Design, Construction and Test of the Propulsion System of a Solar UAV

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Abstract

Pollution problems and the need to achieve a lower oil dependency have given solar and electric technologies, an important role in propulsion systems, from automotive to, more recently, aviation industry. This thesis contains the conceptual design of a hybrid propulsion system of an unmanned aerial vehicle (UAV). The solar-powered plant aimed at a small UAV with a wingspan of 4.5 m and an approximate weight of 5 kg, with a specific civil surveillance mission. Its architecture is completely different from the conventional methods of propulsion. From all the different efficiencies of the components that influence the use of energy, the most important factor is the solar irradiance and the ability that the solar panels have to harvest that energy, that is, their efficiency. The design and sizing of the different components of the propulsion system depends on the available energy stored in the battery or the generate power in the solar panels. As solar radiation is different throughout the year, different combinations of batteries, solar panels or hybrid systems are studied. The propulsion system is designed according to the requirements of energy available and energy required, and after appropriate design, the different components of the propulsion system are selected following design criteria. In the end, a road-map to achieve the necessary tests and check the proper functioning of the designed system will be established.
Keywords: Green aviation, Electric flight, Solar panels, Solar irradiance, Hybrid propulsion

1. Introduction

Solar energy is very important in many sectors because it is a clean energy obtained from the use of electromagnetic radiation from the sun. In the aviation world, this type of energy is the key in some factors, polluting emissions, noise, and reduction of dependence oil as a source of non renewable energy. Uniting these factors, the search for new technologies and forms of propulsion opens a path to include the study of solar power as a energy source in the aircraft.

The ability for an aircraft to fly during a much extended period of time has become a key issue and a target of research, both in the domain of civilian aviation and unmanned aerial vehicles. The latter domain takes an increasingly important place in our society, for civilian and military applications. The required endurance is in the range of a couple of hours in the case of law enforcement, border surveillance, forest fire fighting or power line inspection. However, other applications at high altitudes, such as communication platform for mobile devices, weather research and forecast, environmental monitoring, would require remaining airborne during days, weeks or even months.

For the moment, it is only possible to reach such ambitious objectives using electric solar powered platforms. Photovoltaic modules may be used to collect the energy of the sun during the day, one part being used directly to power the propulsion unit and onboard instruments, the other part being stored for the night time.

Due to the sensitivity to its mass, an electric aircraft was not really feasible for many years, but much has evolved since the first prototypes and, currently, there exist a huge number of projects such as: the Helios, a solar-electric flying wing, remotely piloted aircraft, developed as technology demonstrators under Environmental Research Aircraft and Sensor Technology project [12]; the Pathfinder, a government program in the early 1980s to develop a high altitude, long-endurance aircraft for surveillance purposes [2]; the Zephyr, an aircraft that can fly continuously using solar power and low drag aerodynamics [13]; and the Solar Impulse project, the outcome of a four-year research[14].

2. Energy Management for the Aircraft Mission.

Depending on the characteristics of the aircraft and its mission, the necessary energy requirements can be determined.

2.1. Aircraft Description

The propulsion system to be designed is meant for a small aircraft. This is part of a much larger collaboration project that involves several research institutes of LAETA [8]. At the present, the conceptual design of the airframe has been completed and some of the UAV specifications relevant to the design of the propulsion system are summarized in Tab. 1.

Parameter	Symbol	Value	Units
Wing mean chord	c	0.335	m
Wingspan	b	4.53	m
Wing area	S_{ref}	1.518	m^2
Take off weight	W	48.12	N

Table 1: Solar UAV characteristics.

Although it is a small aircraft, with a mass is of less than 5 Kg, its wing in addition to its aerodynamic function, has an appropriate area to place the solar cells. The airfoil shown in Fig. 1 is another important factor. It is an essential part from the point of view of aerodynamics and, in this project, it has added importance because factors such as the airfoil curvature can be important when attaching the solar panels that, to conform to this curvature, must have some flexibility.

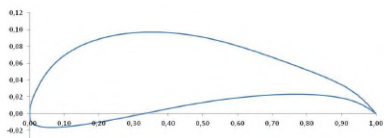


Figure 1: Airfoil of solar UAV.

The solar cells are to be installed on the wing upper surface. The area available S_{PV} will be less than the reference area S_{ref} shown in Tab. 1 due to factors related to the airfoil profile shape. The estimate of S_{PV} is obtained by using three correction factors applied to S_{ref}: curvature correction factor at the leading edge, CF_{LE} (15%), to correct the curvature excess in this area; correction factor at the trailing edge, CF_{TE} (10%), to account for the occupied area by the control surfaces; and the wingspan correction factor, CF_W (18%), to account for a safety zone at each wing tip.

