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Autonomous Systems Laboratory

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Design of Solar Powered Airplanes

for Continuous Flight

given in the framework of the ETHZ lecture

“Aircraft and Spacecraft Systems: Design, Modeling and Control”

partially included in a forthcoming Springer book on

“Advances in Unmanned Aerial Vehicles, State of the art and the road to autonomy”

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Sunrise II, 1975

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1 Introduction

The achievement of a solar powered aircraft capable of continuous flight was still a dream

some years ago, but this great challenge has become feasible today. In fact, significant

progresses have been realized recently in the domains of flexible solar cells, high energy

density batteries, miniaturized MEMS and CMOS sensors, and powerful processors.

The concept is quite simple; equipped with solar cells covering its wing, it retrieves energy

from the sun in order to supply power to the propulsion system and the control electronics,

and charge the battery with the surplus of energy. During the night, the only energy available

comes from the battery, which discharges slowly until the next morning when a new cycle

starts.

Nevertheless, major interdisciplinary effort is necessary to optimize and integrate concepts

and technologies to a fully functional system. As a matter of fact, the major issue is the

combination and sizing of the different parts in order to maximize a certain criterion, for

example the endurance, one parameter being the embedded payload.

In 2004, the Autonomous Systems Lab of EPFL/ETHZ launched the Sky-Sailor project under

a contract with the European Space Agency. The objectives are the study and realization of a

solar aircraft fully autonomous in navigation and power generation flying on Earth and thus

validate the feasibility of a Mars dedicated version.

This lecture presents the methodology used for the global design of solar powered airplanes

that are intended to achieve continuous flight on Earth. It was applied to the first prototype of

Sky-Sailor but it is rather general so that it can be used as much for small airplane weighing

some hundreds of gram as for solar high altitude long endurance (HALE) platforms with a

wingspan of several tens of meters.

1.1 History of Solar Flight

Premises of solar aviation with model airplanes

On the 4th of November 1974, the first flight of a solar-

powered aircraft took place on the dry lake at Camp Irwin,

California. Sunrise I, designed by R.J. Boucher from Astro

Flight Inc. under a contract with ARPA, flew 20 minutes at

an altitude of around 100 m during its inaugural flight. An

improved version, Sunrise II, was built and tested on the

12th of September 1975. The new cells, with a higher

efficiency of 14%, delivered a power of 600 W.

In Europe, the pioneers of solar model airplane were Helmut Bruss and Fred Militky. On

the 16th of August 1976, his model Solaris completed three flights of 150 seconds reaching

the altitude of 50 m [3].

Since this early time, many model airplane builders tried to fly with solar energy, this

hobby becoming more and more affordable. The endurance, limited to a few seconds at the

beginning, rapidly became minutes and then hours... [3]. Some people distinguished

themselves like Dave Beck with Solar Solitude in 1996, Wolfgang Schaeper who set many

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achieve short duration flights. The crucial stage consisting in

flying with the single energy of the sun without any storage

Helios, 1999-2003

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records with Solar Excel in the 90’s and Sieghard Dienlin with his tiny solar model PicoSol

in 1998.

The dream of manned solar flight

After having flown solar model airplanes and proved that it

was feasible with sufficient illumination conditions, the new

challenge that fascinated the pioneers at the end of the 70’s

was solar manned flights.

The first models, Solar One of Fred To in GB and Solar

Riser of Larry Mauro, used the concept was to charge a

battery on the ground using their solar panels and then

Gossamer Penguin, 1980

was reached by Dr. Paul B. MacCready and his company AeroVironment Inc in the US. On

the 18th of May 1980, the Gossamer Penguin realized what can be considered as the

world’s first piloted, solar-powered flight. On July 7, 1981, the next version named Solar

Challenger crossed the English Channel with solar energy as its sole power source.

In Germany, Günter Rochelt built Solair I, a 16 m wingspan solar airplane that

incorporated a battery. On the 21st of August 1983 he flew, mostly on solar energy and also

thermals, during 5 hours 41 minutes. In 1986, Eric Raymond started the design of the

Sunseeker in the US. At the end of 1989, it was test flown as a glider and during August

1990, it crossed the United States in 21 solar-powered flights with 121 hours in the air.

In 1996, the Berblinger Contest took place in Ulm with the objective to develop a real,

practically usable solar aircraft that should be able to stay up with at least half the solar

energy a good summer day with clear sky can give. The team of Prof. Rudolf Voit-

Nitschmann from Stuttgart University won the first prize with Icaré 2.

On the way to HALE (High Altitude Long Endurance) platforms and eternal flight

After the success of Solar Challenger, the US government

gave funding to AeroVironment Inc. to study the feasibility

of long duration, solar electric flight at high altitude. In

1993, the Pathfinder, with its 30 m wingspan and 254 kg,

was tested at low altitude and became in 1994 part of

NASA’s Environmental Research Aircraft Sensor

Technology (ERAST) program.

From 1994 to 2003, this program led to the construction of a

series of three successive solar aircrafts, Pathfinder Plus, Centurion and Helios. The latter

was intended to be the ultimate "eternal airplane”, incorporating energy storage for night-

time flight. In 2001, Helios set an unofficial world record altitude of 29’524 m (96’863 ft)

but unfortunately, it never proved sustainable flight as it was destroyed when it fell into the

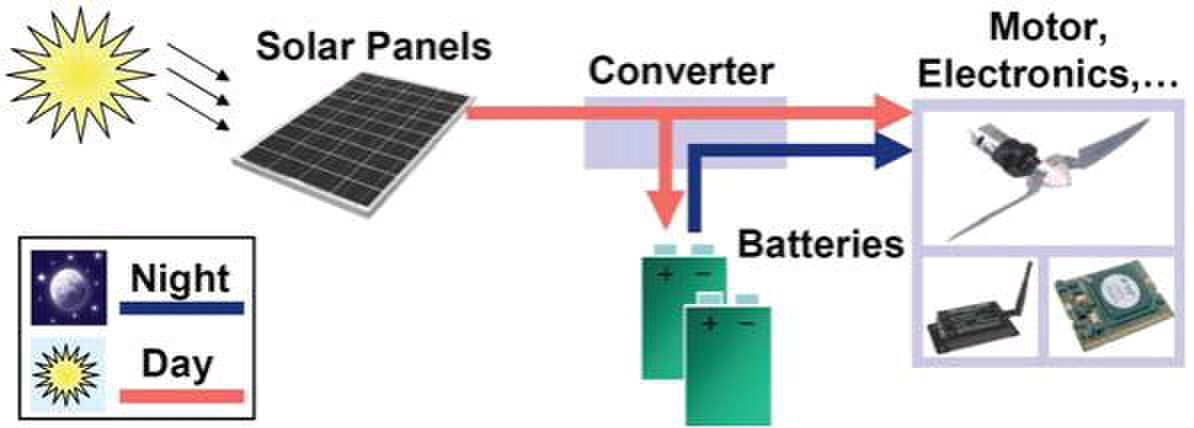
Pacific Ocean on June 26, 2003 due to structural failures.

In Europe, many projects were also conduced on HALE platforms. At the DLR Institute of

Flight Systems, Solitair was developed within the scope of a study from 1994 to 1998 [23].

The Helinet project, funded by a European Program, ran between January 2000 and March

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2003 with the target to study the feasibility of a solar-powered HALE platform for

broadband communications and Earth observation.

QinetiQ, a British company, is also very active in the field of solar HALE platforms with

Zephyr, an airplane which flew in July 2006 for 18 hours, including 7 hours of flying in the

dark. It has recently been selected as the base platform for the Flemish HALE UAV remote

sensing system Mercator in the framework of the Pegasus project. The platform should

fulfill missions like forest fire monitoring, urban mapping, coastal monitoring, etc.

But the objective of Helios to prove the feasibility of eternal flight for an unmanned

airplane was reached on the 22nd of April 2005. Alan Cocconi, president and founder of

AcPropulsion, flew his Solong during 24 hours and 11 minutes using only solar energy

coming from its solar panels and also thermals, currents of warm air rising from the desert

floor. The 4.75 m wingspan and 11.5 kg airplane confirmed its capabilities two months

later on the 3rd of June with a flight lasting 48 hours and 16 minutes.

The next dream to prove continuous flight with a pilot on board will perhaps come true

with Solar-Impulse, a 80 m wingspan lightweight solar airplane built in Switzerland. After

the manufacturing of a 60 m prototype in 2007-2008 and the final airplane in 2009-2010, a

round-the-world flight should happen in May 2011 with a stopover on each continent.

1.2 Brief description of the principle

Solar panels, composed by solar cells connected in a certain configuration, cover a certain

surface of wing or other part of the airplane (tail, fuselage,…). During the day, depending

on the sun irradiance and the inclination of the rays, the convert light into electrical energy.

A converter, called Maximum Power Point Tracker, ensures that the maximum amount of

power is obtained from the solar panels. This power is used firstly to power the propulsion

group and the onboard electronics, and secondly to charge the battery with surplus of

energy.

Fig. 1 Schematic representation of power transfer

During the night, as no more power comes from the solar panels, only the battery supplies

the various elements. This is schematically represented on the figure below.

