Πανεπιστήμιο Κύπρου

PHAETHON CENTRE OF EXCELLENCE | Education & Training Centre

PHAETHON Summer Training School

Lecture Session – Hybrid solar-plus-storage systems

Battery energy storage fundamentals

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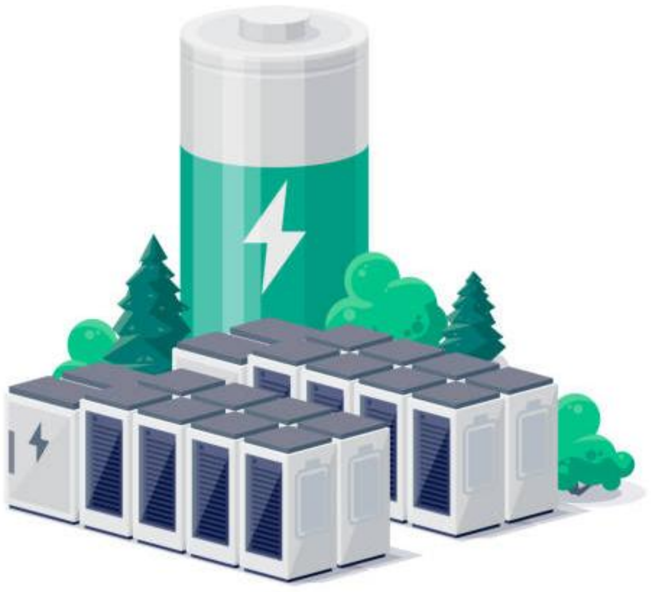
Module Content

- Introduction
- Battery types
- Battery characteristics
- Lifespan
- Battery connection
- System Installation - Health & Safety
- Summary

Introduction

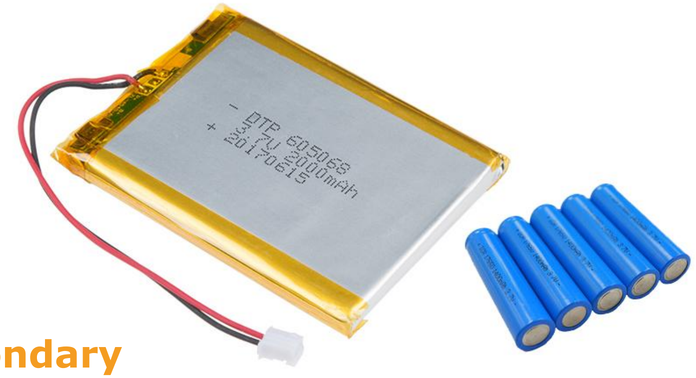
- Energy storage is now a key element of the energy sector:
  - Currently, it is the technology that offers mature energy storage solutions.
  - Significant synergies with renewable energy sources.



Introduction

- Batteries are categorized as primary or secondary.
- Primary are "disposable" and cannot be recharged. Dry cells (Zinc Carbon) and alkaline batteries are examples of primary batteries.
- The second type is rechargeable and is called a secondary battery. Examples of secondary batteries include nickel-cadmium (NiCd), lead-acid, and lithium-ion batteries.

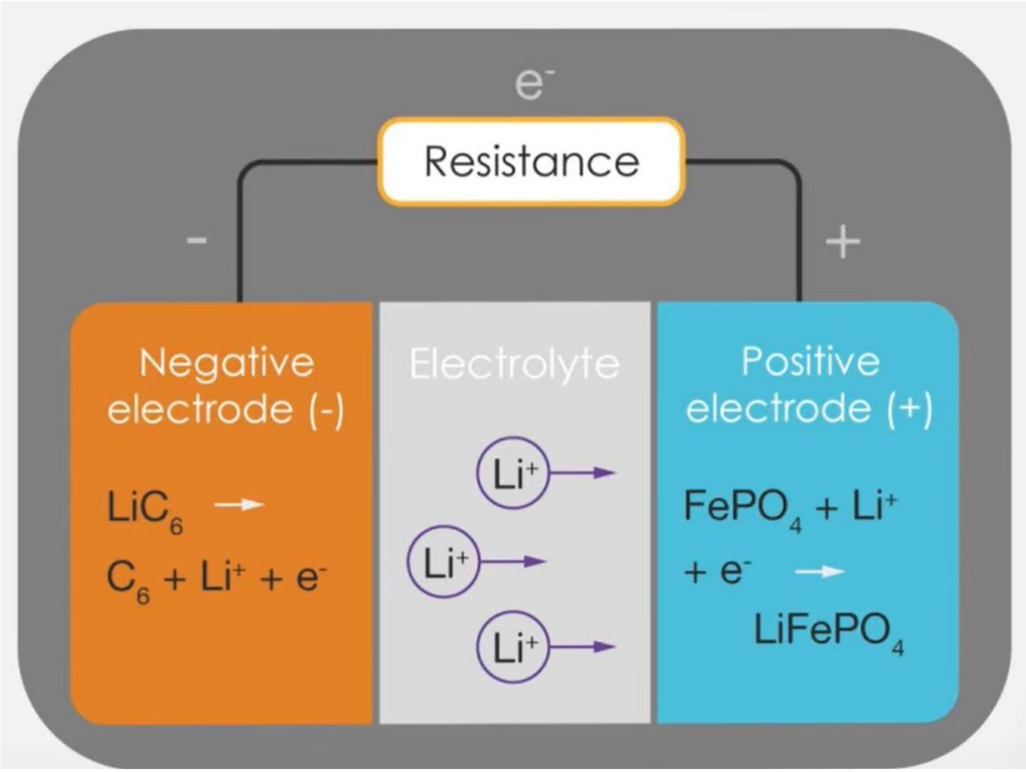
Primary



Secondary

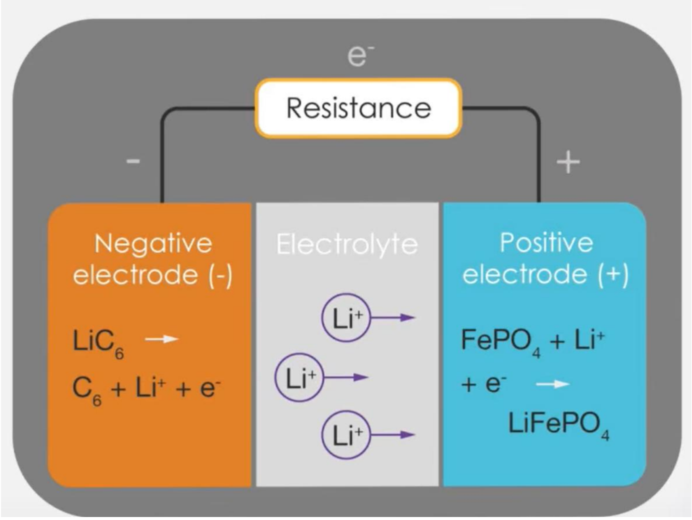
Operating principle

- Three main elements make up the battery:
  - Anode
  - Cathode
  - Electrolyte



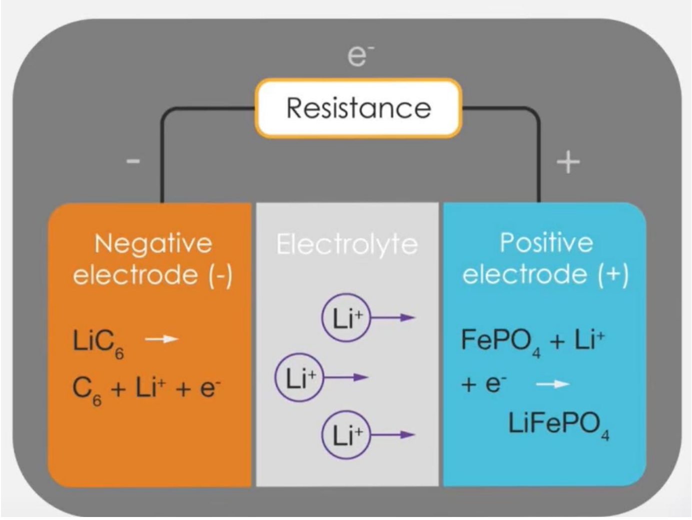
Operating principle

- The anode is the negative electrode that releases electrons into the circuit and is oxidized during the electrochemical reaction.
- The cathode is the positive electrode that receives electrons from the external circuit and is reduced during the electrochemical reaction.
- The electrolyte and separator avoid physical contact with the anode and cathode.



Operating principle

- An ion is an atom or molecule with a net electrical charge (has a surplus of electrons).
- When all ions move from the anode to the cathode, the battery discharges.
- When all ions move from the cathode to the anode, the battery charges.



Battery Characteristics

- Suitable characteristics
  - Energy/power density
  - Lifetime
  - Capital/operating cost
  - Storage capacity/duration
  - Roundtrip efficiency
  - Response time
  - Technological maturity

ImportantBattery Characteristics

- **Energy Capacity (kWh):**
  - The theoretical energy capacity that can be drawn from the battery at a specific constant current, starting from a fully charged state.
  - It is the voltage provided by the battery multiplied by how much current the battery can provide for a specific period (generally one hour).
- **Nominal Power or Rated Power (W):**
  - The amount of power that can be drawn from the battery instantaneously.
  - The W is the voltage provided by the battery multiplied by how much current the battery can provide at a specific moment.

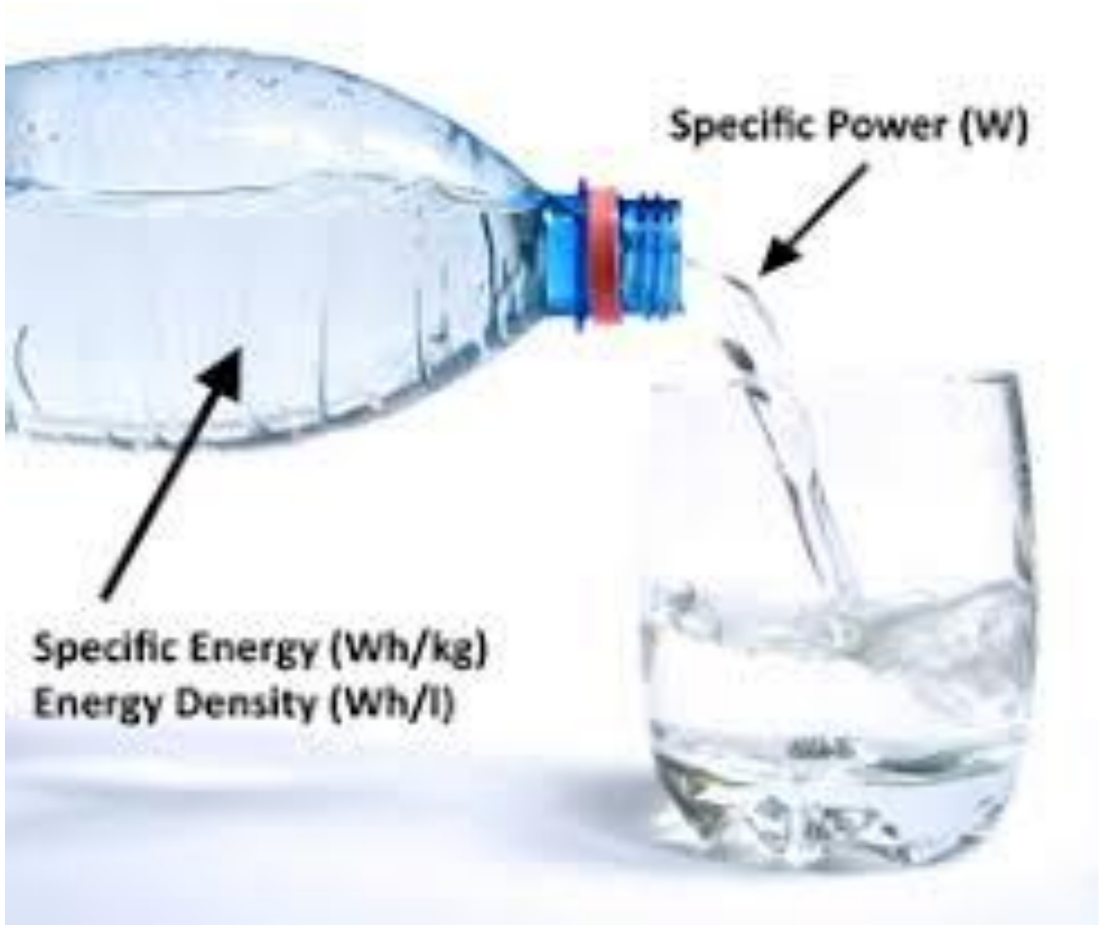
Important Battery Characteristics

Energy Density or Specific Energy (Wh/kg or Wh/L)

- The energy capacity per unit weight of the battery.

