SUN SYNK®

# PHOTOVOLTAIC INVERTERS

## TRAINING MANUAL

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# 1. INTRODUCTION

## 1.1. INTRODUCTION TO SOLAR PHOTOVOLTAIC SYSTEMS

In the last decades, power consumption has widely increased all over the world, and energy price is becoming more expensive. Many governments around the world believe that renewables are a great solution to supply power demand at a lower cost. Wind generation, solar photovoltaic (PV), hydroelectricity are some examples of renewable energy sources. Except for solar, most systems are expensive to buy and install and are generally suited for large scale installations. PV systems vary from nanosystems built into a watch or calculator, micro portable and fixed systems used for home or personal usage, to huge giga-watt solar plants supplying cities.

In 1839, Alexandre Edmond Becquerel observed the photovoltaic effect via an electrode in a conductive solution exposed to light. Since then, the technology has improved due to research and new manufacturing methods. There are many types of solar cell technology, which implies different efficiency and prices.

## 1.2. HOW SOLAR PHOTOVOLTAIC (PV) SYSTEMS WORK?

Solar power is the use of the sun's energy by employing photovoltaic cells in solar panels and transparent photovoltaic glass to generate electricity. In the solar generation, the photovoltaic cell is the basic element to transform the sun's energy into electrical power. A photovoltaic cell (PV cell) is a specialized semiconductor diode that converts the visible light into direct current (DC). These cells are an integral part of solar-electric energy systems, and in order to increase the gathering of energy, large sets of PV cells can be connected to form solar modules, arrays, or panels. The use of PV cells and batteries for the generation of usable electrical energy is known as photovoltaics. The most used material for the manufacture of cells is silicon (Si), which is usually structured in monocrystalline and polycrystalline. In the manufacturing process, one of the Si layers is doped to form the junction, in addition, a metal sheet is attached to the surface on which there will be solar radiation, and another blade is used as a basis for electrical connections, as can be seen in Figure 1. When there is radiation incidence, if the incident photon energy is sufficient, there is a current flow at the cell terminals.

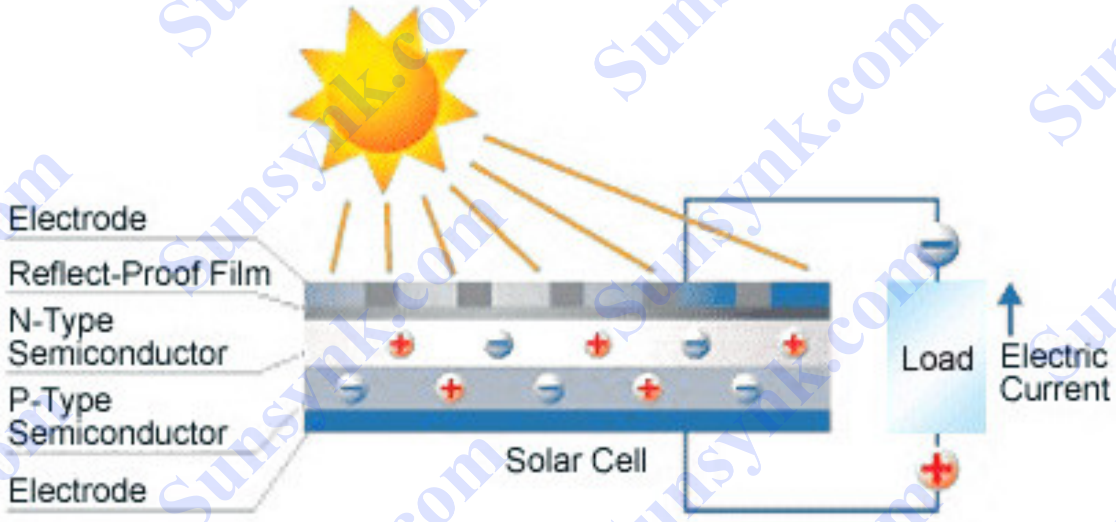

**Figure 1 - PV cell.**

Large sets of PV cells can be connected to form solar modules, which can be associated to create PV arrays. The use of PV cells to generate usable electrical energy is known as photovoltaics. Photovoltaics has many advantages: it is the cleanest and most abundant renewable energy source and requires only real-estate (and a reasonably sunny climate) to function. Once a photovoltaic system has been installed, it can provide energy at essentially no cost for years, and with minimal maintenance.

Photovoltaic systems are basically divided into three types:

1) Off-grid: they do not have a connection to the electric network and make use of energy storage (bank of batteries and supercapacitors);

2) Grid-tied: they can supply load and also partially or integrally insert the power generated by the modules in the electrical grid;

3) Hybrid systems: a PV system that includes other sources of electricity generation, such as wind, fuel cell, or diesel generators.

A basic off-grid/hybrid PV system is composed of four main parts:

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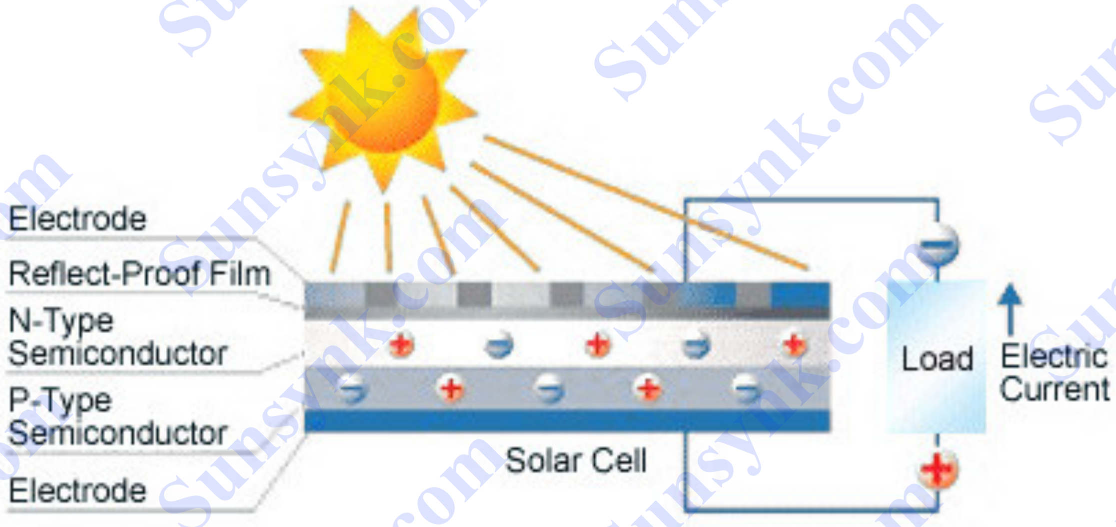

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3) Hybrid systems: a PV system that includes other sources of electricity generation, such as wind, fuel cell, or diesel generators.

A basic off-grid/hybrid PV system is composed of four main parts:

a) Solar panel/array: collects and converts power from the sun into DC.

b) Charge Controller: converts and controls the power to a battery charge.

c) Battery or storage device: stores energy for later use.

d) Inverter: converts the DC power produced from the solar panels and present in the battery to the more useful AC power to use on appliances

Other parts are cabling and electrical accessories to set up a working system.

Until recently, the industry or producing solar power has been unable to store sufficient energy to benefit general daily tasks. However, this problem has been overcome since the arrival of lithium-Ion and AGM batteries and advanced electronic systems to economically manage the storage of power safely.

PV systems convert light directly into electricity and should not be confused with the concentrated solar power (using reflectors) and solar thermal, which directly heats and cools liquids for domestic use. PV systems can range from small rooftops - mounted or building-integrated systems with capacities from 10-500 kilowatts, to large utility-scale power stations of hundreds of megawatts such as those being installed in some of the world's arid areas.

Nowadays, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market. Operating silently and without any moving parts or environmental emissions, PV systems have developed from being niche market applications, into a mature technology used for mainstream electricity generation. A rooftop system recoups the invested energy for its manufacturing and installation within 0.7 to 2 years and produces about 95% of net clean renew- able energy over a 30-year service lifetime.

Conventional c-Si solar cells, usually wired in series, are encased in a solar module to protect them from the weather. The module consists of a tempered glass cover, a soft and flexible case, a rear backsheet made of a weathering and fire-resistant material, and an aluminum frame around the outer edge.

Electrically connected and mounted on a supporting structure, solar modules build a string of modules, often called as solar arrays. A solar array consists of one or many such panels. A photovoltaic array, or solar array, is an association of panels. One module's power is hardly enough to meet the requirements of modern appliances, so the modules are connected to form an array.

## 1.3. PV GLOSSARY

**Absorption coefficient -** the factor by which photons are absorbed as they travel a unit distance through a material.

**Alternating current -** electric current in which the direction of flow is reversed at frequent intervals.

**Amorphous silicon -** silicon without crystalline structure.

**Ampere (A) -** unit of electric current. The rate of flow of electrons in a conductor equal to one coulomb per second.

**Ampere hour (Ah) -** the quantity of electrical energy equal to the flow of the current of one ampere for one hour.

**Anode -** the positive electrode in an electrochemical cell (battery).

**Antireflection coating -** a thin coating of a material, which reduces the light reflection and increases light transmission, applied to a photovoltaic cell surface.

**Array -** electrically connected photovoltaic (PV) modules.

**Array current -** The electrical current produced by a PV array.

**Azimuth -** horizontal angle measured clockwise from true north (180° is true south). In solar energy, engineering azimuth is measured from the south toward W or E (0° is true south, toward west negative)

**Base load -** the average amount of electric power that a utility must supply in any period.

**Battery -** a device that converts the chemical energy directly into electrical energy by means of an electrochemical reaction.

**Battery capacity -** the total number of ampere-hours that can be withdrawn from a fully charged battery at a specified discharge rate and temperature.

**BIPV -** Building Integrated Photovoltaics; A term for the design and integration of PV into the building envelope, typically replacing conventional building materials. This integration may be in vertical facades, replacing view glass or other facade material; into roofing systems, over windows, or other building envelope systems.

**Blocking diode** - a diode used to restrict or block reverse current from flowing backward through a module. It protects modules against the risk of thermal destruction of solar cells due to reverse power flow.

**Bypass diode** - a diode connected anti-parallel across a part of the solar cells of a PV module. It protects solar cells from destruction in case of total or partial shading of individual solar cells.

**Cathode** - the negative electrode in an electrochemical cell. Also, the negative terminal of a diode.

**Cathodic protection** - a method of preventing oxidation (rusting) of exposed metal structures, such as bridges and pipelines, by imposing between the structure and the ground a small electrical voltage.

**Charge Controller** - a device that controls the charging rate and/or state of charge for batteries.

**Converter** - an electrical device that converts a DC or AC voltage to another DC or AC voltage. For DC/AC conversion see inverter, for DC/DC conversion see DC/DC converter.

**Crystalline silicon** - silicon made from a single crystal or poly-crystalline slice of silicon.

**Current** - the flow of electric charge in a conductor between two points having a difference in potential (voltage).

**Cutoff voltage** - the voltage levels (activation) at which the charge controller disconnects the array from the battery or the load from the battery.

**Cycle** - the discharge and subsequent charge cycle of a battery.

**DC/DC Converter** - an electronic circuit that converts DC voltages into other levels. Usually, it is part of a maximum power point tracker (MPPT) and charges regulators.

**Deep cycle** - discharged to a large fraction of capacity many times without damaging the battery.

**Depth of discharge** - the percent of the rated battery capacity that has been withdrawn. Sometimes also expressed as abbreviation DoD.

**Diffuse radiation** - radiation received from the sun after scattering and reflection by the atmosphere and ground.

**Diode** - an electronic part that allows current flow only in one direction.

**Direct radiation** - radiation received by direct solar rays. Measured by a pyrheliometer with a solar aperture of 5.7° to transcribe the solar disc. Sometimes also expressed as "beam radiation".

**Direct Current (DC)** - electric current flowing in only one direction.

**Duty cycle** - the ratio of active time to total time. It is used to describe the operating regime of appliances or loads in PV systems.

**Efficiency** - the ratio of output power (or energy) to input power (or energy). Expressed in percent

**Electrolyte** - The medium that provides the ion transport mechanism between the positive and negative electrodes of an electrochemical cell (battery).

**Electric current** - a flow of electrons; electricity.

**Electrical grid** - an integrated system of electricity distribution, usually covering a large area.

**Electron-volt (eV)** - an energy unit equal to the energy an electron acquires when it passes through a potential difference of one volt; it is equal to 1.602 x 10-19 V.

**Equalisation charge** - the process of mixing the electrolyte in batteries by short periodically overcharging of the batteries.

**Fill Factor (FF)** - the ratio of the maximum power to the product of the open-circuit voltage and the short-circuit current (for an I-V curve).

**Fixed Tilted Array** - a photovoltaic array with a fixed inclination angle with respect to horizontal.

**Frequency** - the number of cycles per unit time expressed in Hertz (Hz).

**Gassing** - gas byproducts (hydrogen) produced during the charging of a battery.

**Gallium arsenide (GaAs)** - a crystalline semiconductor/photovoltaic material.

**Gel Type Battery** - lead-acid battery in which the electrolyte is composed of a gel.

**Grid** - term used to describe an electrical utility distribution network.

**Grid-connected/Grid-tied PV system** - a PV system that is connected to the grid.

**Hybrid System** - a PV system that includes other sources of electricity generation, such as wind, fuel cell, or diesel generators.

**Incident radition** - solar radiation incident on solar cell or module.

**Irradiation** - the solar radiation incident on an area over time. Equivalent to energy and expressed in J/m2. In technical practice, kilowatt-hours per square meter is more often used.

**Inverter** - also named Power Conditioning Unit (PCU), or Power Conditioning System (PCS). An inverter converts DC power from the array (battery) to AC power compatible with the utility (loads).

