Reprint of AIAA/ICAS conference paper 129913, Anchorage, Alaska, September 2008. Author holds the Copyright. A color copy can be obtained from AIAA.org.

Fly around the World with a Solar Powered Airplane

Hannes Ross
Member of the Solar Impulse Team
85640 Putzbrunn, Germany
hannes.ross@t-online.de

Presented at the XXIX OSTIV Congress, 6-13 August 2008, Lüsse Germany

Abstract

Quite a few manned and unmanned solar powered aircraft have been developed and flown in the last 30 years. Objectives and missions cover a wide spectrum ranging from a pure technological goal to “Fly with Solar Energy” to civil or military surveillance and reconnaissance missions. However, none of those aircraft was able to demonstrate a continuous day and night operation until 2005. An overview of the historic solar powered aircraft is provided and the basic challenges which have to be solved for a solar powered aircraft are discussed: 1) geographical area of operation, time windows during the year, mission profiles, payload, 2) energy collection and utilization, 3) typical design parameter for different missions. Today’s technological status in the critical areas (solar cells, batteries, structure/materials) is discussed. It allows developing a solar powered aircraft with the capability not only to fly during the sunshine hours, but to save enough energy during the day to fly throughout the night and recollect energy after sunrise the next day for a perpetual continuation of flight. In 2001 the Swiss Bertrand Piccard, who together with Brian Jones (UK) circled the Earth in a balloon in 1999, proposed to design a manned solar powered aircraft and to fly it around the world. Such an aircraft is now being developed by the Solar Impulse organization in Switzerland. The primary objective of this endeavor is to make people aware of the fact that the conventional energy sources are limited and that renewable energy must and can be used to solve future demands. Development aspects of the Solar Impulse Program are described and a program status is provided.

Solar power collection, the basics

Today solar cells for power generation on houses have an efficiency of up to 17%. For special purposes monocrystaline cells may convert more than 20% of the incoming energy into electric energy. The trivial, but extremely important for flying, conclusion is: the electric energy collected is proportional to the solar cell area (Fig. 1**).**

The orientation and the inclination of the solar cell area relative to the horizon are important parameters, in addition to the geographic location (latitude), the time of the year and the time of the day. Also the altitude and of course the weather (clouds, humidity, temperature) play an important role for the determination of the solar energy collection. Figure 2 illustrates these principal relationships and shows calculated and measured values for solar energy collected for a location near Munich (Germany) on a summer and winter day[1]. A maximum of 900W of beam energy can be collected with an area of 1 m² on a summer day at noon. However, the electrical output of the solar cell is much lower because of the efficiency factor.

Energy required for horizontal flight

A non-propelled aircraft (e.g. a sailplane) will fly in still air with the velocity V and will sink with a velocity Vs. The aerodynamic efficiency of an airplane is characterized by the ratio of flight velocity V divided by sink rate Vs., i.e. V/Vs. For small glide angles at 1g flight this value is equal to the lift/drag (L/D) or weight/drag ratio (W/D).

At an L/D ratio of 20 an airplane can glide 20 km from an initial altitude of 1 km. However, gliding down means losing potential energy, which is used as propulsive force to compensate the drag of the airplane. If the potential energy level is to be kept constant, i.e. if the altitude is to be maintained, the sink rate must be compensated. The required power is weight W times sink rate Vs (Fig. 3). It follows that the higher the weight and the higher the sink rate, the more energy is required to maintain the flight altitude. The power required to compensate the drag in horizontal flight is V * D.

A basic question then is: what is the optimum altitude to fly with a solar airplane, i.e. at which altitude is the required energy a minimum? The efficiency of solar cells is increasing with altitude, because the atmospheric absorption and the temperature (up to 11km) are decreasing with altitude. However, flight velocity must increase with altitude to generate the same amount of lift at the lower air density at the same angle of attack. The consequence is that the required power is increasing with altitude for the same L/D. Figure 4 shows the relative change of power required and power available from the solar cells. The graph clearly indicates that (on a clear day) flying with solar power at lower altitude is more beneficial.

Figure 5 shows the improvement of the aero-dynamic efficiency L/D over the last 100 years[2]. The initial values have improved by a factor of 10. The best glide ratio L/D is achieved by the German “ETA” sailplane (manufactured by Flugtechnik & Leichtbau, Braunschweig). However, the airplane has an extreme wing span (b = 30m) and an aspect ratio AR = b²/S of 50. The wing area S is just 18.6 m².

Assuming a quadratic drag polar, the best L/D is achieved at CLopt, the minimum sink rate and hence the minimum power required is achieved at a relatively high lift coefficient, i.e. at CLvsmin = CLopt * 3^0.5 (see Fig. 6)[3]. In reality this would be close to the maximum lift coefficient. Therefore an operational lift coefficient above CLopt but below the CLvsmin is a good compromise.

Conclusion: The required power for horizontal flight can be reduced by a better lift/drag ratio and by lower flight velocities. Smaller velocities can be achieved by a high(er) lift coefficient and a bigger wing area, which is required anyway to position a sufficient number of solar cells.

History of solar powered airplanes

Since a pilot represents a significant part of the "payload" which needs to be carried and propelled, it is not surprising that the first solar powered aircraft was an unmanned vehicle. The "Sunrise 1", designed by Ray Buchard, took off in 1974 in "sunny" California and reached an altitude of 5000 m in 1975 (Fig. 7). First solar powered flights with unmanned aircraft in Europe were performed by Fred Militky in 1976. The first flight with a manned solar powered aircraft was performed by the son of Paul MacCready, who weighed only 37 kg. The actual test flights were performed by a female pilot with a weight of 45 kg. The aircraft was a 75 % scale version of the Gossamer Albatross, the human powered vehicle designed by Paul MacCready, and was called the Gossamer Penguin. It carried the solar cells on two poles, oriented perpendicular to the sun.

Other important milestones are shown in Fig. 8: MacCready´s Solar Challenger crossed the British Channel in 1981. The "Solair 1", designed by G. Rochelt, achieved a 5 hour endurance world record. Eric Raymond crossed the USA in 1990 within two weeks with intermediate stops. The ICARE, designed at the University of Stuttgart, won in 1996 the Berblinger Price for solar powered aircraft.[4, 5]

In the mean time, people in military and also civil organization got interested in this type of aircraft. MacCready started his own company "AeroVironment" and developed aircraft, which were tested and evaluated in the ERAST program (Environmental Research Aircraft and Sensor Technology), (Fig. 9). These were unmanned tailless aircraft, i.e. "span-loaders", using 6 to 10 engines distributed along the wing span. They achieved quite a number of altitude (~30km) and endurance (>30hrs) records. An unmanned aircraft designed by Alan Cocconi (Fig. 10) established a 48 hrs endurance record in 2005, and the British Zephyr flew 58 hours in September 2007. This demonstrated that the dream of continuous flight with sun power only is possible.

