# PV Feasibility Study

## 1. Output Power Of Solar Panels

The objective of this study is to determine the amount of power generated by the photovoltaic panels. The production of PV will be presented both at the beginning of life and the end of life of the solar cells to determine the feasibility of the system.

### 1.1 Power generated by one side

#### 1.1.1 Example with Ultra Triple Junction (UTJ) Solar Cells –Spectrolab

The characteristics chose correspond to one type of the solar cells described in the State Of the Art (Spectrolab UTJ solar cells).

- BOL: 28.3% efficiency
- EOL: 25% efficiency

#### 1.1.1 Calculation of input power

$$\boxed{P_{in1} = P^*_{in1} - P_{diode1}}$$

With:

$$\boxed{P^*_{in1} = P_{sun} \cdot n \cdot A \cdot \eta}$$

**Psun:** Power input from Sun at LEO (at AM0) = **0,1353 W/cm²**
**n:** number of cells on one side = **2**
**A:** area of one standardised cell **= 30.18cm²**
**η:** efficiency = **0.283**

$$\boxed{P_{diode} = \langle I_{diode} \rangle \cdot \langle V_{diode} \rangle \quad , \quad P_{diode} = \frac{P^*_{in1}}{n_s \cdot V_{mpp}} \cdot V_{diode}}$$

**ns:** number of serial solar cells in one string = **2**
**Vmmp:** maximum power point voltage = **2.35V**
**Vdiode:** voltage drop on a diode = **0.3V**

##### *1.1.1.1 Beginning Of Life (BOL)*

Calculation of the numerical values:

$P^*_{in1}$ =0.1353*2*30.18*0.283=2.311 W

$P_{diode}$ =2.311*0.3/(2*2.35)=0.1475 W

So we can infer the input power:

$$\boxed{P_{in1} = 2.311 - 0.1475 = 2.1635 \text{ W}}$$

One solar panel provides 2.1635 W at its beginning of life. This result assume that only one side of the CubeSat is under the sunlight.

#### 1.1.1.2 End of Life (EOL)

Every solar cells have an efficiency decrease due to photon and electron flux and due to temperature. For the LEO, it is generally assumed that the EOL efficiency is the efficiency under an electron flux of 1E15 at 1 MeV [e/cm²]. Generally, the solar cells designed for 1U CubeSat are between 25% and 27%. For the calculations we will take an efficiency of 25%.
The numerical values:

$$P_{in1}^{*} = 0.1353*2*30.18*0.25 = 2.0417 \text{ W}$$

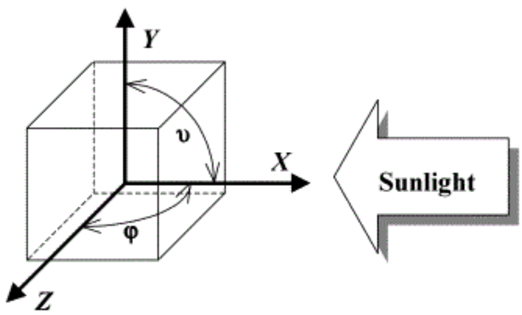
$$P_{diode} = 2.0417*0.3/(2*2.35) = 0.1303 \text{ W}$$

So we can infer the input power:

$$\boxed{P_{in1} = 2.0417 - 0.1303 = 1.9114 \text{ W}}$$

## 1.2 Power generated by the entire CubeSat

The results calculated before are the power generated by only one face of the CubeSat. However the CubeSat has 5 sides with solar panels and between one and three sides can be under Sunlight at the same time. The number of sides which receives solar power is related to the orientation of the CubeSat. To estimate the power generated by the entire CubeSat, the calculations have to take in account the inclination of the satellite, in other words, the angles (here in spherical coordinates).
With angles defined by this configuration:




Then, the formula of the power generated by the PV module is the sum of sunlight received on each of the three sides times the power generated by one face of the CubeSat.