**Irradiance** - the solar radiation incident on a surface that is usually expressed in kW/m².

**Joule (J)** - Unit of energy 1 J = 1/3600 kWh.

**Junction Box** - a PV generator junction box is an enclosure on the module backside, where electrical contacts and protection devices (if used) are located.

**Kilowatt (kW)** - a unit of power equivalent to 1000 Watts.

**Kilowatt Hour (kWh)** - A unit of energy. Power multiplied by time equals energy.

**Load** - the amount of electric power used by any electrical appliance at any given time.

**Load current** - the current required by the electrical device (load).

**Low voltage cutoff** - the voltage level at which a controller will disconnect the load from the battery.

**Maintenance-free battery** - a sealed battery that does not require maintance during lifetime.

**Module** - another name for solar panel.

**MOSFET** - metal-oxid-silicon field-effect transistor; used as semiconductor power switch in charge regulators, inverters etc.

**MPP** - maximum power point; the point on the current-voltage (I-V) characteristic of a PV device, where the current and voltage product is maximal.

**MPPT** - maximum power point tracker; electrical circuit that operates at generators maximum power point. MPP tracker is part of the inverter and charge regulators.

**N-type silicon** - silicon material that has been doped with a material that has more electrons in its atomic structure than silicon.

**NOCT** - nominal operating cell temperature. The estimated temperature of a PV module when operating under 800 W/m2 irradiance, 20°C ambient temperature, and wind speed of 1 m/s. NOCT is used to estimate the nominal operating temperature of a module in its working environment.

**Nominal Voltage** - a reference voltage used to describe system, module or battery.

**Ohm (Ω)** - the unit of electrical resistance.

**Open circuit voltage** - the maximum voltage produced by an illuminated photovoltaic cell, module, or array with no load connected. This value will increase as the temperature of the PV material decreases.

**Operating point** - the current and voltage that a module or array produces when connected to a load. The operating point is dependent on the load or the batteries connected to the output terminals of the array.

**Overcharge** - forced charging of a fully charged battery. The battery can be damaged if overcharged for a long period.

**Panel** - a designation for a number of PV modules assembled in a single mechanical frame.

**Peak load** - the maximum load demand of a system.

**Peak sun hours** - the equivalent number of hours per day when solar irradiance averages 1,000 W/m2 - one peak sun hours means that the energy received during total daylight hours equals the energy that would have been received had the irradiance for one hour been 1,000 W/m2.

**Peak Watt (Wp)** - the amount of power a photovoltaic module will produce at standard test conditions (normally 1,000 W/m2 and 25° cell temperature).

**Photon** - a particle of light that acts as an individual unit of energy. Its energy depends on wavelength.

**Photovoltaic system (PV)** - an installation of PV modules and other components designed to produce power from sunlight.

**Polycrystalline silicon** - a material used to make PV cells which consist of many crystals as contrasted with single crystal silicon.

**Power factor** - the cosine of the phase angle between the voltage and the current waveforms in an AC circuit. Used as a designator for inverter performance.

**Primary battery** - a battery whose initial capacity cannot be restored by charging.

**Rated module current** - the current output of a PV module measured at standard test conditions of 1,000 W/m2 and 25°C cell temperature.

**Reactive power** - the sine of the phase angle between the current and voltage waveforms in an AC system.

**Resistance** - the property of a conductor that opposes the flow of an electric current resulting in the generation of heat in the conducting material.

**Secondary battery** - a battery that can be recharged.

**Self-discharge** - the rate at which a battery, without a load, will lose its charge.

**Series regulator** - a type of battery charge regulator where the charging current is controlled by a switch connected in series with the PV array.

**Short circuit current** - the current produced by module, or array when its output terminals are shorted.

**Silicon (Si)** - a chemical element, atomic number 14, semi metallic in nature, dark gray, an excellent semiconductor material. A common constituent of sand and quartz (as the oxide). The most common semiconductor material used in making photovoltaic devices.

**Stand-alone system** - A photovoltaic system that operates independent of the utility grid.

**Standard test conditions (STC)** - conditions under which a module is typically tested in a laboratory: Irradiance of 1000 W/m2, AM 1.5 solar reference spectrum, a cell (module) temperature of 25°C.

**String** - a number of modules or panels interconnected electrically in series.

**Tilt Angle** - the angle of inclination of a solar array measured from the horizontal.

**Thin-film PV module** - a PV module constructed with layers of thin film semiconductor materials.

**Tracking array** - a PV array that follows the path of the sun. Tracking can be one-axis or two-axis tracking where the array follows the sun in azimuth and elevation.

**Transformer** - converts the AC generator's voltage to higher voltage levels suitable for transmission.

**Trickle charge** - a small charge current intended to maintain a battery in a fully charged condition.

**Uninterruptible power supply (UPS)** - a power that provides continuous uninterruptible service.

**Volt** - the unit of electrical voltage force a current of one ampere through a resistance of one Ohm.

**Voltage** - Potential energy that makes the electrical current flow in a circuit.

**Wafer** - a thin sheet of semiconductor material made by mechanical sawing it from a single-crystal or multicrystal ingot or casting.

**Watt** - The unit of electrical power. The power developed when a current of one ampere flows through a potential difference of one volt.

**Watt hour (Wh)** - a unit of energy equal to one watt of power connected for one hour.

**Waveform** - the characteristic shape of an AC current or voltage output.

**Zenith angle** - the angle between the vertical line and the line intersecting the sun. (90°- zenith).

## 1.4. SI SYSTEM

The SI system, also called the metric system, is used around the world. There are seven basic units in the SI system: the meter (m), the kilogram (kg), the second (s), the kelvin (K), the ampere (A), the mole (mol), and the candela (cd).

In the same way, electrical appliances all use the same SI units. In Table 1, there is a list of the common units employed in the solar industry.

**Table 1 - Usual SI units for electrical measurements.**

| Symbol | Name | Measure |
|---|---|---|
| A (Amps) | Ampere | Electric Current |
| V | Volts | Voltage |
| W | Watts/Wattage | Electric Power |
| kW | Watts/Wattage | Electric Power (Equivalent to 1000 W) |
| Wh | Watt-Hour | Electric Power |
| kWh | Kilowatt-Hour | Electric Power (Equivalent to 1000 Wh) |
| Ω | Ohms | Resistance |

# 2. BASICS

## 2.1. HOW IS ELECTRICITY MEASURED

Watts (W) is a measurement of power, describing the rate at which electricity is being used at a specific moment.

For example, 2 x 100 Watt light bulbs will burn 200 watts per hour.

Watt-Hours (WH) is a measurement of energy, describing the total amount of electricity used over time. Watt-Hours is a combination of how fast electricity is used (Watts) and its length (Hours). For example, if you leave 2 x 100 watt light bulbs on for 10 hours, they would have used 2 x 100 ( Wattage ) x 10 ( Hours ) total 2000 Watt Hours (2000Wh)

Kilowatts (kW) and kilowatt-hours (kWh) are simply watts divided by 1000. This is a more useful figure; also, most house's power is measured in kWh.

Megawatts = One Million Watts

Gigawatts = 1000 x Megawatts (One Billion Watts)

How much will 3.5 Megawatts of free power save me, that all depends upon your tariff?

Feed-in Tariffs (FITs) is a HK Government scheme designed to encourage uptake of a range of small-scale renewable and low-carbon electricity generation technologies.

If you are eligible to receive feedback tariff payments you could benefit in three ways:

Generation tariff: your energy supplier will pay you a set rate for each unit (or KWH) of electricity you generate. Once your system has been registered, the tariff levels are guaranteed for the period of the tariff.

Export tariff: your energy supplier will pay you a further rate for each unit you export back to the electricity grid, so you can sell any electricity you generate but do not use yourself. At some stage, smart meters will be installed to measure what you export.

Energy bill savings: you will be making savings on your electricity bills because generating electricity to power your appliances means you do not have to buy as much electricity from your energy supplier. The amount you save will vary depending on how much of the electricity you use.

If your feedback tariff is Par, then you simply save the KWH 1:1. The average world cost of electricity is around US$ 0.20 per kWh, so your 6-panel array can produce 3558 KWH @ US$ 0.20 = US$ 711 Per year.

However, it gets much more interesting if you are on a good feedback tariff/grant, which can be as much as US$ 0.80 per kWh. In that case, your array can earn you US$ 2,846.00 per year, not a bad payback.

## 2.2. TYPES OF SOLAR PV MODULES

1) **Monocrystalline Silicon (Silicon = 'Si'), or Mono Si**: These solar cells are more efficient and more expensive than most other types of cells. The corners of the cells look clipped, like an octagon, because the wafer material is cut from cylindrical ingots that are typically grown by the Czochralski process. Solar panels using mono-Si cells display a distinctive pattern of small white diamonds.

**Figure 2 - Monocrystalline PV module** *(Haven Hill, 2018)*.

2) **Polycrystalline Silicon or multi-crystalline silicon (multi-Si)**: These PV cells are made from cast square ingots large blocks of molten silicon carefully cooled and solidified.
   They consist of small crystals giving the material its typical metal flake effect. Polysilicon cells are the most common type used in photovoltaics and are less expensive but also less efficient than those made from monocrystalline silicon.

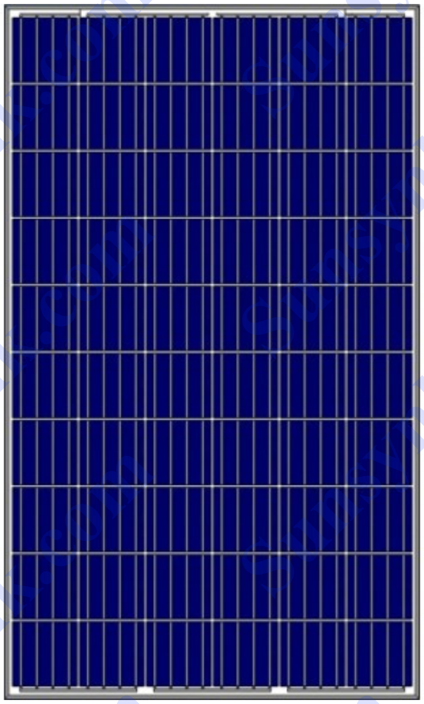


**Figure 3 - Polycrystalline PV module** *(Haven Hill, 2018)***.**

3) **Thin-Film Amorphous Silicon panels or A-Si:** Thin-film technologies reduce the amount of active material in a cell. Most designs sandwich active material between two panes of glass. Since silicon solar panels only use one pane of glass, thin-film panels are approximately twice as heavy as crystalline silicon panels, although they have a smaller ecological impact.

**Figure 4 - Thin-Film Amorphous Silicon** (Haven Hill, 2018)**.**

## 2.3. PV SOLAR CELLS AND PANELS

The number of cells in a solar panel can vary from 36 cells to 144 cells and these elements are connected in series. The two most common solar panel options on the market today are 60-cell and 72-cell. In

Figure 5, polycrystalline and monocrystalline cells are presented.

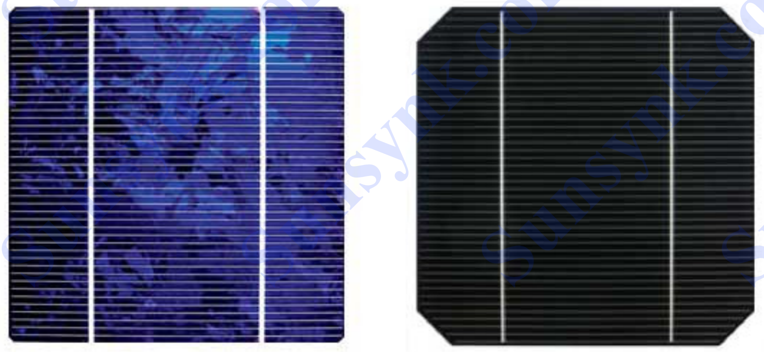
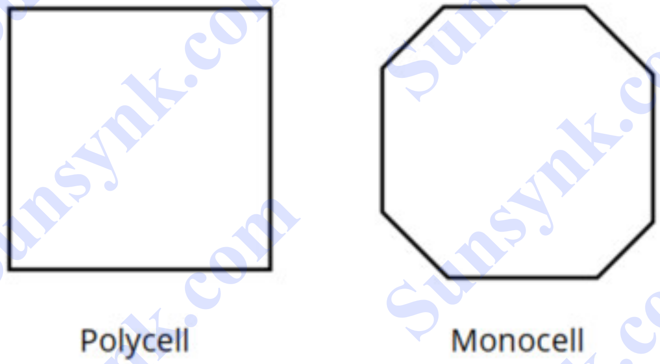


**Figure 5 - Polycrystalline (left) and Monocrystalline (right) cells** (SolarQuotes, 2020)**.**

The most popular solar panel is a 72-Cell 325 W solar panel (composed of 72 cells all wired in series).

- **Cell Wattage Size**

1. Poly 156mm x 156mm 4.51 W
2. Mono 125mm x 125mm 2.6 W



Both types of panel have around 17% efficiency, Voltage per one cell = 0.5V MPP (Maximum Power Point Voltage), Voltage open circuit = 0.6V (for both panels).

The cells are associated in series, therefore, the sum of the voltages of each cell is equal to the total voltage of the panel. If the panel is composed of 72 cells and the voltage at open circuit condition is 0.6 V, the maximum voltage is equal to:

$$72 \text{ x } 0.6 \text{ V} = 43.2 \text{ V} \text{ (This is the MPP voltage)}$$

In popular polycrystalline cells, each cell produces 4.51 W @ 0.5 V – Maximum Power Point:

$$72 \text{ x } 4.51 \text{ W} = 325 \text{ W}$$

A standard 72-cell solar panel presents around 43 V for an open circuit. If you connect a voltmeter to the open ends of a solar panel, you should read around 43 V when the panel is in direct sunlight. The voltage is dependent upon the number of cells in the solar panel.