The values c_{PV}, b_{PV} and S_{PV} were computed as

$$c_{PV} = \frac{100 - CF_{LE} - CF_{TE}}{100} \cdot c\,, \tag{1}$$

$$b_{PV} = \frac{100 - CF_W}{100} \cdot b\,, \tag{2}$$

$$S_{PV} = c_{PV} \cdot b_{PV}\,, \tag{3}$$

obtaining an available area S_{PV} of 0.728 m^2.

2.2. Aircraft Mission

The aircraft mission is the surveillance of land inaccessible to conventional observation methods.

Mission Characteristics

The solar UAV mission is divided into the following stages:

1. Take off: Estimated duration of 1 second, without taking into account the rolling period.
2. Climb: Estimated duration of 10 minutes, to reach a cruise flying altitude of 1000 m above runway.
3. Cruise: Target endurance of 8 hours to perform.
4. Descent: Approximate duration 29 minutes.
5. Landing: Final approach and touch down.

The described nominal mission is graphically shown in Fig. 2.

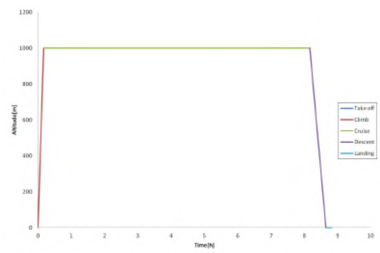


Figure 2: Mission of solar UAV.

2.3. Energy Requirements

The energy requirements have been calculated based on the efficiency of each component of the propulsion system in every stage of the mission. The efficiency of battery, cables and ,electronic speed controller ESC, is fixed for the entire mission while the efficiency of the electric motor and propeller are different in each stage.

The power required for each stage of the mission can be estimated as

$$P_{req} = v_{stage} \cdot D_{stage}\,, \tag{4}$$

where v_{stage} is the corresponding aircraft speed and D_{stage} is the aircraft drag.

Knowing the duration of each stage t_{stage}, it is then possible to calculate the energy required at each stage of the mission,

$$E_{req} = P_{req} \cdot t_{stage}\,. \tag{5}$$

Applying the total efficiency of the components, it is possible obtain the final energy of the propulsion system. In this calculation it is added gravitational potential energy corresponding to the stage of the climb. Below is particularized for each segment of the mission:

1. Take off energy

   The total efficiency of the components for take off can be estimated as

$$\eta_{Ttoff} = \eta_B \cdot \eta_C \cdot \eta_{ESC} \cdot \eta_{E_{toff}} \cdot \eta_{P_{toff}} \,, \quad (6)$$

   where η_B, η_C and η_{ESC} are the efficiency of battery, cables and electronic speed controller, common for all stages . While $\eta_{E_{toff}}$ and $\eta_{P_{toff}}$ are the efficiency of electric motor and propeller for take off.

   Then the required energy can be determined as

$$E_{req} = (\frac{1}{\eta_{Ttoff}} \cdot P_{req}) \cdot t_{toff} \,, \quad (7)$$

   where η_{Ttoff}, P_{req} and t_{toff} are total efficiency, power and time for take off respectively.

2. Climb energy

   The total efficiency of the components for climb can be estimated as

$$\eta_{Tcli} = \eta_B \cdot \eta_C \cdot \eta_{ESC} \cdot \eta_{E_{cli}} \cdot \eta_{P_{cli}} \,, \quad (8)$$

   where $\eta_{E_{cli}}$ and $\eta_{P_{cli}}$ are the efficiency of electric motor and propeller for climb.

   Then the required energy can be determined as:

$$E_p = m \cdot g \cdot h \,, \quad (9)$$

$$E_{req} = E_p + (\frac{1}{\eta_{Tcli}} \cdot P_{req}) \cdot t_{cli} \,, \quad (10)$$

   where E_p is gravitational potential energy, m is the mass of UAV, g is gravitational acceleration constant $(9,81m/s^2)$ and h is the altitude in this case 1000 m. η_{Tcli}, P_{req} and t_{cli} are total efficiency, power and time for climb respectively.

3. Cruise energy

   The total efficiency of the components for cruise can be estimated as

$$\eta_{Tcru} = \eta_B \cdot \eta_C \cdot \eta_{ESC} \cdot \eta_{E_{cru}} \cdot \eta_{P_{cru}} \,, \quad (11)$$

   where $\eta_{E_{cru}}$ and $\eta_{P_{cru}}$ are the efficiency of electric motor and propeller for cruise.