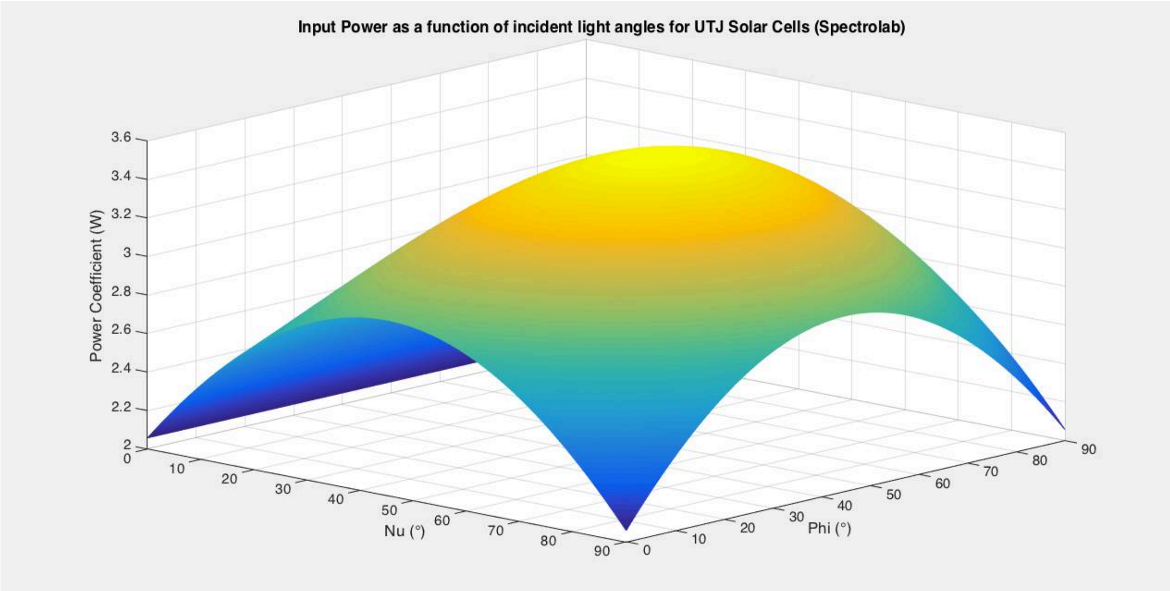
$$\boxed{P = (A_x + B_y + C_z) \cdot P_{in1} = (\cos(\varphi) \cdot \sin(\upsilon) + \sin(\varphi) \cdot \sin(\upsilon) + \cos(\upsilon)) \cdot P_{in1}}$$

Therefore, with the input power of the solar cell, we can simulate this model for different angles:

- φ [0;90]
- v [0;90]

Matlab simulations for two different technology of solar cells have been realized to enable to visualize clearly the result of our calculations.

### 1.2.1 UTJ Solar Cell – Spectrolab at EOL




The maximum value obtained from Matlab is:

$$\boxed{P_{max} = 3.2909 \text{ W}}$$

The simulation shows several things:

-For any φ value, if ν is equals to 0, the power supply is constant. That is explained by the fact that, when ν=0°, there is only one to two sides under sunlight. Because of the symmetry of the sides, the part of solar cells under light gained by one side because of the angle is equals to the part of solar cells under light lost by the other face (surface area "gained" under shadow).

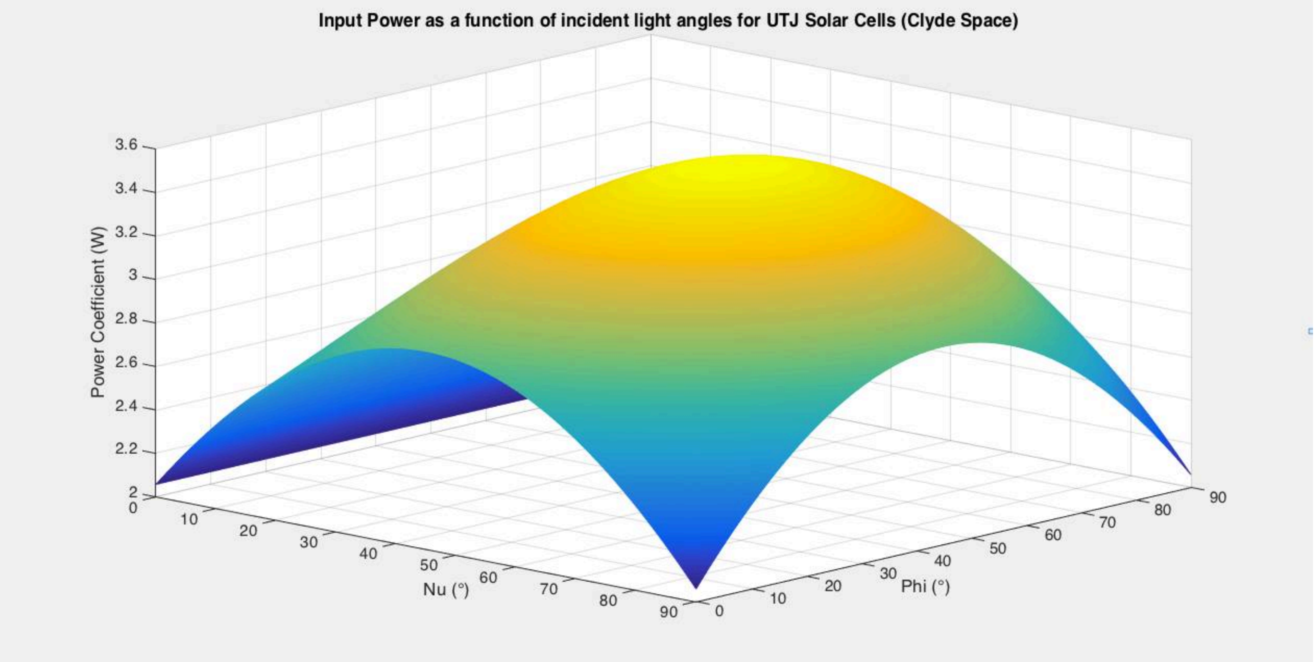
-The minimum power is generated when only one face (or the equivalence regarding the surface area) is under sunlight.

