Design and Selection of the Electrical Power System for CHESS

Semester Project

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Abstract

The electrical power system of a CubeSat is an essential and critical subsystem, allowing for the generation, management and distribution of energy to all of the components withing the satellite. After a change in payload for the CHESS mission, the design and selection of the EPS needed to be reevaluated according to new requirements.

After introducing the project and requirements, the CHESS power budget is presented followed by a study of commercial off the shelf components ending in a selection of solar panels and an EPS. These products are then used to estimate solar power generation and simulate orbit cycles for the EPS. Finally the electrical architecture of the system is presented before explaining the next steps of the project and concluding.

Abbreviated Terms

ADCS . . . . . Attitude Determination and Control System
BMS . . . . . Battery Management System
BOL . . . . . Beginning Of Life
CHESS . . . . . Constellation of High Energy Swiss Satellites
ConOps . . . . . Concept of Operations
COTS . . . . . Commercial Off The Shelf
DL . . . . . Downlink
DOD . . . . . Depth of Discharge
EOL . . . . . End Of Life
EM . . . . . Engineering Model
EPS . . . . . Electrical Power System
FM . . . . . Flight Model
GNSS . . . . . Global Navigation Satellite System
GS . . . . . Ground Station
LEO . . . . . Low Earth Orbit
MPPT . . . . . Maximum Power Point Tracking
OBC . . . . . On Board Computer
PDB . . . . . Power Distribution Board
PL . . . . . Payload
RA . . . . . Radio Amateur
SOC . . . . . State Of Charge
SSO . . . . . Sun Synchronous Orbit
UHF . . . . . Ultra High Frequency
VHF . . . . . Very High Frequency

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1 Introduction

1.1 CHESS

This project is part of the CHESS mission lead by the EPFL Spacecraft Team. CHESS is a constellation of two 3U CubeSat platforms for In-Orbit-Demonstration and Validation of scientific instruments. The aim is to create a CubeSat mission developed by Swiss Universities, and validate the science behind payloads developed by Swiss industry and academia. The TOF Mass Spectrometer developed by UniBe is the primary payload and scientific instrument of the CHESS mission. Its aim is to analyse the composition of the terrestrial exosphere and how it has evolved over time.

1.2 Definition

The electrical power system, or EPS, is responsible for the power management and distribution of a more general system, in our case a CubeSat. It is a critical subsystem as it is always on and distributing energy to the other systems to ensure a successful mission. It generally follows the structure found in figure 1. Indeed, solar panels generate power that is stored in batteries, such as Lithium Ion batteries. The power is then redistributed through output regulators at specific voltages to the different loads or subsystems.

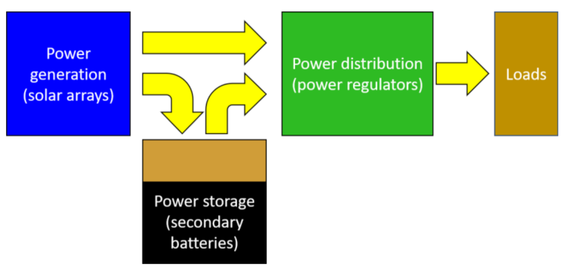


Figure 1: General structure of an EPS

1.3 Goal

The goal of this project is to redefine the requirements and select the solar panels and EPS for the CHESS mission after a change in the payload. An in depth study of COTS products was performed for a final selection of products. Simulations were run with their specifications to confirm the choice and configure the COTS products to the CHESS requirements. The electrical architecture is presented as well as a test plan for the next phase of the mission.

2 Requirements

This section will discuss a brief mission overview and the general requirements of the CHESS mission as well as the more specific requirements for the EPS and solar panels. More detailed information on the mission overview and requirements can be found in the systems engineering and mission design reports.

2.1 Mission Overview

The baseline of the CHESS mission is a constellation of two identical 3U satellites in LEO, one flying in a Sun Synchronous Orbit and a second in an elliptical orbit. Both orbits are described below in table 1. The mission time is of at least 2 years and the launch target is Q1-2023. The mission should not last more than 25 years so a burn wire mechanism shall be used for the deployment of the solar panels, this allows the radiation in LEO to burn the wire in case of a deployment command failure. The EPS and Solar Panels must provide sufficient power for any of the orbits found in table 1, therefore a trade-off between different solar panel configurations can be found in part 5.2.

Table 1: Summary of characteristics for different SSO and elliptical orbits

Orbit	Altitude [km]	Period	Type	Eclipse/ Period	Approx Orbit Cycle	Min DL Time	Max DL Time
SSO	500	5668 s or 94.5 min	6-6	0%	1 pass then 8 without passes	405 s or 6.75 min	717 s or 12 min
			9-9	33%			
			10-10	37%			
			11-11	38%			
			12-12	38%			
Elliptic	1000 apogee 400 perigee	5917 s or 98.6 min	i=90 RAAN=0 AOP=0	37%	2 passes then 7 without passes	903 s or 15 min	2708 s or 45 min

There are four payloads on the CHESS CubeSat:

- A CubeSat-type Time-of-Flight Mass Spectrometer (UniBe)
- A next generation multi-GNSS receiver (ETHZ)
- A linear transponder payload for Radio-Amateurs (HSLU)
- In orbit validation of next generation solar panels (RUAG)

The EPS will harness solar energy to supply power to these payloads, as well as to all of the other subsystems of the satellite. RUAG require one MPPT input and at lest 1U of space for their solar panels. The mission requirements, the payload requirements, the satellite structure, the solar panel configuration (part 5.2), the simulations (part 6.1) and finally the power budget (part 3.2) all lead to the top level requirements listed in table 2.

2.2 Top Level EPS Requirements

Table 2: Top level requirements for the EPS and solar panels

ID	Description	Verification
EPS-ELE-1.1	The main board shall have at least 4 MPPT converters and implement the control algorithm for the battery charging, discharging, balancing and heating	COTS EPS
EPS-ELE-1.2	From the power budget the EPS shall provide a maximal power of 50 W with a contingency of 15-20%	COTS EPS
EPS-ELE-1.3	The batteries DoD shall not exceed 45% in normal operation	SOC estimation
EPS-ELE-1.4	The power system shall be able to communicate via a standard communication protocol with the OBC	COTS EPS and testing
EPS-MEC-1.1	The solar arrays shall be placed at the exterior of the satellite on the Z and Y sides of the satellite	COTS solar panels
EPS-MEC-1.2	The deployment mechanism for the solar panels must be a burn wire	COTS solar panels
EPS-MEC-1.3	The solar panels shall have a free space of at least 1U for potential collaborations	COTS solar panels
EPS-MEC-1.4	The EPS and external battery pack shall fit in a space of 50x100x100mm3	COTS EPS
EPS-MEC-1.5	The EPS shall transfer power and data through the PC104 standard	COTS EPS
EPS-MIS-1.1	The power system shall provide enough power for every planned orbit	Testing and simulations
EPS-MIS-1.2	The power system shall evacuate the excess of energy outside of the system or be managed by MPPT inputs	COTS EPS, testing and thermal

3 Power Consumption

This section will cover each subsystem's role and power needs, give the general power budget considered for the CHESS mission and the total power consumption during each operational mode. More details on each subsystem as well as Con-Ops information can be found in the individual pole reports, the systems engineering reports and the mission design reports, or in the datasheets found in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Datasheets*.

3.1 Subsystems

3.1.1 Critical Subsystems

OBC
The OBC controls the mode of the satellite and the storage and transmission of data. It is a critical system and therefore shall always be on. It will be developed in house in collaboration with HES-SO Valais and will consume an estimate of $1.00W$ on average.

UHF/VHF Transceiver
The primary way to communicate with the satellite is through this system. It will be responsible for emitting the beacon (which contains housekeeping data and telemetry) and for receiving telecommands from the ground station. It is a critical system and therefore shall always be on. It will be developed in house by HSLU and will consume an estimate of $5.00W$ transmitting and $0.07W$ receiving/idle on average.

ADCS
The ADCS is used to determine, stabilise and change the attitude of the satellite. During normal operations modes it will be sun pointing for charging, ground station pointing for communication or nadir pointing for measurements. It is a critical system and therefore shall always be on. It will be bought from CubeSpace and consumes $1.02W$ on average.

EPS
The role of the EPS has previously been described. It is a critical system and therefore shall always be on. It will be bought from Nanoavionics as justified in part 4.1.3 and consumes $0.15W$ on average.

3.1.2 Payloads

Mass Spectrometer
The TOF Mass Spectrometer developed by UniBe is the primary payload and scientific instrument of the CHESS mission. Its aim is to analyse the composition of the terrestrial exosphere and how it has evolved over time. It consumes $0.89W$ to $7.06W$ on average depending on its state.

GNSS
The GNSS board and antennas are developped by ETHZ and will be used for position and housekeeping data for the ADCS and for analysis. It consumes $0.15W$ to $0.20W$ on average.

Radio Amateur
The linear transponder for Radio Amateurs will be developed by HSLU and will allow for communication with the satellite within the Radio Amateur community. It consumes an estimate of $3.30W$ on average.

3.1.3 Other Subsystems

X-Band Transmitter
The X-Band is the communication system which is composed of a high energy frequency band and will be used to downlink the scientific data to the ground station. It will be developed in house by HSLU and will consume an estimate of $12.00W$ transmitting and $0.5W$ idle.

Thermal
Despite the EPS already having battery heaters, the satellite should have a thermal control system to keep all of the components in the correct temperature range. More information shall come after a more in depth thermal analysis in Q2 2020 but it is estimated to consume $1.00W$ of power on average.

