ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Solar Impulse

Solar Impulse Version 1.1
Electrical values presentation

April 2004

Table of contents

1 Introduction

In this document the electrical values of version 1.1 of the Solar Impulse airplane are briefly presented to give an idea of the encountered powers. This version 1.1 is the result of the feasibility study driven by many different people during the year 2003 at EPFL and outside.

2 Values from simulation model

During the feasibility study phase a computer model was built to simulate the flight of the airplane during one day, hour by hour. It was rapidly appearing that this modelling is necessary because there is a strong interaction between the different components of the airplane, and especially with the different conditions of flight encountered during the day. Even the most insignificant part of the airplane has an influence on all the rest.

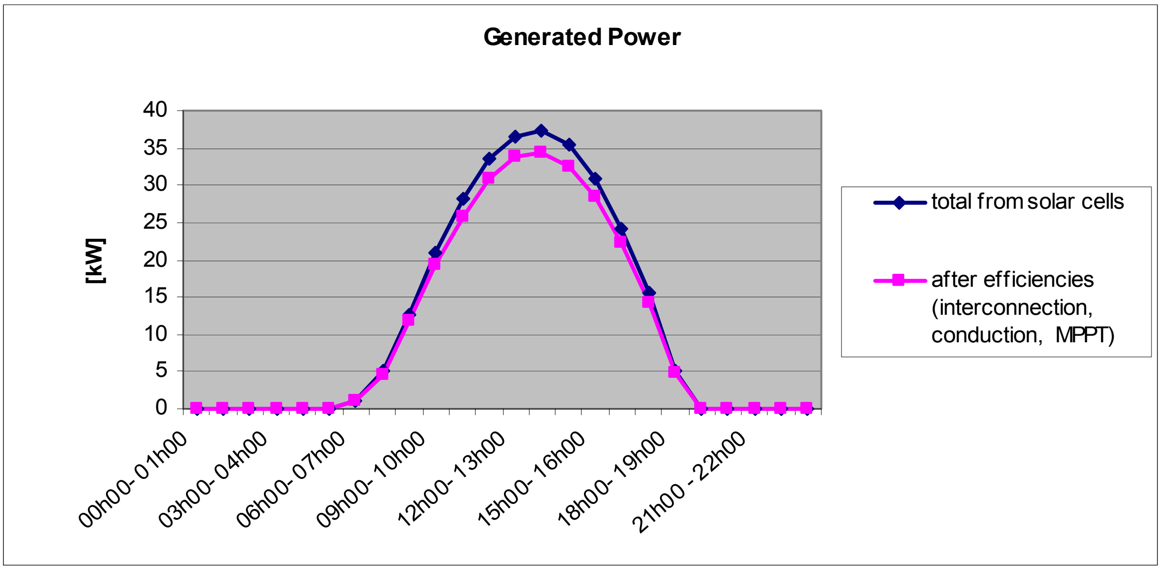
The model is made of energetic equations describing the airplane power fluxes. There is an energy source, the sun, which is converted with different systems that can be described by their efficiencies; in the end the left power, which is aerodynamic power, make the airplane climb or sink. The flight altitude profile is the output of the model. The analysis of this profile allowed taking decision for a configuration of airplane. The power from the sun can be dispatched between the storage and the propulsion, commanded by the pilot. There is an energy management to perform, and graph bellows shows the management done to achieve best performance.

2.1 Solar cells

The orientations and slopes of the different parts of the wings are computed. With those two values the solar irradiance received on each facet was computed hour by hour and a fixed 20% efficiency was used to determine the quantity of energy collected hour by hour. 95% attenuation due to clouds (cirrus) was included in the model as margin.

To get the maximum out of the solar cells, the proper point of operation must be used and a circuit called a MPPT (Maximum Power Point Tracker) is required. An existing circuit is considered to estimate the weight and efficiencies of this device and some interconnection and wiring losses are added. The power tracking will be performed by many different MPPT circuits, each regrouping solar cells with similar orientations. 30 to 45 MPPTs are expected.