-The maximal value is obtained for three sides under sunlight with φ = 45° and ν =55° according to the Matlab simulation.

### 1.2.2 Isis TJ 3G30A model at EOL

**Model:**
Ultra Triple Junction (UTJ)
Efficiency **EOL**: **26.6%**

| | |
|---|---|
| **P*in1**=2.172 W | **Vdiode**=0.235 V |
| **Pdiode**=0.114 W | **Vmp**=2.244 V |
| **Pin1**= 2.058 W | |




The maximum value obtained from Matlab is:

$$\boxed{P_{max} = 3.5654 \text{ W}}$$

The maximum power produced by the solar panel designed for 1U CubeSat is pretty close to the value of the maximum power produced by the solar cell. That prove that solar cells designed are pretty close to those used in the solar array for CubeSat.

## 1.3 Total amount of energy generated by PV during the orbit period at LEO

During the eclipse phase, the solar panels do not produce energy due to the absence of Sun. To study the feasibility of the system regarding the production, the entire production per orbit period has to be computed.

The CubeSat is placed on an LEO (Low Earth Orbit) at 573 km. The revolution's duration is about 1,53h with 0.5h of eclipse and 1,03 hours of sun light.

### 1.3.1 Model UTJ Spectrolab (BOL)

- **Case 1: with the better input power**

$P_{in1} = P_{max}$ = 3.9785 W

P= Pmax*67.32% = $\boxed{2.678 \text{ W}}$

= $\boxed{2.7586 \text{ Wh}}$

- **Case 2: with the worse input power**

$P_{in1}$ = Pmin = 2.151 W

Coherent calculation with the model of AzurSpace sold by Isis, which informs a power delivered around 2W at the BOL.

P= Pmin*67.32% = $\boxed{1.448 \text{ W}}$

= $\boxed{1.491 \text{ Wh}}$

### 1.3.2 Model UTJ Spectrolab (EOL)

- **Case 1: with the best input power**

$P_{in1} = P_{max}$ = 3.2909 W

The sun light's time correspond to 67.3% of the revolution's duration.
Thus, the real power delivered by solar cells during a revolution period is:

P= Pmax*67.32% $\boxed{\begin{array}{l} = 2.215 \text{ W} \\ = 2.281 \text{ Wh} \end{array}}$

- **Case2: with the worse input power**

$P_{in1}$= Pmin = 1.9114 W

P= Pmin*67.32% $\boxed{\begin{array}{l} = 1.287 \text{ W} \\ = 1.3256 \text{ Wh} \end{array}}$

### 1.3.3 TASC cells on a panel

*Let us consider a solar panel with 20 TASC cells on it. Every data come from the thesis NPS-SCAT (Solar Cell, Array Tester), The Construction of NPS' first prototype CubeSat,* **Alexander L. Bein**, 2008, Naval Postgraduate School or a deduced from it.

