POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

Exercise: Electrical Power System

Space System Engineering and Operations I A.Y. 2024/2025

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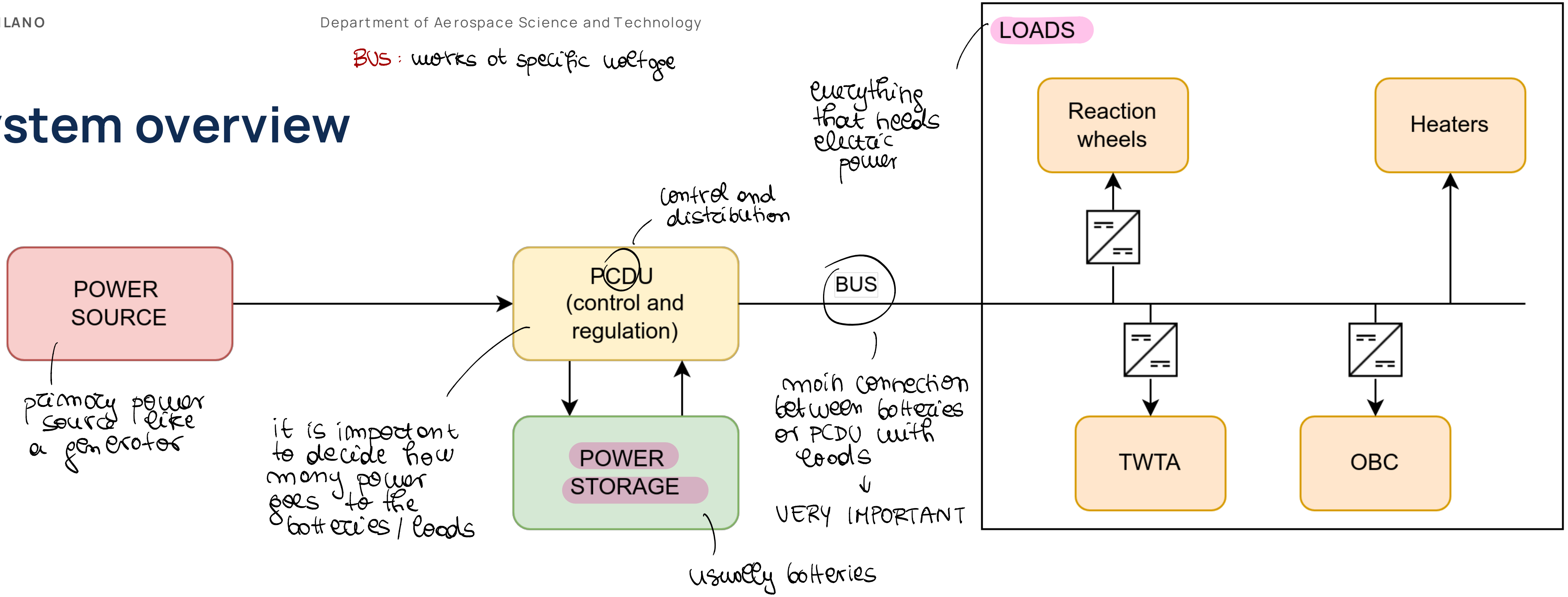
EPS system preliminary design process

- Identify the EPS requirements (Power budget)
- Select and size the power source
- Select and size the energy storage
- Select the power control and regulation strategy
- Draw the system schematics/budgets

Always keeping in mind the mission phases and environment (sunlight, eclipse, power profile...)

BUS : works at specific voltage

Subsystem overview



The EPS shall supply a continuous source of electric power to spacecraft loads during mission life

