Electrical Power Supply

State Of The Art 2016-2017

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2. Terminology

BAT:	Battery
BCR:	Battery Charge Regulator
DOD:	Depth-Of-Discharge
EOC:	End Of Charge
EPS:	Electrical Power Supply
LDO:	Low Dropout
LEO:	Low Earth Orbit
SEPIC:	Single-Ended Primary Inductor Converter
PV:	Photovoltaic

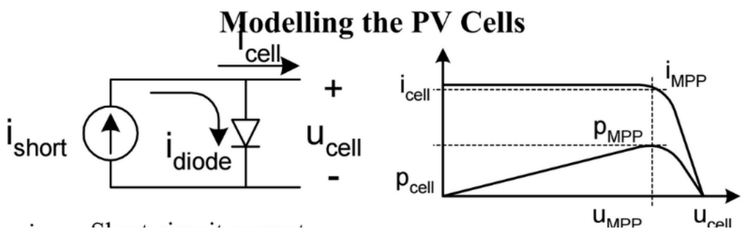
3. State Of The Art

3.1 PV

3.1.1 Solar panels

Solar cells generate electricity by absorbing sunlight using the photovoltaic (PV) effect. Solar intensity varies as the inverse square of the distance from the Sun. The amount of energy converted varies as a cosine function of the angle between the cell and the Sun. Solar cells degrade during their mission lifetime. This is characterized by the End of Life/Beginning of Life (EOL/BOL) ratio, which can be as high as 96% and low as 60%. The solar cell output at EOL will determine size requirements for the particular mission. A protective cover glass material over the cell resists light-reflection, darkening, and ultraviolet radiation damage. Solar panels are assembled from individual cells. Spectrolab Inc. and produce a Triangular Advanced Solar Cell (TASC), which has the advantage of fitting odd form factors on small satellites without the need to custom cut individual solar cells. Other issues with turning cells into panel arrays involve matching individual cells in terms of current and voltage.

<u>Global characteristic of PV cells :</u>



<u>Differences between sunlight in LEO and Earth</u>

The solar arrays use photons, characterized by an energy level and a wavelength, to produce energy. In fact, photons are absorbed by materials by going through a semi-conductor where they "push" electrons. One photon can only move one electron, provided that the photon's energy is higher or equal to the electron ones. It is the reason why the more photons go through the PV, the more electrons are moved and so the more energy we have.

The atmosphere filter some wavelength so a lot of photons are absorbed by it and they never reach the solar arrays on the Earth ground. Therefore, the efficiency of PV in space (LEO such as ATM0) is higher than on the Earth's ground since there is no loss due to the atmosphere filtration.

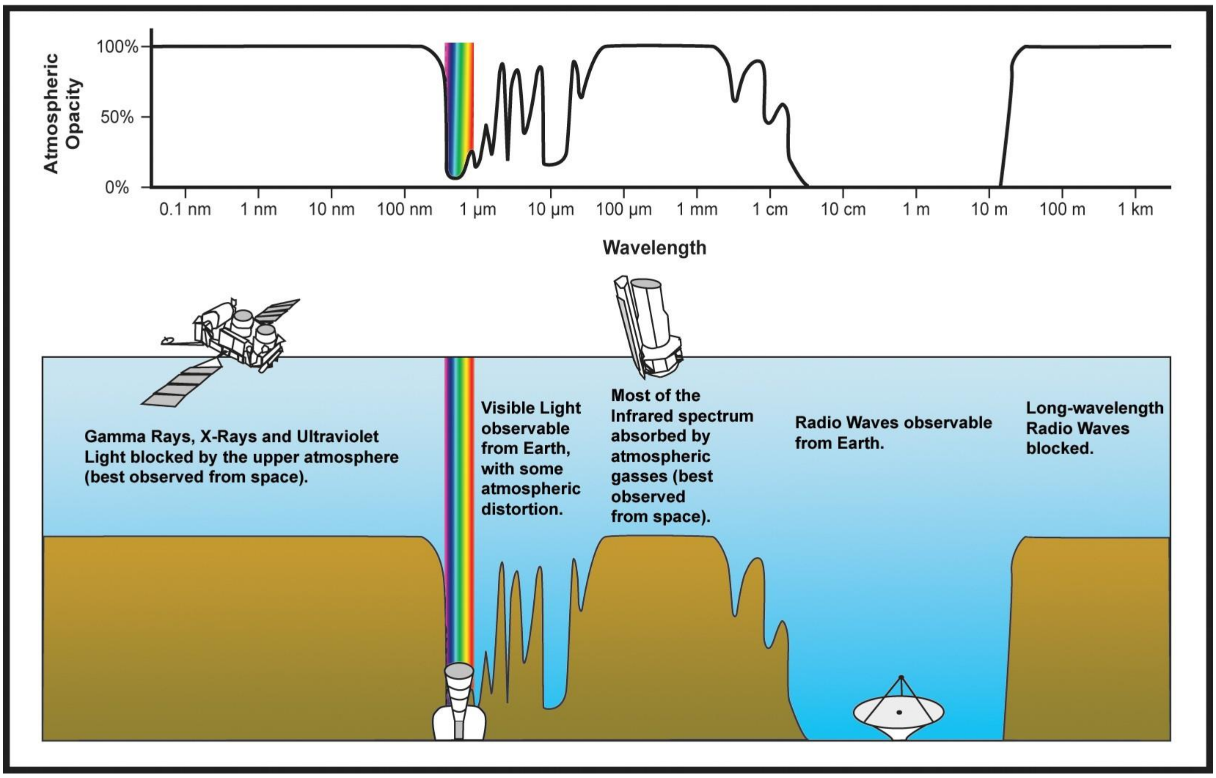


Figure 1 Atmosphere wavelength Filtration

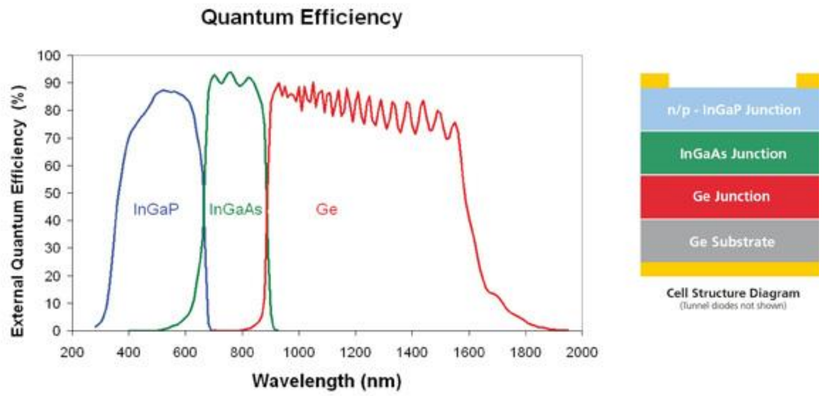
However, there is some negative points due to the lack of filtration by the atmosphere. Some rays such as Ultraviolet can cause damages on the solar cells. So, they need specific protection (coverglass) on the cells. Another challenge is the size of the PV. Usually, it is preferable to use more space when we design a solar panel than to improve its efficiency (due to the increase of the cost of the PV with high efficiency). But, in a space context, the size is limited so it is better to use expensive but small solar cells. A challenge of a CubeSat is that the means and the space are limited. So, the solar arrays should find the optimum compromise between price, efficiency, size and weight.

3.1.1.1 Triple junction solar cells technology

3.1.1.1.1 What is triple junction technology?

All solar cells for space include the latest triple junction technology, where GaInP/GaAs/Ge layers are grown on a Germanium substrate. A triple junction cell is a cell with three sub cells which absorb different wavelengths. It allows to have a big range of absorbed wavelengths in order to increase the yield of the cell.

Figure



1: Wavelengths absorption depending on the layer material

3.1.1.1.2 What are the properties of triple junction technology ?

Triple junction solar conversion efficiency is about 29% in production while it approaches 38% in labs.

Table

Material	Absorbtivity α	Emissivity ε	α/ε
Aluminium (6061-T6 alloy) as supplied	0.379	0.0346	10.
Aluminium (6061-T6 alloy) polished	0.2	0.031	6.
Aluminium with Alodine 1200S Chromate Conversion Coating	0.08	0.15	0.
Gold	0.299	0.023	13.
White epoxy paint	0.248	0.924	0.
Black paint	0.975	0.874	1.
Silver coated Teflon	0.08	0.66	0.
Aluminized Teflon (front surface)	0.163	0.80	0.
Aluminized 25 µm Kapton (back surface)	0.36	0.61	0.
Multi-Layer Insulation with aluminized 25 µm Kapton cover sheet, large areas without seams	0.36	e* = 0.002	1
Silicon solar cells (with cover glass)	0.75	0.83	0.
Gallium-Arsenide solar cells (with cover glass)	0.75	0.83	0.

1: Common materials a/e ratios compared to different solar cell technologies

3.1.1.1.3 Existing Triple junction cell

Clyde space propose triple junctions cells with minimum 28.3 % of efficiency. One solar cell contains a temperature sensor, reverse bias protection diodes and a harness connector.

