COURSE HANDBOOK

SOLAR PHOTOVOLTAIC INSTALLATION SUPERVISION

European Union

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DEUTSCHE ZUSAMMENARBEIT

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FROM THE AMERICAN PEOPLE

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Solar Photovoltaic Installation Supervision

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1. INTRODUCTION TO SOLAR PHOTOVOLTAICS

What this module is about

"The largest and most impressive source of energy in our world and the source of life for every plant and animal, yet a source so little used by mankind today is the sun... Solar energy will continue to flow toward us almost indefinitely".

– David Ben-Gurion (1956)

Learning outcomes

At the end of this module, the participant is able to

- Explain the basics of electricity as they relate to photovoltaics (PV)
- Appreciate various applications of solar photovoltaics
- Describe the different configurations for module and battery interconnection

INTRODUCTION

The energy from the sun (solar energy) can be harnessed to generate electricity. This is done by using solar panels to convert sunlight into electricity via the photovoltaic principle. The electricity produced by the solar panels is said to be "clean" and environmentally friendly, as it does not cause the emission of greenhouse gases (GHGs) into the atmosphere.

1.1. SOLAR RESOURCES

THE SUN AS A SOURCE OF ENERGY

The sun is the main source of energy on our planet as well as the source of all life. In fact, all types of energy are derived from solar energy including wind energy, fossil fuels and even nuclear energy.

RADIATION AND THE VISIBLE SPECTRUM

We are mostly aware of solar energy arriving at the Earth in the form of visible light. To understand light, scientists generally take two basic approaches:

- Geometric optics is used to examine the light falling on a solar collector as well as the shading and design of passive solar systems.
- Quantum mechanics is used to understand the interaction between a solar collector and the incident light impinging on it.

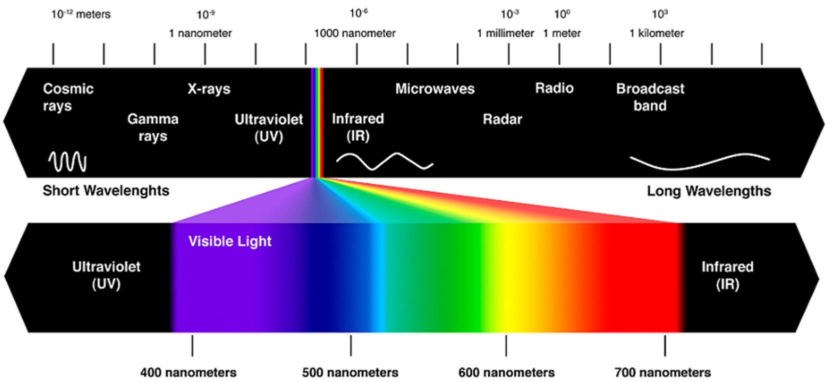


Figure 1.1: Electromagnetic spectrum

The electromagnetic spectrum describes light as a wave at a particular wavelength. In terms of solar energy, however, it is difficult to describe light solely as waves since this perspective fails to explain the interaction of light with solid matter. This interaction forms the basis of the photoelectric effect. Albert Einstein explained this relationship in 1905 by describing light as quantum particles or packets of energy with zero rest mass called **photons**.

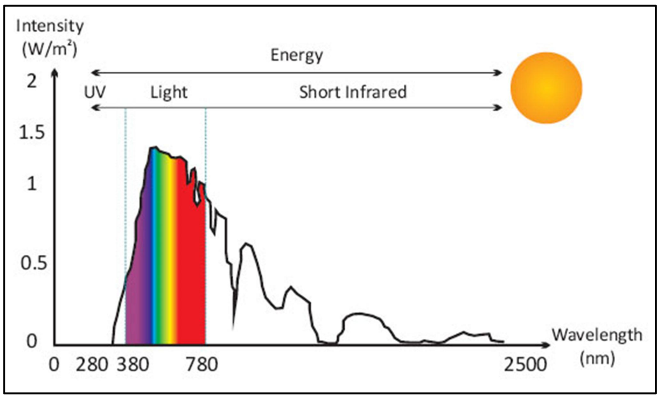


Figure 1.2: The solar spectrum

KEY TERMS

» Types of radiation

DIRECT RADIATION (G_B)

Radiation that reaches the earth's surface instead of being reflected or scattered in the atmosphere. In other words, the radiation from the sun, which is not blocked by clouds.

DIFFUSE RADIATION (G_D)

Radiation that reaches the earth's surface but is first scattered by naturally occurring gasses in the atmosphere (mostly nitrogen and oxygen), clouds, dust, smoke, etc. This type of radiation is why the sky appears blue or the clouds white.

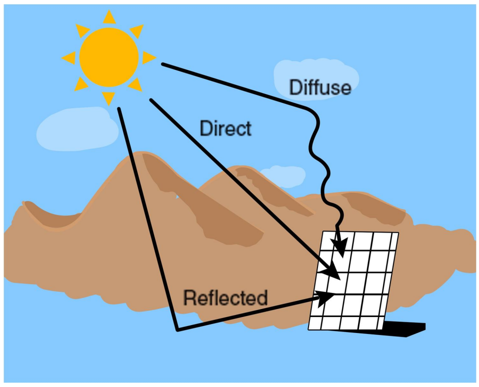


Figure 1.3: Types of radiation

REFLECTED RADIATION (G_R)

Radiation reaching the earth's surface after reflection from objects not in the atmosphere such as the ground or snow.

TOTAL GLOBAL RADIATION (G)

Sum of the three types above: $G = G_B + G_D + G_R$.

For example, on a clear afternoon direct radiation could comprise up to 85% of the total irradiance reaching the earth's surface with diffuse and reflected radiation comprising the remaining 15%.

» Solar power - irradiance

Solar radiation is power and the unit for measuring power is the watt (abbreviated "W"). The term irradiance is used when describing solar radiation as a source of power. The symbol for irradiance is "E". However, as the irradiance depends on the surface of impact it has to be defined in W/m^2 or kW/m^2.

On a cloud-free day in northern Nigeria, the solar irradiance can reach values of 1 kW/m^2. Some regions on the earth can reach up to 1.3 kW/m^2.

» Air mass

This refers to the length of the path through the atmosphere to sea level that is traversed by the solar radiation. This entry point into the atmosphere is called "Air Mass 0" or "AM 0", where "0" indicates that there is no air mass.

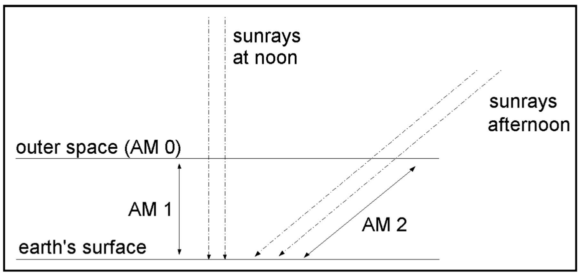


Figure 1.4: Effect of angle of incident on AM

At sea level, the radiation from the sun at its zenith (θz) corresponds to an air mass of 1 (AM 1). AM 1.5 is used to calibrate and gauge the efficiency of solar cells. Air mass is an indicator for the spectrum of radiation reaching the earth's surface. At AM 0, the full spectrum of radiation as emitted by the sun is present. After travelling through the atmosphere to sea level (AM 1), a part of the original spectrum of radiation is filtered out e.g. a large share of ultraviolet radiation.

When radiation hits the surface at an angle (any contact other than vertical), this also changes the space of air the radiation has to travel through meaning the AM increases.

» Solar energy - irradiation

Irradiation refers to the cumulative solar energy striking a given surface within a given time. It is represented by the symbol "H" and measured in *watt-hours per square metre* (Wh/m^2).

When designing a solar system, it is important to know how much energy can be harvested in a day, a month or a year. Therefore, solar energy is measured in *kilowatt hours per square metre per day* ($kWh/m^2/day$) or per month or per year.

1.2. SOLAR RESOURCES IN NIGERIA

Due to Nigeria's geographic location (latitude 3°N – 10°N), there is an abundance of sunshine all year round. It is estimated that Nigeria receives **2,000 kWh/m^2** from the sun each year, which is more than enough to produce energy for all Nigerians.

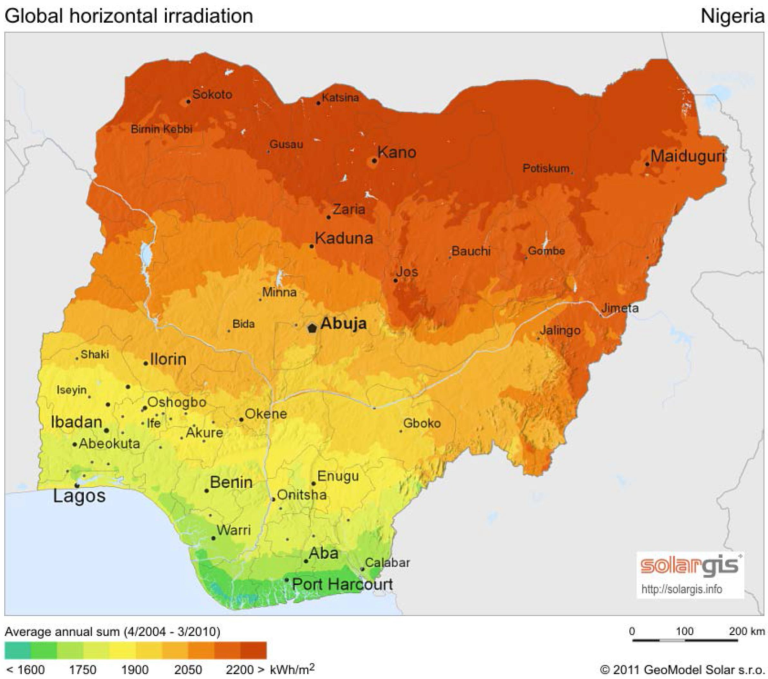


Figure 1.5: Horizontal irradiance reaching Nigeria annually

DISTRIBUTION OF SOLAR RESOURCES IN NIGERIA

Nigeria can be divided into five climatic regions:

- Sahel savannah
- Sudan savannah
- Guinea savannah
- High rainforest
- Mangrove swamp

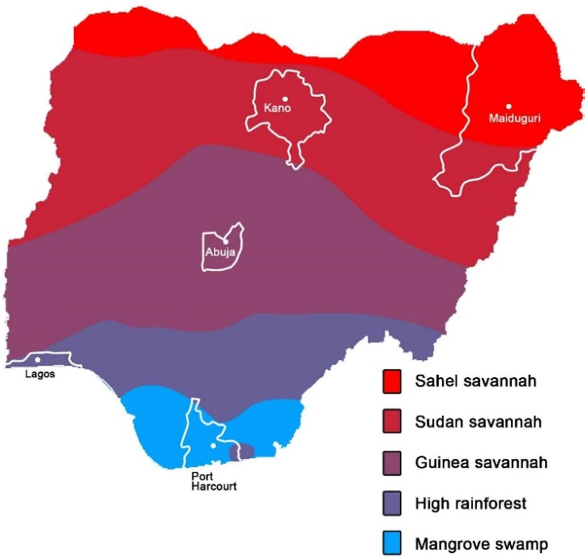


Figure 1.6: Climatic regions in Nigeria

CONCEPT OF PEAK SUN HOURS (PSH)

- The peak sun hours for a particular location identify the total amount of solar resource available at a particular location in one day assuming a value of 1-sun. In Nigeria, the PSH can easily be classified based on the different climatic regions shown in Figure 1.6.
- Peak sun hours is a location-specific concept. It is defined as the average daily solar irradiation incident on the earth surface at a particular location in units of kilowatts per square metre per day (kWh/m²/day).
- The peak solar radiation is 1 kW/m². On a given day, the morning sun does not have its full power of 1 kW/m² and the same is true in the evening. This variance continues throughout the day often reaching its zenith at noon. Over the course of the day, the hours of solar radiation across the day, however, sums up to a certain amount of energy. In central Nigeria on a sunny day, we have about five hours with a solar radiation of 1kW/m², meaning we have five peak sun hours, which is the same as 5 kWh/m²/day.

