# EN671: Solar Energy Conversion Technology

## Standalone Photovoltaic System

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# Standalone PV system

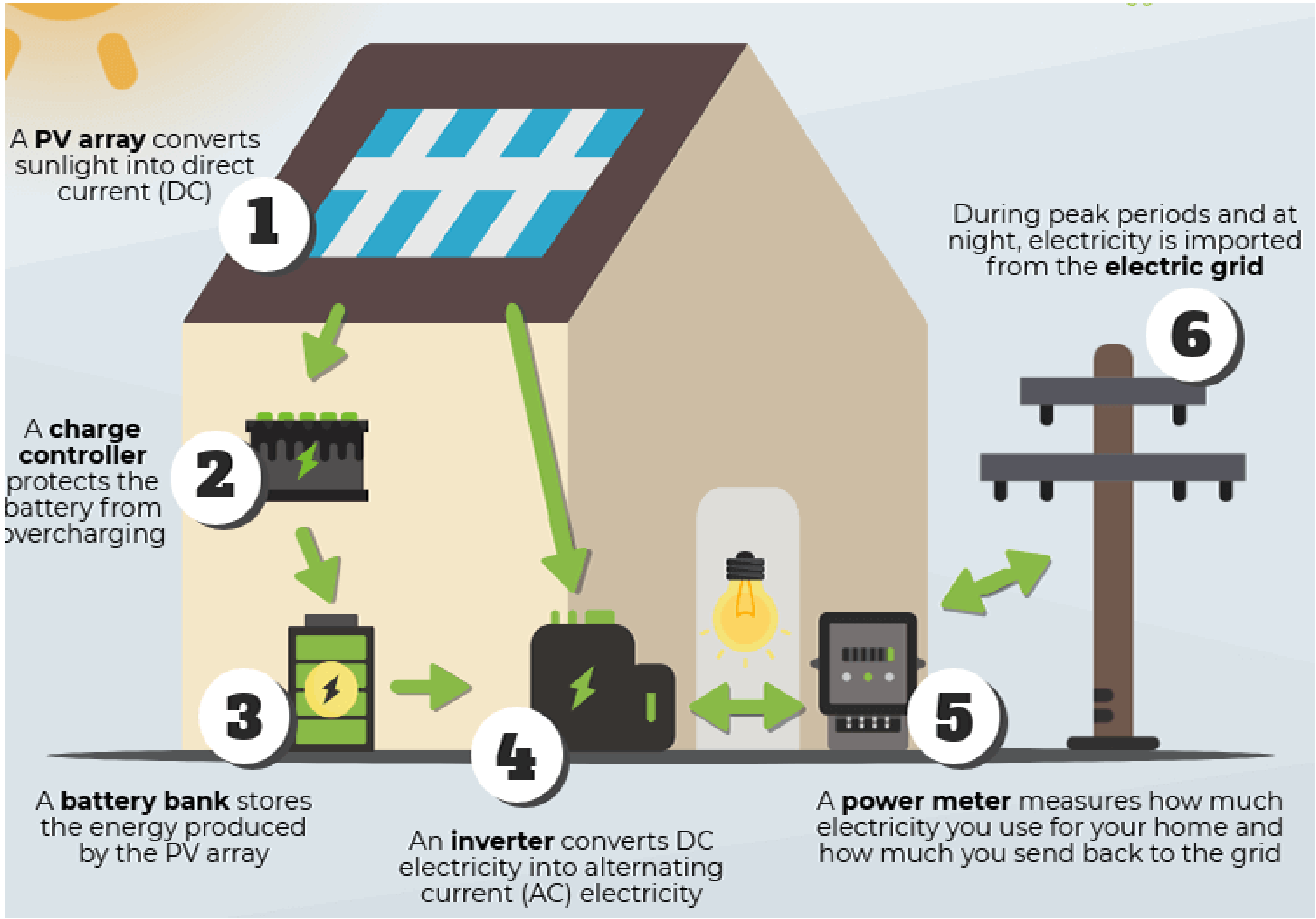
- **Components**
- **System design approach**

# Standalone system

- Solar PV system that produces electrical power to charge banks of batteries during the day for use at night.
- A standalone small scale PV system employs rechargeable batteries to store energy (supplied by a PV panels or array).
- Standalone PV systems are ideal for remote areas where other power sources are either impractical or unavailable to provide power for lighting and other uses.