The table below compares efficiencies, maximum power and temperature between solar cells from Clyde Space, GomeSpace, and Isis.

A fourth comparison is made on cells masses, because weight is one of the most important preoccupancies when dealing with CubeSats.

(a) Comparison of different type of 1U solar panels

	Clyde Space	Gomspace (P110/110U)	Isis
Solar cells efficiency	28,3%	30%	28 %
Vmpp	4,7 V	4,64 – 4,84 V	3V (5V and 8V on demand)
Optimal current		490 mA – 508 mA	
Maximum power	2,08 W	2,27 – 2,4 W	2,3 W
Operational temperature		40°C to +85 °C	-40 to +125°C
Masses	42 g	26 g - 29 g 57-65g with magnetorquer	50 g
Cost	From 2500$	From 2000€	

(b) Comparison of different type of triple-junction solar cells

Model	Type	Weight/cell (g)	Efficiency	Cost	Magnetorquer
NeXt Triple Junction Prime(XTJ)	Ge	0.84	BOL: 30.7% EOL: 26.7%		W/O
NeXt Triple Junction (XTJ)	Ge	0.84	BOL: 29.5% EOL: ~25.5%		W/O
Ultra Triple Junction (UTJ)	Ge	0.84	<32cm²: 27.7% >50cm²: 28.3%	<32cm²: 4786,25$ >50cm²: 4684,76$	W/O
Improved Triple Junction(ITJ)	Ge	0.84	BOL: 26.8% EOL: 22.5%		W/O
Triple Junction	Ge	0.84	BOL: 25.10%		W/O
Dual Junction	Ge	0.84	BOL: 21.50%		W/O
Single Junction	Ge	0.8 or 1	BOL: 19%		W/O

Conditions of measures: AM0 (135.3mW/cm²), 28°C

3.1.1.1.4 Innovation in CubeSat solar panel

Four-junction solar cells are now about to reach 50% efficiency, but current research laboratory cells are at 43% under concentrated solar conditions. Specification sheets are not available, which makes the power-to-weight ratio unknown when adding a fourth layer to the cell. Ideally this ratio should be equivalent to triple junction cells ratio.

3.1.1.2 Performance characteristics

3.1.1.2.1 Diode current

The cells usually include protective diodes to stop reverse current flow when the cells are in partial shadow in space. There are different diodes used in solar cell

- **By-pass diode** : its role is to protect against hot spot damage when the solar panel is partially shadowed.
- **Blocking diode** : it is used when two or more solar panels are connected. Blocking diode's role is to prevent one solar panel to act as a load for the other. Blocking diode are placed in string with solar panels.

The power loss in the blocking diode is significant. That is why we usually use Shottkey diode. The Shottkey diode have a 0.3 Voltage drops.

In the CubeSat domain, one key design issue identified through power system analysis is the significant solar panel losses caused by the 0.3V drop of the Schottkey blocking diode and the voltage drop of current sense resistors. It means that a great attention has to be made on minimizing these losses.

The Schottkey diode is a metal junction, semi-conductor which has a threshold voltage smaller than the PN diode (0.25 V against 0.65 V) with a low-time response.

3.1.1.2.2 Voltage

Batteries fix the operating voltage of the cell, depending on their state of charges.

3.1.1.2.3 Temperature

The thermal regulation has to insure a distribution of temperature so that the CubeSat does not overheat. The functioning temperature of the electronics is generally between 10 and 50 °C, and the temperature of storage between +25 and 60 °C.

According to the conception of the ESEO satellite, the extreme temperatures applied to the CubeSat will be in the range of [-90°C; 120°C].

3.1.1.3 Connection of cells

Solar cells on one wall are wired serially for several practical reasons. The higher output voltage of serial wiring offers higher efficiency of subsequent switched regulators and also the output voltage is better suited to the final voltage of Li-Ion or Li-Pol accumulators which help to enable a safe mode of direct accumulator charging in case of nonstandard situations on nanosatellite power buss after system failure.

On the other hand, such serially connected solar cells are the source of unreliability in the case of cells damage during carrier launch or during the operational temperature cycling with thermal stress (low temperatures in Earth shadow as well as high temperatures in sunlight are expected). Solar cells can also be damaged or broken by micrometeor impacts. The total loss of electric energy from one CubeSat wall is a serious complication for the nanosatellite operation planning.

The parallel connection consists in connecting the poles + together and the poles – together. The voltage remains the same and amperage increases. The parallel connection suffers from a low voltage.

For the connection in series, the voltage is increasing and the amperage remains the same. The series connection suffers from the 'weakest link'. The current is at least as low as the lower current in the sub cell.

It is also possible to organize a connection in series and in parallel and it seems to be the optimum.

A team from Aalborg University (AAU CUBESAT project) used two cells on a side connected in series with a string-diode and five strings connected in parallel.

3.1.1.4 Power Budget

The power budget is the available power to the spacecraft while it is launched in orbit. It can be from internal sources of the CubeSat, or from the outside, and somehow converted to a usable form for the Electrical Power System (EPS). This chapter explores the different possibilities in use for spacecrafts.

A power budget in a communications satellite is the allocation of available power among various functions, such as maintaining satellite orientation, maintaining orbital control and performing signal reception and transmission.

Orbit Average Power (OAP) is one of the most important figures derived from the spacecraft systems design. It defines how much power is available per orbit and it determines how much power can be used. A power budget is basically an OAP minus Average Power Used (APU).

- A negative power budget is where more power is used than available per orbit.
- A positive power budget means there is more power left over.

How can we calculate the OAP ?

Let's consider a simple box satellite with 4 solar panels (X/Y facets) in LEO. When applying the rule of thumb, we get :

OAP = 60% * Power

from one panel. Four 8W panels means an OAP of 4.8W. Orbit models can be used to give more accurate results. Excel is adequate for this, but tools are available such as STK to calculate the OAP more precisely. The power budget must take into account the power usage throughout the orbit, power system efficiencies, design margins, degradation/losses and the solar array configuration.

Power budget will be used when all the different modules power consumptions of the CubeSat will be known.

3.1.1.4.1 Radiation spectrum

Radiation from the Sun, which is more popularly known as sunlight, is a mixture of electromagnetic waves ranging from infrared (IR) to ultraviolet rays (UV). It includes visible light, which is between IR and UV in the electromagnetic spectrum. The Sun does not only produce IR, visible light, and UV. Fusion in the core actually gives off high energy gamma rays. However, as the gamma ray photons make their arduous journey from the core to the surface of the Sun, they are continuously absorbed by the solar plasma and re-emitted to lower frequencies. By the time they get to the surface, their frequencies are mostly within the IR/visible light/UV spectrum. During solar flares, the Sun also emits X-rays.

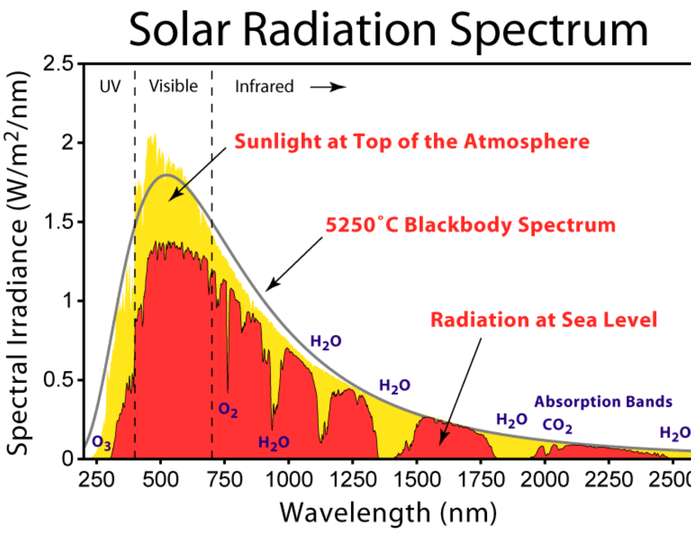


Figure 2: Measure of the solar spectral irradiance and comparison with the blackbody spectrum

3.1.1.4.2 Input power

The input power depends on the orientation of the CubeSat, the orbit, and the number of panels.

3.1.1.4.3 Output power

One CubeSat wall has a area for solar cells which no more than 90 cm2. Such a limited area does not provide a high amount of electrical energy for a CubeSat power supply. When efficient Gallium Arsenide (GaAs) based multi-junction solar cells are used, the amount of generated energy increases up to 3 W. With a limited financial budget, only standardized cell string sizes are used for assembly instead of customized sizes. For 1U CubeSats, a single 100mm x 83mm panel can accommodate two High-Efficiency Large-Area solar cells. This gives a power which is greater than 2W and a terminal voltage between 4V and 6V.

3.1.1.4.4 Power storage

There are five main modules which manage power storage:

- Power collection (solar panels) : main input ;
- Power conversion (EPS): input/output (I/O) ;
- The regulator MMPT : I/O ;
- Energy storage (batteries) I/O ;
- Power distribution (unregulated & regulated buses): main output.