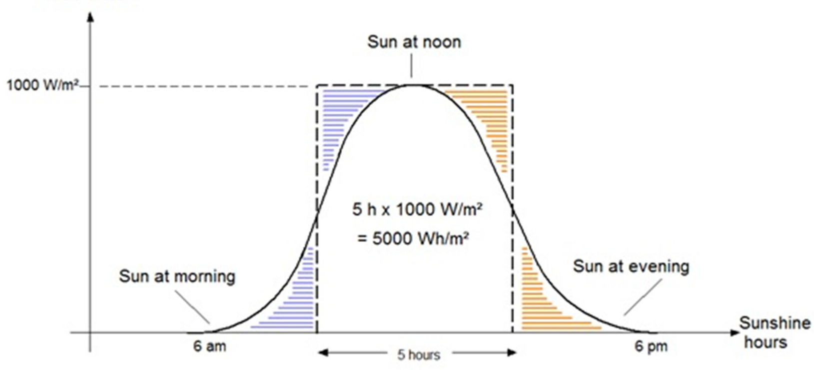


Figure 1.7: PSH as irradiance over time

Climate	PSH	Example location
Mangrove swamp	4	Yenegoa, Port Harcourt, Warri
High rainforest	4.5	Abeokuta, Ibadan, Benin city
Guinea savannah	5	Markurdi, Kaduna, Lokoja
Sudan savannah	5.5	Kano, Katsina
Sahel savannah	6	Maiduguri, Bauchi

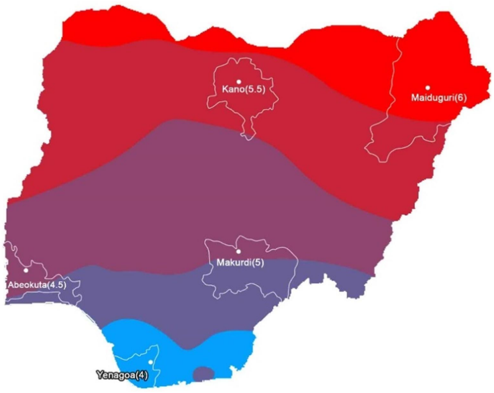


Figure 1.8: Locations showing the different PSH in Nigeria

1.3. THE PHOTOVOLTAIC EFFECT

When an object or material is exposed to light, causing it to generate voltage and current within its molecular structure, that material is said to exhibit the photovoltaic effect. The photovoltaic effect is most commonly observed in semiconductor elements (group IV in the periodic table).

SEMICONDUCTORS

A semiconductor is a material that has electrical conductivity characteristics similar to both a conductor and an insulator. Semiconductors are the foundation of modern electronics and occur in elemental form as one of the following: group IV, a combination of group III and V elements (III-V semiconductors) or a combination of group II and VI elements (II-VI semiconductors). It is imperative to note that different semiconductor materials have different electrical and physical properties. Silicon (Si) is the most commonly used semiconductor material, which forms the basis for electronics and solar photovoltaics.

From Figure 1.9, a semiconductor could be a single element such as silicon (Si) or germanium (Ge). It could also occur as a compound such as gallium arsenide (GaAs) or cadmium telluride (CdTe).

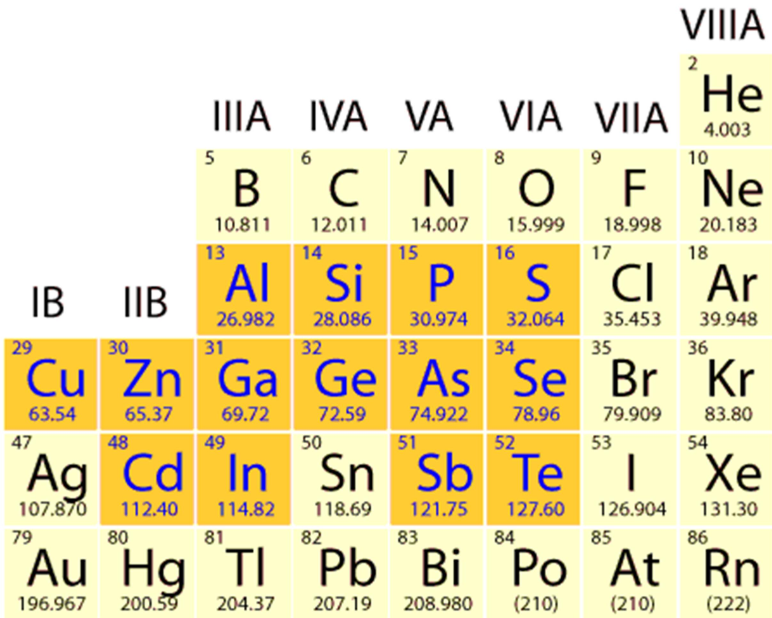


Figure 1.9: Section of periodic table showing semiconductor materials in blue – *Courtesy: www.pveducation.org*

» *Basics of semiconductors*

The photovoltaic effect (conversion of light to electricity) is based on the movement of electrons in a semiconductor atom. Today, silicon is the most commonly used semiconductor material in the world. Pure crystalline silicon is rarely found in nature. It most often occurs in the form of silicate compounds such as common sand. An individual silicon atom is electrically neutral, has an equal number of electrons (negatively charged particles) and protons (positively charged particles) and forms covalent bonds with other silicon atoms. When two atoms share electrons to complete the structure of their outermost shell, this bond is called a covalent bond. Each silicon atom forms four covalent bonds with its four surrounding atoms as shown in Figure 1.10.

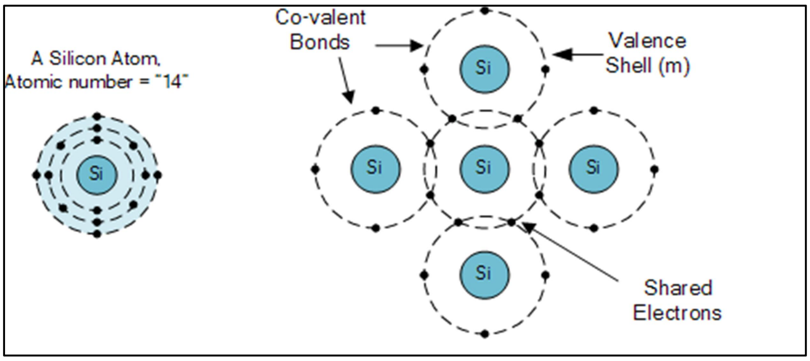


Figure 1.10: Silicon atom (left) with 4 electrons in outer shell, silicon crystal lattice (right) – *Courtesy: Basic electronics tutorials, www.electronics-tutorials.ws/diode/diode_1.html*

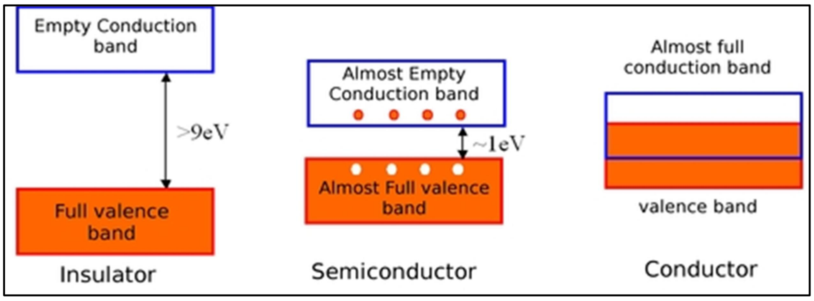


Figure 1.11: Band gaps of various materials

Semiconductors change their properties relative to the temperature. At low temperatures, they act as insulators whereas at high temperatures they act as conductors. At higher temperatures, the electrons on the outermost shell of the atom gain enough energy to break away from the bonds holding them in place, thus enabling them to move about freely in the lattice structure, a typical occurrence in conductors like metals. In reality, electrons are never "stuck" in the covalent bond, except at absolute zero temperature (i.e. 0 K or -273 ^{0}C). The minimum energy required to "excite" an electron so that it can break free of its covalent bond and participate in conduction is called the **band gap**. The space left behind by excited electrons allows the covalent bond to move from one electron to another, thus appearing to be a positive charge moving through a crystal lattice. The band gap is important because it enables excited electrons to remain in higher energy levels for long enough to be exploited to form electric current.

An excited electron leaves behind a hole, which can be filled by an electron from a neighbouring atom. This second electron, on moving in to fill the hole, leaves behind another hole, which is filled by yet another electron. This constant movement of electrons and creation/filling of holes can be illustrated as the movement of positively charged particles through the crystal structure of a semiconductor. Thus, holes and electrons are commonly called "carriers".

» *Intrinsic semiconductor*

A semiconductor material without a significant amount of impurities is referred to as an intrinsic semiconductor. In intrinsic semiconductors, the number of free electrons and holes are equal, since the creation of an electron in the conduction band creates a matching hole in the valence band.

» *Doping*

Doping refers to a method with which the population of holes and electrons is increased by introducing impurities into the lattice structure of an intrinsic semiconductor. These impurities contribute more (n-type) or fewer (p-type) electrons to the silicon crystal than native elements.

N-type semiconductors are created when atoms with one more valence electron (i.e. group V) than group IV are introduced as impurities into an intrinsic semiconductor. The spare electron roams freely about the lattice structure of silicon, thereby increasing its conductivity due to the increased number of available electrons. P-type semiconductors, in contrast, are created when the dopant carries one less valence electron (e.g. group III). The result is a material with a consistent net hole, as four electrons are required to complete the bonding for an intrinsic semiconductor. P-type materials increase conductivity due to the increased number of holes in its structure.

A doped material always contains more of a certain type of carrier than the other type. The carrier with the higher concentration is called the majority carrier while the lower concentration is referred to as the minority carrier.

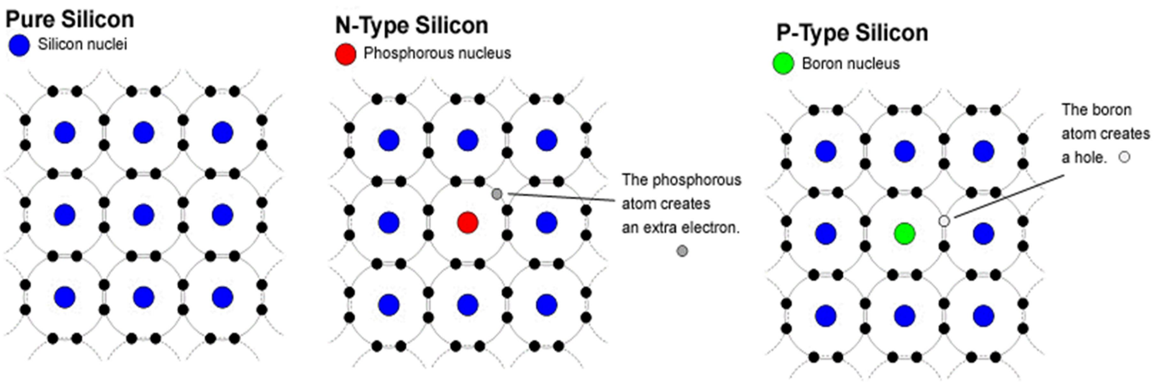


Figure 1.12: Arrangement of electrons in intrinsic silicon (left),N-type silicon (centre), and p-type silicon (right)

Table 1.1: Summary of doping in silicon

	N-type (negative)	*P-type (positive)*
Dopant	Group V (e.g. phosphorous)	Group III (e.g. boron)
Bonds	Excess electrons	Missing electrons (holes)
Majority carriers	Electrons	Hole
Minority carriers	Holes	Electrons

Central parameters of a semiconductor material for solar cell operation:

- Band gap
- Number of free carriers (electrons or holes) available for conduction
- "Generation" and recombination of free carriers (electrons or holes) in response to light shining on the material

» *The P-N junction*

A P-N junction is formed by joining a p-type and an n-type semiconductor material. On one side of the junction, there is an excess of electrons (n-type region) and on the other side, there is an excess of holes (p-type region), creating a concentration gradient across the junction. This concentration gradient causes the free carriers to **diffuse** across the junction in a process termed **recombination**. During recombination, excess electrons in the n-type material diffuse to the p-type side and excess holes from the p-type material diffuse to the n-type side. The movement of free carriers across the junction creates a layer of fixed charge (due to the ionised impurity atoms) on either side of the junction. This charged space sets up an electric field that opposes further migration across the junction and effectively stops the diffusion process. Now devoid of free carriers, this region is called the **depletion region**. As a result of the electric field, a voltage is induced at the junction.

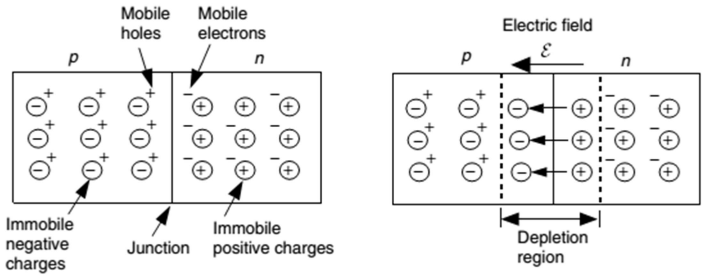


Figure 1.13: P-N junction (left) when first brought together after recombination (right)

1.4. PHOTOVOLTAIC TECHNOLOGY AND SOLAR CELLS

THE PHOTOVOLTAIC CELL

When sunlight or any other light is incident upon a material surface, the electrons present in the valence band absorb energy and being excited, jump to the conduction band and become free. The chemical bonds of the material are vital for the process as crystallised atoms are ionised and create a chemical electric imbalance, which drives the electrons. These highly excited, non-thermal electrons, diffuse and some reach a junction where they are accelerated into a different material by a built-in potential. This generates an electromotive force, and thus, some of the light energy is converted into electric energy. The photovoltaic effect can also occur when two photons are absorbed simultaneously in a process called two-photon photovoltaic effect.

In a photovoltaic cell, when a p-n junction is struck by sunlight, the light is absorbed, forming more electron-hole pairs (provided the energy of the incident photon has an energy greater than that of the band gap). As the free carriers approach the junction, the electric field in the depletion region pushes the holes towards the p-side and likewise the electrons into the n-side material. This movement creates a voltage, typically 0.6 V, which can be used to deliver current.

