed redundancy



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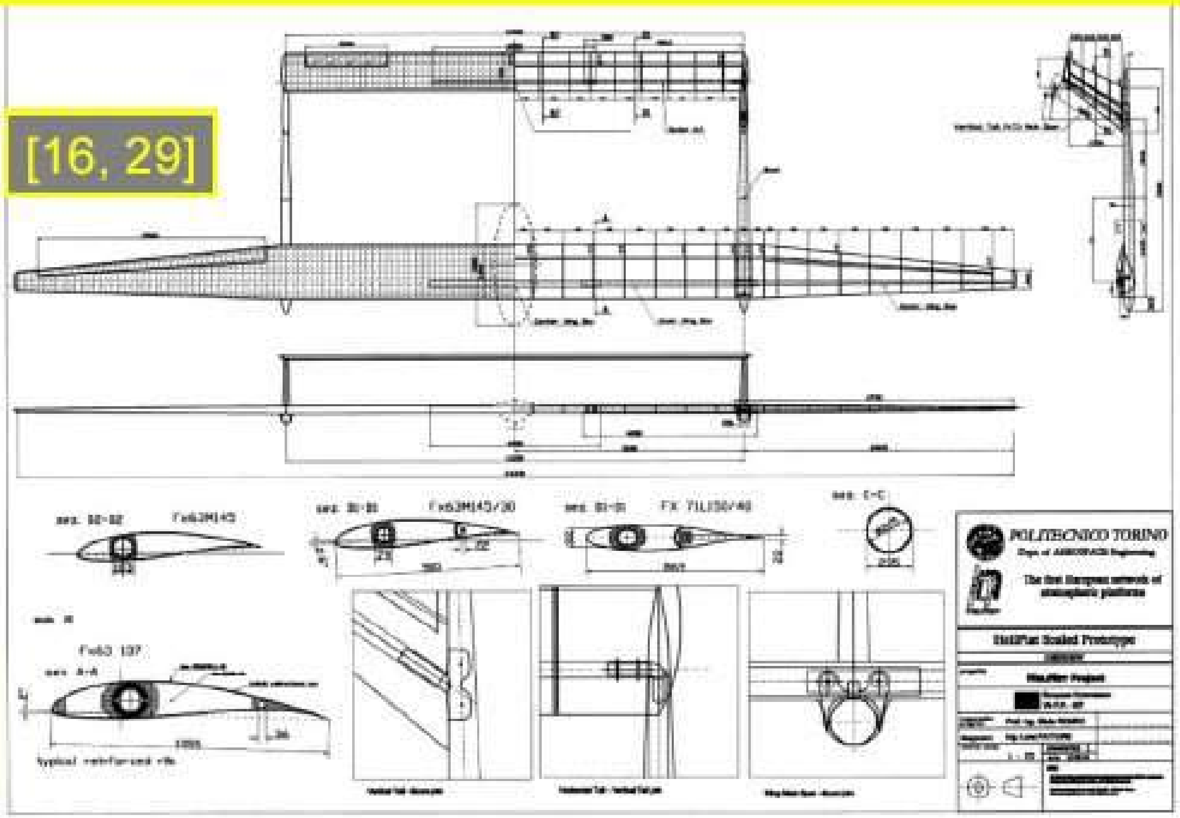
Structural Design

Highest structural efficiencies are required to minimise the airframe weight and increase the payload mass; they are obtained by:

- Wide use of high modulus graphite/epoxy material to obtain a very light-high stiffened structure.
- Numerical structural analysis (MSC/PATRAN/NASTRAN).

- A twin boom configuration would reduce the wing bending moment.
- A tubular spar for wing, tails or booms would allow a very light structure; indeed, it has to fulfil all the JAR requirements.

[16, 29]



