Space Technology

Electrical Power System

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The role of EPS

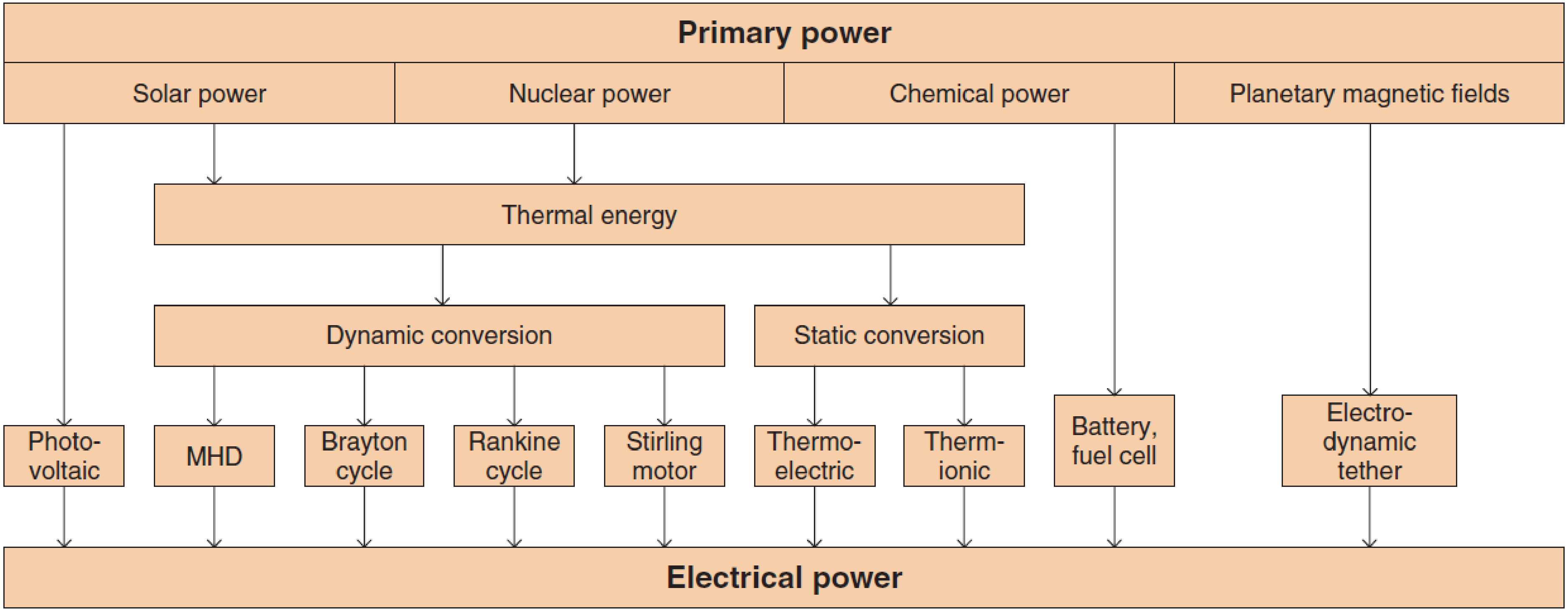
- It is a system component

- generate energy
- power conversion
- power conditioning (controlling voltage and current)
- energy storage
- overvoltage and overcurrent protection
- power distribution

- power levels: from a few watts up to more kW (International Space Station (ISS) 110 kW)
- EPS autonomously maintains the spacecraft power in failure conditions

Energy generation

- onboard energy source
- energy derived from outside environment



Energy generation

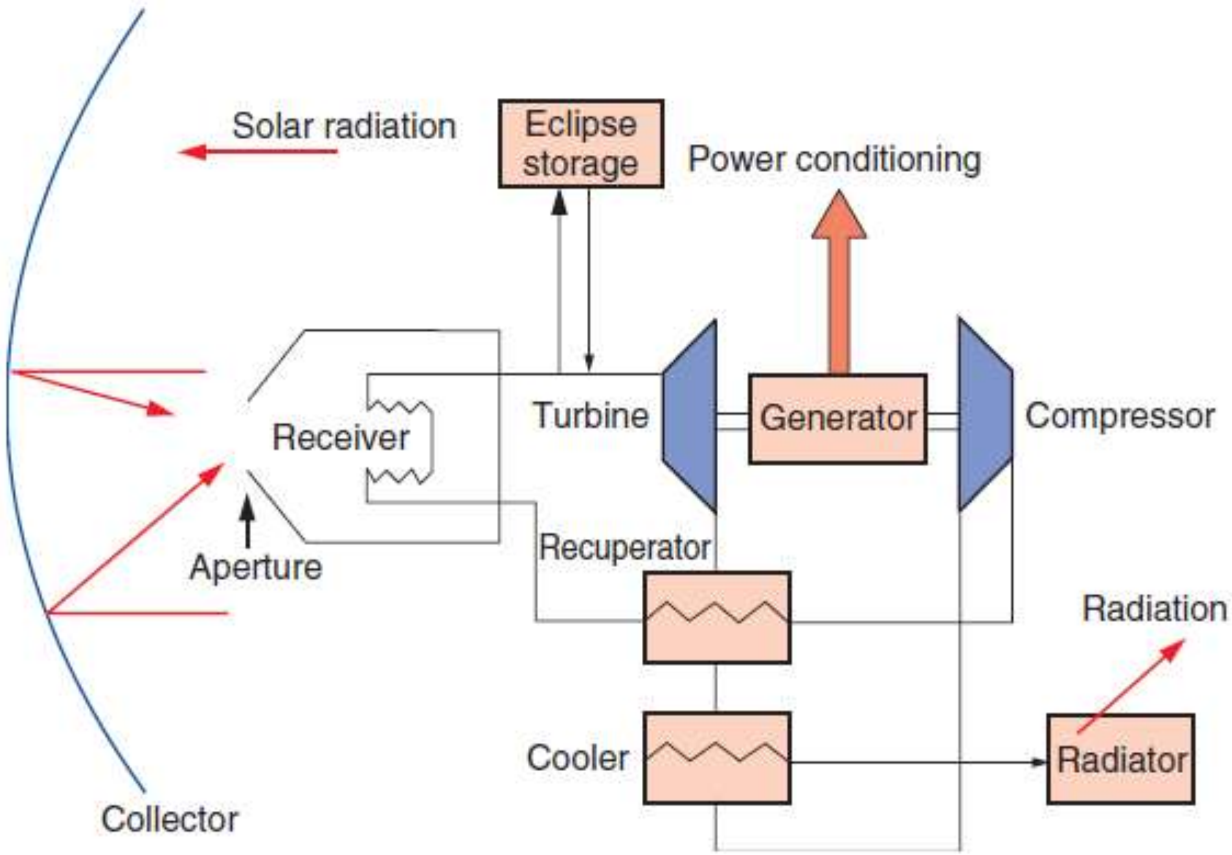
- The most common power source: solar arrays of photovoltaic assemblies (PVAs) + rechargeable batteries (secondary batteries)

- Solar dynamic: heat->rotational energy->electrical energy: mostly LEO orbits
  - **Magnetohydrodynamic** generator
  - **Stirling process** (thermomechanical energy converter)
  - **Brayton (Joule) process** (gas turbine with He/Xe mixture)
  - High-temperature **Rankine process** (steam turbine)
  - Organic Rankine process (ORC) (medium temperature; toluol)