The solar position, irradiance model and the efficiencies of the components give us the electrical energy available to the solar airplane. On the given area of 207.5 m^2 of solar cells the power that can be produced is given with the graphic below.



The peak power available is at 34.4 kW at 13h00.

The temperature of the solar cells will be similar to the outside air and values of air temperature can be found on the graphic of the dedicated section below.

2.2 The energy storage and energy use

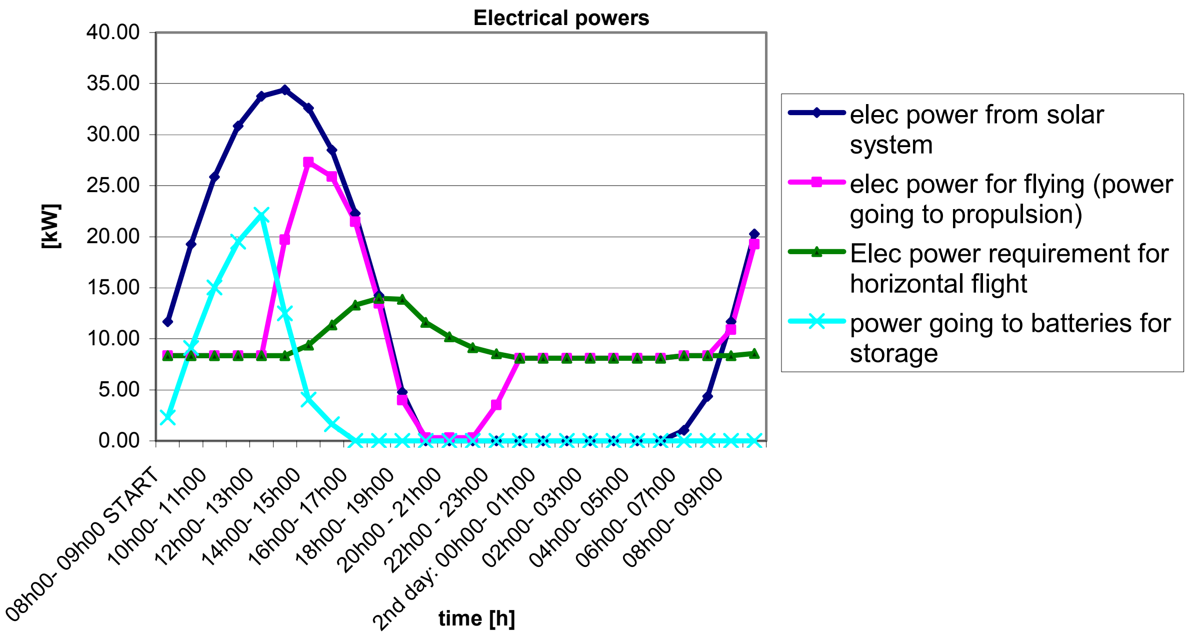
The previous section the model of how the solar power was evaluated and equivalent electrical power deducted. With this electrical power available at the cables of the airplane, there are two options possible:

- Store energy in the batteries.
- Send this power to the propulsion.

Between those two there is a choice and this allows performing a real energy management depending on the flight direction, whether conditions and airplane properties. This energy management will be performed by the pilot that will send or not power to the motor with the control stick. During all the time auxiliary power consumption (radio, computer, avionics…) must also be covered.