Since current flow is determined by the movement of electrons and the fact that holes cannot be conducted via wires, the direction of current flow is as represented in Figure 1.15. As the electrons move around the circuit, they recombine with the holes in the p-type material to complete the circuit.

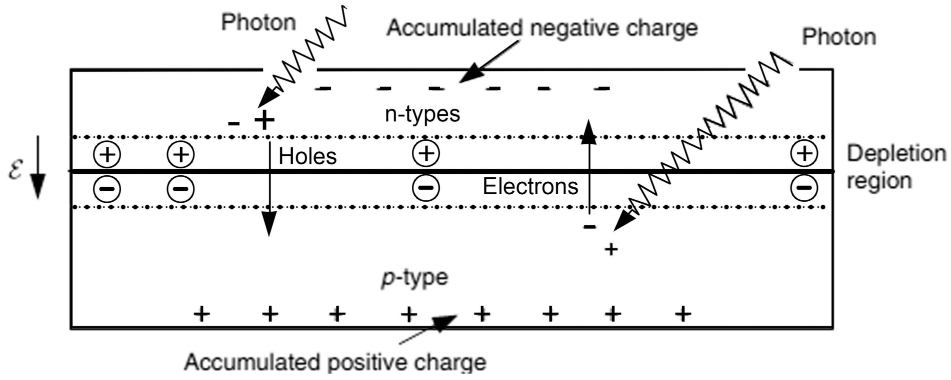


Figure 1.14: The photovoltaic effect

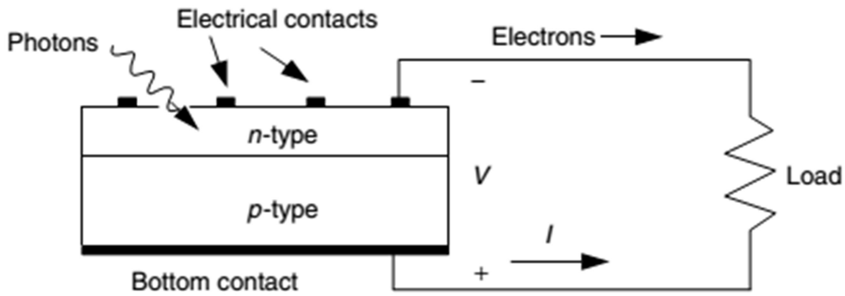


Figure 1.15: Basic circuit showing electron flow from n-type semiconductor material
– Courtesy: G. M. Masters, Renewable and Efficient Electric Power Systems

When exposed to a radiation of 1 kW/m², a typical photovoltaic (PV) cell generates a voltage and current of approximately 0.6 V and 7.5 A, respectively (4.5 W).

» Device structure

The basic solar cell is a semiconductor wafer grown or deposited on a conducting substrate. The area of a solar cell is usually in the range of 10 cm² to 100 cm². The front surface is usually coated with anti-reflective (AR) material and contacted with a fine metal grid. Cells are usually connected in series to deliver a useful voltage (12 V standard) before being encapsulated into modules. A typical device structure is shown in Figure 1.16.

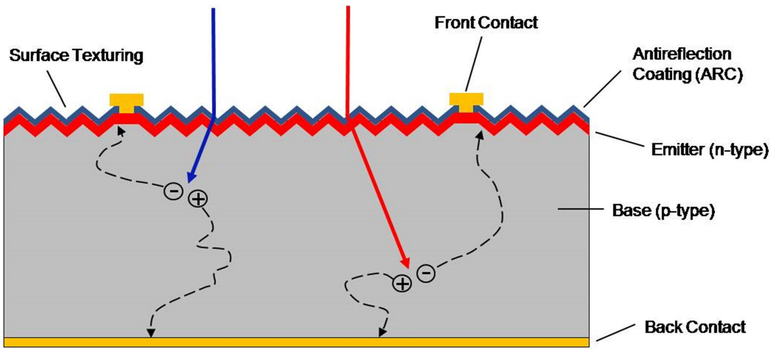


Figure 1.16: Typical structure of solar cell

» Solar cell design

Efficient solar energy conversion requires good optical absorption, efficient charge separation, and efficient charge transport to the external circuit. This places certain requirements on the cell materials and design. High absorption is achieved by making the cell thick enough and by reducing reflection with an AR coating and/or texturing the surface. Efficient charge separation at a p-n junction requires a high built-in bias that can be achieved through sufficiently heavy doping of the P and N regions. Efficient transport requires good quality material with few defects. High doping and high cell thickness can adversely affect carrier transport, however, so the cell design often involves optimising these parameters.

» *Solar cell materials*

The most common material by far is monocrystalline or polycrystalline silicon. Monocrystalline silicon consists of silicon in which the crystal lattice of the entire solid is continuous, i.e. unbroken up to its edges and free of any grain boundaries. Polycrystalline silicon cells consist of small crystals also known as crystallites, giving the material its typical metal-flake effect.

Silicon is a relatively cheap, abundant and non-toxic material, which benefits from the extensive development of silicon technology for the microelectronics industry.

The best laboratory efficiency obtained with a silicon solar cell is 24.7%, and 14% to 20% in mass production, depending on the device technology used. Polycrystalline silicon is cheaper to produce but delivers a lower efficiency around 15% to 18% in the best cells.

Thin-film solar cell materials include amorphous silicon, cadmium telluride (CdTe) and copper indium diselenide (CIS). Although, amorphous silicon has been the base material for inexpensive consumer PV products such as solar-powered calculators, it suffers from material degradation, which may inhibit its use in higher power applications.

Other crystalline materials include gallium arsenide (GaAs) and indium phosphide (InP), which perform well in extra-terrestrial conditions.

Figure 1.17: Types of solar cells: monocrystalline silicon (left), polycrystalline silicon (centre), amorphous silicon (right)

Table 1.2: Characteristics of solar cell materials

Cell type	*Efficiency*	*Advantages*	*Disadvantages*
Mono-crystalline	14-20 %	▪ Higher efficiency ▪ Good low light performance ▪ Good power-to-size ratio ▪ Outstanding performance in cooler conditions ▪ Excellent lifespan ▪ Well understood technology	▪ High waste during manufacturing ▪ High retail cost ▪ Poor performance at high temperatures
Poly-crystalline	15-18%	▪ Less expensive to produce than monocrystalline ▪ Compared to monocrystalline, slightly better performance in warmer conditions ▪ Excellent lifespan	▪ High waste during manufacturing ▪ Poor performance at high temperatures ▪ Less aesthetically pleasing
Amorphous silicon	6-9%	▪ Optimal performance in hot climates	▪ Expected lifespan is less than crystalline panels ▪ Requires 2 to 3 times more panels and surface area for same output as crystalline
Cadmium telluride	7-10%	▪ Low cost of manufacturing ▪ Aesthetic appearance ▪ Can be manufactured to be flexible ▪ Excellent performance at high temperatures	▪ Cadmium is very poisonous ▪ Requires a lot of space ▪ Faster degradation than crystalline silicon
Gallium arsenide	15-30%	▪ Temperature-resistant ▪ For use in space exploration	▪ Expensive to manufacture

» *Equivalent circuit of a photovoltaic cell*

The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure 1.18. The circuit parameters are as follows; the current I at the output terminals is equal to the light-generated current I_L, less the diode current I_d and the shunt leakage current I_{sh}. The series resistance R_s represents the internal resistance to the current flow.

The shunt resistance R_{sh} is inversely related to the leakage current to ground. In an ideal PV cell, $R_s = 0$ (no series loss), and $R_{sh} = \infty$ (no leakage to ground).

In a typical silicon cell, R_s varies from 0.05 to 0.10 Ω and R_{sh} from 200 to 300 Ω. The PV conversion efficiency is sensitive to small variations in R_s, but insensitive to variations in R_{sh}. A small increase in R_s can decrease the PV output significantly. In the equivalent circuit, the current delivered to the external load equals the current I_L generated by the illumination, less the diode current Id and the shunt leakage current I_{sh}.

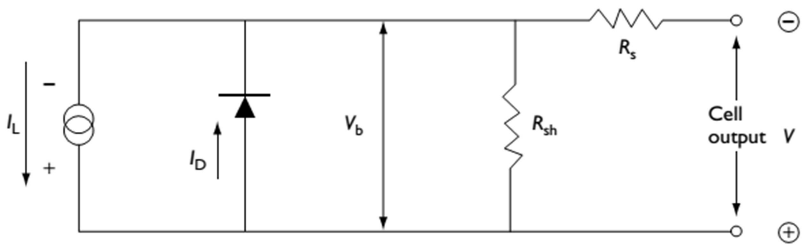


Figure 1.18: Simplest circuit of a solar cell

The open-circuit voltage V_{oc} of the cell is obtained when the load current is zero, i.e. when $I = 0$.

Short-circuit current (I_{SC}): Current flowing through a solar cell when it is not connected to any load and the voltage across it is zero.

Open-circuit voltage (V_{OC}): Voltage across a solar cell when the resistance between the positive and negative terminals is infinite. It is the voltage across the cell under no-load conditions.

CHARACTERISTICS CURVES OF PHOTOVOLTAIC CELLS

Solar cells are characterised by two main parameters: the short-circuit current and the open-circuit voltage. The relationship between these two parameters is useful in analysing the performance of a solar cell and is easily represented by two curves, namely:

IV curve: Shows the relationship of the current flowing through the cell with the voltage across it.

PV curve: Shows the relationship between the power generated and the voltage across the cell.

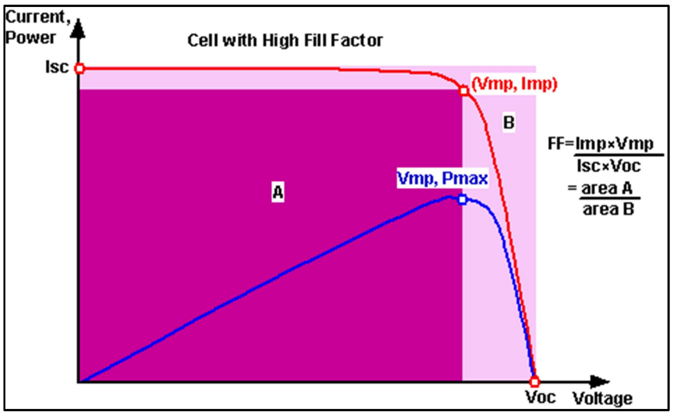


Figure 1.19: IV (red) and PV (blue) curves of a solar cell
– Courtesy: www.PVeducation.org

Fill factor (FF): The theoretical maximum current and voltage of a solar cell are I_{SC} and V_{OC}. However, the solar cell does not generate any power at these points. The fill factor is a measure of the "squareness" of a solar cell. It is defined as the ratio of the maximum power of a solar cell to the product of the short-circuit current and open-circuit voltage.

Maximum power point (MPP or P_{max}): Point where the product of the current (I_{mp}) and voltage (V_{mp}) is greatest. It corresponds to the fill factor.

Efficiency: Ratio of the electrical power output of the cell to the solar power input.

1.5. PHOTOVOLTAIC SYSTEM CONFIGURATION

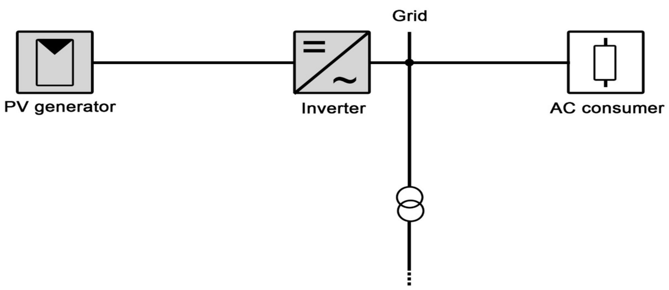
Solar photovoltaic systems are designed in either of the following configurations:

GRID-CONNECTED SOLAR SYSTEMS

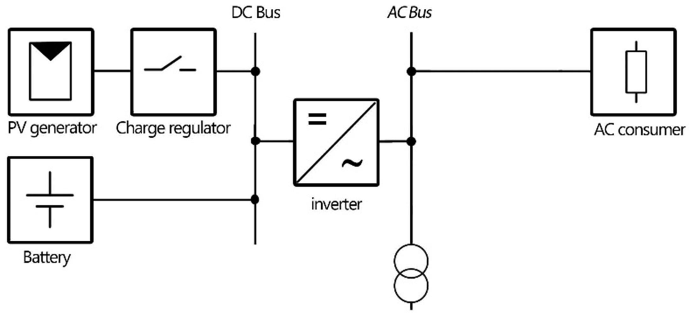
These are usually power plants or systems connected to homes where the grid is stable and there are no blackouts/brownouts. Components commonly used in grid-connected systems include solar PV modules or (one or more) array(s), batteries, charge controller(s), inverter(s), electric load (e.g. lamp, fan, pump), accessories (e.g. switches, sockets, cables, etc.) and the electric utility grid.

