From Sunrise to Solar-Impulse
34 Years of Solar Powered Flight

Ernst Schoeberl
University of Applied Sciences, Wuerzburg-Schweinfurt, Germany
eschoe@fh-sw.de

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Abstract

The solar cell was invented in 1954. It lasted twenty years until the first solar powered aircraft **Sunrise 1** was designed and successfully flown. Several aviation pioneers flew battery buffered solar aircraft in 1979 and later. Dr. Paul MacCready was the first to fly a man carrying aircraft on solar power alone. He also won the Henry Kremer Solar Aircraft Prize for flying his **Solar Challenger** from Paris to England in 1982. The Berblinger Solar Aircraft Competition for practical use solar aircraft was won with **icaré 2** from Stuttgart University in 1996. With unmanned, high altitude, long endurance solar aircraft altitudes up to 29,500 m and durations up to 54 hours were reached. With the ultra light, high capacity lithium battery technology developed in the past years, enough solar energy can be stored for flights even during the whole night. The Swiss **Solar-Impulse** shall make all night flights by 2009, long distance flights by 2010, and the highlight will be a round the world flight by 2011.

The beginning

In the year 2004 there were two jubilees for the solar cell technology:

Fifty years of solar cells - The colleagues of the Bell Telephone Laboratories, NJ/USA presented on April 25, 1954 the first silicon solar cell, which had already 6% efficiency. In the same year Dr. A. Raspet pointed out the possibility of solar powered flight with this technology.

Thirty years of solar powered aircraft - On November 4, 1974, R. Boucher from Astro Flight Inc. tested the 10 meter wingspan solar model aircraft **Sunrise I** in the high-desert of southern California/USA[1] (Fig. 1). A year later, the solar aircraft reached a height of 5,000 m on solar power alone.

The prices of solar cells cost as high as 100,000 $/kW. They were relevant for space flight only. When the prices fell considerably, the first solar model aircraft were built and successfully flown in Germany[2], which is not a sunny country. Fred Militky made his first 3-minute flight with his **Solaris** on Aug. 19, 1976. The American Larry Mauro equipped his light weight double-decker **Solar Riser** with solar cells, storage batteries and an electric drive, and flew it for half a mile in 1979[3]. The Englishmen Fred Too also achieved notable success. He reached, with his similarly equipped **Solar One**, the height of 25 m in 1979.

Solar cells and buffer batteries

A good aerodynamic design, high efficient, safe and reliable components and systems with the lowest weight possible are important for successful solar powered flight, but solar cell efficiency and high specific energy to weight ratio of the batteries are essential.

Although there are solar cells with efficiencies as high as 28% available at high cost, monocrystalline silicon cells are still the best choice for solar flight. The first solar cells had 6% efficiency in 1954, but the efficiency of the Bell Laboratories solar cells quickly reached 10%. Then the efficiency slowly rose from 12% in the early 80's, to 14% in the early 90's, and 18% finally. First selection cells for space flight were always at least 2% more efficient and much more expensive.

The nickel-cadmium-batteries (NiCad) Guenter Rochelt and Paul MacCready used in their solar aircraft in 1981 had a specific energy capacity of 20 watt-hours per kg mass (Wh/kg). Gasoline for comparison has 11,800 Wh/kg as fuel and 4,00 as shaft power from the combustion engine.

Even when the specific capacity rose to 30 Wh/kg in the mid 90's, and with nickel-metal-hydride batteries to 60 Wh/kg in the late 90's, this was only good for a safe launch up from 500 to 1,000 m altitude. In the meantime the lithium-ion-batteries, affordable since the year 2000 have reached a specific capacity of 200 Wh/kg. This makes solar energy storage during the day for the all night flight possible now.

Pioneer-projects and the Kremer prize for solar flight

The first major successes in solar model aircraft and human powered aircraft, and the availability of economical solar cells and low weight, high strength fiber composite materials, together with efficient computer programs, encouraged such pioneers as Paul MacCready and Guenter Rochelt to develop man-carrying solar aircraft.