One thing to remember is if a single cell in the panel is damaged or wrongly cut, the whole panel may not work.

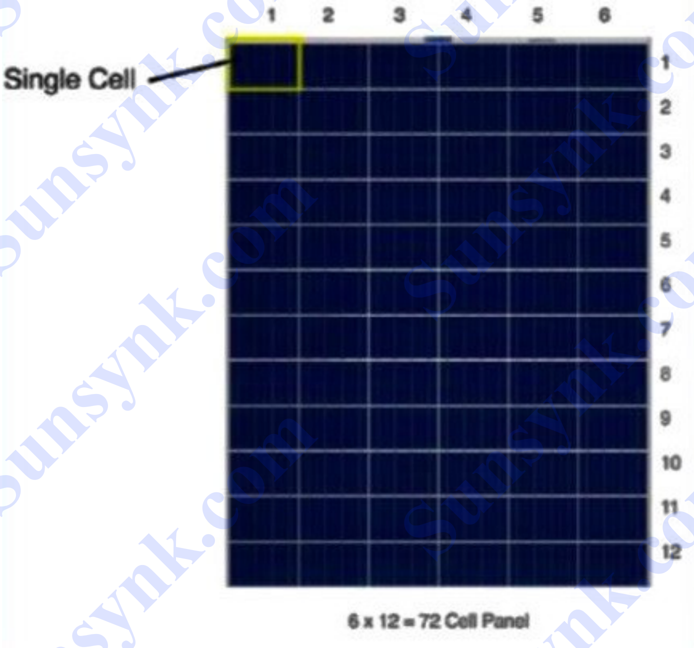


**Figure 6 - A single cell within a PV panel.**

- **Optimization**

Solar cells generally come into two sizes

1) Polly 156 x 156mm and;
2) Mono 125 x 125mm.

Each time a cell is cut, its voltage remains the same, but the current is reduced proportionally. The diagram shown in Figure 7 to the left shows a polycrystalline wafer cut in four. 4 x 0.6 V (4.51 / 4) 1,12 W cells.

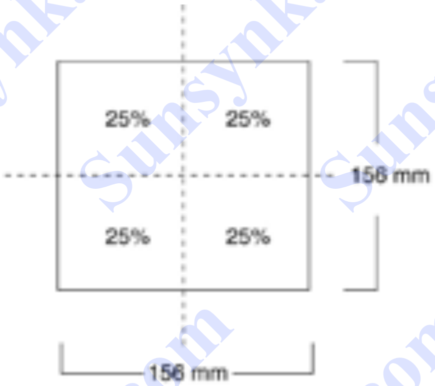


**Figure 7 - 25% cut solar cell.**

If you cut asymmetrically, then like the example below (2.6 V / 2) 1.3 Watt cells 25% of the wafer is scrap.

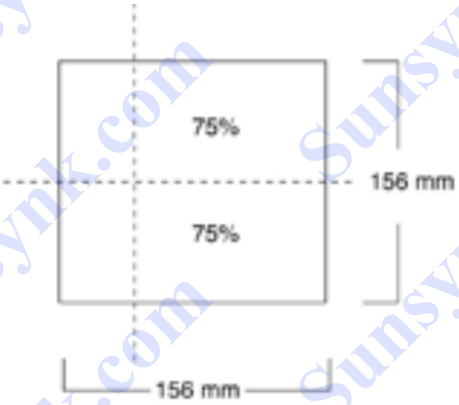


**Figure 8 - 75% cut solar cell.**

Because of the shape, Mono-crystalline cells are a little more difficult to optimize.

**Table 2 - Examples of standard panels.**

| No. of cells wide | No. of cells deep | Total no. of cells | Voltage per cell (V) | Max. voltage of the panel (V) |
|---|---|---|---|---|
| 1 | 5 | 5 | 0.6 | 3 |
| 2 | 5 | 10 | 0.6 | 6 |
| 2 | 10 | 20 | 0.6 | 12 |
| 2 | 20 | 40 | 0.6 | 24 |
| 3 | 8 | 24 | 0.6 | 14.4 |
| 3 | 12 | 36 | 0.6 | 21.6 |
| 4 | 4 | 16 | 0.6 | 9.6 |
| 4 | 10 | 40 | 0.6 | 24 |
| 5 | 10 | 50 | 0.6 | 30 |
| 5 | 12 | 60 | 0.6 | 36 |
| 6 | 6 | 36 | 0.6 | 21.6 |
| 6 | 10 | 60 | 0.6 | 36 |
| 6 | 12 | 72 | 0.6 | 43.2 |
| 6 | 13 | 78 | 0.6 | 46.8 |
| 6 | 14 | 84 | 0.6 | 50.4 |

From the above, you can see all the cells on the solar panel are wired in series/daisy chain.

Each cell is 0.6 V. If you have 72 cells, it is simple:

$$Total\ voltage = Cell\ voltage\ x\ No.of\ cells$$

When cells or batteries are wired in series, the current remains constant, but the voltage increases.

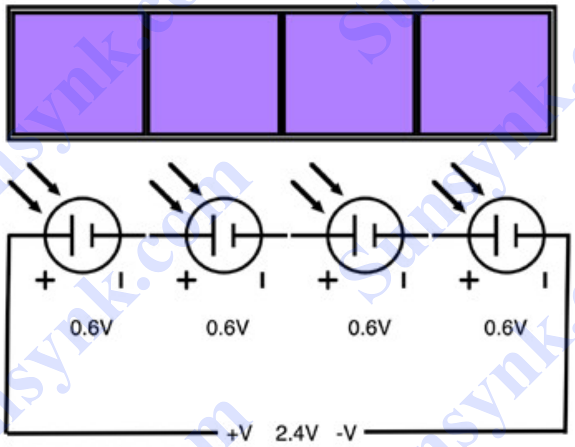


**Figure 9 - Simple 4 cell solar panel 4 X 0.6 V = 2.4 V.**

If a single Polycrystalline cell (156mm x 156mm) is 0.6 V @ 4.51 Watt the current is:

$$Current = \frac{Power}{Voltage}$$

Therefore,

$$\frac{4.51}{0.6} = 7.51\ Amps$$

A full size panel 72 x 0.6V = 43.2V (This is the open-circuit voltage) has the same current 325 / 43.2 = 7.51 Amps.

The same principle when complete solar panels are wired in series the voltage will increase:

$$No. of\ panels\ wired\ in\ series\ x\ panel\ voltage = Array\ voltage$$

## 2.4. PANEL INSTALLATION AND FACTORS AFFECTING PERFORMANCE

Several factors will affect the amount of power a solar array can produce. These are as follows:

1) The direction and angle of your roof: to work at maximum efficiency, solar panels should be installed on a south-facing roof. The angle of the panel is very much dependent on where you live in the world. Many complex formulas exist. Personally, I always suggest directing the panel towards the area in the sky where the 10 a.m. sun is positioned.

2) The amount of shade on your roof: you should avoid installing your solar panels in the shade, even if it is only a small amount of shadow can affect the whole array. If a solar panel is not in direct sunlight, it will work at a much lower efficiency than capable.

3) The temperature effect, solar panels become less efficient at temperatures over 25°C, if wrongly specified my not work at all.

4) The time of year: solar panels work all year round, but they are most efficient in the summer months (June, July, August) when there are more sunshine hours.

5) The amount of debris on your solar panels: solar panels lose efficiency when they are covered with dirt or bird mess. Always clean your solar panels regularly with warm water and a gentle soap to keep them running at their maximum efficiency.

# 3. UNDERSTANDING INVERTERS

## 3.1. HISTORY AND DEVELOPMENT OF INVERTERS

The inverter is a device that converts DC power into AC power. It is the fourth piece of the solar power system, and from this device, AC power is drawn to power utilities and machines. Most electrical items run on AC (alternating current), a battery is DC current, the main purpose of the inverter is to convert the DC power into useable AC power. Many years ago, a motor and generator connected together did this mechanically.

David Prince probably coined the term inverter. It is unlikely that any living person can now establish with certainty that Prince (or anyone else) was the originator of this commonly used engineering term. However in 1925 Prince did publish an article in the GE Review (vol.28, no.10, p.676-81) cited "The Inverter". His article contains nearly all essential elements required by modern inverters and is the earliest such publication to use that term in the open literature. Prince explained that an inverter is used to convert direct current into single or polyphase alternating current. The article explains how: "the author took the rectifier circuit and inverted it, turning in direct current at one end and drawing out alternating current at the other". The subsequent development of the inverter is discussed as are rectifier devices.

The original inverter (converter) was simply a motor connected to a generator. A rotary converter is a type of electrical machine which acts as a mechanical rectifier, inverter, or frequency converter. Rotary converters were used to convert alternating current (AC) to direct current (DC), or DC to AC power, before the advent of chemical or solid-state power rectification and inverting. They were commonly used to provide DC power for commercial, industrial and railway electrification from and AC power source or vice versa. The most important aspect of an inverter is the conversion of DC to AC. Nowadays, converting AC to DC is much easier using rectifiers. Figure 10 presents a ship rotary inverter.

**Figure 10 - Ship rotary inverter.**

When I was young, I built a very simple inverter using a device called an electro-magnetic vibrator or vibrator. The primary use for this type of circuit was to operate vacuum tube radios in vehicles, but it also saw use with other mobile electronic devices with a 6 or 12V accumulator, especially in places with no mains electricity supply such as farms. These vibrator power supplies became popular in the 1940s, replacing more bulky motor-generator systems for the generation of AC voltages for such applications.

This is an electromechanical vibrator (no need to guess why they were called where called vibrators). I remember the noise a little bit like a bee.

**Figure 11 - Electromechanical vibrator.**

Fast-forwarding to modern day, the basic principles still remain the same. A DC Converter that turns the DC into AC is a transformer that is used to step-up the voltage. Modern HF inverter is far more complex. It consists of many stages DC to HF AC, transformer, HF AC to DC-DC to a more usable 50/60 Hz AC the whole process is controlled via a microcomputer running a software program. In order to connect directly to the mains, grid-tied inverters must detect the mains frequency and synchronize the inverter into the main frequency. Also, it must shut-off its power in the absence of a grid connection.

A solar inverter may connect to a string of solar panels or, in some installations, a solar micro-inverter is connected at each solar panel. For safety reasons, a circuit breaker is provided both on the AC and DC side to enable maintenance. The number of modules in the system determines the total DC watts capable of being generated by the solar array; however, the inverter ultimately governs the amount of AC watts that can be distributed for consumption.

For example A PV system comprising 11 kilowatts DC (kW DC) worth of PV modules, paired with one 10 kilowatts AC (kW AC) inverter, will be limited to the inverter’s output of 10kW.

## 3.2. PURE SINE WAVE VS MODIFIED SINE WAVE & LOW FREQUENCY VS HIGH FREQUENCY INVERTERS

After reading through various articles on the internet, it is clear that many people do not fully understand the difference between a pure sine wave and modified sinewave. Many websites give wrong or misleading information. Most LF inverters due to the property of the large transformer only produce pure sine wave current.

A sine wave is a continuous wave, as shown in Figure 12. It is named after the function sine.

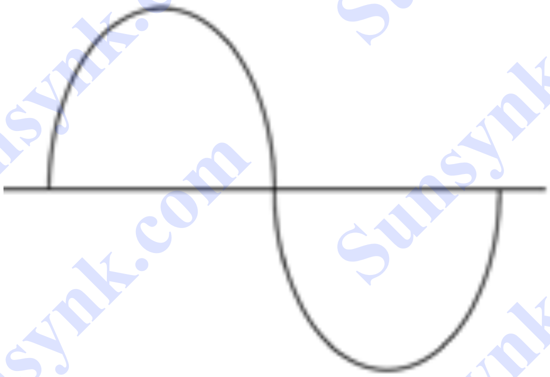


**Figure 12 - Sine wave.**

A square wave is a very simple on-off signal. It is still considered as AC but is very crude; some cheap inverters only operate on square waves.

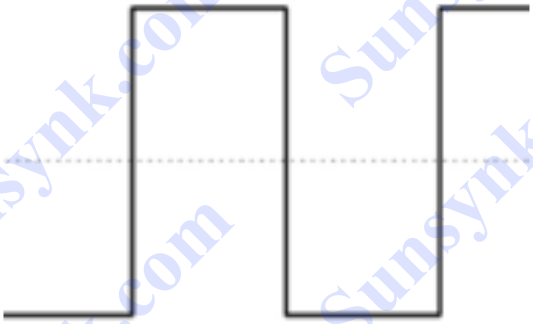


**Figure 13 - Square wave.**

A modified sine wave is a modulation in between a true sine wave or pure sine wave and a secure wave.

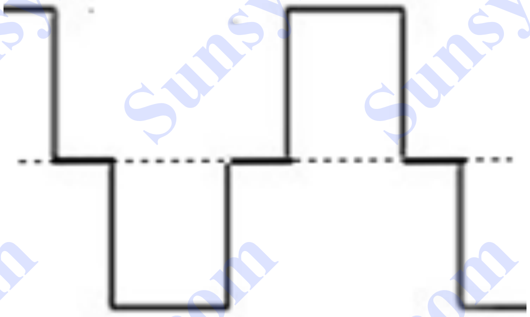


**Figure 14 - Modified sine wave.**

Square wave / modified sine wave generators are far simpler in their construction and tend to run cool, pure, or sine wave generators are much more complex and run much hotter.

For most applications, a modified sine wave is perfect, but for any item that relays on the shape of the wave or runs, then pure sine wave may be better.

Motor-driven appliances such as fans and air conditioning units may not run correctly or make a slight hum. Items that do not rely too much on the mains waveform like TVs, lighting, or laptops, then modified sine wave is ample.