3.1.2 Magnetorquer

Magnetorquer is a satellite system for attitude control built using the electromagnetic coils. There are usually integrated into the solar panels. The magnetorquer creates a magnetic field that interacts with the Earth's magnetism. So that the counter-forces produced by it provide useful torque.

Internal structure

They are essentially composed by array of electromagnetic magnets, or coils combined to create a rotating asymmetric magnetic field. Alimented with electric power.

Usually, three coils are used to provide a complete control of the altitude. But in certain configurations only two or one coil can be sufficient. However that reduces the degree of freedom.

Generally, CubeSat uses permanent magnets rather than coils, to be free of electric power for the altitude control, and to allow a passive and continue control sufficiently precise.

3.1.2.1 Advantages

Magnetorquers are lightweights, reliable and efficient. Moreover, coils induce few electric losses, what's increase their efficiency.

3.1.2.2 Disadvantages

Magnetorquers create a strong magnetic field inside the satellite. This can blur measuring instruments and induce errors of interpretations during the read of the mission's results.

Furthermore, this technology only works for satellites in low earth orbit, and does not works for geostationary satellites. Any spinning satellite made with a conductive material will lose rotational momentum in Earth's magnetic field. This is due to generation of eddy currents in its body and the corresponding braking force proportional to its spin rate. Therefore, the magnetorquer will have to be continuously operated at power level big enough to counter the resistive forces. Moreover with the aerodynamic friction losses which can increase these forces.

3.2 Energy Storage – BAT

3.2.1 Power source

3.2.1.1 Nuclear-Thermal Electrical Conversion

The CubeSat contains radioactive elements which slowly decay, causing a constant release of heat. Using a thermo-generator, the heat is transformed in electricity to power in the system. This is called the Seebeck effect. However, this method has an efficiency of 5% and is mainly used for very long space missions.

3.2.1.2 Chemical-Electrical Conversion

The satellite is launched with a primary battery which is at full capacity. It will slowly be drained through time. The power density is incredibly low because it cannot be recharged, leading to an big increase in satellite weight. This can be used for short missions where the power is needed for a short period of time, or when external elements cannot provide energy.

3.2.1.3 Light-electrical conversion

The sun's radiance is the power source in this case. It can be converted to electricity thanks to PV cells. They are reliable and they can have an efficiency of around 30% depending on the available technology. The available energy can be calculated according to the spacecraft's position to the Earth and Sun, which makes it predictable.

As the energy will be captured from the Sun's radiation, the power budget will be a function of the CubeSat's attitude and position from the earth. Solar power will not always be available as there can be other ADCS needs (rotation of the CubeSat for antenna communication for example), and the CubeSat can be in eclipse behind the Earth. Therefore, a power storage system is needed.

A power storage system has many benefits. In terms of availability, it can provide electricity for modules when there is no income from the Sun. However, it is not a binary system : it will not either be charging or discharging. As the functioning modules will not always consume all the available energy, it needs to be stored or dissipated.

There are two different types of energy that can be stored : chemical energy and mechanical energy. The following section describes both. Note that these have to be adapted to the energy generation method (solar panels, nuclear-thermal reaction) which may modify the process.

3.2.2 Flywheel (mechanical energy)

In a fly wheel based energy storage system, energy captured by PV cells is stored as rotational kinetic energy thanks to an electrical machine. Inversely, the energy is released as electrical energy.

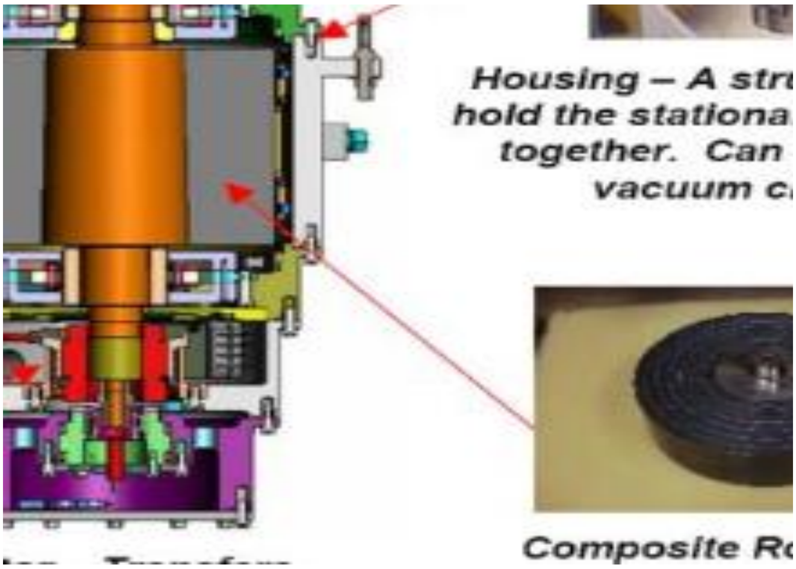


Figure 3: Description of the flywheel components

The basic principle is that a cylinder or dish stores energy by revolving at a high speed.

Charge time	3600 s
Discharge time	1800 s
Minimum speed	20000 rpm
Maximum speed	60000 rpm
Energy efficiency	97%
Mass	1.2 kg
Volume	832 cm^3

Here, the mass and volume are for a LEO satellite, not a CubeSat.

The data indicates that this method of energy storage is highly efficient, on top of having unlimited charge/discharge cycles, high thermal independence and high energy density.

However, when discharging, the revolutions affect the inertia of the satellite, resulting in a change of its attitude.

3.2.3 Battery (chemical energy)

The most common method of energy storage is through the use of secondary batteries, also known as rechargeable batteries. The 4 used types are Nickel-Cadmium, Nickel-Metal Hybrid, Lithium-Ion and Lithium Polymer.

3.2.3.1 Comparison between types of batteries

Type	NiCd	NiMH	Li-Ion
Nominal Voltage [V]	1.2	1.2	3.7
Density of energy [W.h/kg]	39	57	83
Max discharging current [C]	20	4	2
Self-discharge [% per day]	1	1.5	0.5
Charging time [minutes]	15	30	60
Thermal charging range [°C]	0 to +50	0 to +45	5 to +45
Thermal discharging range [°C]	-20 to +50	-20 to +50	0 to +40
Max number of cycles	1000	500	400

Batteries are generally the preferred method of energy storage for CubeSats. There are several factors to be taken into consideration when choosing the dimensions, shown in the table above.

- The nominal voltage has to be line with the buses voltage required by the modules supplied by the battery.
- The energy density determines the size of the battery compared to the needed energy
- The maximum discharging current limits the maximum number of modules running at the same time. This also limits the maximum consumption of any single module.
- The self-discharge will affect the battery capacity, so it must be taken into account when deciding the total capacity.
- The charging time of the battery minus the oversize part cannot be longer than the sunshine time, or else it will be a lack f electricity during the eclipse.
- The thermal charging and discharging range are linked to the space conditions, and must be coordinated with the thermal regulation modules to provide optimal or minimal operating conditions
- The max number of cycles depends on the length of the space mission. As the capacity of the battery diminishes over time, one can choose to over-size the battery or to choose a type which has a higher number of maximum cycles.
  Many kinds of 1U batteries already exist. The power stored in each of these batteries is about 10 to 30Wh.

3.2.3.2 Comparison between Lithium polymer batteries and Lithium ion batteries

	Lithium polymer	Lithium ion
Strengths	Can have different tiny forms	Can have different tiny forms
	Low weight	Low weight
	Safest batteries	Highest power saving
Weaknesses	Less energy saving than Li-ion batteries	Shortest life cycle than Lithium Polymer batteries
	More expensive than Li-ion	Can cause bypass
	Regulated charge	

3.2.3.1 Comparison between commercialized batteries

Name	Chemistry	Capacity (mAh)	Energy (Wh)	Nominal voltage (V)	Mass (g)	Price (€)
Saft	Li-Ion	5400	20.88	3.6	150	
A	Li-Poly	1400	5.18	3.7	23.6	27
B	Li-Poly	1100	4.07	3.7	23.5	32
Clyde space 10 Wh CubeSat battery	Li-Poly	1250	10	7.6	62	

A and B are commercial battery, not designed specifically for space

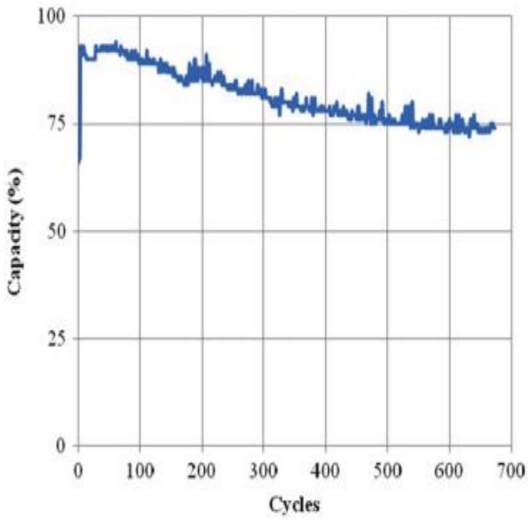
3.2.3.1.1 Battery EOL

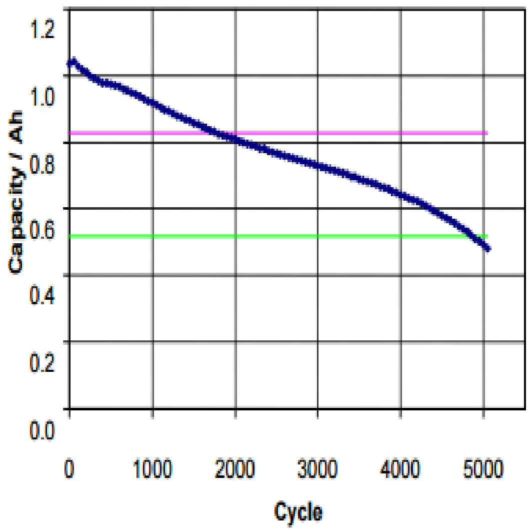
The battery EOL is defined as the point at which the battery does not respect a specified threshold anymore.