Solar Penguin

Paul MacCready and the pilot Bryan Allen won with the man-powered aircraft **Gossamer Condor** Henry Kremer's prize for the first figure eight flight around two pylons half mile apart in 1977. They also won the prize for crossing the English Channel with the larger **Gossamer Albatross** in 1979. In order to gain the necessary experience with solar power as quickly as possible, they equipped their smaller **Gossamer Penguin**[4] (Fig. 2) with solar equipment. The extremely lightweight aircraft could only be flown under calm air in the mornings. The obtained knowledge gave a stimulus to develop a truly practical solar aircraft, the **Solar Challenger**.

Solar Challenger and the Kremer solar flight prize

In order to be able to fly safely and reliably under windy conditions, MacCready and his team chose a conventional high wing monoplane, designed in accordance with the American FAA Glider Handbook and OSTIV-Requirements for Gliders. The conventional configuration **Solar Challenger** (Fig. 3) has a rigid graphite fiber tube spar, and an airfoil with a long flat upper side in the rear, and a large elevator with a similar airfoil, to get a maximum solar cell area of 68% of the wing and elevator surface and 2500 W maximum solar power[4]. The geared electric motor drives a large propeller with pitch control for the best power adaption of the solar cells under variable flight and radiation conditions (maximum power point operation). The aircraft was thoroughly tested with a set of 120 cell NiCd-batteries in November 1980. Then the solar cells were installed and another test program with 6 hours duration in 69 flights was carried out. Equipped for the Kremer prize flight from Paris to England, they optimized all systems in 13 more flights in 23 total hours. The longest flight was a 320 km long triangle flown up to 4,000 m altitude in 8 hours and 23 minutes. After several attempts, they had the favorable weather conditions on July 7, 1981. The pilot Stefan Ptacek (a Czech name which means Little Bird) took off from Pontoise-Comille-Airport near Paris at 9:28 A.M. for his 262 km long distance flight to England. He flew mostly at 3500 m altitude and landed 5 hours 23 minutes later at Manson Royal Air Force Base, England, winning the Kremer solar flight prize.

Solair I

After a remarkable 5 hour flight with his solar model in 1979[2], Guenter Rochelt began his man carrying **Solair I** project (Fig. 4). He based his canard design on the successful Swiss micro light glider from Hans Ulrich Farner and built it in ultra light fiber composite construction in the original molds. In order not to disturb the aerodynamics, he integrated the 2500 solar cells in a flexible silicon layer under the surface. A NiCd-buffer battery with 0.4 kWh capacity was installed for a safe take off. The geared motor drove a large pusher propeller that folded in glide flight.

After several tests, **Solair I** had its maiden flight on December 17, 1980, the 87th anniversary of the **Wright Flyer**[5]. There were several more flights up to 5 m high and 1 km long on that day. Despite the many alterations and optimizations, no take off without battery power was possible. So he had no success in trying to win the Kremer solar prize. Rochelt's longest flight was 5 hours and 41 minutes at Alpen-Segelflugschule Unterwoessen on August 21, 1983.

Sunseeker

The successful hang glider pilot, Eric Raymond, had constructed his **Sunseeker** (Fig. 5). It was a similar solar version of Rochelt's man powered aircraft **Musculair II**[6]. Except for the lack of power of the solar generator, **Sunseeker** is a rather good aircraft for practical operation[7]. Its flying speed ranges from 10 to 38 m/s, combined with the low sinking velocity, makes it possible to use even weak and narrow thermals. Despite the design being in accordance with the OSTIV-Requirements for Glider-Design, the mass of the glider version (without solar equipment) was only 45 kg. The glide ratio reached was between 35 and 38 combined with good flying behavior. Equipped with a thin layer of solar cells on a polymer base, buffer batteries, geared motor and pusher propeller, the mass rose to 89 kg. Due to the added solar generator, the glide ratio dropped to 30. The 2.2 kW electric power, mostly from the battery, brought only 0.25 m/s climb.

As high solar radiation usually brings good thermals, Eric Raymond planned to cross the American Continent. He started on August 2, 1990, from Desert Center in southern California and flew in 21 stages, and 125 hours to South Carolina near the Atlantic Ocean. He always took off with fully charged buffer batteries. His longest day distance was 400 km.