- **Modified Sinewave:**

An inverter can produce a square wave, modified sine wave, pulsed sine wave, pulse width modulated wave (PWM), or sine wave depending on circuit design. The two dominant commercialized waveform types of inverters as of 2007 are modified sine wave and sine wave.

- **Pure Sinewave:**

A power inverter device, which produces a multiple step sinusoidal AC waveform, is referred to as a sine wave inverter. To more clearly distinguish the inverters with outputs of much less distortion than the 'modified sine wave' (three steps) inverter designs, the manufacturers often use the phrase pure sine wave inverter.

Almost all consumer grade inverters that are sold as a pure sine wave inverter do not produce a smooth sine wave output at all, just a less rough output than the square wave (one step) and modified sine wave (three steps) inverters.

As of 2014, conversion efficiency for state-of-the-art converters reached more than 98%. While string-inverters are used in residential to medium-sized commercial PV systems, central inverters cover the large commercial and utility-scale systems. Market-share for central and string inverters are about 50 percent and 48 percent, respectively, leaving less than 2 percent to micro-inverters.

A solar inverter or PV inverter is an electrical device that converts direct current (DC) into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or consumed by local loads.

Regarding the operating frequency, there are mainly two types of inverters on the market, and they have a marked influence on the workings of a solar power system.

- **High-Frequency Inverters (HF):**

The large majority of inverters available in the retail market operate under high frequency. They typically have smaller footprints since the volume of the passive components (capacitors and inductors) is reduced. Moreover, they are much lighter and have a lower tolerance for industrial loads.

If you were looking for something in a mobile device that has less weight, that is going to take up less room, you will want to go with a high-frequency inverter. So, what is the major difference, and how do they make them lighter and smaller? They do not have the big heavy copper transformer in there that a low-frequency unit would have. They use electronics for switching. Either MOSFETs or IGBTs are used to electronically switch the DC voltage to AC voltage. And again, it is quite a complicated process, but essentially, they use electronics for switching the DC voltage to AC. Normally, on a high-frequency inverter, the inverter's surge capacity or surge power is about two times that of the inverter's continuous output. So, this means that if the continuous output rating on the inverter is 1,000 watts, the surge will typically be 2,000 watts on a high-frequency inverter. That is going to be okay for most loads, running electronic loads, will handle that two times the surge.

HF inverters have over twice the number of components and use multiple, smaller transformers. Their application is appropriate for a wide variety of uses like tool battery chargers, small appliances, A/V and computers, but have a decreased capacity for long term exposure to high surge loads like pumps, motors, and some high-torque tools.

- **Low-Frequency Inverters (LF):**

These are much heavier and have a massive iron core transformer capable of absorbing power surges. These types of inverter offer longevity protection against lightning, short circuits and are far more reliable.

Low-frequency inverters have the advantage over high-frequency inverters in two fields: peak power capacity and reliability. Low-frequency inverters are designed to deal with higher power spikes for longer periods of time than high-frequency inverters. Power spikes can occur for a number of reasons (e.g. devices like power tools, pumps, vacuum cleaners and other appliances with electric motors require high starting power); when inverters experience such spikes, they can endure the increased power for a short period of time before shutting down in order to prevent any damage being done to them. Low-frequency inverters have much greater peak power capacity to handle large loads with power spikes than high-frequency inverters.

**Table 3 - Main features of HF and LF inverters.**

| Feature | HF | LF |
|---|---|---|
| Footprint | Small | Large |
| Weight | Light | Heavy |
| Operation with High-Surge Loads | Not suitable | Operates well |
| Cost | Higher | Cheaper |

## 3.3. ON-GRID INVERTER & MICRO-INVERTER (ON-GRID)

This inverter topology converts the DC current generated from the PV panel into AC power that can be consumed by local loads or transferred to the utility grid. These are relatively simple systems that consist of only two key components: a solar array and an inverter

A grid-connected PV power system is an electricity generating solar PV power system connected to the utility grid. In these systems, electricity can flow to and from the grid depending upon demand. If 'Access Power' is produced during the day, this is fed back into the grid via a special power meter that measures power consumption and power fed back; this is often referred to as feedback tariff. Grid-tie inverters are designed to quickly disconnect from the grid if the utility grid goes down this is known as Anti-islanding. The inverter must match the grid's phase and maintain the output voltage slightly higher than the grid voltage. Output voltage and current should perfectly line up, and its phase angle is within one degree of the AC power grid.

The grid-tied inverter is rated in watts. I would always recommend the inverter size should be twice the rating of the array. Using a six-panel array, it can produce maximum power at any point of time:

6 (Panels) x 325 (Panel Wattage) x 2 = 3900 Watts

In this example, the optimum would be a 4000 W or 4 kW on-grid inverter. Our simple on-grid system is composed of 6 x 325 W solar panels, fixings, 1 x 4 kW inverter, cables, and isolators.

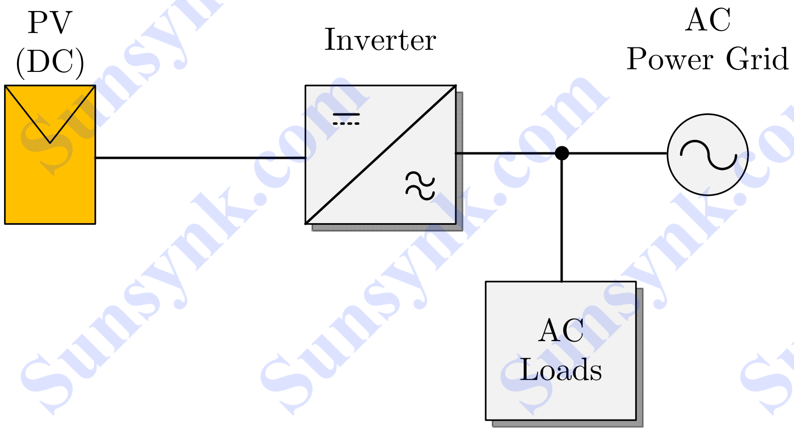


**Figure 15 - Grid-connected inverter diagram.**

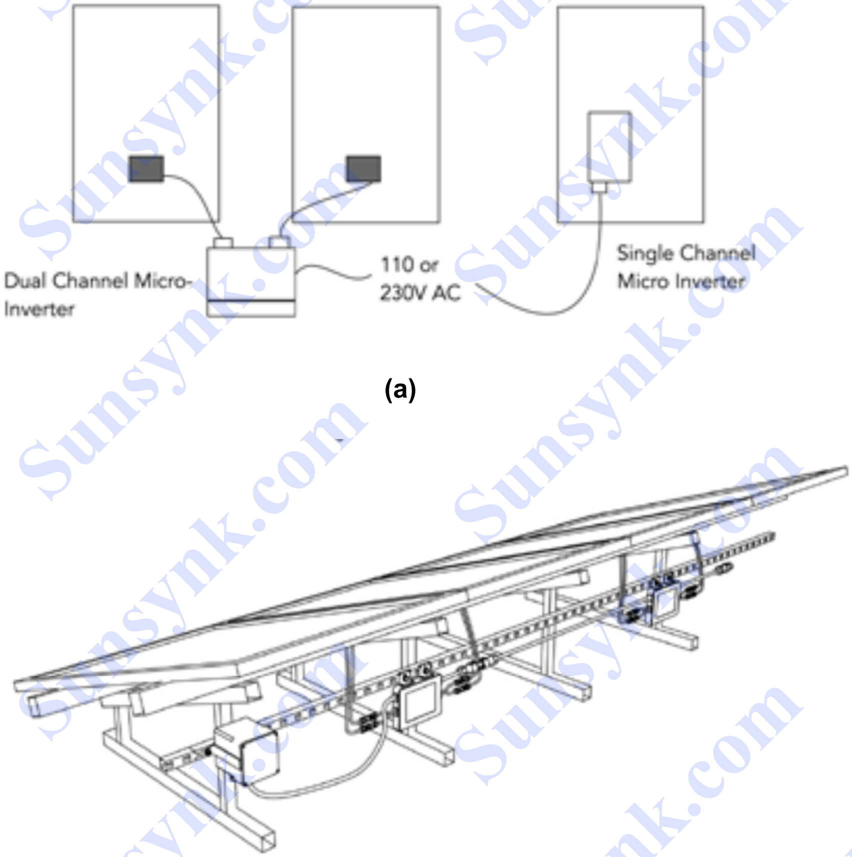
Figure 16 - Sunsynk 3KW On-Grid (String Inverter).

Another type of system is the micro-inverter system, which is usually on-grid. In these systems, each panel is connected to a small inverter that converts the Direct Current (DC) generated by the module into an Alternating Current (AC) that can be directly connected to the building's utility circuit.

Some advantages of this type of system are: easy to install, scalability, fewer problems with shadowing due to the sun's position.

The disadvantages are connecting utility power directly to the solar panel (power flows both ways), so the complete system needs to be installed and commissioned by a licensed electrician. This type of system is not recommended as it requires careful monitoring and needs 24hr access in case of problems. Figure 17 shows an illustration on how a micro-inverter system is installed.

Micro-inverters are small DC to AC inverters designed to handle single or twin panels' power output. Each solar PV module has its own micro- inverter, with no need for a central inverter. Micro-inverters are connected in parallel with each other, and there is no need for a central inverter.



(a)

(b)

**Figure 17 - Micro-inverter installation.**

**Figure 18 – Micro-inverter.**

## 3.4. OFF-GRID INVERTER

Off-grid inverters are applied in situations the electrical grid is not available. Therefore, batteries are used to store energy and supply the loads. In this topology a charge controller is used to control the charge and discharge of the batteries. Off-Grid solar systems are far more complex than on-grid systems. The main difference is that in an Off-Grid system, the power the solar cells produce is stored in batteries and used later when required. An on-grid system transfers power directly into the main grid.

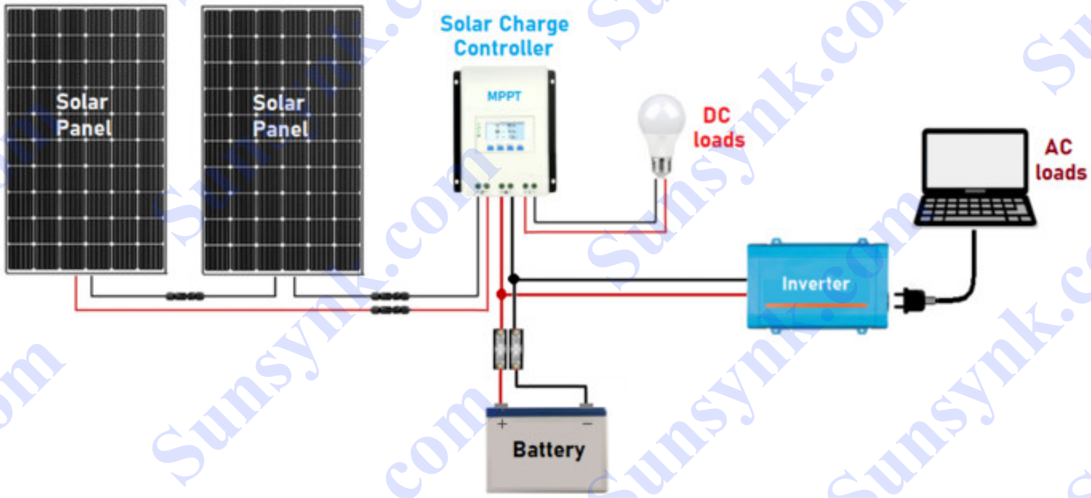


**Figure 19 – Off-grid Inverter** *(Clean Energy Reviews, 2020)***.**

For a better understanding, see Figure 20 comparison. The roof represents the solar panels. The rain comes from the sky and falls onto the roof before running down into the gutter. The gutter is like the installed cabling. Then the rainwater flows into the valve, which controls the flow, rather like a charge controller in a solar power circuit. Subsequently, the water ends up in the tank where it is stored like a battery stores power. Later the water is used by releasing the tap. If you have a large roof and small tank, the tank will fill up very quickly, and the rest of the water will overflow and drain away and be wasted. If you have a very large tank and a small roof, it will take a long time to fill it. When the tap is turned on to full, the tank can empty quickly, just like running the batteries down.

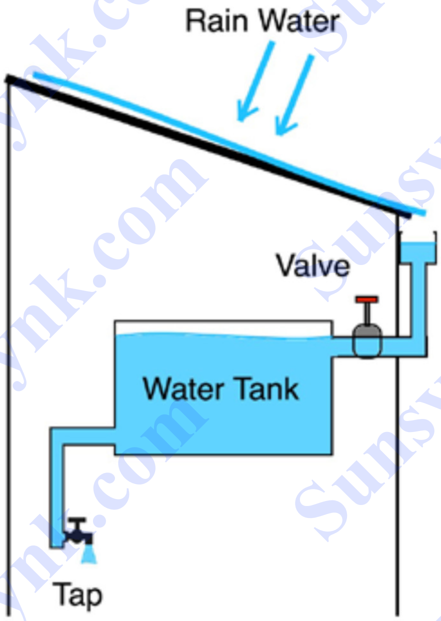


**Figure 20 - Water supply system.**

### 3.5. HYBRID INVERTER

A solar inverter's main job is to convert DC power generated from the array into usable AC power. Hybrid inverters go a step further and work with batteries to store excess power as well. This type of system solves issues renewable energy variability and unreliable grid structures

Hybrid inverters are basically a combination of grid-tied and off-grid inverters. It can inject power into the grid, store energy in the batteries, which can supply loads or transfer the stored power to the grid. In addition to that, hybrid inverters can be connected to other power sources such as wind and diesel generators.

Hybrid inverters can vary in size, performance and features. Most models usually operate bi-directionally, meaning they can convert DC power from modules to usable AC power and then convert stored AC from the batteries to power loads when needed. Hybrids can also remain grid-connected and use a mix of renewable and non-renewable energy to charge batteries and offset loads.