Power Density or Specific Power (W/kg or W/L)

- The maximum power per unit weight of the battery that can be produced in a short period. It is important for reducing the weight of the battery, especially in applications that require high power, such as electric vehicles (Electric Vehicles – EVs).



Important Battery Characteristics

- **Self-discharge (%/day):**
  - Self-discharge is a phenomenon in batteries in which internal chemical reactions reduce the stored charge of the battery without any connection between the electrodes or any external circuit, i.e. the energy capacity lost when the cell is simply idle.
  - Self-discharge increases with age, life cycles, and increased temperature.

Important Battery Characteristics

- **Operating Temperature Range (°C):**
  - Operating temperature is the temperature at which the battery operates. Outside of this safe operating temperature range, the device may fail.
- **Charge/Discharge Duration or Charge/Discharge Time (seconds):**
  - The time required to charge/discharge the battery for a specific current. It also depends on the chemical composition of the battery.

Important Battery Characteristics

- **Charging/Discharging Rate or C-rate (C):**
  - The charge/discharge rate is a measure of the rate at which the battery is charged/discharged relative to its capacity. It is defined as the charge/discharge current divided by the battery's ability to store electrical charge.

Important Battery Characteristics

- C-Rate Equations:

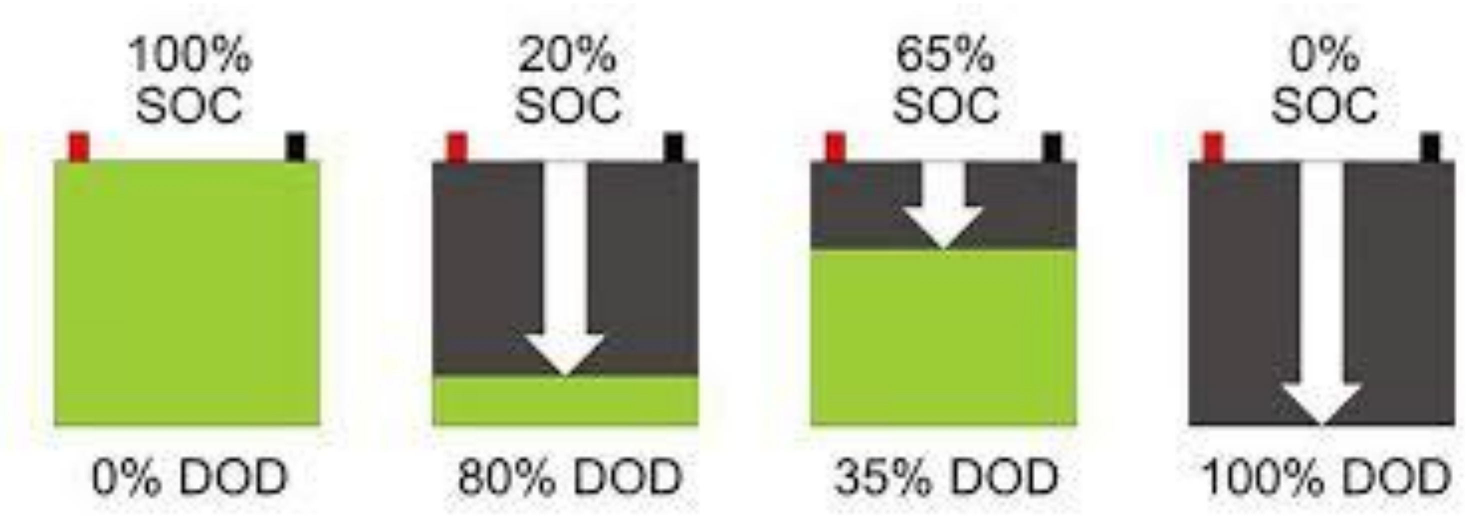
- t = time (hour)
- Cr = C-rate (1/hour)
- T = 1/Cr (to view in hours)

- Er = Rated energy (Ah)
- Cr = C-rate (1/hour)
- I = Cr x Er (to view in Amperes)

Example
2.3 Ah Battery
2C x 2.3 = 4.6 A
1 / 2C = 0.5 hours

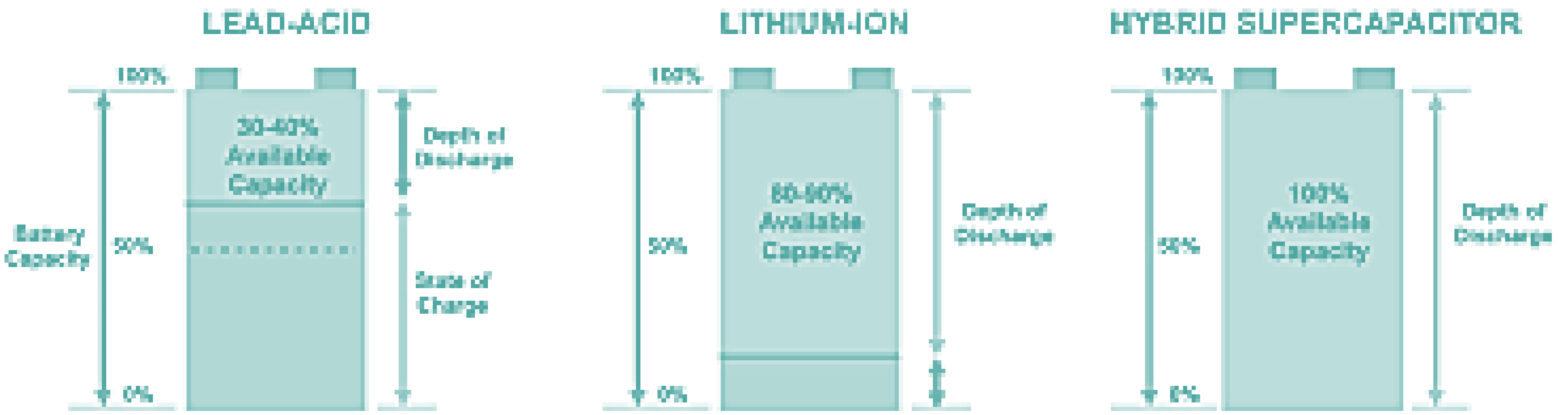
Important Battery Characteristics

- **Depth-of-Discharge (%):**
  - The Depth-of-Discharge (DoD) of the battery is the percentage of the energy capacity to which the battery has been discharged during its use. A battery discharge of more than 80% of capacity is called Deep Discharge (or Deep Cycle).



Important Battery Characteristics

- **Depth-of-Discharge (%):**
  - Different battery technologies have different depths of discharge.



Important Battery Characteristics

- **State-of-Charge (%):**
  - The current energy capacity of the battery. This is the amount of charge remaining compared to the full load capacity. The State-of-Charge (SoC) is complementary to the DoD.
- **State-of-Health (%):**
  - The State-of-Health (SoH) of the battery is a measure of the battery's ability to store and deliver energy, compared to ideal conditions. Typical SoH methods characterize either the power or energy of the battery.

Important Battery Characteristics

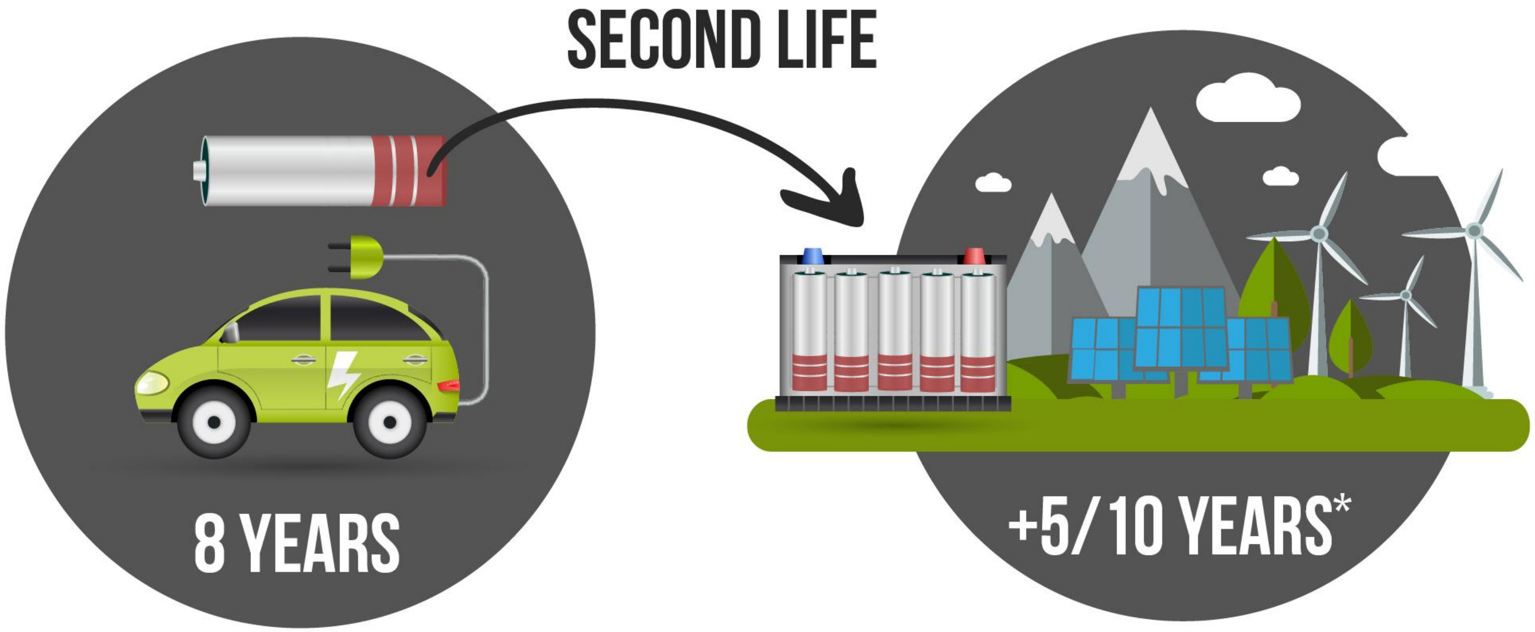
- **Efficiency (%):**
  - Power and energy losses during charging/discharging occur in the form of voltage loss. Thus, the efficiency of the battery during charging or discharging can be defined as the ratio of the cell voltage to the rated voltage.
- **Cycle Life (# of cycles):**
  - Each cycle of full discharge and then full charge is called a battery cycle. The cycle life of a battery can range from hundreds to several thousand cycles. It is affected by DoD and C-rate.
- **Calendar Life (# of years):**
  - The duration the battery is expected to last in calendar years. It is independent of how much the battery is charged and discharged, but is affected by SoC and Operating Temperature.