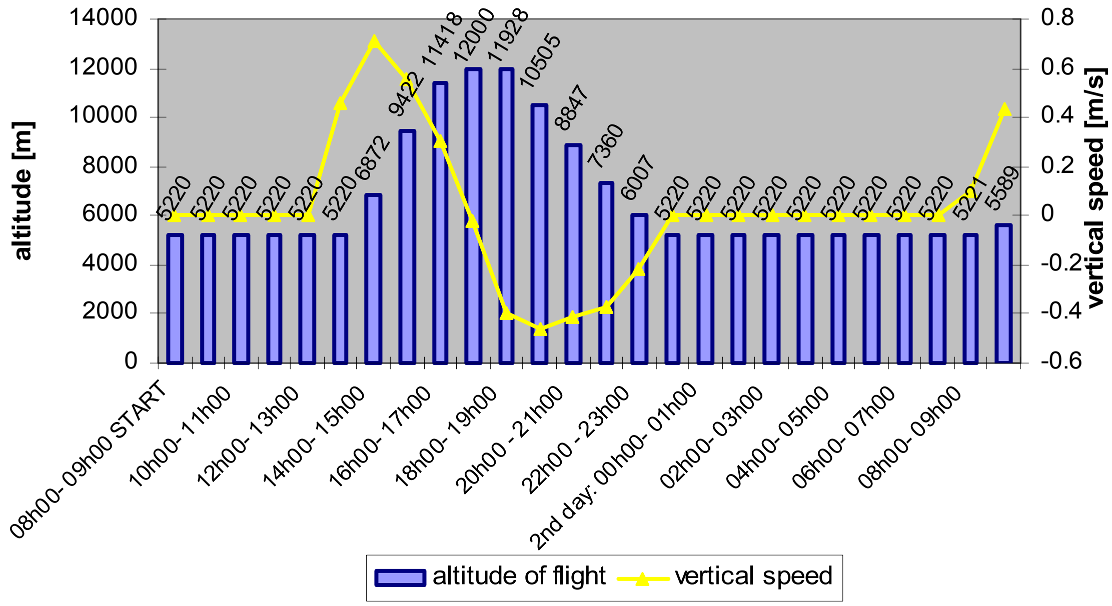
There are many factors that influence the choice of how to use the available energy. For the moment the chosen strategy is to store at the start of the day at lower altitude and when the batteries are full climb. This gave good results in the simulation compared to other strategies.

The graphic below shows the power fluxes for the chosen flight profile of one typical day.



The peak power sent to the motors is 27.3kW and the batteries receive a maximal power of 22.15kW.

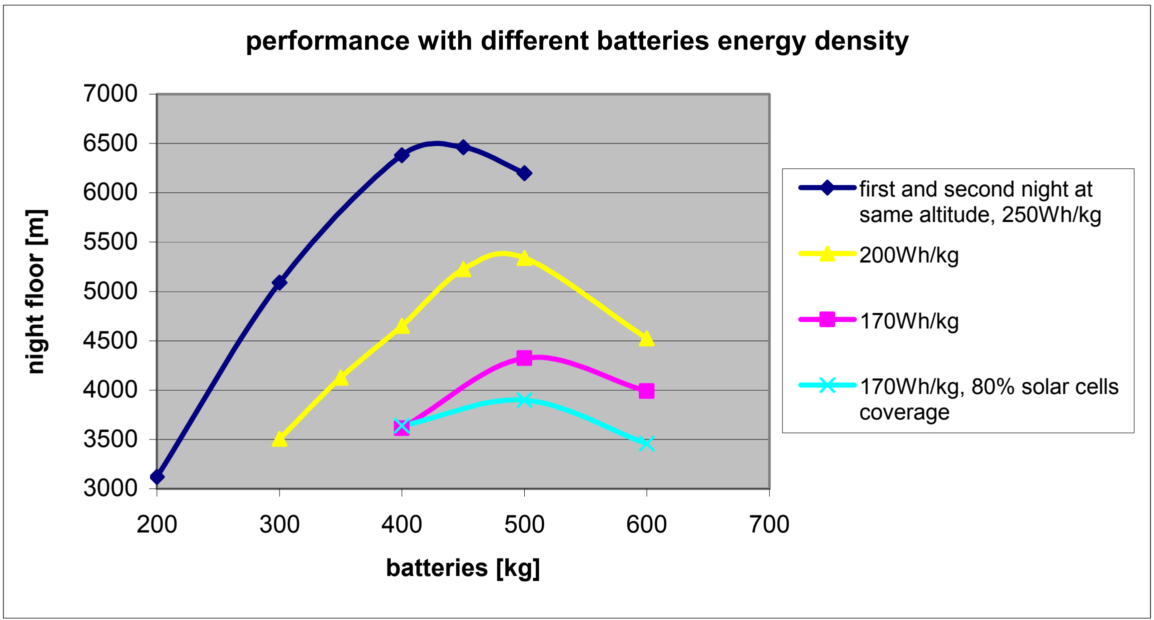
With this configuration the flight profile is the one below; in good conditions we can fly at 5200 meters during the night.