Hybrid inverters can store power in batteries and then drawn upon it as needed for energy stabilization.

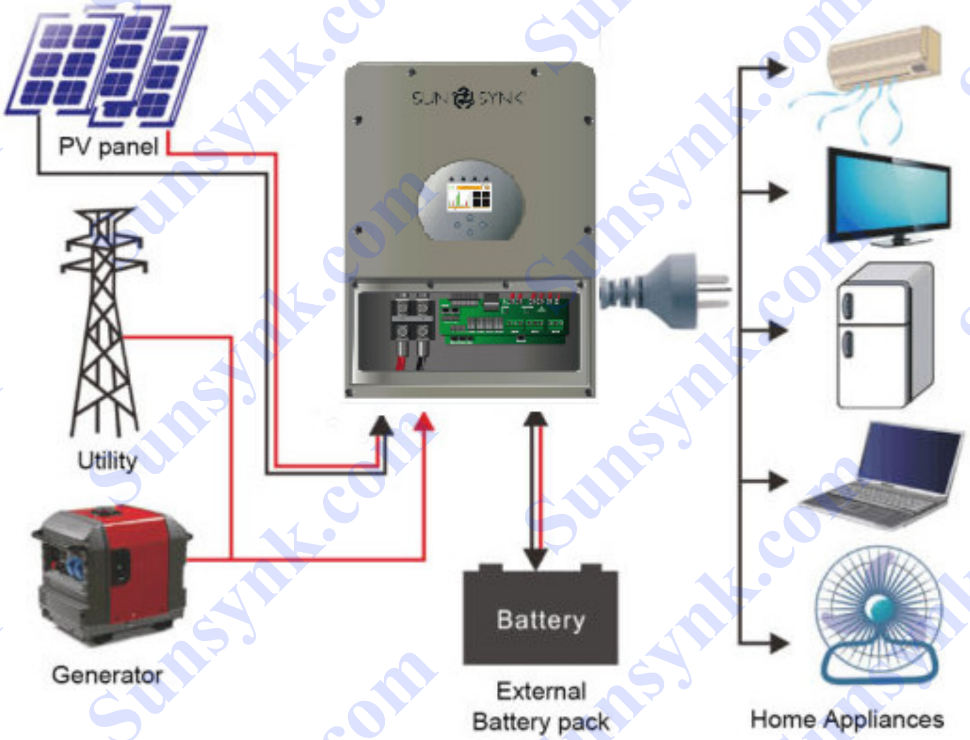


**Figure 21 - Hybrid inverter.**

**Figure 22 - Sunsynk 8.8KW Hybrid Inverter with Storage.**

Unlike conventional inverters, rather than systematically storing energy in batteries, hybrid inverters store energy only when necessary, e.g. when there is more production than consumption. This system also allows choosing whether electricity from photovoltaic panels should be stored or consumed through an internal intelligent apparatus control unit. This is possible through a technique that adds different energy sources (phase coupling: on-grid or grid-tie techniques) and the management of stored electricity in the battery (off-grid technology). Hybrid inverters, therefore, operate on-grid (grid-tie) as well as off-grid, hybrid (both on-grid and off-grid at the same time) and Backup (in case of a blackout)

**Use in off-grid mode** (without network) with the possibility of linking to a generator. The inverter must be connected to a battery bank and must have true off-grid capabilities - not all Hybrid inverters are created equal or can be used in off-grid applications.

**Use in on-grid or grid-tie** (connected to the network) with the possibility of selling energy or excess energy. There is a need to have the norm compliance of protection and decoupling (DIN VDE 0126.1).

**Use in hybrid mode** the inverter functions with a battery bank, but also connected to the grid. This dual functionality is the highlight of hybrid inverters that hence enable energy management (smart grid).

**Use in Backup mode**, or storage mode prevents blackouts by switching from on-grid mode to off-grid mode at the moment of a grid outage, thereby eliminates network cuts.

**Benefits of hybrid inverters:**

Hybrid inverters have many advantages:

**Resiliency**

A common misconception about solar is that if you install a system, you will always have power during outages. In most cases, this is not true: traditional grid-tied solar inverters automatically shut off during power outages for safety purposes, cutting off power generation from your solar panel system.

If you want to keep your property running on backup solar power during a grid outage, hybrid inverters paired with batteries are great solutions. Some hybrid inverters have both on-grid and off-grid capabilities, allowing you to continue running on solar power even if the grid goes dark.

**Monitoring**

With a hybrid inverter, all of your solar electricity–whether being sent to the grid, self-consumed on your property, or being stored in your battery–is converted through one component. This allows for “centralized monitoring,” which means you can monitor both your solar panel system and battery performance through one platform.

**Retrofit battery storage installations**

One of the biggest benefits of a hybrid inverter is that it combines the functionality of two separate pieces of equipment into one. This can mean an easier installation process for your solar installer. Depending on the prices of the individual components and the cost of labor, you may save money by installing a hybrid inverter from the get-go as opposed to paying for both a solar inverter and a battery-specific inverter separately.

## 3.6. SELECTING THE RIGHT TYPE OF INVERTER

To select the right type of inverter, you need to consider several factors:

**On-Grid Inverter:**

1) How large is the solar array?
2) Will the solar array be expanded?
3) Which footprint do you require?

Most grid inverters have the controller built-in normally MPPT. When sufficient power is being generated from the solar array, the inverter will startup. You can connect many on-grid inverters. A good example of this is the use of micro-inverters.

Simple formula:

Max Size of the solar array x 1.5 (This should give enough tolerance for surges etc.)

For example, 2000 W array then 3 kW on-grid inverter is perfect.

**Off-Grid Inverters:**

1) How large is the solar array?
2) Will the solar array be expanded?
3) Which footprint do you require?
4) What is the maximum or peak demand?
5) What is the DC voltage?

Besides the array size, the more important factor with an off- grid inverter is peak demand and DC voltage.

**Example 1:**

You could have a 10kW array but a peak demand of only 500 W, so a 1 kW inverter is ample.

**Example 2:**

You could have a 2 kW array, but peak demand is 10 kW, so you will need 15 kW inverter.

(Peak demand is the maximum power the system will draw if everything is switched on at the same time).

**Example 3 (Off-peak demand):**

If the system is just one appliance, for example, a 50 W floodlight then the peak demand is simply 50 Watts, if its an air-conditioner the running power at 1500 W, while the start-up may be 4000 Watts so the peak demand, is 4 kW x 1.5 and you will need a 6 kW inverter.

**Example 4 (Off-peak demand)**

If the system is a larger domestic premise, then the peak demand would be realistically everything that would normally switch-on at the same time, and it could be 10 kW, so a 15 kW inverter is perfect.

*Most household and small business utility-supply is limited to a maximum of 100 Amp @ 230 V - that is absolute maximum power of 23kW. In most households, 15 kW is enough.

- **Ratio:**

Besides peak demand is the second most important factor in selecting your off-grid solar system is the DC Voltage.

If your invert runs on 12 V and the output is 240 V, that is a 20:1 ratio, why does this matter?

A good example if you are running a 12 V 2 kW inverter the maximum output power is 2000 Watts

Watts / Volts = Amps

Therefore, 2000 / 240 = 8.3 Amps, not much power not enough for an electric kettle, but the input current is much higher.

(240 / 12) x (2000 / 240) x 1.25 (loses) = 208 Amps

That is huge. To understand how much power is required, one should think of two large car batteries wired together. Then they would run flat in less than 30 mins. You would need hook-up cable the same size as jump leads to power the inverter from the batteries.

Another problem besides damaging the batteries, the volt drop on the interconnect cables becomes larger when the current travels from an inverter that is too far away from the battery. The inverter low voltage detection may trip. Because of this, we run the DC voltage as high as possible.

24V - 240V system is a ration of 10:1 is recommended.

**Table 4 - Ratio examples.**

| Inverter power (W) | Peak Demand (W) | System Voltage (V) | Output Voltage (V) | Ratio | Max. Input Current (A) | Max. Output Current (A) |
|---|---|---|---|---|---|---|
| 50 | 37.5 | 12 | 240 | 20.00 | 5.00 | 0.21 |
| 100 | 75 | 12 | 240 | 20.00 | 10.00 | 0.42 |
| 150 | 112.5 | 12 | 240 | 20.00 | 15.00 | 0.63 |
| 250 | 187.5 | 12 | 240 | 20.00 | 25.00 | 1.04 |
| 500 | 375 | 12 | 240 | 20.00 | 50.00 | 2.08 |
| 750 | 562.5 | 12 | 240 | 20.00 | 75.00 | 3.13 |
| 1000 | 750 | 12 | 240 | 20.00 | 100.00 | 4.17 |
| 1500 | 1125 | 24 | 240 | 10.00 | 75.00 | 6.25 |
| 2000 | 1500 | 24 | 240 | 10.00 | 100.00 | 8.33 |
| 3000 | 2250 | 24 | 240 | 10.00 | 150.00 | 12.50 |
| 4000 | 3000 | 24 | 240 | 10.00 | 200.00 | 16.67 |
| 5000 | 3750 | 24 | 240 | 10.00 | 250.00 | 20.83 |
| 8000 | 6000 | 48 | 240 | 5.00 | 200.00 | 33.33 |
| 10000 | 7500 | 48 | 240 | 5.00 | 250.00 | 41.67 |
| 15000 | 11250 | 48 | 240 | 5.00 | 375.00 | 62.50 |
| 20000 | 15000 | 48 | 430 | 8.96 | 500.00 | 46.51 |
| 30000 | 25500 | 96 | 430 | 4.48 | 375.00 | 69.77 |
| 50000 | 42500 | 96 | 430 | 4.48 | 625.00 | 116.28 |
| 75000 | 63750 | 180 | 430 | 2.39 | 500.00 | 174.42 |
| 100000 | 85000 | 180 | 430 | 2.39 | 666.67 | 232.56 |
| 250000 | 212500 | 360 | 430 | 1.19 | 833.33 | 581.40 |
| 500000 | 425000 | 360 | 430 | 1.19 | 1666.67 | 1162.79 |
| 1000000 | 850000 | 620 | 430 | 0.69 | 1935.48 | 2325.58 |

## 3.7. CHARGE CONTROLLER

A charge controller controls the charge and discharge of the batteries. It prevents overcharges and can protect against overvoltage; therefore, it provides a better performance to the battery and increases the lifecycle. There are three main types of charge controllers:

1. PWM
2. Bulk Chargers
3. MPPT

The following table presents the characteristics of each charge controller:

**Table 5 - Main characteristics of each charge controller**.

| | PWM | Bulk Charges | MPPT |
|---|---|---|---|
| Efficiency | Lowest | Good | Higher |
| Cost | Cheapest | Reasonable | Expensive |
| Size | Small foot print | Small footprint | Large foot print |
| Suitable for | Budget projects or very large scale installations | Vehicles and boats | House installation |
| Benefits | Cheap | Low RF noise | High Efficiency |
| Benefits | Runs cool | Low heat | Good installations that requires long cabling |
| Disadvantages | Poor efficiency and RF Interference | Basic control | Expensive, high temperature, and RF Interference |

The size of the charge controller is very much dependent upon the system voltage. When using PWM or Bulk chargers, then the solar panel must match the controller. If the panel/array voltage is too high, then the system will run very inefficiently. Moreover, if the panel or array voltage is too low, then the system will not work.

Either the terms charge controller or charge regulator may refer to a standalone device, or to control circuitry integrated within a battery pack, battery-powered device, or battery charger.

Charge controllers are sold to consumers as separate devices, often combined with solar or wind power generators, for uses such as RV, boat, and off-the-grid home battery storage systems.

In solar applications, charge controllers may also be called solar regulators. Some charge controllers/solar regulators have additional features, such as a low voltage disconnect (LVD), a separate circuit which powers down the load when the batteries become overly discharged (some battery chemistries are such that over-discharge can destroy the battery)

A series charge controller or series regulator disables further current flow into batteries when they are full. A shunt charge-controller or shunt-regulator diverts excess electricity to an auxiliary or ‘shunt’ load, such as an electric water heater, when batteries are full.

Simple charge controllers stop charging a battery when they exceed a set high voltage level and re-enable charging when the battery voltage drops back below that level.

Pulse width modulation (PWM) and maximum power point tracker (MPPT) technologies are more electronically sophisticated. It adjusts charging rates depending on the battery's level, to allow charging closer to its maximum capacity.

A charge controller with Maximum Power Point Tracking (MPPT) capability frees the system designer from closely matching available PV voltage to battery voltage. Considerable efficiency gains can be achieved, particularly when the PV array is located at some distance from the battery.

By way of example, a 150 V PV array connected to an MPPT charge controller can be used to charge a 24 V or 48 V battery. Higher array voltage means lower array current, so the savings in wiring costs can more than pay for the controller.

Charge controllers may also monitor battery temperature to prevent overheating. Some charge controller systems also display data, transmit data to remote displays, and data logging to track electric flow over time.

# 4. BATTERIES

A battery is a device that stores chemical energy and converts it to electrical energy. The flow of electrons provides an electric current that can be used by electrical loads. In off-grid or hybrid PV systems, batteries are the elements used to store energy to supply loads. Batteries can also be associated in series or parallel to store more energy.

Batteries store electrical energy on their internal plates in the form of a chemical charge, and once fully charged. An ideal battery could store this potential energy indefinitely until released through an externally connected load. However, batteries are not ideal, and due to internal leakage currents or parasitic loads, batteries will slowly discharge themselves when not in use. Until then, they can store electrical energy for very long periods of time. Then we can say that a battery is a power storage device capable of storing and producing electricity until it is needed.