Battery loses capacity over time because of several factors such as operating temperature, charge and discharge rate and the DOD (Depth-Of-Discharge). The number of cycles of a battery defines how many times a battery can fully charge and discharge before to be under a certain rate of its original capacity. It is determined by the constructor since he has to choose at which level of the original capacity the battery is at the End Of life. For example, some constructors consider that if the current capacity of the battery reach 80% of the original capacity then it is the end of life point of the battery. Others consider that the end of life is only when the capacity is at 60% at least.

So, cycles of a battery are important for the sizing (taking into account the number of eclipse/sunlight phases corresponding to a charge/discharge phase). However, the battery requirements shall consider the decrease of the capacity with the mission timeline.

The figures below show how the capacity decreases when the number of cycles increase.





A typical DOD for a satellite in LEO is between 20-30%. That means that if the battery charge is under 20-30% of the global capacity, it will be irreversible damage.

For our mission the CubeSat have to stay less than one month in space (mission estimated to 2-3 weeks). Since the duration of the mission and the exact orbit are not set for now, we have to take margin on the battery's number of cycles. Let us compute the number of cycle needed with a mission of 30 days and an altitude of 573km (orbital period of 136 min or 1.56 h). Number of cycle requirement is determine by the following calculation :

NCycle = mission lifetime (h) / orbite duration (h)

NCycle = 30 * 24 / 1.56 = 461 cycles

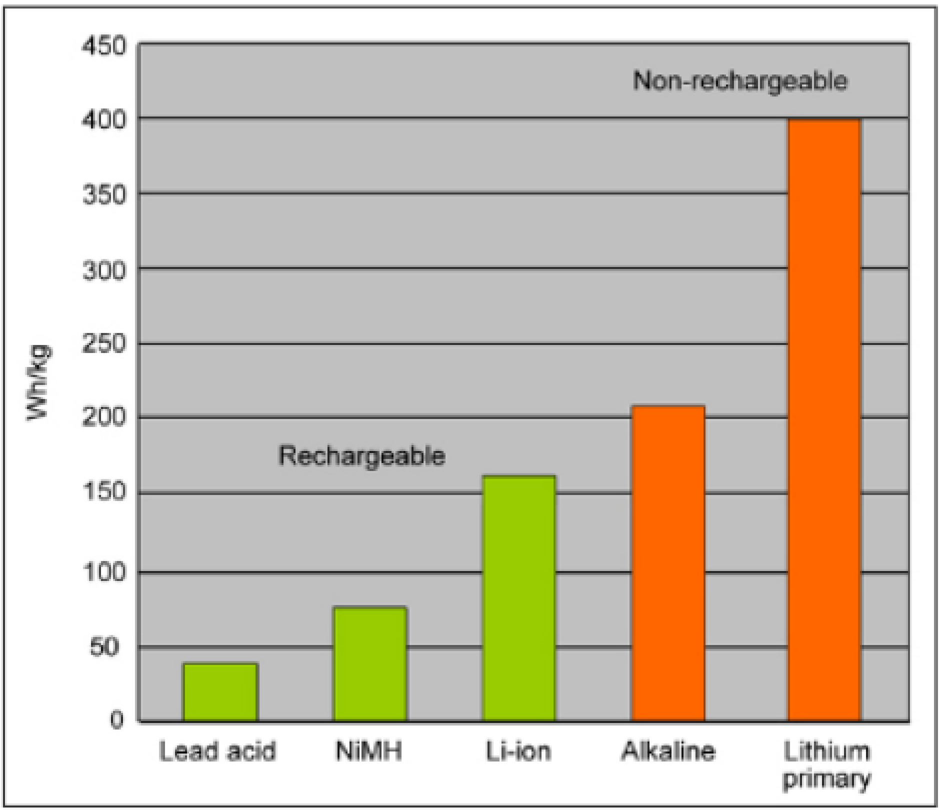
3.2.4 Primary Battery

To store the energy for the ECE³SAT's mission, the primary batteries or non-rechargeable batteries have to be considered.
The average power budget is about 2.25Wh when calculating the average power consumption from other 1U CubeSats (see the battery feasibility study for more details).
The mission duration is at least of seven days (two days of stabilization, and then some days for the de orbiting phase). Therefore, the total amount of power consumption during the entire mission is at least of

$Mission\ duration\ (in\ hours) * energy\ consumption$
$= 7(days) * 24(hours\ of\ one\ day) * 2.25\ (average\ power\ consumption) = 378\text{Wh}$

However, this energy estimation does not consider the peak power consumption like the de-tumbling phase of magnetorquers (which add around 700mWh during the first days), or the tether's spreading (which consume 4Wh).

<u>See below the energy density of mainly used primary batteries</u>



2 Specific energy comparison of secondary and primary batteries

Courtesy of Cadex - http://batteryuniversity.com.

The energy density measures the amount of energy that a battery can store. We can see on the diagram above that the better non-rechargeable battery can store 400Wh/kg. Since the EPS usually weight between 20-30% of the total weight of the CubeSat (so 266-399g), the battery weight cannot exceed an average of 300g. Indeed, the EPS modules have a battery but also buses, switch and microcontroller even if a solution without solar panels is considered.
That means that the maximum energy of a classic non-rechargeable battery designed for the ECE³SAT is about 120Wh.
This result shows that, without considering any margin or peak of consumption, the weight constraint by itself prevent the utilization of a non-rechargeable battery.

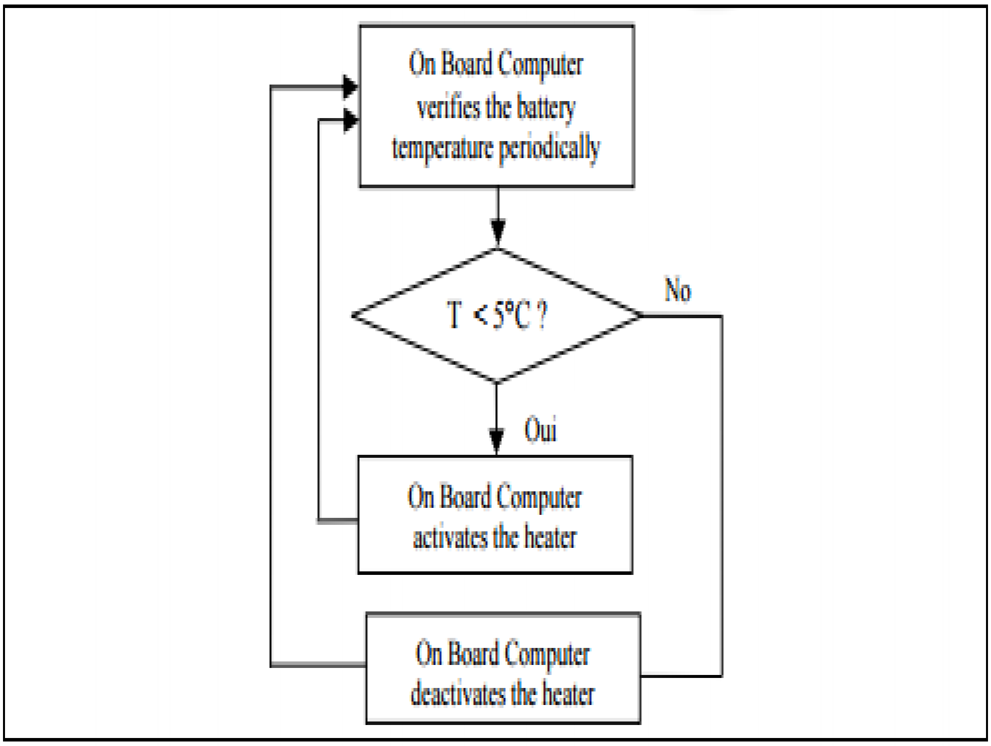
3.2.5 Battery Heater

During the mission, the temperature in the CubeSat has to keep its industrial standard. In fact, all electronic devices are designed to work in specific temperature range.

There are two different type of methods of thermal control:

- Passive methods (used for the protection of the entire satellite)
- Active methods (used to protect specific components such as the battery)

We are going to focus on the thermal control of the batteries.