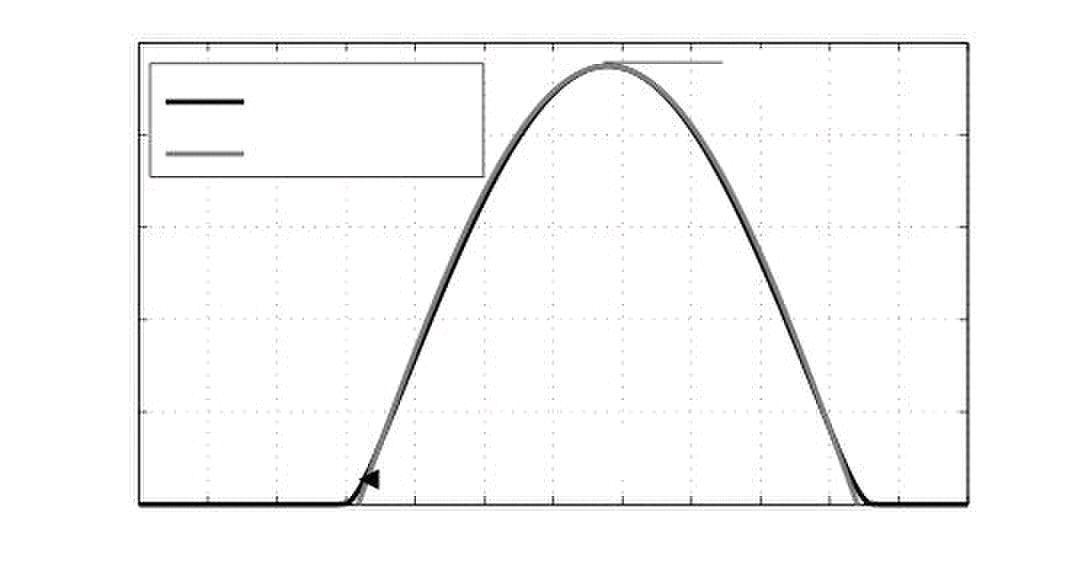
2 Conceptual Design Methodology

Aircraft design is the name given to the activities that span the creation on paper of a new

flight vehicle. The design process is usually divided into three phases or levels of design

[Leland]: Conceptual Design  Preliminary Design  Detail Design.

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(1)

T

solmargin

max day

/2

 k

Imax

(Duffie & Beckman)

Sinusoidal model

600

400

0 2 4 6 8 10 12 14 16 18 20 22 24

I

day density

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This methodology will only focus on conceptual design where the general configuration and

size is determined. Parametric trade studies are conducted using preliminary estimates of

aerodynamics and weight to converge on the best final configuration. The feasibility of the

design to accomplish a given mission is established but the details of the configuration are

not defined.

One will also consider only level flight. Whether it is intended to achieve surveillance at low

altitude or serve as a high altitude communication platform, a solar aircraft capable of

continuous flight needs to fly at constant altitude. In fact, the first one would be useless for

ground surveillance at high altitude and the second one wouldn’t cover a sufficient area at

low altitude.

In this case, the energy and mass balances are the starting point of the design. In fact, the

energy collected during the day by the solar panels has to be sufficient to power the motor,

the onboard electronics and also charge the battery that provides enough power to fly from

dusk to the next morning when a new cycle starts. Likewise, the lift force has to balance

exactly the airplane weight so that the altitude is maintained.

This leads finally to an hen and egg problem: the required power consumption allows

dimensioning the various parts, like motor, solar cells, battery, etc. but at the same time these

parts determine the airplane gross weight used for the calculation of the required power.

These relations are described in this section.

2.1 Irradiance model

A good model of irradiance depending on variables such as geographic position, time, solar

panels orientation and albedo was developed based on [7]. For our need here, this model

was simplified for flat surfaces by a sinusoid as shown on Fig. 2.

1000

Exact model

800

I2]

200

Tday

0

Time [hours]

Fig. 2 Approximation of irradiance with a sinusoid (Lausanne, June 21)

The maximum irradiance Imax and the duration of the day Tday, which are depending on the

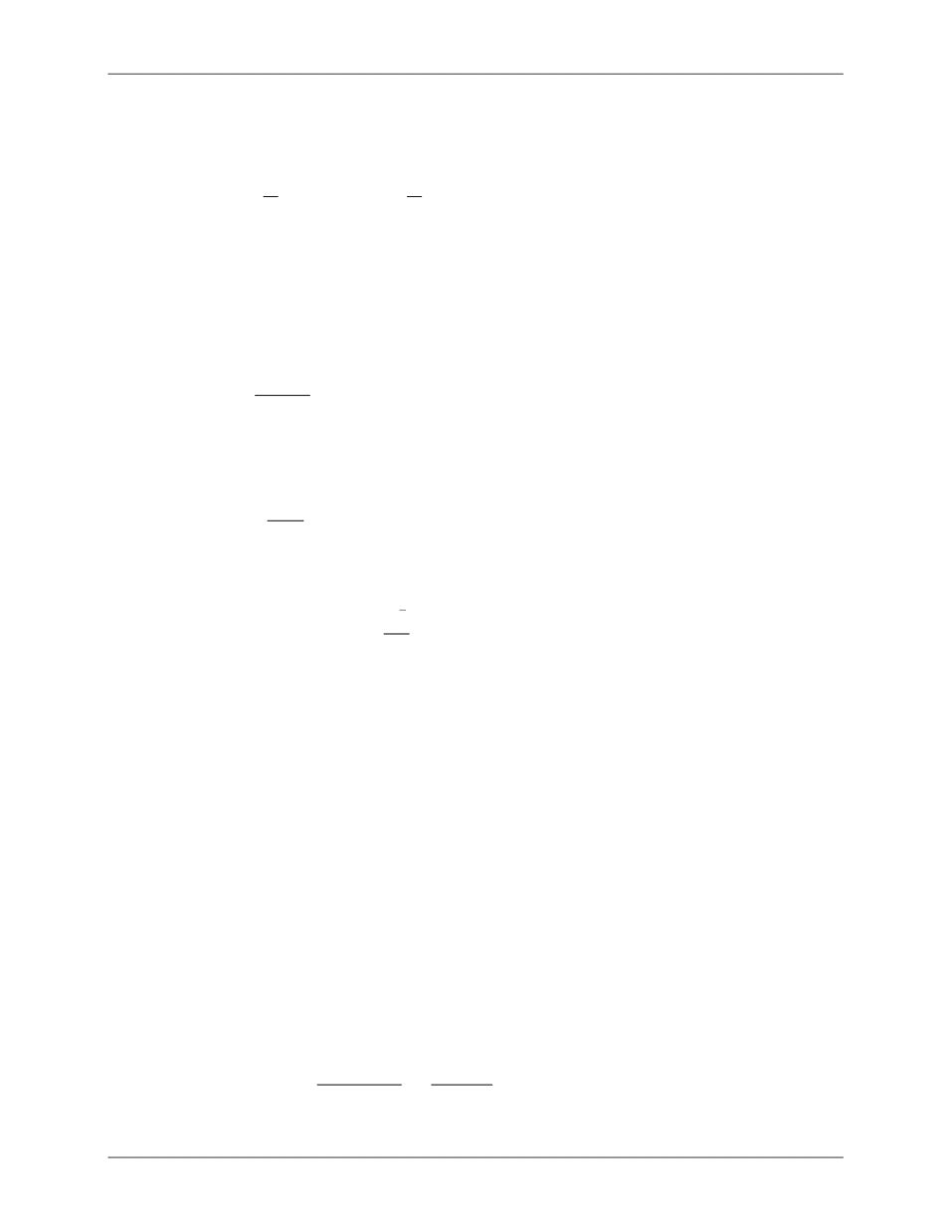
location and the date, allows to compute the daily energy per square meter as depicted in

Eq. 1. In order to take into account cloudy days, a constant is added with a value between 1

(clear sky) and 0 (dark). This constitutes a margin for the calculation.

E

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 (6)

solar

k A 

max day

solmargin

I T

⎟

⎟ 

(4)

night

⎠



T

  /2

mg 2

(5)

T 

D

(3)

D

32 S 

2

⎝

D  C SV (2)

e AR

C

C

AR g m

32  b

⎜

2 2

2 2

2

L

i



D

C

⎜

 

L

C

D

level

C 2

level

⎛

elec tot day

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2.2 Power balance for level flight

The forces acting on the airplane during level flight are the lift L and the drag D defined as:

L C SV

where CL and CD are respectively the lift and drag coefficients, ρ the air density, S the wing

area and V the airplane relative speed which is similar to the ground speed if one assume no

wind. CL and CD heavily depend on the airfoil, the angle of attack α, the Re number and

Mach number. The drag coefficient is the sum of the airfoil drag CDa, the parasitic drag of

non-lifting parts that will be neglected here and the induced drag CDi than can be estimated

by:

C 

where e is the Oswald’s efficiency factor and AR the aspect ratio of the wing, the ratio

between the wingspan and the chord. From Eq. 2 one can find the power for level flight

3

P

L

Using the relation between S, b and AR, one can rewrite:

3

P 

L

Then, to obtain the total power consumption, efficiencies of the motor, its electronic

controller, the gearbox and the propeller have to be taken into account, as well as the power

consumption of the control and navigation system and the payload instruments. In order to

lighten the reading, these relations will not be written here but further illustrated on Fig. 7.