Conclusion: Solar powered aircraft have so far demonstrated, 1) unmanned flight up to high altitude is possible with a limited payload, 2) unmanned long endurance flight for multiple days is possible with a limited payload, 3) manned flight during the day is feasible.

Technology challenges for solar aircraft for long endurance

Jeanna Yaeger and Dick Rutan flew nonstop around the world in 1986 with the Voyager (piston engine). Steve Fossett did this with the Global Flyer in 2005 with a jet engine. But they both burned fuel. So far nobody has successfully demonstrated the repetitive day and night flying capability for a manned (= large payload) solar powered aircraft. The reasons are obvious: it is difficult to save enough energy either in batteries or potential energy (altitude). But also other aspects, like the efficiencies of the electrical propulsion system components and the aircraft structure, play an important role.

Mass breakdown

A comparison of the mass breakdown for a typical commercial airliner (A-320, Boeing-737 type) and a typical fighter aircraft with a solar powered airplane indicates that the sum of structure and propulsion system comes up to about 40% of the maximum take-off weight for these conventional aircraft, whereas this value is about 85% for the solar powered aircraft (Fig. 11). To provide enough mass allowance for equipment and payload, the structure and propulsion system must be light, i.e. the efficiencies must be high. Specific requirements are outlined below for the various systems:

Electric -

- high efficiency of the solar cell's, > 20 % at low cost
- optimal utilization of each solar cell through a maximum power point tracking system
- specific energy of the batteries: >200 Wh/kg
- high efficiency and large rpm range for the electric motor
- high propeller efficiency for the whole speed range, preferably without a variable pitch propeller
- thermal monitoring and control of the battery containers and the electric motors to assure good operating conditions throughout the mission envelope

Structure -

- extremely high stiffness at high stress levels
- a structural concept for wings, tails and fuselage that satisfies aero elastic design criteria

Flight control system -

- light system combined with efficient control effectors, i.e. low energy consumption if electrical energy must be used for surface actuation, e.g. for autopilot mode, induced oscillations by pilot or autopilot must be avoided
- a simple autopilot system must be available to allow sufficient pilot rest periods for the long endurance missions

Aerodynamic -

- wing and propeller profiles for low Reynolds numbers

Systems -

- light and efficient environmental control system (ECS) for manned systems
- all pilot functions must be supported for an extended

period, i.e. a couple of days

- NAV/COM Systems for long range and low energy consumption

The integration of these various high technology systems into a flying vehicle is an art of itself. If this would be easy, somebody would have done it already!

Electrical system

The principle scheme of the solar powered propulsion system is shown in Fig. 12. Typical efficiencies are provided for individual components. Consideration of all losses along the route from the solar beam to the propelling force (including battery charging and discharging) results in losses of 87 to 89%. This figure clearly indicates that each system component must be optimized to result in a good overall system.

Theoretical values for maximum efficiency for solar cells are between 25 and 30% depending on material characteristics (Fig. 13) and are not achieved for serious production cells. Most solar cells are mechanically cut Silicon slices and the material is too thick to be light. To protect the cells from mechanical damage, humidity and temperature, they must be embedded in a foil or glass fiber. New manufacturing processes have been developed to put a thin Silicon layer onto a foil, which is light and also flexible. The efficiency of thin solar cells has considerably improved during the last years (Fig. 14). Figure 15 shows the structural arrangement of the embedded cells. The individual cells are connected to a module, then the protective cover is applied to allow the “skin“ to be connected to the substructure, i.e. ribs to transport the air loads into the wing structure. Many cells have to be connected in series within a module to achieve the voltage level of 200 to 270 Volts. And many parallel modules are required to provide the necessary power output. To optimize this process “Maximum Power Point Tracking” units are required. For a solar cell area of 200m² typical characteristics are given in Fig. 16.

To allow a continuous day and night operation, energy obtained during the day must be preserved for the night. This is being done by climbing to higher altitudes and thereby storing potential energy and also by charging the onboard batteries. Unfortunately regenerative batteries do have a lower power density than “one shot” batteries, see Fig. 17. Considerable improvement of battery characteristics (performance and cost related to battery mass and volume) were achieved in the last 15 years, see Fig. 18.

New production methods allow the manufacturing of bigger units and - even more attractive - rectangular formats of the battery packages, allowing a higher packaging density. Typical data for a battery package are shown in Fig. 19. Another important operational characteristic for the batteries is the operating temperature, which must be maintained between 15 and 35°C. Depending on the altitude profile this might require heating at higher altitudes and/or cooling of batteries during the mission. In the last few years, engines have been developed for airplanes which satisfy the requirements of being light, small, and controllable over a wide rpm range at outside temperatures from -50 to 110°C. Sailplanes with electrical engines like the “Antares” and “Silent” are now in series production (Fig. 20).

The principle scheme of an electrical propulsion system for a solar powered aircraft is depicted in Fig. 21. The serial arrangement provides the necessary voltage, parallel arrangement the required power output. A power management system monitors and controls the power distribution to the engines, other consumers and the batteries. A safe operation of the system, even during a malfunction of system components, must be assured by separation into separate circuits to provide sufficient flight performance and flight safety.

Structure

The aircraft structure is the second high-tech element for the design of a solar powered aircraft. Concepts used for human powered aircraft and unmanned solar powered aircraft have been considered and improved. The primary material is carbon fiber; grid structure and sandwich are used in most places as the structural concepts (Figs. 22 and 23). Providing a weight estimate for such unconventional structure presents a problem, because there is hardly any statistical data available. Therefore, verification by component design and tests are required to support the design assumption.

The large wing areas required to provide low speed capability and enough area for solar cells result in rather large wing spans and consequently in an elastic structure. Special effort is necessary to assure the structural integrity and adequacy of the airplane within the operational environment. The unmanned “Helios“ aircraft ran into a control and structural problem in turbulent air during a test flight, after the aircraft was modified to carry additional batteries. Extremely high bending of the wing, resulting also in a vertical shift of the c.g. which caused inappropriate control inputs, led to the loss of the vehicle (Fig. 24) in 2003. The accident report recommended:

> Develop more advanced, multidisciplinary (structures, aero-elastics, aerodynamics, atmospheric, materials, propulsion, controls, etc.) “time-domain“ analysis methods, appropriate to highly flexible, “morphing“ vehicles.

It must be assured that the integration of the flight control system and the structural behavior of such a large and flexible vehicle is properly analyzed and understood.