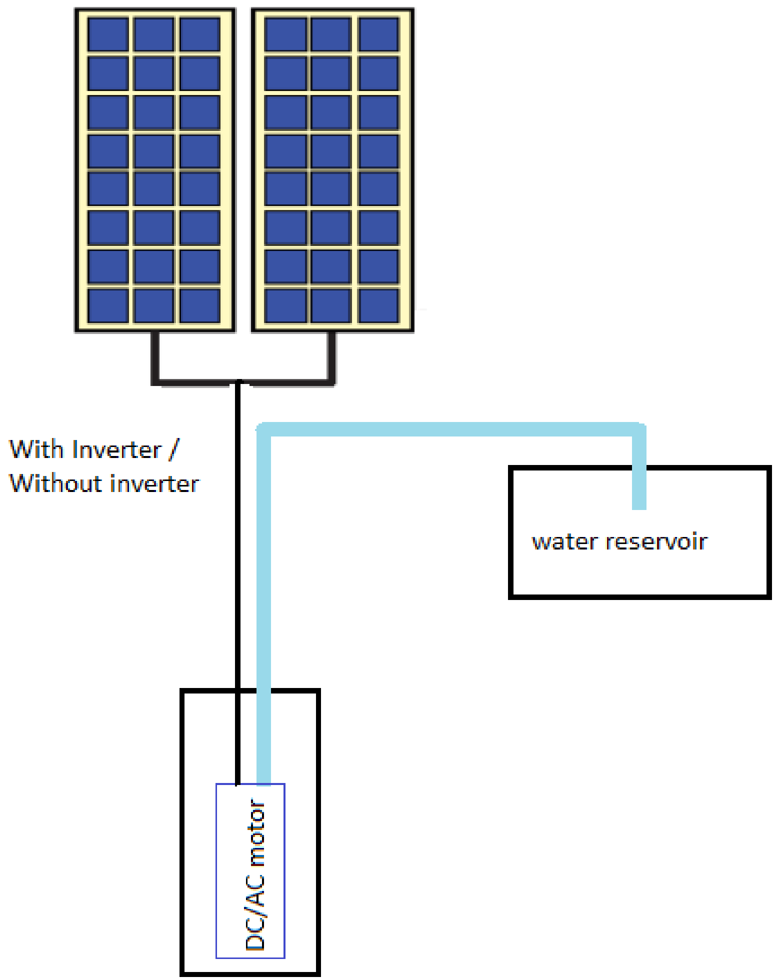
# Different components of PV systems

- PV Modules
- Mounting structure
- Charge controller
- Battery
- Inverters /DC-DC converter
- Cables