Measures have been took for one cell and for 20 cells. One cell produces 0.75 mW (31 mA at 2.5 V) under sunlight at AM1 (one atmosphere). Therefore, four cells connected in series produce 0.31 W (31mA at 10V). Since the PV can be damaged under a too high voltage (usually 10V), solar cells are separated in string. Each string is composed of four solar cells, and are wired in parallel with the other string. The tests measured a total power of 1.55W for the solar panel of 20 TASC (five strings of four cells).

These measurement was unexpected. Indeed, according to the datasheet constructor, the estimation of production is as follow:

**Psun1:** Power input from Sun at LEO (at AM1) = **0,1000 W/cm²**
**n:** number of cells on one side = **20**
**A:** area of one standardised cell **= 2.277 cm²**
**η:** efficiency = **0.27**

P*in1 = Psun1*n*A* **η** =1.230 W

Pdiode (1 string) =$\frac{1.230}{4*2.19} * 0.3$=0.042 W

Pdiode (5 strings) =0.21 W

Pin1=1.02 W

And at AM0:
P*in1=1.663W
Pdiode (1 string)=$\frac{1.663}{4*2.19}*0.3$= 0.057 W
Pdiode (5 strings)=0.285 W
Pin1=1.378 W
P=67.32%*Pin1=0.928 W
P=0.928*1.03 Wh = 0.955 Wh

### 1.4 Comparison of existing solar cells

| | Model | XTJ Premium | XTJ | Improved TJ | TJ | Dual Junction | TJ 3G30A |
|---|---|---|---|---|---|---|---|
| | Company | Spectrolab | Spectrolab | Spectrolab | Spectrolab | Spectrolab | Isis |
| | Vdiode(V) | 0,3 | 0,3 | 0,3 | 0,3 | 0,3 | 0,3 |
| BOL | Efficiency | 30,70% | 29,50% | 26,80% | 26% | 21,50% | 29,60% |
| BOL | Vmmp(V) | 2,39 | 2,348 | 2,27 | 2,275 | 2,085 | 2,085 |
| BOL | P*in1 | 2,4922 | 2,3948 | 2,1756 | 2,11068 | 1,74537 | 2,409 |
| BOL | Pdiode | 0,1564 | 0,1530 | 0,1438 | 0,1392 | 0,1256 | 0,1733 |
| BOL | Pin1 | 2,3358 | 2,2418 | 2,0319 | 1,9715 | 1,6198 | 2,2357 |
| BOL | P (W) | 1,5725 | 1,5092 | 1,3679 | 1,3272 | 1,0904 | 1,5051 |
| BOL | P(Wh) | 1,6196 | 1,5545 | 1,4089 | 1,3670 | 1,1232 | 1,5502 |
| EOL | Efficiency | 26,70% | 25,50% | 22,50% | 21% | 17,50% | 26,60% |
| EOL | Vmmp(V) | 2,127 | 2,089 | 1,997 | 2,093 | 1,897 | 2,244 |
| EOL | P*in1 | 2,1675 | 2,0701 | 1,8266 | 1,7048 | 1,4207 | 2,1594 |
| EOL | Pdiode | 0,1529 | 0,1486 | 0,1372 | 0,1222 | 0,1123 | 0,1443 |
| EOL | Pin1 | 2,0146 | 1,9214 | 1,6894 | 1,5826 | 1,3083 | 2,0150 |
| EOL | P(W) | 1,3563 | 1,2935 | 1,1373 | 1,0654 | 0,8808 | 1,3565 |
| EOL | P(Wh) | 1,3970 | 1,3323 | 1,1714 | 1,0974 | 0,9072 | 1,3972 |

***Final power P is computed in the worst case (only one side under sunlight)***

## 2 Power Generation VS Power Budget

Our power generation is highly dependent of the incidence angle chose by the ADCS. A power budget from Cubeflow from the Utah State University.