Concept of a manned solar powered aircraft for long endurance, i.e. – day and night flight

The Swiss Bertrand Piccard, who together with the British Ian Jones flew around the world first time with a balloon in 1999, is the initiator of the idea to fly around the word with a solar powered aircraft. The Solar Impulse team was established in Switzerland to achieve this goal. In a world depending on fossil energies, the Solar Impulse project is a paradox, almost a provocation: it aims to have a manned airplane take off and fly autonomously, day and night, propelled uniquely by solar energy, around the world (with intermediate stops because of pilot endurance limits) without fuel nor pollution. That goal would be unachievable without pushing back the current technological limits in many fields.

What are the design requirements for such a vehicle? A design mission profile has to be defined which considers the flight performance and energetic aspects. As explained in "The energy required for horizontal flight" section, it is not optimum to continuously fly at high altitudes. On the other hand, today's batteries are too heavy to allow a continuous low altitude flight. It is, therefore, necessary to climb to a certain altitude during the day to gain potential energy which can be used after sunset to glide down (like a sailplane) to the minimum mission altitude and continue with battery power until sunrise. A minimum altitude is required to safely clear all ground obstacles, mountains, etc. A simplified mission profile is shown in Fig. 25.

What are the design characteristics of an aircraft to fly such a mission? The following considerations describe the "design window", i.e. the range of critical design parameters which lead to a feasible solution[6]. The maximum solar power which can be received by an area perpendicular to the sun beams outside the atmosphere is about 1300 W/m². Considering the damping at an average altitude this value will be reduced to about 1000W/m² (Fig. 26). Distributing the available energy, collectable during the sunshine hours, over 24 hours results in an average value of about 260 W/m²/day. To make this energy available during the 24 hour cycle it is necessary to store it in batteries and in potential energy during the day.

The required energy for the horizontal flight is defined by the following equations:

$$Power = Drag * Velocity \longrightarrow P = D * V$$

$$Drag \sim Velocity\hat{}2 \longrightarrow D = CD * \tfrac{\rho}{2} * V\hat{}2 * S$$

$$Power \sim V\hat{}3$$

$$Velocity\_Definition \longrightarrow V = \sqrt[2]{\frac{2}{\rho} * \frac{W}{S} * \frac{1}{CL}}$$

$$P = CD * \tfrac{\rho}{2} * V\hat{}3 * S$$

W = aircraft weight, S = aircraft wing area
Rho = air density, CL = lift coefficient,
CD = drag coefficient

$$P = CD * \tfrac{\rho}{2} * \left(\sqrt[2]{\frac{2}{\rho} * \frac{W}{S} * \frac{1}{CL}} \right)\hat{}3 * S$$

$$\frac{P}{S} = \sqrt[2]{\frac{2}{\rho}} * \left(\frac{W}{S} \right)\hat{}3/2 * \frac{CD}{CL\hat{}3/2}$$

It is evident, that the power required at a certain altitude is primarily dependent on the wing loading W/S and the lift and drag coefficients. Since the available solar power per area (P/S) is known, the above equation can be rewritten to determine the allowable wing loading for a given power:

$$\frac{W}{S} = \left(\frac{P}{S} \right)\hat{}(2/3) * \left(\frac{\rho}{2} \right)\hat{}(1/3) * \frac{CL}{CD\hat{}(2/3)}$$

Figure 27 shows the possible design window (gray area) as a function of the available power for a CL = 1 and an air density of 1 kg/m³ (equivalent to about 2 km) with the parameter L/D. Considering the losses in the electrical and propulsion systems from the solar cell to the propeller (see Fig. 12), the available power for pushing the aircraft through the sky is even further reduced, i.e. from the initial 260 W/m² to only 28 W/m². For an aircraft with an L/D = 35 the maximum permissible wing loading to fly the mission is then reduced to 7.8 kg/m². For higher L/D´s (i.e. higher aspect ratios) and/or better efficiencies, a larger wing loading can be allowed. It follows that the prime design characteristics for such an aircraft are:

- a low wing loading which will result in low air speeds and low power requirements and also allow the installation of sufficient solar cells
- a large wing span (i.e. high aspect ratio) to achieve an acceptable aerodynamic performance (L/D)
- low structural weight
- light and efficient propulsion system and other electrical consumers (NAV, COM, FCS, etc.)

Figure 28 shows a conventional configuration which satisfies the design requirements. Batteries are housed in the four engine gondolas; the pilot is located in the cockpit mounted below the wing. There is a single main gear located aft of the cockpit and outriggers supporting the aircraft during take off and landing.

Like in any other aircraft development process a lot of design parameters have to be investigated to find the best/optimum configuration. This requires the clarification of some basic questions:

- Which combination of wing loading and aspect ratio/span results in the minimum energy required and hence in the minimum take-off weight?
- What is the thrust sizing requirement: take-off, maneuvering, mission climb?
- How many batteries are required to store the energy collected during the day?
- How sensitive is the design to variations of weight, drag, efficiencies?

All these questions can best and consistently be answered with a computer aided design and scaling program. These kinds of programs have been used for about 40 years in a more or less complex form. High speed computing and sufficient memory allow running these programs today on normal laptops or PC´s. The principal scheme of such a program is shown in Fig. 29. The data of a baseline configuration (geometry, weights, aero data, propulsion characteristics etc.) will be used as inputs. The calculation of mission, field and maneuver performance will indicate any deficiency or exceedance of requirements and the aircraft will be scaled and iterated until the design requirements are met. The challenge for the development of the program are the many assumptions in various disciplines which have to be made in order to allow a correct scaling process, because for this type of aircraft there are no statistical data available. That is in particular true for weight assumptions and efficiencies in the electrical chain, which have to be confirmed or updated during the development process. A specific task is the calculation of the solar power received by all surfaces covered with solar cells (wing, fuselage, tails), because the power is dependent on the orientation of the cells, which varies with mission time, and in real flight with the flight direction.

Important mission parameters are plotted as a function of time during a one day/24 hour mission cycle in Fig. 30. The available sun power resulting from the mission profile on a west to east track (Solarpower line) does also consider the altitude effects. The total power required for the propulsion system and all other electrical systems on board the aircraft is represented by the Power required line. This power is provided either from the solar cells directly during the day and/or from the battery during the night operation. The Battery power line indicates the battery utilization. Negative values indicate it is providing power; positive values characterize the charging process.

Figure 31 shows the design mission altitude, the accumulated values for total energy collected, total energy used and the battery energy status. It is mandatory that the battery energy status at the start and the end of a cycle must be the same to support a multi-day mission. These curves are of course dependent on the mission parameters, in particular the rate of climb, maximum and minimum altitude and the aircraft characteristics, i.e. geometry, mass, aerodynamic characteristics like wing loading and aspect ratio, and the efficiencies of the electrical power system. These parameters have to be properly balanced in a complex multidisciplinary design and mission iteration process to obtain a solution at all and furthermore to obtain an optimum solution, e.g. a minimum weight aircraft. The design iteration is only completed if the wing has the right size to allow the installation of enough solar cells to generate the right amount of power for one day, the batteries have the right capacity to store the energy required for the night operation and the overall aircraft mass reflects these data for the mission.