3.2 Power Budget

Table 3 is a summary of the power consumption of each subsystem at a component level. These are the values and margins used during the power consumption simulations for the CHESS mission (part 6). Note that some values are estimations and most peak values are estimated because a lot of the components are built in house and have not been tested yet. More information concerning the power budget can be found in the excel spreadsheet in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Power Budget*.

Table 3: Average and peak power consumption for each component for different states

Component	State	Average Power [W]	Peak Power [W]	Margin	Voltage [V]
Mass Spectrometer Payload	Neutral	6.92 ± 0.14	~ 9.00	15%	12
	Ion	5.11 ± 0.10	~ 7.00		
	Loaded	2.45 ± 0.05	~ 4		
	Standby	0.87 ± 0.02	~ 2		
X-Band Transmitter	Transmit	12.00	~ 14.00	20%	12 and 3.3
	Idle	~ 0.50	~ 1.00		
UHF/VHF Transceiver	Transmit	5.00	~ 7.00	20%	3.3
	Receive	0.07	~ 0.15		
Radio Amateur Payload	On	3.30	~ 5.00	20%	3.3
GNSS Payload	On	0.20	1.00	15%	5
ADCS	On	1.02	4.25	15%	3.3, 5 and Vbat
	Idle	0.20	~ 1.00		
OBC	On	~ 1.00	~ 2.00	20%	3.3
Thermal	On	~ 1.00	~ 2.00	20%	Vbat
EPS	On	0.15	~ 0.30	15%	-

Estimations are marked with the "$\sim$" symbol. Margins are of 15% when we are sure of the component or its power consumption is known, if not a margin of 20% is considered. Note that the average and peak values in table 3 do not consider these margins, but they will be used during power consumption calculations during each operational mode.

3.3 Operational Modes

The CHESS mission Con-Ops define that the satellite will always be in one of four operational modes (five if you include deployment). Figure 2 illustrates the transitions between different modes. After deployment and system check-outs, the satellite is in charging mode. It will then change between measurement and communication mode according to the mission needs with a charge between each change, these are the normal mission operations. Safe mode is only activated in critical situations such as a component failure or an insufficient battery voltage.

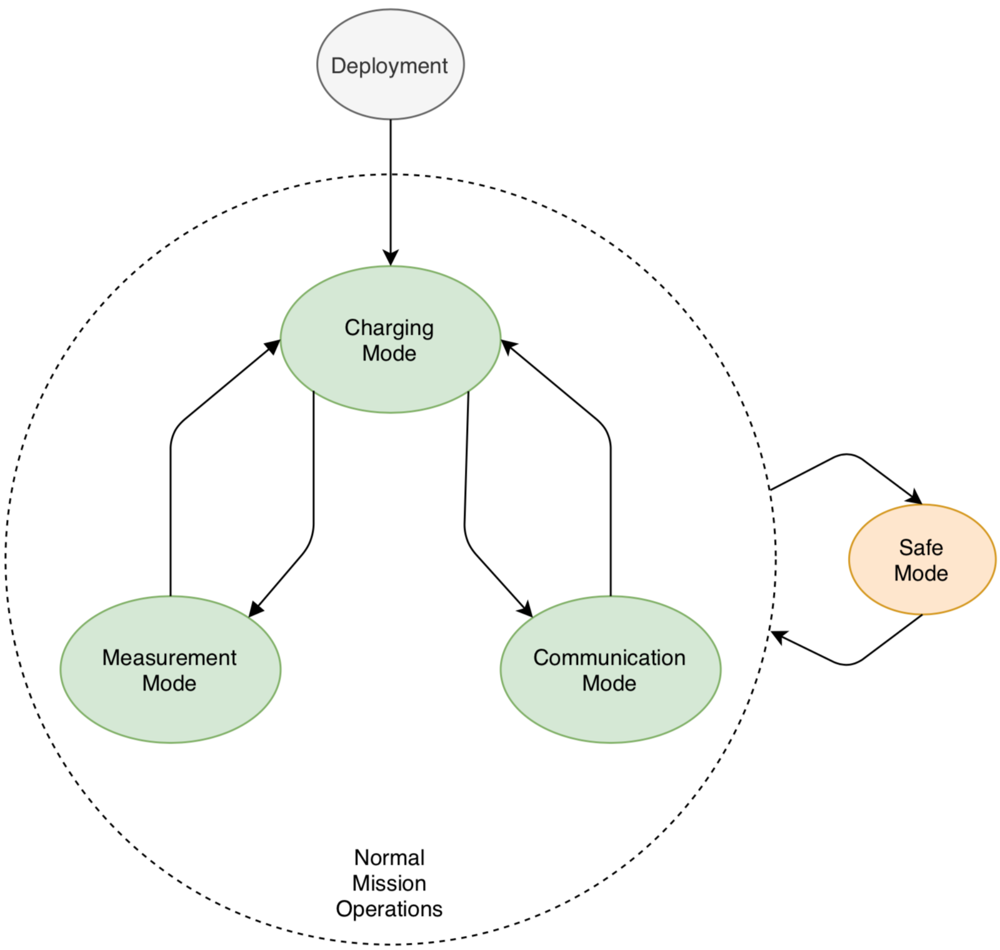


Figure 2: Operational modes for the CHESS mission

3.3.1 Safe Mode

Safe mode is only activated during a critical situation. The aim is to only give power to critical systems such as the OBC, EPS, UHF/VHF Transceiver and ADCS. We want to allow basic station keeping while communicating with the ground station to determine the problem and perform the appropriate tasks to regain normal mission operations. Table 4 shows the power that the EPS needs to provide (output power) with the margins found in table 3:

Table 4: Satellite average and peak power consumption during safe mode

Component	State	Duty Cycle	Average Power [W]	Peak Power [W]
Mass Spectrometer Payload	Off	100%	0.00	0.00
X-Band Transmitter	Off	100%	0.00	0.00
UHF/VHF Transceiver	Transmit	10%	0.60	8.40
	Receive	90%	0.08	0.18
Radio Amateur Payload	Off	100%	0.00	0.00
GNSS Payload	Off	100%	0.00	0.00
ADCS	On	50%	0.59	4.89
OBC	On	100%	1.20	2.40
Thermal	Off	100%	0.00	0.00
EPS	On	100%	0.17	0.35
Safe Mode Output Power	-	-	**2.64**	**16.21**

The duty cycle in this case is the fraction of time the component is in the mentioned state during this mode. For example the UHF/VHF transceiver can only transmit 10% of the time, if not it is in the *receive/idle* state for the other 90% of the time. The ADCS is only considered to be on 50% because it will be allowing the satellite to detumble and not point accurately, therefore using approximately half of its power.

3.3.2 Charge Mode

Between measurements and downlinks the CHESS satellites will be in charge mode, where the they will be sun pointing. In this mode the Z face will be facing the sun, harvesting the most solar energy possible to recharge the batteries. Table 5 shows the power that the EPS needs to provide (output power) with the margins found in table 3:

Table 5: Satellite average and peak power consumption during charge mode

Component	State	Duty Cycle	Average Power [W]	Peak Power [W]
Mass Spectrometer Payload	Off	100%	0.00	0.00
X-Band Transmitter	Idle	100%	0.60	1.20
UHF/VHF Transceiver	Transmit	10%	0.60	8.40
	Receive	90%	0.08	0.18
Radio Amateur Payload	On	30%	1.19	6.00
GNSS Payload	On	100%	0.24	1.15
ADCS	On	100%	1.17	4.89
OBC	On	100%	1.20	2.40
Thermal	On	20%	0.24	2.40
EPS	On	100%	0.17	0.35
Charge Mode Output Power	-	-	5.48	26.96

Critical systems are on at 100% but the scientific measurement module is turned off and the X-Band transmitter is in and idle state to save power. The RA payload can be turned on about 30% of the time in normal operations as it is a secondary payload. GNSS is on the whole time for housekeeping and measurement data. ADCS is on at 100% to keep sun pointing and the thermal system is on with a duty cycle of 20% to heat the system when necessary for better battery charging.

3.3.3 Measurement Mode

Apart from the educational goal the main goal of the CHESS mission is the validation of the scientific instrument: the Mass Spectrometer payload developed by UniBe. Measurement mode is when the instrument is measuring and gathering data to send back to the ground station for analysis. Table 6 shows the power that the EPS needs to provide (output power) with the margins found in table 3:

Table 6: Satellite average and peak power consumption during measurement mode

Component	State	Duty Cycle	Average Power [W]	Peak Power [W]
Mass Spectrometer	Neutral Ion	100% 100%	8.12 5.99	10.35 8.05
X-Band Transmitter	Idle	100%	0.60	1.20
UHF/VHF Transceiver	Transmit Receive	10% 90%	0.60 0.08	8.40 0.18
Radio Amateur Payload	On	30%	1.19	6.00
GNSS Payload	On	100%	0.24	1.20
ADCS	On	100%	1.17	4.89
OBC	On	100%	1.20	2.40
Thermal	On	20%	0.24	2.40
EPS	On	100%	0.17	0.35
Neutral Mode Output Power	-	-	**13.60**	**37.31**
Ion Mode Output Power	-	-	**11.47**	**35.01**

During normal mission operations all systems stay in the same state except the high frequency communication system (X-Band) and the primary payload (Mass Spectrometer). During measurement mode, the Mass Spectrometer can be in one of two states, *Neutral* or *Ion*, depending on what we are measuring. For future calculations we will only consider the *Neutral* state because it consumes more power.

