

# 8. Stand-alone photovoltaic system components

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## Learning outcomes

This section aims to present current technology stand-alone photovoltaic system components. After studying this chapter, the reader should be able to:

- Comprehend how PV panels produce energy
- Understand the function and characteristics of accumulators (batteries)
- Understand the necessity and function of a charge controller
- Realise how inverters operate.
- Possess basic knowledge of the other components required for a stand-alone PV system (mounts, protection, etc.)

## Introduction

Stand-alone photovoltaic (PV) systems give to the electricity producer/energy consumer the capability to cover all the electricity needs with his own means of production. They are very common either when it is technically difficult, impossible or costly to receive a connection to the existing electricity grid. With the stand-alone systems, as well as with the rest of autonomous electricity systems from renewable sources of energy (such as the small wind turbines), the economic benefit of the producer-consumer is promoted alongside with the common benefit of gradual energy independence from solid and liquid fuels.

The components included in a stand-alone PV system are presented as a whole, but a part of them is common with the PV systems that are connected to the grid or are used for self-consumption.

All of the equipment mentioned in this text should be made and selected according to regulations/standards as these are formed by national (e.g. ELOT in Greece), European (EN, DIN), and international level (ISO, IEC) standards for the construction, design, connection and maintenance of PV systems.

## Photovoltaic panels

Photovoltaic (PV) panels are the core part of the PV installation, as they generate the electrical energy. Their function is based on the photovoltaic phenomenon. They are the configuration that converts solar energy from direct and diffuse radiation directly to electrical energy. For this purpose, semi-conductive materials are used for the construction of photovoltaic cells which are then connected in series or in parallel (or both), depending on the technology, and create the PV panels.

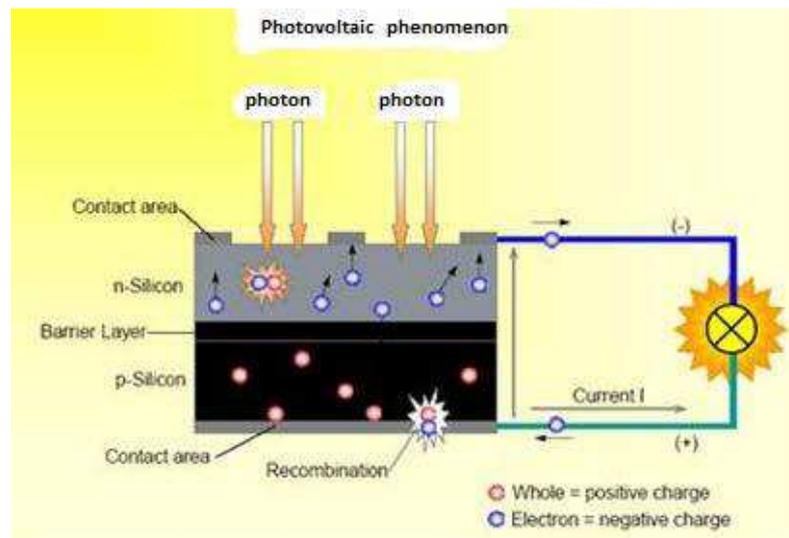


Figure 1 - Photovoltaic phenomenon

### How electrical energy is produced ?

PV cells are semiconducting diodes, usually p-n (positive-negative), without excluding other diodes (e.g. Schottky).

When photons fall into the semi conductive material, as sunlight falls, photons with energy equal or greater than the energy gap of the semi conductive material collide to the valence electrons of the semi conductive material and transfer to them all their energy. Energy equal to the energy gap of the semi conductive material is absorbed and leads to the release of electrons that attach in atoms or take the place of a hole that is lost. If there is energy left, it is converted to kinetic energy of electrons and, ultimately, is lost as thermal energy<sup>1</sup>. As a result, electrons and holes are moving irregularly. In order to direct this movement and create electric current, semi conductive materials with impurities are needed. The role of these impurities is to create two different sides in the material, one with more valence electrons (n type) and one with less valence electrons (p type). The connection of the two parts is creating a diode. This way, the movement of electrons can be orientated (potential difference) and electric current can be created when two electrodes of different but

specific direction are connected (Fig. 1).