Of course there is more than one solution to satisfy mission requirements. The goal is to find a configuration with a low weight which meets the design requirements and constraints.

For the external configuration the most important parameters are the wing size/wing loading and the aspect ratio/wing span. Figure 32 shows a diagram with potential solutions which exactly fulfill the design criteria (diagonal grey line with triangles). The configurations in the grey area exceed the criteria resulting in a too heavy, unbalanced solution; i.e. wing size, aspect ratio and battery size are not properly correlated. And it identifies the (hatched) area, where no design solutions are possible.

Theoretically there seems to be no lower limit for the wing area and hence the aircraft weight. However, if the resulting wing span is considered, it becomes evident that there is a minimum wing span and that with further reduction of wing area the wing span increases considerably. Considering flight mechanics and the aero elasticity, wing span becomes for practical reasons a design constraint (Fig. 33). This effect has also been realized in studies for a solar powered aircraft for the planet Mars[7].

This kind of a design program also allows the determination of sensitivities, which are used to easily judge the effects of changes in mass, drag increments and efficiency on takeoff mass. These sensitivities are helpful in the evaluation of trade-offs. Of course the accuracy of the scaling process and the resulting data is decreasing with increasing distance from a verified starting point.

A comparison of manned and unmanned solar powered aircraft with civil and military aircraft is shown in the next figures. Figure 34 is the classical aircraft design diagram using the thrust/weight ratio and the wing loading as the axis. It is impressive that solar powered aircraft are located in the lower left corner, close to zero. Sport utility aircraft and commercial and military vehicles cover a significant area with much higher values for these two important parameters.

A comparison of the aerodynamic quality in terms of lift/drag ratio and the aircraft cruise velocity indicates the solar powered aircraft at moderate L/D and rather low velocities (Fig. 35**)**.

Take-off weight as a function of wing area for human powered, manned and unmanned solar powered aircraft, for battery powered sailplanes and the ETA sailplane (with a maximum L/D ratio of 70) are provided in Fig. 36. It is clearly evident, that the design area for the Solar Impulse aircraft is far outside the range of conventional sailplanes or sport utility aircraft. Weight and wing loading are about twice the size as for unmanned solar powered aircraft, which operate at even higher altitudes.

Fuselage and cockpit are relatively independent from the wing design. However, special care must be taken to assure that the pilot functions can be properly supported in this area for up to 4-6 days and the pilot can safely land the aircraft after completion of a mission. This includes all bodily functions and must also assure acceptable environmental conditions in terms of breathing air (oxygen and nitrogen in particular), humidity and temperature throughout the flight. Rescue equipment, ingress and egress in case of emergency must be considered as well. A cockpit mock-up (Fig. 37) has been developed to study the space situation and to evaluate and derive functional requirements**.**

A comparison of the Solar Impulse aircraft to an Airbus A-380 clearly shows the enormous wing span of this solar powered airplane (Fig. 38).

The general approach used by the Solar Impulse team is to first develop, build and test a “Demonstrator” aircraft. This will allow demonstrating a full solar cycle flight, lasting between 24 and 36 hours. This vehicle will verify the design assumptions and tools and provide the necessary inputs for the design of the bigger “Record” airplane, which is to be used to fly around the world with solar power only. Mission duration for those flights will be 4 to 6 days.

The development of the “Demonstrator” aircraft is in full swing. A wing spar test was conducted already in 2007 (Fig. 39), sample ribs have been built and structurally tested (Fig. 40) to verify weight assumptions.

The cockpit structure has been built (Fig. 41) and has been exposed to flight loads. Equipment is being integrated. The cockpit has been used in long time flight simulations (25 hours) to also gain experience about the support systems for the pilot (Fig. 42).

The engine gondola with the integrated battery pack has completed structural testing (Fig. 43). Engine runs have been performed as well. An artist concept of the Demonstrator aircraft is shown in Fig. 44. Manufacturing of the structural components of the aircraft is well underway, with final assembly scheduled for late summer and a possible roll out end of 2008. Flight tests will start in 2009.

Considering the sunshine duration at different latitudes and the maximum energy which can be accumulated, extended flights are possible even in central European airspace (Fig. 45).

Summary

Many manned and unmanned solar powered aircraft have proven that aircraft can fly with solar power as the only energy source. A number of altitude and endurance records have been achieved during these flights.

What is still missing, and that is the goal of the Solar Impulse program, is a manned aircraft capable of flying day and night with solar power only and with an endurance which allows it to fly around the world in a few segments. The Solar Impulse teams’ (Fig. 46) ambition is to contribute in the world of exploration and innovation to the use of renewable energies and to demonstrate the importance of the new technologies for a sustainable development.

Solar Impulse was founded in 2003 by Bertrand Piccard (President and designated pilot) and André Borschberg (CEO and designated pilot).

Acknowledgements

Many of the thoughts and results for the conceptual design of the manned solar airplane presented in this paper were generated by the Solar Impulse team. In particular Peter Frei conducted many of the basic studies for the configuration definition.

References

[1]Keidel, B., “DLR Forschungsbericht 2002-1: Auslegung und Simulation von hoch-fliegenden dauerhaft stationierbaren Solar-Drohnen“, DLR, ISSN 1434-8454, 2002, 32 pp.

[2]Brinkmann and Zacher, “Die Evolution der Segelflugzeuge“, ISBN 3-7637-6119-5, 1999, 245 pp.

[3]Thomas, F., *Fundamentals of Sailplane Design*, College Park Press, ISBN 0-9669553-0-7, 1999, 44 pp.

[4]Stadt, U., *Fliegen mit Licht,* ISBN 3-88 294 240-1, 1997, 75 pp.

[5]Voit-Nitschmann, “Solar-und Elektroflugzeuge: Geschichte und Zukunft“, publication unknown, 1998.

[6]Basien, M., “Grundsatzüberlegungen zur Auslegung, Interner SI Bericht“, unpublished internal report, 2006.

[7]Colozza, A., “Preliminary Design of a Long Endurance Mars Aircraft”, *AIAA Paper 902000,* April 1990, 2 pp.

[8]Sachs, G., J. Lenz, O. da Costa, H. Ross, “Solar aircraft trajectory optimization for performance improvement”. CEAS Conference September 2007, Berlin, CEAS-2007-412

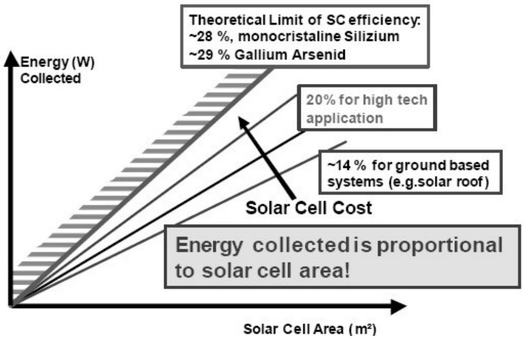


Figure 1 Solar energy collection.