    - day-night cycles problem: heat accumulators; flywheel storage

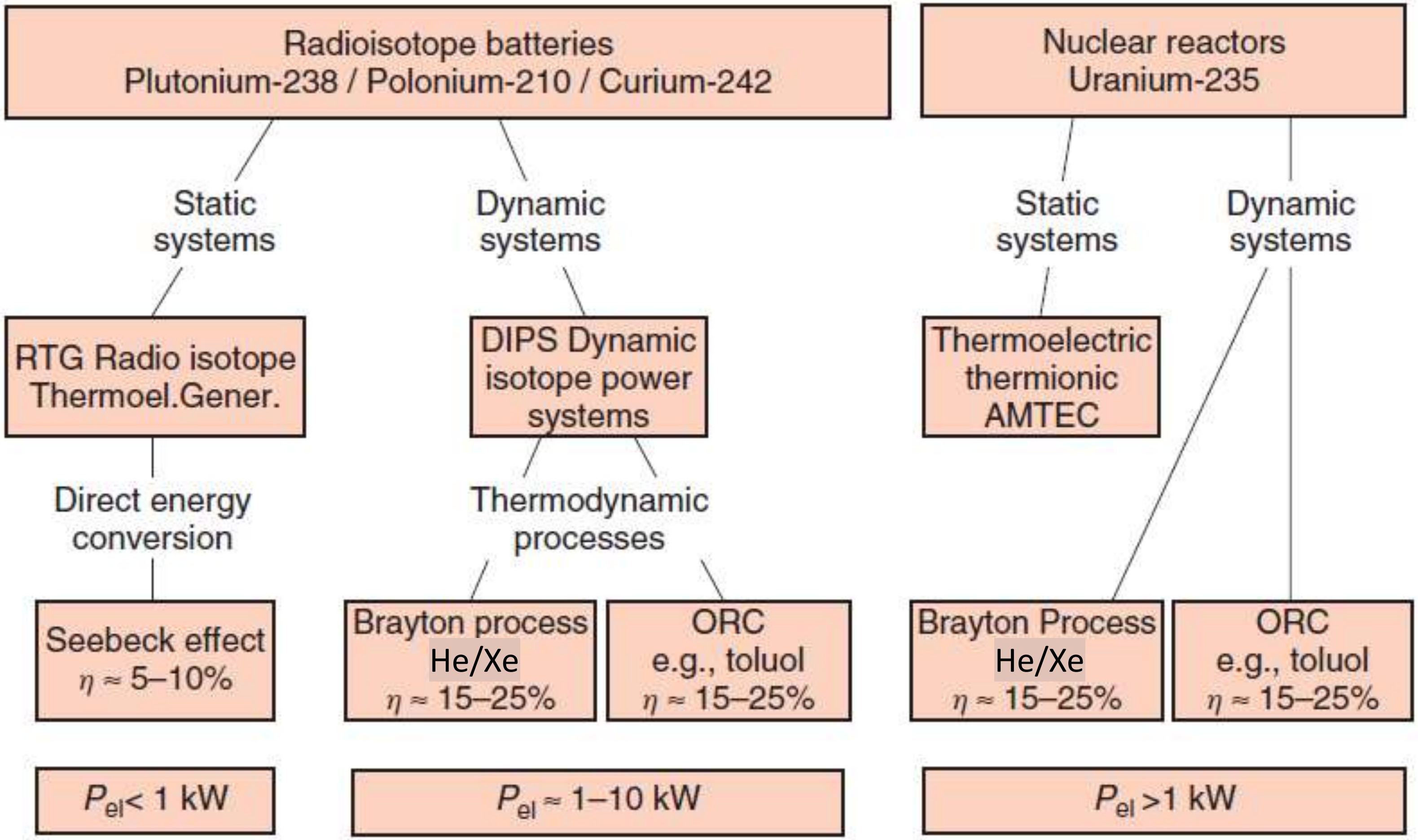
- Nuclear power supply
  - radioisotope thermoelectric generators (RTGs): Plutonium-238/Polonium-210/Curium-242
  - nuclear reactors: Uranium-235
    - direct energy conversion: thermoelectric effects
    - thermodynamic processes
  - **Pros and Cons** (e.g. Curiosity, Voyager)

Solar dynamic system



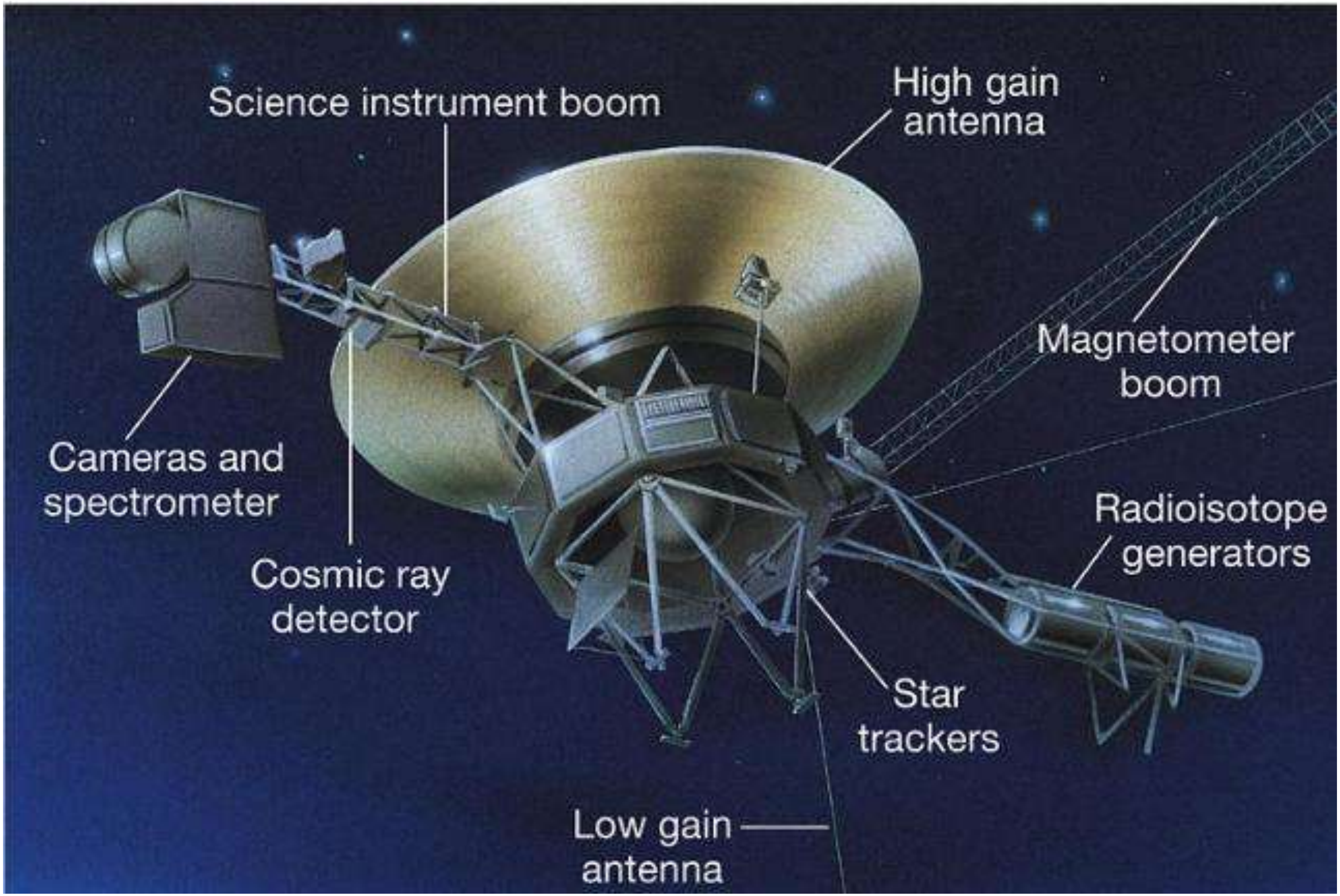
- ❑ High power can be generated (~100kW)
- ❑ Large additional mass
- ❑ Rotating elements problem (microgravity)
- ❑ Day/night cycles: flywheel energy storage is possible