3.2.5.1 Active methods

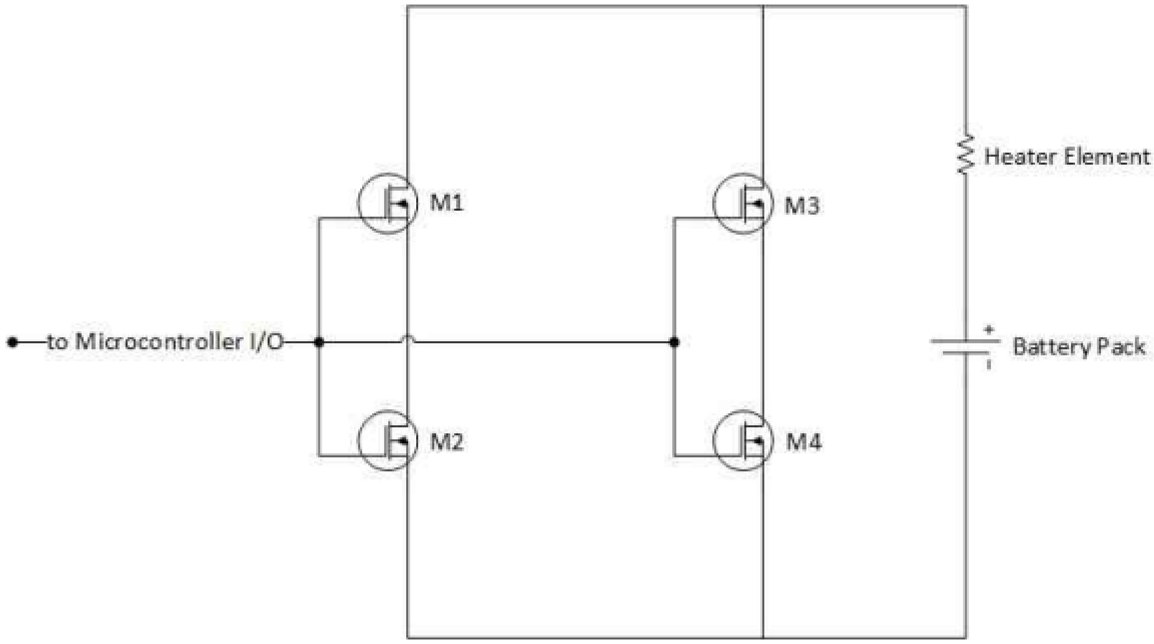
3.2.5.1.1 Heaters

When the battery temperature is below 0°C, its capacity is reduced. To avoid low temperature, particularly during an eclipse, it is necessary to use heaters for the batteries.

Heaters and a temperature sensor are attached to the battery box. Thanks to a timer we can read periodically the batteries temperature. The heater will be activated each time the batteries temperature drops below 5°C.

Flow chart of the battery temperature control

Heaters can be autonomous or controlled by the electrical power system microcontroller. The circuit bellow has two redundant power paths. The both paths have two N-Channels MOSFETs in series to increase reliability.



Example of redundant battery heater circuitry controlled by EPS-microcontroller

3.2.6 Battery Charge Regulator – DC-DC voltage converter

A battery charge regulator (BCR) or controller is an automatic system linked between solar arrays and battery. Each component is usually designed to operate only for some supply voltage which is assumed to be constant. However, the voltage output of the photovoltaic panels depends of the sunlight exposition and intensity. Therefore, it change with time and is not always adapted to the battery requirements.

The role of a BCR is to adapt the dropout voltage of the solar cells to the battery input requirements. The BCR is a DC-DC voltage converter which adapts the way of charging the battery (number of series, pulse width, etc depending of the BCR type) to its state of charge. The goal is to improve the lifetime of the battery as longer as possible. The BCR has several protections integrated into it such as prevent over-loading, short circuits or over discharge. When the battery is at the EOC, the BCR will stop to charge the battery to focus all the power from PV on the load. At the opposite way, if a battery is over discharged, the BCR shall charge the battery as much as possible even if the load has to be stopped. The battery has the charge priority from the BCR.

3.2.6.1 Linear Regulator

Linear regulators can only regulate the voltage by step it down. It is a very simple design and so a cheap component.

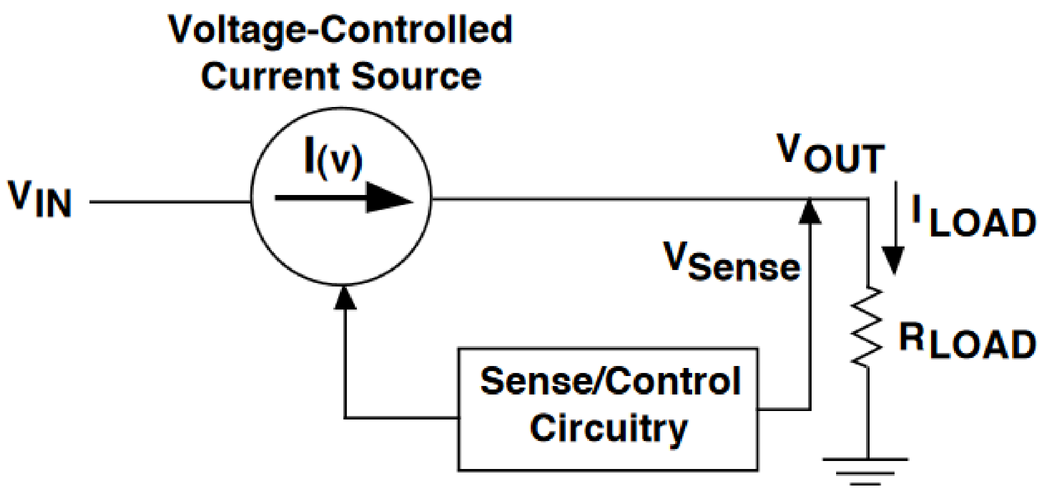


FIGURE 1. LINEAR REGULATOR FUNCTIONAL DIAGRAM

Linear and Switching Voltage Regulator Fundamental, Texas Instrument

Using sensors, the dropout voltage is controlled and the current source is adapted to keep the voltage to the required value. It is not a real-time adaptation since there is a lapse following each change in current demand before adapting the output voltage. The lapse is the transient response and depends of the regulator.

The control acts through a feedback loop. Therefore a compensation through external components or built-in components shall be applied to assure the stability of the loop. For some linear regulators, there is no need to add external components because a compensation already exists inside the linear regulator.

Thermal control, current limit and voltage control have priority in this order in the build-in circuitry inside every linear regulator. In fact, that means that if the regulation of the output voltage cause the increase of the current above the limit, the circuitry which limits current will force load current to this limit. So limit current circuitry will override voltage output regulator orders and will avoid the overload. In the same way a thermal shutdown will be caused by a temperature too high (around 160 °C) regardless the reason of this overheating.

It exists two mains type of linear regulators named standard and low dropout or LDO regulator. The main differences between them are the dropout voltage (minimum voltage drop required to maintain the regulation: the smaller it is, the least internal power is dissipated) and the ground pin current (current supplied by source but not useable to power the load: it is a “wasted” current).

	Standard	**LDO**
Dropout voltage	high	low
Ground Pin Current	low	high

LDO are best suited for battery-powered applications. Therefore, they are preferred in CubeSat when the global design uses a linear regulator.

A LDO can be shutdown which could be useful to avoid overvoltage. It also contains an “error flag” to inform control circuitry that the dropout voltage is too low (5% under its nominal value).

However, the impossibility for the linear regulator to step-up the voltage leads to the stop of circuit operating when the dropout voltage is too low.

3.2.6.2 Switching Regulator: Buck-Boost Regulator

Some switching regulators can both step-up and step-down the input voltage. This is the Buck-Boost regulator. The output voltage is opposite in polarity to the DC input voltage.

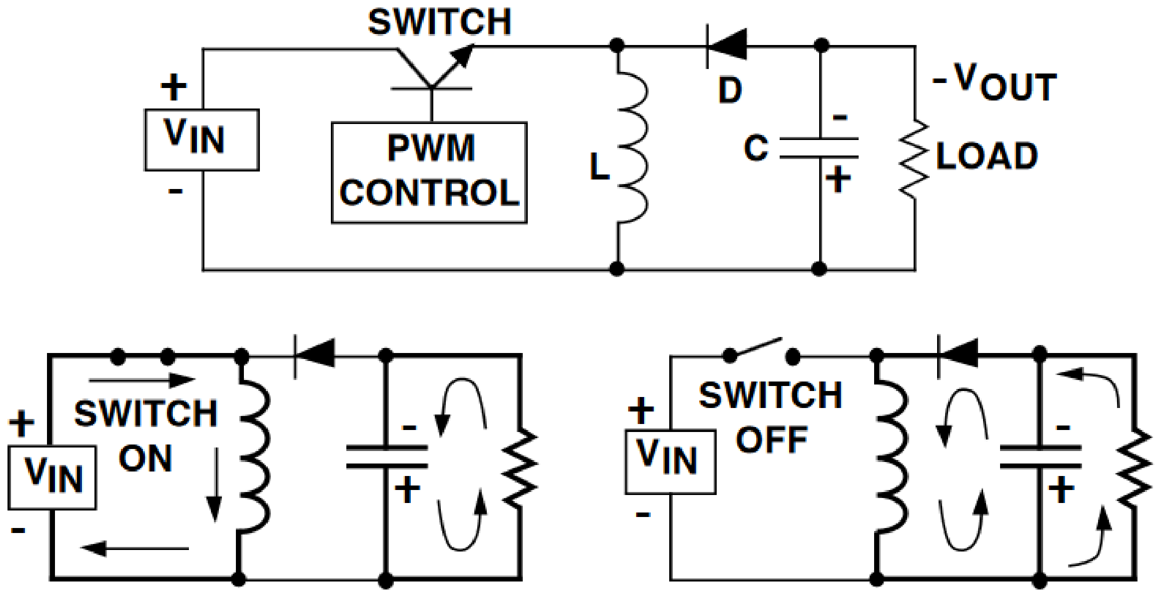


Figure 2 : Buck-Boost (Inverting) Regulator -Linear and Switching Voltage Regulator Fundamental, Texas Instrument

When the switch turns on, the voltage pass through the inductor. Therefore the current accumulates into it. The capacitor supply the load using its own charge.