   Then the require energy can be determined as

$$E_{req} = (\frac{1}{\eta_{Tcru}} \cdot P_{req}) \cdot t_{cru} \,, \quad (12)$$

   where η_{Tcru}, P_{req} and t_{cru} are total efficiency, power and time for cruise respectively.

4. Descent energy

   At this stage no energy is required because it is assuming that the engine is stopped then the UAV descends planning.

The values for the required power and energy for each mission stage are summarized in Tab. 2. The total energy required ($E_{req} = 1737KJ$) and the maximum power required ($P_{req} = 455W$) will be the basis for the sizing of the propulsion system. Figure 3 shows the power distribution for the complete mission.

Stage	η_T [%]	P_{req} $[W]$	E_{req} $[KJ]$
Take off	14.54	32.07	0.03
Climb	21.55	455.75	273.45
Cruise	35.51	50.81	1463.34
Descent	0	0	0
TOTAL			1736.82

Table 2: Energy required for the propulsion.

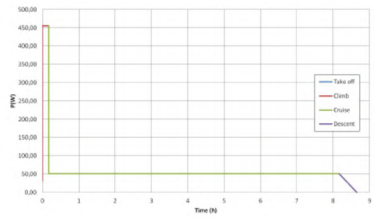


Figure 3: Power required at every stage.

3. Solar Radiation Model

The radiation of the Sun is different in every part of the planet and this changes over the day, that is, the radiation is variable with time.

3.1. Solar Irradiance

During the day, the propulsion energy of an electric UAV can be obtained by batteries, solar panels or a combination of both (hybrid). The batteries can operate in any part or region of the world because they are independent of solar radiation.

The energy coming from the sun depends on the wavelength, leading to the solar spectrum. The standard spectrum for space applications is referred to as AM0. It has an integrated power of 1366.1 W/m^2. Two standards are defined for terrestrial use: the AM1.5 Global spectrum is designed for flat plate modules and has an integrated power of 1000 W/m^2 (100 mW/cm^2); and the AM1.5 Direct (+circumsolar) spectrum, defined for solar concentrator work, which includes the direct beam from the sun plus the circumsolar component in a disk 2.5 degrees around the sun. The direct plus circumsolar spectrum has an integrated power density of 900 W/m^2 [11].

The SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine) program is used to generate the standard spectra and can also be used to generate other spectra as required [4].

An ideal (perfect) solar cell that would cover the entire spectrum and convert all this energy into electricity would have an efficiency of 100 %. In reality, depending on the semiconductors used, only a part of this spectrum is covered. The ratio of converted energy to the received radiation energy define the efficiency of a photovoltaic cell.

The solar irradiance intercepted by the earth at the top of the atmosphere, the solar constant, is quite stable with an observed value of 1365 W/m^2 $\pm$ 0.3%. However, on average, only about half of this energy reaches the surface and is available to drive surface and biological processes. Of the other half, approximately 30% is reflected back to space, and the remaining 20% is absorbed by clouds, dust, and "greenhouse" gases such as water vapor, carbon dioxide, and ozone [11].

3.2. Daily Solar Energy

The irradiance depends on a lot of variables such as geographic location, time, plane orientation, weather conditions and albedo (or reflection coefficient of the surface) that represents the reflection on the ground surface. A good model was developed based on *r.sun* software [3]. This model allows to calculate the daily radiation profile for the aircraft mission given the following input data [7]:

1. Geographic location

   The city of Covilhã (Portugal) is the location selected for the solar UAV primary mission.

2. Time

   Since the mission is interest to take place over a single daylight period, average daily iradiation profiles in different months are used.

3. Plane orientation

   For this study, horizontal solar panels are considered, so the tilt and orientation of the panels is always 0^o.

The output data obtained are the various components of irradiation. Using this data table, it is possible to create a graphic of the daily irradiance as shown in the Fig. 4. In the graph, two characteristic parameters can be obtained: maximum daily irradiation (I_{max}) and daily irradiation time (T_{day}).

As mentioned before, the two parameters $Imax$ and $Tday$ depend on the location and date. Figure 5 shows the evolution of these parameters throughout the year for Covilhã, Portugal.

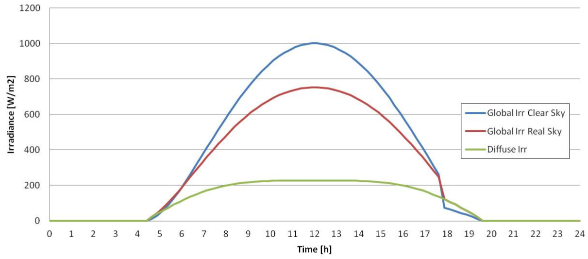
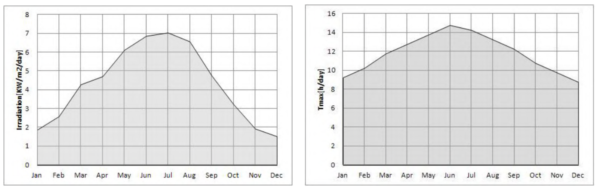


Figure 4: Daily irradiance (June average).