Nuclear power sources

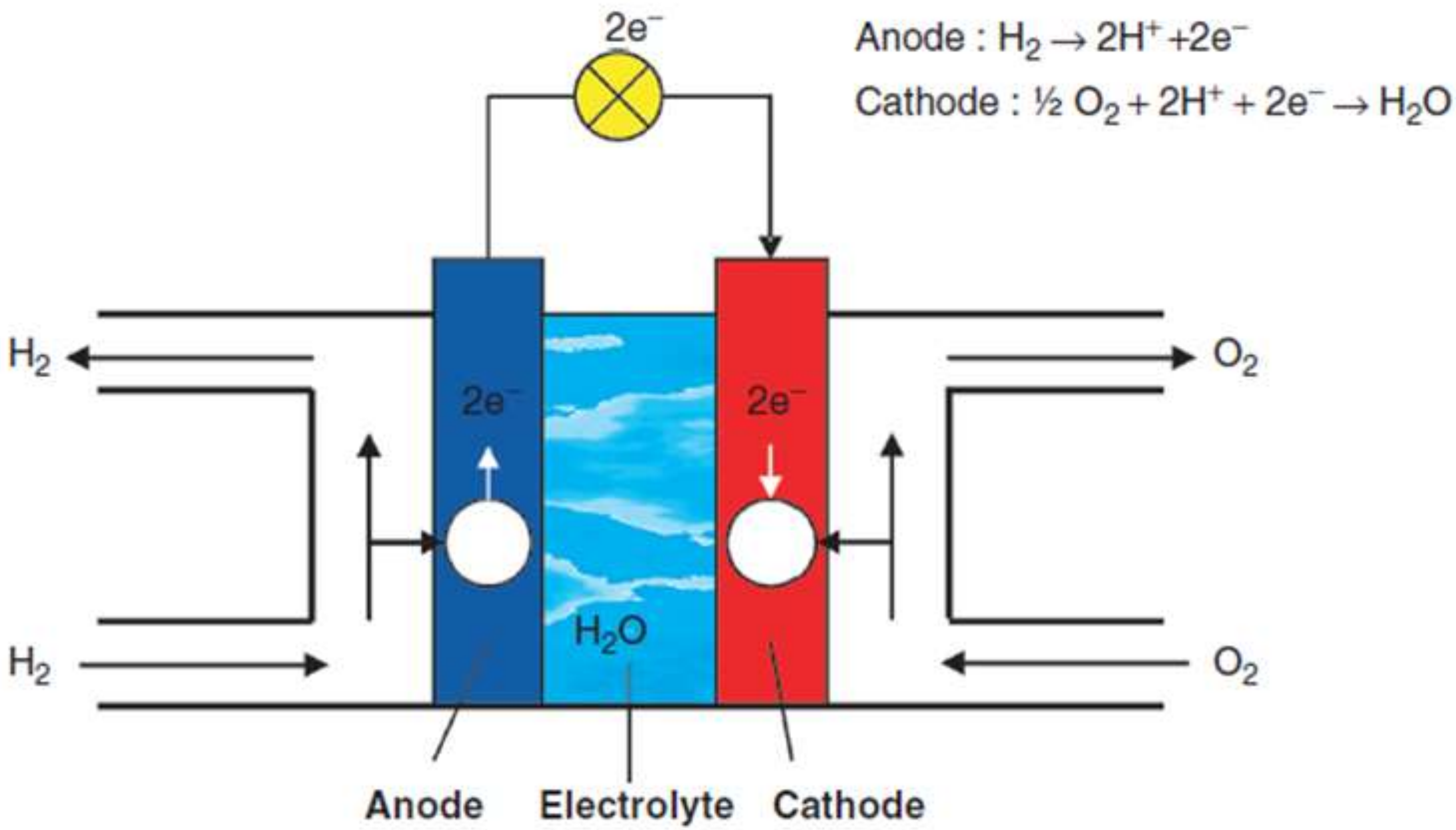


- Radioisotope thermoelectric generators (RTGs)
  - low efficiency (5-10%) and power (1kW)
- Nuclear reactors (fission system)
  - efficiency (10-20%), power (>20kW)

Voyager-1 (1977-2025?)



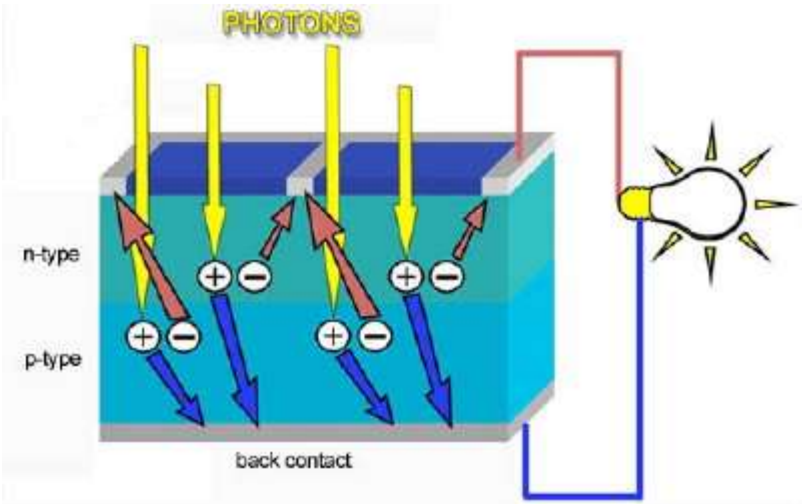
Fuel cells



- ❑ A reversed H_2O electrolysis
- ❑ Electrolyte (phosphoric acid H_3PO_4)
- ❑ Platinum catalyst on electrodes
- ❑ Open cell voltage: 1.2V

Solar cells/arrays 1.