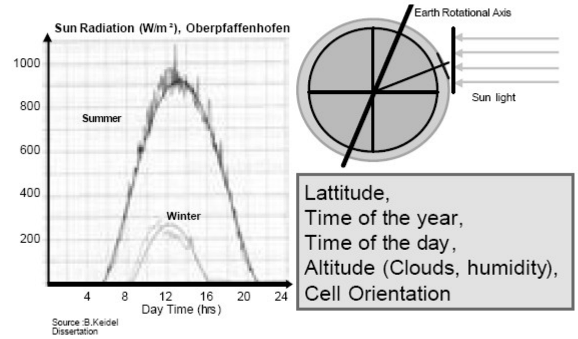


Figure 2 Primary parameters for energy collections.

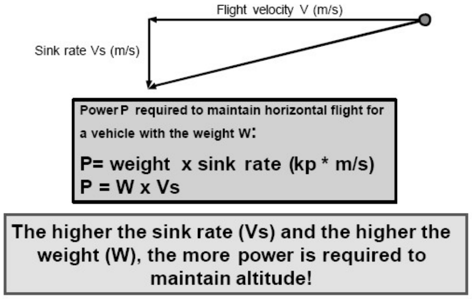


Figure 3 Power required for sink rate compensation.

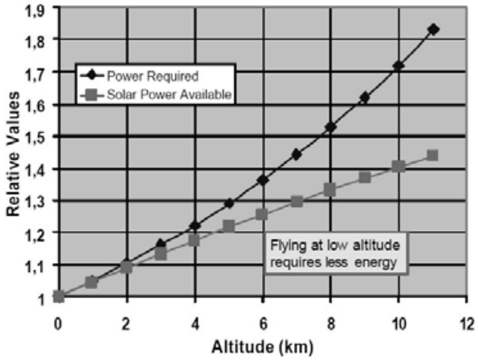
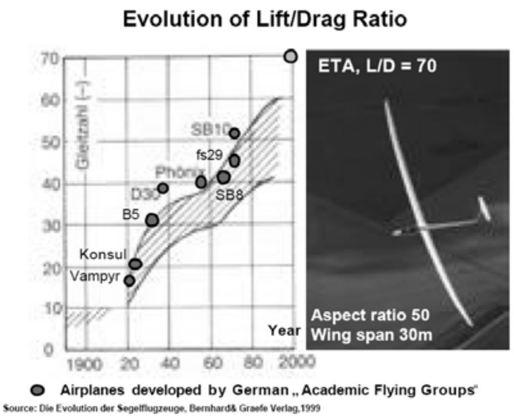
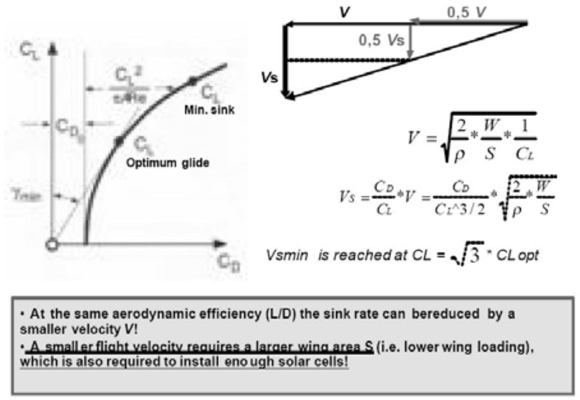


Figure 4 Relative power for horizontal flight and available solar power as a function of altitude.



Source: Die Evolution der Segelflugzeuge, Bernhard& Graefe Verlag,1999

Figure 5 Evolution of lift/drag ratio $(L/D)^2$



$$V = \sqrt{\frac{2}{\rho} * \frac{W}{S} * \frac{1}{C_L}}$$

$$V_S = \frac{C_D}{C_L} * V = \frac{C_D}{C_L\text{^}3/2} * \sqrt{\frac{2}{\rho} * \frac{W}{S}}$$

Vsmin is reached at $CL = \sqrt{3} * CL\,opt$

- At the same aerodynamic efficiency (L/D) the sink rate can bereduced by a smaller velocity *V*!
- A smaller flight velocity requires a larger wing area S (i.e. lower wing loading), which is also required to install enough solar cells!

Figure 6 Reduction of sink rate.

Figure 7 The first solar powered aircraft.

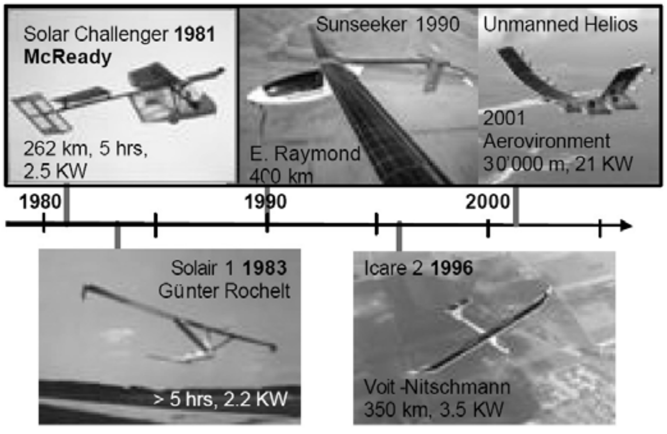


Figure 8 Milestones of solar powered flight.

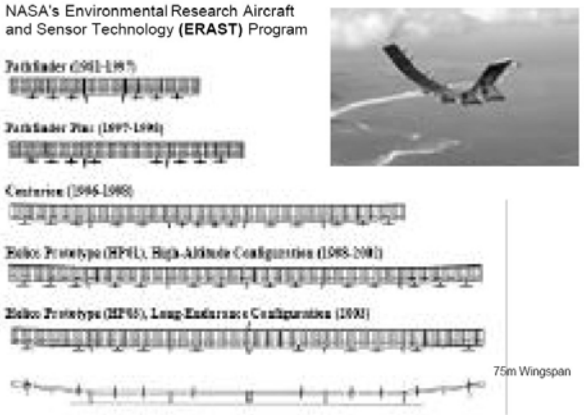


Figure 9 Unmanned solar planes.