Important Battery Characteristics

- **Battery degradation (%):**
  - Battery degradation is a natural process that permanently reduces the amount of energy a battery can store or the power it can deliver. It is highly dependent on various factors such as C-rate, DoD, Operating Temperature etc.
- **Mass (kg):**
  - The measure of the battery's resistance to acceleration when a force is applied.
- **Size (W x H x D in mm):**
  - The size or dimensions of the battery.
- **Warranty (# of years):**
  - A type of guarantee offered by the manufacturer regarding the condition of the battery. It also refers to the terms and conditions under which repairs or replacements will be made in the event of battery failure.

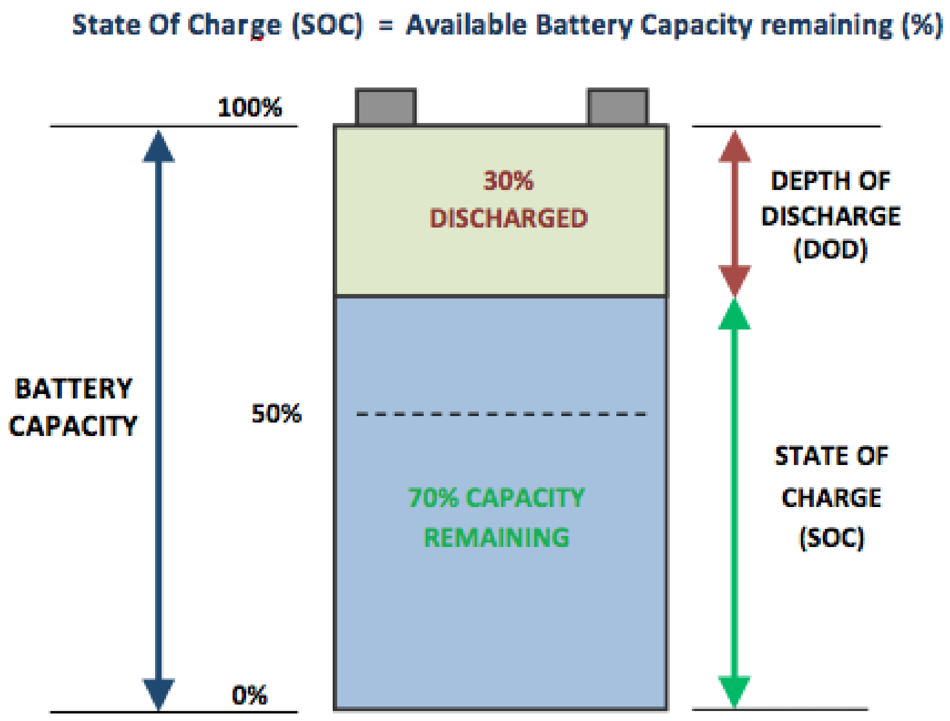
Important Battery Characteristics

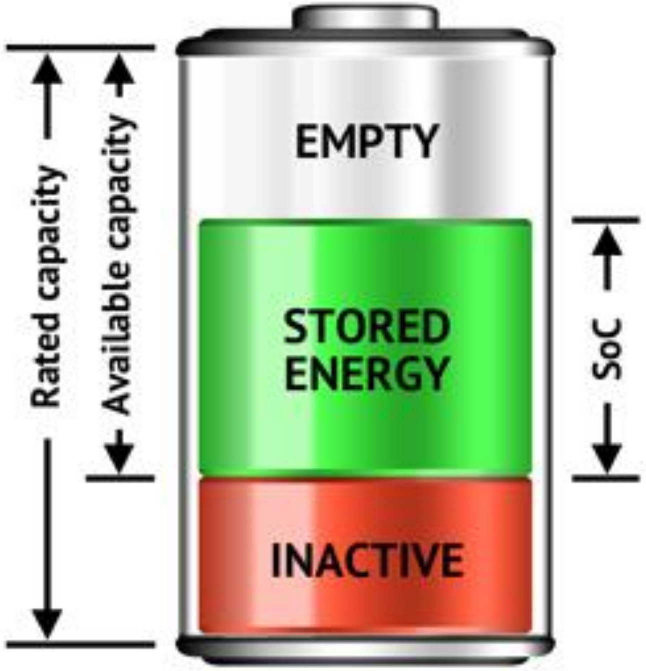
- **End-of life (%):**
  - The battery life is at 70% at which point the battery will have much faster degradation and potentially some heating issues.

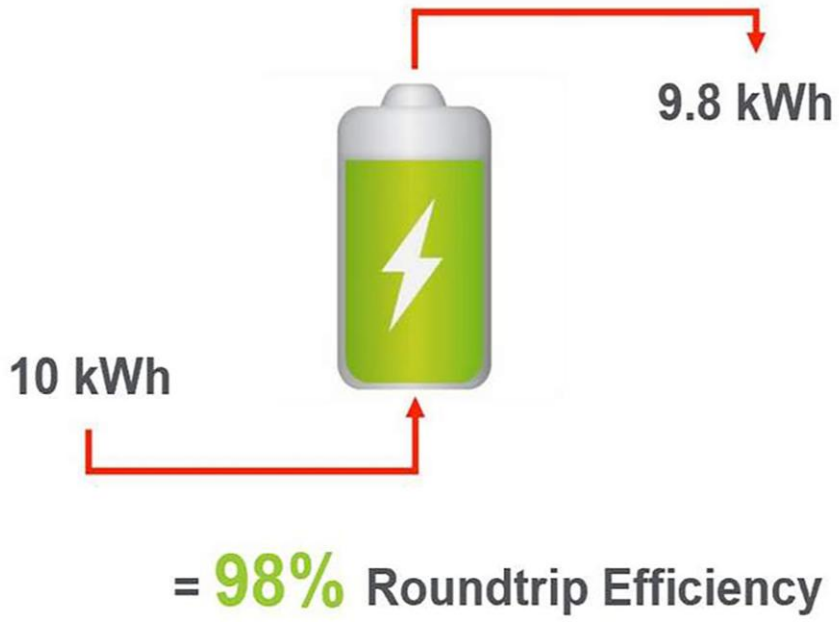


Important Battery Characteristics

- Battery characteristics – State of Charge and Discharge.



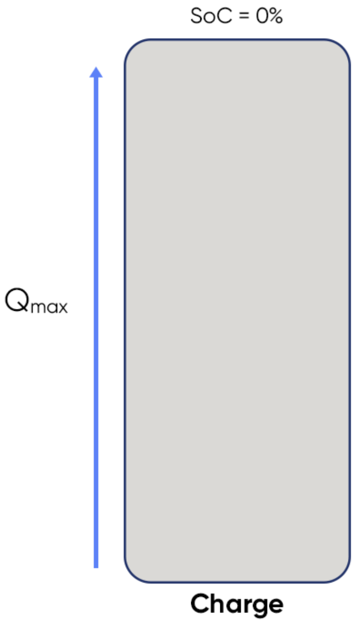




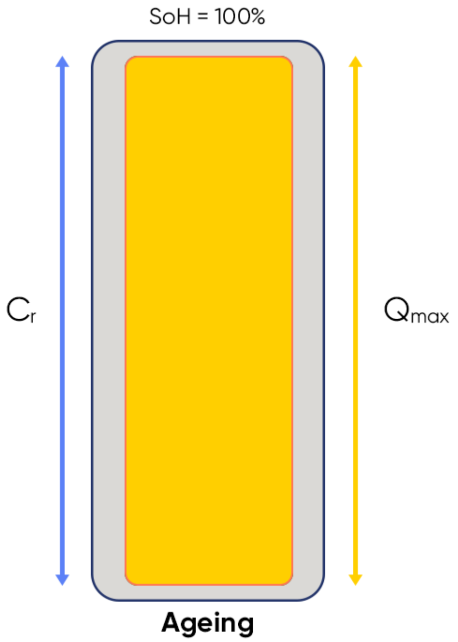
(Battery University, 2020)

Important Battery Characteristics

- State of charge (SOC) - Estimate of how much charge the battery currently has - while in use.
- State of health (SOH) - Estimate of the capacity/aging condition of the battery. Battery aging indicator.



$$\mathrm{SoC}/\% = 100\frac{(Q_0 + Q)}{Q_{\mathrm{max}}}$$



$$\mathrm{SoH}/\% = 100\frac{Q_{\mathrm{max}}}{C_{\mathrm{r}}}$$

Important Battery Characteristics

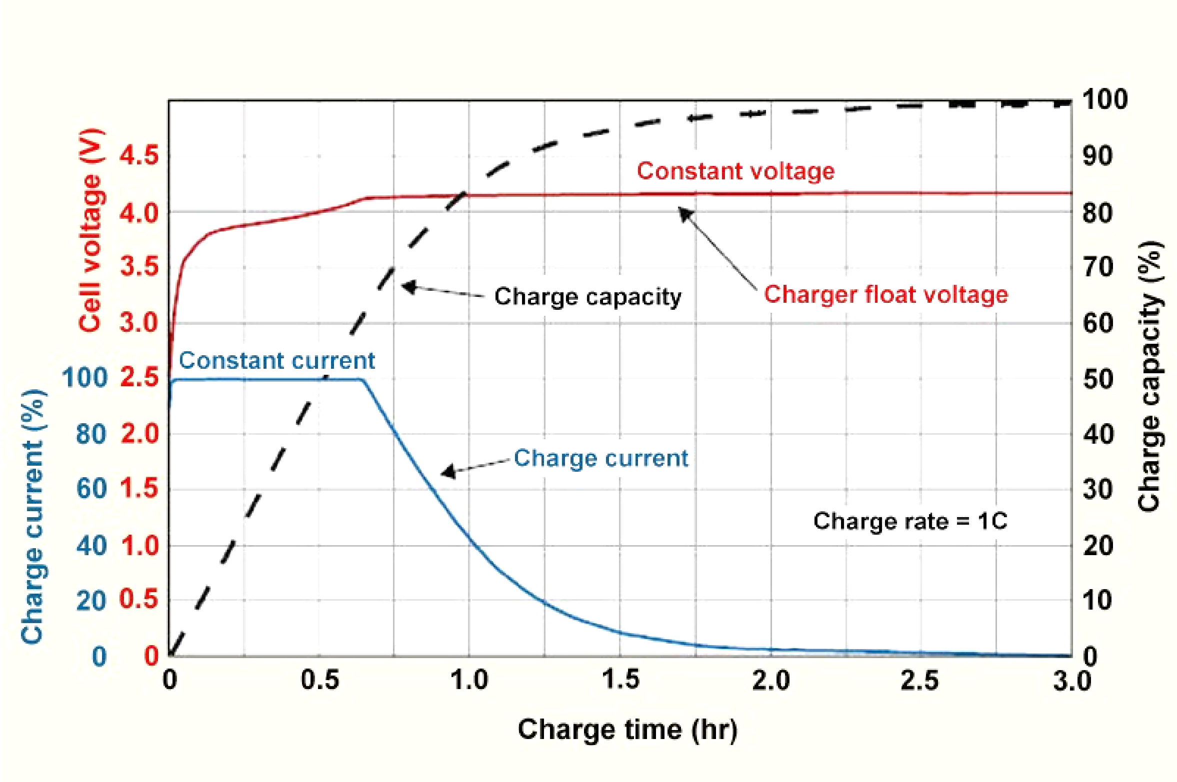
- Summary of the main characteristics of the most common BESS types
  - Lead-/Nickel-based: Widespread in the field of autonomous PV systems
  - Lithium-based: Growing interest for electric vehicles and hybrid applications