When the switch turns off the voltage cannot pass into the circuit. The load and the output capacitor use the current of the inductor to charge and to work.

The switching regulators are more flexible than the linear regulators. The peak of efficiency of the buck-boost regulators is higher than 92%.

3.3 Electrical Power System

This part is one of the main part of the CubeSat.

It manages the power system (the way the energy is consumed). It also stores the energy using capacitors or batteries. In this case the energy will be provided by solar panels.

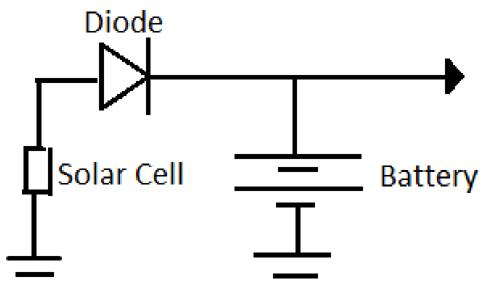
3.3.1 Goal

This system will have to determine the total amount of energy required by the entire system and the energy currently stored to ensure that the CubeSat will be able to reach its goal. The system will also communicate with the on board computer to warn if the power consumption is too high or if the energy is coming low. It also has to manage the charge and the protection of the batteries to ensure the longest life cycle possible.

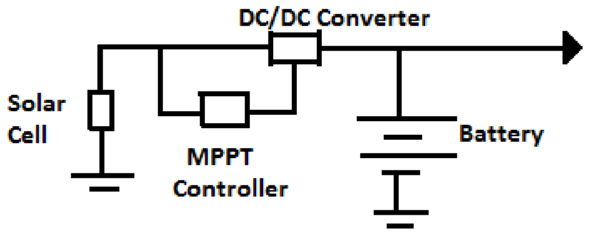
3.3.2 Power Management

For the power management, the most used technology for CubeSat are the Direct Energy Transfer (DET) and the Most Power Point Tracking (MPPT). With the DET architecture, the solar array and the battery are directly connected (with the same bus) through a diode protection. It requires the battery and the solar array to be voltage matched. When the condition is respected, it's the most efficient architecture because there is no other devices which can dissipate power. With the MPPT architecture, we place a DC-DC converter between the solar array and the battery and it maintains the solar array at its Most Power Point (MPP). It's a more complicated architecture but it's the more realizable because usually the battery and the solar panel are mismatched and this constraint prevents us from using the DET architecture (with the MPPT, they don't need to be matched because of the DC-DC converter which provides a voltage regulation). In addition, current limitation circuit will be added to ensure the protection of the entire system in case of bypass or over power cases.

DET Architecture :



MPPT Architecture:



	DET	MPPT
Battery and solars array must be voltage matched	YES	NO
Use the maximum energy of the solar array	NO	YES

3.3.3 Protection

The EPS needs to implements current limitation circuits to protect the other modules of the CubeSat in case of malfunction.

3.3.4 Architecture

There is two main architectures for CubeSats which are centralized and distributed. Each one has several advantages and disadvantages. According to a survey on 25 CubeSats led by university or affiliated university whose purpose was to determine what type of architecture was implemented, 80% of the CubeSats used centralized architecture while 20% used distributed architecture.

3.3.5 Centralized architecture

Centralized architecture is the most common architecture used in CubeSats, mainly because this is very space efficient with little waste, and do adapt well to changes in requirements from mission to mission. The principle is to distribute all or most of the voltage rails used by the CubeSat from one central location. In addition to the battery bus, the CubeSat will distribute 5V bus, 3.3V bus and sometimes another regulated bus.

The primary advantage of a centralized architecture is that fewer regulators are required since one regulator can provide the same regulated voltage to multiple subsystems or components. The regulators must be sized to the loads and other potential loads that they will be connected to it.

The regulator should be sized considering it should work at the worst case expected load. When the worst case load is not connected the regulator is not optimized, that means the regulator is operating down on its curve efficiency.

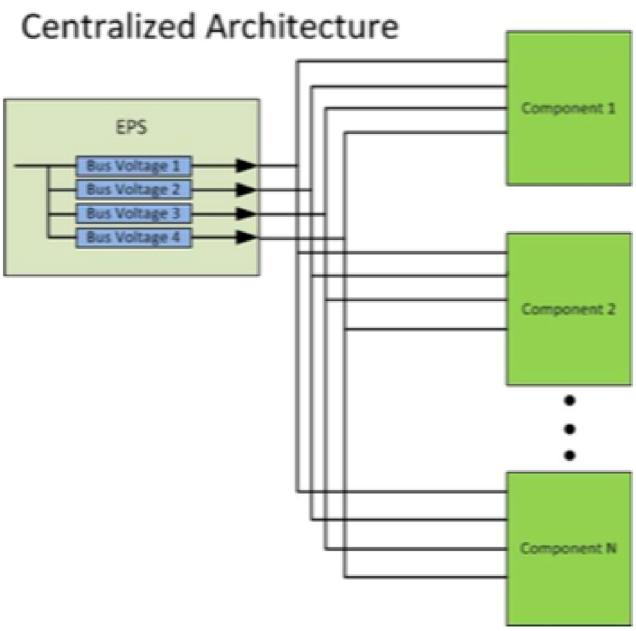


Figure 1: Electrical Power System Centralized Architecture

3.3.6 Distributed architecture

In this architecture, each subsystem has its own dedicated bus. One component can be switched on and off without affecting the others. Most information about distributed architecture can be found on publications on Cubeflow (variant of CubeSats). Cubeflow are specialized CubeSats designed to meet the standards size requirements. This architecture is based on an Air Force Research Laboratory (AFRL) Plug-n-Play (PnP) concept. Each load in a PnP system has its own dedicated switched power input of 28 volts. For the distributed architecture to effectively work, point of load conversion must be the standard.

The concept is to demonstrate the interest in creating a CubeSat class EPS system that can distribute the unregulated battery voltage to the different spacecraft loads. Each spacecraft subsystem or card is responsible for regulating its own lower level bus voltages. Because of this, it is critical to understand the various point of load converters available on the market and which ones will provide the greatest efficiency, smallest footprints, and best opportunity to optimize.

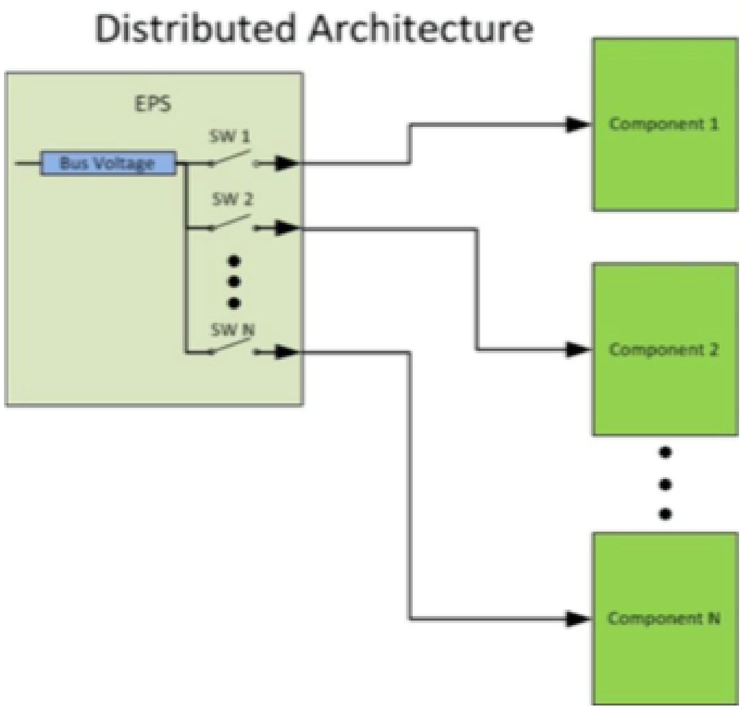


Figure 2: Electrical Power System Distributed Architecture

<u>Features of one typical example of CubeSat using distributed architecture :</u>

_Lithium-ion battery for power storage and operation during the eclipse

_Use of Sepic (buck-boost) converter for regulating battery output.