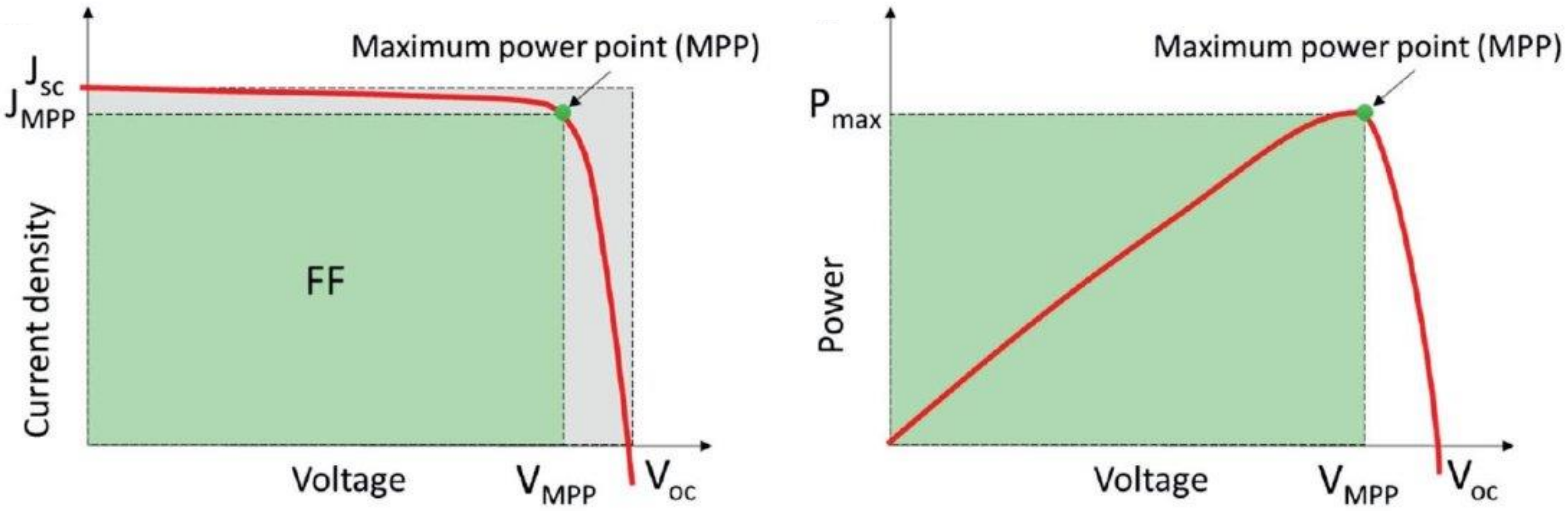
- **Generate power**
- **Store power**
- **Control, regulate and distribute power**

Subsystem overview

Power sources:

- Primary Batteries
- **Solar Cells – photovoltaic generator**
- RTGs: Radio Isotope Generators
- *Fuel Cells*
- *Solar Dynamics*
- *Nuclear Reactors*

equivalent to current generator
the power they give depends
at which voltage they operate
↓
after a certain voltage is applied,
they stop working



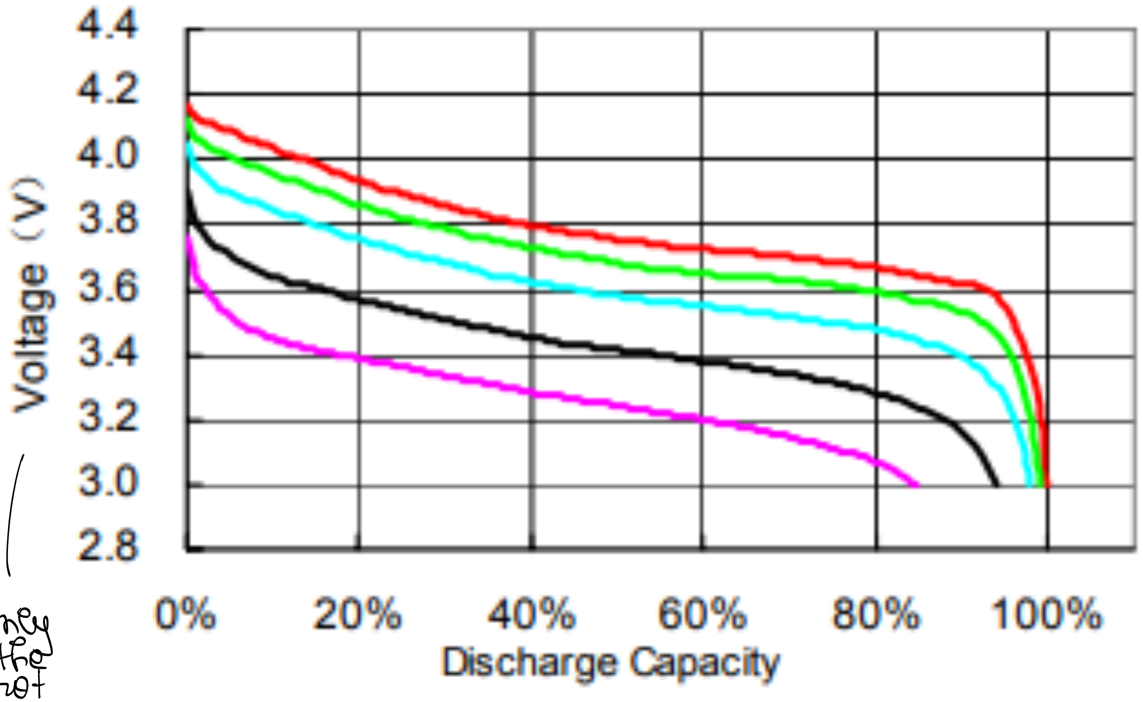
Solar cells are equivalent to a current generator