- The photovoltaic effect:
  - light generates electron-hole pairs
  - electrons and holes are separated by the electric field in the semiconductor’s junction
- The solar cell: a large-area semiconductor with an integrated p/n-junction beneath its surface
- Orbit-dependency of the illumination



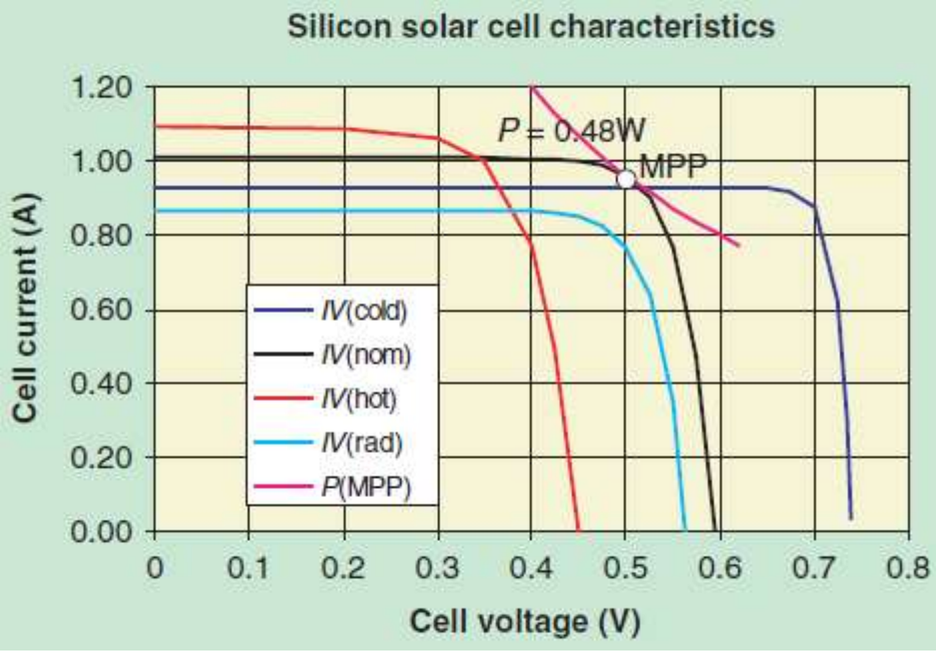
Solar cells/arrays 2.

Solar cell parameters:

- ❑ Short circuit current I_{sc} (voltage $V = 0$; load resistance $R = 0$)
- ❑ Open circuit voltage V_{oc} (current $I = 0$ at infinite load resistance $R = \infty$)
- ❑ Maximum power point current I_{mp} (current at maximum solar cell output power)
- ❑ Maximum power point voltage V_{mp} (voltage at maximum solar cell output power)
- ❑ Fill factor $(I_{sc} \times V_{oc})/(I_{mp} \times V_{mp})$
- ❑ Efficiency (10-15%)
- ❑ Changes of the above parameters caused by temperature or radiation

Typical current–voltage characteristic of a $26 cm^2$ silicon cell

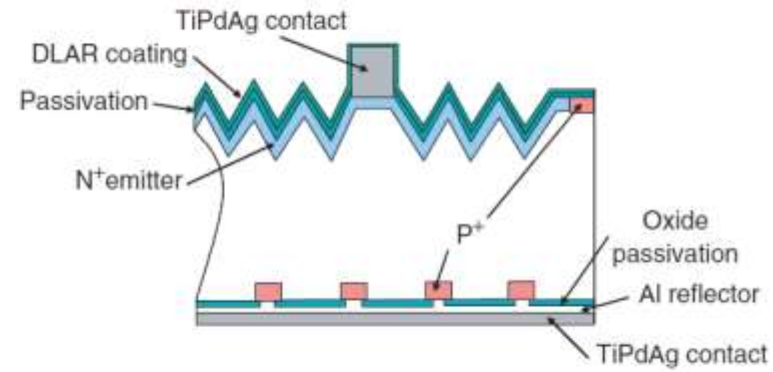
- Maximum power point (MPP) = 0.48 W
  - with photon intensity: ↑
  - with temperature: ↓
  - with radiation: ↓
- Operating in visible solar spectrum, but
  - ultraviolet and infrared sensitivity also exists



Solar cells/arrays 3.

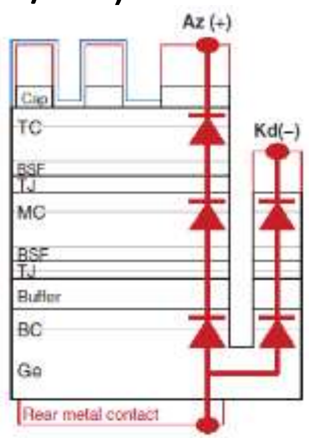
- Standard silicon solar cells
  - 0.18 mm thickness; built on a p-doped Si base material and a shallow p/n-junction
  - V_{mp}: 0.5V, I_{mp}: 43 mA/cm^2

- Hi-Eta (conversion efficiency) Si cells
  - 0.1 mm thickness, texturized surface
    - more sunlight absorption
    - higher efficiency (~17%)
  - V_{mp}: 0.5V, I_{mp}: 43 mA/cm^2



- Multijunction Gallium Arsenide on Germanium Solar Cells (Mj-GaAs/Ge)
  - grown by epitaxial processes on a Ge wafer (Ge wafer)
  - 0.14 mm thickness
  - reverse biasing sensitivity :

  each single cell is protected by shunt diode
  - V_{mp}: 2.3V, I_{mp}: 16 mA/cm^2



Solar cells operating conditions

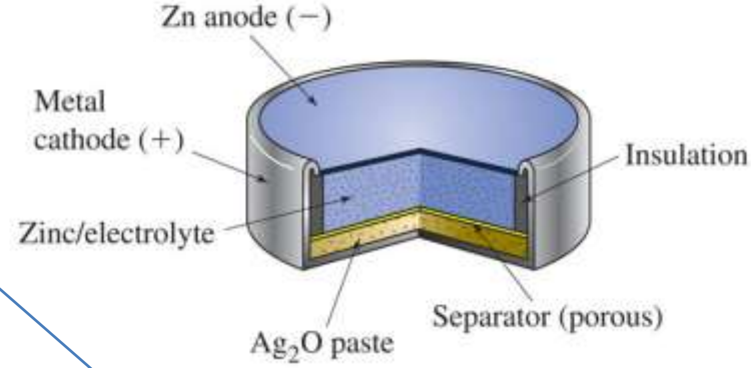
- Configurations
  - Body mounted
  - Deployable rigid/flexible or rollout

- Temperature, deployed, GaAs:
  - LEO, Sun synchronous: 70°C
  - LEO + Earth IR: 80°C
  - MEO: 65°C
  - GEO: 60°C
    - For body-mounted: additional ~20°C
    - Silicon cells: 10°C less

Energy storage: primary battery

Non-rechargeable

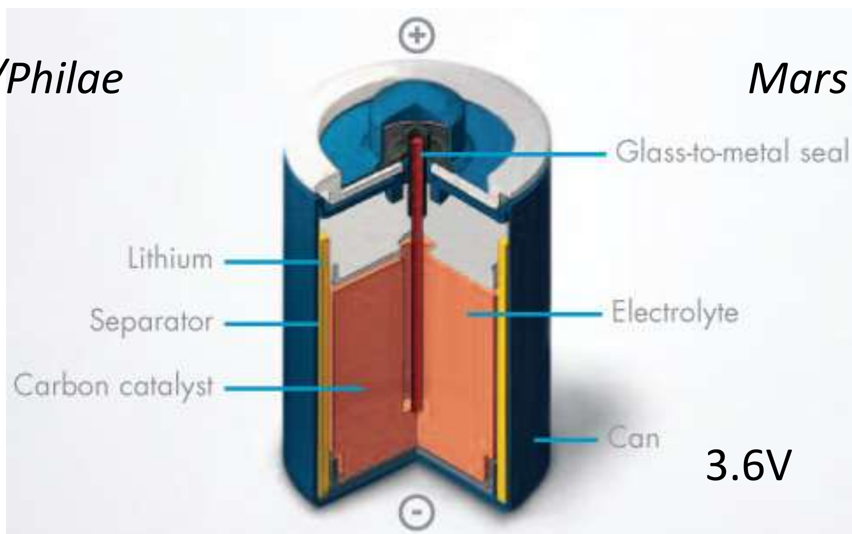
- ❑ silver–zinc, Ag-Zn
- ❑ lithium–sulfur dioxide Li-SO_2
- ❑ lithium thionylchloride Li-$SOCl_2$