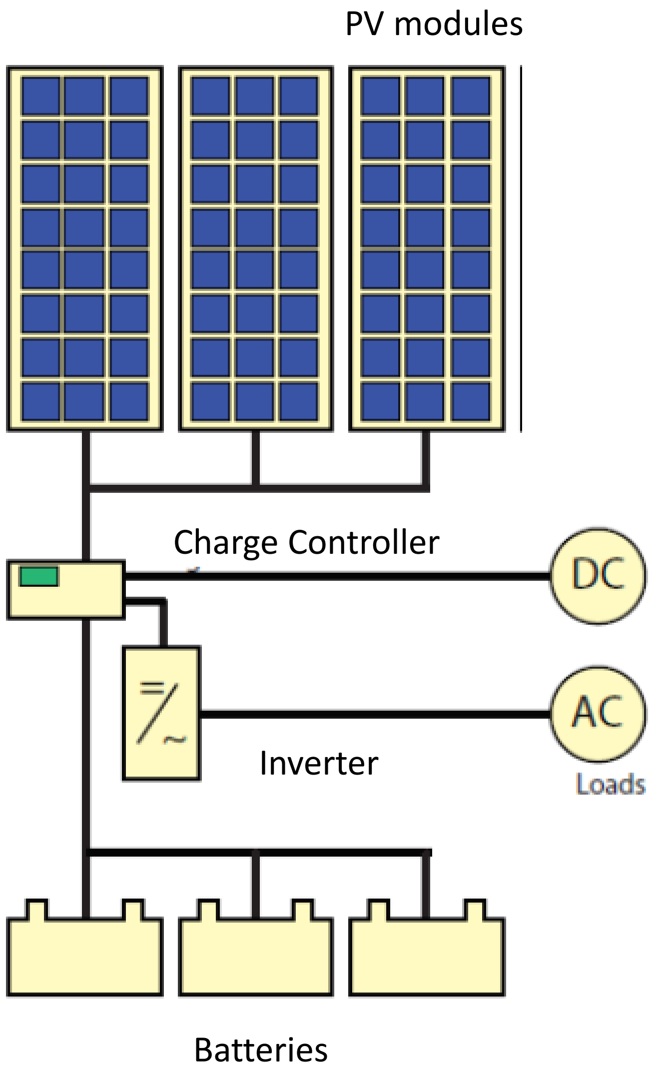
# Standalone systems

Irrigation



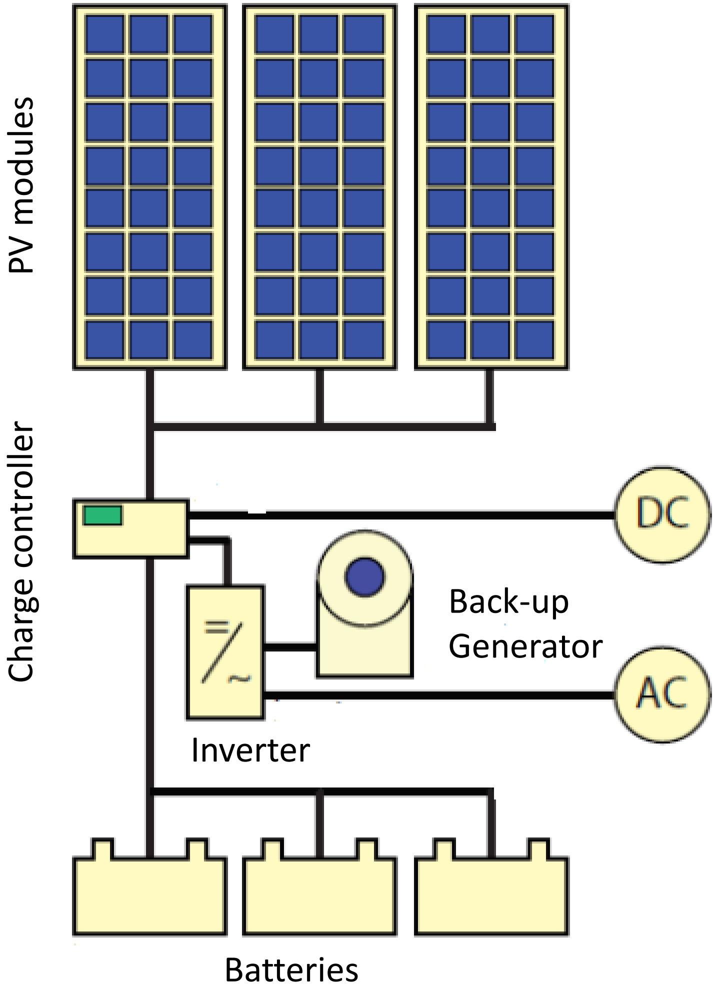

A simple DC PV system to power a water pump with no energy storage

Street light




A complex PV system including batteries, power conditioners, and both DC and AC loads.