Lifespan

- Battery life is usually expressed in number of calendar years (Calendar Life) or number of cycles (Cycle Life)
  - During the life of the battery, the nominal capacity decreases as a result of system aging
- Calendar Life and Cycle Life are not independent of each other
  - Increasing the number of battery cycles used reduces the Calendar Life and a battery stored for a long time gives a smaller number of charging cycles
- Battery life depends significantly on various operating factors such as:
  - **Depth-of-Discharge (DoD)**
  - **Discharge Rate (C-rate)**
  - **Operating Temperature**

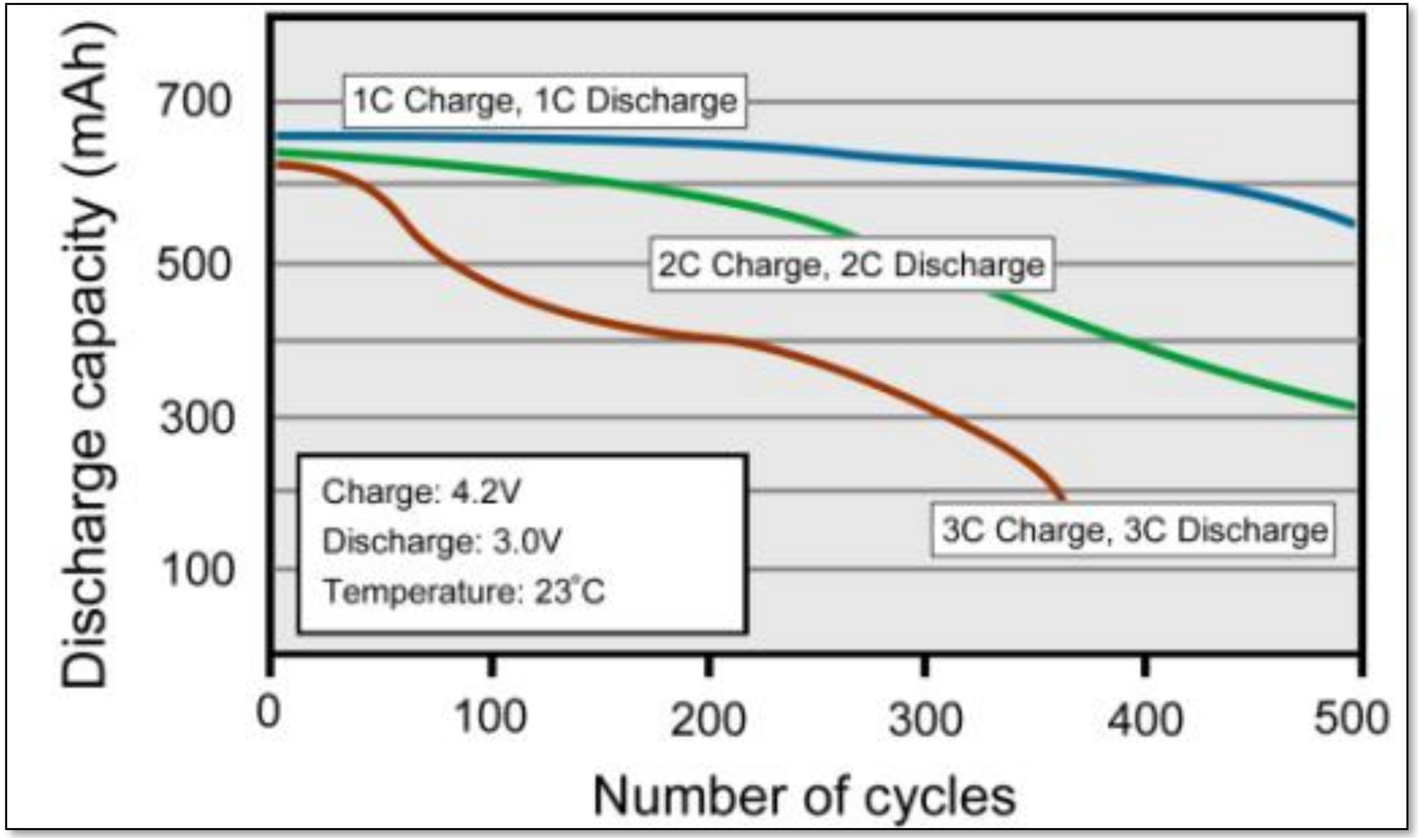
Charging Characteristic

- The charging characteristic is the identity of a battery.
- When the battery is first charged, the voltage rises rapidly.



Lifespan

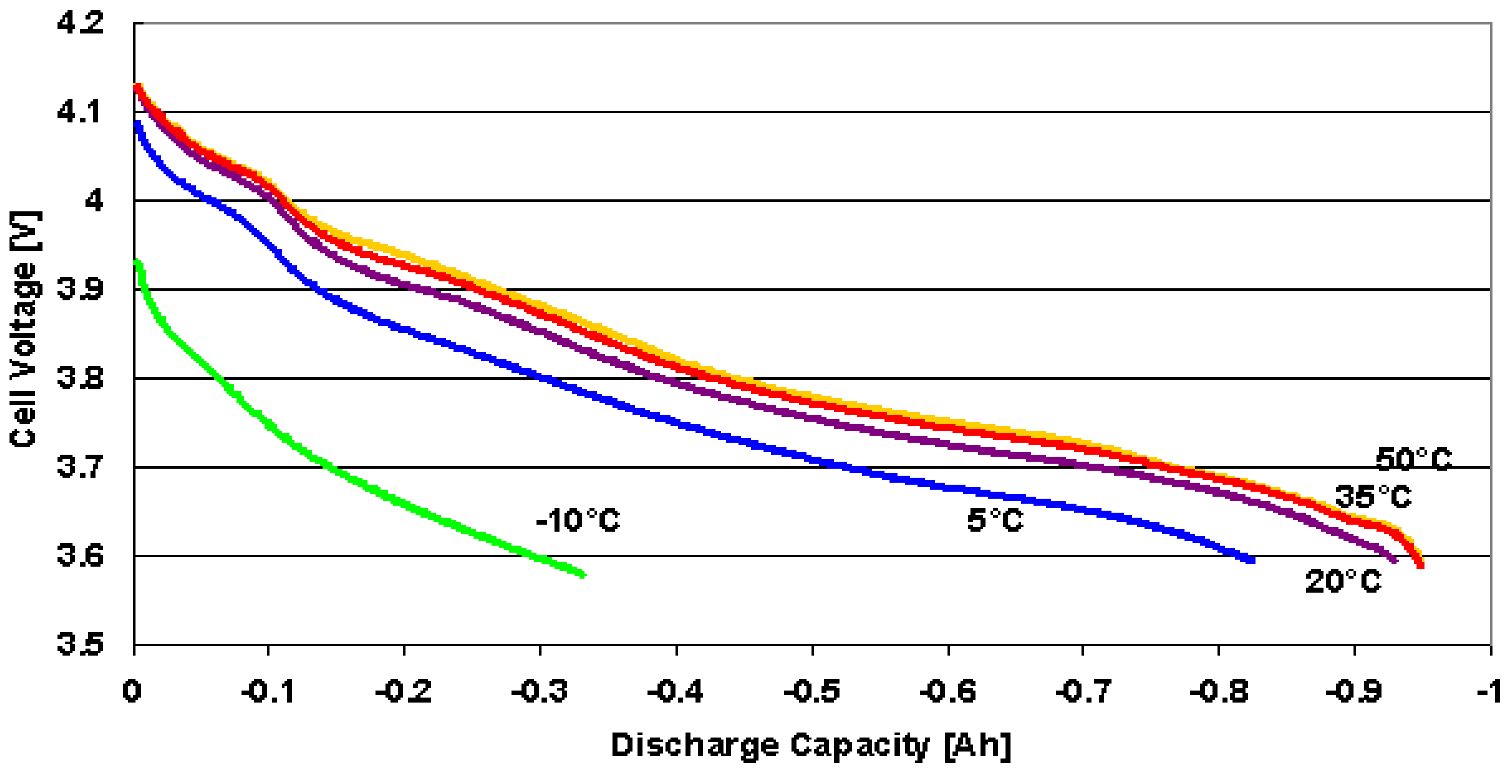
- Effect of discharge rate (Discharge Rate (C-rate)) on lifespan (see manufacturer's datasheet).



Charging and discharging above 1C reduces service life

Lifespan

- Effect of operating temperature on lifespan (see manufacturer's datasheet).



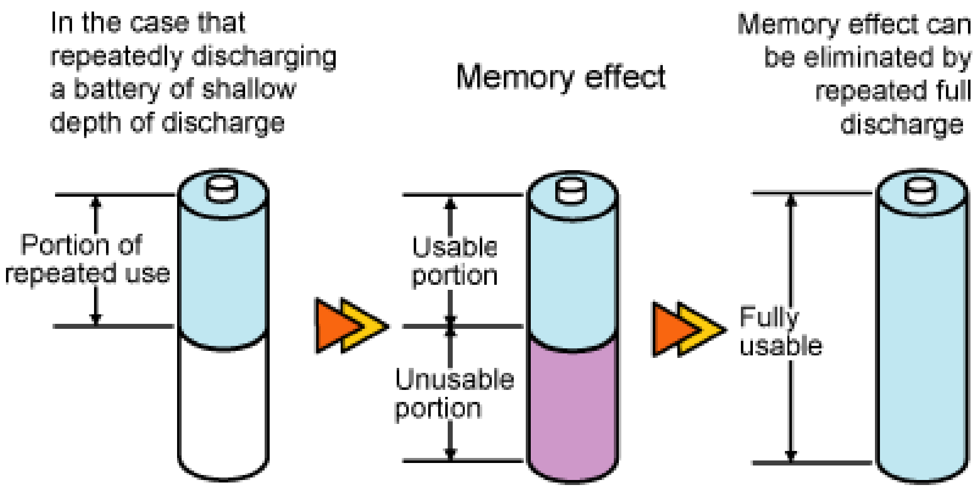
Lifespan

- Guidelines for extending the life of a lithium-based battery:
  - Avoid extreme high and low charge states (keeping cells continuously charged between 2% and 95%)
  - Avoid fast charging to promote energy stability and healthy internal temperatures
  - Avoid charging in cold conditions
  - Avoid rapid discharge while limiting current requirements per cell

Memory effect

- The "battery memory effect" is the reduction in the longevity of a rechargeable battery, due to incomplete discharge in previous uses. Some types of batteries, such as nickel-cadmium and nickel-metal hydride, can develop a memory effect when only partially discharged before recharging.