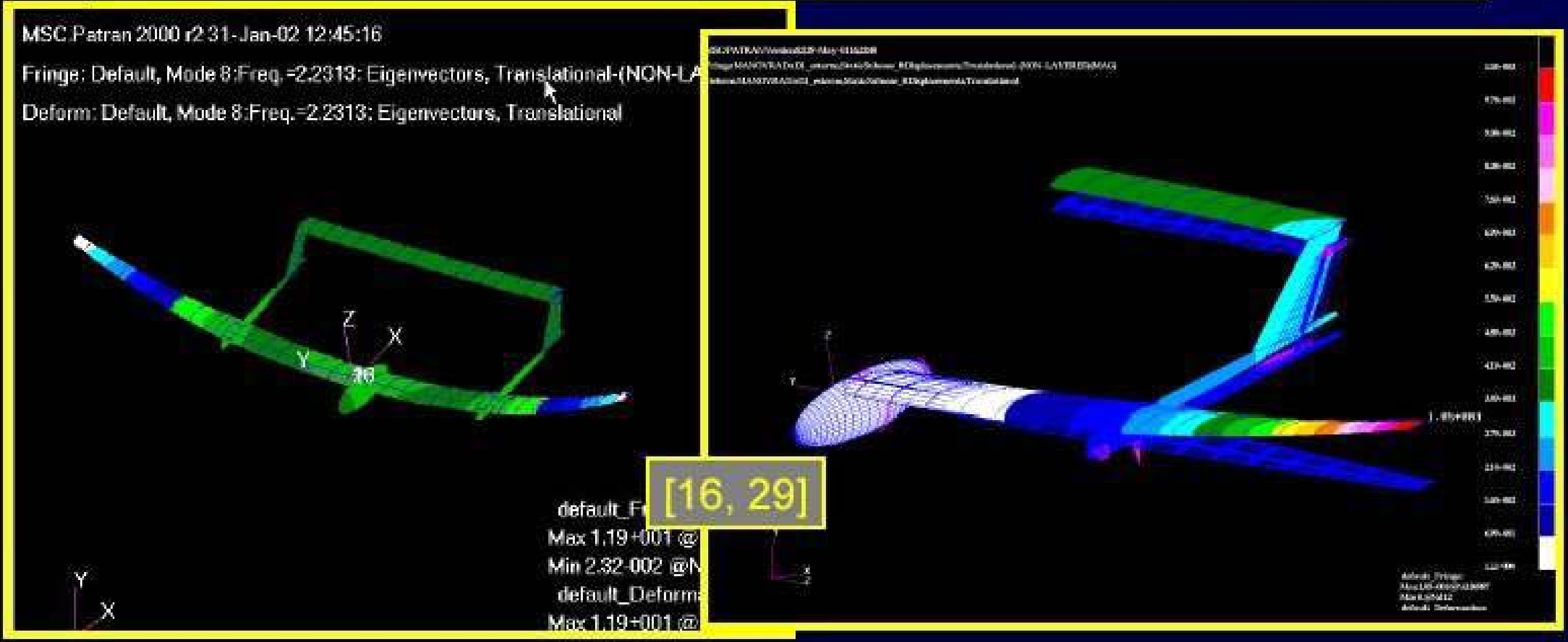
HELIPLAT® Scaled Prototype Design

G. Romeo – POLITECNICO TORINO, DIASP, email: romeo@polito.it

HELIPLAT® Scaled Prototype Design

FEM Static and Modal Analysis by NASTRAN

FE Analyses have been successfully applied to most composite design. In region of high stress gradients (cut-outs, stiffener drop-offs, etc.) a finest mesh should be used to obtain better results.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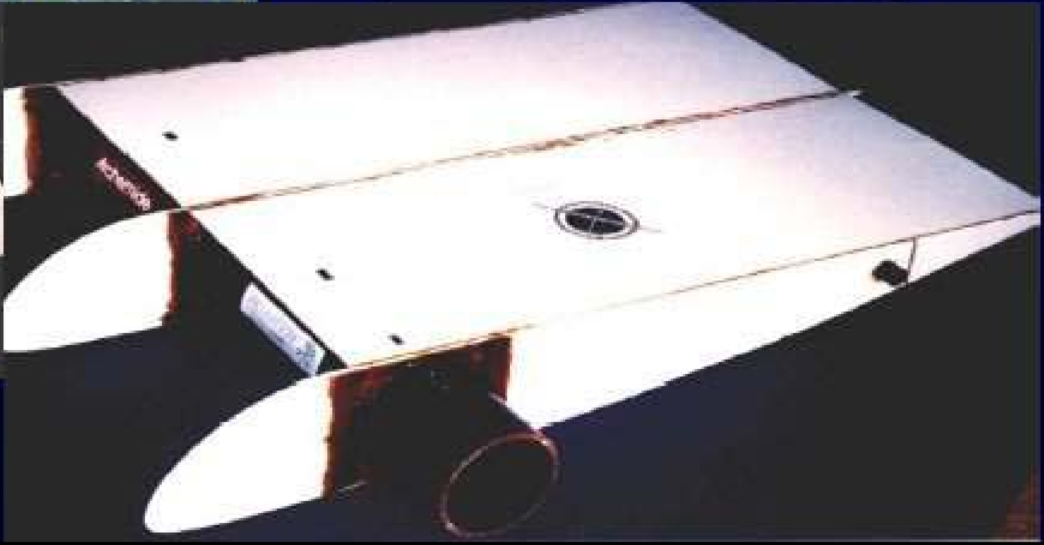
[16, 29]

CFRP Tubular Spar Manufacturing for Wing and Tails

[6,9,11]