Subsystem overview

Power Storage:

- **Secondary Batteries**
- *Regenerative Fuel Cells*

voltage generator that is NOT really constant. It depends on the level of charge of the battery



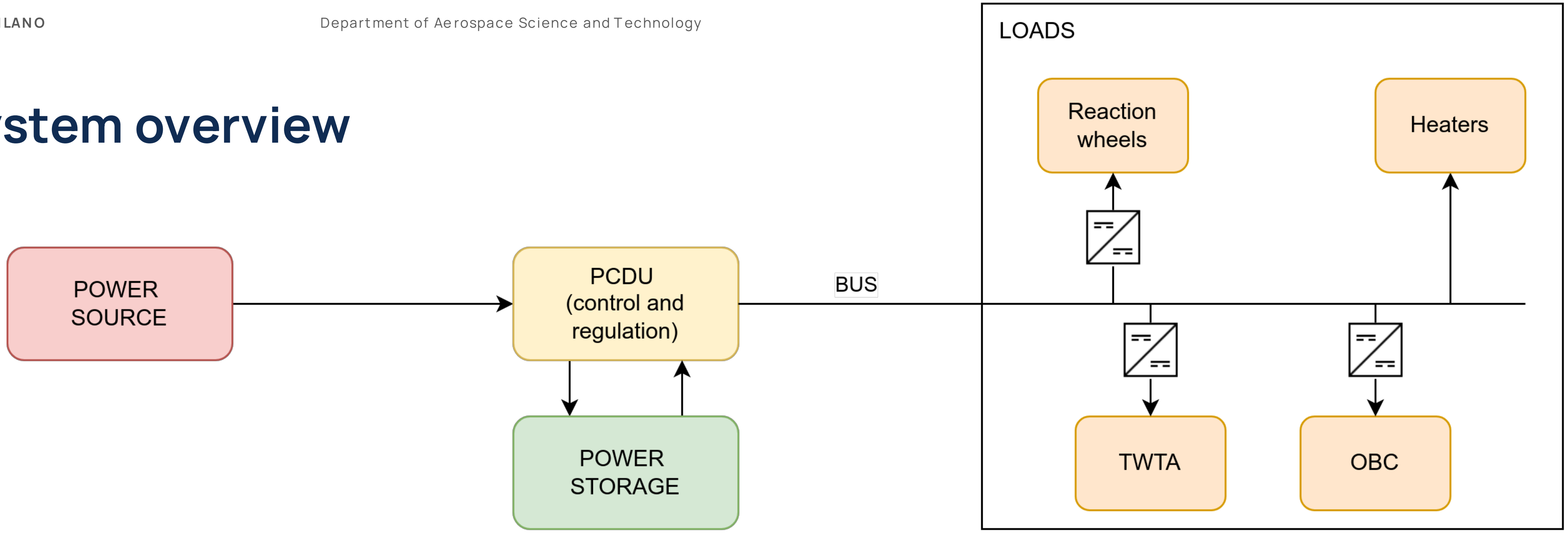
we can only measure the voltage, not the discharge level

Batteries are equivalent to a voltage generator.

Note:

- The voltage is not constant: it varies depending on the state of charge, loads applied, temperature…
- The voltage is the only indication available on the state of charge of the battery.

Subsystem overview



Power control: strategy used to manage how electrical power is extracted from the solar arrays and delivered to the spacecraft's energy storage (battery) and power bus.

- **DET (Direct energy transfer)**: Solar arrays are connected to the power bus through a shunt regulator. When the arrays produce more current than needed, the excess is dissipated by a shunt.
- **PPT (Peak Power Tracking)**: Continuously adjusts the solar array’s operating voltage to stay at the Maximum Power Point (MPP) on the I–V curve.