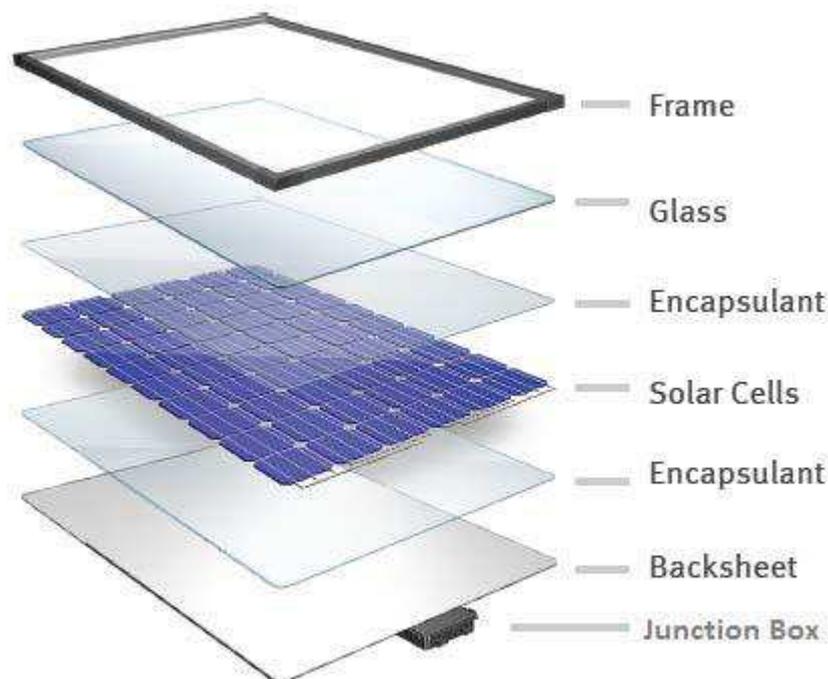


Figure 2 - PV panel's layers [1].

<sup>1</sup>The negative influence of the temperature increase is represented by a specific characteristic value of each panel.

In order to increase the voltage and current they produce, PV cells are connected in series and in parallel respectively. This kind of arrangement creates the core of the PV panel.

Except for PV cells, five more components are included in the PV panel (Fig. 2):

1. Backsheet, for the protection against UV radiation, increased temperatures (with heat diffuse) and moisture, as well as the necessary electrical insulation of the panel and the restriction of its mechanical degradation. The demands for a 25 years' resistance, high efficiency and low cost had established Tedlar till nowadays (PVF sheet - polyvinyl fluoride) and the manufacture of TPT sheets, that included three levels of PET (polyethylene terephthalate) between the 2 layers of Tedlar. The new generation includes Tedlar/PET/TPA (polyamide), with a layer of TPA that definitely supports a sheet's reflectance (15-20% increase) [2].
2. Encapsulates, which consist of vitreous, permeable by light membrane of special fabrication that provides long term protection of the most sensitive parts of the PV cells. They usually are silicone type or EVA (ethylene-vinyl acetate).
3. Protective glass, which offers mechanical resistance and protection against

damages, from low-iron material. The surface is anti-reflecting in order not to obstruct the incoming radiation and its absorption.

4. Frame, which is metallic or polymer. In some occasions it may not exist at all. It is used for the protection of the glass and also for the stability assurance of the PV panel.

According to technological sequence, PV panels can be divided to three general categories:

1. Crystalline Silicon (c-Si)
2. Thin films
3. Other technologies

The first category is also divided to three basic sub-categories:

A) Monocrystalline silicon elements. The crystalloid mesh of Si atoms approaches a perfect crystal (max efficiency 25%). They are constructed after cooling melted Si and cutting it in very thin sheets, which are the PV cells. Their thickness is about 0.3 mm.

B) Polycrystalline silicon elements include in their mesh crystals of many orientations. The cause of this difference is the mass and less controlled cooling of Si. As with the monocrystalline silicon, after cooling, the poly crystalloid web is cut in very thin PV cells. The existence of different crystals in the web increases the internal resistance at the connection points (max efficiency 21.2%).

C) Silicon films. They are using up to 50% less Si compared to "traditional techniques" of construction monocrystalline and polycrystalline PV Si cells (max efficiency 16%). Their thickness is about 0.3mm.