3.3.4 Communication Mode

Communication mode is on when the satellite is passing over the ground station and the scientific data is being downlinked. All systems are in their normal operational states but the Mass Spectrometer payload is turned off and the X-Band transmitter is transmitting the data. Table 7 shows the power that the EPS needs to provide (output power) with the margins found in table 3:

Table 7: Satellite average and peak power consumption during communication mode

Component	State	Duty Cycle	Average Power [W]	Peak Power [W]
Mass Spectrometer Payload	Off	100%	0.00	0.00
X-Band Transmitter	Transmit	100%	14.40	16.80
UHF/VHF Transceiver	Transmit	10%	0.60	8.40
	Receive	90%	0.08	0.18
Radio Amateur Payload	On	30%	1.19	6.00
GNSS Payload	On	100%	0.24	1.20
ADCS	On	100%	1.17	4.89
OBC	On	100%	1.20	2.40
Thermal	On	20%	0.24	2.40
EPS	On	100%	0.16	0.35
Communication Mode Output Power	-	-	**19.28**	**42.56**

All systems stay the in the same state for normal mission operations except for the Mass Spectrometer and the X-Band Transmitter. In communication mode the payload is turned off and the high frequency transmitter is transmitting, this is the main power consumer. This mode is only active during communication windows when the satellite is passing over the GS.

3.4 Summary

Each operational mode has a total power consumption being the sum of the power consumption of each subsystem. This gives us the EPS output power. Note that the input power will have to be higher because of losses, channel efficiencies and charging efficiencies within the solar panels, EPS and batteries. Table 8 gives a recap of the EPS output power needed for each operational mode of the CHESS mission.

Table 8: Satellite average and peak power consumption during summary for each mode

Mode	Average Power [W]	Peak Power [W]
Safe	2.64	16.21
Charge	5.48	26.96
Measurement	13.60	37.31
Communication	19.28	42.56

4 COTS Solutions

In this section we will first justify the decision to buy COTS components rather than build them in house. We will then discuss and compare COTS options for the EPS and Solar Panels. An in depth study of battery technologies was conducted previously justifying a choice of Lithium-Ion batteries last semester [2]. Another project also compared solar cell technologies and decided with the use of triple junction cells [1]. Finally a first look at some COTS EPS solutions was also in last semester's report on the design of the EPS [2]. All of this information is considered in the following trade-offs and COTS components comparisons. More information on each COTS component can be found in their datasheets in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Datasheets* or in last semester's report on the design of the EPS.

4.1 EPS

4.1.1 Build or Buy

Despite previous work in the autumn semester of 2019-2020 [2], the build or buy trade-off for the EPS was reevaluated with the change in payload leading to new requirements, as well as different debates amongst the CHESS team.

The main arguments for an in house build are that we would have a requirement based architecture of the EPS, indeed we would have an optimal design for the mission requirements and all of the wanted redundancy features. Indeed the OBC pole was interested in having a double communication bus between the EPS and the OBC and most COTS solutions did not offer this solution. It would also have a great educational advantage where a student could invest his time in the design and build of the system leading to great personal experience. This would also have given a perfect knowledge of the EPS during the mission.

The main arguments against an in house build were the lack of knowledge and expertise on the matter. Building a space grade EPS would add complexity to the mission since the CHESS team has no experience or collaborators with experience with CubeSat electrical power systems. It would also have been a big setback in time. We can rely on COTS products as they are flight proven solutions with flight heritage. Finally, with a COTS product we can focus on testing and integration for a higher probability of a successful mission. Therefore a COTS EPS shall be purchased for the CHESS mission, but perhaps developed in house for a future EPFL Spacecraft Team mission.

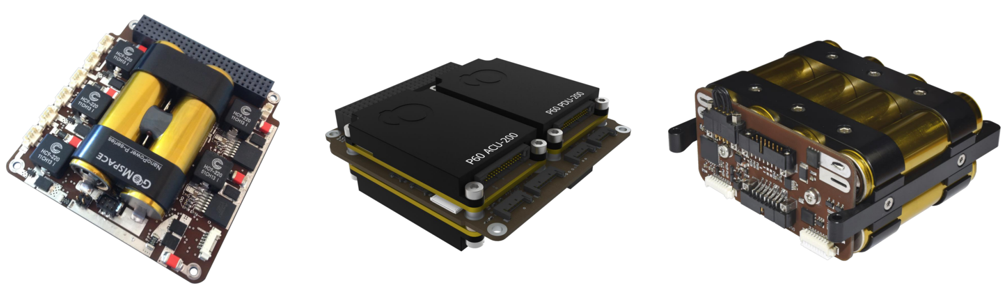
4.1.2 COTS Solutions

GomSpace

Two GomSpace products were considered for the EPS: the P31U EPS and the P60 EPS, both with an external Lithium-Ion battery pack.

The P31U is designed for 1U to 3U CubeSats with 3 MPPT inputs, 6 switchable outputs and 4 permanent outputs at $3.3V$ and $5V$ with $Vbat$. This option was not further examined because the requirements in table 2 dictate that the EPS needs 4 MPPT inputs and the power budget in part 3.2 shows that some subsystems are powered through $12V$ channels.

The P60 is a more modular EPS that requires at least one GomSpace NanoPower BPX external battery pack, up to two PDU-200 power distribution units and up to two ACU-200 array conditioning units. The ACU-200 units have up to 6 MPPT inputs and the PDU-200 units have 9 switchable output channels from $3.3V$ to $24V$ with $Vbat$. It fills all of the electrical requirements of the EPS in table 2, but it takes up 0.7U of the CubeSat which is more than the available space. Therefore this option was not further examined.



(a) GomSpace P31U EPS (b) GomSpace P60 EPS (c) GomSpace NanoPower BPX Battery Pack

Figure 3: GomSpace EPS and Battery Pack solutions

Endurosat

The Endurosat EPS II is also a modular EPS that can combine multiple Battery Packs and Electrical Power Systems to adapt to medium to large satellites. Each EPS module has 3 MPPT inputs, and each battery pack module has four, six or eight integrated Li-Po or LiFePO4 battery cells connected in series or parallel ranging from $42Wh$ for 4 cells to $84Wh$ for 8 cells. It has 15 switchable outputs from $3.3V$ to $12V$ including 5 that are fully redundant. Its output power is up to $250W$ so much higher than the CHESS EPS requirements found in table 2. However this solution was not selected because it is yet to be flight tested as of Q3 2020. It is also a large system taking up approximately 1U of space which is too large.

Figure 4: Endurosat EPS (2x) and Battery Pack (2x) solution

Nanoavionics

The Nanoavionics EPS has two on-board Lithium-Ion batteries and requires an external battery pack for the mission requirements. It has four output converters, two of which can be voltage configured (3–18V), with ten configurable output channels from 3V to 18V. The 2S3P configuration which is the appropriate size for the CHESS mission has 6 cells with an energy capacity of 69W, up to 75W output power and 30W charging power. It takes up 0.5U and has 4 MPPT inputs, therefore fulfilling all of the CHESS requirement found in table 2.

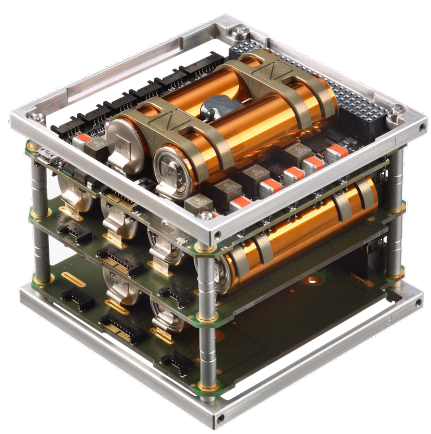


Figure 5: Nanoavionics EPS with two external battery packs for a 2S4P configuration

4.1.3 EPS Trade-off

Table 9 is a summary of the four analysed COTS EPS components. Despite the GomSpace p60 and Endurosat EPS II being good solutions, the main issue was their size. The Nanoavionics EPS checks out all of the CHESS mission requirements and will be selected as the baseline product for the simulations in part 6 and the electrical architecture in part 7. Discussions and negotiations have started with Nanoavioncs and a fully configured EPS shall be purchased for Q4 2020.

Table 9: Comparison between the four analysed COTS EPS solutions

	Nanoavionics EPS	**GomSpace p31U**	**GomSpace P60**	**Endurosat EPS II**
Flight Heritage	Yes	Yes	Yes	No
MPPT Inputs	4	3	3-6	3-6
Switchable Output channels	10 (Vbat, 3.3V, 5V and 3-18V)	6 (Vbat, 3.3V, 5V and 3-5V)	9 (Vbat, 3.3V, 5V and 3-24V)	15 (Vbat, 3.3V, 5V and 3-12V)
Battery Size	69Wh (6 cells)	58Wh (6 cells)	77Wh (8 cells)	63Wh (6 cells)
Maximum Input Power	25W per MPPT and 30W charge power	17W per MPPT and 30W charge power	50W per MPPT	144W total
Maximum Output Power	75W	-	-	250W
Size	0.5U	0.5U	0.7U	1U
SOC Estimation	No	-	-	Yes

4.2 Solar Panels

4.2.1 Build or Buy

Despite the previous study during the autumn of 2019-2020 [1], the new payload and requirements demanded that the in house against COTS trade-off was reevaluated for the solar panels.

In house production of solar cells for a 3U CubeSat would have been a significant project involving many students, and the expertise in space-grade small sized solar cells is not within the reach of the CHESS team. Many companies are pushing the boundaries in solar cells for small satellites and it would be difficult to build a robust system with better efficiencies than what is found commercially. Therefore to reduce mission complexity, to gain time and to use flight proven systems the CHESS mission will fly with COTS solar cells as the main power source of the satellite.

The deployment mechanism and solar panels has to be a burn wire mechanism. The in house construction of such a mechanism is feasible but for time gain, and mission complexity it was decided to go for a COTS solution. Many companies already have flight proven deployment mechanisms and solar panels, and discussions have started to see if custom solar cell placements are possible as well as openings in the panels for the placement of the Mass Spectrometer Payload.