There are two possibilities for grid-connected systems, namely:

» ***Systems connected directly to the national grid***



» ***Grid back-up systems***



OFF-GRID SOLAR SYSTEM CONFIGURATIONS

» ***Off-grid system without battery storage and DC-only load***

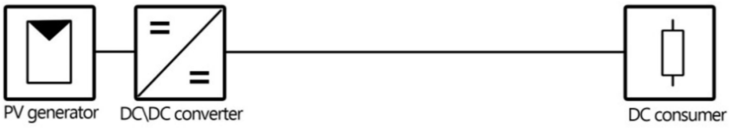


Figure 1.20: A DC solar pump powered by solar panels to bring water to grazing cattle in the field – *Courtesy: Prof. Dr.-Ing. Habil Ingo Stadler*

» Off-grid system with battery storage and DC-only loads

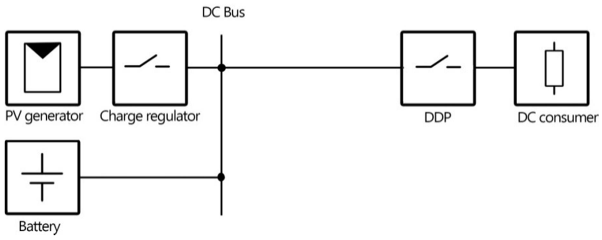


Figure 1.21: Power supply exclusively for lighting loads in Australia
– Courtesy: Prof. Dr.-Ing. Habil Ingo Stadler

» Off-grid system with AC-only loads

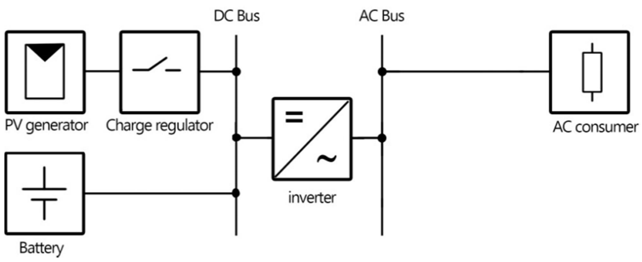
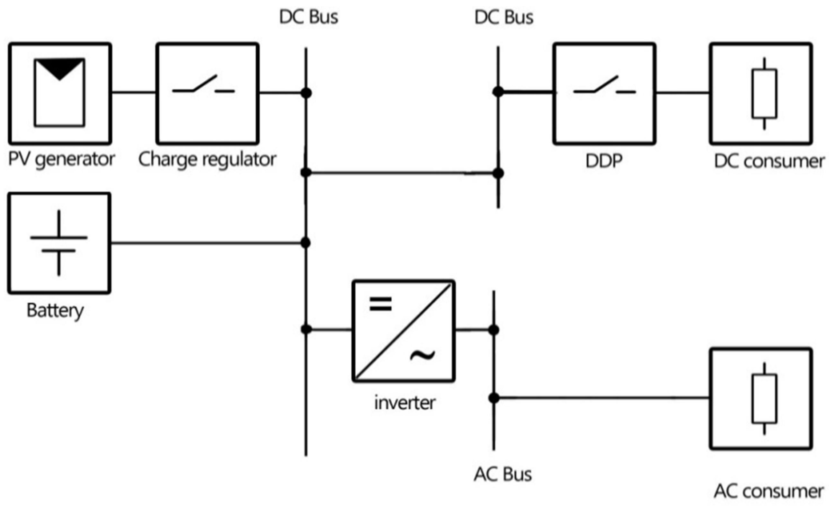


Figure 1.22: Solar PV system to power a base transceiver tower

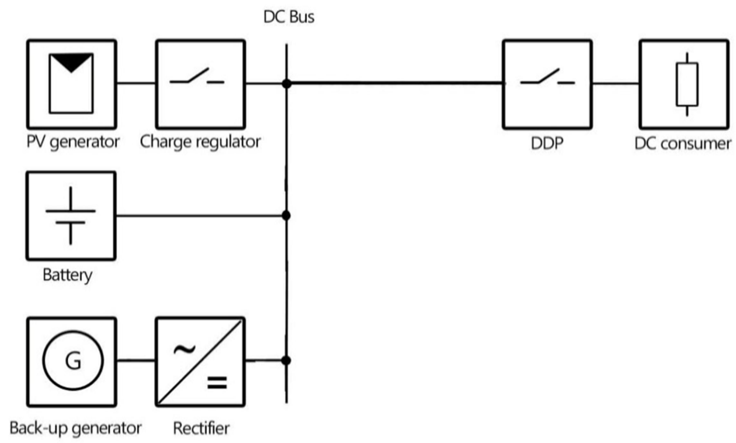
» ***Off-grid system with both AC and DC loads***



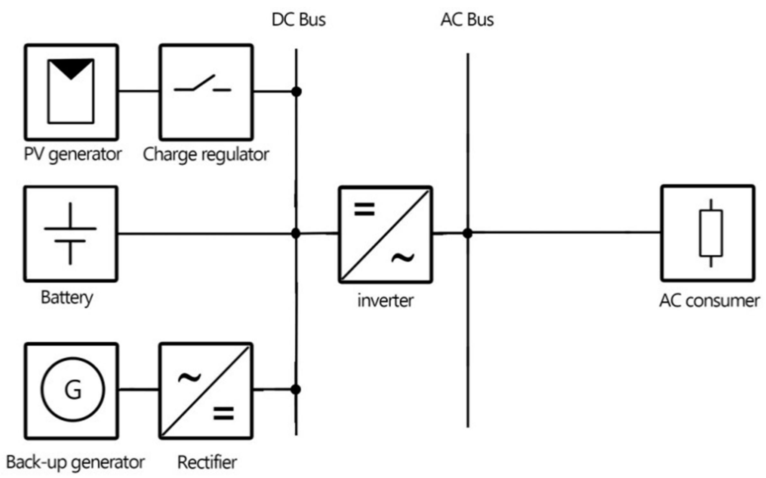
HYBRID SYSTEM CONFIGURATIONS

There are various ways in which a hybrid system can be connected.

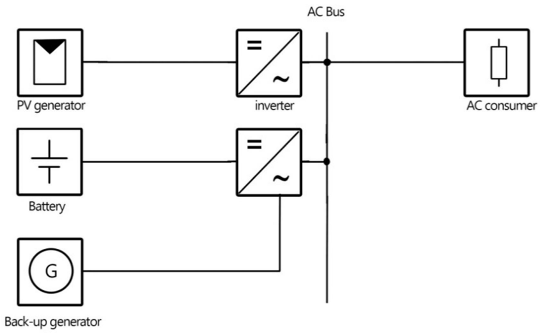
» ***Connection through a DC bus to supply a DC load***



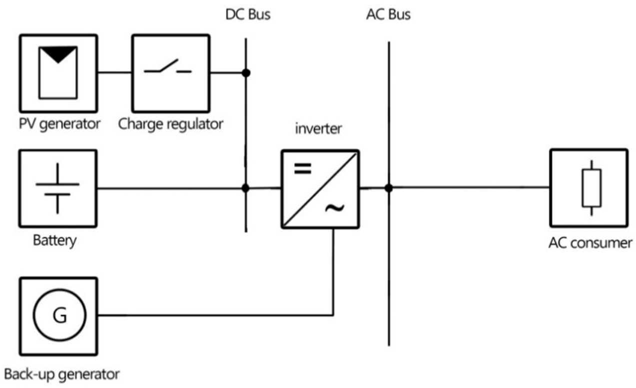
» ***Connection via a DC bus through an inverter to supply an AC load***



» ***Connection through an AC bus to supply an AC load. Solar panel inverter option***



» ***Connection through an AC bus to supply an AC load. Charge controller option***



1.6. APPLICATIONS FOR SOLAR PHOTOVOLTAIC SYSTEMS

Solar photovoltaic systems are used in a variety of applications. Some of the most common examples are below.

STREET LIGHTING

The simplest and most common application of solar photovoltaic systems is the solar street light. These systems are DC-connected systems with storage.

RURAL ELECTRIFICATION

Solar PV systems are used to provide electricity to rural communities with no previous access to electricity. This could be in the form of a solar home system or as a mini-grid.

Figure 1.23: Solar street light in Umuahia, Abia State

SOLAR HOME SYSTEMS

Solar systems for use in single homes are referred to as solar home systems (SHS). These systems come in two basic forms:

- Plug & play systems combine a battery, charge controller and power outlets in a single enclosure, usually with sockets to connect pre-wired lamps.
- In mains power supply systems, the solar system supplies electricity to the whole home through the main grid.

Figure 1.24: Mains supply solar home system with rooftop mounted panels

MINI-GRIDS

Mini-grids are large solar electric systems with one or several solar module arrays and central battery storage. They are called "mini-grids" as they supply power to several buildings via an AC distribution line. An example for this system type is the mini-grid system set up by Schneider Electric on behalf of the Federal Ministry of Power, Works and Housing (Power) in Mpape, Abuja.

Figure 1.25: Solar-powered mini-grid
– Courtesy: SMA solar technology, www.SMA.de

WATER PUMPING AND IRRIGATION

Solar photovoltaic systems are used to provide electricity for irrigation systems on farms. These systems are usually DC-connected systems with or without storage.

Figure 1.26: Solar powered irrigation system in Daura, Katsina

POWER PLANTS

This is the fastest growing application field for solar energy. More and more countries are including solar power plants in their energy mix. Nigeria has numerous solar power plants planned, but none constructed as of April 2016.

2. WORKPLACE SAFETY AND FIRST AID

What this module is about

Accidents may happen during the installation of solar systems. This module provides students with the necessary information to work safely and provide first aid in the event of injuries during installation.

Learning outcomes

At the end of this module, the participant is able to

- Demonstrate familiarity with common workplace safety rules and regulations
- Assess possible health and safety threats and describe how to avoid them
- Identify the different types of protective clothing and equipment
- Recognise the signs and symbols for work site safety

All safety measures on the site are the direct responsibility of the supervisor. It is your duty as a supervisor to ensure that workers perform their jobs in a safe manner.

2.1. RISKS AND HAZARDS

GENERAL RISKS

When you work with electrical equipment and appliances, the most obvious danger is electrocution or electric shocks. Electric shocks occur when current flows through your body, offering a passage of little resistance on the current while your body is connected to ground. These shocks could be minor (when working with lower voltages) but could lead to other more serious injuries such as:

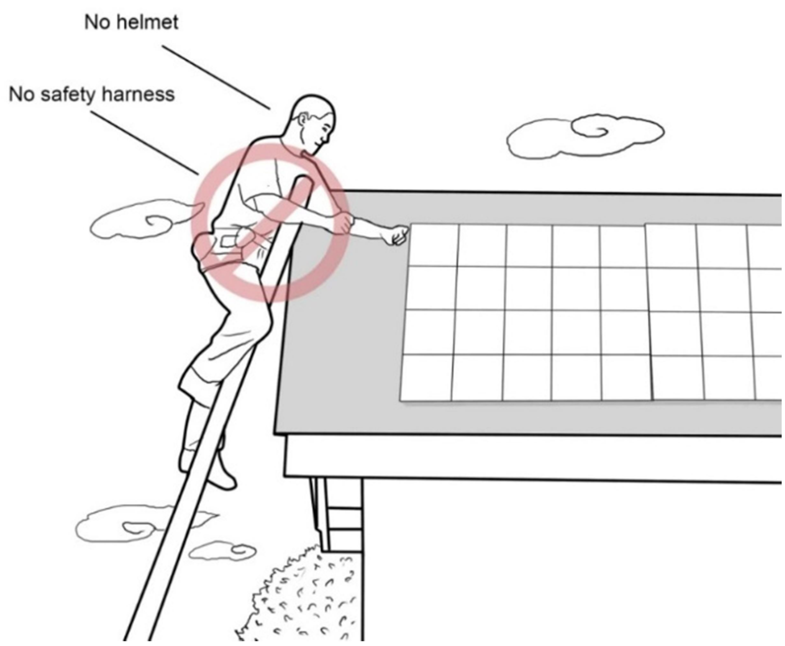
- Burns on affected skin areas
- Injury sustained due to falls, e.g. from a ladder when working at heights
- Loss of consciousness
- Vision, hearing and speech impediments

A second major risk associated with electrical installations is the outbreak of fire. This could occur if there is an electrical spark near a combustible substance. When connecting to a solar battery bank, for instance, a nearby bucket of petrol could lead to an explosion and, subsequently, fire.

When working on electrical installations, safety is paramount. Serious injuries, even death can result from failure to adhere to best practices.

Accidents are usually caused by the following factors:

- Unsafe equipment and installations, e.g. improper grounding of equipment.
- Unsafe working environment, e.g. work conducted in an improperly designated area.
- Unsafe procedures, e.g. working at heights without appropriate fall protection.