(a) Maximum daily irradiation.

(b) Daily irradiation time.

Figure 5: Evolution of the irradiation characteristic parameters throughout a year in Covilhã, Portugal.

4. Architecture of the Propulsion System for Solar UAV

The different components of the solar powered system have a particular architecture, such as the one shown in Fig 6.

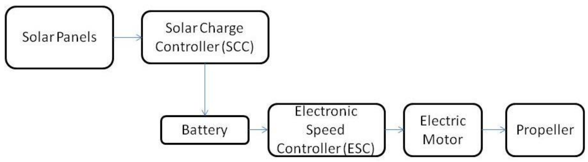


Figure 6: Architecture of propulsion system.

4.1. Solar Panels

A solar panel (also known as module, photovoltaic module or photovoltaic panel) is a packaged, connected assembly of photovoltaic (PV) cells. PV modules are usually made from arrays of crystalline silicon solar cells. These cells are made of extremely thin silicon wafers (about 300 μm) and hence are extremely fragile. To protect the cells from damage, an arrays of cells is hermetically sealed between a layer of toughened glass and layers of ethyl vinyl acetate. It can be distinguished three types of silicon solar cells according to the type of crystal:

- Monocrystalline, for which absolutely pure semiconducting material is used which gives a high level of efficiency but at a high cost;
- Polycrystalline, composed of crystal structures of varying sizes. The manufacturing process is more cost efficient but leads to less efficient solar cells;

- Amorphous, or thin-layer cell, where a silicon film is deposited on glass or another substrate material, even flexible. The thickness of this layer is less than 1 μm, thus the production costs are very low, but the efficiency is poor as well.

Then, the efficiency of solar cells is defined as

$$\eta_{PV} = \frac{P_{PV}}{I_{max} \cdot S_{PV}} . \tag{13}$$

where ($Pmax$) is the cells power output (in watts), (I_{max}) is the input irradiance and (A) is the surface area of the solar cell . This is efficiency is measure under standard test conditions (STC): ($I = 1000W/m^2$), Air-mass 1.5 reference spectral distribution and 25^oC.

4.2. Solar Charge Controller
A charge controller limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may also prevent completely draining ("deep discharging") a battery.

4.3. Batteries
There are numerous types of rechargeable batteries. Several technologies are available and, currently, the lithium-ion (Li-ion) or lithiumion- polymer (Li-Po) (where the electrolyte is a gel and not a liquid) technology are the best concerning gravimetric energy density, compared to lead-acid, nickel-cadmium (NiCd) or nickel-metal-hydride (NiMH). Nowadays, most electric powered aircraft use battery systems of the Lithium-polymer type, producing a specific energy of about 200 Wh/Kg [16, 10].

4.4. Electronic Speed Controller
An electronic speed control (ESC) is an electronic circuit with the purpose to vary the speed of an electric motor, its direction and possibly also act as a dynamic brake.

4.5. Electric Motor
DC (Direct Current or Continuous Current) motors will be used as they are designed to run on DC electric power supplied by a battery. By far, the most efficient type is the brushless type, which use electronic commutation, to create a rotating magnetic field vector that pulls an electromagnet or a permanent magnet.

The advantages of BLDC, brushless DC motors, are numerous : very precise speed control, high efficiency, high reliability, reduced noise, longer lifetime (no brush abrasion), no ionizing sparks.

4.6. Propeller
The propeller is a device consisting of a set of two or more twisted, airfoil shaped blades mounted around a shaft and spun to provide propulsion of a vehicle through a fluid. It accelerates incoming air particles creating a reaction force called thrust.

The propeller efficiency η_P is defined as the ratio between the propeller thrust T times the propeller axial speed v and the resistance moment M_P times the rotational speed ω,

$$\eta_P = \frac{T \cdot v}{M_P \cdot \omega} . \tag{14}$$

A good propeller designed for a specific flight domain should have an efficiency of at least 80%, 85% being an excellent value that is difficult to surpass. Unfortunately, it is not constant and varies with air speed and rotational speed, or more precisely with the dimensionless propeller advance ratio

$$J = \frac{v}{n \cdot d} , \tag{15}$$

where n is the number of blades and d their diameter.