4.2.2 COTS Solutions

Isis Space

Isis Space 3U deployable solar panels have 6 Azur Space TJ Triple junction cells ($181.08cm^2$ total area) with a BOL efficiency of 28.3%. They have long and short end deployables with a burn wire mechanism to fulfil the Chess requirement. Their six cells were estimated to provide a total of $5.80W$ of power on average per solar panel when sun pointing during the CHESS mission (following the calculation methods in part 5.1). This value is too low for the CHESS mission and this solution was disregarded.

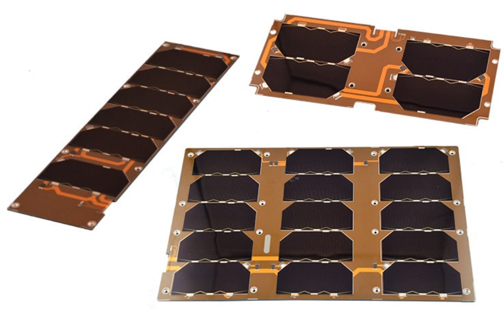


Figure 6: Isis Space solar panels for different sized satellites (3U six cells on the left)

Pumpkin Space

Pumpkin Space 3U deployable solar panels can have 7 or 8 Spectrolab XTJ triple junction cells ($212.80cm^2$ total area) with a BOL efficiency of 30.7%. They have a very large variety of configurations include long and short side single, double and triple deployables. Despite their high efficiency and larger number of cells, the deployment hinge is their own proprietary hardware and is not a burn wire. Therefore this solution was disregarded.

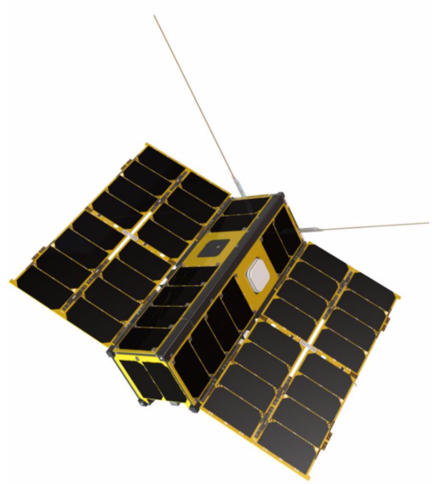


Figure 7: Example of long side hinge deployment of Pumpkin Space solar panels on a 3U CubeSat with 8 cells per panel

Endurosat

Endurosat 3U deployable solar panels have 7 CESI CTJ30 triple junction cells ($211.05cm^2$ total area) with a BOL efficiency of 29.0%. They only have a short side deployables but this is sufficient as explained in part 5.2. The deployment mechanism is a burn wire and they are the most affordable solution studied. They provide sufficient power with an estimate of $6.84W$ of power (following the calculation methods in part 5.1). After talking with the manufacturers they also confirmed having flight heritage of their panels after removal of multiple cells, allowing for the collaboration with RUAG.

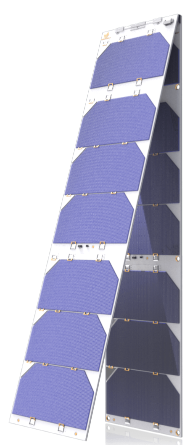


Figure 8: Endurosat short side 3U deployable solar panel

4.2.3 Solar Panel Trade-off

Table 10 is a summary of the three analysed COTS solar panels and cells. The Isis Space solution with the CHESS configuration would not provide sufficient power for mission success. The Pumpkin Space solution does not have a burn wire deployment mechanism therefore it is not conform with the requirements in table 2. Discussions and negotiations have started with Endurosat and they have confirmed the possibility of removing cells for the CHESS collaboration with RUAG. Their deployment mechanism shall also be purchased for Q4 2020 for testing with the EPS.

Table 10: Comparison between the three analysed COTS Solar Panel solutions

	Isis Space	Pumpkin Space	Endurosat
Deployable Mechanism	Yes	Yes	Yes
Burn Wire	Yes	No	Yes
Solar Cells	6 Azur Space TJ cells	7 or 8 Spectrolab XTJ prime cells	7 CESI CTJ30 cells
Cell Efficiency (BOL)	28.3%	30.7%	29.0%
Estimated Average Sun Pointing Power in LEO (per panel)	5.80W	7.09	6.84
Price (per panel)	8'000	13'000	5'000

5 Power Generation

In this section we will explain how we estimated the power generated by the solar panels during the CHESS mission, we will then justify the chosen solar panel configuration. More information on the CESI CTJ30 solar cells can be found in their datasheets in *CHESS_Subsystems/08_Power_System/ Summer 2019-2020/Datasheets*, and more information concerning solar power generation can be found in the power budget excel sheet in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Power Budget*.

5.1 Estimated Solar Power Generation

The solar power estimations are based on values from the CESI CTJ30 triple junction solar cells and the Endurosat 3U deployable solar panels. The cells have the following BOL characteristics with a solar irradiance of $H_0 = 1367\ W/m2$ and at $T_{ref} = 25°C$:

- Area: $a = 30.15\ cm^2$
- Efficiency (BOL): $\eta = 29.0\ \%$
- Max. Power: $P_m = 1.2\ W$
- Voltage at max. Power: $V_m = 2.33\ V$
- Current at max. Power: $I_m = 517\ mA$

We estimate that at $500km$ altitude the solar irradiance is of $1361\ W/m2$ so we must multiply the values by $C_{H0} = 1361/1367 \approx 99.5\%$.

To calculate the EOL values for the CHESS mission we assume the following values (from manufacturers) for radiation degradation and temperature coefficients:

- Electron Energy: $1\ MeV$
- Electron Fluence: $5 \cdot 10^{14}\ e/cm^2$
- Proton Energy: $100\ keV$
- Proton Fluence: $1 \cdot 10^{10}\ p/cm^2$
- Operational Temperature: $T_{op} = 50°C$
- Temperature Variation: $\Delta T = |T_{op} - T_{ref}| = 25°C$

We also consider cell to module losses over time to be of $L_{cm} = 2\%$ and a pointing accuracy of $\alpha = 5°$ from the ADCS pole. With this information we can use the values on the CESI CTJ30 datasheet to estimate the EOL power, voltage and current per cell in equations 1, 2 and 3 respectively:

$$P_{cell} = C_{H0} \cdot (P_m + \Delta T \cdot \frac{\Delta Pm}{\Delta T}) \cdot e_P \cdot p_P \cdot (1 - L_{cm}) \cdot cos(5°) \approx 0.973W \quad (1)$$

$$V_{cell} = C_{H0} \cdot (V_m + \Delta T \cdot \frac{\Delta Vm}{\Delta T}) \cdot e_V \cdot p_V \cdot (1 - L_{cm}) \cdot cos(5°) \approx 1.955V \quad (2)$$

$$I_{cell} = C_{H0} \cdot (I_m + \Delta T \cdot \frac{\Delta Im}{\Delta T}) \cdot e_I \cdot p_I \cdot (1 - L_{cm}) \cdot cos(5°) \approx 487mA \quad (3)$$

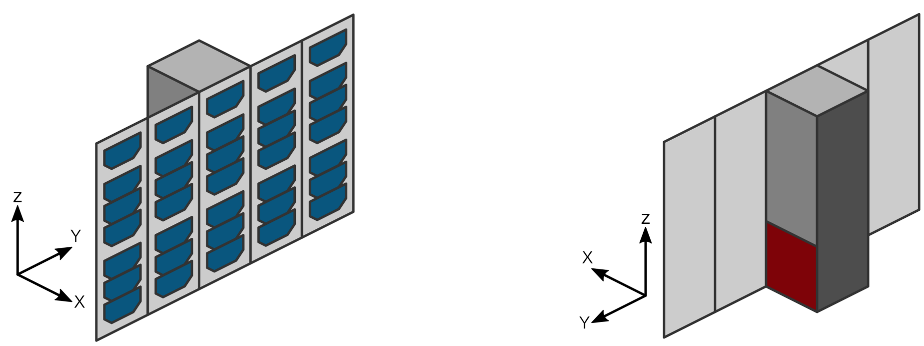
With e_P the electron radiation degradation for power, e_V for voltage and e_I for current, p_P the proton radiation degradation for power, p_V for voltage and p_I for current.

5.2 Solar Configuration

5.2.1 Long Side Deployables 90°

Payload on Y face of the satellite

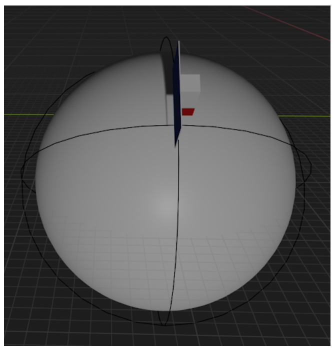
The Mass Spectrometer payload has to be facing the direction of movement, if placed on the Y face of the CubeSat we get the configuration shown in figure 9.



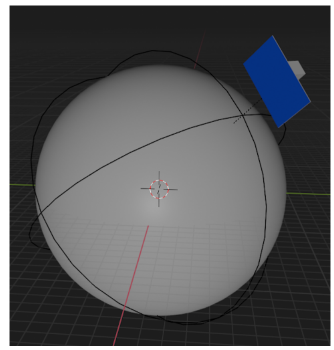
(a) View a　　(b) View b

Figure 9: Long side 90°deployables with payload on the Y face (in red)

We can clearly see that with this configuration, the solar panels do not gather any solar energy for 12am-12pm sun synchronous orbits (figure 10). We therefore can not consider this configuration.