2.3 Mass estimation models

For each part on the airplane, a good mass model is necessary in order to calculate the total

mass m and use it in Eq. 5. The simple models will not be expressed in equation but only

shortly described as they will be further illustrated in Fig. 7.

The mass of the control and navigation system is considered as fixed, just like the payload

that is a requirement defined at the beginning. Concerning the battery, its mass is directly

proportional to the energy it needs to store, which is the product between power

consumption and night duration, and inversely proportional to its energy density.

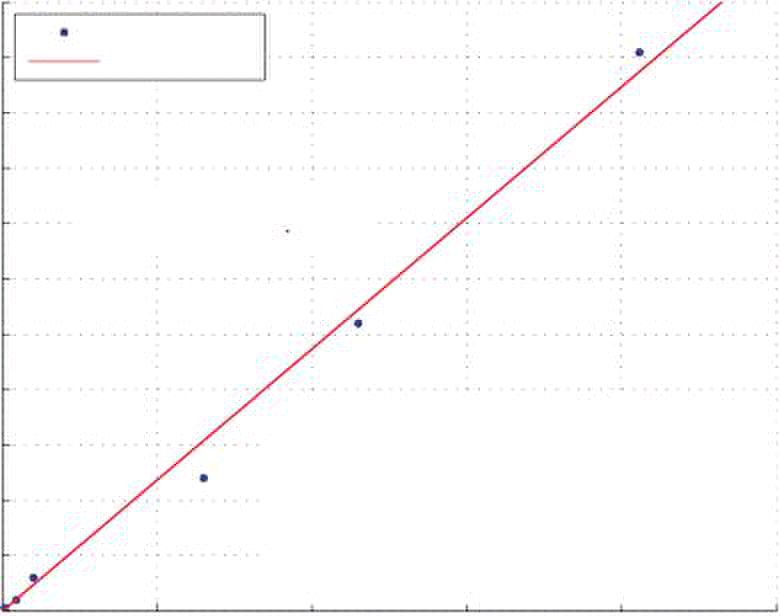
In the case of the solar panels, one can find the area they cover by putting into equality the

total electric energy consumed each day with the total electric energy obtained from the

sun.

P

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 A (7)

max solar

 k I 

solmax mppt

 k P

Eff [%]

2600

(8)

mppt mppt

Fitting curve

Max Power = 2368 Mass

2000

Sky-Sailor 7.55 30 97

Sommerauer 45 100 98

AcPropulsion Solong 100 300 98

Biel MPPT 650 1200 99

Brusa Elektronik MPT-N15 1150 99

Icaré 2 2058 5046 98

0 0.5 1 1.5 2 2.5

prop prop

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The obtained area Asolar is then used to calculate the mass of the solar panels, taking into

account the mass of the cells themselves and their encapsulation made of nonreflective

sheets of polymer.

A special electronic device, called Maximum Power Point Tracker (MPPT) is required to

adapt the voltage of the solar panels so that they provide the highest power possible. Its

mass is proportional to the maximum power it has to convert, which can be calculated

using the solar panels area calculated above as showed in equation Eq. 7. The constant kmppt

was found based on a study of existing high efficiency products (Fig. 3).

m

5500

Mppt products

5000

4500

4000

3500

3000

2500

M

Mass [g]Power [W]

1500

1000

500

0

Mass [Kg]

Fig. 3. Power density of high efficiency MPPTs

The mass of all the electric cables, especially those connecting the solar panels to the

MPPT, can be modeled according to the airplane wingspan and the electrical current.

However, in order to avoid a too complex model, this mass is included in the onboard

electronics.

Concerning the propulsion group, composed of the motor, the gearbox and the propeller,

[8] and [9] proposed a model, adapted from civil aircraft to solar airplane, which takes into

account the number of blades, the propeller diameter and the power of the motor. Some

calculations show that the estimation is far too optimistic for model aircraft. [18] and [25]

propose very similar models exclusively based on power, where the mass of the propulsion

group is estimated as

m  0.0045

For real large scale solar airplanes like Helios, Icaré 2 or Solair II, this factor is

respectively 0.0033, 0.0012 and 0.0008 kg/W whereas the first experiments with Sky-Sailor

showed a factor of around 0.010 kg/W. The reason is that for an airplane taking off on a

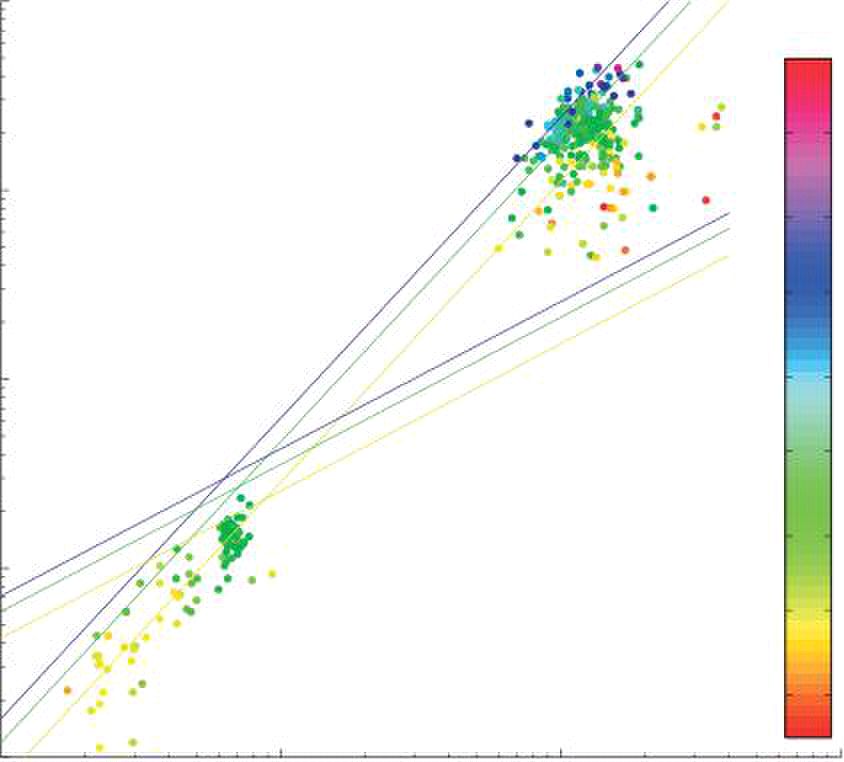
runway, the difference between start power and mean power for level flight is low. At the

opposite, in the case of a hand launched model airplane that needs to increase its speed and

take altitude rapidly, the start power is far higher than the mean power required for level

flight. Thus, the motor has to be oversized and its mass increases.

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0.467

S AR (9)

0.311 0.778

0.71

0.88

8.763 n

5.58 S AR (10)

5.58 ⋅ b ⋅ AR− (11)

25

10

af

1.59

af

3.18

af

4

3

30

2

Stenders equation

1

0

-1 0 1 2

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Finally, the mass of the airplane structure is the most difficult part to model and the two

main approaches mainly used in the literacy for solar airplanes appear inadequate. That is

the reason why we will study this part more in details and propose a new model

The first approach from D.W. Hall [8] consists in calculating separately the mass of all the

elements constituting the airframe, i.e the spar, the leading and trailing edge, covering, ribs,

control surfaces, fuselage and tail as functions of the total mass, aspect ratio and wing area.

It was applied by [6] on airplane with more than 60 m wingspan but shows to be

inapplicable for model airplane. The second approach, proposed by W. Stender in 1969

[20], is based on statistical data for sailplanes with twin boom tails. The entire airframe

weight is estimated parametrically as a function of aspect ratio, surface and number of

boom tails.

W 

This simple model was adopted by [17], [18] and [25] for their solar airplane design. In

order to verify this model, a database containing wingspan, wing area, aspect ratio,

structure weight and gross weight of 415 sailplanes of various dimensions was created.

They are divided into 92 radio controlled unmanned models and 323 manned sailplanes.

The weight of these samples is represented on Fig. 4 as function of the wing area and the

aspect ratio. Eq. 9 is obviously very optimistic for large scale sailplanes and too pessimistic

for model airplane. Thus, using a least-square fitting method, we propose a new equation

based on the sailplane database described above.

W 

Using the definition of aspect ratio, it can of course also be expressed as a function of

wingspan:

W 

10

AR

40

10

35

Proposed equation

W = 5.58 S1.59 AR0.71

10

W

W = 8.763 S0.778 AR0.467 20

15

10

10

5

10

10 10 10

Wing area [m2]

Fig. 4 Comparison of two airframe mass models with real data

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AR (12)

1.55 1.3

0.25

0.84

 0.44 S

0.44 ⋅ b ⋅ AR− (13)

 0.59 ⋅W ⋅ AR (15)

af

3.1

af

1/3

0.35

af af

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But these equations only give the mean tendency of all the 415 records, in which the

construction quality of airplane varies. As we are interested in having a model of the

highest quality sailplanes only, we propose to separate the records in two groups, the one

that have a lower weight than it would have been estimated by the interpolation and the

others. Keeping only the first group and applying one more time the curve fitting process,

we obtain after five iterations an equation that models the 5% best sailplanes

W

Here again, one can rewrite Eq. 12 using wingspan instead of surface

W 

It is interesting to see the evolution of the constant and the two exponents during the

iterations when construction quality increases. The wing area is always related to the

weight with a power of around 1.55 to 1.59, this exponent doesn’t change significantly. At

the opposite, the influence of the aspect ratio increases with the quality.