5. Design of the Electric Propulsion System for Solar UAV

The variation of solar radiation over time requires a detailed study to decide which of the electric propulsion methods will be appropriate for the mission. There will be months, with low irradiation, in which the output power of the solar panels will be insufficient to ensure a flight. So it must study the three possibilities of propulsion: batteries, solar panels or a hybrid selection of both.

5.1. Battery Based Propulsion
First, it supposed that the aircraft flies only with energy stored in batteries. With the energy data for the mission and the different type of batteries,it is possible to create comparative graphs to estimate the required size of the battery.

Two safety factors will be considered:

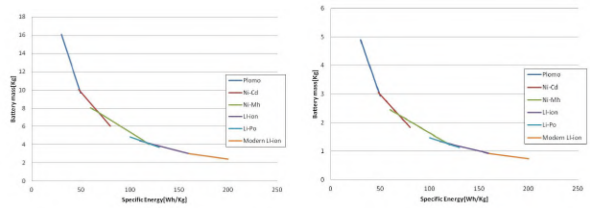
1. The system consists of two separate batteries, one stores energy for propulsion system and another stores energy for flight systems. The primary battery (propulsion) will have a capacity of 482.4 Wh, while the secondary battery capacity has been estimated by the specialists of the aircraft project to be 146.7 Wh, being the total capacity 629.1 Wh.

2. An additional energy percentage will be considered in each battery. In this calculation; a value of 10% was used, that is the self-discharge percentage of the lithium batteries.

The mass of each battery will be calculated as

$$m_{bat} = \frac{E_{req}}{E^*_{bat}} , \tag{16}$$

where E_{req} is the required energy and E^*_{bat} is the mass specific energy of the battery. Calculating it for different types of batteries, one obtains Fig. 7. Figure 7 shows that with increasing mass specific energy, it is possible to reduce the mass of the batteries. It is checked that Li-ion batteries have the best properties. Therefore, if the aircraft is only powered by lithium batteries to achieve our mission, the batteries should have the properties shown in Tab. 3.



(a) Batteries for propulsion energy. (b) Batteries for flight systems.

Figure 7: Battery types, mass and specific energy.

E^*_{bat} (Wh/Kg)	$m_{bat1}(Kg)$	$m_{bat2}(Kg)$
200	2.41	0.73

Table 3: Battery mass for mission with battery only.

If one recalls the estimated total aircraft weight of 5 Kg, it is clear that a battery only solution is not possible due to its excessive weight.

5.2. Solar Panel Based Propulsion
The selected PV cell is the SunPower C60 [15] because it has the best characteristics for our aircraft. It has high efficiency and also meets the requirements regarding flexibility and weight are designed for installation in the aircraft.

The number of PV cell (N_{SC}) can be calculated as

$$N_{SC} = Floor\left(\frac{S_{PV}}{S_{SC}}\right), \qquad (17)$$

where S_{SC} is the area of one PV cell. Therefore, will be possible install 44 PV cells, generating a set of 22 arrays per wing as shown Fig 8.

Figure 8: Distribution of solar panels on wing.

It will be assumed that the aircraft flies only with solar panels. Knowing the solar radiation values, which were explained in section 3, it will be possible to determine the solar cells power considering their efficiency according with the equation 13. This way, it is possible to determine the daily power profile for each month of the year.

Two factors were assumed to calculate the power of the solar panels: first, the start time of the mission will be the hour of the day in which is the generated power value is greater than the minimum power required for take off. Second, the area under the curve of daily power is the energy provided by the solar panels and will be calculated by the method of trapezoids. Calculating the generated energy for every month and comparing with the energy that the mission require, there are months with excess energy (spring and summer) and months with deficiency of energy (autumn and winter). Although there are months in which the aircraft could fly only with solar panels, in energy terms, one can not achieve a mission with these features, due to the high require power in climb. The solution is to opt for a hybrid propulsion.

5.3. Hybrid Propulsion
The proposed solution is to use a hybrid propulsion combining solar panels and batteries where the battery will be used primarily for climb.

5.3.1 Excess Energy

This study was achieved with July irradiation values because they are the highest in the year and the results can be extrapolated for all summer period. In Fig. 9, one can see areas with excess energy and the climb area where exist energy deficiency. Therefore two options will be considered:the battery is not recharged in flight and the possibility of recharging the battery in flight.

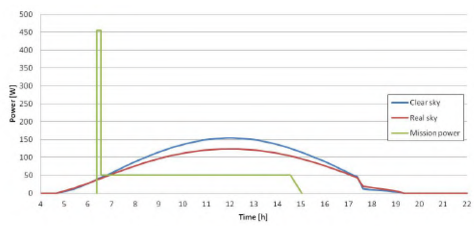


Figure 9: Power provided by the solar panels in July and power required by the mission.