(a) 12am-12pm SSO: No power

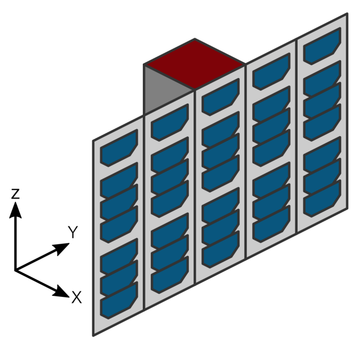


(b) 9am-9pm SSO: Enough power

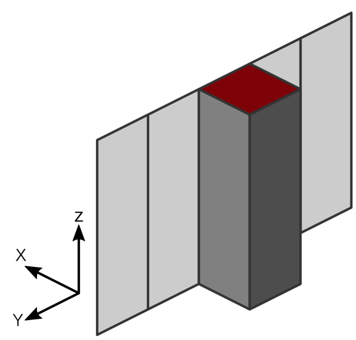
Figure 10: Example of different orbits for long side 90°deployables with payload on the Y face (in red)

Payload on Z face of the satellite

The Mass Spectrometer payload has to be facing the direction of movement, if placed on the Z face of the CubeSat we get the configuration shown in figure 11.



(a) View a



(b) View b

Figure 11: Long side 90°deployables with payload on the Z face (in red)

This configuration has conflicts with the satellite structure and the components in the stack. Despite the solar panels being able to generate enough power, some antennas could not be placed in the correct positions to allow for communication with the ground station and the payload would not be secure. We therefore can not consider this configuration.

5.2.2 Long Side Deployables 135°

The Mass Spectrometer payload has to be facing the direction of movement, if placed on the X face of the CubeSat with long side 135° deployables we get the configuration shown in figure 12.

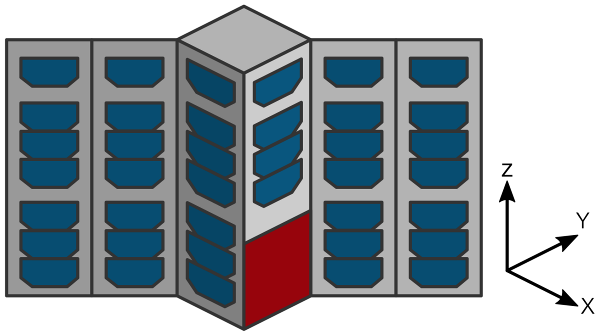
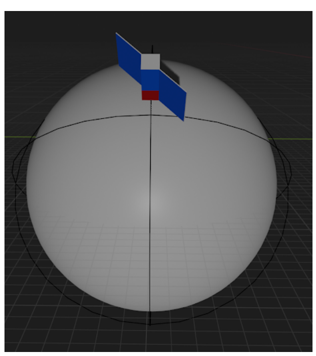
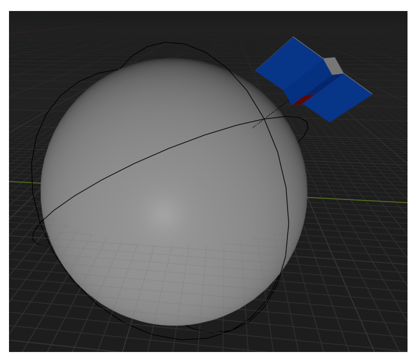


Figure 12: Long side 135°deployables with payload on the X face (in red)

This configuration works well for orbits between 11am-11pm and 9am-9pm, but doesn't provide enough power for 12am-12pm orbits. Indeed we can see in figure 13 that once the CubeSat passes the equator, the solar panels no longer face the sun. We therefore can not consider this configuration.



(a) 12am-12pm SSO: Not enough power

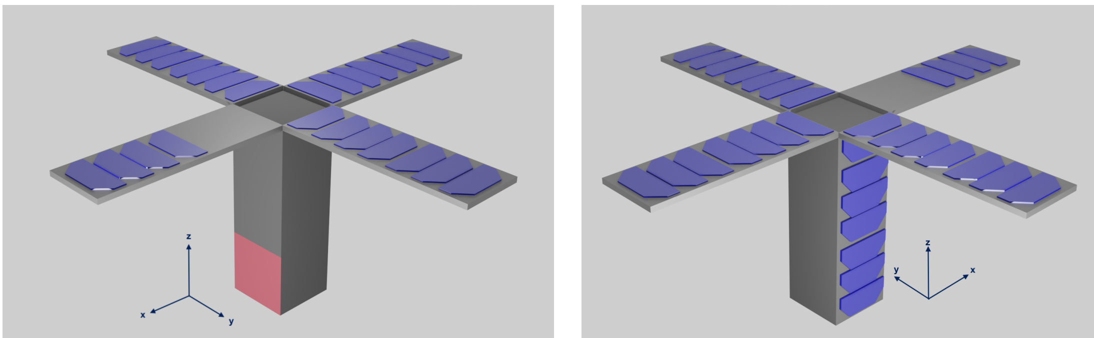


(b) 9am-9pm: Enough power

Figure 13: Example of different orbits for long side 135°deployables with payload on the X face (in red)

5.2.3 Final Configuration

The solution found in figure 14 works for all orbits as justified in part 6. There are 25 cells on the Z+ plane allowing for the RUAG collaboration, and 7 cells on the Y- plane allowing for more power generation during 11am-11pm to 9am-9pm sun synchronous orbits.



(a) View a (b) View b

Figure 14: Final CHESS satellite configuration with payload on the X face (in red)

6 Simulations

This section covers the method and the results of battery energy cycles for the CHESS mission using the Nanoavionics EPS and the Endurosat and CESI solar panels. We will evaluate this cycle for normal operational modes for different types of orbits. More information concerning the simulations, the code and the power budget can be found in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Matlab Simulations* and *Power Budget*.

6.1 Method

The power generated by the solar panels follows the method explained in part 5.1. As a recap, the Z+ plane of the satellite has 25 triple junction cells and the Y- plane has 7. Each cell has an EOL sun pointing power generation of $P_{cell} = 0.973$ W. Therefore we get the following power generations for each normal operational modes, using the angles found in figure 15:

- Charge Mode (Z face sun pointing):

$$P_{ChargeSolar} = 25 \cdot P_{cell} = 24.32 \; [W] \tag{4}$$

- Measurement and Communication mode (Nadir pointing): (note that equation 5 is only true when the sun is facing the appropriate satellite faces)

$$P_{MeasSolar} = P_{ComSolar} = 25 \cdot P_{cell} cos(\Omega) sin(\nu) + 7 \cdot P_{cell} sin(\Omega) \; [W] \tag{5}$$

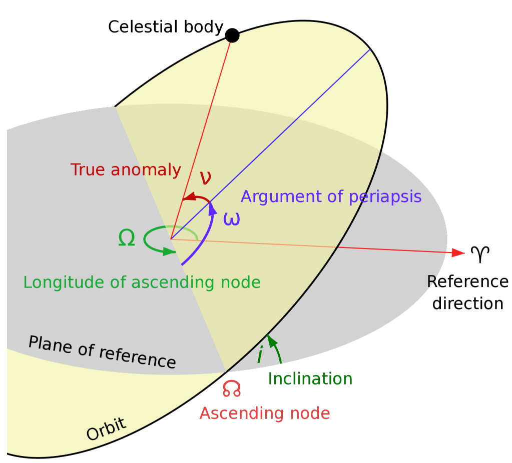


Figure 15: Orbital elements of celestial body, in our case the CHESS CubeSat around the Earth, with the plane of reference being the equator and the reference direction being the direction of the Sun and $i = 90°$

From these calculations we have the EPS input power, and from the power budget and power consumption according to each normal operational mode in part 3.4 we have the EPS output power. We need to consider efficiencies and losses within the EPS for our battery energy simulations. From the Nanoavionics EPS datasheet we have the efficiencies of each output regulator estimated to be of 91 %, and the MPPT input efficiencies estimated to be of 96 %. Table 11 shows the EPS input power needed to power each normal operational mode:

Table 11: EPS input power needed to power normal operational modes

Mode	Needed Input Power [W]
Charge	6.34
Measurement	15.73
Communication	22.30

We must also calculate the DOD limit for the mission. The mission lifetime is at least of 2 years and we have a repeatable cycle of approximately 9 orbits for every downlink. In each cycle of 9 orbits we have 5 battery discharges. With a high contingency of 50% we can get the number of battery cycles during the mission time (equation 6) using the following parameters:

- Contingency: $C = 1.5$
- Mission time: $T_{mission} = 2.5\ years = 78.84 \cdot 10^6\ s$
- Orbit time: $T_{orbit} = 94.5\ mins = 5668\ s$
- Orbits in a cycle: $n_{orbitcycle} = 9$
- Discharges in a cycle: $n_{discharges} = 5$

$$n_{cycles} = C \cdot \frac{T_{mission} \cdot n_{discharges}}{T_{orbit} \cdot n_{orbitcycle}} = 1.16 \cdot 10^4 \tag{6}$$

Figure 16 shows the best curve fit for a study of DOD as a function of cycle life for lithium ion batteries [3]. Therefore from this graph we get a CHESS mission DOD limit $of DOD = 45\%$.