Assume that we're using solar cells + batteries:

we're in sunlight, batteries are half empty and loads are consuming 100 W and we're producing 300 W

optimize power production: 100 W to loads
200 W to batteries

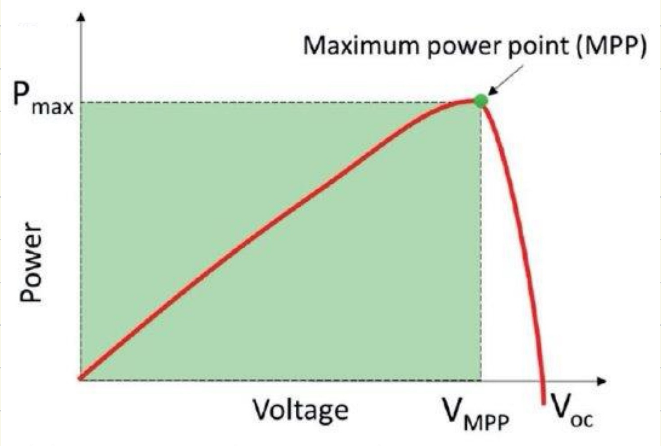
but if batteries are fully charged, we have to regulate the power coming to the source because if we don't dissipate the power we break the loads

2 ways to do that (if using solar cells)

* DET: simpler, put a resistance parallel to the cells to dissipate the exceeding current

solar cells works always at constant voltage, always produce the same power but the exceeding one is dissipated through heat

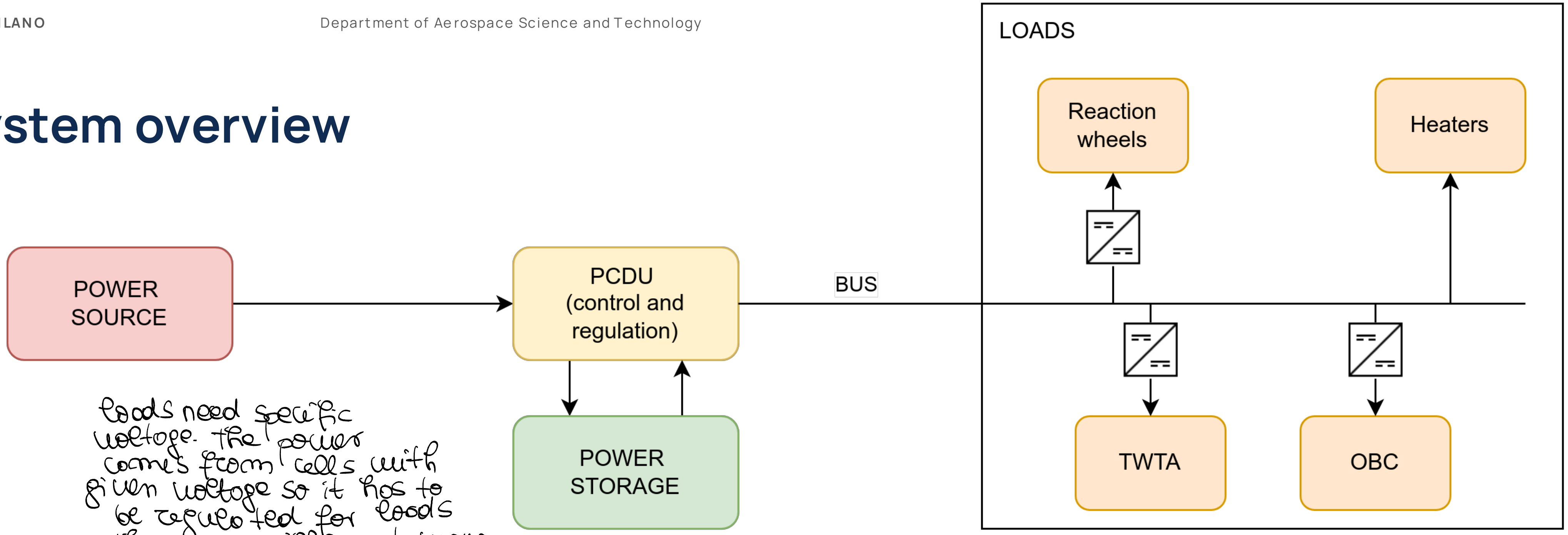
* PPT: complex but most used because can regulate the operate voltage point



when the maximum power is requested by the loads, it gives the max power with the max voltage. Then if the loads request lower power, the voltage is regulated in function of the requested power

in this way no dissipation through heat is requested!!