COMMON INJURIES FOR PHOTOVOLTAIC SYSTEM INSTALLERS

The most common injuries experienced by electrical installation workers include:

- **Electrocution,** which can occur when a person is in contact with a voltage high enough and long enough to maintain a flow of current through the body, which can cause muscle cramps and ventricular fibrillation. A current of 50 mA, which lasts for more than 1 second is probably fatal. A current of 200 mA is already fatal after 0.2 seconds. Whether that current flows through the body depends on the body resistance, which can be very much influenced by the skin (dry or wet) and by footwear. Safety boots with rubber soles that are resistant to electrical shocks have saved many lives. Under some conditions (e.g. barefoot on wet ground) AC voltages above 50 V and DC voltages above 120 V can be life-threatening.
- **Burns or eye irritations** as a result of direct contact with current or arc flashes.
- **Injuries sustained after a fall** are among the most common injuries when working on solar systems.
- **Acid splashing and spilling,** which could harm skin and eyes when working with batteries.

MINIMIZING HAZARDS

To minimise the possibility of electric shocks or other hazards associated with installation, the following should be taken into consideration before installation work begins:

- Evaluate and identify possible hazards like falling from the roof.
- Use a body harness for added safety.
- Monitor environments/locations where hazards cannot be eliminated to reduce risks. For example, working in pairs to reduce the risk of falling while using ladders.

2.2. SITE SAFETY

Site safety is a very important but often neglected aspect of installation. On a construction site, there are numerous safety symbols, which are generally classified according to their colours as described below:

» ***Red* – prohibited (never do these)**

A red sign means that an activity is prohibited and must be avoided at all costs. These activities are **life-threatening**.

For example, the symbol beside tells you never to extinguish fire with water.

» ***Yellow* - hazard**

A yellow sign is a warning sign that indicates the need for **extreme caution**.

For example, the symbol beside indicates the presence of live electrical connections.

» ***Blue* – compulsory (to be obeyed at all times)**

A blue sign indicates a specific instruction, mostly involving the use of compulsory personal protective equipment (PPE).

For example, the symbol beside indicates that a safety helmet must be worn at all times.

» ***Green* – no danger**

A green sign signifies that there is no danger. It mostly refers to opportunities to escape from or treat hazards.

For example, the symbol beside shows that there is a first aid box or clinic on site.

» Other symbols used to mark obstacles and hazardous areas (where falls could occur or where objects could fall from) generally look like this:

2.3. PERSONAL SAFETY

As with all other electrical equipment, safety precautions must be taken when installing solar photovoltaic systems to prevent possible injuries to personnel.

PERSONAL PROTECTIVE EQUIPMENT

Equipment used to protect a construction site worker or installer from bodily harm or injury is referred to as personal protective equipment (PPE).

Figure 2.1: Solar PV installers wearing all required PPE – *Courtesy: The Solar Planner, www.thesolarplanner.com*

PPE		Importance
Hard hat		Protects against falling objects. Hard hats of various colours are also used to identify responsibilities of workers on a construction site.
Goggles		Protect the eyes from sparks and flints when drilling or cutting
Earmuffs		Protect the ears from loud sounds which occur during construction

Gloves		Protect the hands from cuts and provide insulation when working with heavy-duty cables or when drilling or cutting
Safety boots		Insulating footwear to protect the feet from impacts
Body harness		Protects against falls when working at heights

Other safety equipment required to prevent or treat personal injury:

Equipment		Importance
Emergency first aid kit		Used to treat work-related injuries
Fire extinguisher		Used to put out fires that may arise during installation

2.4. WORKING ON ROOFTOPS AND FACADES

Figure 2.2: Solar PV installer in Hawaii with fall protection
– *Courtesy: SolarPro Magazine*

When working on rooftops and facades, maximum care is essential to avoid accidents.

When working at heights above 2 metres, the use of fall protection such as a body harness or safety net is mandatory.

A safety net is used to protect workers at a construction or installation site from injury and/or death in the case of a fall. The safety net reduces the distance of the fall and absorbs and dissipates fall-related energy to protect the victim.

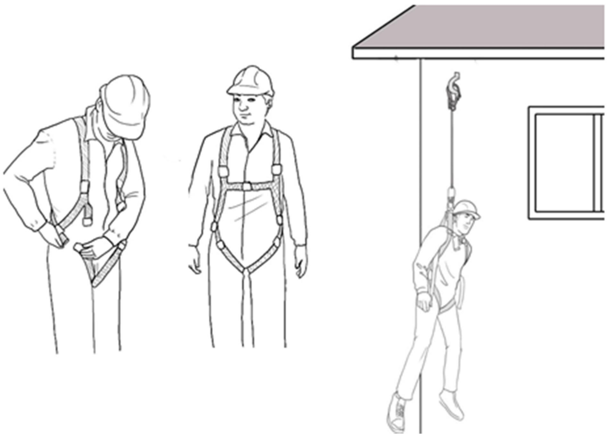


Figure 2.3: Body harness protecting installer from falling to the ground

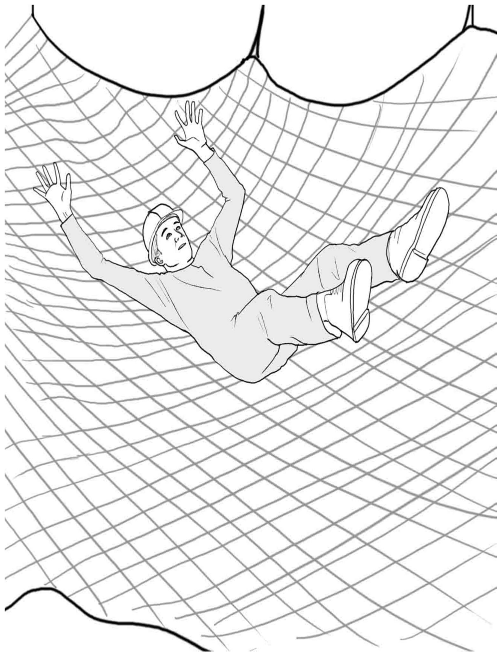


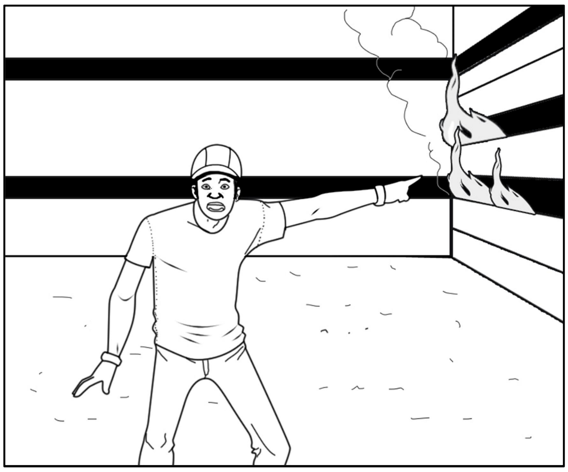
Figure 2.4: Safety net when using a ladder or working at great heights

In most cases, especially when performing installations on domestic buildings, you will need to use a ladder. Here are the basic safety instructions to follow when using ladders:

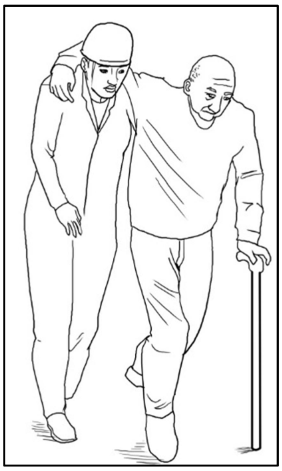
- Ensure that the ladder you are using is non-conductive and equipped with a non-slip base.
- Make sure that your ladder is in good condition and that someone is present to assist you.
- Always secure the ladder to a fixed position and make sure that it rests on a stable base before climbing. If there is none, ensure there is someone to hold the ladder.
- There should never be more than one person on a ladder at any given time.
- Always face the ladder; never turn your back on it.
- Always use both hands when climbing up and down a ladder.
- Never perform work while on the topmost four rungs of the ladder unless you are using a step ladder.
- Always maintain a distance of at least 3 metres from power lines.

2.5. FIRE HAZARDS

Fire outbreaks can occur if proper precautions are not taken to avoid them. In the event that a fire does occur, follow these steps:



1. Draw attention to the fire



2. Assist persons who require support to escape

3. Attempt to extinguish only after activating and assisting

Remember!! Only attempt to put out a fire if:

- The fire is small and contained.
- You are safe from toxic smoke.
- You have a means of escape.
- Your instincts tell you it is okay.

Fires can break out at an installation site. As the site supervisor, it is your duty to ensure the fire is put out whenever possible.

» *Types of fires and appropriate fire extinguishers*

Class and type	Symbol	Extinguisher type
Class A fires Fires in common items such as wood, paper, cloth, plastic, etc.		Water and foam
Class B fires Fires in flammable fluids such as petrol or kerosene		Carbon dioxide, dry chemical
Class C fires Fires in flammable gases such as cooking gas		Carbon dioxide, dry chemical
Class D fires Fires in combustible metals		Dry powder
Class E fires Electrical fires		Carbon dioxide, dry chemical
Class F fires Fires in cooking oils and greases		Wet chemical

Note: Follow these steps when putting out a fire

- Pull the pin.
- Aim the nozzle at the base of the fire.
- Squeeze the operating lever to release the extinguishing agent.
- In a sweeping motion, move the hose from side to side until the fire is completely put out.

When trying to extinguish fire, always spray the extinguishing agent at the base of the fire.

	Water	Foam	Dry Powder	CO2 Carbon Dioxide	Wet Chemical
Solids (wood, paper cloth etc)	✓	✓	✓	✗	✓
For Flammable Liquids	✗	✓	✓	✓	✗
For Flammable gasses	✗	✗	✓	✗	✗
For Electrical equipement	✗	✗	✓	✓	✗
For Cooking oils and fats	✗	✓	✗	✗	✓
For Use on all risks	✗	✗	✓	✗	✗

Figure 2.5: Fire extinguishing compounds and associated types of fire

When working with CO_2 fire extinguishers:

- Avoid use in contained spaces
- Do not hold the horn during operation

2.6. LIFTING HAZARDS AND SAFE LIFTING

During the installation of a photovoltaic system, some lifting of heavy equipment or tools is required. Lifting at a construction site involves the mechanical and manual movement of materials and equipment.

In a solar system, the equipment to be lifted includes:

- PV modules
- Batteries
- Inverter
- Mounting systems

DANGEROUS LIFTING

Manual lifting of heavy loads can be dangerous and lead to permanent injuries, which are predominantly back-related. Furthermore, if the load to be lifted has sharp edges, the worker might sustain lacerations if not wearing protective gloves. You must ensure that all workers at your construction site know the procedures for safe lifting. Workers must avoid lifting in the following situations:

- The load is too heavy for an individual to carry alone.
- The load is unbalanced or unstable.
- The load does not provide sufficient surface for a firm grip.
- The load is too large and bulky for an individual to carry alone.
- The worker has to assume an awkward position while lifting the load.
- The space available for lifting is insufficient.
- The floor is wet, slippery or uneven.

DANGEROUS LIFTING PRACTICES

Generally, when working with heavy loads, workers should mind the following instructions for manual lifting:

- Never lift heavy loads by bending forward from your back. Bend your hips and knees to squat down. Keep the load close to your body and then straighten your legs to lift it up.
- Never lift a heavy object above shoulder level.
- Do not turn or twist your body while lifting or holding a heavy object.

» Step-by-step instructions for safe lifting

- Keep your feet apart, around shoulder width, one foot is slightly forward (feet are a half step apart).

- Bend your hips and knees to squat down. One knee might be on the floor while the other is bent.

- Keep your back straight

- Slowly stand up by straightening your knees. Do not turn or twist your body while lifting. Hold the load close to your body with your arms kept straight.

- Do not twist your body to change direction; always take small steps.
- Your shoulders should remain in line with your hips when you move.
- When putting your load on the ground, reverse the squat you did to lift the load.
- When working on a rooftop or at heights, never carry heavy or voluminous equipment like PV modules while ascending or descending a ladder. Always use a line for those items or, if safety precautions are followed, two persons can work together to bring the load up on two ladders.
- Never lift a heavy object above shoulder level.

2.7. PREVENTING ELECTRICAL HAZARDS

Electrical hazards are common in the form of electrocution. Electrocution can occur either through direct or indirect contact.

- **Direct contact**: The term "direct contact" is used when a person touches a part of a functional electric device or circuit, which is energised under normal operation.

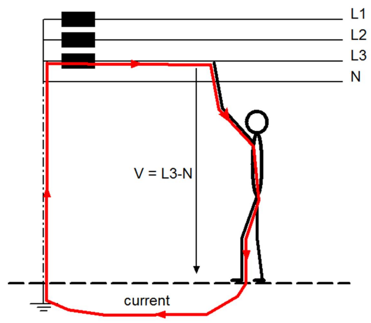


Figure 2.6: Direct contact with dangerous voltage

- **Indirect contact**: The term "indirect contact" is used when a person makes contact with dangerous voltage due to faulty insulation.