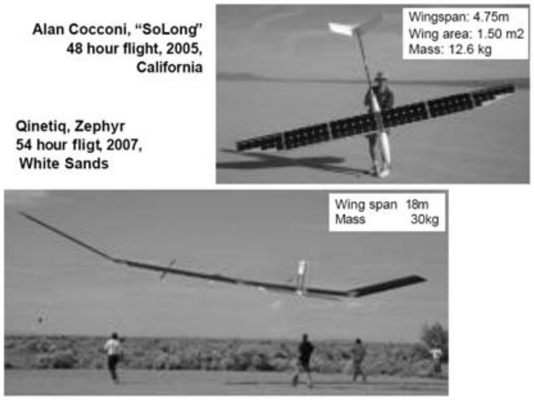


Figure 10 Unmanned long endurance record airplanes.

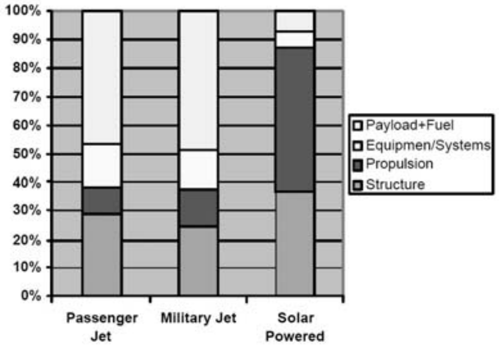


Figure 11 Relative mass breakdown (Max TOGW).

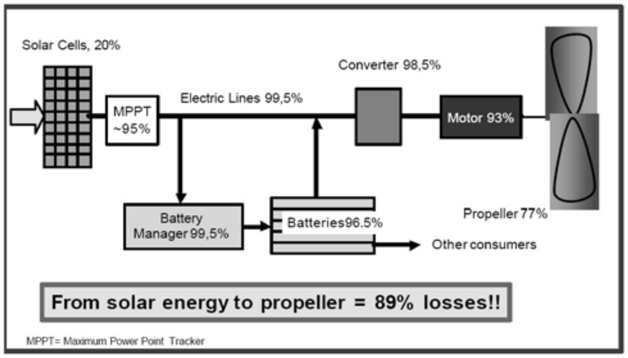


Figure 12 Solar powered propulsion system.

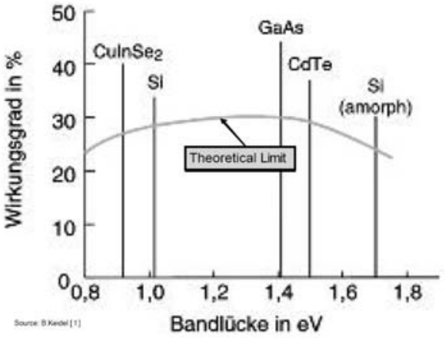


Figure 13 Efficiencies of solar cells[1].

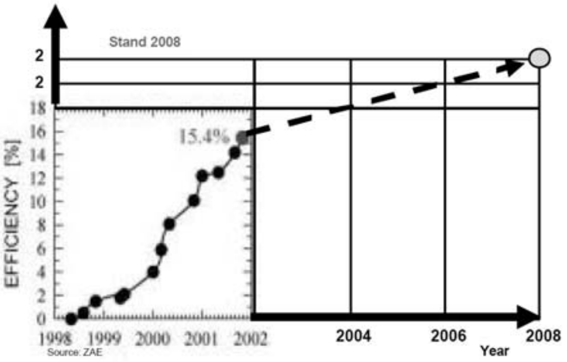
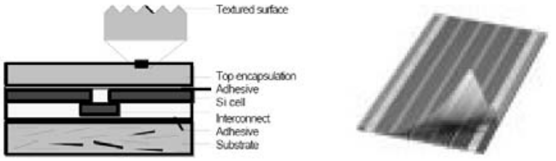


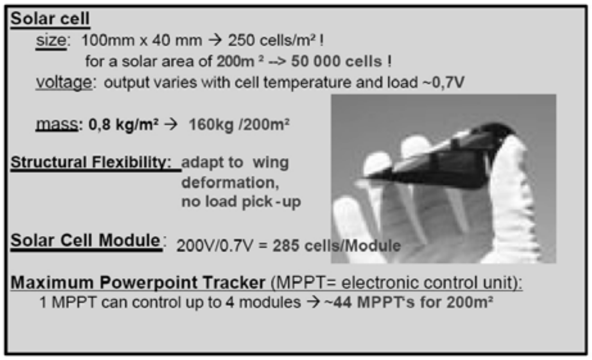
Figure 14 Efficiency evolution for thin solar cells.



Requirements:

- Thin and light
- Very high light transmission (>95%)
- High UV resistance
- Service temperature -60 to 80 °C
- High moisture penetration resistance
- The film has to allow bonding with encapsulation glue

Figure 15 Embedded solar cells (source: EPFL Lausanne).



Solar cell

size: 100mm x 40 mm → 250 cells/m² !
for a solar area of 200m ² --> 50 000 cells !
voltage: output varies with cell temperature and load ~0,7V

mass: **0,8 kg/m² → 160kg /200m²**

Structural Flexibility: **adapt to wing deformation, no load pick-up**

Solar Cell Module: 200V/0.7V = 285 cells/Module

Maximum Powerpoint Tracker (MPPT= electronic control unit):
1 MPPT can control up to 4 modules → ~44 MPPT's for 200m²

Figure 16 Typical data for a solar generator.

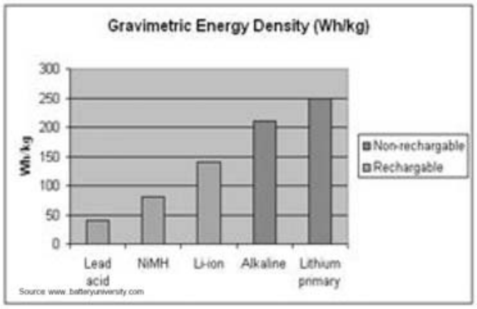


Figure 17 Energy density of batteries.

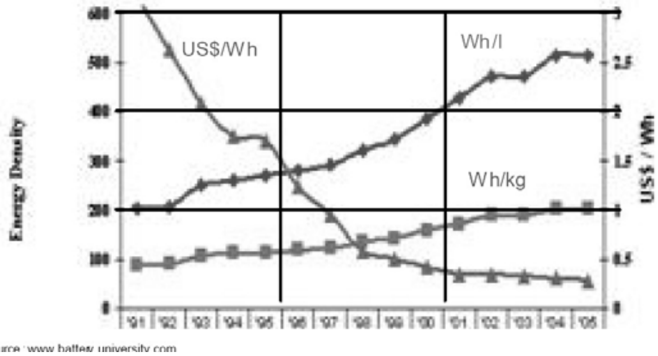
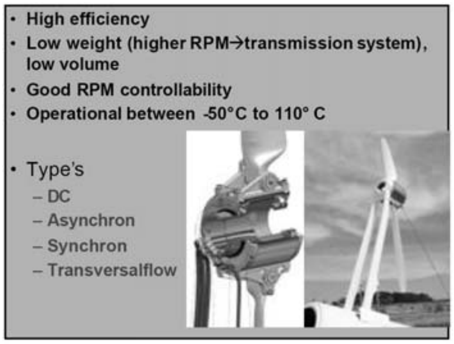


Figure 18 Characteristics of Lithium-ion batteries.