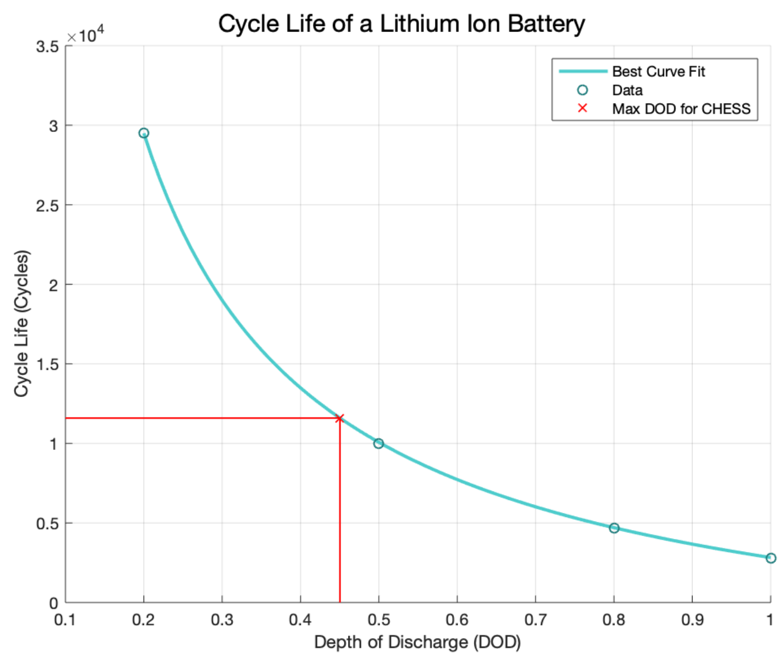


Figure 16: DOD as a function of cycle life for lithium ion batteries with the CHESS mission DOD limit at 45% for approximately 11'600 cycles in red

The following simulations show the energy capacity of the Nanoavionics 2S3P battery pack over time by subtracting the EPS input power and the generated EOL solar power. We use EOL values as a worse case scenario. If the solar power is higher than the MPPT input's maximum value it stays as such. finally the EPS is protected from overcharging therefore having a threshold at its nominal energy capacity of 69 Wh.

6.2 Orbits

6.2.1 6am-6pm SSO

For 6am-6pm sun synchronous orbits the CHESS CubeSat will always have its Z+ face sun pointing during measurement mode and charge mode. As we have $P_{ChargeSolar} > P_{MeasMode}$ the satellite will always be at its maximum energy capacity during measurement mode. During downlink the CubeSat will be ground station pointing, still gathering some solar energy from the Y- face. The main issue for this orbit is not the EPS and solar panels, but the thermal management. Indeed one side of the CubeSat is constantly exposed to the sun, further thermal analysis shall be lead during Q4 2020.

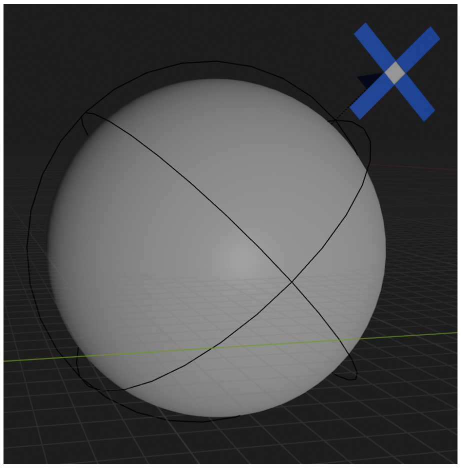


Figure 17: Example of a 6am-6pm SSO with the CHESS configuration

6.2.2 9am-9pm SSO

Figure 18 shows the generated solar power by the Z+ face (green), Y- face (blue) and total (red) for the CHESS CubeSat over one orbit. The dip in the middle is when the Y- face is covered by a shadow while passing over the equator.

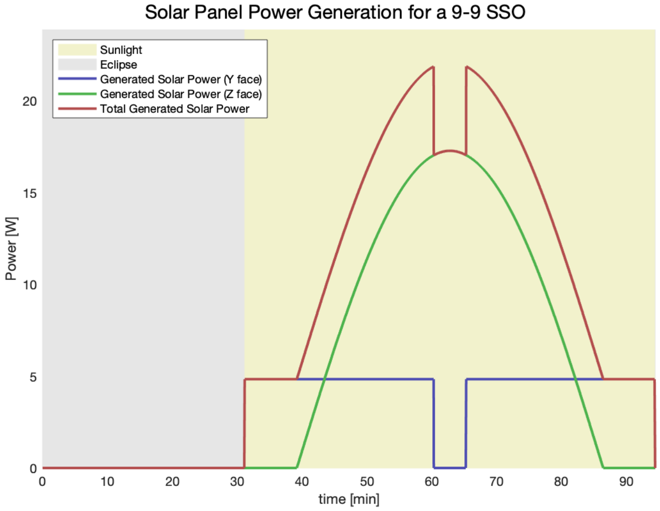


Figure 18: Solar power generated during measurement over one orbit for a 9am-9pm SSO

Figure 19 shows a nine orbit cycle consisting of one orbit of communication (with a 13 minute downlink window) followed by 8 orbits without passing over the ground station used for measurement (as seen in table 1).

Measurement time considers 30 minutes of conditioning to turn on, stabilise and calibrate the Mass Spectrometer payload, followed by 1.5 orbits of measurement in neutral mode (approximately 142 minutes), followed by 2 minutes of standby mode before turning off. To prepare for a worst case scenario, we assume that conditioning and standby consume the same amount of power as neutral mode, for a total of 174 minutes of measurement.

We are able to get 4.5 orbits of measurements over the 9 orbit cycle without going beneath the DOD limit.

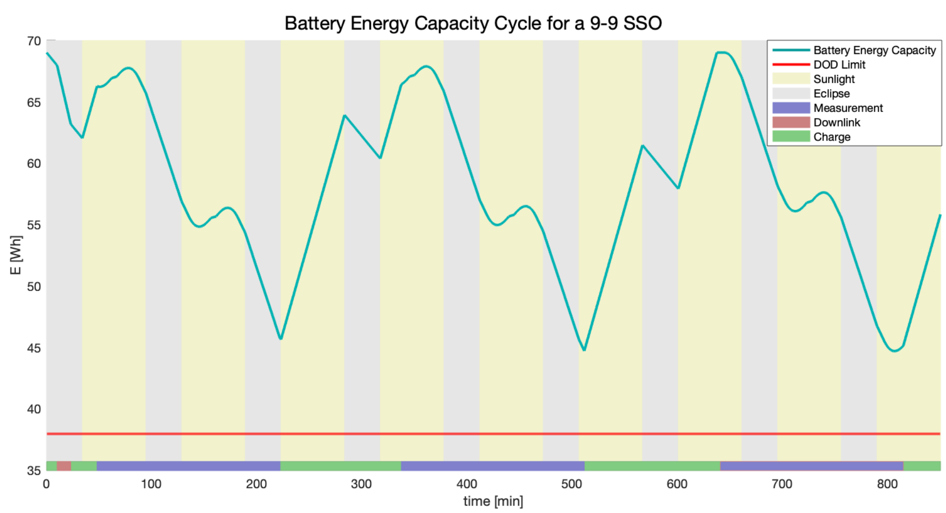


Figure 19: Battery Energy Cycle for a 9am-9pm nine orbit cycle

6.2.3 10am-10pm SSO

Figure 20 shows the generated solar power by the Z+ face (green), Y- face (blue) and total (red) for the CHESS CubeSat over one orbit. The dip in the middle is when the Y- face is covered by a shadow while passing over the equator.

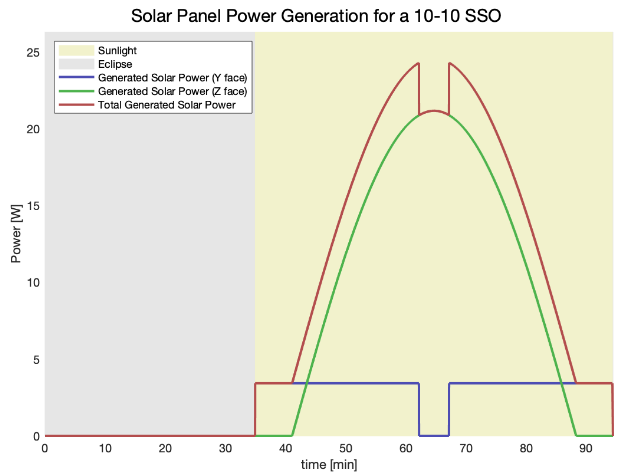


Figure 20: Solar power generated during measurement over one orbit for a 10am-10pm SSO

Figure 21 follows the same methodology as previously explained. Again with a 10am-10pm SSO we are able to get 4.5 orbits of measurements over the 9 orbit cycle without going beneath the DOD limit.

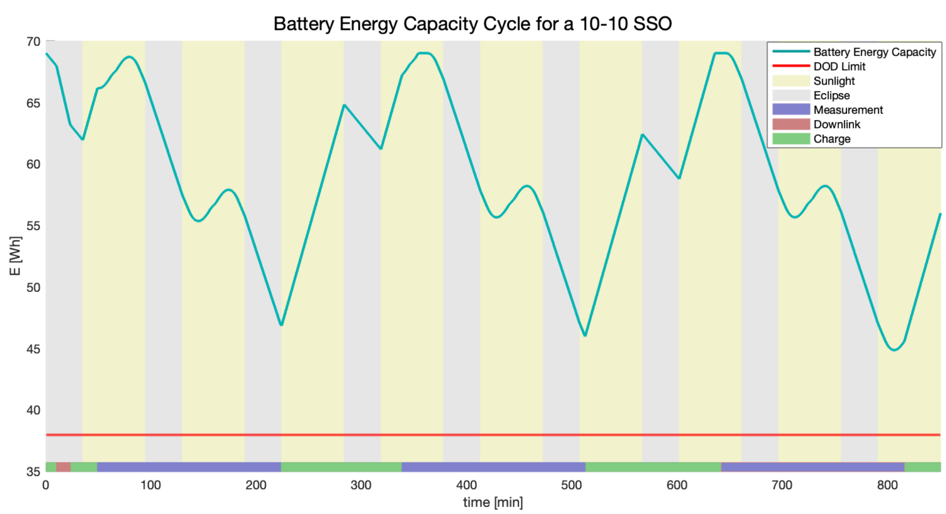


Figure 21: Battery Energy Cycle for a 10am-10pm nine orbit cycle

6.2.4 11am-11pm SSO

Figure 22 shows the generated solar power by the Z+ face (green), Y- face (blue) and total (red) for the CHESS CubeSat over one orbit. The dip in the middle is when the Y- face is covered by a shadow while passing over the equator.