Several scientists studied the correlations between gross weight, wingspan, wing area and

speed more generally including all the commercial flying machines, from the hang glider to

the big airliners, and also in the animal kingdom, from the flies to the albatross. Above this

amount of work, [19] offers an excellent and concise review of all these correlations.

One of the best contributors in this field is Henk Tennekes who presented very interesting

correlations that he summarized in a log-log diagram named “The great flight diagram”

[22]. The result is impressive: from the common fruit fly to the Boeing 747, all points

follow approximately a line corresponding to Eq. 14.

W S  47 ⋅W (14)

The concept of geometric similarity is the base of this equation; if one assumes geometric

similarity among flying objects, the weight W is proportional to the cube of a characteristic

length l, the surface S to the square and consequently the wing loading is linear with l and

thus with W1/3. It is interesting to notice that if we transform Eq. 12 that represents our

model in the form above, the weight is linked to the wing loading with an exponent of 0.35

which is close to the model proposed by Tennekes.

W S

Fig. 5 presents, superposed on the great flight diagram, the position of the 415 sailplanes as

well as the mean and the top 5% model developed above. A model from B.W. McCormick

[12] for the estimation of the wing loading of manned airplanes, also based on square-

cubing scaling laws, is also represented. One remarkable point is its asymptote at a weight

of 1000 N which corresponds to the weight of a single human person in an incredibly

lightweight airplane. The airplane approaching the most this asymptote is the Gossamer

Albatross, the human powered aircraft built by Dr. Mcready that crossed the English

Channel in 1979.

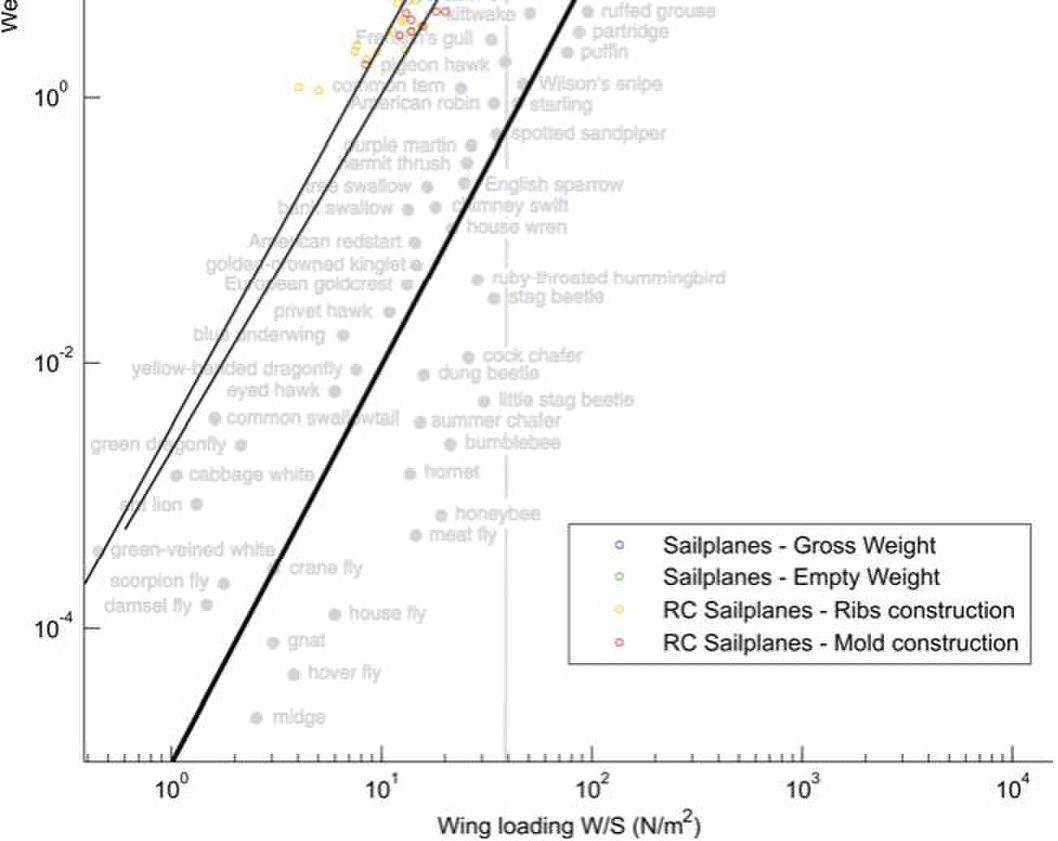
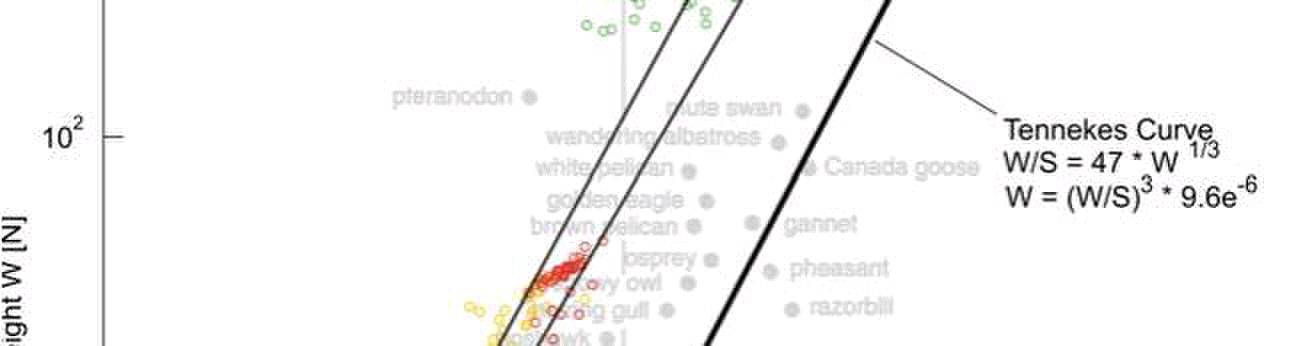
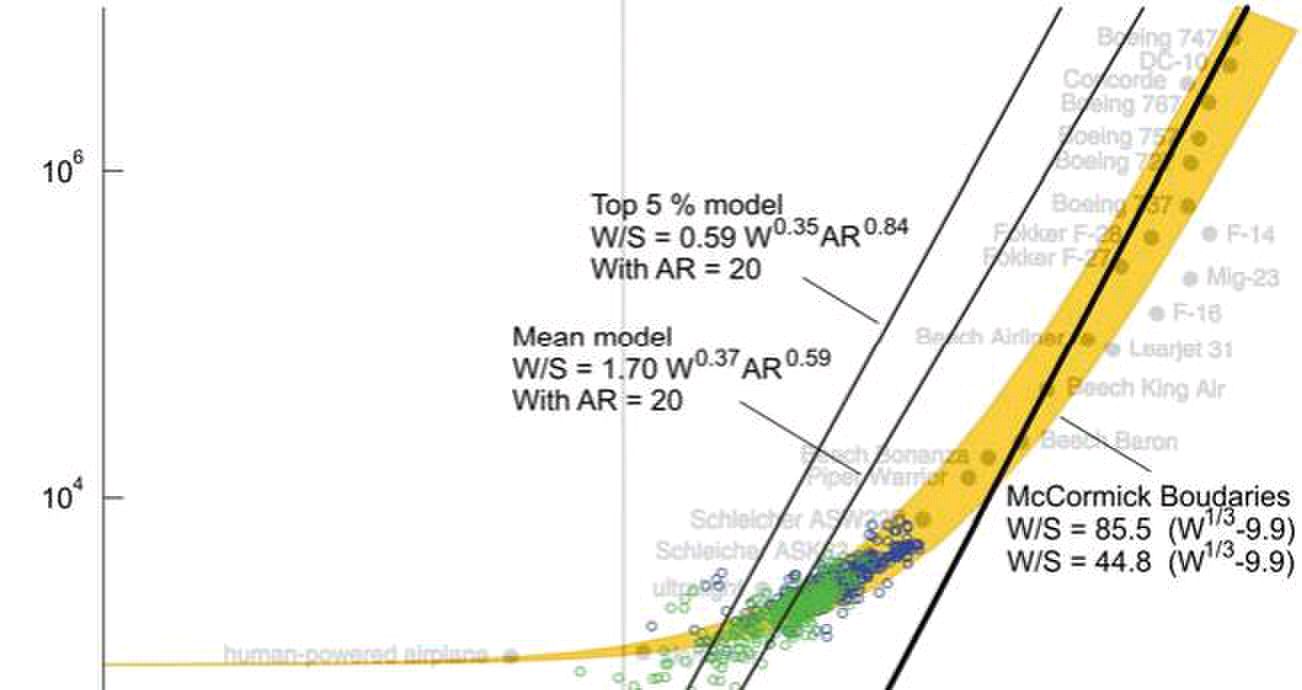
Sixty-two of the most famous solar airplanes flown to date, from RC models to HALE

platforms, are represented in the same way on Fig. 6. One can observe that whereas the

small scale models are located in the same region than the non-solar one, the large scale

solar airplanes are far away from the model we developed.