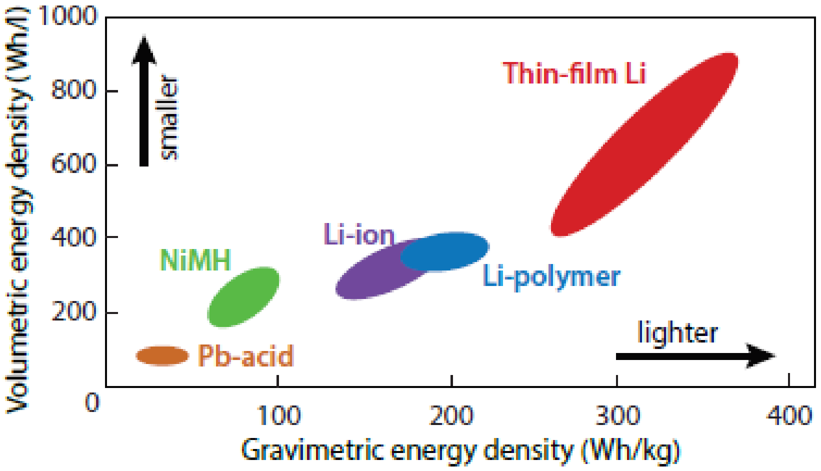
# Hybrid systems with diesel generator



# Batteries

❑ Batteries are electrochemical devices that converts chemical energy into electrical energy.

- ✓ **Primary batteries** **(convert chemical energy to electrical energy irreversibly)** - Zinc Carbon and alkaline batteries are primary batteries.
- ✓ **Secondary batteries** **(rechargeable batteries, convert chemical energy to electrical energy reversibly)** - lead acid or lithium ion batteries.


A Ragone chart

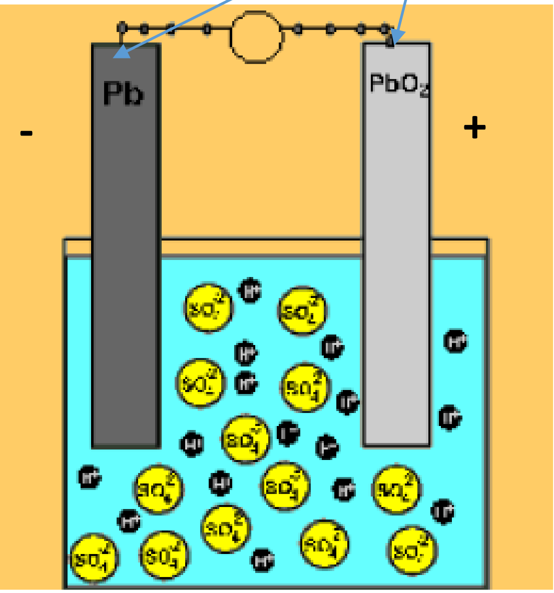
- ➢ The gravimetric energy density is the amount of energy stored per unit mass of the battery (Wh/kg).
- ➢ The volumetric energy density is the amount of energy stored per unit volume of battery (Wh/l).

- ✓ The higher the gravimetric energy density, the lighter the battery can be.
- ✓ The higher the volumetric energy density, the smaller the battery can be.

# Lead- acid batteries

- ✓ Oldest
- ✓ Technology is mature

The electrodes contain grid shaped lead carrier and porous active material.




- A typical battery is composed of several individual cells of which each has a nominal cell voltage of about 2 V

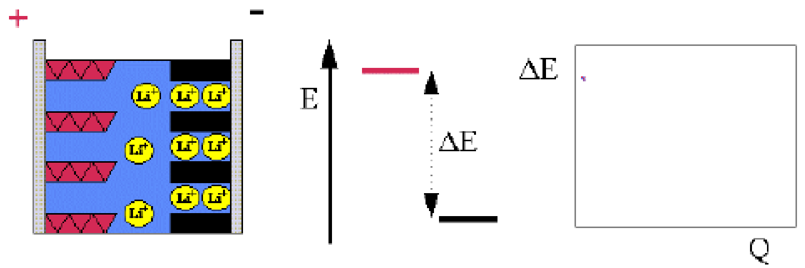
- When the battery is discharged, electrons flow from the negative to the positive electrode through the external circuit, causing a chemical reaction between the plates and the electrolyte. This forward reaction also depletes the electrolyte, affecting its state of charge (SoC).
- When the battery is recharged, the flow of electrons is reversed, as the external circuit does not have a load, but a source with a voltage higher than that of the battery enables the reverse reaction.