In cases where the battery is not recharged in flight, the mission will need to have a battery with enough energy to satisfy the energy deficit in climb. In cruise, the solar panels have excess energy to propel the aircraft. The excess energy can be utilized in flight auxiliaries systems or as propulsion power for additional payload. In this case, one just has to add a battery that allows to realize the climbing maneuver. The values obtained are shown in Tab. 4.

$E_{req_{cli}}$	79.9 Wh
$E_{PV_{cli}}$	21.7 Wh

Table 4: Energy required versus solar energy available for climb.

Rechargeable Battery in Flight

For rechargeable batteries, two new studies are possible: changing the start time of the mission and reducing the number of solar cell, the latter is more interesting. It consist in determining how the generation of output power varies depending on the number of solar cells. Figure 10 shown this variation, calculated by varying the surface of the solar panels considering equation 13.

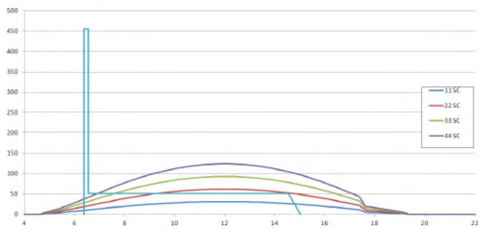


Figure 10: Power levels for different number of solar cells.

The mission could be achieved with only 31 solar cells and a battery for climb, being the energy produced by the other solar cells used to recharge the battery. Figure 10 shows clearly the trend. Only values near to forty-four solar cells allow to fully recharge the battery.

5.3.2 Deficient Energy

This study was achieved with the lowest values radiation corresponding to winter, in particular, the month of December. In this case, one has to correct the deficiency of battery total energy, peak power common to all months and the power deficit corresponding to the weaker radiation, as shown Fig. 11. Now the battery is not rechargeable in flight due to the low power of the solar panels.

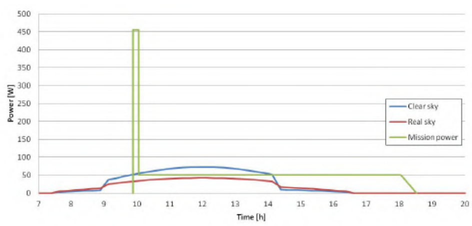


Figure 11: Power provided by the solar panels and power required by the mission.December.

It can be clearly seen in Fig. 11 the values of power and energy-deficient areas, then one can calculate the energy that the battery should provide so that the mission duration is achieved. The results are shown in Tab. 5, where E_{SC} is the value of generated energy, in December and E_{bat} will be the needed capacity to complete the mission.

E_{SC}	198.0 Wh
E_{bat}	431.2 Wh

Table 5: Energy required from battery and solar panels for a winter mission.

5.4. Final Configuration of the Electric Propulsion System

After studying the three possible forms of electric propulsion, a hybrid propulsion has been selected system as shown in Fig 12.

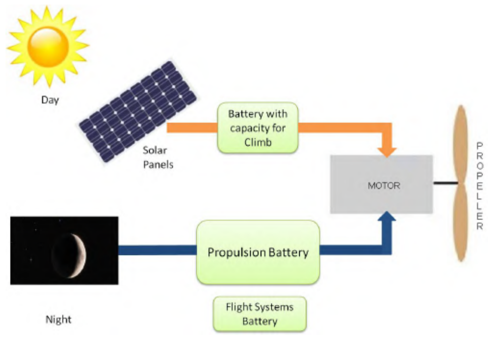


Figure 12: Selected propulsion architecture.

The system consists of 44 solar cells, and a rechargeable battery with a capacity of 79.9 Wh. In these conditions, the solar UAV may only satisfy the mission requirements during the summer months and so the battery will recharge during flight theoretically, being recharged for the next operation.

6. Selection of System Components

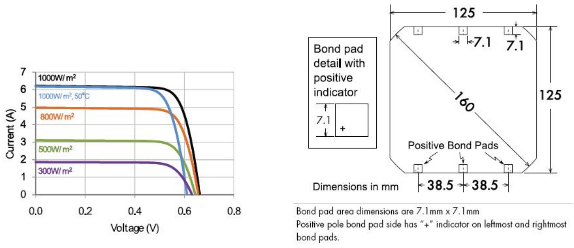
For each component, the most appropriate reference will be selected according to the calculated requirements.

The solar panel will be made of SunPower C60 cells whose main characteristics are shown in Fig. 13 and Tab. 6 [15].

P_{mpp} (Wp)	η_{SC} (%)	V_{mpp} (V)	I_{mpp} (A)
3.43	22.6	0.583	5.94

Table 6: Electric characteristics of SunPower C60 at STC [15].