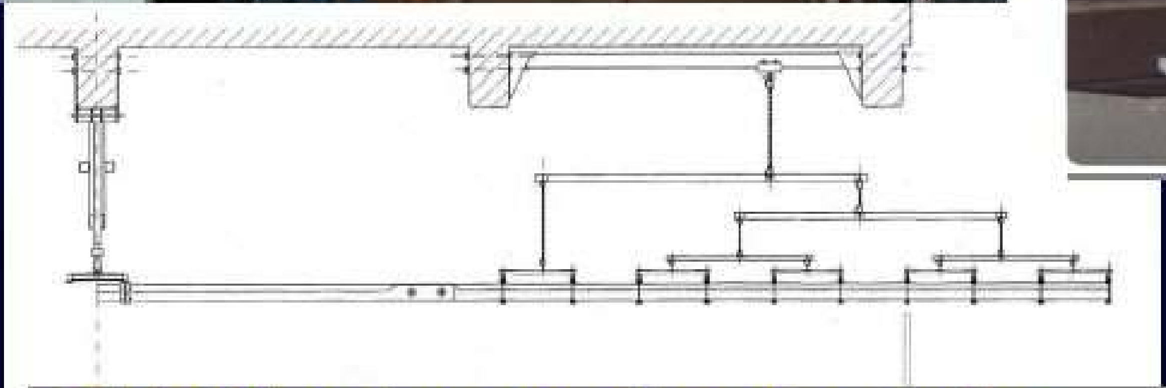


CFRP-Nomex lay-up, vacuum bag and autoclave cured

A 21m wing-box was manufactured to show the strength and stiffness of very light airplane structure. The main wing box structure, two spar and two sandwich panels, was manufactured in three pieces, each one 7.5m long, by using a graphite/epoxy pre-preg tape and autoclave cured.

CFRP-Nomex Wing box manufacturing

The whole mass resulted of 70 kg, including 8kg for steel fittings and bolts. The classical hydraulic loading rig was designed for applying the ultimate shear-bending-torsion load to the structure and to verify the theoretical behaviour.