The second category is divided into four basic sub-categories:

D) amorphous Si cells. A special characteristic of this category is the non-crystalloid structure. They are constructed by applying Si in a special glass layer. The lack of crystalloid web limits the efficiency (max efficiency 13.4%) [3].

E) Chalcopyrite compounds (CuInSe<sub>2</sub> or CIS, with Gallium CIGS). It offers exceptional absorbance of falling light. With Gallium, the efficiency can rise up even more (max efficiency 21.7%).

F) Cadmium telluride, Cd-Te. Its energy gap is around 1eV, very close to the solar spectrum, that gives to Cd-Te the capability to absorb 99% of the falling radiation (max efficiency 21,5%). A hindrance to its usage is the fact that cadmium, according

to some researches, is carcinogenic.

Arsenic Gallium, GaAs. Its energy gap is 1.43eV, ideal for solar radiation absorption (max efficiency 38.8% when it is in multi-junction form).

The third category includes the mass technologies that are under formation. They are mainly categorized to organic/polymer elements (OPV), non-organic, and hybrid (HIT) that consist of amorphous Si and monocrystalline Si layer.

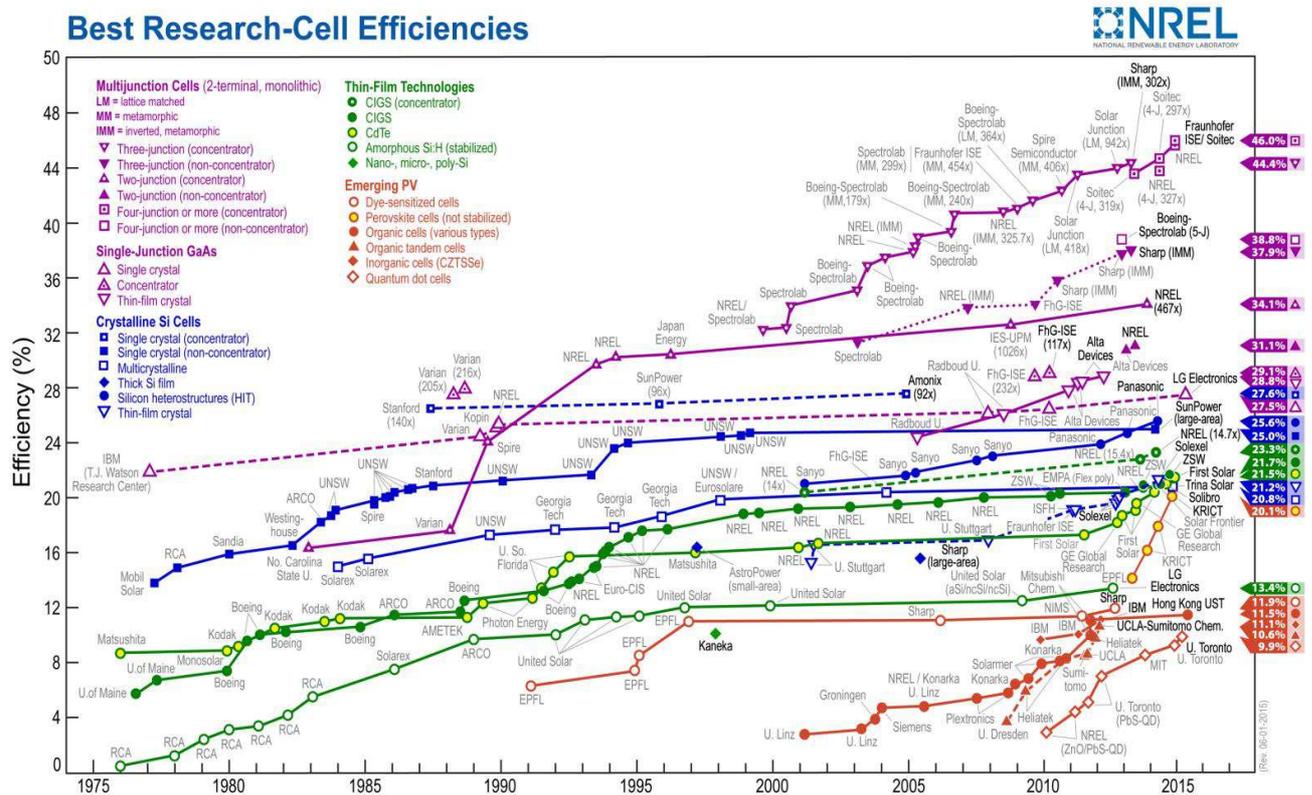


Figure 3 - Technological improvement of pv cells – dependence of technology and efficiency degree during time [4]

Categories A and B currently dominate in PV projects, as they combine high efficiency and low budget.