| Power (mW) Component | Power Peak | Power mWatts | Duty Cycle % | Orbit Average | 10% Contingency | % Margin | Margin | Total Power |
|---|---|---|---|---|---|---|---|---|
| ADCS Card | | 160 | 100% | 160.00 | 16.00 | 10% | 17.6 | 193.60 |
| PIC CPU | | 60 | 100% | 60.00 | 6.00 | 10% | 6.6 | 72.60 |
| Comm Tx | | 9300 | 3% | 279.00 | 27.90 | 10% | 30.69 | 337.59 |
| Comm Rx | | 80 | 100% | 80.00 | 8.00 | 10% | 8.8 | 96.80 |
| Magnetometer | | 10 | 0% | 0.00 | 0.00 | 10% | 0 | 0.00 |
| GPS | | 950 | 5% | 47.50 | 4.75 | 10% | 5.225 | 57.48 |
| Torque Coils | | 750 | 0% | 0.00 | 0.00 | 10% | 0 | 0.00 |
| Sun Sensor 1 | | 25 | 100% | 25.00 | 2.50 | 10% | 2.75 | 30.25 |
| EPS | | 285 | 100% | 285.00 | 28.50 | 10% | 31.35 | 344.85 |
| Payload | | 300 | | 200 | 20 | 10% | 22 | 242 |
| Magnetometer | | 90 | 100% | 90.00 | 9.00 | 10% | 9.9 | 108.90 |
| DC-Probe | | 40 | 100% | 40.00 | 4.00 | 10% | 4.4 | 48.40 |
| E-Field | | 40 | 100% | 40.00 | 4.00 | 10% | 4.4 | 48.40 |
| Motor Control | | 100 | 0% | 0.00 | 0.00 | 10% | 0 | 0.00 |
| Payload Controller | | 30 | 100% | 30.00 | 3.00 | 10% | 3.3 | 36.30 |
| Orbit Period | | Average Power | | 1136.50 | Power w/Margin | | | 1375.17 |

*1 DICE Power Budget from Utah State University*

**Table 2.** Power budget of the ESTCube-1 flight model. The mission average power marked with an asterisk is for subsystems that are used only for specific mission phases and can be scheduled if enough power is available

| Component | Peak power, mW | Mission average power, mW |
|---|---|---|
| Attitude determination sensors | 300 | * |
| Attitude control coils | 840 | * |
| Tether end mass imaging subsystem | 300 | * |
| Command and data handling subsystem | 300 | 220 |
| Communication subsystem | 2000 | 550 |
| Electrical power subsystem | 150 | 150 |
| Payload | 4200 | * |
| Antenna deployment subsystem | 4200 | * |

*2 Power Budget of the ESTCube-1 flight model*

The second estimated power budget is around 2,36W in average without considering Antenna deployment (EDT) power peak and payload power peak. The first one does not have the magnetorquer value in its computations, then it is about 2,22W needed.

In the worst case, the solar arrays does not produce enough to fit the power budget requirement. It is the reason why the ADCS angle control is really important to supply enough power to the modules. However, a lot of factors have not been take in account. Indeed, the losses due to the DC-DC converter and MPPT study (BCR), the battery losses due, for example, to the cold temperature or to the vacuum and the margin due to the estimation of the consumption and not the real power budget are not in the budget.

The only possibility to produce more is to use deployable solar arrays (4 solar arrays fully under sunlight of one of the side instead of one side fully under sunlight). But, due to the high price of these panels (around 6,000$ to add to the current price of solar panel), this option is unthinkable.

Therefore, the power budget has to **decrease**.

## 3. Resources

Thesis *NPS-SCAT (Solar Cell, Array Tester), The Construction of NPS' first prototype CubeSat,* **Alexander L. Bein**, 2008, Naval Postgraduate School

*A Study on the Usage of TASC and UTJ Solar Cells in the Design of a Magnetically Clean CubeSat,* **Christopher Shaffer**, 2013, 27th Annual AIAA/USU Conference on Small Satellites

*System Analysis, Chapter 3*, **Aalborg University, Institute of Energy Technology**

*Distributed Electrical Power System in Cubesat Applications*, **Robert Burt**, 15/11/2011, Utah State University

*ESTCube-1 nanosatellite for electric solar wind sail in-orbit technology Demonstration*, **Proceedings of the Estonian Academy of Sciences,** 2014,63, 2S, 200–209 doi: 10.3176/proc.2014.2S.01 Available online at www.eap.ee/proceedings

*www.spectrolab.com*

https://www.**clyde.space** - *EPS, Battery And Solar Panels For Cubesats,* **Craig Clark,** 28 April 2008, Document No.: CS-RP-084A
https://www.**isis**space.nl - **30% Triple Junction GaAs Solar Cell Assembly,** Type: TJ Solar Cell Assembly 3G30A, AzurSpace solar Power GMBH
**https://www.gomspace**.com