Electrical energy in the form of a DC (Direct Current) supply creates a battery as the result of a chemical reaction between two metal plates, one called the positive electrode, and the other called the negative electrode, which are both immersed in a chemical solution called an electrolyte.

## 4.1. TYPES OF BATTERIES

### 4.1.1. Lead-Acid

Consist of two plates of lead, which serve as electrodes, suspended in diluted sulphuric acid, which is then the electrolyte. In conventional lead-acid cells, the diluted acid is in liquid form, hence the term 'flooded' or 'wet' cells. Valve Regulated Lead Acid (VRLA) cells have mostly the same lead-acid chemistry, but the Absorbent Glass Mat (AGM) and Gel-types have the diluted acid electrolyte solution immobilized, either by soaking a fiberglass mat in it (hence: glass-mat batteries), or by turning the liquid into a paste-like gel by adding silica and other gelling agents (hence: gel batteries). The wet cell type contains acid in the liquid form, similar to the flooded lead-acid batteries, just the wet cell VRLA battery case is better sealed. The layers of a lead-acid battery is presented in Figure 23.

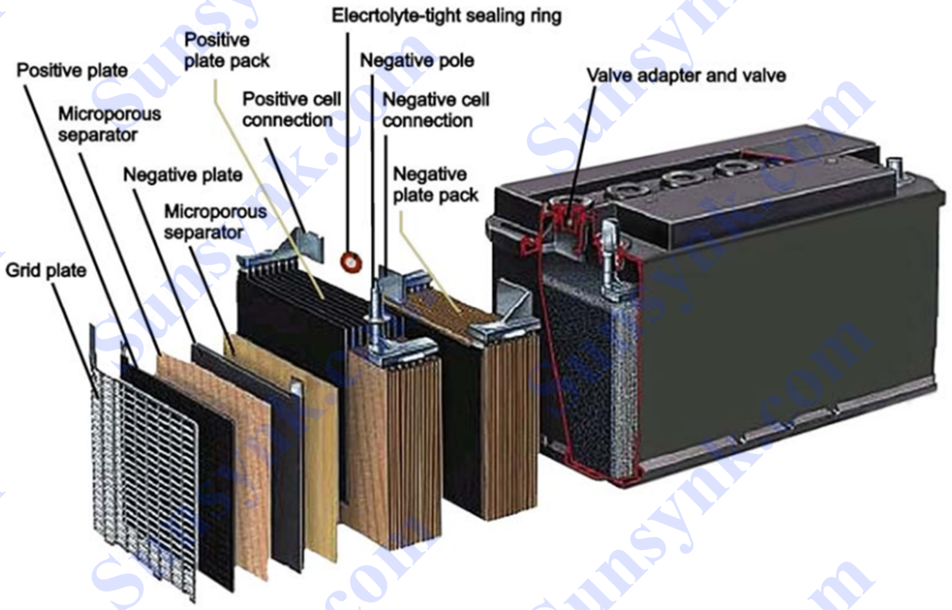


**Figure 23 - Lead-Acid battery** *(Pavlov, 2019)***.**

### 4.1.2. Absorbent Glass Mat (AGM)

Absorbed Glass Mat batteries are constructed differently than the traditional flooded battery. In AGM batteries (also called starved electrolyte), there is a thin ultra-fine fiberglass mat sandwiched between the plates that are saturated with battery acid to about 95% of what they can hold. This mat is then packed in between the plates and slightly compressed, then welded/soldered in place. Because the plates and mats are packed fairly tight, they are almost immune to vibration.

AGM (Absorbed Glass Mat) sealed battery technology was originally invented in 1980, and developed and introduced in 1985 for military aircraft, vehicles, and UPS to reduce weight and improve reliability, where power, weight, safety, and reliability were paramount considerations. The sulfuric acid is absorbed by a very fine fiberglass mat, making the battery spill-proof. This enables shipment without hazardous material restrictions. The plates can be made flat to resemble a standard flooded lead acid pack in a rectangular case; they can also be wound into a cylindrical cell.

AGM has very low internal resistance, is capable to deliver high currents on demand and offers a relatively long service life, even when deep cycled. AGM is maintenance free, provides good electrical reliability and is lighter than the flooded lead acid type. While regular lead acid batteries need a topping charge every six months to prevent the buildup of sulfation, AGM batteries are less prone to sulfation and can sit in storage for longer before a charge becomes necessary. The battery stands up well to low temperatures and has a low self-discharge.

AGM's leading advantages are a charge that is up to five times faster than the flooded version, and the ability to deep cycle. AGM offers a depth-of-discharge of 80 percent; the flooded, on the other hand, is specified at 50 percent DoD to attain the same cycle life. The negatives are slightly lower specific energy and higher manufacturing costs than the flooded, but cheaper than the gel battery.

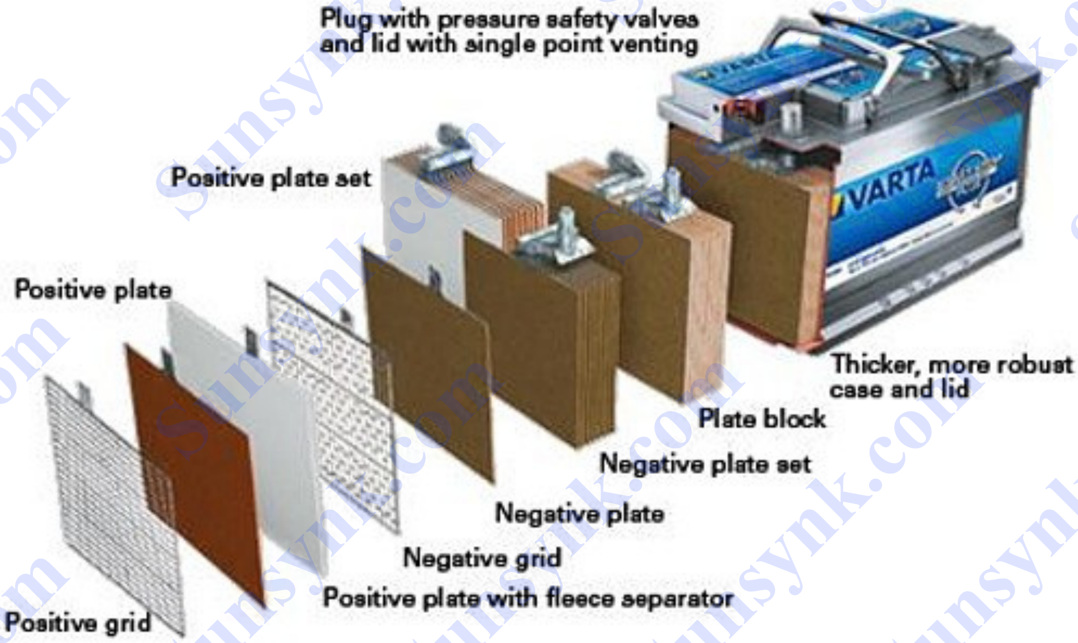


**Figure 24 - AGM battery** *(Manbat, 2016)*.

### 4.1.3. Lithium

Lithium batteries, including both lithium-hydride and lithium-ion batteries, have become popular for consumer electronic devices because of their low weight, high energy density, and relatively long lifetimes.

The use of lithium batteries in grid and utility applications is beginning to grow with units being tested in a number of locations. One large installation, due to start operating in 2013, is a 2 MW lithium-ion facility for the Orkney Islands off the northwestern coast of Scotland. The future development of lithium batteries may benefit from interest by automotive manufacturers in their use in hybrid and electric vehicles.

These batteries are usually called Li-ion or LIB batteries. It is a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Li-ion batteries use an intercalated lithium compound as one electrode Lithium-ion batteries are common in home electronics. They are among the most popular types of rechargeable batteries for portable electronics, with a high energy density, little memory effect, and low self-discharge.

Rechargeable lithium batteries have conquered the markets for portable consumer electronics and, recently, for electric and hybrid power trains for different types of vehicles. Consumer applications such as mobile telephones, laptops and calculators, digital cameras and camcorders, portable radios and televisions, electric razors and toothbrushes, and medical and communications equipment have created an ever-increasing market for powerful rechargeable batteries since the 1990s. Lithium batteries have been fast replacing nickel–metal hydride cells. Since the early twenty-first century, large advanced lithium batteries are becoming the new power sources in both the transportation and stationary power markets, including electric vehicle propulsion, standby power, mobile robots for ocean observing, and mission critical applications. To date, lithium-ion batteries have not been exploited largely for storing renewable energy and for grid balancing.

Beyond consumer electronics, LIBs are also growing in popularity for military, battery electric vehicles, and aerospace applications. For example, lithium-ion batteries are becoming a standard replacement for the lead-acid batteries that have been used historically for golf carts and utility vehicles. Instead of heavy lead plates and acid electrolyte, the trend is to use lightweight lithium-ion battery packs that can provide the same voltage as lead-acid batteries, so no modification to the vehicle's drive system is required. Figure 25 presents a schematic drawing showing the shape and components of various Li-ion battery configurations.

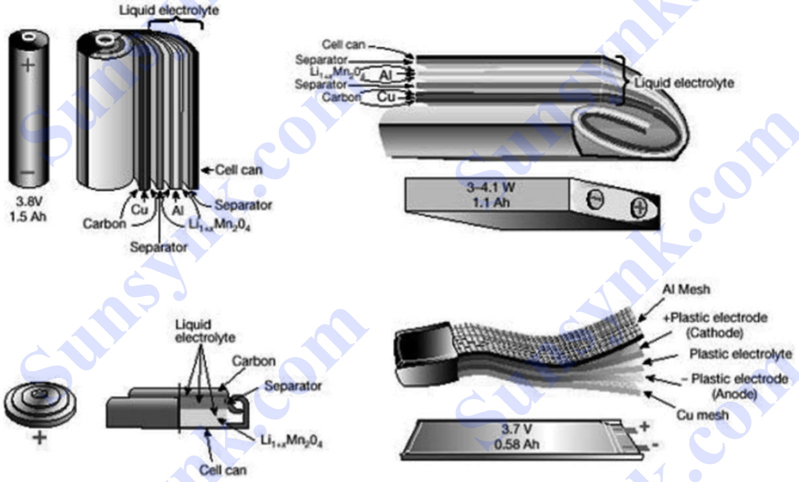


**Figure 25 - Shapes and components of various Li-ion battery configurations** *(Kato, Ogumi, & Perlado Martín, 2019)*

Under some conditions, Lithium-Ion batteries and can pose a safety hazard since they, unlike other rechargeable batteries, contain a flammable electrolyte and are kept pressurized. Thus, the testing standards for these batteries are more stringent than those for acid electrolyte batteries, requiring both a broader range of test conditions and additional battery-specific tests. It had to be established due to reported accidents and failures, and there have been battery-related recalls by some companies. Lithium is extremely reactive and can burst into flames if exposed to water, but modern lithium cells use lithium bound chemically so that it cannot react easily. As with nickel, there are a number of lithium cell variants but the most popular today is the lithium-ion cell. These are designed so that there is no free lithium present at any stage during the charging or discharging cycle..Currently, lithium-ion batteries are the most efficient method of holding a substantial charge in smaller systems.

## 4.2. WIRING BATTERIES

### Series Connection

Individual batteries are connected together in “series” to increase the output terminal voltage while keeping the amp-hour rating the same as for a single battery. The negative (-) terminal of the first battery is connected directly to the positive (+) terminal of the second battery, and so on as shown.

Figure 26 shows the twelve batteries of 2 V each connected in series, resulting in a total voltage of 24 V. These elements are associated in series to provide more power with reduced current.

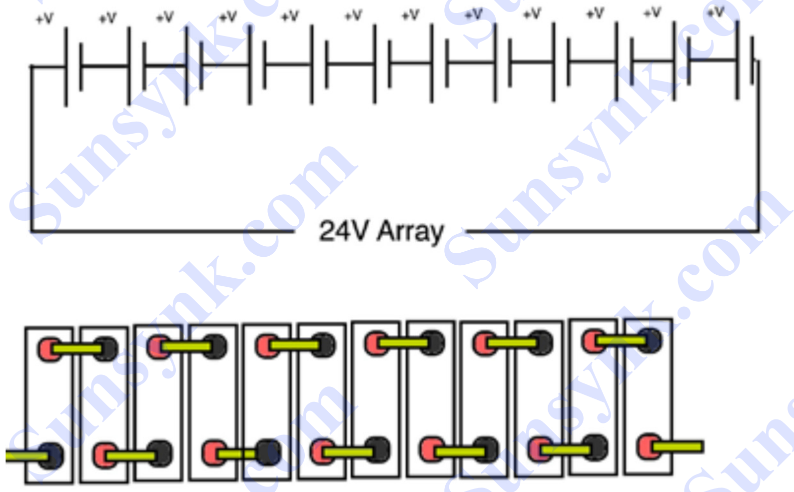


**Figure 26 - Twelve batteries of 2 V connected in series.**

The amount of energy you can store in your battery array depends upon the Ah of each cell (Amps per 1 hour). To convert Ah to Wh:

**Table 6 - Battery cells conversion.**

| No. of Cells | Voltage of cell | Ah per Cell | Storage Wh | KWh Storage |
|---|---|---|---|---|
| 1 | 12 | 100 | 1,200 | 1.2 |
| 2 | 12 | 100 | 2,400 | 2.4 |
| 6 | 2 | 250 | 3,000 | 3 |

| | | | | |
|---|---|---|---|---|
| 12 | 2 | 500 | 12,000 | 12 |
| 24 | 2 | 1000 | 48,000 | 48 |
| 48 | 2 | 1000 | 96,000 | 96 |

Depending upon the type of cell, the useable storage may be as little as 40% of the total capacity. Deep discharge batteries can offer up to 75% and Lithium-based cells almost 100%.