It can be seen that a single solar cell produces about 0.5 volts (V_{mpp}) but the propulsion system



(a) Typical I-V curve.

(b) Cell and bond pad dimensions.

Figure 13: SunPower C60 cell properties [15].

will need at least a voltage of 12V, the typical working values of rechargeable batteries. To produce those 12 V, it is necessary to connect 22 cells in series.

Morningstar SunKeeper solar charger controller will be selected which, despite being more expensive, has better characteristics in terms of weight, size and working solar current [9].

The battery selection depends solely of its capacity since the nominal voltage is fixed at 11.1 V corresponding to three Li-Po cells connected in series (3S). In this case, one is looking for batteries that allow a flight with hybrid propulsion with a minimum capacity of 58.1 Wh or 5239 mAh. The capacity required for additional safety is 7202 mAh. For additional safety the battery Turnigy nano-tech with 8400mAh of capacity will be selected [5].

For the ESC selection, one has to take into account the type of battery chemistry (always Li-Po) and an adequate current, without forgetting the compatibility with the type of electric motor. The appropriate ESC must be able to work with a higher current than the maximum current that the electric motor draws, so the selection of the electric motor and ESC are strictly linked [5, 6].

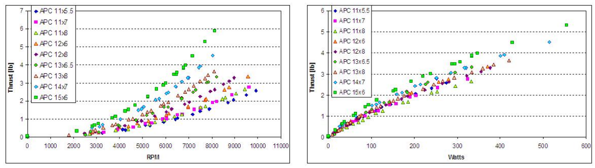
The selection criteria for the electric motor will be those that allow to have the power needed in every stage of the mission and also take into account other factors such as weight and cost. The maximum power occurs in the climb stage (450W), so the motor selected must be able to provide this power.

Typically, the propellers are identified by a set of two values in the form $d \times p$, where the first term (d) is the propeller diameter and the second (p) is the blade pitch. Therefore, diameter and pitch will be the global parameters that characterize the propellers. In Tab. 7, the recommended propellers that can be used with each electric motor to generate the required power are listed. Other cases exist so it will always be necessary to do some tests.

The data shown in Tab. 7 were tested with battery, ESC, motor and propeller, and contains the voltage, currents and power for a particular propeller test. The propulsive power can be estimated as

$$P_{Propulsive} = \eta_E \cdot \eta_P \cdot P_{Electric} \,. \qquad (18)$$

The calculation is not so simple because the efficiency of the propeller depends on many factors, such as: speed, thrust, rpm and advance ratio, and the combination of these values will only be achieved through an experimental test as shown Fig. 14.



(a) Experimental test values of thrust-rpm.

(b) Experimental test values of thrust-power.

Figure 14: Experimental tests for different models of APC propellers [1].

The propulsive power will be estimated with the theoretical values of efficiency for this two components, propeller and motor, $\eta_E = 89\%$ and $\eta_{Plr} = 85\%$ respectively. The value obtained in each case has to ensure the necessary power for climb ($P_{Propulsive} \geq 450W$). As seen in the Tab. 7 there are values near 450 W , it serves as a first reference for pre-selecting one or the other but consider that the component will be selected and then necessarily it will be tested.

6.1. Final Configuration of the Propulsion System Components

At this point, by looking at table 7, the selection of the combo ESC-Motor-Propeller can be made. The selected components are a speed controller Turnigy Super Brain, a electric motor NTM Prop Drive Series and a APC 11x5.5 propeller. The selected ESC is light compared to the other three, only Hyperion Atlas 45A has less weight but its price is very high. The electric motor is chosen based on the lowest weight and price, which also coincides with the best value of provided power. Finally, the selection of the propeller is in accordance with the recommendations of the manufacturer since in this case the cost price is similar in all models. The scheme of the selected components is illustrated in Fig. 15.

7. Experimental Test of Propulsion System and Subsystems

A road-map for the different experimental tests of the designed system will be proposed.

7.1. Experimental Test of the Solar Panels

It is necessary to test the solar panels to ensure that the solar cells are providing values near the

E. Motor	Propeller	Voltage (V)	Current (A)	Elec.power (W)	Prop.power (W)
NTM Prop Drive Series	APC 10x5 - 11x5.5	11.1	46 - 49	510 - 543	386 - 411
Turnigy D3548/4	APC 11x7	11.1	40	483	366
Hyperion ZS3020-8	APC 11x5.5E	11.1	49	545	412
Hyperion ZS3025-10	APC 15x8E	10	51	514	389

Table 7: Data propeller-electric motor manufacturer [5, 6].