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The reason is that Helios, Centurion, Pathfinder, Pathfinder Plus and Zephyr have a major

difference in their configuration compared to all other models; in fact, their wing

extremities are supported by several wheels, when not in flight. The flexion constraints on

the wing are reduced which allows using a lighter construction method. These big models

have impressive low weight but the direct consequence is their incredible fragility. That

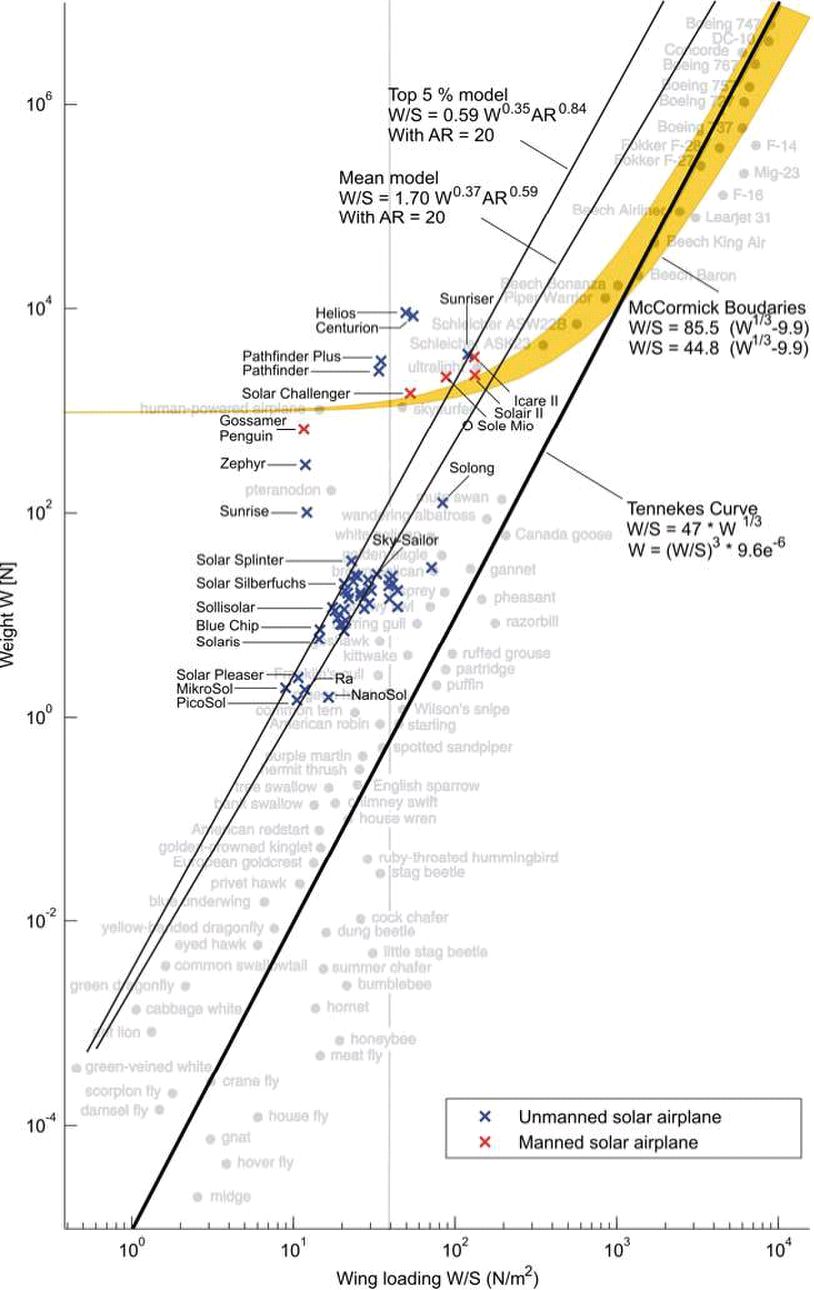
was the cause of Helios crash in 2003. The five manned solar airplanes are slightly above

McCormick upper boundary, except Gossamer Penguin, the solar version of human

powered Gossamer Albatross.

Fig. 5. The Great Flight Diagram [22] completed with 415 sailplanes

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Fig. 6. The Great Flight Diagram [22] completed with 62 solar airplanes

2.4 Summary of the problem

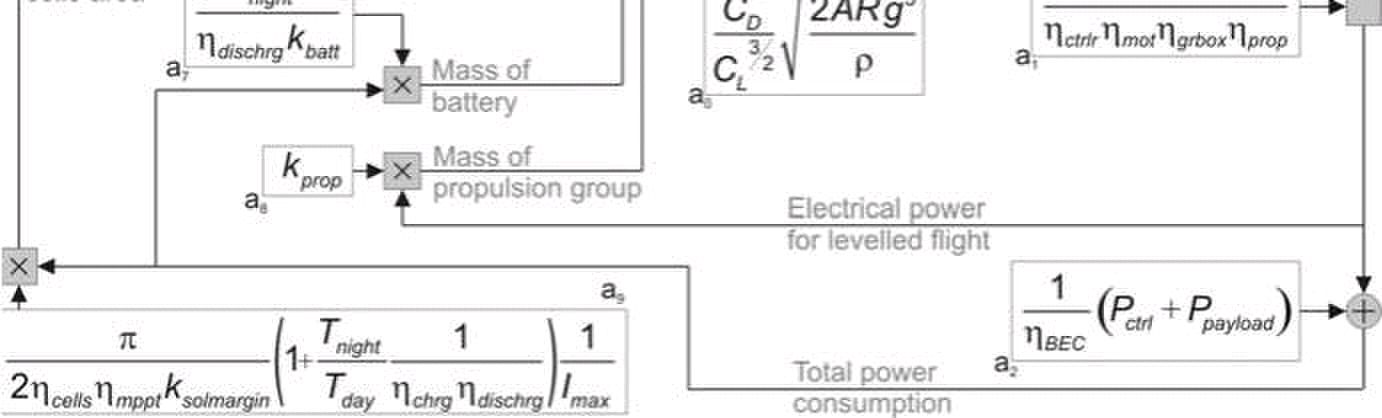
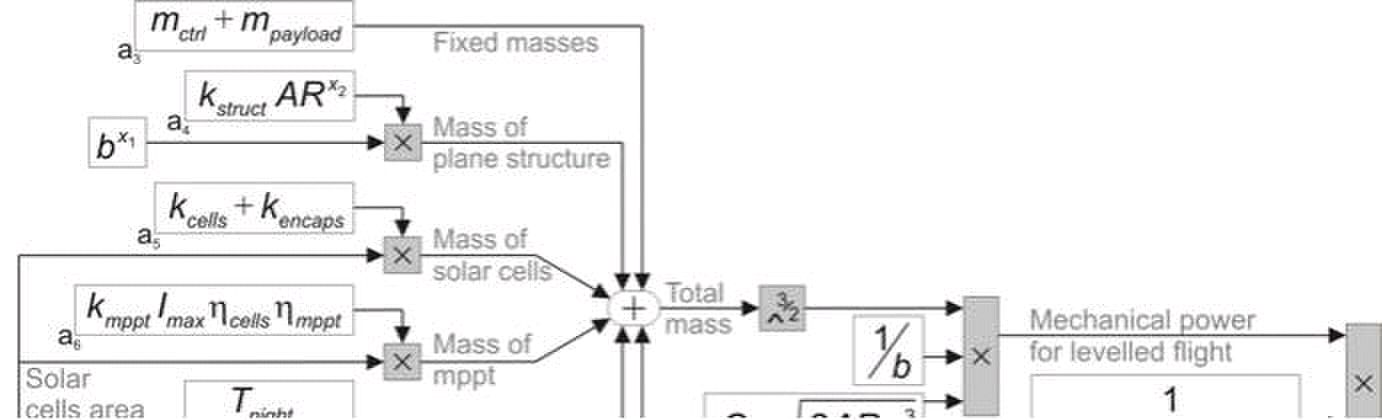
A schematic representation of the power balance and the mass balance is shown on Fig. 7

where all the relations stated above are represented. In order to avoid the use of heavy

equations in the following equations, the main expressions are replaced by variables a0 to

a9.

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x

3



(18)

a a a a a b (17)

1

2 7 5 6

a b

(19)

3

2 1

b

x

11

4

27

 

a 

≤

1

5 6

11

3

2

13

13

m m m m (16)

 a a a a m a a 

a

m

a

a

ctrl payload struct solar batt mppt prop

0 1 7 8

10

1

10

N

12

2

12

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Fig. 7. Schematic representation of the design methodology

We are now able to solve this cyclic problem by using all these relations

m  m m m 

m aa a

a

Reducing one more time the complexity of the equation by using substitution variables, one

obtains.

m a

a

It can be shown that Eq. 19 has only a positive non-complex solution for m, which makes

physically sense, if

a

For a given airplane configuration, the feasibility is proved if this inequality is respected

and at the same time if the surface of solar cells is smaller than the wing area.