1.6V

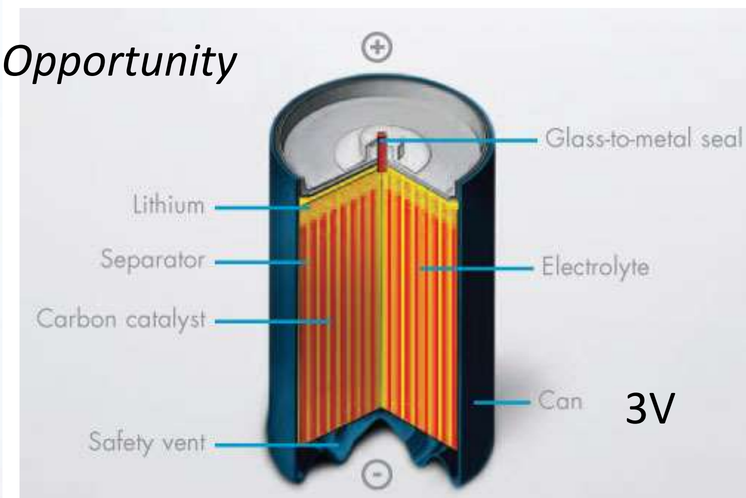
Sputnik-1

Rosetta/Philae



3.6V

Mars Opportunity



3V

-60 to +150°C, long term low current applications / high current applications

(Saft)

Energy storage: secondary batteries

<u>Rechargeable</u>

- ❑ nickel–cadmium (NiCd), ISS
- ❑ nickel–hydrogen (NiH_2), Hubble
- ❑ lithium-ion (Li-ion) (since 2002)

NiH_2 battery with 20 cells

- excellent lifecycle
- allow deep discharge
- tolerate reverse current

Li-ion cells (Saft)

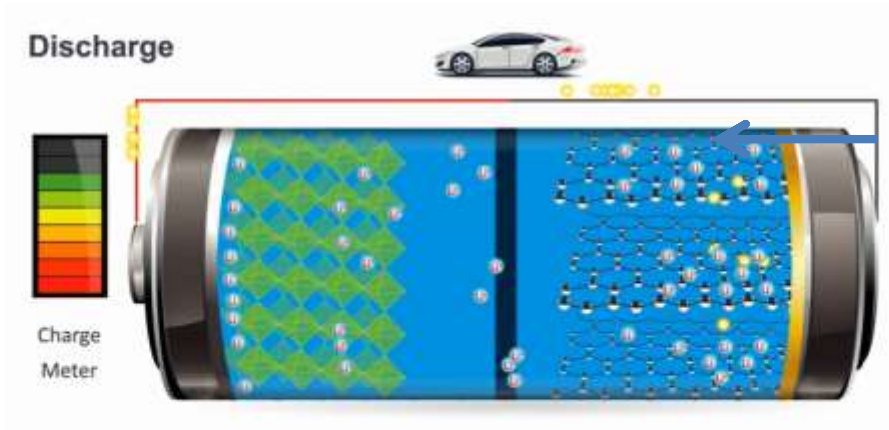
- double capacity vs. the others
- low voltage variation
- low power loss
- high protection is required
- battery management system is needed

NiCd cell

- similar to NiH_2
- lower overcharge and reverse current tolerance

Energy storage: secondary batteries

- How lithium-ion (Li-ion) battery works

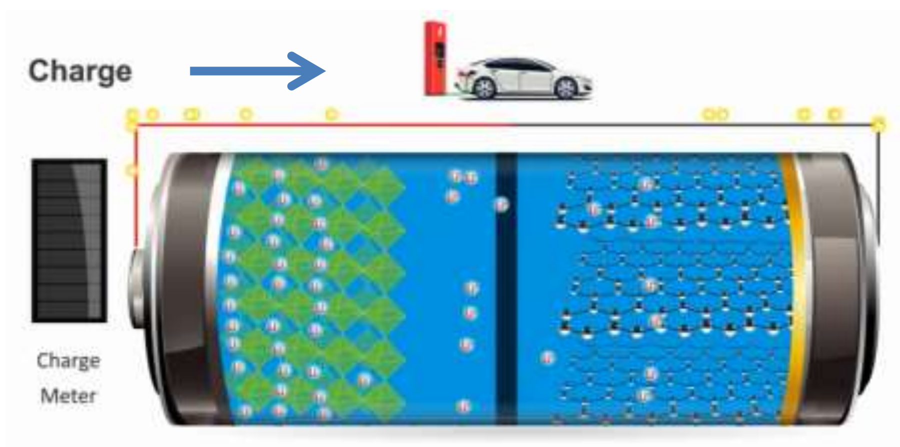


Electrolyte: Li salts

Anode

Separator

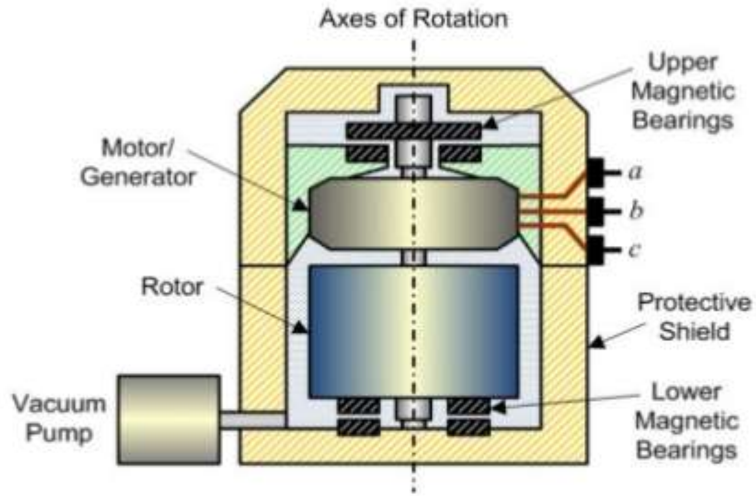
Cathode



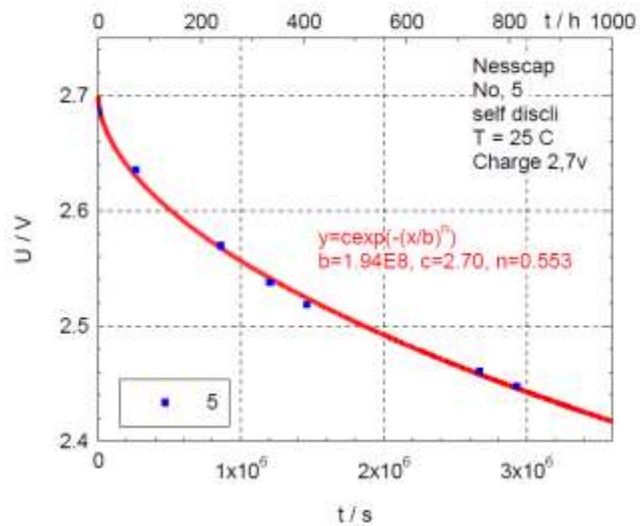
https://energy.gov/eere/articles/how-does-lithium-ion-battery-work