CFRP Wing-box shear/bending testing

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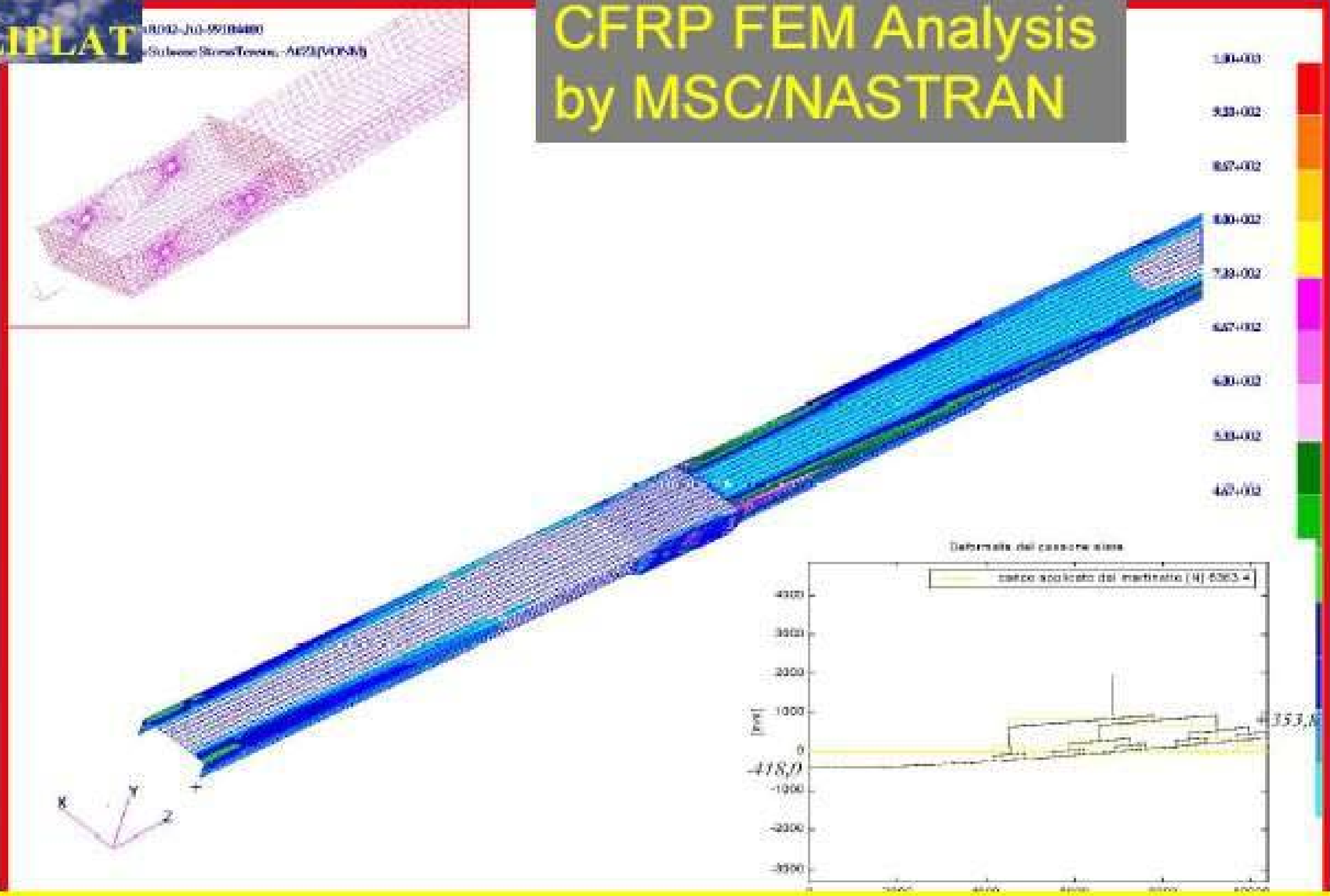
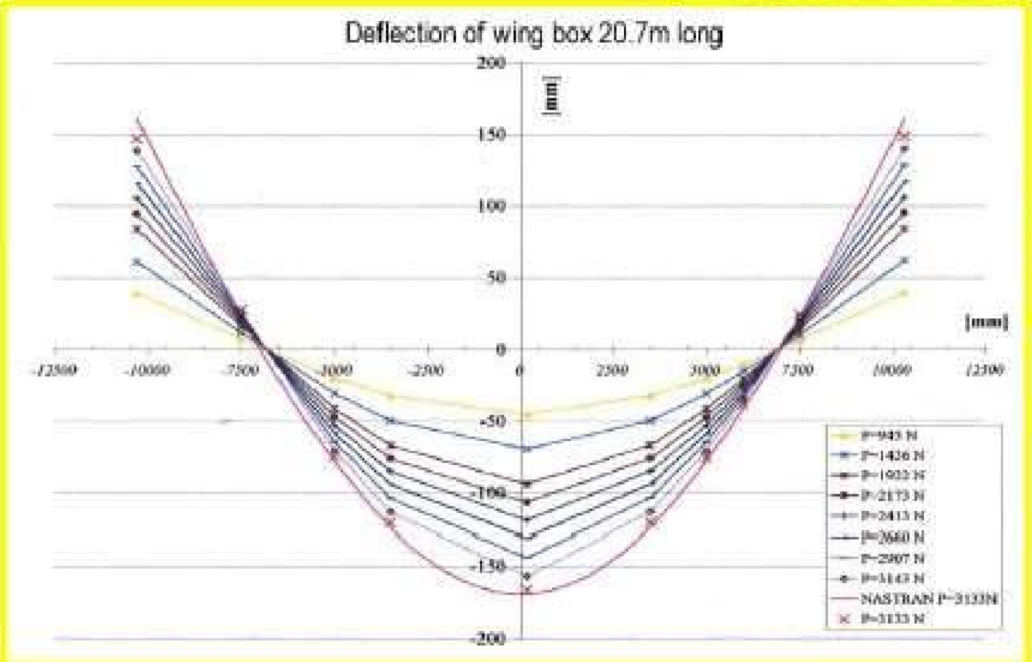
CFRP FEM Analysis by MSC/NASTRAN



A finite element analysis has been carried out by using the MSC/PATRAN/NASTRAN code in order to predict the static and dynamic behaviour. A good correlation has been obtained between the theoretical, numerical and experimental results up to a load corresponding to 5g.

21m Long CFRP Wing-box Experimental Test



Comparison between numerical and experimental results

CONCLUSION

- Possible realisation of High Altitude Very-long Endurance solar-powered UAV at least for low latitude sites in Europe and for 6-9 months.
- Most significant reduction in platform size, or expanding mission range or altitude or latitude sites, could occur by increasing the fuel cells specific energy to 600Wh/kg and efficiency to 70%, obtainable at a reasonable production cost.
- Solar cells efficiency & weight play an important role to satisfy the flight performances. Today 21% solar-cell efficiency would be very useful if obtainable at lower cost.
- Airfoils with high Lift coefficient and small Drag coefficient and at low Reynolds number should be designed, by Xfoil code, for the wing and horizontal tail.
- The aerodynamic performances of the full airplane have to be optimised by a CFD software, as VSAERO code, for obtaining the highest efficiency.
- Showed feasibility of very light composite structural elements. However, design & certification of composite structures are more conservative & expensive than for metals.
- A good analytical knowledge is necessary in order to properly exploit the excellent mechanical properties of composite structures, especially in the detail design of joints, cut-outs and discontinuities, buckling and post-buckling, etc.
- FE Analyses have been successfully applied to most composite design. Good correspondence between experimental analytical and FEM analysis is verified and expected also from the test of the complete airplane.

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