The characteristic sizes of each PV panel given by the manufacturers are the short circuit current  $I_{sc}$ , the open circuit voltage  $V_{oc}$ , the nominal power  $P_{nom}$ , the maximum power point voltage  $V_{mpp}$ , the maximum power point current  $I_{mpp}$ , the maximum power  $P_{max}$ , and the solar panel's efficiency (%), as these are defined for standard test conditions (STC: 25°C, radiation 1000W/m<sup>2</sup>).

PV panels produce DC depending on the sunshine. PV panels produce most of the energy during a clear day, when sun is vertical to the PV panels of each array, and less energy in the morning and afternoon, during seasons that sun is higher or lower

at the sky, and in cloudy days. PV panels of course do not produce energy during the night.

It is worth mentioning that PV panels used in stand-alone systems can be, according to the size and the cost of the system, the same or different with those used by PV systems connected to the electrical grid. The difference of the installations, besides the financial cost, is the different electric connection to accumulators and the use of (or not using at all) different equipment (e.g. inverter etc).

## Accumulators-storage batteries

**Accumulators** or rechargeable batteries or storage batteries, constitute the element that provides to the electrical energy production system with autonomy. The electrical energy that is produced and not used at the time can be stored in order to be used whenever and wherever is needed (e.g. when due to weather there is no energy production, or after sunset). The quantity of electrical energy that has to be stored depends on the local conditions, the user's needs and especially to the maximum number of possible cloudy days in line, the peaks of consumption and the reliability degree of the system, in combination with the existence or not of any auxiliary energy sources. Usually, stand-alone PV systems are designed so as to reassure energy autonomy for three to ten days [5]. At the same time, accumulators have the role of preserving the PV system voltage within defined boundaries, for it to be usable by the connected load.

Accumulators are charged during the time that the produced electrical energy exceeds the demand and discharged in the opposite case. The time period from the complete charge till the complete exhaustion of the stored energy and the restart of charging is named **charging cycle** (the reverse procedure constitutes the equal discharging cycle).

The characteristic figures for each accumulator is: voltage (V), capacity<sup>2</sup> (Ah) and depth of discharge (DOD)<sup>3</sup>. Because the product of charging cycles and the depth of discharge remains stable, meaning that the more an accumulator is discharged the total charging cycles (i.e. the lifetime) are respectively reduced. At the same time, in the lifetime of the accumulator, the usable capacity is reduced more and more because of their aging. The number of autonomous days that each user demands, defines the total capacity of the accumulator/accumulators<sup>4</sup>.

Some of the most important demands that need to be taken under consideration for the sizing of the energy storage system are the following:

- Efficiency-duration: high energy efficiency, long lifetime (counted in years) and

capacity stability, high charging efficiency even with a low current, low rate of self-discharging.

- Financial cost: low cost for the acquisition of the equipment, low maintenance costs and needs, high availability internationally, capability of quick charging.
- Material: Low exposure to inappropriate conditions, easily recyclable, low toxicity.
- Security - reliability: Secure behavior in the case of overcharging or deep discharging, easily extendable voltage and capacity through connections in series and parallel, small gap of voltage between charging and discharging (it allows connecting loads directly to the accumulator), low explosive attitude, high long-term reliability.

In stand-alone PV systems, deep discharging batteries with many charging cycles are used. Common value for charging cycles is 1500 for discharging even down to 80% of its nominal capacity for 12V.

Lead-Acid accumulators cover most of the current market demands. They are separated in two types according to the manufacturing method and are both used in stand-alone PV systems. The first type is the open or flooded or vented type and the second type is the closed or sealed type. All Lead-Acid accumulators produce hydrogen and oxygen gases (gasification) in the electrodes when charging due to a procedure called electrolysis. Those gases either escape from an open type element (as a result the specific element needs electrolyte replenishment), or the closed type element is constructed in that way that gases are restrained and recombined. It is worth mentioning that oxygen gases are explosive in the air with only 4% per volume.