Energy storage: other possibilities

- Flywheel



- Fuel-cell
  - Solar Power->Electrolyzer->Fuel Cell

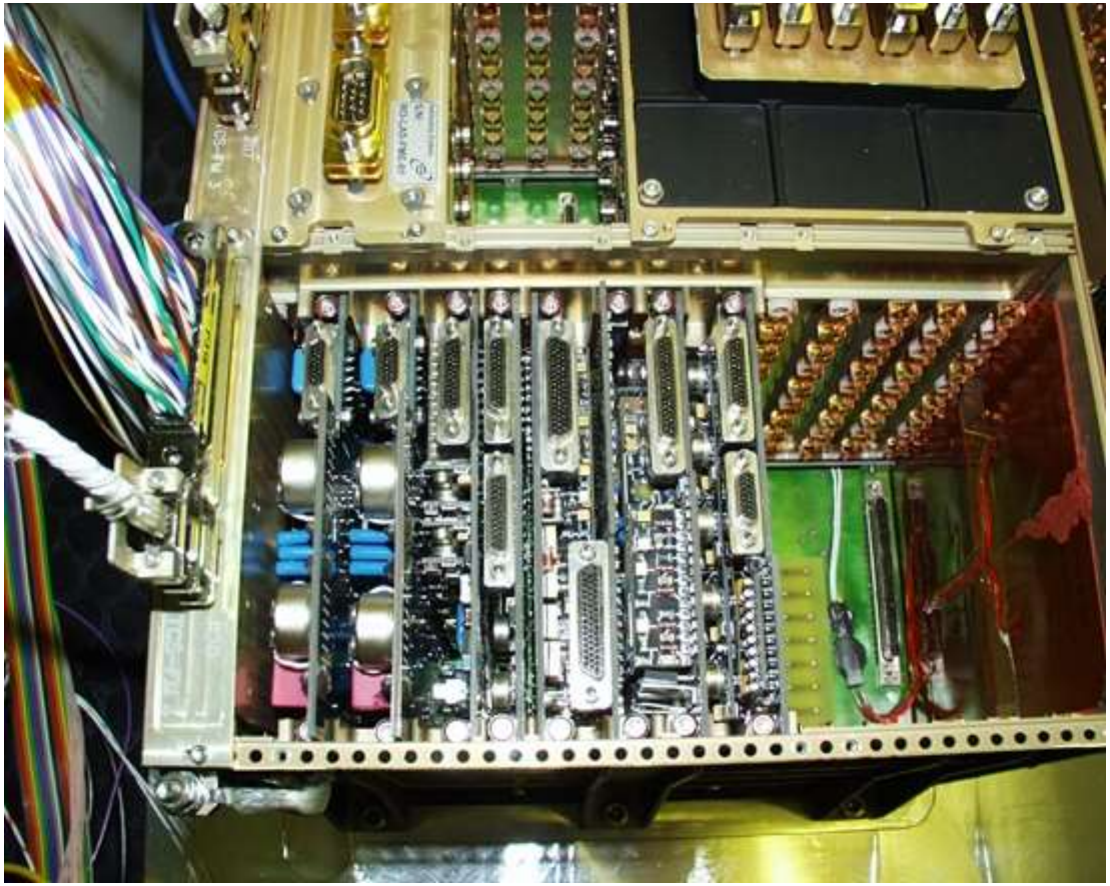


- Super-capacitor
  - 10-1000F !! capacitance

Self-discharge (NessCap 10 F/2.7 V) *Source: ESA*

Electrical Power Control & Distribution (PMU and PDU)

❑ Regulated power bus ❑ Unregulated power bus ❑ Combinations	❑ Solar array regulations: ▪ Shunt ▪ Linear power reg. ▪ String switching	❑ Supply the main bus: ▪ DC/DC converters ▪ MPPT control	❑ Distribution: ▪ Limiter switches

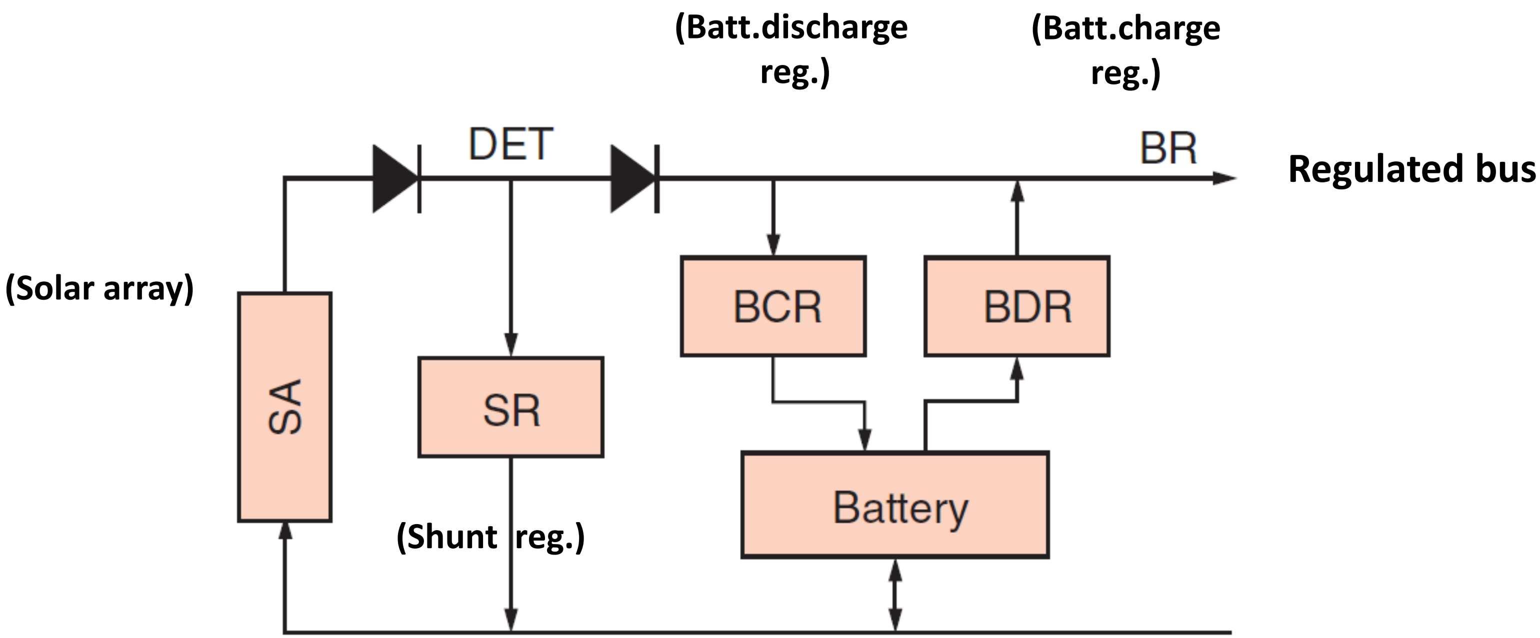


Rosetta Lander
EPS

Design basics

- Bus voltage: 20-128V
- DET (simpler electronics) or PPT (maximum of SA power can be utilized)
- Voltage converters and regulators: efficiency is a key issue
- Grounding: single point, the spacecraft is connected to the negative bus
- Power bus protection: passive or active limiters (overload or short-circuit protection)