Voltage: **4,2 V fully charged, 3.2 V fully discharged**
Specific energy: **200 Wh/kg**
Number in Battery Pack: 280 (Max Voltage)/4,2 = **67 units**
Total Battery Capacity for an aircraft: **75kWh**

Total Battery Mass: **→ 375kg**
Battery Unit Capacity, Mass and Volume: **variable, → manufacturer**
Temperature: **15°C < T < 35°C, requires monitoring & conditioning**

Figure 19 Characteristic data of a battery pack.



- **High efficiency**
- **Low weight (higher RPM→transmission system), low volume**
- **Good RPM controllability**
- **Operational between -50°C to 110° C**
- Type's
  - DC
  - Asynchron
  - Synchron
  - Transversalflow

Figure 20 Electric engine of the Antares sailplane.

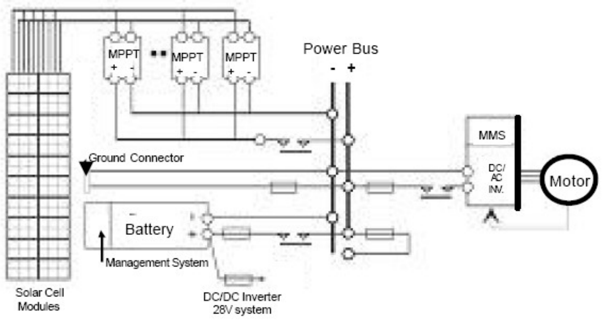


Figure 21 Schematic of the electrical system.

Primary materials:
- Carbon Fibre Composites,
- Foam,
- (Transparent) plastic skin

Structural concepts
- Tubular / Box spar
- Sandwich
- Gridstructure

Specific wing weight ~ 2kg/m²
Ground handling is a challenge

No statistical data available!!

Figure 22 Materials and structural concepts.

Figure 23 Wing structure of the Pathfinder (source AeroVironment)

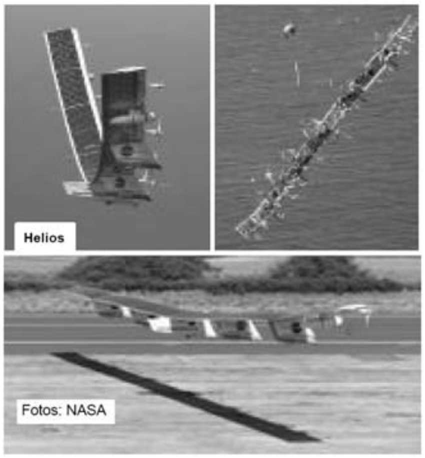
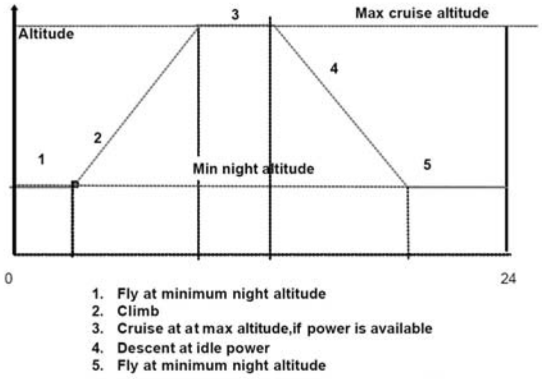


Figure 24 Helios, normal and large wing bending and loss of vehicle.



1. Fly at minimum night altitude
2. Climb
3. Cruise at at max altitude,if power is available
4. Descent at idle power
5. Fly at minimum night altitude

Figure 25 Simplified mission profile.

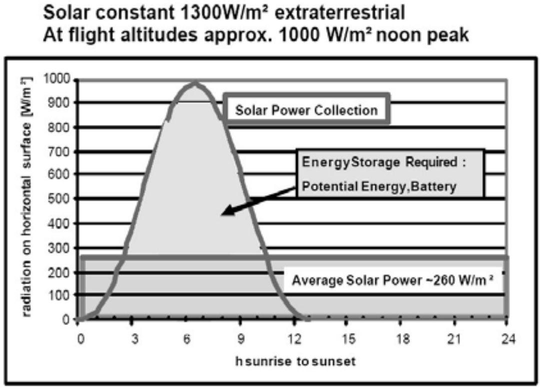


Figure 26 Available solar power.

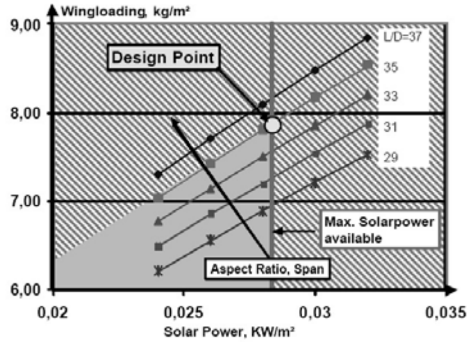
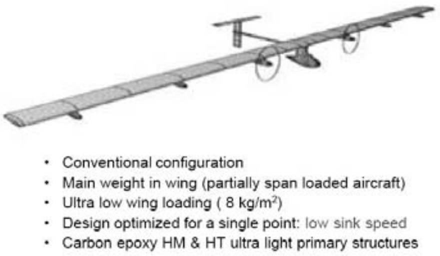


Figure 27 Maximum wing loading possible as a function of available solar power and aerodynamic efficiency.



- Conventional configuration
- Main weight in wing (partially span loaded aircraft)
- Ultra low wing loading (8 kg/m²)
- Design optimized for a single point: low sink speed
- Carbon epoxy HM & HT ultra light primary structures

Figure 28 Potential configuration.

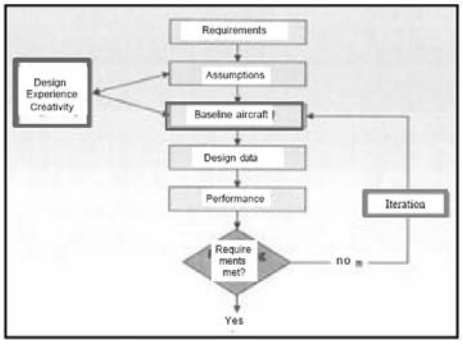


Figure 29 Computer aided design scaling program.