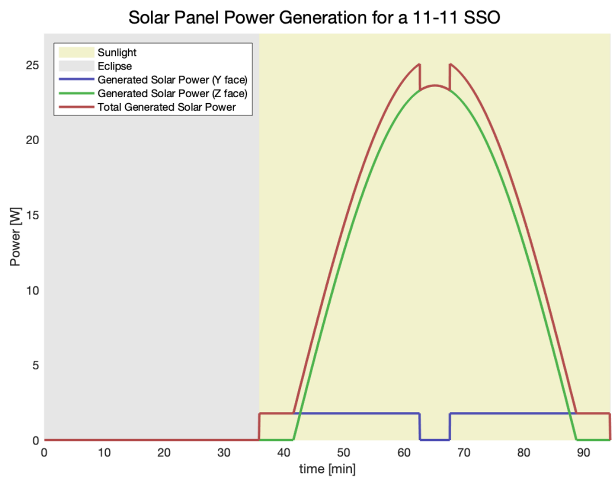


Figure 22: Solar power generated during measurement over one orbit for a 11am-11pm SSO

Figure 23 follows the same methodology as previously explained. Again with a 11am-11pm SSO we are able to get 4.5 orbits of measurements over the 9 orbit cycle without going beneath the DOD limit.

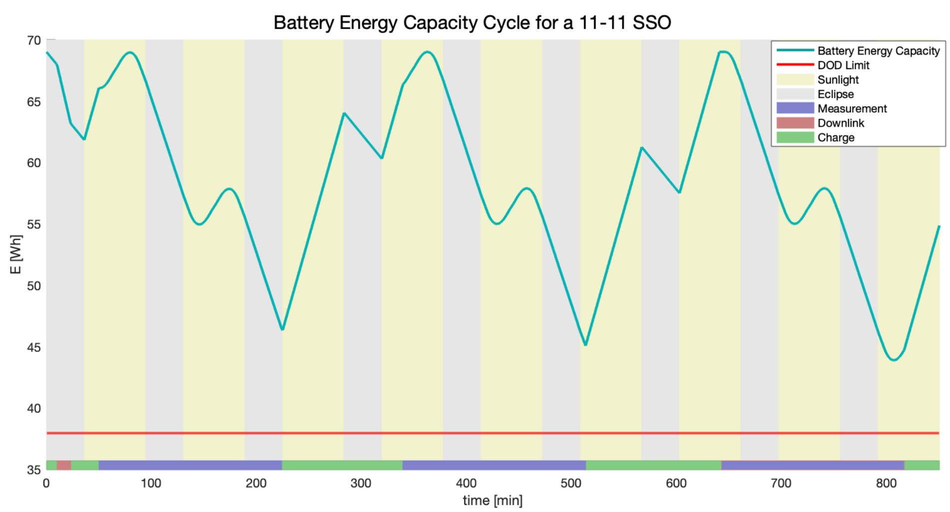


Figure 23: Battery Energy Cycle for a 11am-11pm nine orbit cycle

6.2.5 12am-12pm SSO

Figure 24 shows the generated solar power by the Z+ face (green), Y- face (blue) and total (red) for the CHESS CubeSat over one orbit. The Y- face cells have no use in this orbit, all of the energy comes from the Z+ face of the CubeSat.

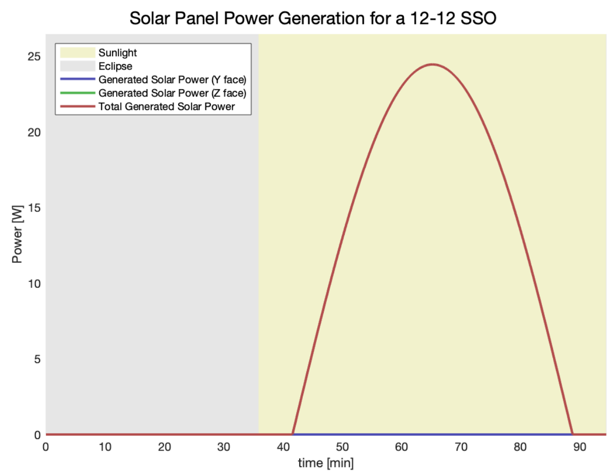


Figure 24: Solar power generated during measurement over one orbit for a 12am-12pm SSO

Figure 25 follows the same methodology as previously explained. This is considered as a worse case scenario so the energy cycle is very close to the DOD limit, but we still are able to get 4.5 orbits of measurements over the 9 orbit cycle.

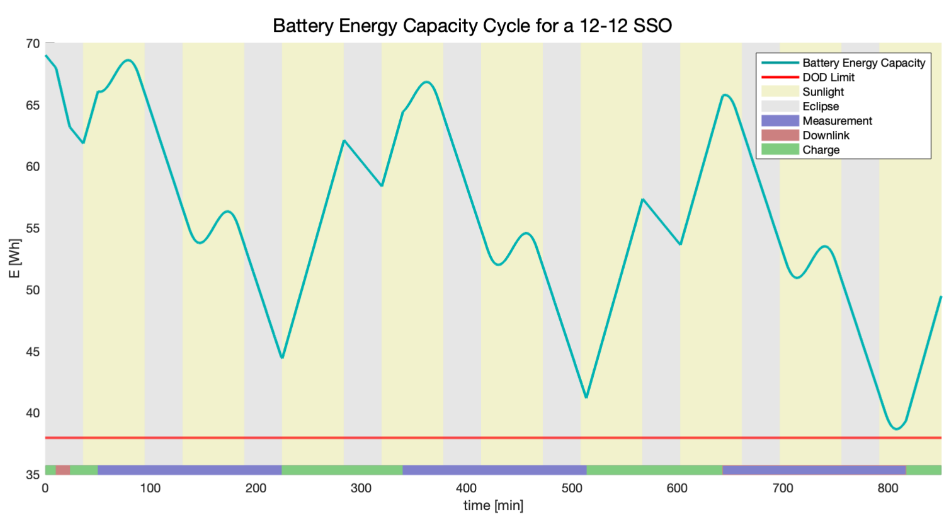


Figure 25: Battery Energy Cycle for a 12am-12pm nine orbit cycle

7 Electrical Architecture

In this section we will look at the inputs and outputs of the EPS and give a general view of the system with a block diagram. We will show the PC104 pins used for power and give a summary of the redundancy of the whole system. More information on the input solar power can be found in the power budget in *CHESS_Subsystems/ 08_Power_System/Summer 2019-2020/Power Budget*, and more information on the PC104 pin layout used for the CHESS mission can be found in *CHESS_Subsystems/ 04_OBC/System's Architecture/High level architecture*.

7.1 MPPT Inputs

From the Nanoavionics EPS datasheet we have that each of the four MPPT converters has 2 solar panel inputs for panels facing opposite directions. The solar panel voltage range is of $2.6V$ to $18V$, the maximum input power per MPPT converter is $25W$ and the maximum charging power for the 2S3P configuration is $30W$. The MPPT converter solar inputs are the following:

- **MPPT 1**: Z+ face, 1 input, 3 panels in parallel of 7 cells in series
- **MPPT 2**: Z+ face, 1 input, 1 panel of 4 cells in series
- **MPPT 2**: Y- face, 1 input, 1 panel of 7 cells in series
- **MPPT 4**: Z+ face, RUAG cells

Table 12 is a summary of each CHESS MPPT solar input's power, voltage and current values. We can see that MPPT 1 has its maximum power value limited at $25W$. The Z+ face (MPPT 1 and 2) has a maximum sun pointing charge power of $29.80W$ which is below the $30W$ EPS charging power.

Table 12: Summary of MPPT converter solar input characteristics (each cell is assumed to be sun pointing)

MPPT converter	EOL Power [W]	Max Power [W]	Max Voltage [V]	Max Current [A]
MPPT 1	20.43	25.00	16.31	1.55
MPPT 2	3.89	4.80	9.32	0.52
MPPT 3	6.81	8.40	16.31	0.52

7.2 Output Channels

From table 3.2 we have the voltage levels of each component of the CubeSat. As a recap we need the following outputs:

- **12V**: x2 (Mass Spectrometer and X-Band)
- **5V**: x2 (GNSS and ADCS)
- **3.3V**: x5 (OBC, UHF/VHF, RA, X-Band and ADCS)
- **Vbat**: x3 (ADCS, Thermal and Deployment)

The Nanoavionics EPS has two always on outputs at $3.3V$ and $5V$, and two $Vbat$ outputs that are not controlled, these will be used to power the critical systems. It also has 10 configurable switched output channels. Some critical systems will also use switched outputs for redundancy. The other subsystems will all be powered with switched outputs to be able to turn them on and off when desired. All output channels (always on and switched) are described in figure 26.

7.3 PC104

PC104 is a a modular embedded computer standard which allows for stacking of boards from a variety of COTS or built components. Power and data can be transmitted through the pins but we will only focus on power for this project. Figure 26 shows the power pins on the EPS after configuration for the CHESS mission. It shows the placement of the always-on and switched outputs and what subsystem is powered by each pin.