- **Lithium-ion batteries, on the other hand, are considered to have no memory effect.**



Subsection – Lifespan

Lifespan

- **Energy Throughput:**
  - Energy throughput is the total amount of energy a battery is expected to store and deliver over its lifetime.
  - This term would be particularly useful written on the warranties of all battery products.

$$\text{Energy Throughput} = \text{Nominal Capacity x Roundtrip Efficiency x DoD x Battery Cycle Life}.$$

Lifespan

- **Energy Throughput:**
- For example, a battery has a normal capacity of 10.2 kWh and excellent round-trip efficiency of 98%. The lifespan is 6000 cycles at 80% Depth of Discharge (DoD). The total energy output you can get from the battery will be 47000 kWh.
- The battery costs €7000 for a homeowner.
- The energy cost of the battery is approximately €0.15/kWh (€7000/47,000 kWh = €0.15/kWh).

Sub-section – Battery Connections

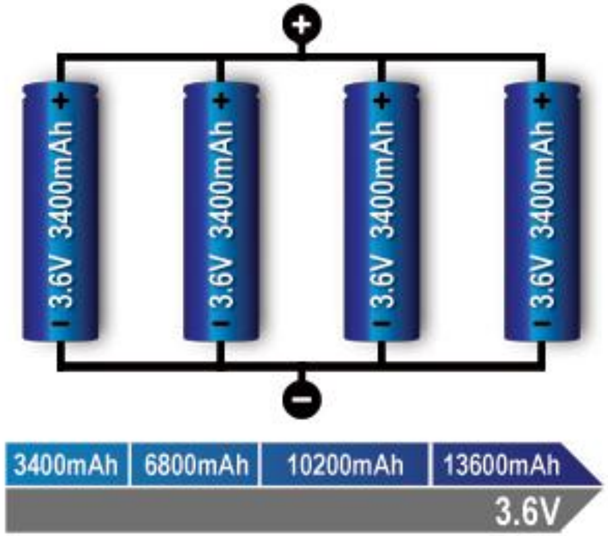
Cell Connection

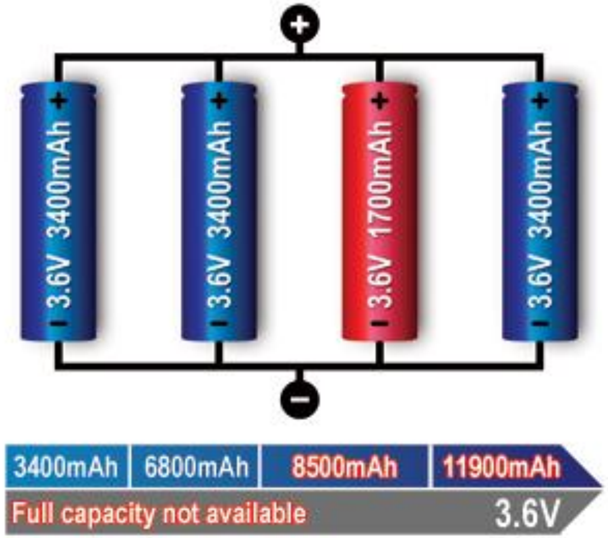
- Adding battery cells in series increases the voltage, while the capacity remains the same.
    - A faulty cell lowers the voltage and shuts down the equipment prematurely.
- With parallel battery cells, the capacity in Ah and the operating time increase, while the voltage remains the same.
    - A weak cell will not affect the voltage but will provide a low operating time due to reduced capacity.
    - A shorted cell can cause excessive heat and fire hazard.
    - In larger packs, a fuse prevents high current by isolating the cell.

Cell Connection

- In series

- Parallel

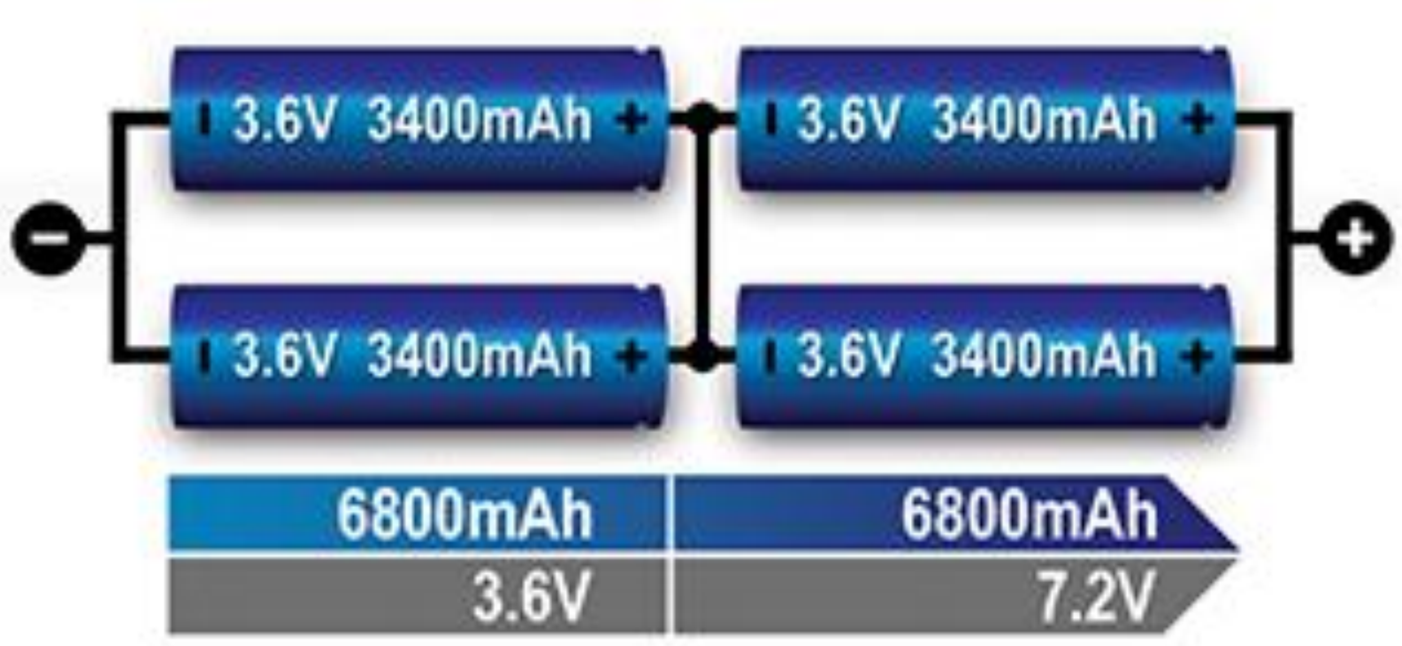




(Battery University, 2019)

Cell Connection

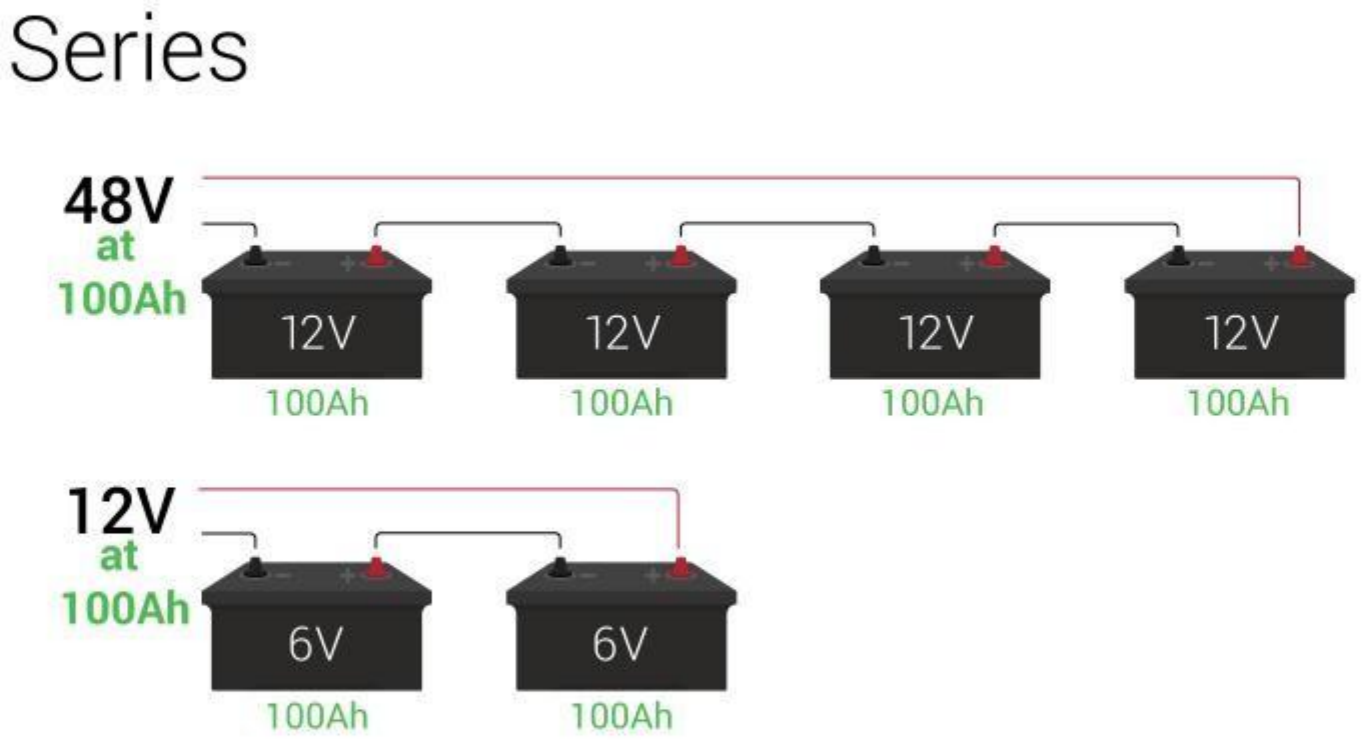
- The combined series/parallel arrangement provides maximum design flexibility.



(Battery University, 2019)

Connecting Batteries - Series

- Wiring batteries in series.



Connecting Batteries - Series

- **Advantages of wiring batteries in series:**
  - Increased voltage: The main advantage of series connections is the increased output voltage. This is especially useful when higher voltages are required to drive specific applications or power electronic devices.
  - Stable current: Series connections help maintain a more consistent current flow. This can be beneficial in applications that require a stable power supply, such as electric vehicles or uninterruptible power supplies (UPS).