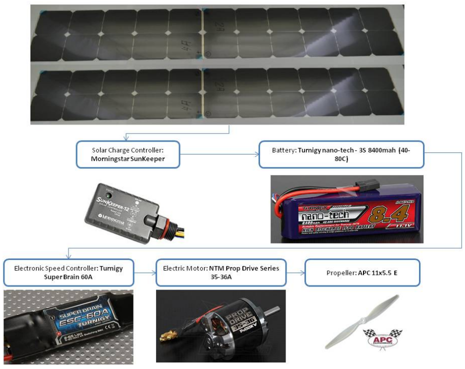


Figure 15: Scheme of the propulsion system components selected.

nominal voltage and current. It will be possible to experiment with different array configurations and at different times of the day to see how these values evolve.

The first test will be to characterize a single PV cell as shown in Fig. 16. With a multimeter, the voltage and current values will be measured and compared with the nominal values. This data will help to form arrays optimally, where the cells are matched.

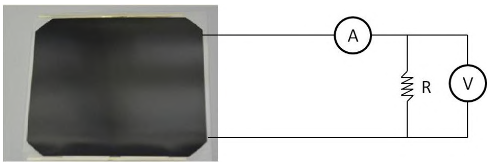


Figure 16: Test of an individual PV cell.

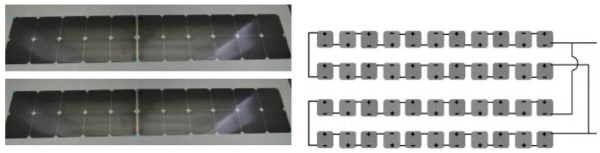
Different configurations can be tested to study the difference between series connections or parallel connections. The two tests with different solar array configurations are proposed:

Ten cells connected in series(10S);

Two sets, each of 5 cell connected in series, connected in parallel (5S2P).

Finally, the final configuration of the solar panel of the UAV will be tested. This configuration contains two sets, each of 22 cells connected in series, connected in parallel (22S2P) as shown in the Fig. 17.

In the test will be check that the solar arrays produce approximately 12 V and 12 A approximately.



(a) Physical layout. (b) Scheme of electronic connection.

Figure 17: Test of 22S2P configuration.

7.2. Experimental Test of the Electric Motor and Propeller

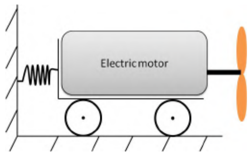


Figure 18: Installation for motor-propeller test.

The installation to measure the thrust of the propeller is depicted in Fig. 18. It can be made easily with a mechanism which measures the force of the propeller and so determines the thrust produced.

7.3. Experimental Test of the Solar Charger

Tests are needed to study how the different levels of solar radiation influence the battery charge. For this test, it will be assembled the subsystem consisting of solar panels, solar charger and batteries as shown Fig. 19.

Figure 19: Experimental test of the solar charger controller.

7.4. Experimental Test of the Speed Controller

Another important subsystem is shown in Fig. 20, which consist of battery, ESC and the link motor-propeller.

It would be interesting to obtain graphs that relate the rpm with the throttle values, and thus it can determine the motor answer in based on the operation of ESC.

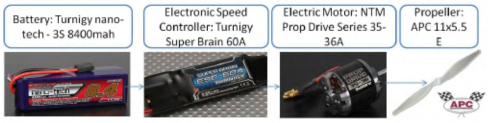


Figure 20: Experimental test of the electronic speed controller.

7.5. Experimental test of the Complete Hybrid System

When all other tests have been successfully completed, it is then possible to test the final and complete architecture shown in Fig. 15. The voltages and currents have to be adequate and the propeller parameters (trust and power) must have the value that the mission requires.

8. Conclusions

In this thesis, the architecture of the propulsion system of a solar UAV has been defined and has been particularized for a specific mission. It was found that the design of the solar-powered plant depends not only on the mission but also the type of aircraft. According to these two conditions, it was possible to calculate the mission energy requirements that affect all design process. It was seen that batteries store energy, but the important part was the evolution of the solar radiation profiles. These values mean that the mission specified is only possible in the summer months when the radiation values are higher.

The solar-powered system is designed with a Li-Po battery and mono-crystalline solar panels with an efficiency of 22.6%, concluding that it is only possible to achieved the mission with a hybrid propulsion system.

Once defined the hybrid propulsion system, the components were selected. Finally, it was established a test plan to value the proper functioning of the designed system.

The next phase in the immediate future, is to acquire all these components and test then according to the defined test-planning. Once the tests have been successfully overcomed, the system would be in the right conditions to be installed in the aircraft and carry out the corresponding flight tests.

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