**Table 7 - Capacity of different types of batteries.**

| Battery Type | Total Storage | Max Discharge | Useable Storage |
|---|---|---|---|
| Flooded Cell | 10kWh | 40% | 4kWh |
| Flooded Cell | 20kWh | 40% | 8kWh |
| AGM Cell | 10kWh | 75% | 7.5kWh |
| AGM Cell | 20kWh | 75% | 15kWh |
| Lithium Cell | 10kWh | 95% | 9.5kWh |
| Lithium Cell | 20kWh | 95% | 19kWh |

### ■ Parallel Connection

Individual batteries are connected together in “parallel” to increase the output current, or Amp-hour storage capacity while the output terminal voltage remains the same as for a single battery. For parallel connected batteries, all the positive (+) terminals of each battery are connected together, and all the negative (-) terminals of each battery are also connected together as shown. Figure 27 shows four 12 V batteries paralleled to increased storage capacity.

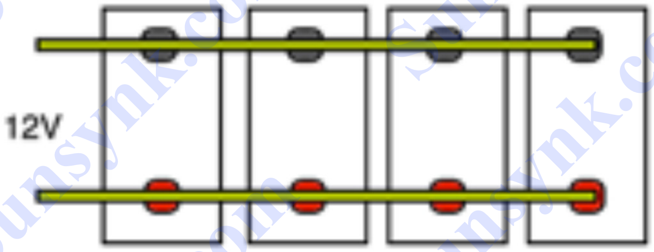


**Figure 27 - Paralleling four 12 V batteries.**

**WARNING:** Power batteries have very low internal resistance, even though the voltage is very low; therefore, if wired incorrectly or short-circuited, it can go on fire and result in several burns.

Simple Rules:

1) Batteries connected in series keep the same capacity of the weakest cell, but the total voltage increases.
2) Batteries wired in parallel means that all voltages must match, then the power or Ah will increase.

# 5. CABLES AND PROTECTION DEVICES

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## 5.1. CABLES

The Photovoltaic cable is the interconnection used in a solar system. Solar cables connect solar panels and other electrical components of a photovoltaic system.

Solar cables are must be UV resistant and weather resistant and able to withstand safely high voltages.

Underwriters Laboratories (UL) published the UL subject 4703 Photovoltaic Wire. It covers single conductor, insulated and integrally or non-integrally jacketed, sunlight resistant, photovoltaic wire in several temperatures, and voltage ratings for interconnection wiring of grounded and ungrounded photovoltaic power systems.

It is important to select the correct cable if the cable is too thin, then the efficiency of your system will be massively reduced cables usually have a cross-section of 4 to 10 mm². See Principles for cable calculations

**Typical PV Cable Rating**

Voltage Rating (Uo/U) AC: 600/1000V

DC: 900/1800V

Temperature Rating

Fixed: -40°C to +90°C

Minimum Bending Radius

Fixed: 4 x overall diameter Flexed: 5 x overall diameter

Maximum Voltage (Umax)

**Figure 28 - PV cables.**

## 5.2. BATTERY HOOK UP OR INTERCONNECT CABLES

Battery hook up cables generally carry much larger currents than the solar cables. Make sure to check your battery posts to ensure they can accept this type of connection then select the length of cable. Always avoid selecting an interconnect cable that is too long, tight bends can cause wear or cracks in the insulation or damage the conductors and should be avoided.

# 6. BASIC PRINCIPLES

## 6.1. WIRING PRINCIPLES

In photovoltaic systems, the panels can be associated to generate more power, forming arrays. The modules can be connected in series or parallel depending on the application. When modules are associated in series, the total voltage increases and the current is the same. On the other hand, when modules are associated in parallel, the voltage is the same, but the total current is the sum of all currents. Figure 29 shows many a PV arrays in a solar power plant.

**Figure 29 - Many arrays in a PV solar power plant** *(MIT News, 2020)***.**

An aspect that is **IMPORTANT** to verify is that if associating modules in series, the total open-circuit voltage of the array does not exceed the maximum input voltage of the inverter. In addition, you have to verify the maximum input current of the inverter. You must always refer to the manufactures instructions.

- **Series Association**

In this connection, the voltage V is the sum of the voltage across each component, but the current is the same for all elements.

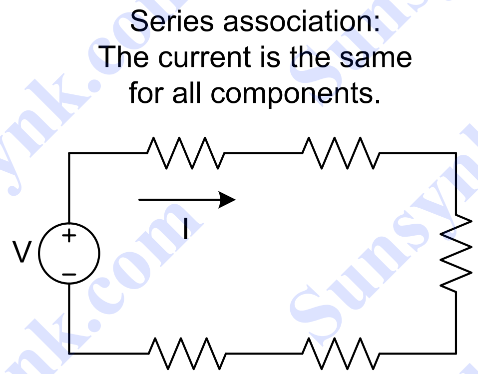
Series association:
The current is the same
for all components.

**Figure 30 - Series association of resistors.**

When connecting panels in series, the sum of the voltages of each panel will be the total voltage of the array, which will feed the PV inverter. In Figure 31, it is shown an association of three panels in series. If each panel generates a voltage of 48 V, the total voltage of the array is 144 V.

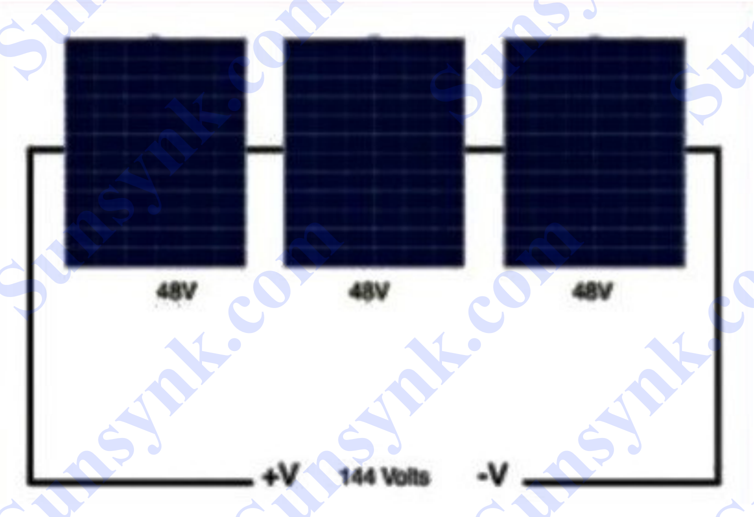

**Figure 31 - Series association of three panels.**

- **Parallel and Mixed Associations**

In parallel associations, the voltage is the same across all paralleled elements, but the current is different in each one.

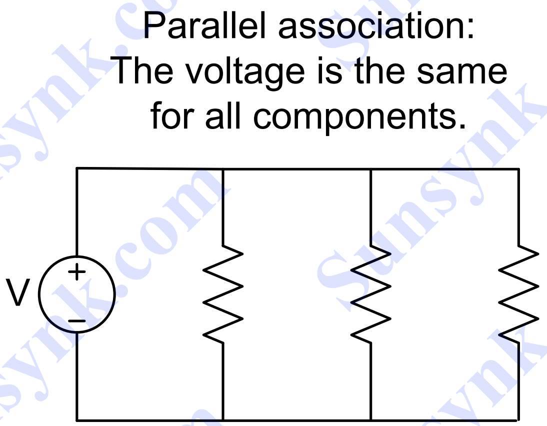

Figure 32 - Parallel association of resistors.

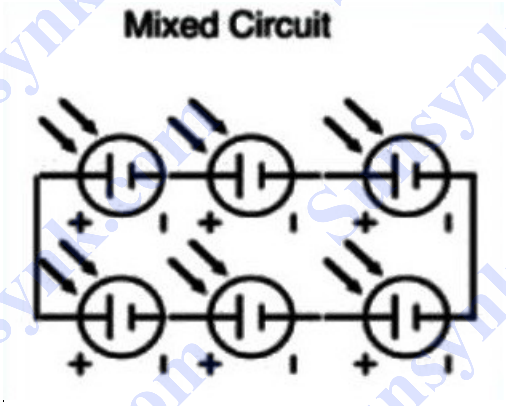

Figure 33 - Mixed association.

Considering that you need to install six 48 V modules to supply your power consumption, but your inverter allows only 150 V in its input; therefore, either you change the inverter or you can perform a parallel association of the modules. Figure 34 shows three modules associated in series, but these three modules are associated in parallel with other three modules connected in series, constituting a mixed association. In this case, the total voltage is also 144 V.

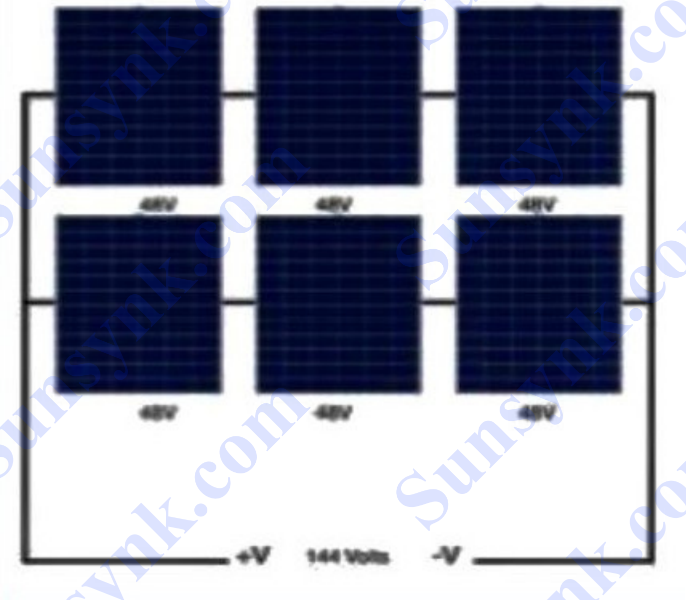

**Figure 34 - Parallel association of six modules.**

Most solar configurations would be a mixed circuit, and when constructing one, the user should consider:

- What is the maximum input voltage of your inverter or charger
- What is the voltage of each panel
- Divide the maximum input voltage of the inverter by the voltage of each panel to verify the maximum number of panels that can be wired in series.
- Ensure you have a balanced circuit (important)
- Configure the solar panels into a series or mixed circuit.
- If the supply voltage required is very low, i.g, to charge a 12V battery, then a single panel is enough, but you must check if the load of the panel(s) matches your charger /inverter input.

When mixing series and parallel circuits, it is important to maintain a voltage balance, if not, then you will waste power and possibly create a fire risk:

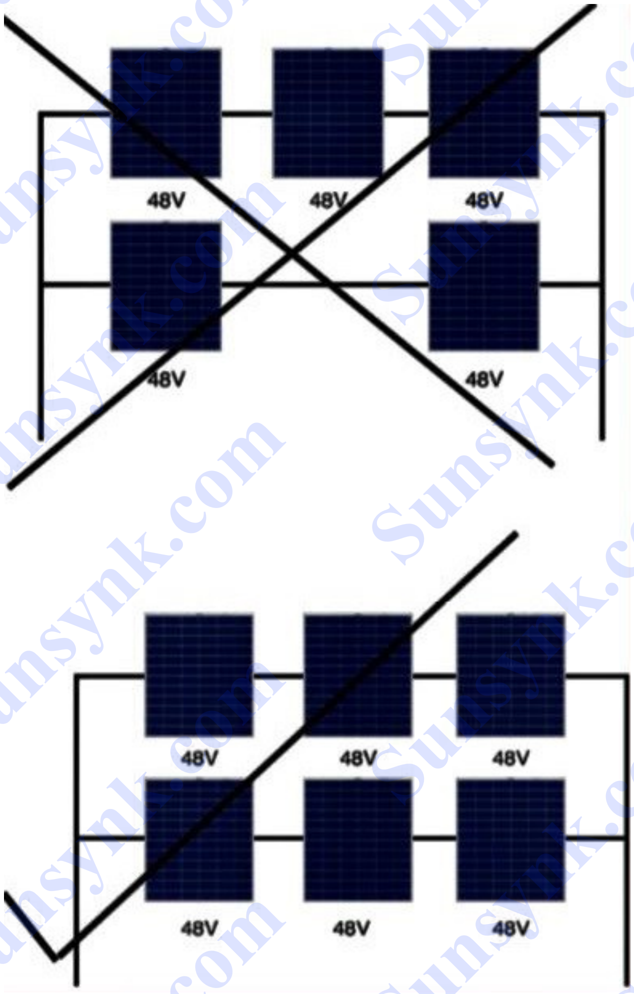

**Figure 35 - Wrong and right array balance.**

The installer must match the solar panels to the maximum input voltage of the inverter or charge controller.

**Table 8 - Equipment and typical voltages.**

| Equipment | System | Typ. min voltage | Typ. max voltage |
|---|---|---|---|
| PWM Charge Controller | 12V car | 16V | 22V |
| PWM Charge Controller | 24V car | 32V | 40V |
| PWM Charge Controller | 48V System | 60V | 70V |
| PWM Charge Controller | 96V System | 110V | 130V |
| MPPT Charge Controller | 150V System | 120V | 150V |
| MPPT Charge Controller | 300V System | 250V | 300V |
| On Grid Inverter | 5kW | 100V | 130V |
| On Grid Inverter | 25kW | 200V | 300V |
| On Grid Inverter | 50kW | 350V | 600V |

## 6.2. MAXIMUM POWER PEAK (MPP)

MPP is the maximum power peak that you can load the panel without losing power. Normally this number is around 0.45 V.

**Example:**

- Maximum voltage: 21.60 V 36-cells solar panel 36 x 0.6 V (0.6 V maximum voltage per cell)
- Optimum voltage 18 V 36-cells solar panel 36 x 0.6V (0.5 V minimum voltage per cell)
- MPP voltage 16.2 V 36-cells solar panel 36 x 0.6V (0.45 V MPP voltage per cell)

If the load drops from the panel voltage by more than 0.45 V per cell, it is inefficient. For charging a 12 V battery near a 36-cell solar panel, then MPPT would not work, (this would need 14.5 V to charge + control and cable losses). If you want to use a much higher voltage panel, for example, 72 cell array, then MPPT would massively improve the efficiency.