Connecting Batteries - Series

- **Disadvantages of connecting batteries in series:**
  - Reduced capacity: A significant disadvantage of connecting batteries in series is that the total capacity remains the same as that of a single battery. This means that although the voltage increases, the operating time or duration of operation decreases.
  - Voltage mismatch: It is important to note that in series connections, each battery must have the same nominal voltage. Otherwise, the battery with the lowest capacity will drain faster and potentially damage the rest of the series.

Connecting Batteries - Series

- **Risk when connecting batteries with different voltages in series:**
  - When connecting batteries with different voltages in series, the total voltage is the sum of the individual voltages. However, there are several concerns to be aware of:
  - Unbalanced discharge: The battery with the smallest capacity will discharge faster than the one with the largest capacity. Once the smaller capacity battery is fully discharged, it may act as a load, causing it to reverse charge, which can be dangerous.

Connecting Batteries - Series

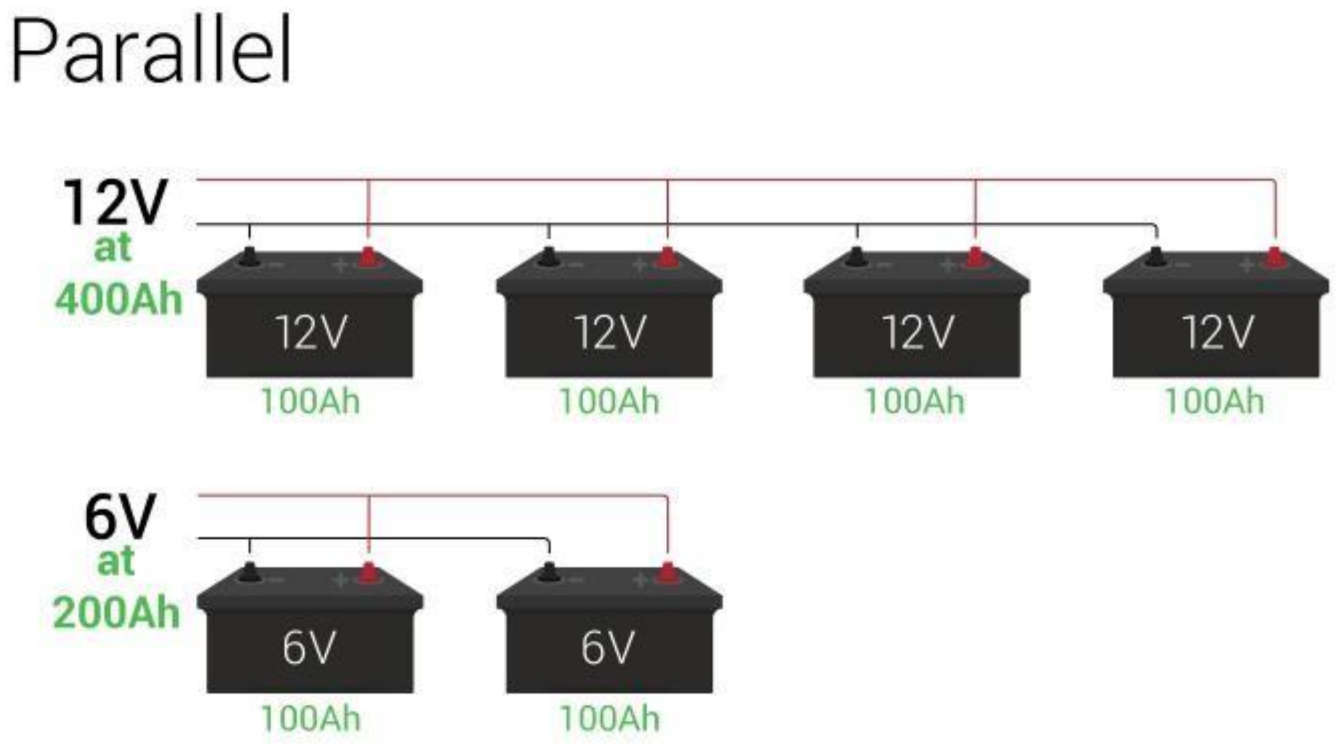
- **Risk when connecting batteries with different voltages in series:**
  - Reduced capacity: The total capacity of the series connection will be limited by the battery with the smallest capacity.
  - Different chemistry issues: If the batteries have different chemical compositions, they may have different voltage curves, discharge rates, and other characteristics. This can lead to imbalances and potential damage.
  - Potential damage: If one battery is fully charged or discharged before the others, it may be damaged or have a reduced lifespan.
  - Safety concerns: Mixing batteries can lead to overheating, leakage, or even explosion in extreme cases.

Connecting Batteries - Series

- The number of batteries you can connect in series depends on:
  - Intended Voltage: Wiring batteries in series increases the overall voltage. The number of batteries you can connect in series will depend on the desired total voltage for your application.
  - Battery Specifications: Always refer to the manufacturer's specifications and guidelines. Some batteries, especially certain types of rechargeable batteries, may have limits on how many can be connected in series due to concerns about voltage imbalances, charging, and management.
  - Battery Management System (BMS): If you are using a BMS (especially common with lithium-ion batteries), the BMS may have a limit as to how many cells or batteries it can manage in series.

Connecting Batteries - Parallel

- Wiring batteries in parallel.



Connecting Batteries - Parallel

- **Advantages of wiring batteries in parallel:**
  - Increased Capacity: The primary advantage of parallel connections is increased overall capacity. This means that devices and systems can operate for a longer duration without needing to recharge or replace the batteries.
  - Flexible Voltage: Parallel connections allow for greater flexibility in voltage requirements. By connecting batteries with different voltage ratings, it is possible to achieve the desired output voltage while maintaining a higher capacity.

Connecting Batteries - Parallel

- **Disadvantages of connecting batteries in parallel:**
  - Unbalanced Charging and Discharging: When batteries are connected in parallel, they may not charge or discharge at the same rate. This can lead to an imbalance where some batteries may reach their maximum capacity while others lag behind. It is important to monitor and manage the charging and discharging process to avoid such imbalances.
  - Complexity in Battery Management: Managing batteries in parallel requires careful attention to ensure that all batteries are operating optimally. This includes monitoring individual battery health, equalizing charge levels, and promptly replacing any faulty batteries.

Connecting Batteries - Parallel

- **It is generally not recommended to wire batteries with different voltages in parallel:**
  - Voltage Equalization: When batteries of different voltages are connected in parallel, the higher voltage battery will attempt to charge the lower voltage battery until their voltages equalize. This can lead to a rapid and uncontrolled flow of current between the batteries, which can generate heat and damage the batteries.
  - Unbalanced Discharge: Even if the batteries start with the same voltage, they may not discharge at the same rate if they have different capacities or chemistries. This can lead to one battery discharging more quickly than the others, which can cause imbalances in the system.

Connecting Batteries - Parallel

- **It is generally not recommended to wire batteries with different voltages in parallel:**
  - Different Chemistry Concerns: Batteries with different chemistries have different voltage curves, discharge rates, and other characteristics. When connected in parallel, these differences can lead to imbalances and potential damage.
  - Reduced Lifespan: The lifespan of the batteries can be reduced due to the stresses of unbalanced charging and discharging.

Subsection – System Installation - Health & Safety

Health and Safety

What is "Health and Safety"?

- Health:
  - Taking protective measures to avoid accidents with immediate and/or short-term effects
  - Examples:
    - Cut by a sharp object
    - Falling from a height
- Safety:
  - Take protective measures to avoid incidents with indirect and/or long-term effects
  - Examples:
    - Hearing problems after many years of working in a noisy environment
    - Diseases due to continuous exposure to chemical/radioactive agents

Health and Safety

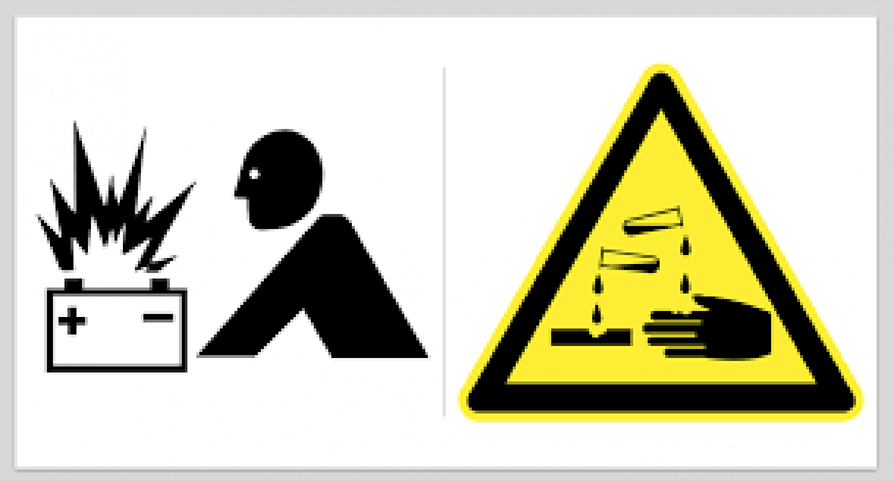
The main pillars of Health and Safety include:

- Safe work practices
- Assessment of potential hazards (risk analysis)
- Safety with electrical installations
- Safety measures when working at height
- Use of safe equipment (insulated equipment)
- Fire hazard
- Other hazards

Safety & Health

Main safety issues in battery systems:

- The power supply to the battery terminals cannot be switched off.
- The systems include DC cabling, with which (relatively) few installers are familiar.
- Batteries have considerable weight.
- Risk of electric shock and difficulty in manual handling during installation.



Safety responsibility

The battery system installer is responsible for:

- The health and safety of personnel working on the system installation site.
- The health and safety of customers and anyone else working on the site and associated with this work.
- The long-term operational safety of the installed system.

Safe work practices

- Safe work practices can be achieved through the following:
  - Identifying and minimizing, if possible, all hazards at the site where the system will be installed (height, scaffolding, electrical work). All installers must first assess the workplace and check whether their equipment and safety rules are adequately followed.