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<sup>2</sup> The product of current (A) that a battery can provide with the time period (h) for which can provide that current under specific voltage conditions as well as temperature and rate of discharging.

<sup>3</sup> The percentage of total capacity that is accumulated in a cycle of charging and is consumed in a cycle of discharging.

<sup>4</sup> When we put two batteries in series, the capacity remains the same, when the voltage is added (the opposite happens when we put in parallel two batteries).

Open type accumulators (common type OpZs) require good ventilation and electrolyte refilling, but also have large capacities, combined with many charging cycles and a relatively low cost. On the contrary, closed type accumulators, usually moderated by a valve (valve regulated lead acid, VRLA) with absorbed glass mat

(AGM), have very good efficiency at high current (short time of discharging) and include very little quantity of acid. That means that they are prone to water losses that occur mainly at high temperatures, but also resist freezing as there is enough space for expansion in AGM [6]. Also, they do not need maintenance, but they are more expensive and have fewer charging cycles.

Besides lead-acid accumulators, we can also find Ni-Cd accumulators (with restricted use in PV systems) as well as Li-ion accumulators, that were evolving the last few years in order to be used in PV systems.

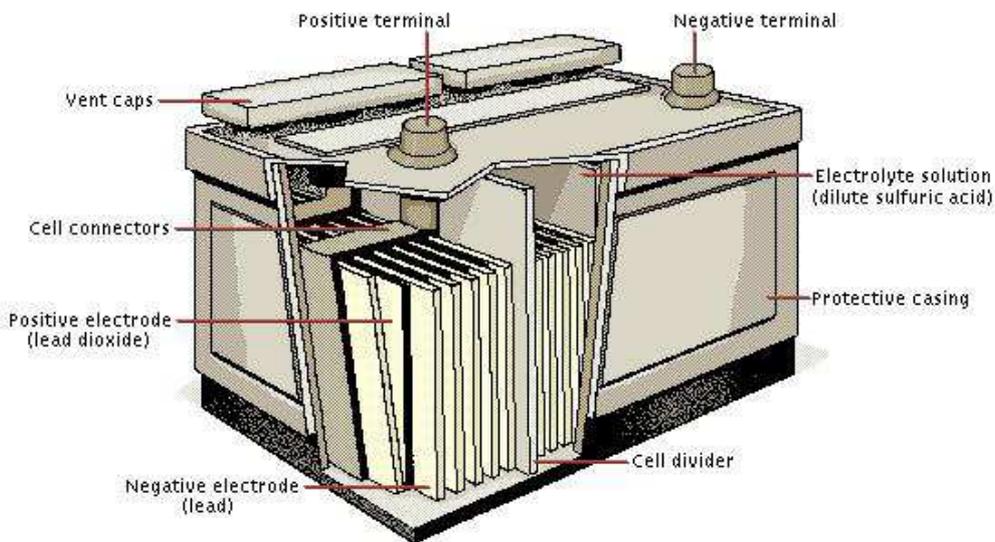


Figure 4. Lead-Acid accumulator cutted [10]

## Charger – Charge controller

The procedures of charging and discharging of the accumulators, as well as their control, are essential for upholding them in good condition and, as a result, prolonging their life. The charging of batteries must be done with DC. AC must be transformed (rectified). To that purpose, semiconductor rectifiers are being used [7]. For AC voltage, chargers convert the AC to DC (converters) in order to recharge the batteries. Charging can be held in several ways, but its purpose, leading current to the opposite direction than that of discharging, remains the same in any case [8].