Subsystem overview



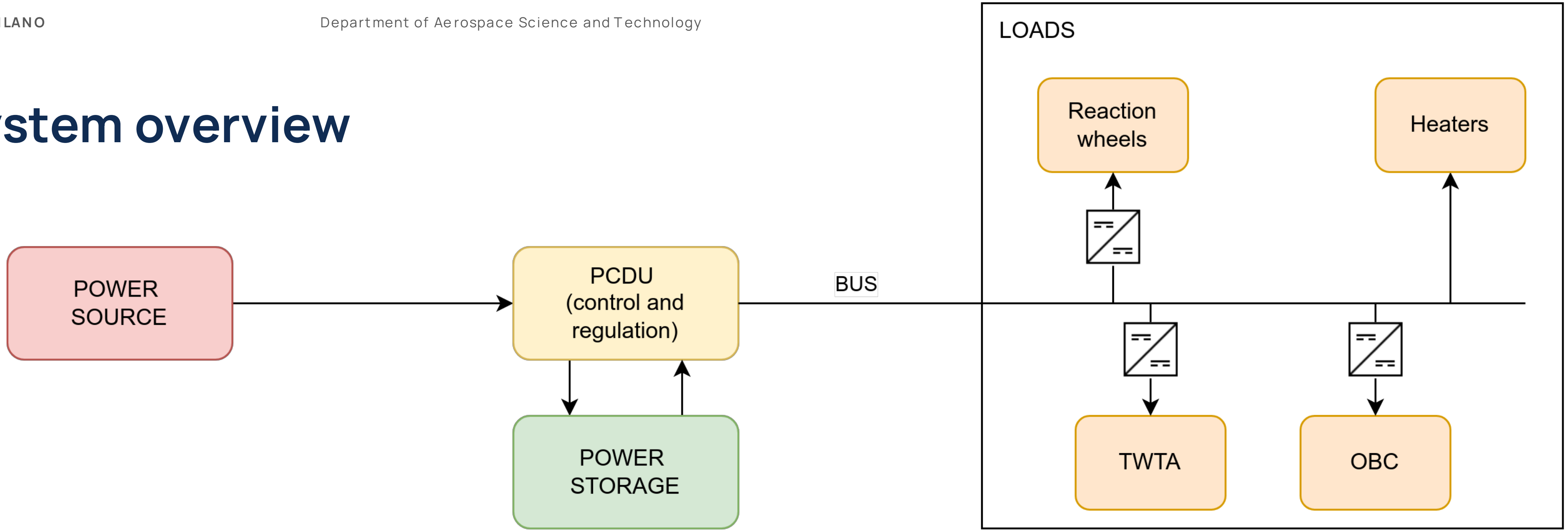
loads need specific voltage. the power comes from cells with given voltage so it has to be regulated for loads there are different ways to do that

Power regulation: method used to control and stabilize the voltage on the spacecraft power bus to ensure it stays within acceptable limits for onboard subsystems and loads.

a little bit higher than loads one because of losses

- **Fully regulated**: The BUS voltage is kept constant
- **Quasi-regulated**: The BUS voltage is regulated during battery charging and unregulated during discharge
- **Unregulated**: The BUS voltage varies according to the battery voltage

Subsystem overview



The working voltage of the EPS usually is:
- 28V: for power consumptions lower than 2 kW
- 50/100/150V: for power consumptions higher than 2 kW

The power distribution takes into account the EPS internal hardware.
At early stage of sizing is typically to consider the mass for the power distribution equal to the 15% to 25% of the total EPS mass.

EPS margins

MAR-PWR-010	At equipment level, the following design maturity power margins shall be applied: - 5 % for off-the-shelf products without modifications (Product Category A and B) - 10 % for off-the-shelf products with modifications (Product Category C) - 20 % for newly designed and developed products (Product Category D)
MAR-PWR-040	The total power budget of a spacecraft shall include **a 20% system level power margin of the nominal power requirements of the spacecraft**.
MAR-PWR-060	Solar arrays and batteries shall be **sized to provide the spacecraft required power, including all specified margins, at EoL, and taking into account one string failure (for the solar arrays) and one cell failure (for the batteries).** Note: In batteries with series-parallel (S-P) architecture, a cell failure implies a loss of one full string.