✓ The porous active material has a sponge-like structure (provides sufficient surface area for the electrochemical reaction).

$$\mathrm{Pb}(s)+\mathrm{PbO_2}(s)+2\mathrm{H_2SO_4}(aq)\rightarrow 2\mathrm{PbSO_4}(s)+2\mathrm{H_2O}(l);\ E^o_{cell}=2.05\ \mathrm{V}$$

# Lithium-ion/ Lithium-ion polymer batteries

- High energy density has made them favorable technology for light-weight storage applications (mobile)
- These technologies still suffers from high costs and low maturity.




# Battery parameters

- **Voltage:** The voltage at that the battery is rated is the nominal voltage at which the battery is supposed to operate.
  - Solar batteries or lead acid grid plate batteries are usually rated at 12 V, 24 V or 48 V
- **Capacity:** Refers to the amount of charge that the battery can deliver at the rated voltage.
  - The capacity is directly proportional to the amount of electrode material in the battery.
  - The voltage of the cell is more chemistry based, while the capacity is more based on the quantity of the active materials used.

✓ The capacity ($C_{bat}$) is measured in ampere-hours (Ah).
✓ Charge usually is measured in coulomb (C).
✓ As the electric current is defined as the rate of flow of electric charge, Ah is another unit of charge. Since 1 C = 1 As, 1 Ah = 3600 C.

**The energy capacity of a battery :** $E_{bat} = C_{bat} \times V$ Wh

# Battery parameters

- **C-rate:** A measure of the rate of discharge of the battery relative to its capacity. It is defined as the multiple of the current over the discharge current that the battery can sustain over one hour. A brand new battery with 10 Ah capacity theoretically can deliver 1 A current for 10 hours at room temperature.
- C-rate of 1 for a 10 Ah battery corresponds to a discharge current of 10 A over 1 hour.
- C-rate of 2 for the same battery would correspond to a discharge current of 20 A over half an hour.
- C-rate of 0.5 implies a discharge current of 5 A over 2 hours.
- In general, it can be said that a C-rate of “n” corresponds to the battery getting fully discharged in 1/n hours, irrespective of the battery capacity.

# Battery Parameters

- **Battery efficiency**
  - Voltaic efficiency: The ratio of the average discharging voltage to the average charging voltage.

$$\eta_V = \frac{V_{discharge}}{V_{charge}} \times 100\%$$

  - Coulombic efficiency (or Faraday efficiency): Ratio of the total charge got out of the battery to the total charge put into the battery over a full charge cycle.

$$\eta_c = \frac{Q_{discharge}}{Q_{charge}} \times 100\%$$

- Battery efficiency is defined as the product of these two efficiencies:

$$\eta_{bat} = \eta_V \times \eta_c = \frac{V_{discharge}}{V_{charge}} \times \frac{Q_{discharge}}{Q_{charge}} \times 100\%$$

✓ Battery efficiency is considered for comparison of different storage devices.
✓ It includes all the effects (chemical and electrical) occurring in the battery.

# Battery Parameters

- **State of charge (SoC):** It is defined as the percentage of the battery capacity available for discharge.

$$\text{SoC} = \frac{E_{bat}}{C_{bat} \times V}$$

A 10 Ah rated battery that has been drained by 2 Ah is said to have a SoC of 80%.

- **Depth of discharge (DoD):** It is defined as the percentage of the battery capacity that has been discharged.

$$DoD = \frac{C_{bat} \times V - E_{bat}}{C_{bat} \times V}$$

A 10 Ah battery that has been drained by 2 Ah has a DoD of 20%.

The SoC and the DoD are complimentary to each other.

- **Cycle lifetime:** It is defined as the number of charging and discharging cycles after the battery capacity drops below 80% of the nominal value.
  - Colder operating temperatures mean longer cycle lifetimes.
  - The smaller the DoD, the higher the cycle lifetime

# Battery Parameters

- **Temperature effects:**
  - Battery life is increase at lower temperature.
  - Lower the temperature - lower the battery capacity.