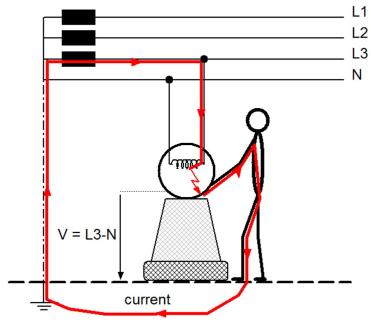


Figure 2.7: Indirect contact with dangerous voltage

Table 2.2. Protective measures against electrocution

Protection against direct and indirect contact	***Protection against direct contact***	***Protection against indirect contact***
Extra-low voltage (ELV) installation	Insulation Enclosures Spacing Additional protection by RCD	Automatic disconnect of power supply Equipotential bonding Double insulation Non-conductive spaces Electrical separation Non-grounded local equipotential bonding

2.8. FIRST AID

First aid refers to the emergency treatment or assistance provided to the victim of an accident by the first responders on site. The purpose of first aid is to preserve life, prevent the condition from worsening and to promote quick recovery before the victim receives attention from qualified medical personnel.

You must ensure that before installation work begins, there is a first aid kit/box on site and all workers are familiar with its location.

The first aid box should contain the following equipment:

Equipment	
Stainless-steel bandage scissors	
Stainless-steel pointed splinter forceps	
Steel angle-tip forceps (3.5")	
Safety pins	
Sterile adhesive bandages (plasters) 2.5 cm × 7.5 cm (1"× 3")	
Assorted adhesive bandages (plasters)	
Sterile gauze pad, about 10 cm × 10 cm (4" × 4")	

Sterile conforming bandage roll 50 mm × 3.7 m (2" × 4.1 yd)

Triangular bandage 1 m × 1 m × 1.4m (40" × 40" × 56")

Sterile compress bandage 4" (10 cm)

Sterile abdominal compress 20 cm × 25 cm (8" × 10")

Adhesive tape 2.5 cm × 3 m (1" × 118") hypoallergenic

Adhesive tape 1.3 cm × 3 m (0.5" × 118") hypoallergenic

Benzalkonium chloride swab pads

Alcohol swab pads

Latex gloves (4 medium pairs + 4 large pairs) vacuum sealed

CPR (cardiopulmonary resuscitation) face shield with fabric filter

CPR face shield with one-way valve and filter

CPR pocket mask with one-way valve and case

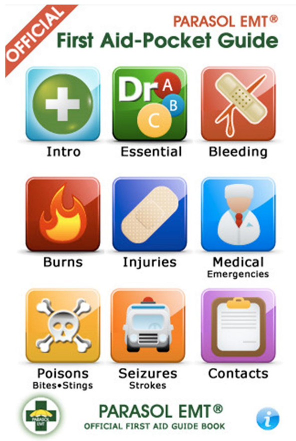
Additional replacement one-way valve for CPR pocket mask

Emergency blanket

Wax-lined paper bag for vomiting

Instant cold pack

First-aid pocket guide



Notepad, pencil and sharpener

Black plastic garbage bag

List of kit contents

A list of all contents in the first aid box/kit

STEPS TO TAKE IN THE EVENT OF AN ACCIDENT

If an accident occurs on site, the supervisor is expected to take charge of the situation by ensuring that the victim receives the necessary first aid before more qualified health care professionals arrive. You must act quickly and decisively.

Steps to follow:

- Call for emergency help if necessary with major accidents.
- Minimise the injury. Only move the victim if necessary.
- Control severe bleeding.
- Ensure that the victim's air passage is not constricted. If necessary, use a cardio-pulmonary resuscitation (CPR) mask.
- Treat the victim for shock if necessary.

FIRST AID FOR COMMON SITE INJURIES

» *Bleeding*

In the event of bleeding, follow these steps:

- Apply direct pressure to the wound.
- Raise the injured area to a level above the heart.
- Apply a pressure bandage and wrap tightly over the wound.
- Call and wait for emergency healthcare personnel if necessary.

» *Burns*

In the event of a burn, follow these steps:

- Remove the victim from the source of the burn or extinguish the flames (in case of electrical burns, isolate the victim from the source or isolate the source).
- Cool the burn by immersing in cool water or placing the burnt area under a running tap.
- Using a clean bandage, cover the burn.
- Call and wait for emergency healthcare personnel if necessary.

» *Electrocution*

In the event of electrocution, follow these steps:

- Turn off the power source. Do not make contact with the victim until power has been disconnected.
- Do not move a victim unless they are in immediate danger.
- Administer CPR if necessary.
- Treat for shock.
- Call and wait for emergency healthcare personnel if necessary.

» *Shock*

In the event of a shock, follow these steps:

- Ensure the victim lies down on his/her back.
- Ensure that the victim’s breathing passage is not obstructed.
- Ensure that the victim’s body temperature is maintained at 37 °C by placing a cold wet bandage around their wrist.
- Call and wait for emergency healthcare personnel if necessary.

3. COMPONENTS AND ELECTRICAL CONNECTIONS

What this module is about

A photovoltaic system is made up of various components, each with a specific function. For electricians to successfully install these systems they need to understand the importance of these components, their functions within the system and how they are interconnected. This module describes each component and its function.

Learning outcomes

At the end of this module, the participant is able to

- Explain the functions of system components
- Explain the meaning and application of battery state of charge
- Identify and select protective devices

3.1. SOLAR PHOTOVOLTAIC MODULES

Solar PV module is the electricity-generating component of the system, which converts sunlight into electric energy. A PV module is the smallest complete assembly of solar cells, which are connected in series and sealed from environmental degradation.

PV modules are rated in terms of their power output under standard test conditions (STC). However, because PV modules seldom work under STC in the real world, they are also qualified by the nominal operating cell temperature (NOCT).

PV modules commonly range in size from 5 W_P to 300 W_P.

CHARACTERIZATION OF PV MODULES

» Standard test conditions (STC)

PV modules are manufactured across the globe. In order to normalise the performance evaluation of PV modules, manufacturers have agreed on standard testing conditions for modules irrespective of the facility where they are manufactured. The process by which PV modules are tested is called **flash testing**.

Standard test conditions (STC):

- Light exposure with an intensity of 1,000 W/m^2
- Ambient temperature: 25 °C
- Air mass (AM): 1.5

» Nominal operating cell temperature (NOCT)

In real-life situations, PV modules hardly ever operate under STC. Industry practitioners worldwide have therefore adopted the NOTC, which assumes the following set of conditions for PV module operation:

- Light exposure with an intensity of 800 W/m^2
- Ambient temperature: 45 °C
- Air mass (AM): 1.5

- Prevailing wind speed: 1 m/s
- Mounting method: back side of the PV module remains open

TYPES AND TECHNOLOGIES OF PV MODULES

The most common type of commercially available PV module is the crystalline silicon PV module manufactured using either monocrystalline or polycrystalline silicon. Another common type of PV module technology is amorphous silicon, also called thin film. This type of PV module has become increasingly popular because it enables the integration of PV cells and modules into everyday items.

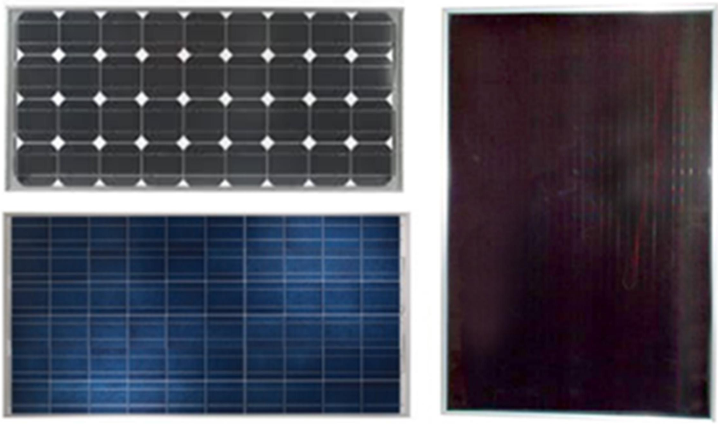


Figure 3.1: Monocrystalline (top left), polycrystalline (bottom left), amorphous (right) solar panel types

Table 3.1: Comparison of different PV module technologies

	Monocrystalline	*Polycrystalline*	*Amorphous*
Cell efficiency	14-20%	15-18%	6-9%
Approximate area required for 1 kW_P	10 m^2	11 m^2	15 m^2

INTERCONNECTION OF PV MODULES

Two or more interconnected PV modules form what is called an array. The power generated by the PV array is theoretically the sum of the power rating of each PV module. For instance, when you have three interconnected PV modules of 100 W_P each, the resultant power output is 300 W_P.

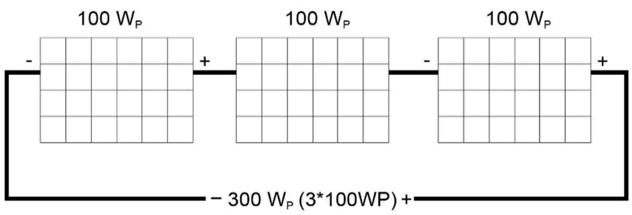


Figure 3.2: Interconnected PV modules

There are three different ways in which PV modules can be interconnected.

- **Series connections** increase the output voltage of the solar PV array. With this connection method, the negative terminal of a PV module is connected to the positive terminal of the next PV module.

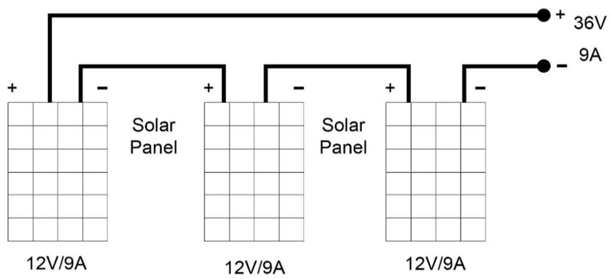


Figure 3.3: Series-connected PV modules

- **Parallel connections** increase the output current of the solar PV array. With this connection method, negative terminals are connected to negative terminals in the PV module and positive terminals to positive terminals.
- **Series-parallel** connections increase both output voltage and current of a solar PV array.

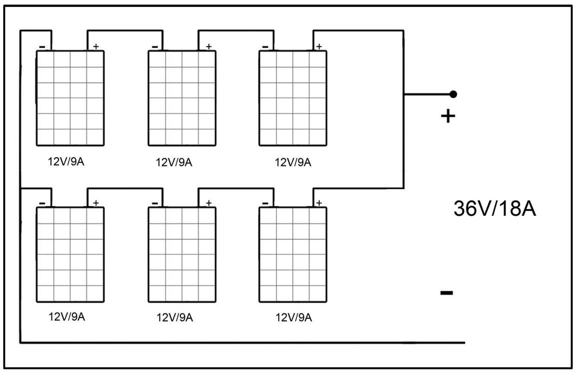


Figure 3.4: PV panels in series-panel connection

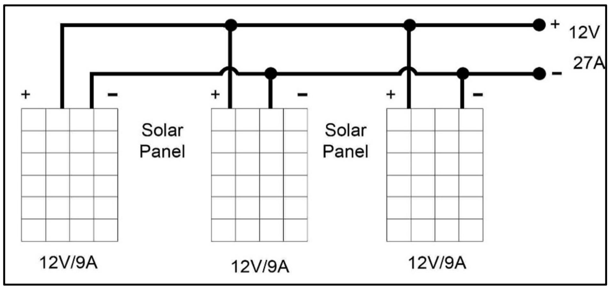


Figure 3.5: PV panels in panel connection

PV MODULE ARRAY CONNECTION AND MISMATCHING

Earlier in this module, it was mentioned that when you connect PV modules, either in series or parallel to form an array, the total output is the sum of the individual power ratings for each solar panel. However, this only applies when modules with identical electrical specifications are connected. If modules with different electrical specifications are interconnected this can result in a big waste of installed PV output power, depending on the degree of mismatch (the difference in electrical specifications) the type of connection and the operation mode (solar radiation, connected load). Interconnected PV modules of different electrical specifications are said to be “**mismatched**”.

» Mismatched series-connected PV modules

When mismatched PV modules with different voltages but the same current are connected in series then the total power is the sum of the individual powers of the modules.

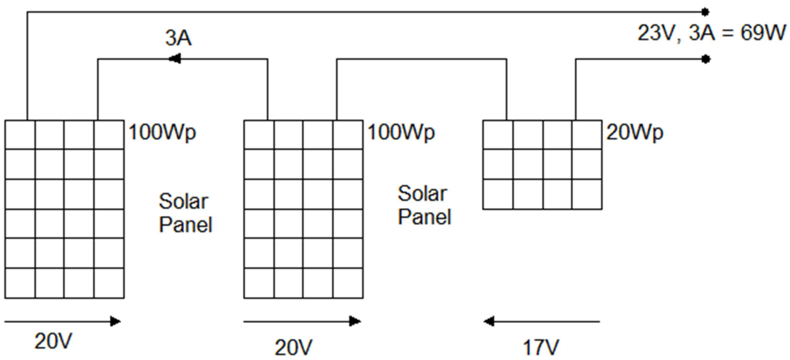


Figure 3.6: Different (mismatched) PV modules connected in series

But when mismatched PV modules with different currents are connected in series then the module with the weaker current acts as a resistor in the circuit. The stronger module(s) generating current, which flows through the circuit. This current is reduced due to the resistance of the weaker module and it creates a voltage drop over the weaker module. This voltage drop has a polarity in the opposite direction, therefore reducing the total voltage of the series connection of all modules. How big the voltage drop will be depends on how big the difference between the modules is and on the strengths of solar radiation. A higher mismatch and a strong current generates a higher voltage drop.