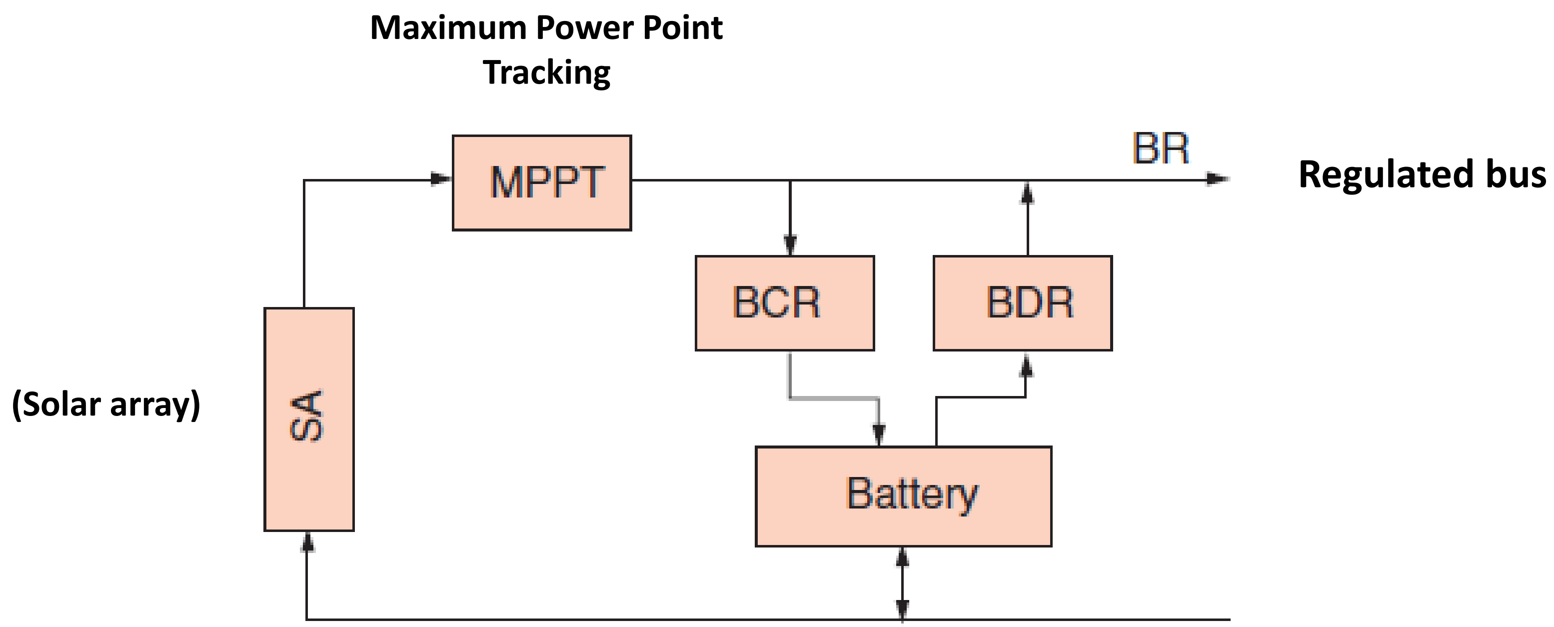
Power Control architectures 1. (parallel, regulated)



Regulated bus with Direct Energy Transfer (DET)

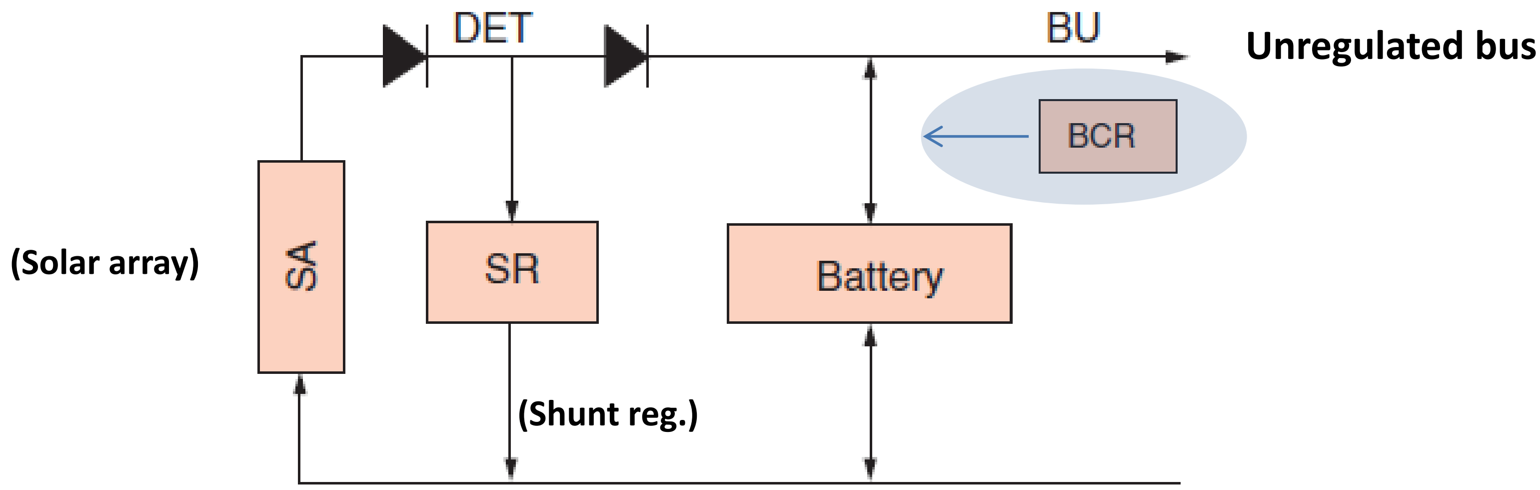
- **typically 28/50/100/125V, $\pm 0.5 - 5\%$**
- **users may powered directly from the bus / or using simple DC/DC converters**
- **excellent for two or more batteries if battery cannot connected parallel (single BCRs/BDRs)**
- **low source impedance**
- **power lockup-free**
- **complex control loop required**
- **power loss on BCR/BDR**

Power Control architectures 2. (serial, regulated)