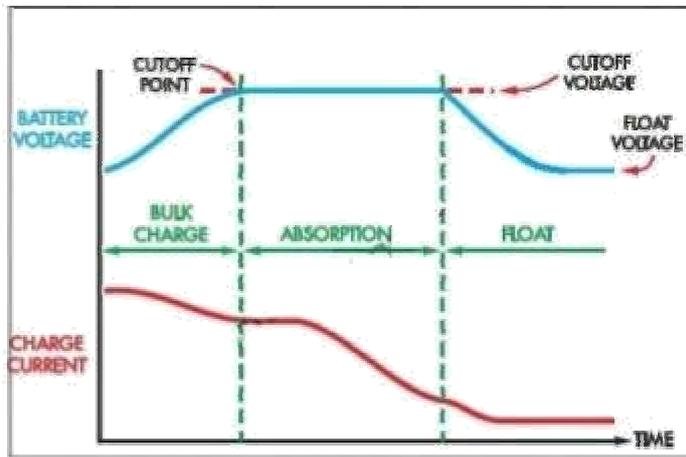


Figure 5 - Ideal conditions of charging a Lead-Acid Accumulator [11]

The basic methods that have been developed for charging Lead-Acid accumulators are:

1. Stable current – one current
2. Stable current – multiple steps of decreasing current
3. Modified stable current
4. Stable potential
5. Modified stable potential with stable initial current
6. Modified stable potential with stable final pace
7. Modified stable potential with stable initial and final pace
8. Taper charge
9. Pulse charge
10. Trickle charging
11. Stable charging / float charging
12. Rapid charging

An integral part for safe and efficient accumulator function is operation at the highest possible charging level. That role is undertaken by the **charge controller**, which also reassures the protection of the accumulator from overcharging and over discharging.

What a charge controller controls:

A) Protection against overcharging. Usually, the controller restricts the accumulator's voltage to a maximum value (voltage regulation set point - VR). The respective current is either regulated as long as the set voltage is stable or it remains disconnected until accumulator's voltage drops below the value set as the reconnect voltage-AVR.

B) Protection against over discharging. Usually, this is achieved by open circuiting the connection between the accumulator and the load when the voltage reaches a predefined/set point of low voltage load disconnect set point-LVD. Most of charge controllers have either a light or audio alarm that inform the PV system user of the load's disconnection. After a specific point of recharging the accumulator, the loads are connected again.

C) Provision for controlled loading. It is possible to define the automatic connection and disconnection of one or more electric loads at a specific time during the day, e.g. for the function of a light load when PV system does not work (from sunset till dawn).

There are two basic categories of charge controllers that are the basis for many other variations: in-series adjustable controllers and in-parallel adjustable controllers. In-series controllers work in series between the PV array and the accumulator, open circuiting the PV array. This system is used both in small and large stand-alone PV systems. The in-parallel controller regulates charging, internally short circuiting the PV array<sup>5</sup>. Its usage is restricted to PV systems with an array current less than 20 A.

The technology of charge controllers has evolved and now the most used systems are PWM and MPPT. To be more specific, PWM system (pulse width modulation) gradually decreases the power provided to the accumulator as it reaches the point of full charge. Longer lifetime of the accumulator is achieved this way, as it is less worn out when it is charged. On the other hand, the most popular and better charge controlling system is MPPT (maximum power point tracking). Its function is based on matching the PV panel voltage at its exit with the voltage of the accumulator and, as a result, we have the maximum charging efficiency. Its efficiency can reach +30% higher than other controllers and that is because it exploits almost all of the provided power. This is especially true during the very early and late hours, when the power output of the PV system is low, that would be excluded when a

predefined value of voltage is set in the other technologies. The MPPT controller also needs to be connected to a DC/DC buck-boost converter in order to regulate the output voltage and to decrease or increase voltage if needed.