The resulting output voltage of the circuit is the voltage(s) of the stronger module(s) minus the voltage drop created by the weaker module. In our example it is: 2 x 20 V – 17 V = 23 V. As the voltage drop over the weaker module is 17 V opposed to the voltage of the other modules this module consumes 17 V x 3 A = 51 W power form the other modules.

The resulting power is the product of the output voltage and the current of the solar modules, which is much lower than the maximum current of the stronger modules.

In our example it is 34 V x 3 A = 69 W.

In case of a substantial mismatch of electrical specifications the resulting power can be even less than the individual power of the strongest module(s).

If modules are equipped with a so called bypass diode, the effect of power loss across each module is less significant as the opposing voltage drop over the weaker module is limited to the diode voltage of approximately 0.6 V. Also, the current in the circuit will be higher as some current passes through the diode and the total resistance of the circuit will be lower.

» *Mismatched parallel-connected PV modules*

When mismatched PV modules with same voltages are connected in parallel, then the total power is the sum of the individual powers of the modules.

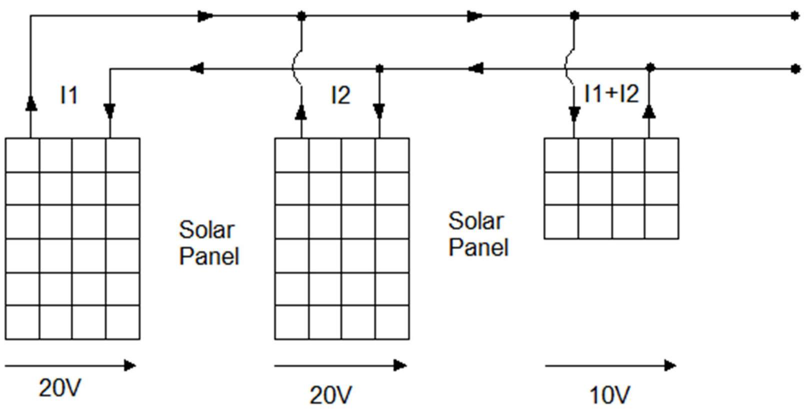


Figure 3.7: Different (mismatched) PV modules connected in parallel

However, when mismatched PV modules with different voltages are connected in parallel, then the module with the lower voltage can act as a load in the circuit. How strong the effect is depends on the consumer load (e.g. charge controller + battery), which is connected to the circuit. If the consumer load voltage is still below the voltage of the weaker module then the current of all modules of the circuit will go to the load. And when the load is disconnected (e.g. when battery is full) then the current of the modules with the higher voltage will flow into the module with the lower voltage. Depending on the difference of the voltage and the strength of the current, this can lead to damage of the module with the lower voltage.

INTERPRETING THE NAMEPLATE

Every PV module comes with an adhesive nameplate attached to the back of the panel that contains vital details for optimum system performance. Figure 3.8 shows the nameplate of a 200 W_P photovoltaic module. The nameplate specifies the module's electrical and mechanical characteristics under STC.

Figure 3.8: A nameplate of a 200 W_P photovoltaic module

Table 3.2: PV module nameplate data

Parameter	***Explanation***
Rated maximum power	Power generated by the solar panel under STC
Output tolerance	Output of the PV module under STC may vary between 200 W and 210 W
Current at Pmax	Maximum current generated under STC
Voltage at Pmax	Maximum voltage across the terminals of the PV module
Short-circuit current	No-load current flowing through the photovoltaic module under STC. This is the current when the voltage across the PV module is zero.
Open-circuit voltage	No-load voltage across the PV module
Nominal operating cell temperature	Cell temperature, which is reached under real-life operation of the solar module.
Weight	Weight of the PV module
Dimension	Length, breadth and width of PV module
Maximum system voltage	Maximum array voltage possible for this type of module
Maximum series fuse rating	Maximum rating of a fuse, which protects a series connection of this type of module
Cell technology	Technology used to manufacture the photovoltaic module

3.2. INVERTERS

An inverter is an electrical device that converts direct current (DC) to alternating current (AC). Inverters have an input side and an output side.

Figure 3.9: Typical 3.5 kVA battery inverter used in Nigeria

CLASSIFICATION OF INVERTERS

Inverters are broadly classified based on two criteria.

» Input voltage

The input voltage is also referred to as the system voltage on the DC side of the inverter. The system voltage is usually graduated in steps of 12 V (12 V, 24 V, 48 V, 60 V, etc.). On the input side, the inverter is connected to the DC input power source, e.g. directly to the battery or solar array. The output side supplies AC power to the consumer, usually 220 to 240 V.

» Output waveform

There are three types of output waveforms found in most inverters:

- **Square wave inverters** are the simplest and most basic. It is useful in only a handful of applications such as lighting. This option makes for the cheapest type of inverter.
- **Pure sine wave inverters** give an output that is very similar to the output waveform from the electrical grid. You must use this type of inverter if there is any sensitive equipment connected to your system. This is the most expensive type of inverter.
- **Modified sine wave inverters** are the mid-point between the square wave and pure sine wave. Most household and small office equipment will run on this type with no problems.

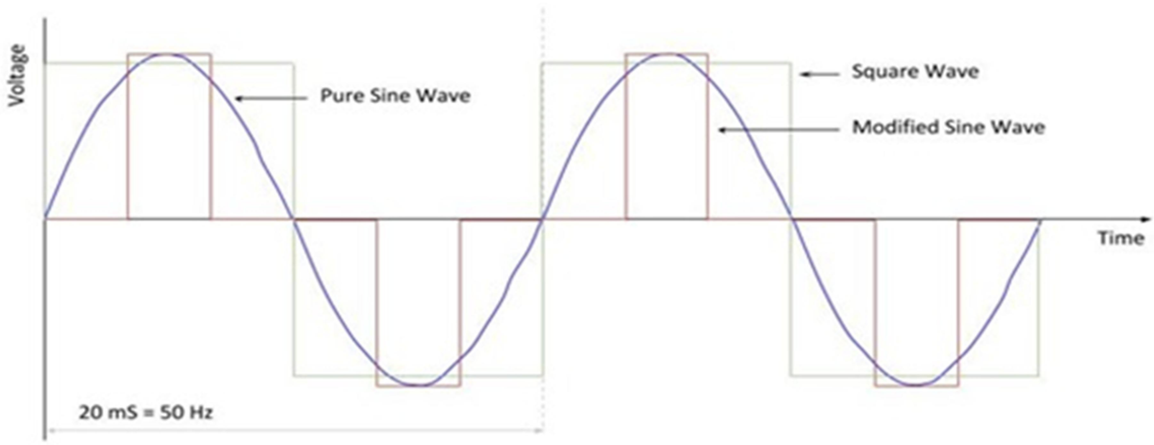


Figure 3.10: Types of waveforms

3.3. BATTERIES

A battery is an electrochemical device, which is used to store energy. In photovoltaic systems they store electrical energy generated by the photovoltaic modules, which can then be used at night when there is no sunlight.

CLASSIFICATION OF BATTERIES

Batteries are classified into:

» ***Primary batteries***

Primary batteries irreversibly transform chemical energy into electrical energy. These batteries cannot be recharged once they go dead.

Figure 3.11: Primary batteries

» ***Secondary batteries***

Secondary batteries transform chemical energy into electrical energy and vice versa, and are easily recharged.

BATTERY TYPES AND TECHNOLOGIES

There are various types of batteries, which can be used with photovoltaic systems for different applications.

» ***Lithium-ion battery***

Lithium-ion batteries are a new technology. They are most often used in high-end electronics such as laptops and mobile phones. However, due to their high cost, they have had limited use in the photovoltaic industry, but have recently started to gain market share.

Table 3.3: Strengths and weaknesses of lithium-ion batteries

Advantages	*Disadvantages*
▪ High energy density ▪ Low self-discharge ▪ High efficiency ▪ High cell voltage	▪ Moderate discharge current ▪ High manufacturing costs ▪ Susceptible to explosion due to mechanical, thermal or chemical stress ▪ Requires built-in protective circuit to keep current and voltage within safe limits ▪ Subject to ageing even when unused

Figure 3.12: Powered by Tesla Inc. – *Courtesy: www.inhabitat.com*

An example of the increasing market share is the electric car company Tesla, which recently launched Powerwall®, a lithium-ion battery designed for photovoltaic back-up service. Powerwall is offered in two variants, 7 kWh and 10 kWh, which retail for NGN 1,000,000 and NGN 1,300,000 respectively[1].

[1]Price as of November 2015

» *Lead-acid battery*

The lead-acid battery is the most commonly available and widely used battery with photovoltaic systems in Nigeria. Lead-acid batteries are classified according to the following criteria:

APPLICATION AND USAGE

There are two types of batteries, starter and deep-cycle. These two differ by the depth of cycling (charging) that they can withstand. A typical use for a starter battery is in a motor vehicle. Starter batteries cannot sustain long periods of deep discharge but are primed to supply very large amounts of current instantaneously. Deep-cycle batteries are used in photovoltaic systems. They support long periods of deep discharge but cannot sustain high currents for long periods.

Figure 3.13: 6 V and 12 V wet cell batteries

TYPE OF ELECTROLYTE

- Flooded lead-acid battery

This type of lead-acid battery consists of a lead anode and lead oxide cathode immersed in a liquid electrolyte, sulphuric acid. The lead-acid battery is the most common battery type available and has been used for decades in various applications.

- Valve-regulated lead-acid (VRLA) or dry-cell battery

Also known as the sealed or dry battery, the VRLA battery operates on the same chemistry as the flooded battery, but the electrolyte is semi-solid in nature. These sealed batteries are constructed to prevent gas development, which means that they do not require topping off with distilled water.

There are two common types of sealed batteries:

Absorbed glass mat (AGM) battery: Electrodes are separated by a mat of glass fibres, which completely absorbs the electrolyte. These are the most common type of sealed battery in the Nigerian market.

Gel battery: Silicic acid is added to the electrolyte of this battery making it a gel. These batteries have a longer life cycle than the AGM battery.

Figure 3.14: Typical 12 dry-cell battery
– Courtesy: www.chargeinverters.com

CHARGE PROCESS

When current is connected to a battery, it drives electrons through it, causing reactions at the poles. The lead sulphate becomes lead oxide at the positive electrode, while lead sulphate becomes lead at the negative electrode. The charging process is defined by the following chemical reaction:

$$PbO_2 + Pb + 2H_2SO_4 \xleftarrow{charge} 2PbSO_4 + 2H_2O + 2\acute{e}$$

DISCHARGE PROCESS

When the battery is connected to a load, lead dioxide (PbO_2) reacts with the sulphuric acid (SO4) ion to produce lead sulphate ($PbSO_2$) and two parts water at the positive plate. Lead reacts with acid to produce lead sulphate at the negative plate. When the discharge reaction occurs, acid is reduced and water is produced, therefore the acid concentration in the cell drops with an increasing discharge. The discharge process is defined by the following chemical reaction:

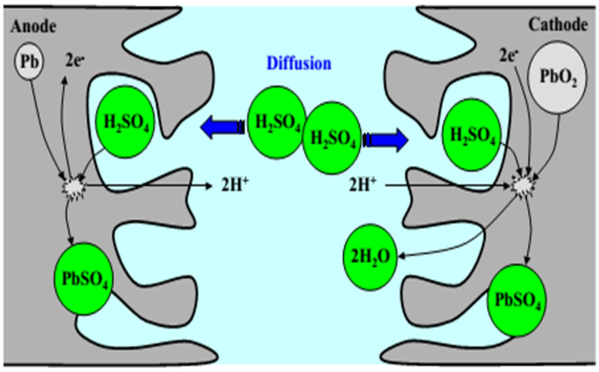


Figure 3.15: Chemical reaction in a lead-acid battery during the discharge process

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{discharge} 2PbSO_4 + 2H_2O + 2é$$

Table 3.4: Strengths and weaknesses of lead-acid batteries

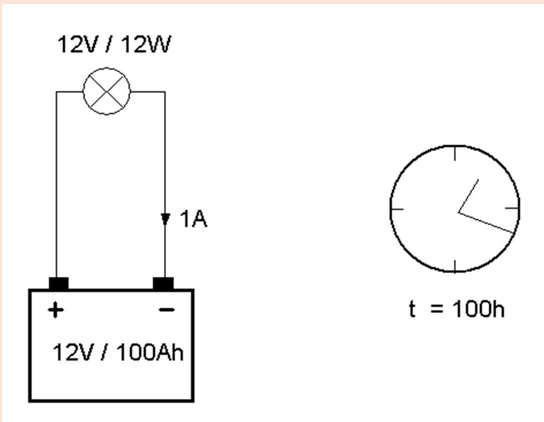
Advantages	*Disadvantages*
▪ Mature and dependable	▪ Heavy
▪ Cost effective	▪ Low cycle and deep discharge stability
▪ Low self-discharge	▪ Cannot be stored in discharged mode
▪ Low maintenance	
▪ Recyclable	

INTERPRETING THE NAMEPLATE

A battery is rated as a device that stores electrical energy, which is measured in watt-hours (Wh). In addition, batteries are rated by their capacities, which are in **ampere-hours (Ah)**. The voltage across a battery is determined by the number of cells it possesses. As seen in Figure 3.16, a lead-acid battery has 6 cells, each of 2 V, which amount to 12 V in total.