In order to be able to extract meaningful information, it is necessary, among the thirty

parameters that our model contains, to distinguish between three different classes:

1. The first group is composed of the parameters which are linked to a technology

and are constant or can be regarded as constant for very good design. This is for

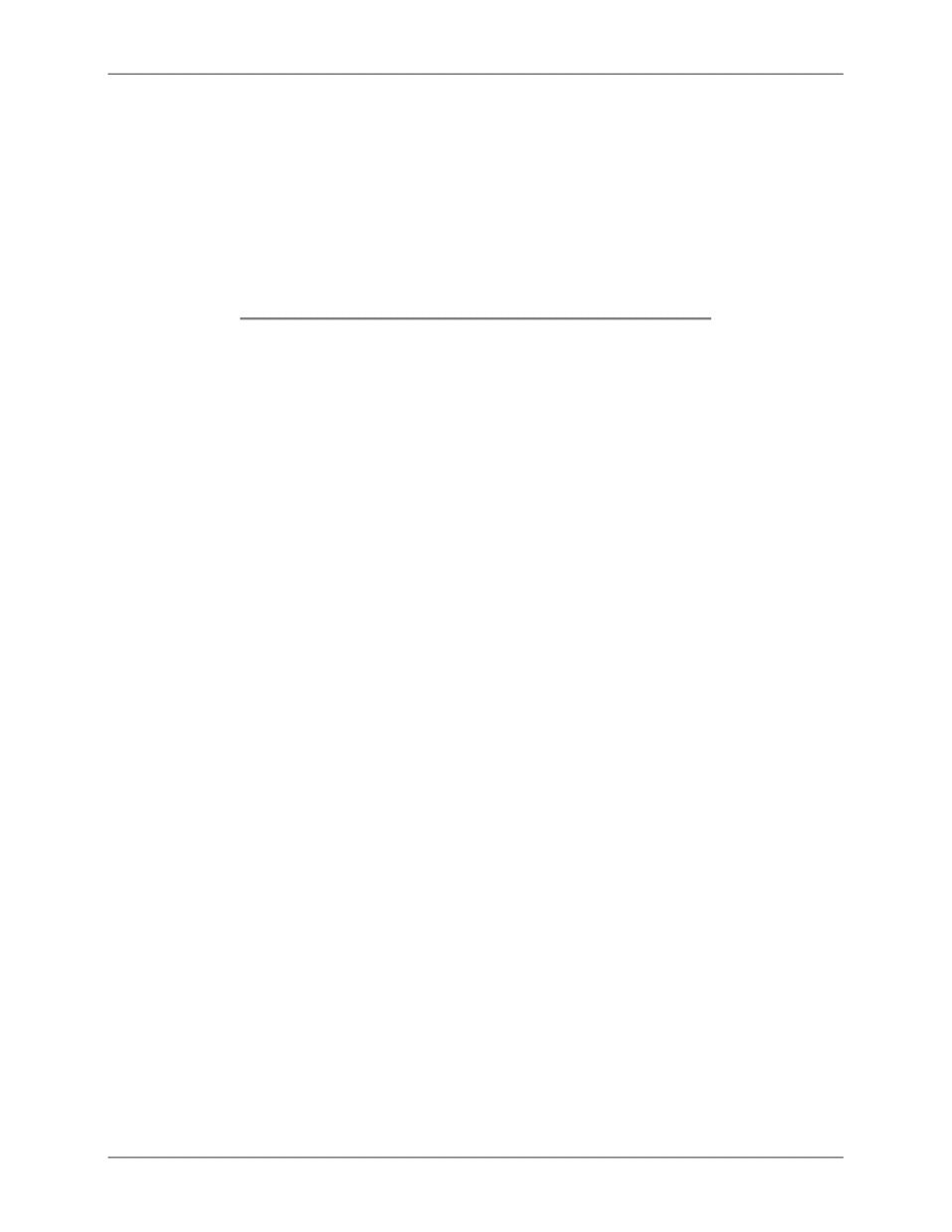
example the case of motor or propeller efficiencies that should be around 85 %

when optimized for a special application.

2. The second group of parameters is linked to the type of mission; they concern

flight altitude, date and payload.

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Airfoil drag coefficient

0.013 [kg/W] Mass to power ratio of propulsion unit

[kg] Payload mass

[kg/m3] Air density (500 m)

0.44/9.81 [kg/m3] Structural mass constant

0.5 [W]

14⋅3600 [s]

-

[W/m2] Maximum irradiance

[kg/m2] Mass density of solar cells

0.22 [kg/m2] Mass density of encapsulation

0.00047 [kg/W] Mass to power ratio of mppt

kprop

1 [W] Power of navigation & control system

3.1 - Structural mass area exponent

-0.25 - Structural mass aspect ratio exponent

mpayload 0.25



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3. Finally, the last group is composed of the parameters that we vary during the

optimization process in order to determine the airplane layout, that is why one

should use here the term variable that parameter. They are for example the

wingspan or the aspect ratio.

A complete listing of these parameters is presented in the tables below. The values that are

mentioned were used for the design of Sky-Sailor first prototype.

Table 1 Parameters that are constant or assumed constant

Parameter Value Unit Description

CL

CDa

e 0.9 - Oswald’s efficiency factor

Imax 950

kbatt 190⋅3600 [J/kg] Energy density of battery

kcells 0.32

kencaps

kmppt

kstruct

melec 0.25 [kg] Mass of navigation & control system

bec 0.7 - Efficiency of step-down converter

cells 0.169 - Efficiency of solar cells

chrg 0.98 - Efficiency of battery charge

ctrlr 0.95 - Efficiency of motor controller

dischrg 0.98 - Efficiency of battery discharge

grbox 0.95 - Efficiency of gearbox

mot 0.85 - Efficiency of motor

mppt 0.97 - Efficiency of mppt

prop 0.85 - Efficiency of propeller

Pctrl

x1

x2

Table 2 Parameters determined by the mission

Parameter Value Unit Description

ksolmargin 0.7 - Irradiance margin factor

Ppayload

1.1655

Tday Day duration

Table 3 Variables linked to the airplane shape

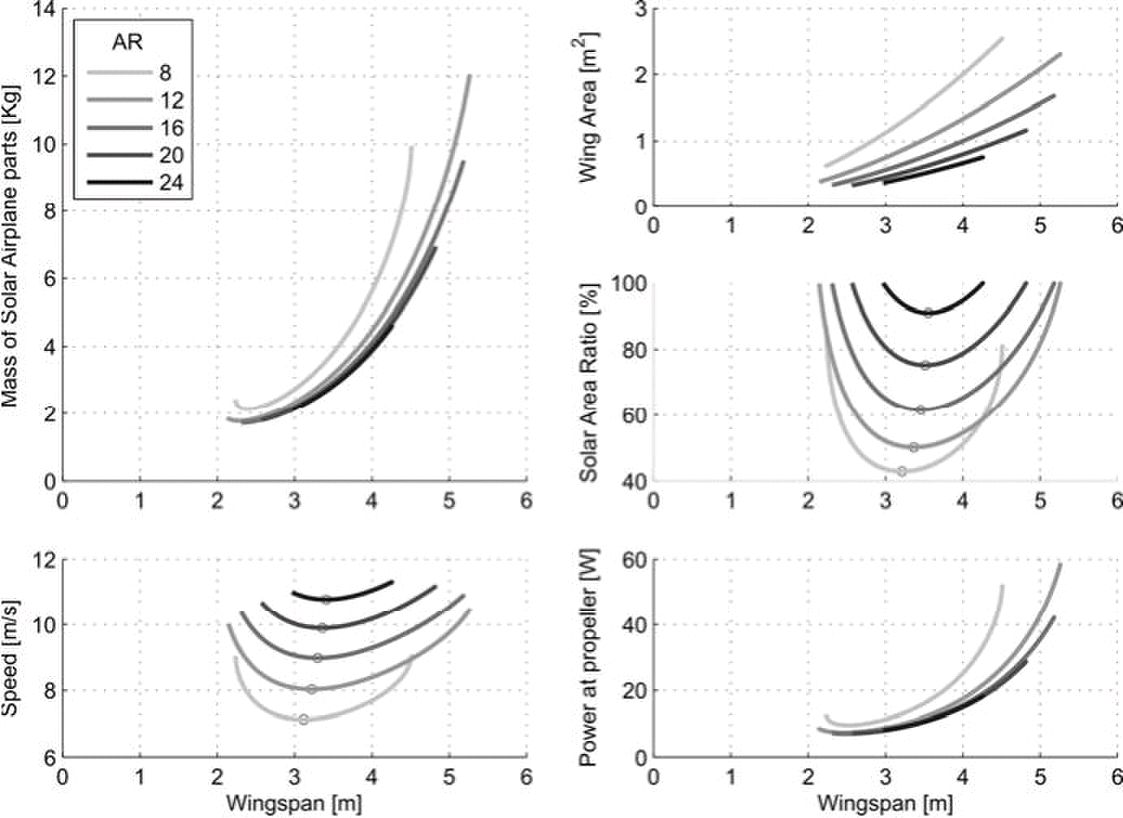
Parameter Value Unit Description

AR 12.9 - Aspect ratio

b 3.2 [m] Wingspan

m 2.6 [kg] Total mass

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3 Application of the methodology

Having the mission requirements, the method explained here above can be applied in order to

evaluate the possible shapes of a solar airplane. This will be illustrated with the example of

the Sky-Sailor prototype. The objective here is to embed a 250 g payload consuming 0.5 W

and fly continuously at low altitude during two months in summer. These mission parameters

allow plotting the relations between the main variables, i.e. wingspan and aspect ratio, and

the flight characteristics for all the possible configurations.