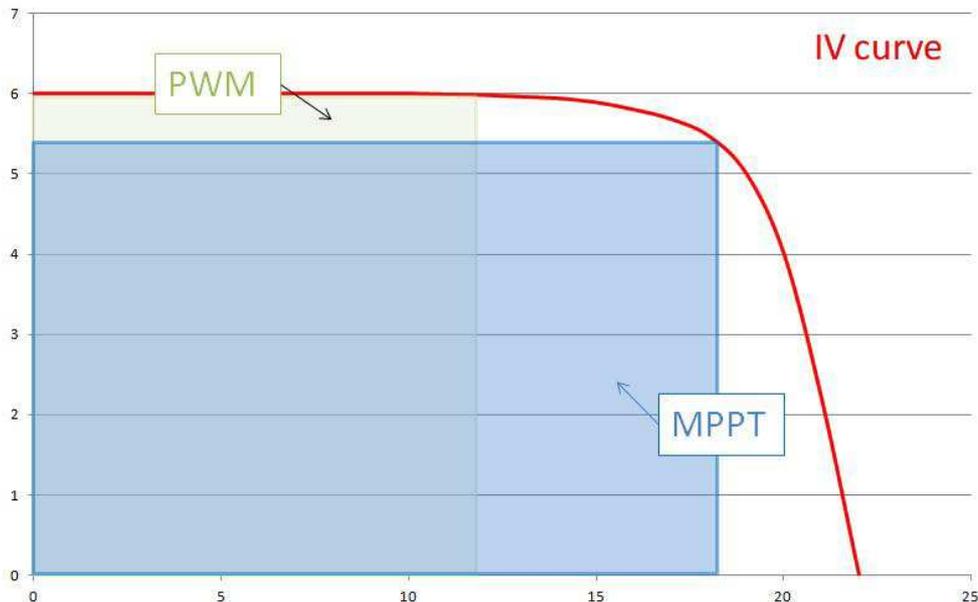


Figure 6. Comparison of PWM and MPPT efficiency[9]

Chargers and charge controllers must operate under the same charging conditions for the highest system efficiency. In PV installations, they usually are individual items (charger - charge controller). Nevertheless, there are certain types of inverters with an integrated charger and with the capability of charging by an external / backup generator or from the grid. In this occasion, there is no need for a separate charger/controller.

Furthermore, for security reasons, accumulators must be placed in well ventilated spaces and isolated from inhabited spaces as well as electronics rooms, because they encase dangerous chemical substances and release hydrogen and oxygen during charging. Moreover, the installation area should be protected against high temperatures and provide easy access for their maintenance, service and installation. Accumulators can be recycled at the end of their lifetime.

## DC/AC INVERTERS

In order for the installation's loads to exploit the PV energy, the DC that is produced

needs to be converted to AC, because consumptions/loads generally are designed to operate on grid AC voltage. The inverter is an electronic device that converts DC voltage into AC. The inverter (or inverters, depending on the size of the plant) is connected directly to the batteries on the DC side and on the AC side to the load's electric panel.

Depending on the PV panels selected, the appropriate inverter is selected, taking into account the maximum operation voltage and maximum operation power.

In stand-alone PV systems, unlike PV systems connected to grid, two types of inverters are used: pure sine wave inverters and modified sine wave inverters (Fig. 7), depending on the generated voltage wave. Pure/true sine wave inverters are preferred as certain devices require pure sine wave current. Modified sine wave can be widely used, except for specific loads, e.g. capacitive and electromagnetic loads. The second category of inverters is preferred because of its lower cost, other than for certain occasions e.g. for the operation of sensitive electronic devices that require low total harmonic distortion (THD).

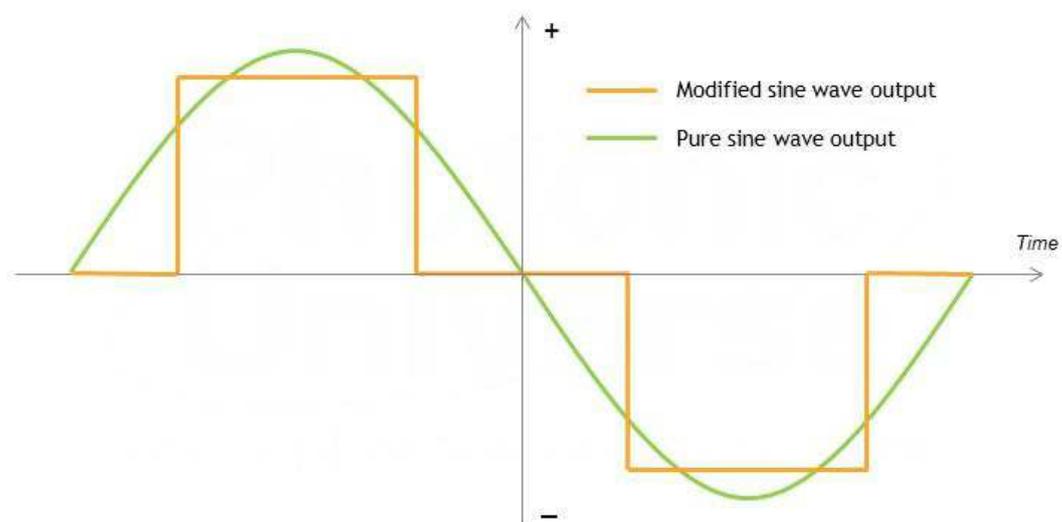


Figure 7 - Pure sine wave and modified sine wave

## Other equipment

Besides the basic equipment that was analyzed in the previous chapters, each PV system consists of the following parts:

A) PV panels mounting system



For proper operation of a stand-alone PV system, proper design and construction of the electrical installation is necessary.