Regulated bus with MPPT

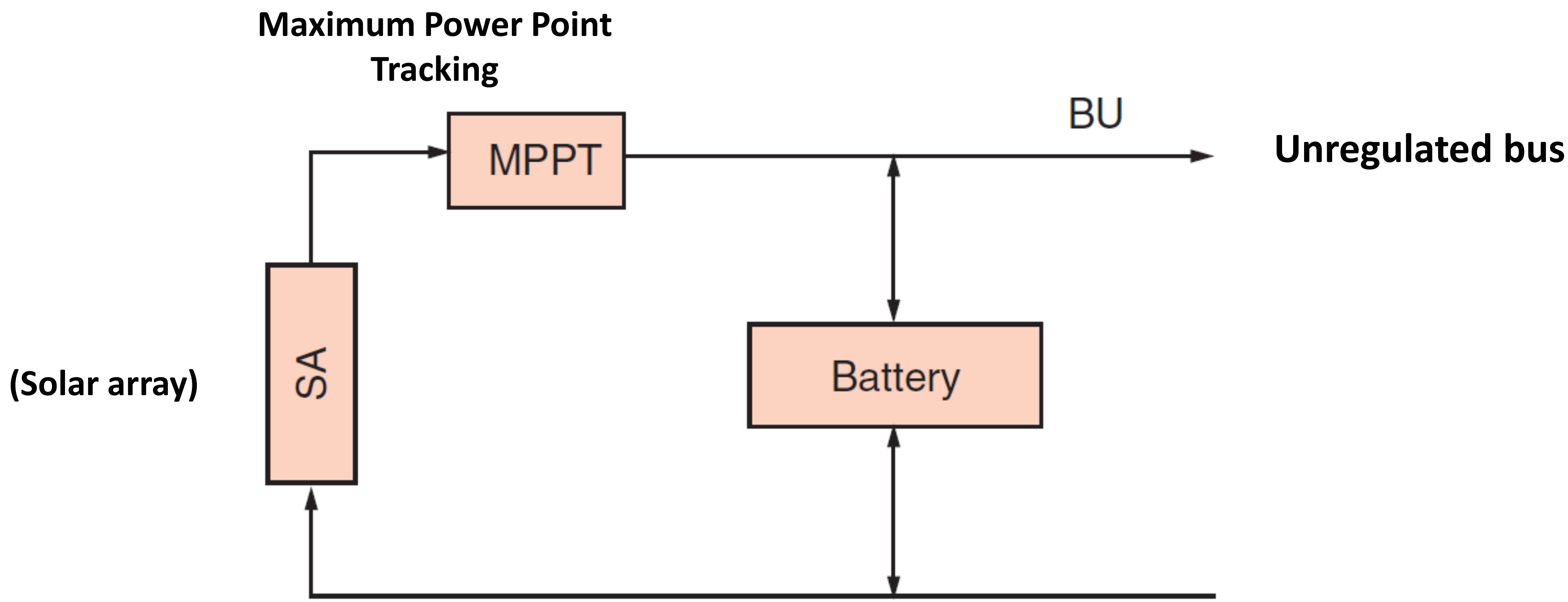
Power Control architectures 3. (parallel, unregulated)



Unregulated bus with DET

- Power lockup may occur (e.g. during dark->light transition):
  - solar array power is low (not in maximum power mode)
  - bus voltage clamped to battery
  - battery provides the power difference
  - battery is further (fully) discharged
- Solution:
  - reduce the load
  - increase solar power (turn toward the Sun)

Power Control architectures 4. (serial, unregulated)



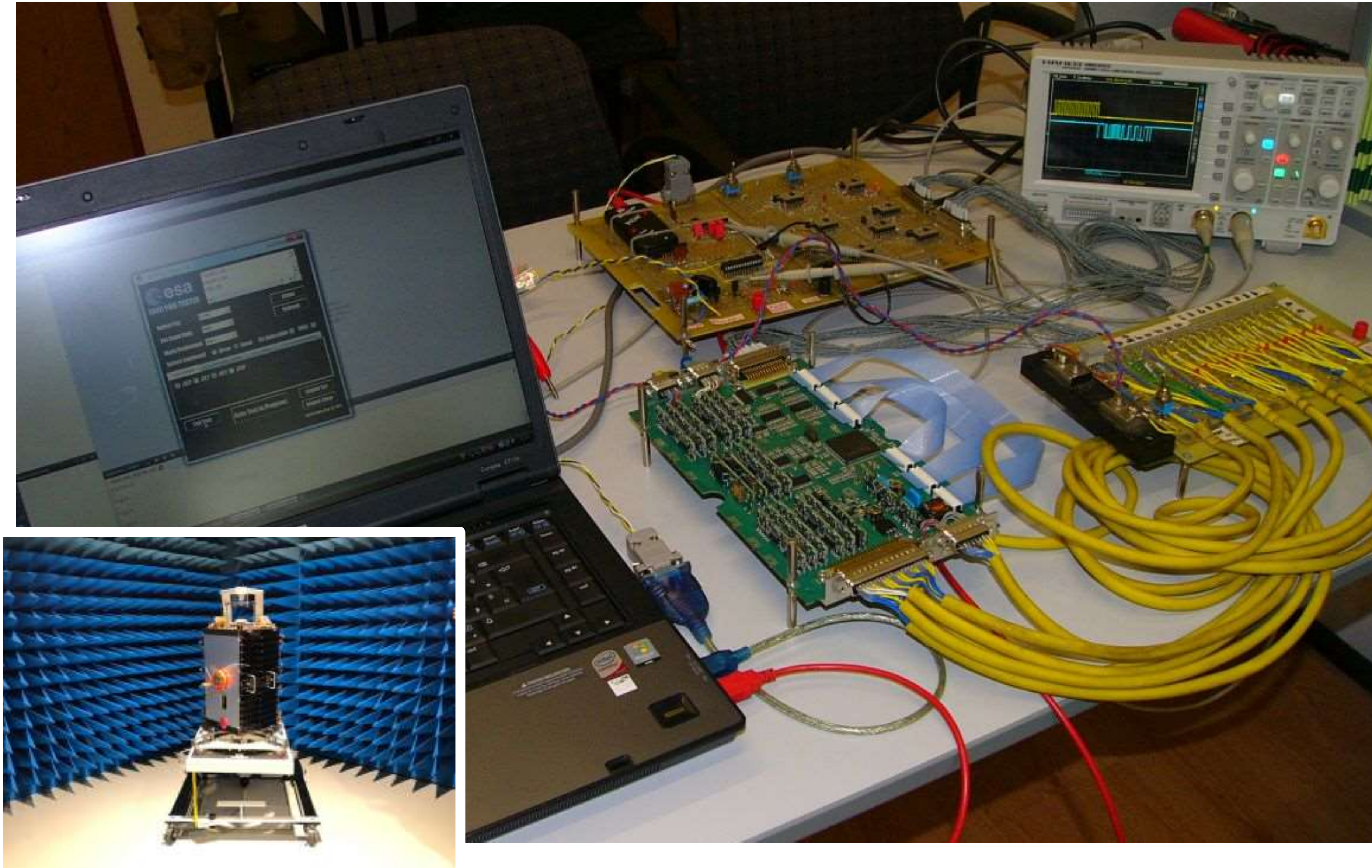
Unregulated bus with MPPT

- simpler
- 28/35/42V with $\pm$20% voltage fluctuation
- serially connected battery string is possible
- weight and cost saving
- less solar power is needed
- users need auxiliary power supply
- not suitable for more than one battery

Power Distribution

- Bus voltage
- Voltage fluctuation
- Impedance
- Bus capacity
- Loads on the bus:
    - Subsystem
    - Payload
    - Redundant/non-redundant systems
    - Load impedance
- Switches: semiconductor, relay
- Protection: fuse, PTC/NTC, diode, electronic
- Controlling the loads:
    - SW, LSW, LSW2, 2LSW2

Power Distribution Unit of the ESEO satellite



Sources:

- Gary D. Gordon, Walter L. Morgan:
  Principles of Communications Satellites
  Wiley, ISBN: 978-0-471-55796-8
- Wilfried Ley, Klaus Wittmann and Willi Hallmann (ed):
  Handbook of Space Technology
  Wiley, ISBN: 978-0-470-69739-9

Main topics / questions

- Energy generation methods: indirect and direct generation of electrical energy
- Converting non-electrical energy to electrical energy
- Energy storage methods
- The DET and the MPPT regulation
- Power distribution: application of LSW, LSW2 and 2LSW2