The Berblinger solar aircraft competition of the City of Ulm, Germany in 1996[8]

In the year 1811, Josef Albrecht Berblinger was the first glider pilot to fly short distances. His attempt to cross the Danube River failed because of poor flight stability. In memory of him, the City of Ulm organizes regular aviation competitions. They decided to announce a competition for practical, usable solar aircraft on September 7, 1990. The following requirements were specified[8] (pg.120):

- Aerodynamic three axis controls.
- Airworthiness equal to ultra light aircraft requirements or better.
- Minimum glide ratio 20 and maximum sinking velocity 1.0 m/s.
- Take off with buffer battery assistance up to 450 m altitude with minimum 2.0 m/s climbing velocity.
- A stationary constant level flight should be possible with 500 W/m^2 solar radiation.

The participants had 3½ years to plan, construct and test their aircraft. There were 64 applicants from 12 countries. Seventeen proposals were presented until October 12, 1995, however some were incomplete. They were checked by the scientific committee[8] (pg.127-150). From the 17 aircraft, only 5 were brought to the military airfield Laupheim near Ulm for the necessary checks and flight preparations by end of June 1996. **icaré 2** from the aircraft design faculty of Stuttgart University was complete and aviation certified and got an unlimited take off permit. The remaining aircraft listed below did not pass the checks and preparations to obtain a permit to fly:

- **O sole mio** from Antonio Bubicco/Italy
- **Lo 100 Solar** from Hugo Post/Germany

- **Solarflugzeug** from Uwe Heinemann/Germany, and
- **Solair II** from Guenter Rochelt/Germany

They were only allowed to roll along the taxiway or to make short flights just over the runway. The highlight and final of this competition was the solar aviation day at the military airfield Laupheim with impressive flight demonstrations of the winning aircraft **icaré 2** and the solar powered airship **Lotte**, both from Stuttgart University. The first prize, donated 100,000 DM (German Marks) about 50,000 Euro, was awarded to **icaré 2**. There was not a second place winner, however two prizes for 3rd, one 4th and one 5th place winners. The 3rd place prizes were presented to Prof. Guenter Rochelt for his **Solair II**, and to Dr.-Ing. Antonio Bubicco for his **O sole mio**. Hugo Porst got the 4th prize for **LO 100 Solar**, and Uwe Heinemann was presented for 5th place for the **Solarflugzeug.** More prizes were awarded for outstanding designs that were honorable mentioned. The solar aircraft team from University of Applied Sciences of Augsburg, Germany, which supported Prof. Ossner and Prof. Mueller-Horsche, was awarded 15,000 DM. The academic aviation group from Darmstadt University got a 15,000 DM prize for its outstanding design of the Solar-Elektro-Motorsegler D42 (Solar Electric Motor Glider).

icaré 2

This aircraft was designed and constructed under the direction and supervision of Prof. R. Voit-Nitschmann with M. Rehmet and W. Scholz as project engineers[9]. All essentials were investigated in 40 research studies and a diploma thesis. **icaré 1** was the first project with Peer Frank's wing of his **Velair 88** human powered aircraft, and the spare drive and propulsion unit of the solar airship **Lotte** to test further details in flight. To get an unlimited flight permit, **icaré 2** was designed according to JAR 22, with 37.5 m/s design speed. The three-piece wing with 25 m span and 26 m^2 wing area had to be large enough to reach the constant level flight requirement at 500 W/m^2 solar radiation. The 21.6 m^2 monocrystalline solar cells have 3.67 kW output that drive a 2.4 m diameter pusher propeller via a gearless motor. The tests of both performance and characteristics showed that **icaré 2** is rather close to the practical use solar aircraft specified with high performance. Prof. R.Voit-Nitschmann started with **icaré 2** from Aalen Elchingen airfield near Ulm on June 17, 2003 in preparation for a test flight. Because of the good flying conditions, he soon climbed over the cloud base and flew with the power from his solar cells NE until he reached 350 km distance of Jena, Germany. He easily could have continued this flight but had not the necessary aviation maps in his cockpit. **icaré 2** is still in use and serves as test bed for new technologies, i.e. batteries, electronics a.s.o.