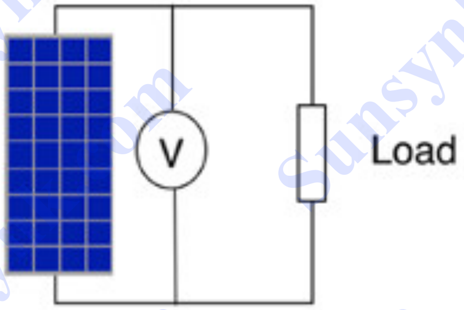

**Figure 36 - Voltage module and load.**

## 6.3. SOLAR PANELS AND THE EFFECT OF THE SUN

Panels are the part everyone sees, but there is much more to a solar system than just panels. The panels are a little like the leaves of a plant or tree, except they produce energy by converting the sunshine into power.

A typical 150 W PV module is about a square meter in size. Such a module may be expected to produce 0.75 kilowatt hour (kWh) every day, on average, after taking into account the weather and the latitude, for an insolation of 5 sun hours/ day. In the last 10 years, the efficiency of average commercial wafer-based crystalline silicon modules increased from about 12% to 16%, and CdTe module efficiency increased from 9% to 13% during the same period. Due to the higher temperatures generated on the PV due to the exposure to the sun's energy, the module output and the panel's life can be degraded. Allowing ambient air to flow over, and if possible, behind the PV modules reduces this problem.

Photovoltaic installations in the southern latitudes o Europe or the United States may expect to produce 1 kWh/m²/day.

A typical 1 kW photovoltaic installation in Australia or the southern latitudes of Europe or the United States may produce 3.5–5 kWh per day, dependent on location, orientation, tilt, insolation, and other factors. In the Sahara desert, with less cloud cover and a better solar angle, one could ideally obtain closer to 8.3 kWh/m²/day provided the nearly ever-present wind would not blow sand onto the units. The area of the Sahara desert is over 9 million km², 90,600 km², or about 1%, so in theory, the area could generate as much electricity as all of the world's power plants combined

## 6.4. SUN HOURS AND THEIR RELEVANCE TO SOLAR

Sun hours indicate the average (over the course of the year) amount of solar insolation (full sun hours) for these zones.

These figures are based on the yearly average; consequently, systems based on these figures will provide more power in summer and less in winter. Winter figures for daily solar gain may be from 25% to 50% LESS than these average figures.

Solar panel footprint is everything. The most common type of solar panel is Polycrystalline Silicon, which generally comes in 320 W panels. Each panel measures just less than 2 metre by one metre and you need to allow an extra 20% for panel mounting.

If you have a flat roof of about 22 metre x 22 metre then you can fit roughly 200 panels, each producing 300 Watts; that is 60,000 W of power or 60 kW per sun hour.

Table 9 shows a guide on the productivity of a 325 W panel.

**Table 9 - Power production depending on sun hours.**

| No. of modules | Module power (W) | Total power (W) | Sun hours (h) | Total daily energy (kWh) |
|---|---|---|---|---|
| 2 | 325 | 650 | 5 | 3.25 |
| 4 | 325 | 1,300 | 5 | 6.5 |
| 6 | 325 | 1,950 | 5 | 9.75 |
| 8 | 325 | 2,600 | 5 | 13 |
| 16 | 325 | 5,200 | 5 | 26 |
| 32 | 325 | 10,400 | 5 | 52 |
| 64 | 325 | 20,800 | 5 | 104 |

Figure 37 shows the world map with the annual number of sun hours. Note that the red/dark red areas are the most productive in sun hours. Therefore, a 60 kW array in the UK may only produce around 197 kWh of power per day, whereas the same array in the Egypt may produce approximately 658 kW per day, which is a huge difference.

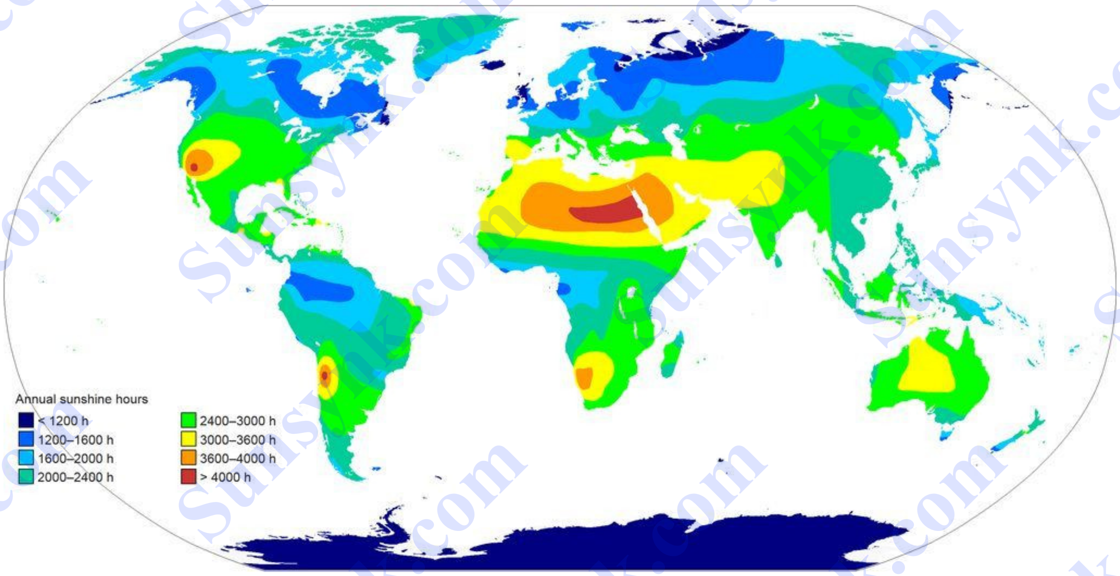

**Figure 37 - Map with global sun hours.**

## 6.5. EFFICIENCY

Efficiency is a term frequently used when discussing solar power systems. All solar cells have specific efficiency. The simple answer is the size of the panel. If you had unlimited space for your solar array, then having a 100 W panel that was 10% efficient or a 100 W panel that was 25% efficient would not make any real difference in power, just physical size. The lower efficiency would roughly be 150% larger. The sun shining on every 1 square meter of the earth's surface produces 1 kW in power. If a 1-meter panel can only produce 200 W out of this 1 kW, it means that panel's efficiency is only 20%.

Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current.

Solar panels are typically measured under STC (Standard Test Conditions) or PTC (PV USA Test Conditions), in watts. Typical panel ratings range from less than 100 watts to over 400 watts. The array rating consists of a summation of the panel ratings, in watts, kilowatts, or megawatts.

Efficiency is a measure of how much work or energy is conserved in a process. In many processes, work or energy is lost, for example, as waste heat or vibration. The efficiency is the energy output, divided by the energy input, and expressed as a percentage. A perfect process would have an efficiency of 100%.

$$Efficiency\ (\%) = \frac{output\ energy}{input\ energy} x\ 100$$

The efficiency of solar cells are still low, varying from 16% to 20% usually. In Table 10 the PV panels with highest efficiencies currently are presented.

**Table 10 - PV Panels with the highest efficiencies in 2020** *(Clean Energy Reviews, 2020)*.

| | Manufacturer | Headquarters | Manufacture | Eff% | Warranty* |
|---|---|---|---|---|---|
| 1 | LG | Sth Korea | Sth Korea, USA | 21.7% | 25 yr |
| 2 | Sunpower | USA | USA, Mexico, China, Philippines | 22.6% | 25 yr |
| 3 | REC | Norway | Singapore | 21.7% | 20 yr |

|  | Manufacturer | Headquarters | Manufacture | Eff% | Warranty* |
|---|---|---|---|---|---|
| 4 | Solaria | USA | USA | 20.5% | 25 yr |
| 5 | Panasonic | Japan | Japan, USA | 19.7% | 25 yr |
| 6 | Qcells | Sth Korea | Sth Korea, China, USA | 20.1% | 25 yr |
| 7 | JinkoSolar | China | China, USA | 20.4% | 12 yr |
| 8 | Trina Solar | China | China, Vietnam | 20.5% | 12 yr |
| 9 | Canadian Solar | China | China, Vietnam | 20.3% | 12 yr |
| 10 | LONGi Solar | China | China | 20.6% | 12 r |

## 6.5. POWER LOSSES / EFFICIENCY

- **Matching:**

Here is a very simple example of poor matching.

A 325W 48V panel charging a 12V battery compared to a 135W 18V charging a 12V battery,

Q. Which panel will put more power into the battery?

Both the same.

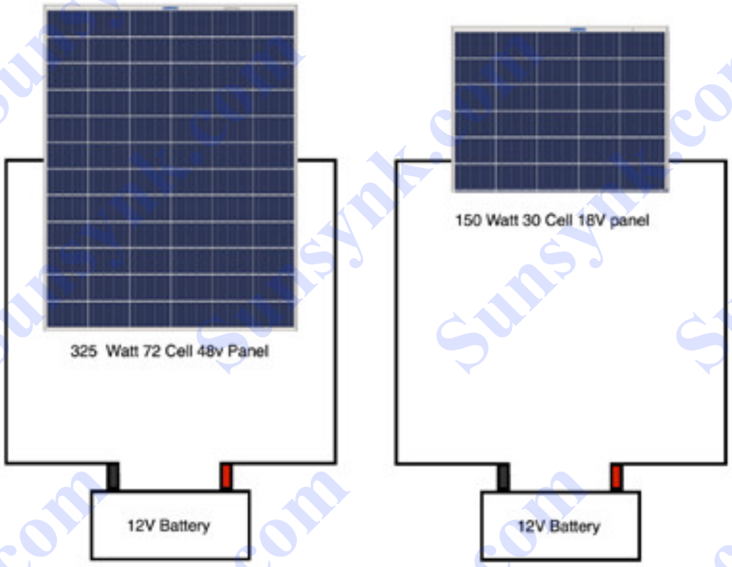

**Figure 38 - Matching.**

Both panels, in this example, produce 7.5 Amp. The larger one is 7.5 Amp x 48V = approx 360 Watts and the smaller panel 7.5 Amp x 18V = 135 Watts.

Because the current is the same for both panels, the maximum current is 7.5 Amp. The system voltage is pulled down to match the battery:

7.5 Amp x 14.5 (12v battery actually charges at around 14.5V )

7.5 x 14.5 = 108.75 watts

Both panels will charge at 108 Watts, by mismatching, you can reduce a 325 Watt panel into 108 Watt panel, which is undesirable.

- **Temperature Effect on solar Panels**

There is a standard test criterion, which is 25°C, so that when the temperature rises, then the voltage drops. If the temperature rises to 50°C, then the voltage drops to 90% and If it rises to 75°C then it drops to 80% That means that in hot countries, an 18 V current is not enough to charge a 12 V battery.

## 6.6. CALCULATING POWER USAGE

In order to calculate how much power you need, the user should list down all of your power and lighting needs for a 24-hour period. Moreover, a good idea is to consider using all energy-saving devices such as inverter-type air conditioning and refrigeration.

**Table 11 - Power usage.**

| Device | Power Usage (W) | Hours run a day | Duty cycle | Total power usage (W) |
|---|---|---|---|---|
| 10 x 20 W LED Lights | 200 | 10 Hours a Day | 25% | 500 |
| Large AC | 1500 | 5 Hours a Day | 50% | 3750 |
| Small AC | 500 | 10 Hours a Day | 50% | 2500 |
| Electric Kettle | 2000 | 30 Min a Day | 100% | 1000 |
| TV | 20 | 5 Hours a Day | 100% | 100 |
| Satellite RX | 20 | 5 Hours a Day | 100% | 100 |
| Computer | 50 | 5 Hours a Day | 100% | 250 |
| Charge Mobile Phones | 10 | 5 Hours a Day | 100% | 50 |
| Toaster | 800 | 30 Min a Day | 100% | 400 |
| Peak Load in Watts | 5100 |  | Total Wh | 8650 |

From the list, it can be seen that the following have been included: A device, max power, hours used a day.

I have added 10 lights, but not all the lights are on at the same time; hence I added 25% duty cycle. The same for the AC, if it’s running for 5 hours, it will be switching off and on (you need to ask the vendors for its duty cycle) often the better quality the device, the longer the duty cycle.

Power of each device x hours used a day x duty cycle

For example, an air conditioner used for 5 hours a day

1500 ( device Wattage ) x 5 ( hours used ) x 0.5 (duty cycle) = 3,750 Wh in a 24 hour period.

That figure is potential power usage. I always recommend adding tolerance, especially if you are totally off-grid, maybe x 1.5 or 2, depending on how much you can afford.

Buffer power = Calculated power x 1.5 or 2.00

Example: an 8.65 kW array

8650 x 1.5 = 12,975 Wh

The system must be able to supply this power over 24 hours

In addition to power usage, you need to know the peak demand. It is calculated by adding all power consumption of devices that are likely to be switched on simultaneously.

If the look at the previous table you will see the peak demand is 5,100 Watts or 5.1 kW for safety tolerances, I suggest you double this to work out the inverter's size.

5.1 kW x 2 + 10.2 kW round it to 10 kW Inverter

**Advice**

If your planning s budget / entry-level system ensure your inverter is large enough to cope with future expansion unlike charge controllers or on Grid systems, off-grid inverters can’t normally be connected together  The charge controller size is dependent upon the solar array size. The larger the array, the larger the charge controller.

Inverter size is dependent upon your peak power usage it’s nothing to do with the solar array size.

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