_A battery charge regulator is used to charge the battery and source power to the main bus regulator during sun lit portions of the orbit.

_Power delivered to the loads must pass through two regulators and is subject to the associated losses.

Placing the bus regulators on each loads, rather than on the EPS board (regulated bus on board), improves the ability to optimize for efficiency.

Advantages of single voltage, sun regulated, distributed battery bus:

_Unregulated battery bus is higher voltage than the regulated one. It implies less Joule Effects ($I^2R\ losses$)

_Placing the regulator at the point of load allows the designer to optimize for the single load. Variation of load is smaller than at the system level

_Point of load regulators are typically smaller and require smaller inductors and/or capacitors as compared to a multi-load single bus regulator. In the case of charge pumps, no inductor is required at all.

_It is possible to isolate specific loads by using point of load converters. Isolated converters topologies can be used if required. Even without full isolation, each load is less subject to interference from other loads.

_Simple and consistent ON/OFF control can be implemented. Since only one voltage is distributed, the switch design for each bus is the same.

_The utility of this distributed architecture would be significantly increased if a common battery voltage standard could be established.

The main disadvantage of this design is that it requires more regulators. Four loads will require four separated regulators located at each load rather than a single regulator located at the EPS. However this disadvantage can be balanced thanks to the vast assortment of low power regulators currently available.

3.4 EPS Boards

3.4.1 Clyde Space

Clyde Space is a company specialized in the support of space missions. Especially, this company provide modules for CubeSat such as the EPS modules for 1U satellites.

3.4.1.1 Design

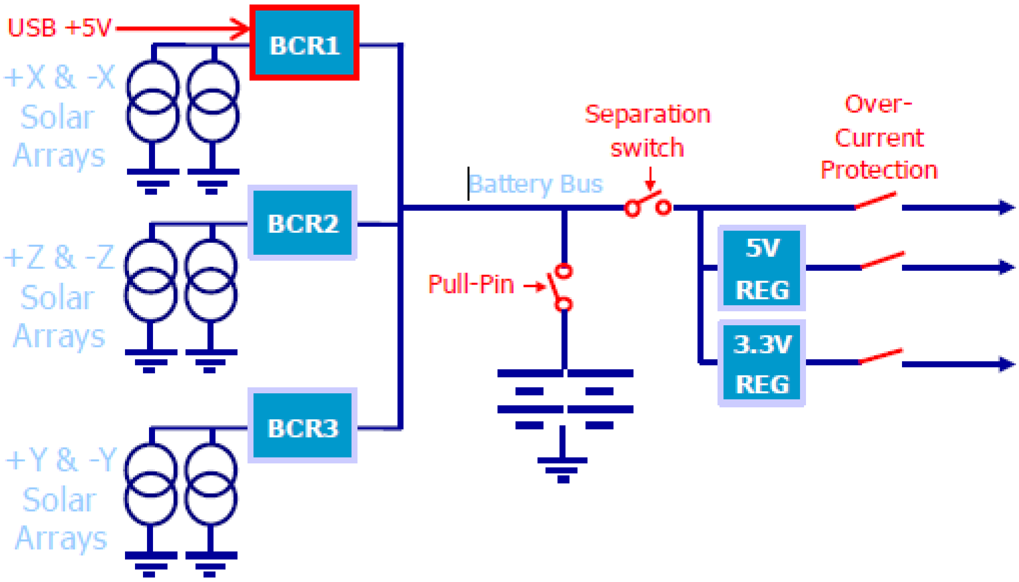


Figure 3 : 1U Power System Block Diagram - EPS, Battery And Solar Panels For Cubesats, Clyde Space

The CubeSat designed here has six sides covered by solar arrays (SAs). The SA generates energy using sunlight. That energy pass across BCR before to go into the battery. Then, energy is sent to modules which need it. There is three BCR for these six SA. Each BCR is linked to a side of the cube and the opposite side of the cube (that is impossible for these sides to be under sunlight in the same time) to minimize the number of components and the consumption. The BCR regulates the voltage through a DC-DC converter to fit with the battery requirements. The EPS has an over-current protection to protect modules integrated into the board. The switch prevent this type of damage by switching off during few milliseconds. There is also two different voltage regulations which are 3.3V and 5V.

The distribution modules weighs around 80g and each battery unit weighs 62g. So, the EPS weighs between 142g and 204g without the solar panels.

3.4.1.2 Solar Panels

The solar panels are available with two different types of three-junction solar cells.

The first ones are the large areas cells in CIC (Coverglass Interconnected Cells). These solar cells are already interconnected and have coverglass to protect the connections (cells in CIC). The coverglass is applied on the front of the cells to capture high energy electrons which could damage cells and reduce their efficiency. The interconnections bringing power from cells outside them are interlocked into both sides of the cells. Solar cells are protected against partial shadow by a bypass diode which inverse polarisation of these cells.

The second ones are TASC (Triangular Advanced Solar Cells). That is rectangular special cells divided into two triangle sub-cells. Each solar cell matched to charge a 1.2V battery cell. Solar cells can be wired in parallel (to increase current) or in series (charge one 3.6V Li-ion battery cell). TASC do not have coverglass. Therefore they need a protection for their silver circuitry (through an adhesive coverglass). This type of solar cells is not suitable for short mission (those whose lifetime is less than one year).

Below are the estimation of the flight panels performance gave by Clyde Space depending of the type of solar cells.

Panel Type	1U Side/ Top 3U Top	1U Side/ Top 3U Top
Type	ATJ	TASC
Junctions	Triple	Triple
String Length	2	2
No. of Strings	1	13
BOL Voc at Min Temp	5.95V	5.88V
BOL Vmpp at Min Temp	5.41V	5.35V
BOL Vmpp at Max Temp	3.98V	3.92V
BOL Vmpp at 28C	4.60V	4.27V
BOL Power at Min Temp	2.29W	2.41W
BOL Power at Max Temp	1.83W	1.92W
BOL Power at 28C	2.04W	2.15W

Figure 4: Estimated Panel Performance - EPS, Battery And Solar Panels For Cubesats, Clyde Space

3.4.1.3 BCR

The voltage output regulator is a special switching regulator: the SEPIC (single-ended primary inductor converter). Unlike a classic switching converter, SEPIC's input and ouput voltage have the same polarity which enable to reduce the complexity of the design. It is also less expensive to create and smaller than the classic switching regulators. Moreover, the ouput of the SEPIC regulator is at 0V when the switch is turned off. It is autonomous and does not need battery power to work.

However, the SEPIC is less efficient than the step-up/step-down regulators with a peak of efficiency higher than 90% for SEPIC against 92% for classic switching regulators.

Each of the three BCR rated at 3W and can drop voltage from 20V in input to 10V in output at most.

3.4.1.4 Battery

The battery used in the CubeSat is Lithium Polymer battery with a capacity of 1.25Ah delivered at 8.2V. The battery board has an integrated heater which works depending on a thermostatic command. The board has also an over current protection and a battery and cell voltage telemetry.

3.4.1.5 Prices

The commercial price of the electrical power system board is 2900$, the price of one battery is around 910$ and the price of six solar panels with two EMCORE large area cells is around 20,500$.

SO, 3810$ for the board including the battery, and 20,500$ for six panels (we need only five for the CubeSat).

3.4.2 Crystalspace P1U "Vasik" Power Supply

Crystalspace P1U power is one of the most advanced and smallest power supply in the market. It uses fast MPPT (Maximum Power Point Tracking) boost converters to charge integrated doubled battery pack. Battery output is fed through duplicated converters that can provide 3.3 V, 5 V, 12 V. Unregulated 3.7 V battery and regulated buses are available through individually selectable current limited and latch-up protected switches. The power consumption of the board is 15mW.