Fig. 8 shows the electrical configuration a stand-alone PV system. The electrical connections of the various devices are done with DC voltage wiring (for the part until the DC side of the inverter) and AC voltage wiring (for the part from the AC side of the inverter to loads/consumptions). For safety and isolation of DC and AC side, as shown in the picture, suitable electrical panels are positioned each time with rapid melting fuses, miniature circuit breakers, overcurrent devices (RCD), protection devices against overvoltage (OVR) with refillable cartridges, isolating switches, lightning protection devices. The selection of the aforementioned equipment depends on the specifics of each project. In large installations (over 100kW) the voltage is increased of from low to medium via a transformer, because it usually is connected to an electrical generator for the safety of the installation. In this case, it is additionally required that the relevant safety devices for medium voltage are added as well (Automatic switches, fuses, leak relay, devices against overvoltage and overcurrent, lightning protection devices, protection relay, circuit breaker, etc.).

For large facilities, there are clustering boxes at the DC side (string boxes, circuit monitoring and protection units), on the mounts at the rear side of the PV panels of some arrays, so as to allow the easy and with fewer losses and stress DC cabling till the charge controller.

Specifically, for DC wiring installed outdoors, low voltage cables should be "Solar Cable" type, i.e. to have protection and resistance against UV radiation - protection class II.

PV panels usually are received with the required DC cables so that they can be connected in series with each other. From the edge of each array, cables are leaving to connect to a clustering box. Routing of these cables directly underground is even possible without "T" pipes or channels. Most of these cables are arranged in trays located directly below the fixed bases. Those that cannot be driven through the trays to the clustering boxes, they can alternatively be routed underground.

All power and communication cables (for the system's connection and the connection to low voltage devices) are installed in well-designed channels and, regarding underground routing, grids in ditches, according to construction designs.

Moreover, depending to the installation there is an **UPS Unit** (Uninterruptible Power Supply) to serve the basic needs in case of battery or power failure to strictly indispensable equipment.

## Protection - security system for PV installation and humans

Usually in PV systems an **Automatic or Manual Fire Detection and Fire Protection System** is included. In case of an Automatic Fire Detection System and Fire Declaration System, there are fire detectors that are connected to a fire alarm panel and from there commands are given to the alarm siren. In the case of a Manual Fire Alarm System, there usually are only preventive means, such as extinguishers or fire extinguishing systems (water pump).

The **grounding system** is also crucial for seamless system operation, as it is the main means of protection for people and equipment. The choice of the grounding system of a PV installation will be made in order to:

- ☐ Minimize the grounding resistance of the PV installation (<1 Ohm).
- ☐ Minimize material cost.
- ☐ Ease of installation of the grounding system.

The grounding system is designed after measuring the soil resistivity at each site a PV system is installed, and by using an appropriate software package. The usual grounding means is a steel film/ribbon, hot galvanized (St / tZn) in a closed loop. It is installed around the electrical panel or the Production Substation (depending to the size of the installation) and usually attached to copper earthing rods. The system of the surrounding earthing, where the cathode and the anti-lightning conductors end, will be connected to the rest of the earthing system of the PV station.

Last but not least, there is the system of **anti-lightning protection (S.A.P.)**. After assessing the danger from lightnings, in order to be above the affordable risk limits that are defined each time from legislative standards, it may or not be necessary to install external S.A.P. I, II, III or IV. If there is no external S.A.P., the protection is covered by the internal system of SPDs. Each S.A.P. consists of the external and the internal anti-lightning protection system. The *external anti-lightning protection system* protects equipment and its contents, as well as people, from direct lightning. It consists of the earthing system, the surge protection system, and the lightning collection system. The *internal anti-lightning protection system* protects equipment and people from electromagnetic influences due to direct and indirect lightning. It consists of the equipotential system and the surge protection system.

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