EPS sizing: power budget

(expected in the report)
IT IS NOT THE MAX POWER CONSUMPTION
reason about the power consumption
in the different modes

The power budget should contain at least the information about the subsystems demand in the different modes.
A more refined work would also include the peak power demand, and the single components demand.

ex: RW never
use max power,
only when apply
max torque at
max speed

Subsystem	Science	Maneuver	Comm	Eclipse
PS	-	55 W	-	-
TMTC	20 W	20 W	120 W	20 W
ADCS	90 W	90 W	90 W	70 W
TCS	25 W	25 W	80 W	80 W
Other System (OBDH, EPS, …)	130 W	130 W	130 W	110 W
PL	140 W	60 W	60 W	50 W
Total	**420 W**	**380 W**	**480 W**	**330 W**
+20% margin	84 W	76 W	96 W	66 W
Total margined	**504 W**	**456 W**	**574 W**	**396 W**

Example of power budget (averages only)

NOTE:
- Not all subsystems are active during all modes
- The subsystem power demand will be different in different modes (e.g. TMTC and ADCS)

EPS sizing: solar arrays

The power to be produced by the solar arrays:

$$P_{sa} = \frac{\frac{P_e T_e}{X_e} + \frac{P_s T_s}{X_s}}{T_s} \quad [W]$$

- P_s: Power requested by the loads in sunlight
- P_e: Power requested by the loads in eclipse
- T_s: Sunlit time
- T_e: Eclipse time
- X_s: Lines efficiency in sunlight
- X_e: Lines efficiency in eclipse

	X_s	X_e
DET	0.85	0.65
MPPT	0.80	0.60

Note: by eclipse is intended any situation for which the panels cannot produce power

EPS sizing: solar arrays

To know the SA area, we need to compute the specific power output at EOL:

$$P_{BOL} = \varepsilon\ P_0\ I_d \cos(\theta) \qquad [\text{Wm^-2}]$$

$$P_{EOL} = (1 - dpy)^{years}\ P_{BOL} \qquad [\text{Wm^-2}]$$

- P_0: Solar radiation [Wm^-2] (To be scaled at the mission AU)
- ε : Solar cells efficiency
- θ: Sun incidence angle
- I_d: Inherent degradation factor (Misalignment, diodes, current mismatch, dust…)
- dpy: Yearly degradation factor (Radiations, meteoroids)
- $years$: Expected mission lifetime in years

ε	I_d	dpy
0.3	0.5 – 0.9	0.03

Reference values for multi-junction solar cells

EPS sizing: solar arrays

The area of solar arrays needed is then:

$$A_{SA} = \frac{P_{SA}}{P_{EOL}}$$

Therefore, the number of cells will be:

$$N_{cells} = \frac{A_{SA}}{A_{cell}}$$

Given that the solar arrays electrical parameters should about match the system one, given the selected system voltage V_{sys}, we can size the number of series and in parallels:

$$N_{series} = ceil\left(\frac{V_{sys}}{V_{cell}}\right) \text{ and } N_{parallel} = ceil\left(\frac{N_{cells}}{N_{series}}\right)$$

Therefore, the real number of cells and the real area will be (considering also MAR-PWR-060):

$$N_{cells,real} = N_{series}N_{parallel} + N_{series} \text{ and } A_{SA,real} = N_{cells,real}A_{cell}$$

Cell datasheets: [1] [2]

EPS sizing: solar arrays

Given the computed real capacity and the statistical specific energy, it is possible to compute the mass and volume:

$$M = \frac{P_{real,BOL}}{\text{Specific Power}}$$

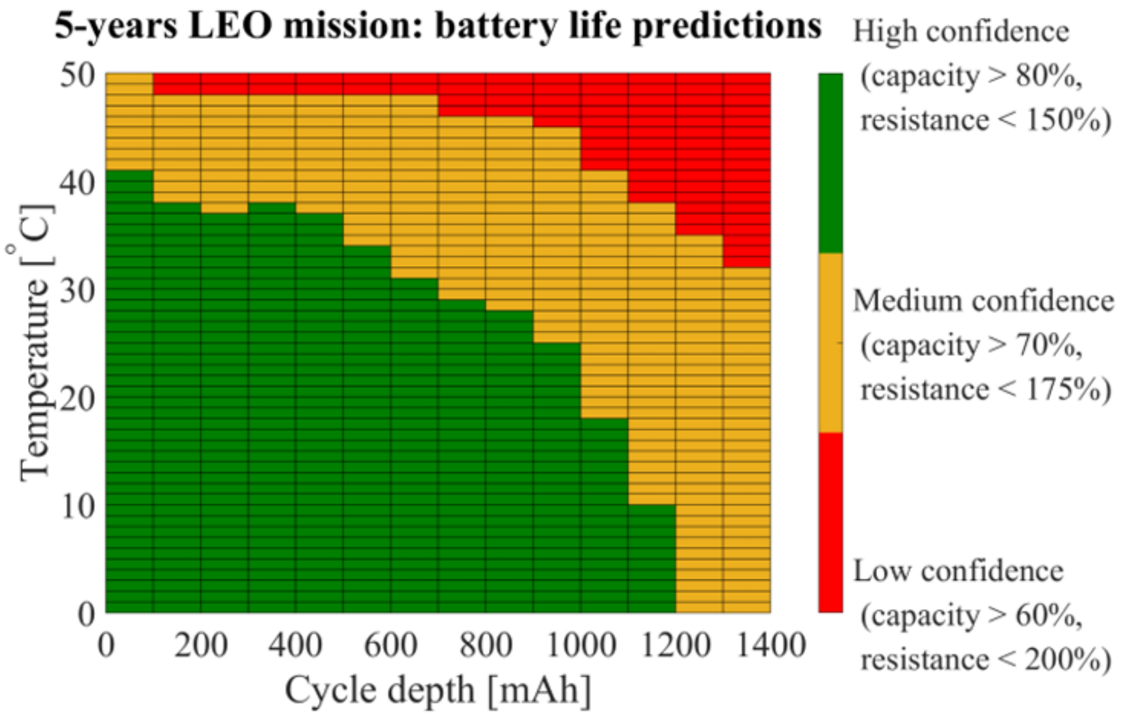
Array Technologies		
Cell Type	**BOL Efficiency**	**Specific Power**
	(%)	**(W/kg)**
Si	10	25
GaAs	19	40
GaInP/GaAs (2J)	23	60
GaInP/GaAs/Ge (3J)	26	80
InGaAlP/GaAs/In GaAs/Ge (4J)	**35**	**100**
Amorphous Si	10	100
CuInGaSe2(CIGS)	15	200

EPS sizing: secondary batteries

The battery capacity can be sized as:

$$E = \frac{\frac{P_e T_e}{X_e}}{\mathrm{DoD}\ \eta\ N}\ [\mathrm{Wh}]$$

- P_e: Power requested by the loads in eclipse
- T_e: Eclipse time
- X_e: Lines efficiency in eclipse
- N: Number of batteries (usually 2 to 5)
- DoD: Depth of discharge (30 – 50%)
- η: End of life efficiency



From [1]

The DoD the amount of capacity used during each cycle. The higher the DoD the lower the battery life. For LEO mission, usually to have a EOL efficiency of 80% it's better to have a DoD in the span of 30 to 50% or lower.

EPS sizing: secondary batteries

Similarly to what done for the solar panels, the number of battery cells in series can be computed as:

$$N_{series} = ceil\left(\frac{V_{sys}}{V_{cell}}\right)$$

And the number of batteries in parallel can then be computed as:

$$N_{parallel} = ceil\left(\frac{E}{E_{string}}\right) \text{ where } E_{string} = \mu C_{cell}\left(N_{series}V_{cell}\right) \text{ [Wh]}$$

- μ: Pack efficiency (0.8 – 0.9)
- C_{cell} : Cell electric charge, can be found in the datasheet [Ah]

So, the number of strings in parallel and the real battery capacity will be:

$$N_{real} = N_{series}N_{parallel} + N_{series} \text{ and } E_{real} = E_{string}N_{parallel}$$

Cell datasheets: [1]

EPS sizing: secondary batteries

Given the computed real capacity and the statistical specific energy, it is possible to compute the mass and volume:

$$V = \frac{E_{real}}{\text{Energy Density}} \quad \text{and} \quad M = \frac{E_{real}}{\text{Specific Energy}}$$

Technology	Energy density (Wh/l)	Specific Energy (Wh/kg)	Specific power (W/Kg) (short pulse)	Cycle number (100% DOD)	Optimum operating temperature range (°C)	Energy efficiency	Self discharge	Comments
Ni-Cd	90	30	200	2000	0 to 40	70-75%	Moderate	
Ni-H2	50	55	150	2500	-10 to 30	70-75%	High	
Li-ion	250	150	2000	3000	10 to 40	>95 %	Low	Low Thermal dissipation
Advanced Li	>300	>200	>2000	>2000	-10 to 40	>95 %	Low	