Potential Hazards

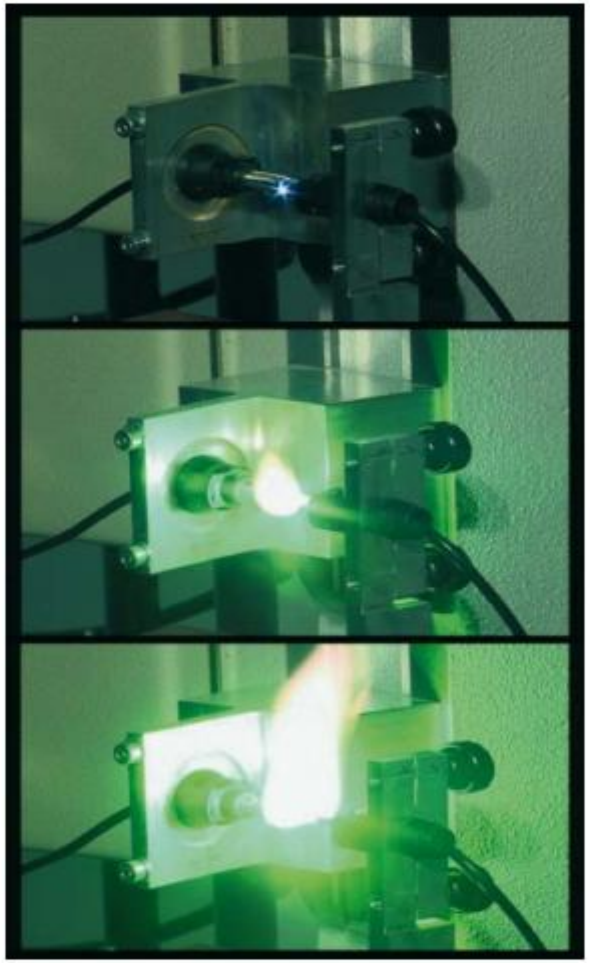
- Construction sites contain numerous and often dynamic hazards, such as:
  - Slips and falls
  - Minor to serious cuts
  - Heat generation from the environment and equipment
  - Smoke and fire
  - Electrical burns
  - Electric shock and electrocution
  - Falling objects
  - Manual handling of equipment and heavy devices

- Injuries from the above are due to human errors, such as carelessness and non-compliance with safety rules.

Safety with electrical installations

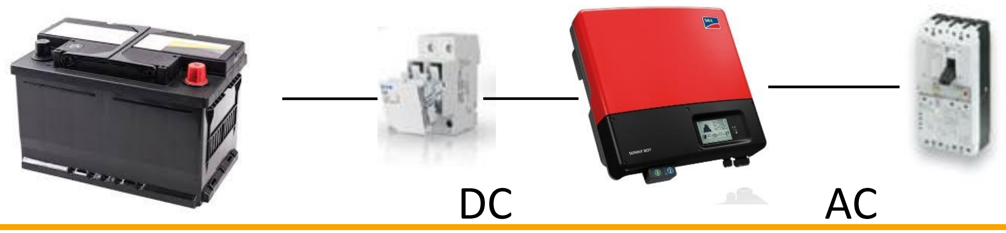
- When opening a DC circuit in the presence of a load, an electric discharge (electric arc) is observed.

Source: SMA Solar Technology



Electrical Installation Safety

- There are two sources of power in battery systems:
  - The battery system itself.
  - The grid to which the battery system is connected
- Turning off the main disconnect of the battery system does not mean that the DC side of the battery system stops producing voltage. Even in low radiation it produces voltage that is dangerous.
- The inverter capacitors can store potentially dangerous energy. It is always best to turn off the inverter and wait at least 15 minutes before starting work.
- There are two ways to minimize DC voltage, either disassemble the battery array, or cover the array with a non-transparent cover. Always turn off the DC breaker before working with the array. Whenever you disassemble DC panels the risk of electric shock is high.



Electrical Installation Safety

- Technicians working with batteries must be aware of all hazards and comply with safety regulations. The following must be considered when working with batteries:
  - Carefully study the instructions provided by the manufacturers for the correct use, application and connection of the batteries.
  - Do not eat or drink next to the batteries.
  - Batteries contain chemicals that can harm technicians if not used properly.
  - The DC switch (fuse box) between the batteries and the inverter must be open (OFF) before starting work.
  - Metal tools are prohibited. Special insulated tools are required for working with batteries. There are special glasses for eye protection.
  - Empty batteries must be recycled.

Electrical Installation Safety

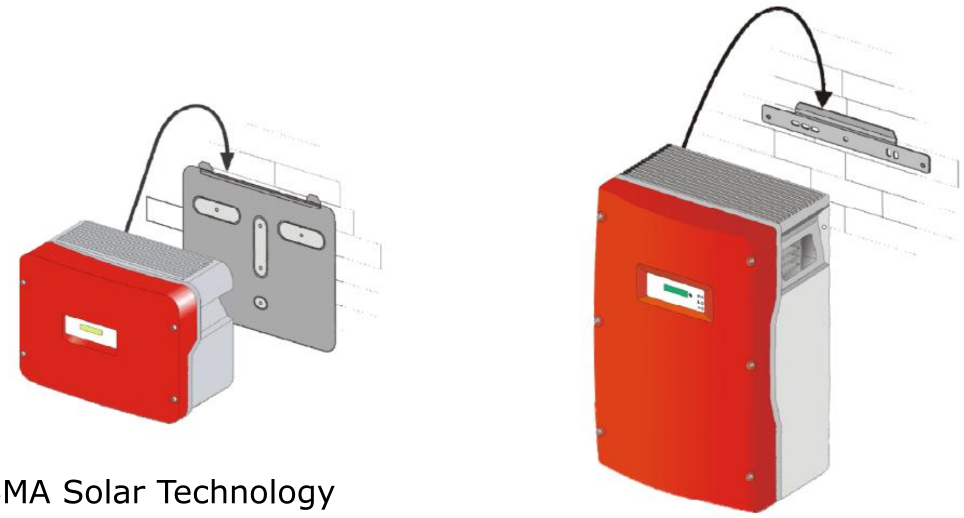
- Special Feature: Working with Electricity

Use of safe equipment

- Safe equipment is essential to protect the worker from potential hazards and injuries in the workplace.
- All employers must provide the necessary equipment to their employees.
- Employees must keep the equipment in good condition.

Connecting the inverter to the grid

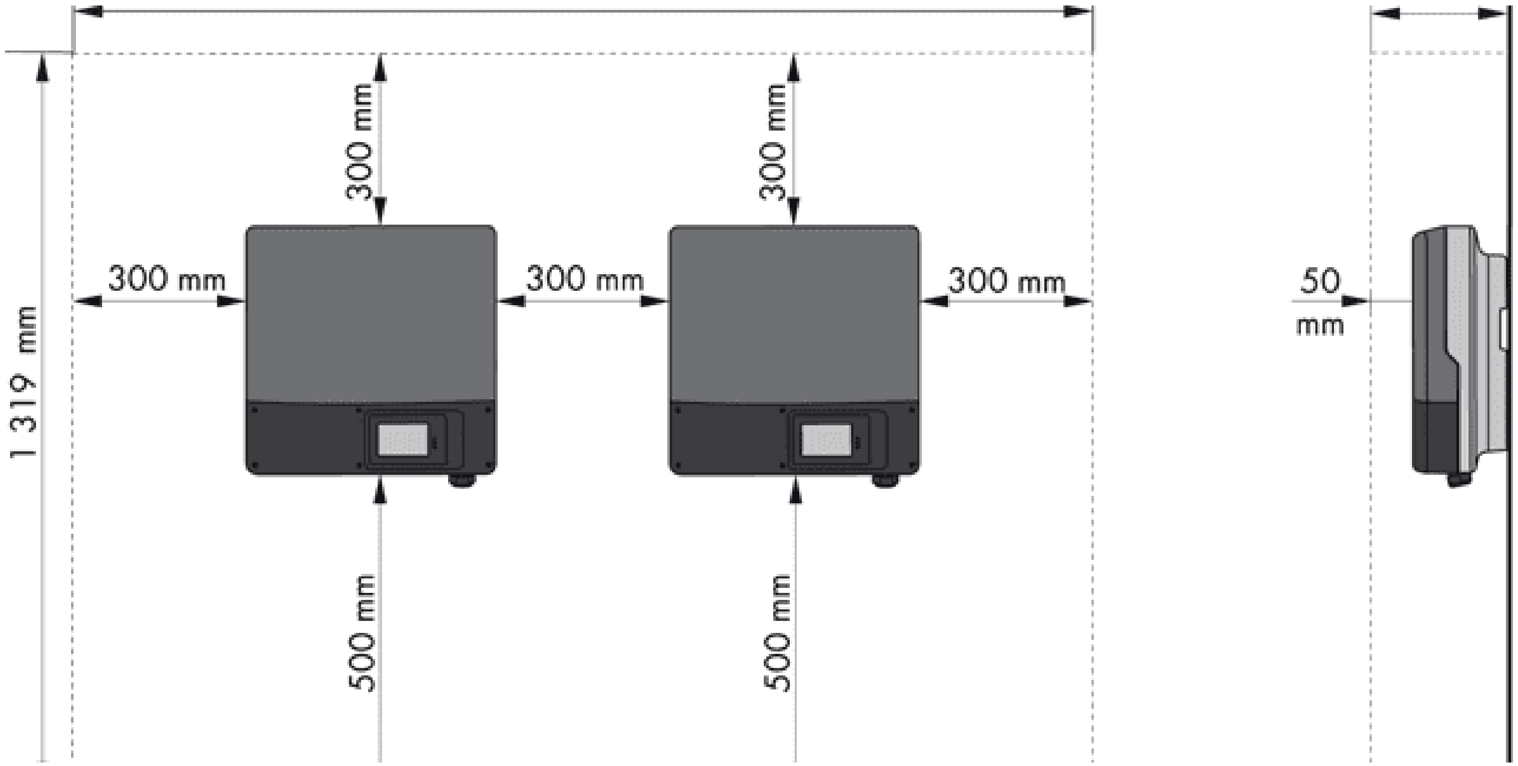
- Installing the inverter to the grid:



Source: SMA Solar Technology

Connecting the inverter to the grid

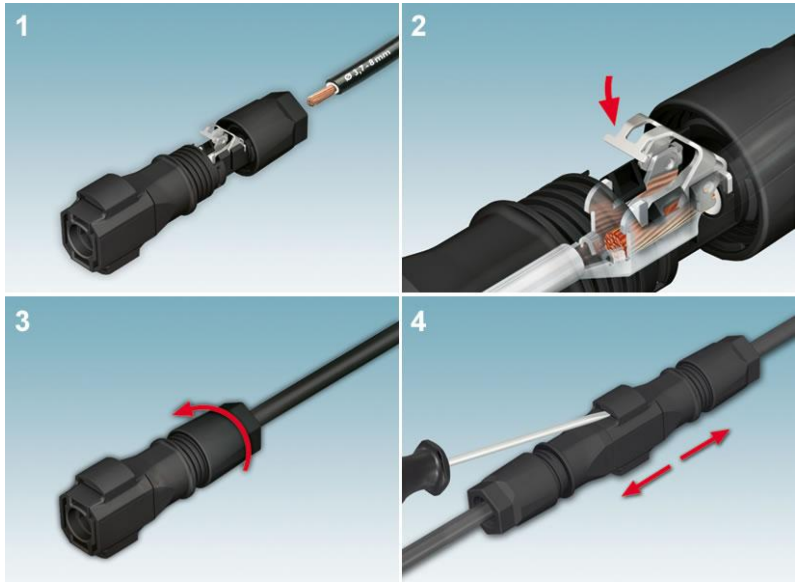
- Installing the inverter to the grid:



Source: SMA Solar Technology

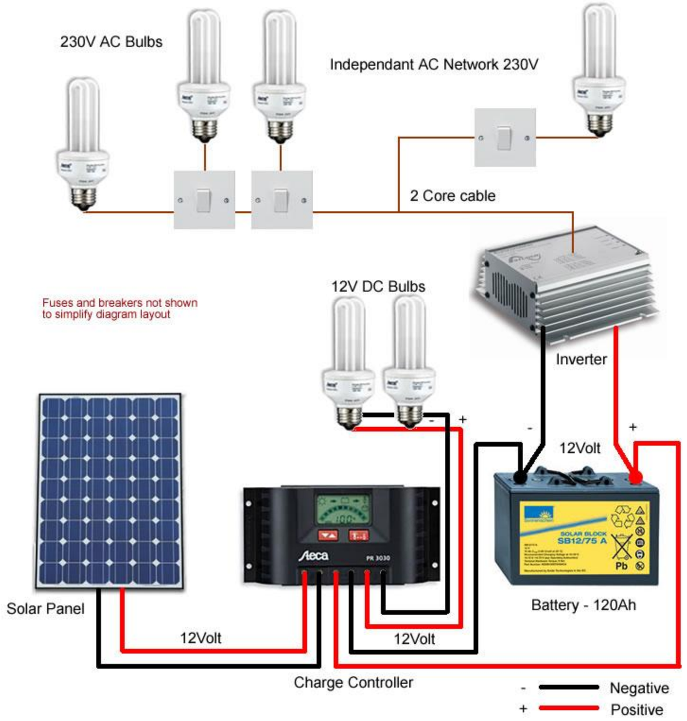
Connecting the inverter to the grid

- Installing the inverter to the grid:
  - The DC cables from the batteries are connected either with MC4 or other connection plugs.
  - The AC cables are connected either to a screw block or to a socket provided by the inverter manufacturer.