The chemicals in the battery are more active at higher temperatures, and the increased chemical activity leads to increased battery capacity.

- **Ageing:** The major cause for ageing of the battery is sulphation.
  - If the battery is insufficiently recharged after being discharged, sulphate crystals start to grow, which cannot be completely transformed back into lead or lead oxide. Thus the battery slowly loses its active material mass and hence its discharge capacity.
  - Corrosion of the lead grid at the electrode is another common ageing mechanism. As a result of corrosion grid resistance increases due to high positive potentials. Further, the electrolyte can dry out.
  - At high charging voltages, gassing can occur, which results in the loss of water. Thus, demineralized water should be used to refill the battery from time to time.

# Charge Controller

- Charge controllers are used in PV systems that use batteries (stand-alone systems).
- It is very important to charge and discharge batteries at the right voltage and current levels in order to ensure a long battery lifetime.
- A battery is an electrochemical device that requires a small over-potential to be charged.
- The amount of current sent to the battery by the PV array and the current flowing through the battery while being discharged have to be within well-defined limits for proper functioning of the battery.
- PV array responds dynamically to ambient conditions like irradiance, temperature and other factors like shading.

Directly coupling the battery to the PV array and the loads is detrimental to the battery lifetime. Therefore a device is needed that controls the currents flowing between the battery, the PV array and the load and that ensures that the electrical parameters present at the battery are kept within the specifications given by the battery manufacturer.

**FUNCTION OF A CHARGE CONTROLLER**

# Functioning of a Charge Controller

- ✓ When the sun is shining at peak hours during summer, the generated PV power excesses the load. The excess energy is sent to the battery. When the battery is fully charged, and the PV array is still connected to the battery, the battery might overcharge - cause several problems like gas formation, capacity loss or overheating. *The charge controller plays a vital role by de-coupling the PV array from the battery.*

- ✓ During severe winter days at low irradiance, battery is heavily discharged as the load exceeds the power generated by the PV array. Over-discharging the battery has a detrimental effect on the cycle lifetime. The charge controller prevents the battery from being over-discharged by disconnecting the battery from the load.

- ✓ The PV array will have its $V_{mpp}$ at different levels, based on the temperature and irradiance conditions. Hence, the charge controller needs to perform appropriate voltage regulation to ensure the battery operates in the specified voltage range, while the PV array is operating at the MPP. Modern charge controllers often have an MPP tracker integrated.

- ✓ A charge controller that contains a proper current regulation is also able to control the C-rates. Finally, the charge controller can impose the limits on the maximal currents flowing into and from the battery.

# Cables

PV systems usually contain DC and AC parts. For correctly installing a PV system, it is important to know the color conventions.

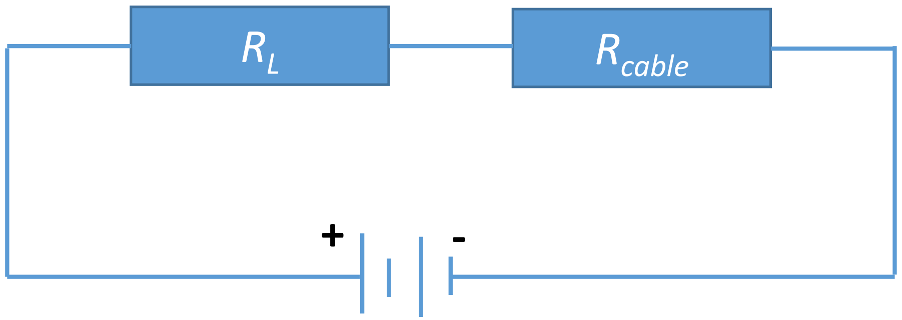
- **Red** is used for connecting the **+-** contacts of the different system components with each other
- **Black** is used for interconnecting the **--**contacts.

For AC wiring, different colour conventions are used around the world.

- ✓ For example, in the European Union, **blue** is used for neutral, **green**-**yellow** is used for the protective earth and **brown** (or another color) is used for the phase.
- ✓ In the United States and Canada,**silver** is used for neutral, **green**-**yellow**, **green** or a **bare** conductor is used
- ✓ for the protective earth and **black** (or another color) is used for the phase.
- ✓ In India and Pakistan, **black** is used for neutral, **green** is used for the protective earth and **blue**, **red**, or **yellow** is used for the phase.