Solair II

The design of this aircraft is like a glider with a high aspect ratio wing[10] (Fig. 7), the inner part tilted forward and the outer part rearward. The solar cells are embedded in a thin flexible shell with a glass fiber laminate on the upper side and on a Conticell (polyacrylate foam) base. These solar generators are inserted on the upper side of the wings. Another specialty is the rearward tilted V-type elevator with the geared motors and counter rotating propellers in the tips. Due to extreme light weight design, the gross tare mass is 140 kg, and the take of mass is only 230 kg.

After completion and proof of airworthiness, **Solair II** had its maiden flight in May 1998. With several improvements, it is a good practical use solar aircraft with high performance, flown after Guenter's death by his son Holger.

O sole mio

The design of this aircraft[8] (Fig. 8) is also derived from gliders but different from the others in two aspects: (1) the energy should be stored in a fast rotating flywheel and (2) the elevator is large in area to get more solar power and is low positioned. Therefore, the designer reaches the 20 m^2 solar cell area necessary for constant level flight at lower solar radiation. The pusher propeller with 2.1 m diameter is behind the wing. Due to the light weight design, **O sole mio** has only 130 kg gross tare mass, 220 kg take off mass, and 1,500 W power demand for constant level flight. Although the necessary load tests were successful, this aircraft could not be completed for the Berblinger Competition. Unfortunately nothing is known about completion and solar flights.

Unmanned High Altitude Long Endurance (HALE) aircraft

Pathfinder, Centurion and Helios[12]

This straight mono-wing with 30 m span and 2.5 m width was already planned as HALSOL (high altitude solar energy). Because of the too heavy and inefficient technology in the fields of solar energy storage and drive technology, this project was cancelled. Ten years later, when this technology was available, MacCready's company AeroVironment realized this project as **Pathfinder**[11]. To minimize the wing load, eight drive and propulsion units were distributed along the span (Fig. 9). A large span is important as the induced drag significantly increases with altitude. The S-shaped airfoil with a long flat rear surface at the upper side gives good longitudinal stability and a maximum surface for the solar cells. It reached 15,400 m altitude in a 15 hour flight in 1995 and two years later 21,800m.

Centurion, a similar aircraft with twice the span and 14 drive units should be a HALE-demonstrator that should fly for weeks or month with approximately 250 kg payload at altitudes up to 24,000 m. The battery technology available at that time was not sufficient enough to stay overnight in air[13].

The last prototype invented by AeroVironment was **Helios** (Fig. 10) with 76.8 m span an even larger mono-wing with 14 drive units should be the first "eternal aircraft" that should operate between 15,000 and 30,000 m altitude[12]. Equipped with only solar cells, test flights began at a US Navy airbase in Hawaii in 2001. On the second flight, **Helios** achieved an altitude of 29,500 m but it never reached the second goal of flying non-stop for at least 24 hours. Flights to test telecommunication equipment at 20,000 m altitude were successful in 2002. Unfortunately it was destroyed due to a failure and fell into the Pacific Ocean on June 26, 2003.

Other HALE-projects[14]

The DLR-Institute of Flight Systems in Germany developed **Solitair**, a 5.2 m span demonstrator with adjustable solar panels in 1998. Flight tests achieved good results[15].

The Helinet project funded by the European Community had the goal to study the feasibility of the HALE platform **Helipat** with 73 m span from 2000 to 2003[16]. A scaled 23 m span prototype of the structure was built at Politecnico di Torino. They are still doing research on **Helipat** and on the new platform **Shampo**.

The **Zephyr** solar model with lithium sulfur batteries, having only 30 kg mass for 18 m span, is a platform from the British company QinetiQ[17]. After several test flights they succeeded with a 54 hour flight on September 10, 2007. Flights of several month duration at altitudes above 15,000 m are expected.

New technology solar model aircraft

Only two epoch-making projects with new technology are mentioned here. They are equipped with lithium-ion-batteries and automatic flight control with GPS.

The feasibility of "eternal flight" was proved by Alan Cocconi, founder of ACPropulsion, when his 4.75 span solar model **Solong**[14] flew 24 hours 11 minutes in California on April, 22, 2005. Two months later he made a 48 hour 16 minutes flight.

With the sophisticated, light weight and high efficient technology available now, even small models can stay in air for several days. The Swiss **Sky-Sailor** model with 3.2 m span and 2.4 kg mass flew 27 hours on June 21, 2008[18].