Standalone inverter

- Standalone inverters are only used for standalone systems.
- The PV installer should keep in mind that the input voltage of the inverter is usually 12 V, 24 V or 48 V.
- The output voltage is usually 230 V.



Batteries

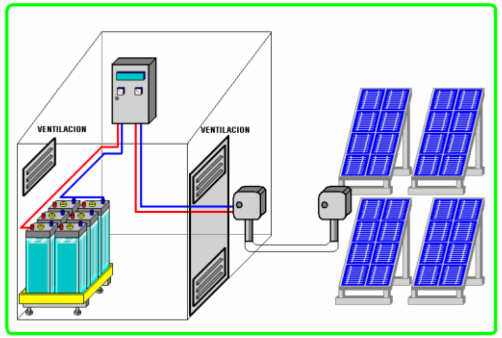
- The most important characteristics of the batteries used are the following:
  - Battery technology (Lead-acid, nickel-cadmium, lithium-ion)
  - Type (liquid or sealed)
  - Capacity (ampere-hours, charge and range for electrical charging/discharging)
  - Physical characteristics
  - Ease of installation

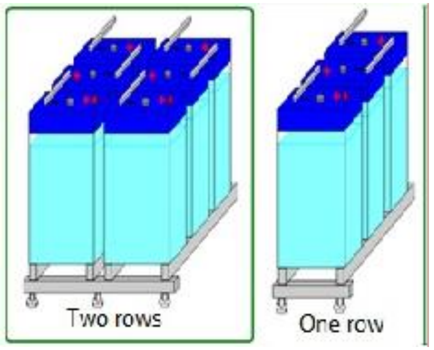
Lead-acid
mono block 12V (6 2V cells)

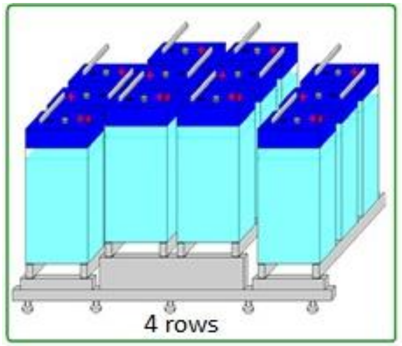

Nickel-cadmium

Batteries

- Batteries must be installed in enclosed spaces and must be protected from environmental conditions.
- When the battery electrolyte is not sealed, then the battery installation location must be well ventilated.
- There should be no other devices in the installation location that can cause sparks and, as a result, fire.
- When working with batteries, special insulated tools must be used.

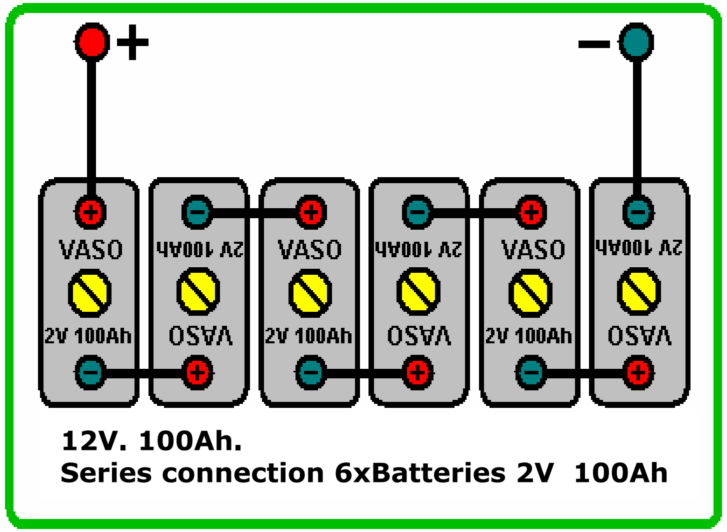


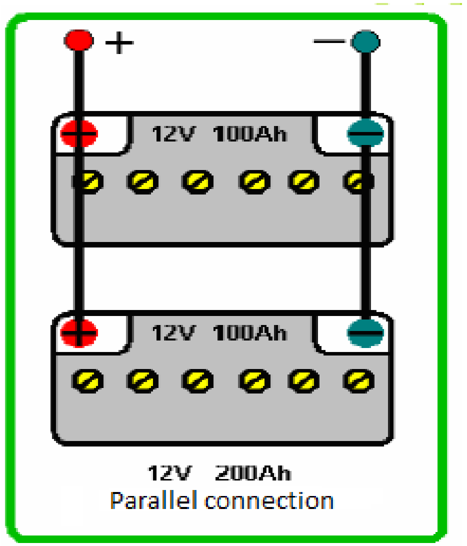




Batteries

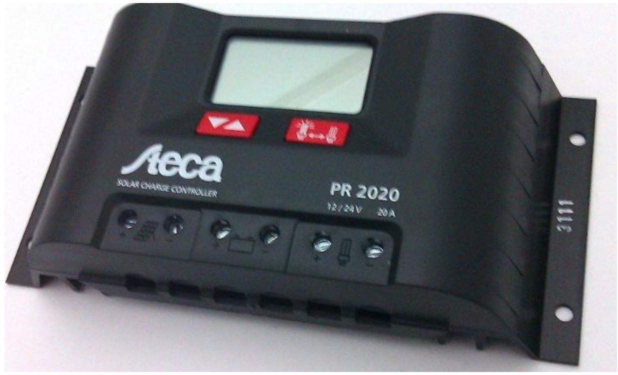
- Batteries can be connected either in series or in parallel.

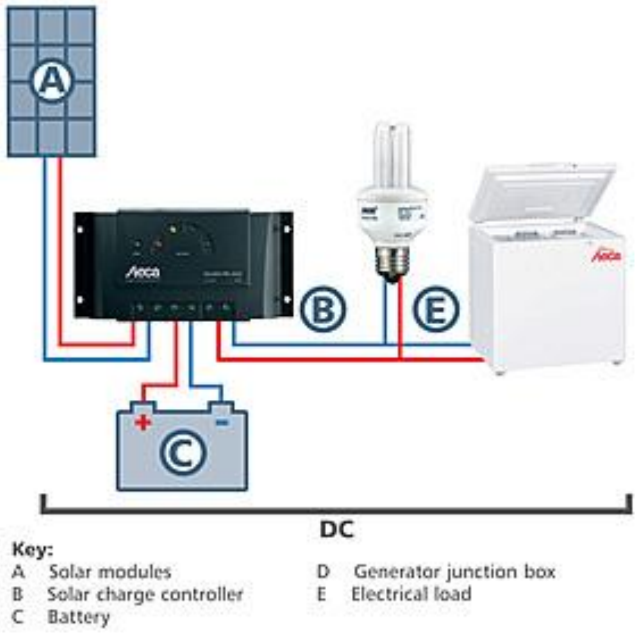




Charge controller

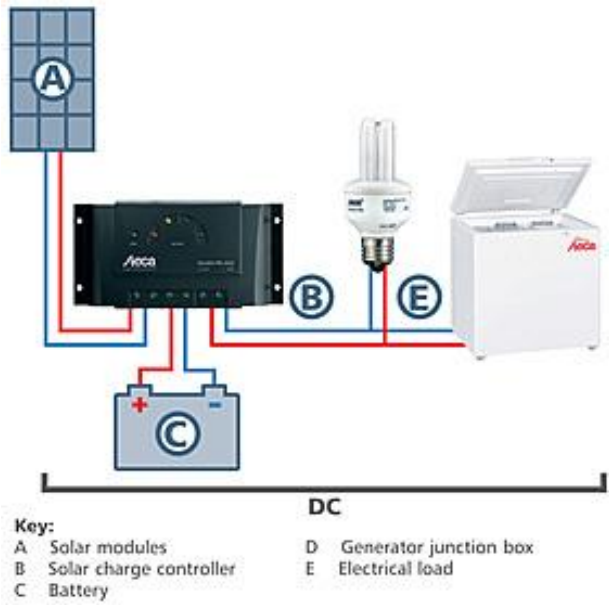
- The most important characteristics of the charge controllers used in standalone PV systems are:
  - Type (for 24 V or 48 V applications) – Most charge controllers are set to operate at both voltages
  - Current capacity
  - Easy application





Charge controller

- Before installing the charge controller, it is important to know the polarity of each DC line.
- When interconnecting the charge controller, it is important to pay attention to the following steps:
  - First connect the batteries to the input of the charge controller. Make sure you have installed the fuse or switch on the positive side of the DC cable which must be open (OFF).
  - Connect the PV panel to the input of the charge controller.
  - Connect the load to the input of the charge controller.
- In the event that the charge controller needs to be disassembled, the reverse procedure must be followed.



Residual Current Devices

Residual Current Devices (RCDs) are classified based on their response to AC and DC signals, as follows:

- Type AC: Devices in this category generally only detect alternating sinusoidal currents. They may not detect non-sinusoidal, non-alternating components of the current. Non-sinusoidal currents are present in many items of equipment, e.g. virtually all equipment with a switched-mode power supply will contain a DC component.

- Type A: This category of devices detects both AC and DC pulsating currents and are known as DC sensitive RCDs. They cannot be used on constant DC loads.

- Type B: This type detects AC, pulsating DC and constant DC currents.

Residual Current Devices

Supply	Form of Residual Current	Recommended type of symbol		
		AC	A	B
Sinusoidal A. C.	Suddenly applied Slowly rising	✓	✓	✓
Pulsating D.C.	Suddenly applied Slowly rising		✓	✓
Smooth D.C.				✓

Source: MCS

Good practices during installation

Conclusions

- Batteries are categorized as primary or secondary.
- Battery life depends significantly on various operating factors such as:
  - Depth-of-Discharge (DoD)
  - Discharge Rate (C-rate)
  - Operating Temperature
- Batteries are connected in series and in parallel.
- Health and Safety is taking protective measures to avoid accidents with immediate and/or short-term effects.

Thank you for your attention!