# Cable losses

- ✓ The cables have to be chosen such that resistive losses are minimal.
- ✓ For estimating these losses consider a system consists of a power source and a load with resistance $R_L$ and the cables have a resistance $R_{cable}$




Power loss at the cable: $\boxed{P_{cable} = I \times \Delta V_{cable}}$

$\Delta V_{cable}$ Voltage drop across the cable

$$\boxed{\Delta V_{cable} = V \times \frac{R_{cable}}{R_L + R_{cable}}} \qquad \boxed{V = I \times \left(R_L + R_{cable}\right)}$$

$$\boxed{P_{cable} = I^2 \times R_{cable}}$$

Hence, as the current doubles, four times as much heat will be dissipated at the cables. It now is obvious why modern modules have connected all cells in series.

# Resistance of Cable

Let us now calculate the resistance of a cable with length "*l*" and cross section "*A*". It is clear, that if "*l*" is doubled, also $R_{cable}$ doubles. In contrast, if "*A*" doubles, $R_{cable}$ decreases to half. The resistance thus is given by

$$\boxed{R_{cable} = \rho\frac{l}{A} = \frac{1}{\sigma}\times\frac{l}{A}}$$

where $\rho$ is the specific resistance or resistivity and $\sigma$ is the specific conductance or conductivity. If both, "*l*"\` and A are given in metres, their units are $[\rho] = \Omega.\mathrm{m}$ and $[\sigma] = \mathrm{s/m}$ where S denotes the unit for conductivity, which is Siemens.

**The most widely used metals used for electrical cables are copper and aluminium.**

$$\rho_{\mathrm{Cu}} = 1.68\cdot 10^{-8}\,\Omega\cdot\mathrm{m} = 1.68\cdot 10^{-2}\,\Omega\frac{\mathrm{mm}^2}{\mathrm{m}},$$

$$\sigma_{\mathrm{Cu}} = 5.96\cdot 10^{7}\,\frac{\mathrm{S}}{\mathrm{m}} = 59.6\,\mathrm{S}\frac{\mathrm{m}}{\mathrm{mm}^2},$$

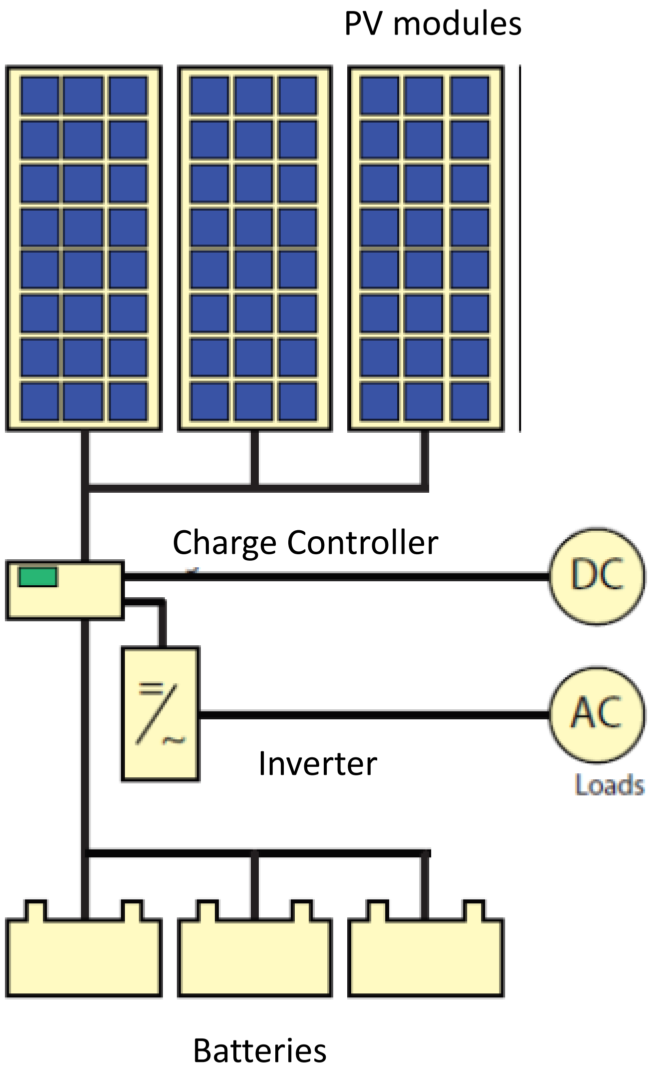
$$\rho_{\mathrm{Al}} = 2.82\cdot 10^{-8}\,\Omega\cdot\mathrm{m} = 2.82\cdot 10^{-2}\,\Omega\frac{\mathrm{mm}^2}{\mathrm{m}},$$