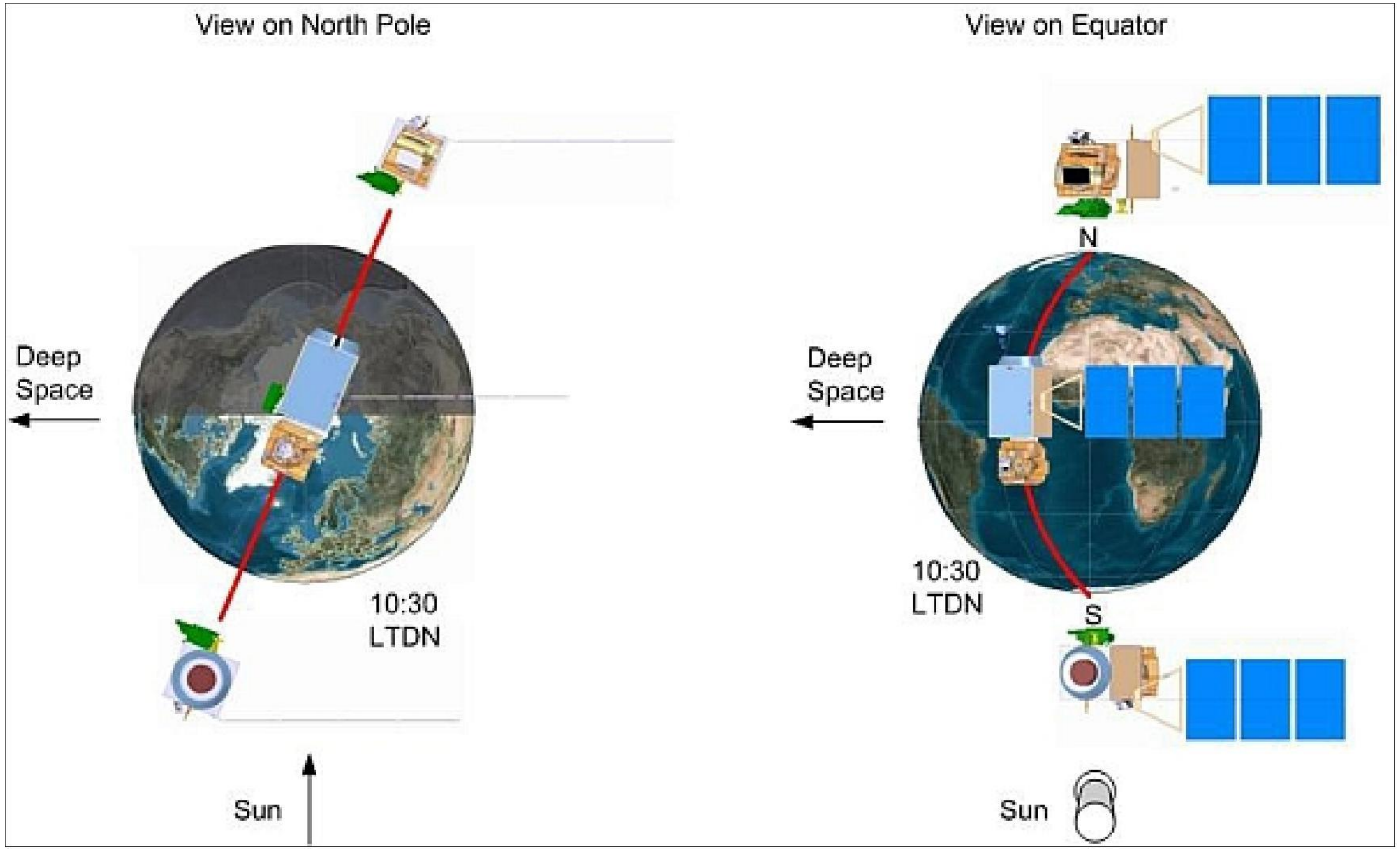
Exercise: Sentinel 2

02

Sentinel 2 data

Orbit:
- 780 km SSO (LTAN 10:30)
- Period: 101 minutes

EPS:
- **Triple junction cells**
  - Solar arrays area: 7.1 m^2
  - Number of cells: 2016
  - P_{EOL}: 1730 W
  - P_{BOL}: 2300 W
  - 1-axis solar array drive
- **Li-Ion batteries**:
  - Battery electrical charge: 102 Ah
  - Number of cells in series: 8
- **Bus voltage**: 28 (unregulated)



Sentinel 2 data

Subsystem / Mode	Science-Sunlight	Eclipse	Telecom	Safe Mode
Payload	266	0	0	0
OBDH	100	100	100	50
ADCS	150	150	70	20
TT&C	34	34	200	80
Thermal Control	120	160	120	120
EPS	80	80	80	50
Total Consumption	**750**	**524**	**570**	**320**
System Margin (20%)	150	104.8	114	64
Total Required Power	**900**	**634**	**684**	**384**

Approximated power budget (all values are in W)