Fig. 8. Design plots of a solar airplane with a payload of 250 g

This is done on Fig. 8 where one can first observe that the minimum airplane wingspan is

around 2.5 m and that keeping the same construction quality the airframe will become too

heavy from a certain point and make continuous flight impossible. This means that for larger

airplanes, the quality of the wing structure in terms of weight becomes more and more

important. In the range of ten to twenty meters wingspan, which corresponds to commercial

sailplanes, the construction method used today should be massively improved to see one day

a model in this range fly continuously.

In our case, among the many possible configurations, the final choice will be guided by

considerations on the flight speed, size or even production costs that can be estimated

knowing the prices of the different elements.

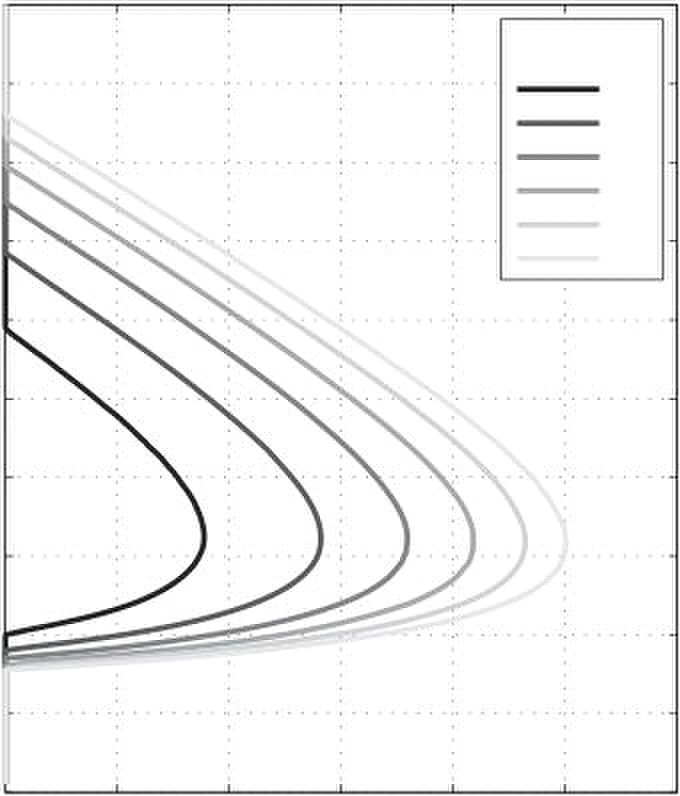
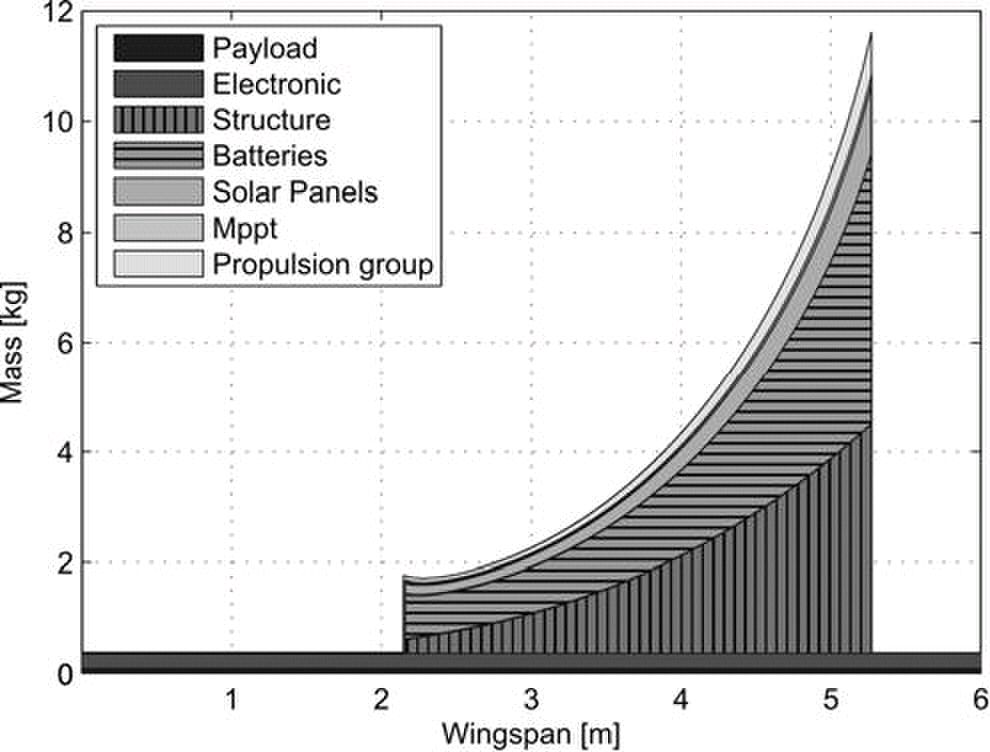
It is also interesting to have a look on mass distribution. Fig 9 shows that the half of the

weight is only due to the battery and that the structure constitutes also an important part that

increases with wingspan as said before. This knowledge allows putting efforts on the critical

parts instead of working on elements that play a minor role in overall mass.

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batt

200

280

360

400

4

0 2000 4000 6000 8000 10000 12000

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Fig. 9. Mass distribution with respect to wingspan assuming AR = 12

3.1 Influence of Technologies on the feasibility

By changing the value of parameters belonging to the first group of parameters listed in

Table 1, one can evaluate what is the effect of technological changes or improvements. For

example, concerning the choice of solar cells, one can compare the use of lightweight cells

with low efficiency compared to heavier ones that are two times more efficient.

With the results that the methodology gives in the case of Sky-Sailor as explained in the

previous chapter, one can see that the two major contributors in terms of weight are the

battery and the wing structure. That is the reason why one will focus here on the two parts

and observe the influence of the technology adopted.

Considerations about battery technology

Today, the highest energy ratio for rechargeable battery is around 200 Wh/kg for Lithium

Polymer technology. But one can expect in some years an import increase of this value.

The miniaturization of fuel cells will also make them suitable for small solar UAVs.

10

k [Wh]