$$\sigma_{\mathrm{Al}} = 3.55\cdot 10^{7}\,\frac{\mathrm{S}}{\mathrm{m}} = 35.5\,\mathrm{S}\frac{\mathrm{m}}{\mathrm{mm}^2}.$$

- ✓ Usual thicknesses for cables are 0.75 $mm^2$, 1.5 $mm^2$, 2.5 $mm^2$, 4 $mm^2$, 6 $mm^2$, 10 $mm^2$, 16 $mm^2$, 25 $mm^2$, 35 $mm^2$.
- ✓ Since DC circuits are driven at lower voltages than AC currents, the currents are higher, requiring thicker cables.

# A simple approach for designing off-grid systems

- Total load current and operational time
- System losses
- Solar irradiation in daily equivalent sun hours (ESH)
- Total solar array current requirements
- Optimum module arrangement for solar array
- Battery size for recommended reserve time



A

A 12 V PV system has two DC appliances A and B requiring 15 and 20 W respectively. The average operational time per day is 6 hours for device A and 3 hours for device B. The daily energy

Device A: 15W x 6 h = 90Wh
Device B: 20W x 3 h = 60Wh
Total: 90Wh + 60Wh = 150Wh
150Wh/12V = 12.5Ah

I

B

An AC computer and TV set are connected to the PV system. The rated power of computer is 40W, runs 2 hours per day and the TV set with rated power of 60W is 3 hours per day in operation. Inverter efficiency = 0.85. The daily energy requirements of the devices expressed in DC Ah are calculated as

Computer: 40W x 2 h = 80Wh
TV: 60W x 3 h = 180Wh
Total: 80Wh + 180Wh = 260Wh
DC requirement: 260Wh/0.85 = 306 Wh
306Wh/12V = 25.5Ah

II

C

**System losses is about 20-30%.** By considering 20% system losses, the total DC requirement of loads (using equation 1 and 2)

**(12.5Ah + 25.5Ah)x 1.2 = 45.6Ah**

D Equivalent sun hours for Guwahati = 4 hrs

E The required total current generated by the solar array is total DC loads to the ESH,

45.6Ah / 4 h = 11.4 A.

| Number of cells | 36 |
| --- | --- |
| Nominal voltage | 12 V |
| Voc | 21.2 V |
| Isc (rated current) | 4.9 A |
| Conversion efficiency | 12.5 % |

F
- ✓ The number of modules in parallel is 11.4 A / 4.9 h = 2.32~3 nos. of modules.
- ✓ The nominal voltage of the PV system is 12V and the nominal module voltage is 12V. The required number of modules in series thus is 12V/ 12V = 1 module

G
- ✓ The total DC requirements of loads plus the system losses are 45.6Ah. The recommended reserve time capacity for Guwahati is 2 days.
- ✓ The Battery capacity required by the system is 45.6Ah x 2 = 91.2 Ah.
- ✓ The minimum battery capacity for a safe operation = 114 Ah (by considering 80% of its capacity)
- ✓ If 12V, 90 Ah battery is considered then no of batteries required approx. ~ 2

# Summary

- Components of a standalone PV system
  - PV module
  - Charge controller
  - Battery
  - Inverter
  - Load
- Design step of a standalone PV system
- Working example

Thank you