PC104 Pins

H2	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48: OC9	50: OC10	52: OC10
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47: OC7	49: OC8	51: OC9
H1	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48: OC4	50: OC5	52: OC6
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47: OC1	49: OC2	51: OC3

Legend

(grey)	PGND	-
(red)	Vbat	Always On
(orange)	5V	Always On
(yellow)	3.3V	Always On
(green)	5V	Switched
(light blue)	3.3V	Switched
(dark blue)	12V	Switched
(purple)	Vbat	Switched

Always On Outputs

H2-27/28	OBC	H2-25/26	ADCS	H2-45/46	ADCS
H2-27/28	ADCS				
H2-27/28	UHF/VHF				

Switched Outputs

OC1	ADCS	OC3	OBC	OC7	MS	OC9	Thermal
OC2	GNSS	OC4	ADCS	OC8	X-Band	OC10	Deployment
		OC5	X-Band				
		OC6	Radio Amateur				

Figure 26: PC104 voltage pins with EPS output channels

7.4 Redundancy

The priority for redundancy goes to the critical systems: the OBC, ADCS, UHF/VHF and the EPS. The EPS powers itself, which leaves us with the three first components.

After powering the critical components with the always on $Vbat$, $3.3V$ and $5V$ outputs, and powering all of the other components with switched or controllable outputs, we are left with output channels 1 ($5V$), 3 and 4 ($3.3V$). We use these to give redundancy for the ADCS and the OBC: in case of failure of the always on output we can use the switched outputs.

However this leaves the UHF/VHF module vulnerable but this is a risk we have to take at this stage of the mission. There is still a possibility of merging the COM system and the RA Linear transponder, and this would lead to the freeing up of a switches output for redundancy of the UHF/VHF. The thermal channel is also waiting on the thermal analysis for Q4 2020/Q1 2021 to determine its necessity, so we could also use this channel for redundancy in the UHF/VHF module.

Concerning the deployment mechanism, it is a dual burn wire. So we have some redundancy here in case the first wire fails to burn during deployment. For more information on this, please refer to the *Solar panel deployment system* project [1].

7.5 Block Diagram

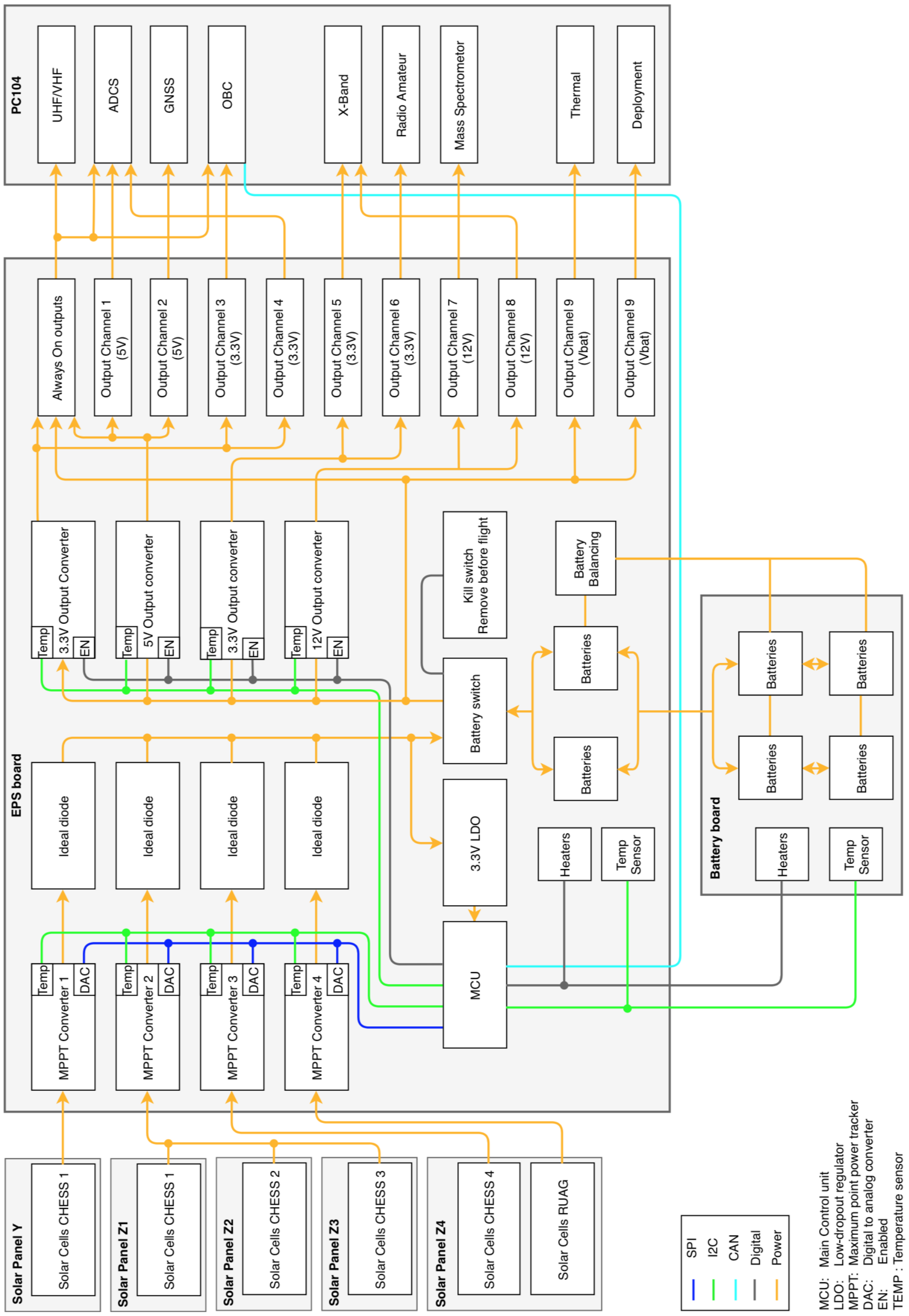


Figure 27: Block diagram of the EPS including the EPS board, the external battery pack, the solar inputs and the CHESS outputs

8 Next Steps

In this section we will explain the next steps moving from phase A to B of the CHESS mission. We will first give a summary of the discussions with each manufacturer concerning the purchase of the EPS and Solar panels and proceed to introduce a testing plan for Q4 2020.

8.1 Nanoavionics

Discussions with Nanoavionics concerning the purchase of the EPS with a 2S3P configuration have started and an option sheet with the correct specifications has been sent, and a quote received. Four EPS modules will be bought:

- one EM for testing
- one EM for the satellite on the ground
- two FM for the CHESS satellites

The first EM shall be bought at the end of June 2020/early July 2020 to start testing in Q4 2020. Negotiations with Nanoavionics have started concerning the price and the need of engineering support. The option sheet and quote can be found in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Nanoavionics*.

8.2 Endurosat

Discussions with Endurosat are not as advanced as with Nanoavionics as we will purchase the EPS before the solar panels. However discussions have started concerning the CHESS configuration found in part 5.2.3. This configuration seems the most probable so far as it does the PCBs on the solar panels are not blocked nor removed by the lack of cells on some panels, or the payload's opening. This shall be further discussed within the structure pole.

It would be interesting to purchase the burn wire deployment mechanism and the metallic structure (in aluminium) for testing with the EPS so a request has been made to Endurosat. The quote for the solar panels, their options and the deployment mechanism will be found in *CHESS_Subsystems/08_Power_System/Summer 2019-2020/Endurosat* when available.

8.3 Simulations and SOC estimation

Before testing, the student taking on the next part of the EPS project will have to confirm the simulations run for sun synchronous orbits on an elliptical orbit model. They will also have to include the thermal analysis in the simulation and implement SOC estimations for battery DOD monitoring. This step is very important because the Nanoavionics EPS BMS does provide SOC estimations. A study on different SOC estimation methods was conducted in *Design of The Electric Power System for CHESS* [2]. This will have to be done as part of the next CHESS EPS project.

8.4 Testing

An extensive review of different testing methods was conducted last semester, for this information refer to the concerned project, *Design of The Electric Power System for CHESS* [2], as we will not review these testing methods again. The main tests to be run when the EPS and batteries are in our possession can be divided into two categories that are EPS testing and battery cell testing.

Battery cell tests to be run:

- Cell force (EMF) testing
- Cell rate capability testing
- Vacuum Testing
- Temperature cycling in a vacuum testing
- Life cycle testing

EPS tests to be run:

- PC104 voltage loss testing
- Efficiency testing
- Vacuum testing
- Deployment testing
- Component level testing for voltage spikes

Along with these hardware tests, the EPS software will have to be tested and familiarised. Gathering real time information and feedback from the EPS will be vital and communication with the OBC will have to be tested.

9 Conclusion

This report based on previous work on the CHESS EPS, [1] and [2], provides a summary of the requirements, the power consumption and generation of the CHESS CubeSat, a study of COTS solutions and the first steps in integration of the near purchased EPS and Solar Panels.

The power will be generated by 4 Endurosat deploayable solar panels with CESI CTJ30 triple junction cells. This configuration ensures an EOL sun pointing value of approximately $24W$ and permits a collaboration with RUAG leaving them 3 cells of space. Negotiations have started but this will have to be followed up by the next project in Q4 2020.

The power will be stored and distributed by the Nanoavionics EPS 2S3P configuration. This EPS and battery pack were selected in accordance with the defined requirements and will provide power for at least two years of mission life without going below 45% DOD according to our calculations. The PC104 pins have been selected to distribute the power to each subsystem at the correct voltage levels and an EPS shall be purchased before mid July 2020.

This project marks the near end of Phase A of the CHESS mission EPS design and selection. The future work will therefore be final steps in simulations and estimations, followed by the testing and integration of the selected modules.

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