9

240

8

320

7

6

5

W

3

2

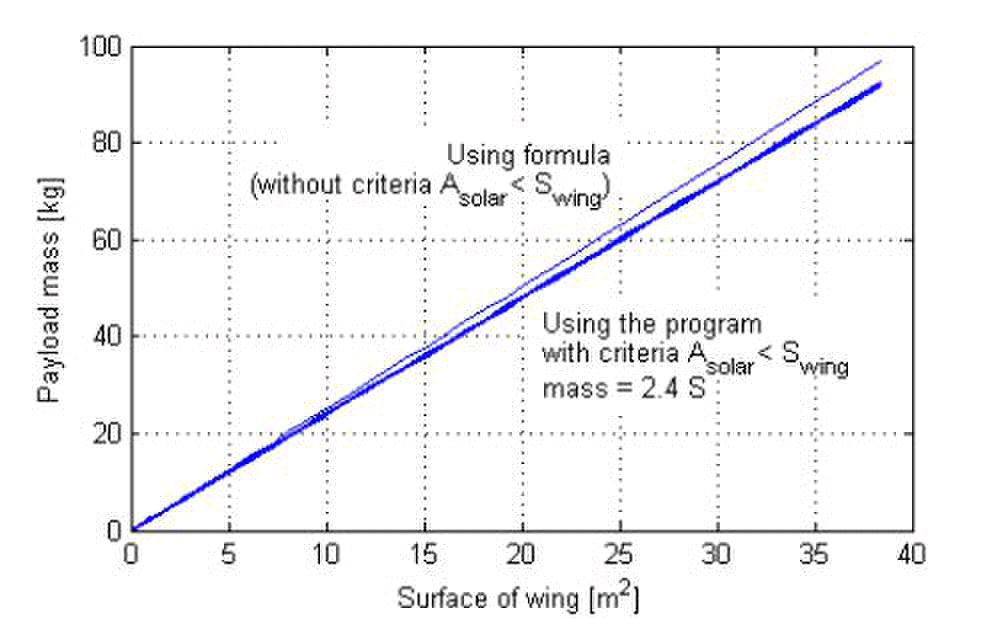
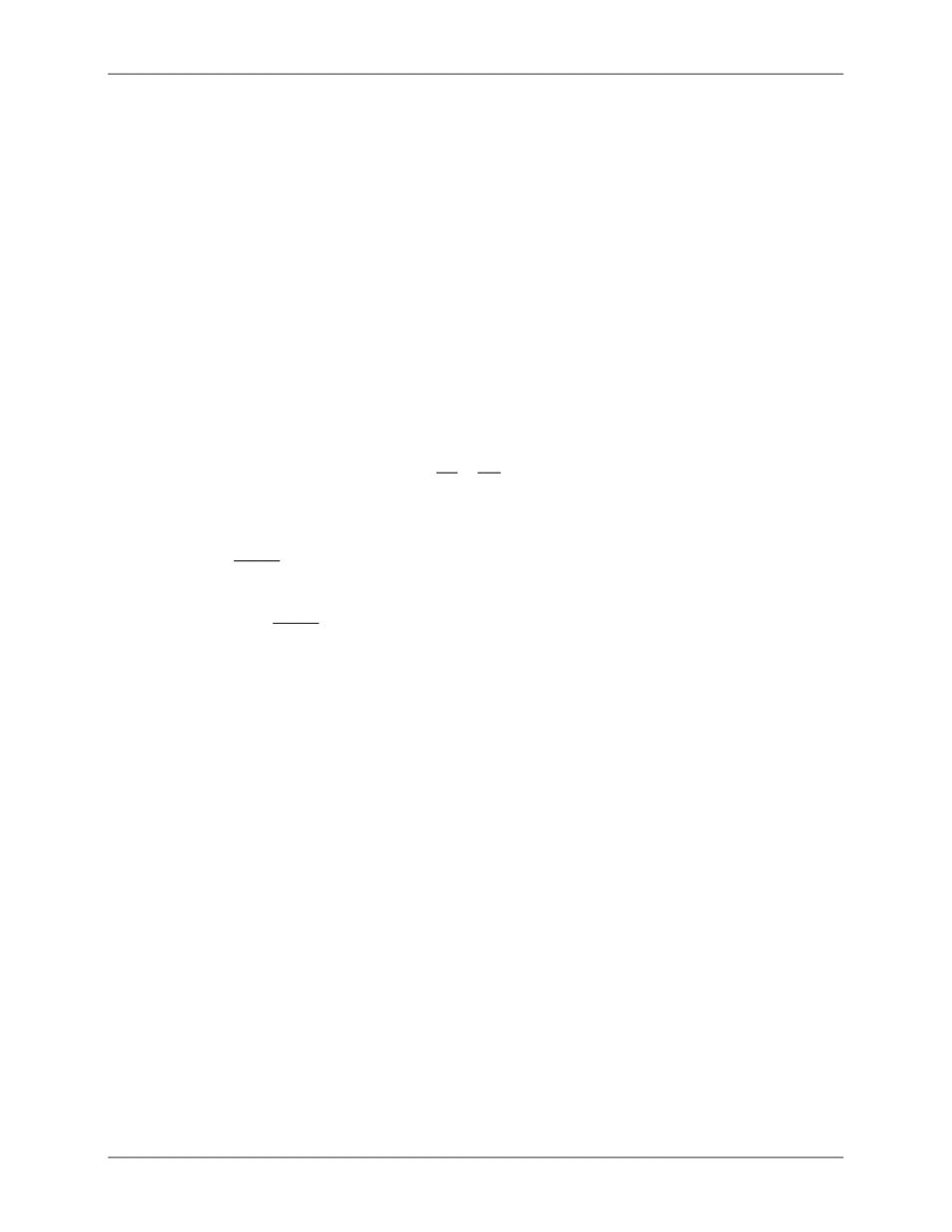
1

0

Maximum altitude of flight [m]

Fig. 10. Impact of the battery capacity on the flight altitude

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(20)

1 4

b 27



 a ≤





5 6 3

6

 

a  a (21)

a a  a

9 5

7 9

 



2 7

  

a a 

b − a a  a

S − a a  a a  a (22)



2

27a

27a

2

10 2

4

3 2

4 AR

payload 2 7 9 5 6

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Fig. 10 shows that in the case of Sky-Sailor, doubling the capacity of the energy storage

system would make continuous flight at 10’000 m altitude possible.

Considerations about airplane structure

The application we saw with a payload of 0.5 kg showed us that continuous flight is

possible for wingspan from 2.5 m to 5 m. Even in the scenario where no extra payload is

embedded, these two limits exist. The reason is that using our cubic structural weight

scaling law, the empty airframe becomes too heavy for high dimension. Hence, one can

wonder what shape should this structural weight scaling law have to make continuous flight

possible with all wingspan.

This is done, using our methodology, by setting kstruct to zero which means that we consider

an ideal wing structure that has no mass. Then, try to know for a specified b and AR what

the maximum payload weight that can be embedded is. Hence, this value will also be the

maximum weight that the wing can have if we assume no payload. Starting with Eq. 19, we

have:

a

Then, isolating a3 which corresponds to the payload mass, we have:

a ≤

10

m ≤

10

One can then express the maximum admissible wing structure mass depending on its

surface as depicted on Fig. 11.

Fig. 11. Maximum admissible structure mass depending on wing surface for AR = 15

It is interesting to see that the relation is linear, which means that the ratio between mass

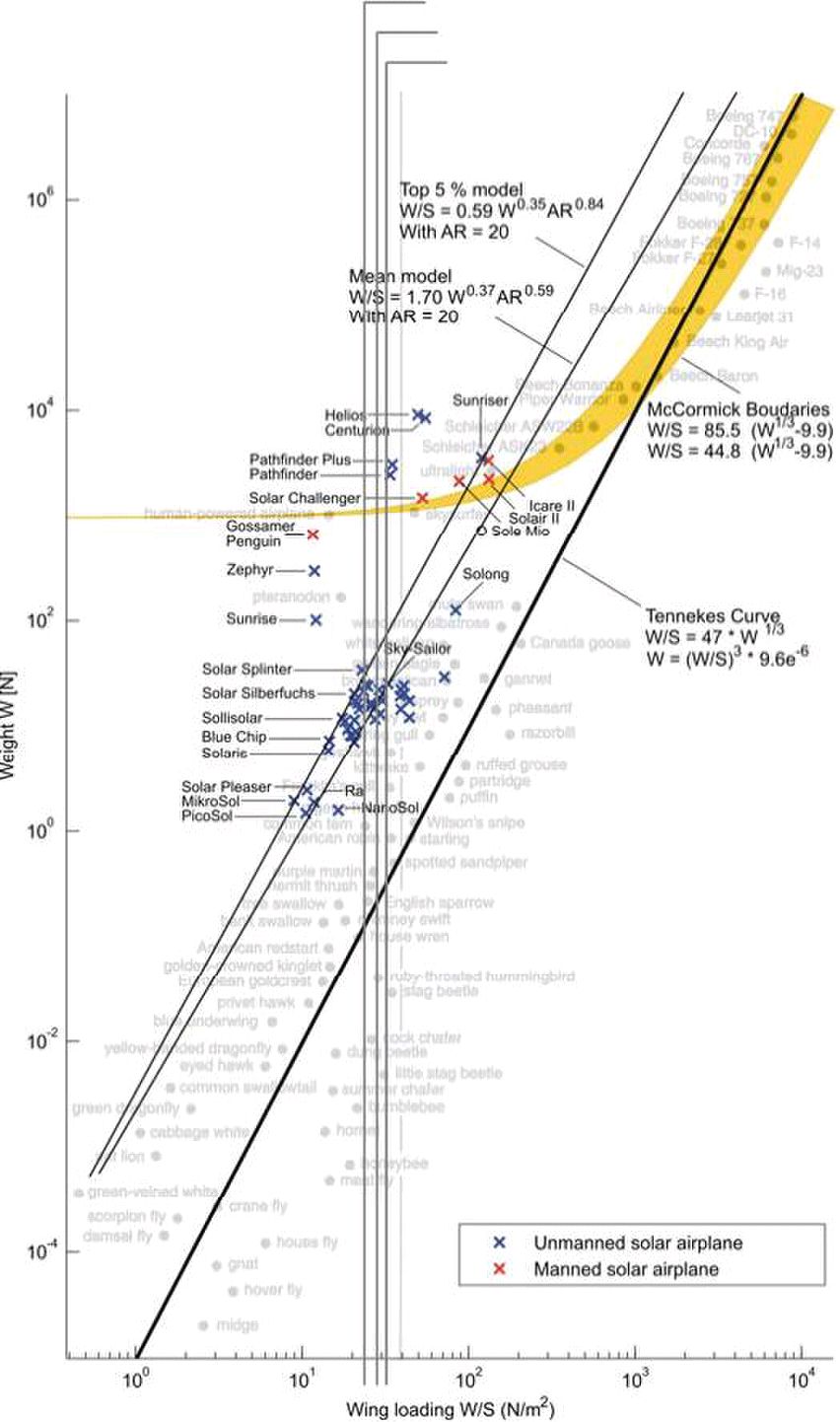
and surface has to remain under a certain value. When plotting this relation on the Fig. 6, it

proves clearly as it was said before that the realization of a solar airplane flying

continuously is more difficult for higher wingspan. In fact, the top 5% model we identified

has a surface density that increases whereas it should stay constant to guaranty feasibility.

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AR = 15

AR = 20

AR = 25

Fig. 12. Maximum admissible wing surface density

4 Conclusion

This lecture presented the global methodology that was developed for the design of the Sky-

Sailor solar airplane. It was applied on our first prototype and revealed to be very useful,

efficient and accurate [26]. The great benefit is that it is general enough to be applied to a

wide range of size, from small model airplane to large scale high altitude platforms.

Moreover, the analytical form of the method allows identifying clearly some general

principles, like the constancy of wing surface density, the designer should be aware of.

Hence, it was proved here that the realization of such airplane is more difficult for higher

dimension. Of course, after this conceptual design phase, the next step is to achieve the

preliminary design where the design of all the parts is approached more into details.

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