2.3 The batteries

In the feasibility study the different ways to store electrical power were considered and the batteries appeared to be the most appropriated choice. Between all the existing types the lithium technology has no competitors. It reaches high energy density and good efficiency in the cycling efficiency. The progresses in the traditional Li-ion and Li-polymer batteries has been of about 10% improvement of energy density a year and the best lithium polymer are now at 170 to 190Wh/kg (also available in large cells). Considering the evolution of the batteries an energy density of 200Wh/kg was used in V1.1 but variants are presented in this report. The ability of keeping the batteries at a proper temperature for operating is essential.

A weight of batteries required to have a certain capacity was considered in the study phase according to a given energy density. The total weight chosen is of 450kg of batteries with 200Wh/kg giving an energy storage capacity of 86.5kWh. The maximal power sent to the batteries is of 22kW and the discharge is at constant power (constant horizontal flight) of 6kW. With this power the current in each cells is pretty low (order of magnitude of C/4 charging and C/8 discharging) and a good efficiency could be expected (but the rough condition of the high altitude in temperature, make the efficiency lower if the cells are not kept at proper temperature. 450 kg of batteries allows the best performances with good conditions of flights (floor over 5000meters) for an 80 meters wingspan.



The floor level can be above 3000 meters already with today technology of batteries with 170 Wh/kg density.

2.4 Weights

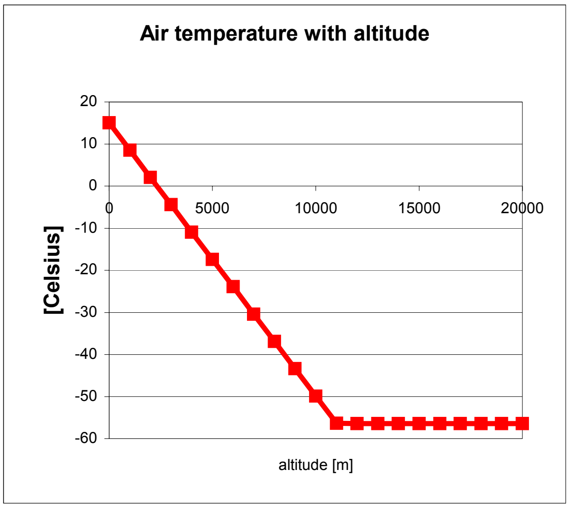
The total weight of the airplane has been estimated component by component. The electrical components weight is taken as function of their describing quantity; it can be surface, power or length:

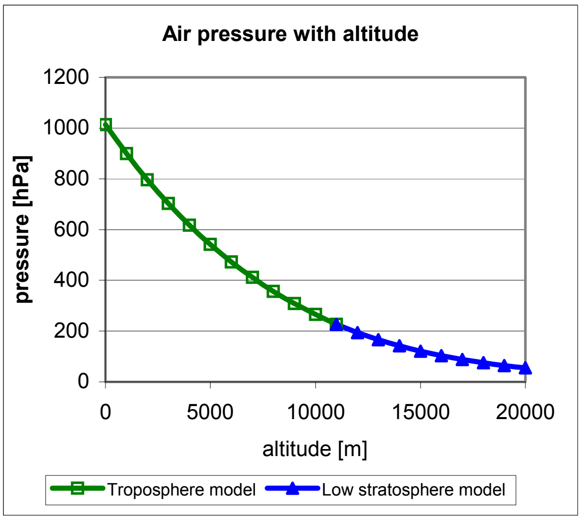
The weights found with those are:

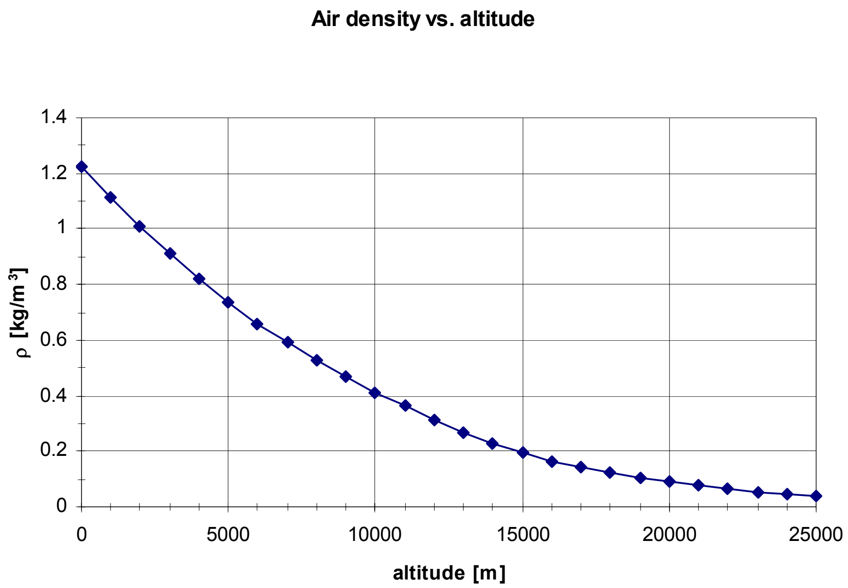
Components	Base unit	Total Weight [kg]
Solar cells (encapsulated)	0.8 kg/m^2	166
Cables	0.060 kg/m	41.28
MPPTs	0.650 kg/unit	27.3
Electrical engine and propeller	1.210 kg/kW	43.76
Electrical system	0.500 kg/kW	18.09

2.5 Atmosphere

The atmosphere varies with altitude *h*. The model of the US standard atmosphere of 1976, which is based on mathematical models and collected data is used. The US std. atm.1976 and the ICAO (International Civil Aviation Organization) standard atmosphere of 1964 are identical from 0 to 32000 m.
The atmosphere is divided in zones, and here we use the Troposphere model, which goes from 0 to 11000 m, then the lower stratosphere up to 25000m.







The solar cell will be at the temperature of outside air, but the batteries must be insulated. The pressure will influence the batteries and the air density modifies the heat exchanges.

3 General data of the airplane

Size:	Wingspan	80 m, 83.5 with winglets
	Total length	19.2 m
	Total height	9.5 m

	Wing area	230 m2
	Wing cord, root	3.05 m
	Wing cord, tip	2.12 m
	Horizontal tail area	14.3 m^2
	Vertical tail area	12.4 m^2
Weight:	Structure weight	800 kg
	Batteries weight	450 kg (for best night floor in clear sky conditions)
	Weight of solar cells	166 kg
	Pilot and life support	100 kg
	Rescue equipment	10 kg
	Avionics and system	10 kg
	Reserve weight	10 kg
	Weight of cables	41 kg
	Weight of MPPTs	27 kg
	Weight of electrical engines and propellers	44 kg
	Weight of diverse electrical systems	18 kg
	Total Weight	1677 kg
Solar Energy:	Surface of solar cells	207 m^2 85% wingarea + stabilizers (12m^2)
	Collected energy/day	271 kWh
	Peak Power	35 kW ~ 47 hp
	Needed Irradiance to fly horizontally (Max sun≈1000 watts/m2)	221 watts/m2 at 4808 m (Mt-Blanc)
Performance	Distance flown in 24 h	1400 km
	True airspeed varying with altitude	13 to 20 m/s 46 to 72 km/h
	Night floor	~5000 m
	Δh	7000m
Electrical	cables	~700 meters (first approx)
	Solar cells	13'200 high performance cells ~20% efficiency (first approx)
	Electronic converters for solar cells	42 Units (first approx)
	Engines	27kW max~ 36 hp for a typical day dimensioned for 34.4kW for peak power available and take off. 2 engines, 17.2kW each