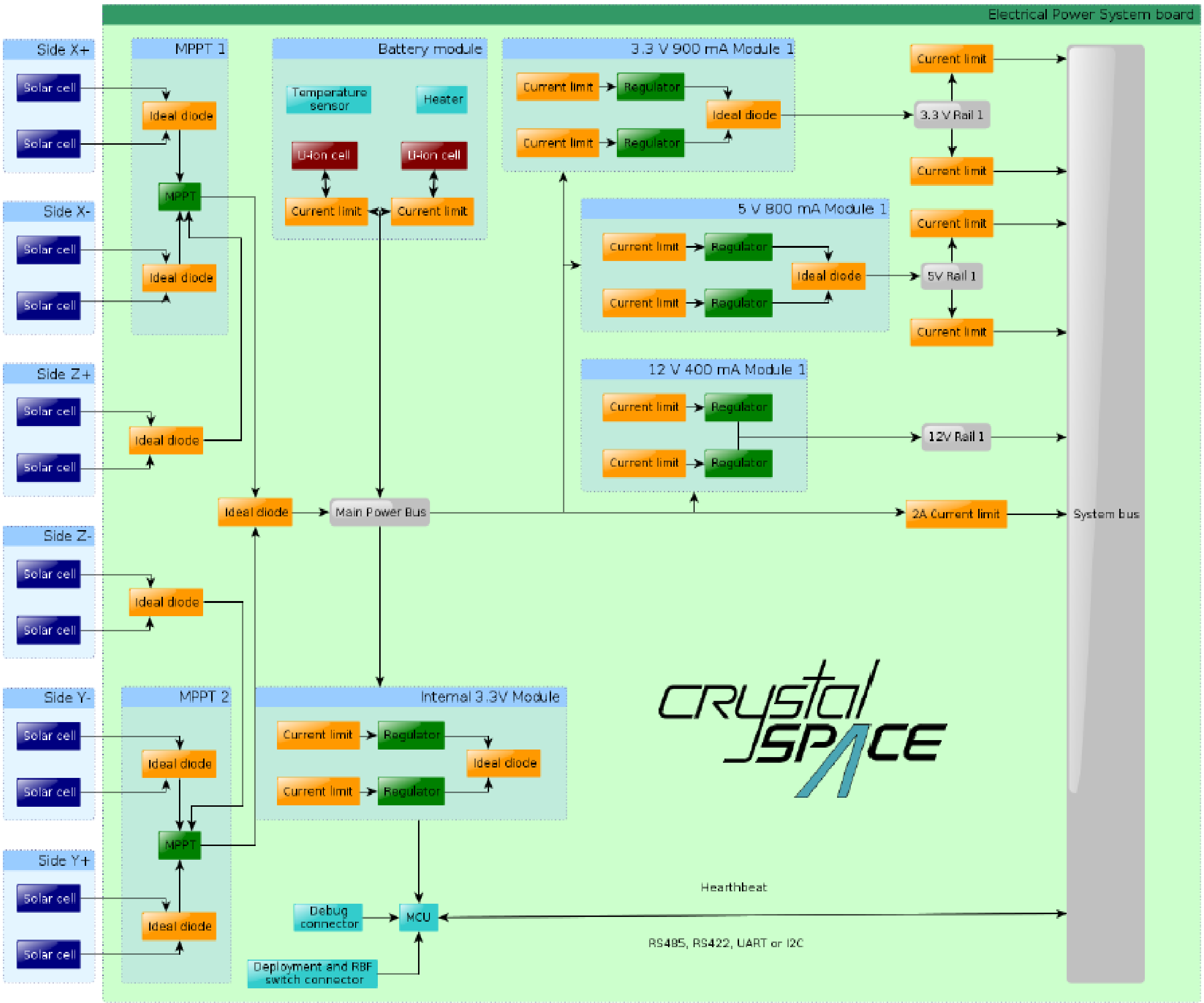


Figure 1: Internal block diagram

3.4.2.1 System overview

MPPT is a technique used to maximize power extraction. P1U power is an efficient MPPT power supply. In fact, Solar panel input is directly converted to battery voltage level by MPPT converter and gets highest efficiency even in low light

.

Parameter	MIN	TYP	MAX	Unit
System power consumption			20	mW
System energy efficiency from input to output		80%		

Tabel 1: Internal characteristics

3.4.2.2 Battery parameters

The two lithium ion battery cells are used in parallel. They are protected by microcontroller and separate monitoring circuits.

Symbol	Parameter	MIN	TYP	MAX	Unit
V_{batt}	Battery voltage	3.3	3.7	4.2	V
Q_{batt}	Cell capacity		1500		mAh
I_{batt}	Single battery current limit (both directions)		4		A
t_{batt}	Safe battery operating temperature	0		+45	°C

Table 2: Battery parameters

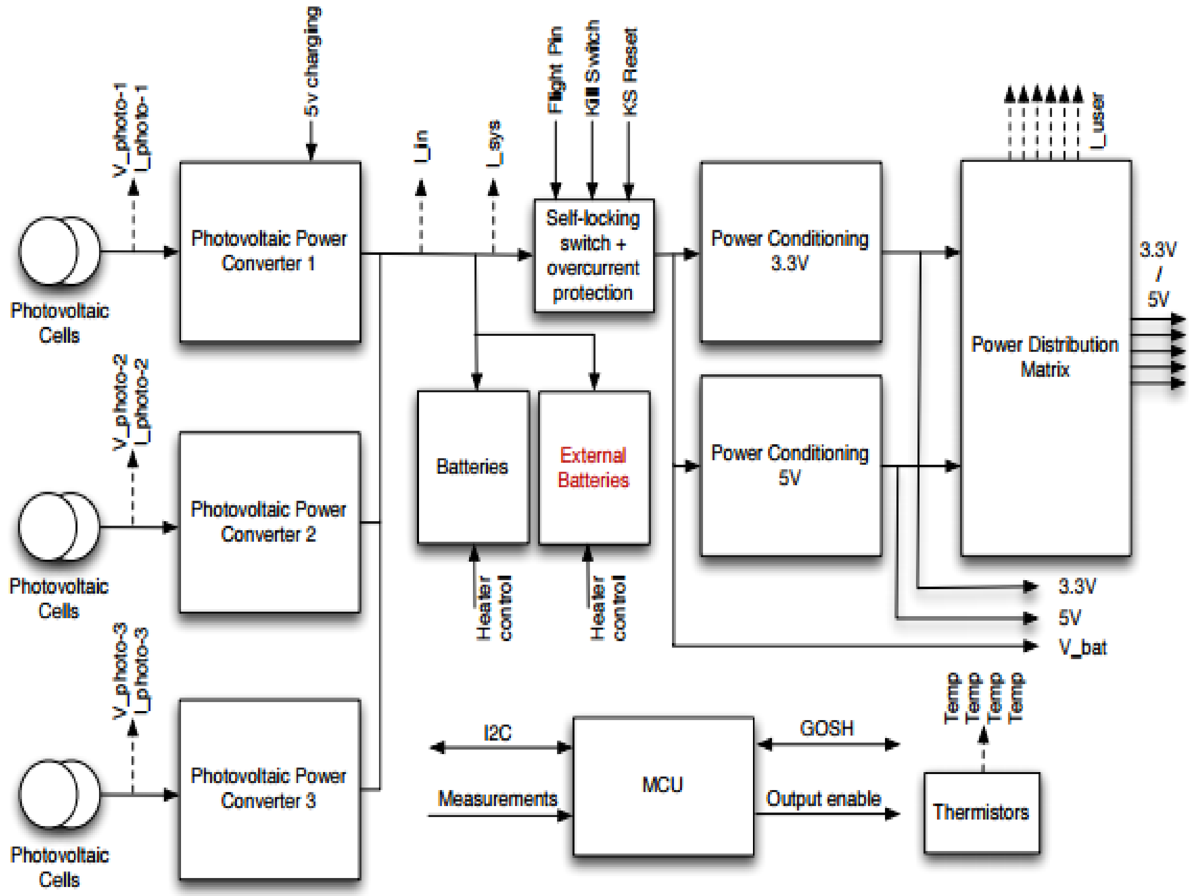
So the heater has to raise the temperature of the battery to 0 Celsius degree at least. The automatic controlled heater is included on the board.

3.4.2.3 Prices

The price of the 1U EPS board with the battery and with pinouts output voltage selection customizable depending of our need is available for 2 900€.

3.4.3 NanoPower P31U by Gomspace

3.4.3.1 Design



The solar arrays output voltage is regulated by a BCR. There is three BCR for six solar arrays (one for two opposite sides). Then, as in every CubeSat, the battery is charged by the electric current applied on it. An external battery is available to have a higher capacity but the consequence is a heavier module. The modules are protected against over-current. Three buses with different voltage are present on the system (3.3V, 5V and the output voltage of the battery). The heater and the MPPT are controlled thanks to a microcontroller. The power of the battery is distributed to six different modules.

3.4.3.2 Battery

The battery as every batteries available from GomSpace is a lithium ion battery.
Here are the characteristics of the battery provided:

2600mAh

Parameter	Condition	Min	Typ	Max	Unit
Lithium-Ion Cell					
- Voltage		3.0	3.7	4.2	V
- Charge current			1000	2500	mA
- Discharge current			1000	3750	mA
- Charge temperature		-5		45	ºC
- Discharge temperature		-20		60	ºC
- Storage temperature	80% recovery after 1 year	-20		20	ºC
- Internal impedance				70	mOhm
- Cycle life (20% capacity loss)	DOD: 100%, Temp 25degC Charge/discharge: 1C/1C		350		cycles

The DOD or Depth-of-Discharge represents the level of discharge of the battery at every cycle. The less the battery is discharge during a cycle (sunlight + eclipse, around 1h30 for the EOL), the more the better the cycle life.

3.4.3.3 BCR

The battery charge regulator uses between the PV and the battery is a boost-converter. It is designed to convert a voltage up around 4.2V from the solar cells up to 8.4V to fit the battery requirements. The efficiency of the converter depend of the current apply on and is between 88% and 95%.

The weight of the battery is around 200g for the NanoPower P31u with a battery of 2600mAh.