Solar Impulse

No other scientific family has made such an impact in the field of exploration as Auguste, Jacques and Bertrand Piccard. Inventing and exploring has been going on for three generations: the pressurized capsule and the first stratospheric flight, the bathyscaphe achieving the absolute diving record, and the first round-the-world balloon flight.

The challenge of the solar aircraft project is to show that a man can fly overnight or even around the world without any fuel and at zero emission on solar energy alone[19] (Fig. 11). The low weight, high efficient technologies available with lithium batteries make it possible. The one seat, 61 m span aircraft in ultra light carbon sandwich construction has 1500 kg gross tare mass and is propelled by four units with maximum 30 kW electric power. All components and systems are designed, constructed and will be operated at the highest efficiency level and reliability as possible. At present[20], 35 specialists and some 100 scientific advisors are working on the first prototype of **Solar Impulse** that will have its maiden flight in late 2008. The first night flights will take place in 2009.

With the second prototype, long distance flights across the American Continent and across the Atlantic Ocean are planned for 2010.

The round the world flight, scheduled for 2011, will be the epoch making highlight of solar flight and aviation.

Conclusions

The development of solar flight is a process of slow but steady improvement. The efficiency of affordable solar cells soonwill reach 20% and more. To make solar power attractive for motor gliders and General Aviation the cost has to be reduced drastically.

The light weight lithium-ion-batteries will soon make unmanned solar aircraft possible, staying above the troposphere for weeks. These batteries will also have an impact on motor gliders. As the German **Antares** or the Italian **Silent** already show that these batteries will allow them to climb up to 3,000 m (10,000 ft) or higher with only one charge.

Another future application will be to drive the suction ventilator of a high performance full laminar flow glider.

The most important solar powered aircraft are listed in Table 1.

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Figure 1 The first solar powered model aircraft SUNRISE 1 at Camp Irwin, California, 1974. Photo courtesy by Astro Flight Inc.

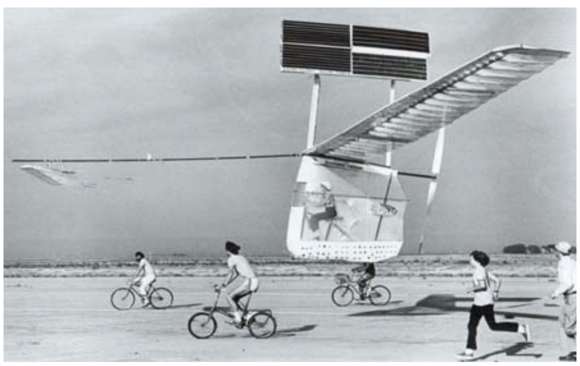

Figure 2 GOSSAMER PENGUIN at its longest flight with 3 km distance at NASA Dryden flight Center, California on August 7, 1980. Photo courtesy by Dr. Paul MacCready, AeroVironment.

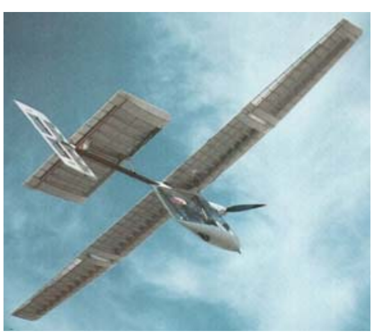

Figure 3 SOLAR CHALLENGER at its maiden flight in 1980. Photo courtesy by Dr. Paul MacCready, AeroVironment.

Figure 4 SOLAIR I at a test flight in spring 1981. Photo by E. Schoeberl.

Figure 5 SUNSEEKER in September 1993. Photo by E. Schoeberl.

Figure 6 ICARE 2 at a cross country flight. Photo courtesy by University Stuttgart.

Figure 7 SOLAIR II at airfield Laupheim, Germany in July 1996. Photo courtesy by P. F. Selinger.

Figure 8 Solar aircraft O SOLE MIO with human powered aircraft VELAIR from Peer Frank behind at airfield Laupheim. Photo by E. Schoeberl.