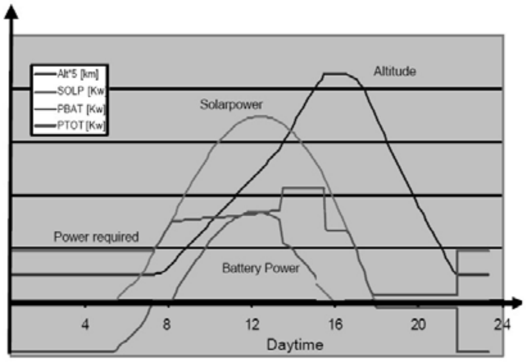


Figure 30 Missions parameter = f(day time), (1)

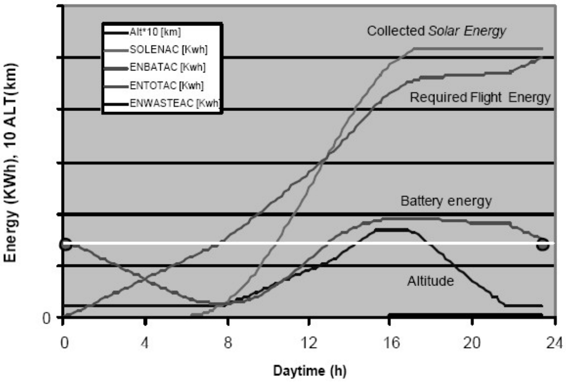


Figure 31 Mission parameter = f(day time), (2)

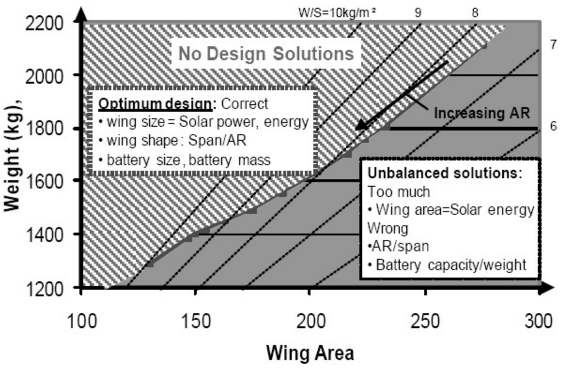


Figure 32 Design window optimal parameter combinations.

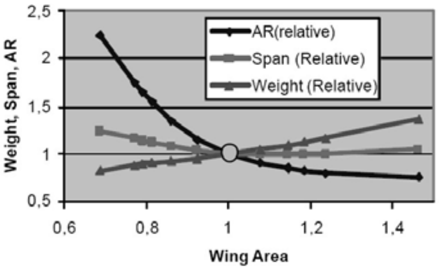


Figure 33 Design constraint wing span.

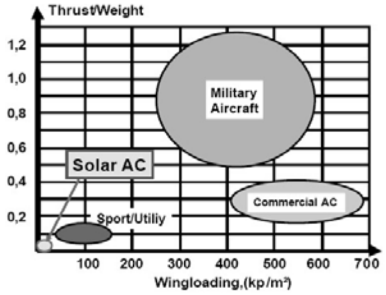


Figure 34 Aircraft design windows.

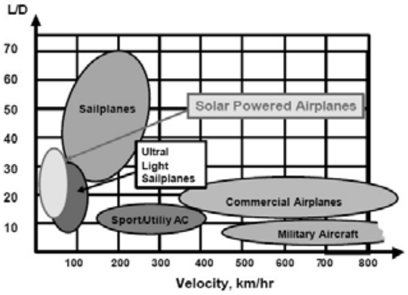


Figure 35 Lift/Drag and velocity range for different aircraft types.

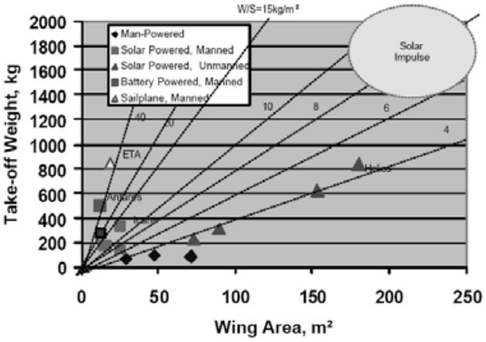


Figure 36 Take-off weight and wing area of solar powered airplanes.

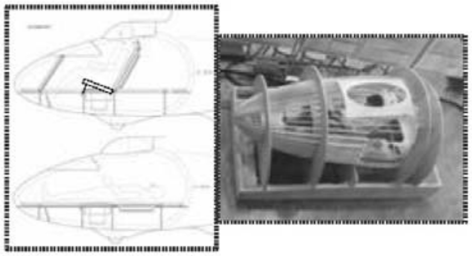


Figure 37 Solar Impulse cockpit mock-up.

Figure 38 Size comparison A-380 and Solar Impulse.


Source: Solar Impulse

Figure 39 Wing box structure test.


Source: Solar Impulse

Figure 40 Horizontal tail, rib spar arrangement.


Source: Solar Impulse

Figure 41 Cockpit structure and half-shell.


© Solar Impulse

Figure 42 Aircraft simulator.

Source: Solar Impulse

Figure 43 Engine/gondola integration/testing.


© Solar Impulse/EPFL Claudio Leonardi

Figure 44 Artist concept of the HB-SIA Demonstrator.

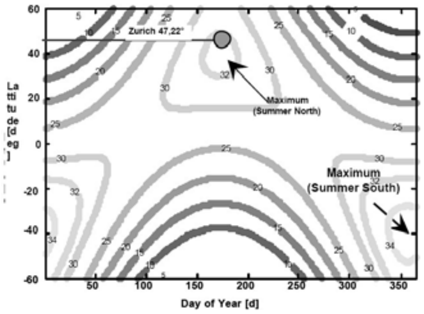
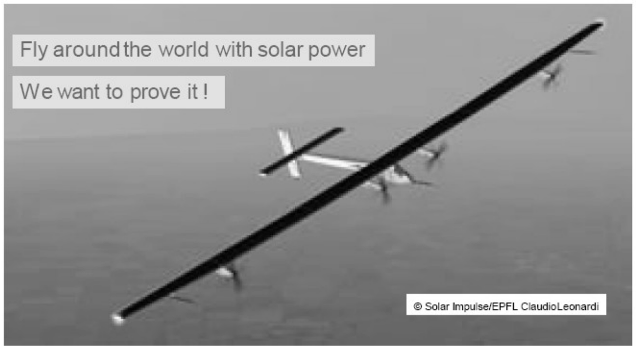


Figure 45 Regions of maximum available solar energy (MJ/m^2).


© Solar Impulse

Figure 46 Leaders and members of the Solar Impulse team.



© Solar Impulse/EPFL Claudio Leonardi

www.solarimpulse.com