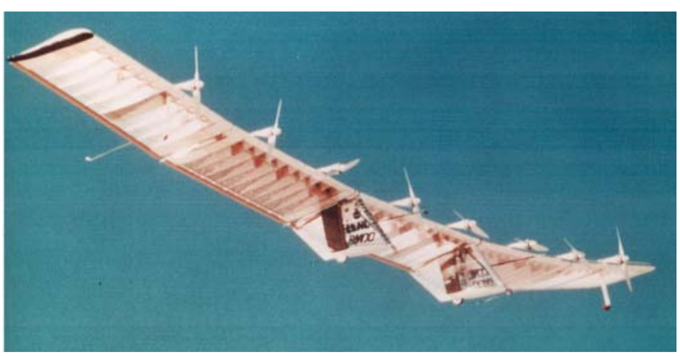

Figure 9 PATHFINDER at a test flight. Photo courtesy by Dr. Paul MacCready, AeroVironment.

Figure 10 HELIOS near the Navy airfield Kanai, Hawaii. Photo courtesy by Dr. Paul MacCready, AeroVironment.

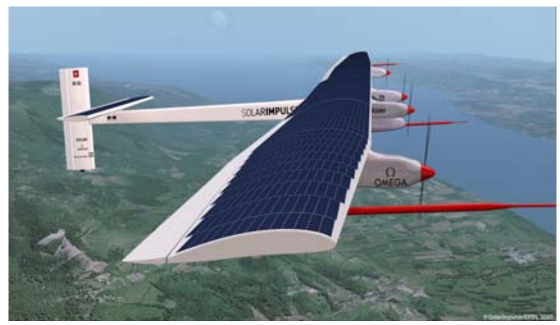

Figure 11 SOLAR-IMPULSE in flight. Computer animation courtesy by Solar-Impulse.

Table 1
The most important solar powered aircraft

Aircraft	Design & Construction. First flight	Solar Power at 1.0 kW/m^2 solar radiation Watt	Gross tare mass kg	Wing span m	Specific power Watt/kg	Maximum climb m/s	Flying velocity on solar power m/s	Remarks
Sunrise	R. J. Boucher 1974	570	10.34	9.75	55.1	2	6.1-9.2	Unmanned high flying solar model.
Gossamer Penguin	P. MacCready 1980	540	68…75	21.9	7.5	-	6.6	2.6 km distance flight in August 1980.
Solar Challenger	P. MacCready 1981	2,500	145	14.3	14.3	0.75	8.5-19.7	Kremer Solar Flight Prize for flight from Paris to England in July 1981. Flights up to 4000 m altitude and 8 hour duration.
Solair I	G. Rochelt 1981	2,200	180	16.0	12.2	-	8-13	Take off with battery power. No constant level flight with solar power alone.
Sunseeker	E. Raymond 1990	appr. 250	160	16.6	1.6	0.25 x)	10-39	x) Because of low solar cell efficiency take off and constant level flight with battery power only. Flight across the US-Continent in 21 stages in August 1990.
Pathfinder	P. MacCready 1994		180	30			Approximately. 7 near the ground	Unmanned high altitude and long endurance monowing. Highest altitude 21,800 m. Longest duration over 15 hours.
Icaré 2	Stuttgart University 1996	3,670	295	25	9.4	2.1	13-33	Winner of the Berblinger Solar Aircraft Competition 1996. Longest distance flight 350 km in June 2003.
Solair II	G. Rochelt 1996	2,320	140	20	10		13-33	Maiden flight in May 1998.
Centurion	P. MacCready 1997	31,000 xx)	529	61.8	appr. 50 xx)		7.5-9	HALE-monowing. Payload 50 to 270 kg, depending on mission altitude 30,000 m to 24,000 m.
Helios	P. MacCready 1999	42,000 xx)	727	76.8	appr. 50 xx)		7.5-9	HALE-monowing. Highest flight 29,500 m. Crashed into the Pacific Ocean near Hawaii in June 2003. xx) Solar power assumed at 1.36 kW/m² solar radiation in the stratosphere.
Solar-Impulse	Bertrand Piccard by late 2008	48,000 xxx)	1,500	61	appr. 32 xxx)		appr.. 20	First manned solar aircraft that with lithium batteries will be able to stay in air overnight. xxx) Estimated solar power at 1.2 kW/m² solar radiation at mission altitude.