Example: A 12 V battery with C = 100 Ah can therefore store 1,200 Wh (12 V × 100 Ah = 1,200 Wh)

As a practical explanation: if a 12 V light bulb of 12 W is connected to the battery in the above statement, it will draw a current of 1 ampere. Starting at a full charge, the battery can supply that current for 100 hours. However, due to inefficiencies within the battery and the inverter during discharging, not all of the energy stored can be used.



Note: Do not confuse the battery's stored energy with its capacity. Energy stored by a battery is a function of the battery capacity. For example, a battery rated at 200 Ah is able to store 2,400 Wh.

BATTERY CYCLE LIFE

Figure 3.16: 12 V sealed gel battery
– Courtesy: www.safe-start.com

Battery life is expressed in cycle life, meaning a battery can be used for a certain number of cycles or charges. After that it gets weak and loses its capacity (i.e. ability to store energy). For example, a 12 V/100 Ah battery, which has been used for many cycles may have a remaining capacity of only 50 Ah. It has essentially become a "smaller" battery.

Even when a battery is just stored and not used, the useful lifespan is still "consumed". This is called the **float life or shelf life**. The float life depends very much on the temperature at which the battery is stored and on its state of charge. A good quality gel battery can be stored up to 10 years at 20 °C but only 6 years at 30 °C. During storage, the state of charge (SoC) must always be kept at 100%. This requires regular recharging every three to four months or a constant 'trickle charge'.

The number of life cycles remaining in a battery depends on:

- Discharge frequency: Frequent discharging reduces the number of available cycles, making the battery smaller.
- Depth of discharge (DoD): Deep discharging causes the formation of crystals at the electrode, which reduces the area available for chemical reactions in the battery.
- State of charge (SoC): The battery's charge state should be maintained at 100% whenever possible.
- Storage and operation temperature: Batteries have specific operating temperatures for optimum performance. Always follow these recommendations. For example, a lead-acid battery loses some of its capacity at lower temperatures, with the reverse being the case at higher temperatures. However, increasing battery temperature does not guarantee increased battery capacity and will instead damage your battery.

Note

- The process of discharging and recharging a battery is called a cycle.
- In solar PV systems, a cycle is usually one day, as the battery gets discharged at night and recharged during the day.
- Discharging only 10% of the capacity (DoD = 10%) is a shallow cycle. Discharging 100% of the capacity (DoD = 100%) is a deep cycle.
- Deep cycles are more harmful and shorten the battery life more than shallow cycles.

INTERCONNECTION OF BATTERIES

When batteries are interconnected to form a bank, the total voltage and capacity of the battery bank is dependent on whether batteries are connected in series, parallel or both. There are three interconnection methods for batteries:

- **Series connections** increase the output voltage of the battery. The negative terminal of a battery is connected to the positive terminal of the next battery.
- **Parallel connections** increase the output capacity of the battery bank. All negative battery terminals are connected to negative terminals and positive terminals alike.

- **Series/parallel connections** increase both output voltage and battery bank capacity.

» *Series connection*

For example, if you have four batteries that are rated at 200 Ah/12 V and they are connected in series combinations, the total output power from the battery bank will be 200 Ah/48 V.

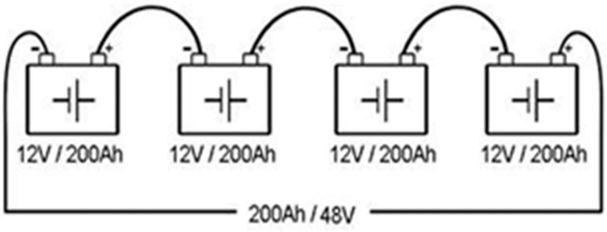


Figure 3.17: Batteries connected in series

» *Parallel connection*

For example, if you have four batteries that are rated at 200 Ah/12 V and they are connected in parallel combinations, the total output power from the battery bank will be 800 Ah/12 V.

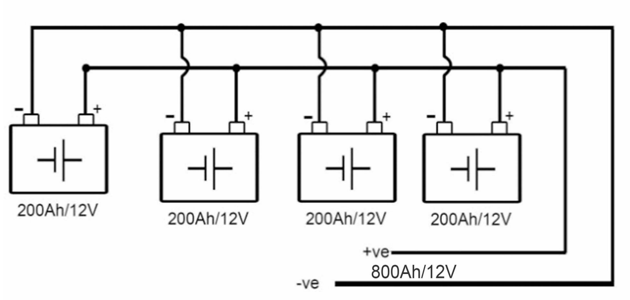


Figure 3.18: Batteries of the same size connected in parallel

» *Series/parallel connection*

These connections are made when you have to create a large battery bank where the required capacity and voltage are not attainable using one string of either series or parallel connections.

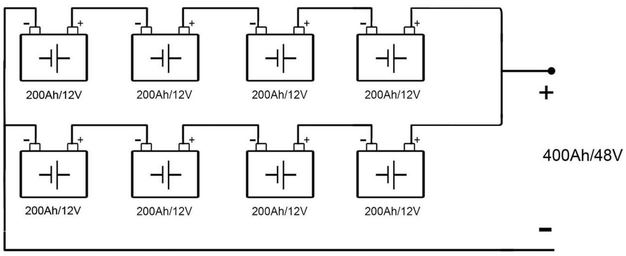


Figure 3.19: Series/parallel connection of batteries

MISMATCHED BATTERIES IN A BANK

Various types of mismatching can occur. Four possible cases are discussed below.

Case 1*: In series connections – batteries with same voltage but different capacities*

For example, in a battery bank of four batteries, one battery is rated 150 Ah/12 V and the other three are rated 200 Ah/12 V The output voltage from the battery bank is 48 V, but the output capacity is controlled by the battery with the lowest capacity rating, in this case, the 150 Ah/12 V battery. The battery bank will have a capacity of 150 Ah and 48 V. You should never connect a battery bank in this manner because the battery with the smaller rating would reduce the useful storage capacity of the three larger batteries.

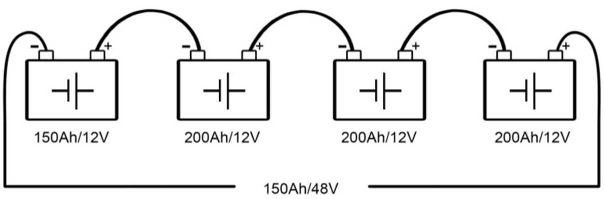


Figure 3.20: Batteries of different sizes connected in series

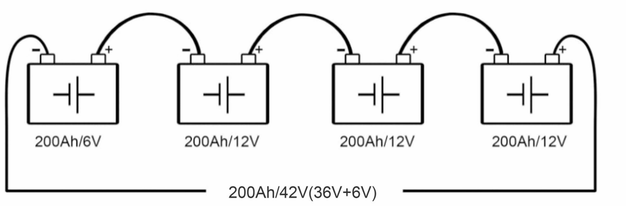


Figure 3.21: Batteries of different voltages connected in series

Case 2: *In series connections – batteries with same capacities but different voltages*

For example, a battery bank of four batteries where one is rated 200 Ah/ 6 V and the other three are rated 200 Ah/ 12 V, all connected in series. The total voltage of the battery bank becomes 42 V (36 V + 6 V), but the capacity remains 200 Ah.

Case 3: *In parallel connections – batteries with same voltage but different capacities*

For example, a battery bank of four batteries where one is rated 150 Ah/12 V and the other three are rated 200 Ah/ 12 V, all connected in parallel. The output voltage from the battery bank is 12 V while the output capacity is

150 Ah + 200 Ah + 200 Ah + 200 Ah = 750 Ah.

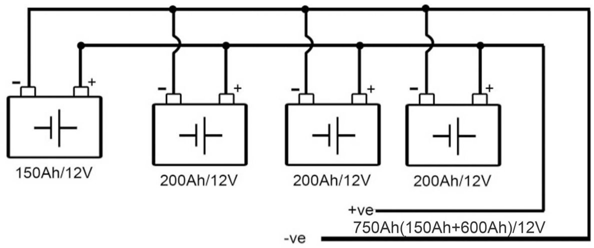


Figure 3.22: Batteries of different sizes connected in parallel

Case 4: *In parallel connections – batteries with same capacities but different voltages*

For example, a battery bank of four batteries where one is rated 150 Ah/6 V and the other three are rated 200 Ah/12 V, all connected in parallel. The output voltage from the battery bank is 6 V (12 V − 6 V) while the output capacity is 350 Ah (150 Ah + 200 Ah).

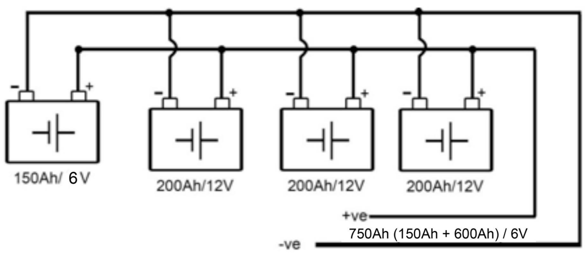


Figure 3.23: Batteries of different voltages connected in parallel

Connecting 6 V to 12 V in parallel will result in heavy discharge of the 12 V battery into the 6 V battery, causing short-circuit currents that destroy the 12 V battery.

The 6 V battery will receive a heavy charging and rise to a voltage much higher than 6 V, also causing destruction. This is a dangerous and potentially explosive situation.

Note

In series connections, mismatched batteries result in:

- Faster and deeper discharging of smaller (or older) batteries as well as faster failure.
- Faster charging and overcharging of smaller (or older) batteries as well as faster failure.
- Consistently incomplete charging of bigger (or newer) batteries, as the smaller battery is the signal for the charge controller to stop the charging process. Battery lifetime will be shortened as well.

In parallel connections, mismatched batteries result in:

- Faster and deeper discharging of smaller (or older) batteries discharge as well as faster failure.
- Batteries with higher voltage will discharge into the ones with lower voltage; energy is wasted or the battery damaged.
- An old battery has lost its capacity. It has become a “smaller” battery. An old 200 Ah battery connected in series with new 200 Ah batteries will affect the system as described above

CHARGE AND DISCHARGE LEVELS

The battery state of charge (SoC) is a parameter used to indicate a battery's charge level. It is a ratio between the amount of charge still held by the battery and the rated capacity. The SoC is represented as a percentage. Conversely, the depth of discharge (DoD) describes how much of the battery has been discharged by use. Like the SoC, the DoD is represented as a percentage.

Hence, you can say that a fully charged battery has 100% SoC, while an empty battery has 0% SoC.

As a practical example: A 12 V light bulb of 12 W is connected to a battery that will draw a current of 1 ampere. If it runs for 10 hours, it discharges 10 Ah from the battery. If you have a 100 Ah battery, this is 10% of the battery capacity; the DoD is said to be 10%. If the same lamp runs for 50 hours on a 200 Ah battery, the DoD will be 50%.

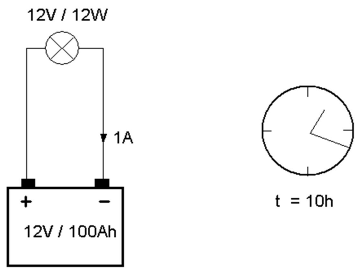


Figure 3.24: DoD of 10% from a 100 Ah battery

3.4. CHARGE CONTROLLERS

In a solar PV system, a charge controller is a device that regulates the state of charge of a battery bank. The charge controller performs the following functions:

- To charge the batteries safely, quickly and completely.
- To protect the batteries from deep discharge, if the charge controller has a load controller function included.
- To protects the battery from overcharging.
- To prevent reverse current from the battery to the solar panels.
- To prevent unwanted discharge of the battery banks.

TYPES OF CHARGE CONTROLLERS

Charge controllers are classified based on their voltage and ampere rating. Commercially available charge controllers come in two common types:

Figure 3.25: Victron 12 V, 10 A PWM charge controller

» Pulse-width modulator

The pulse-width modulation (PWM) charge controller is the most common type. These charge controllers operate using basic ON/OFF switching to regulate the charging voltage.

Figure 3.26: Victron 12 V/24 V/ 20 A MPPT charge controller

» Maximum power point tracking (MPPT)

Also referred to as maximum power point trackers, these charge controllers are mostly used in systems larger than 1 kWP. MPPT regulation is performed by scanning and locating the characteristic I-V curve of the photovoltaic array and determining the **maximum power point**. The MPPT charge controller is more expensive than a PWM charge controller but it generally increases the energy output from the PV modules by up to 30%.

3.5. PROTECTIVE MEASURES

It is important that you select and install the appropriate kind of overcurrent protective device. Failure to do so could result in damage to the photovoltaic system equipment, system failure, bodily injury or even death. Overcurrent protective devices (OPCD) in photovoltaic systems operate differently from conventional electric power generation systems due to the fact that the OCPDs are expected to operate effectively on very low levels of fault current.

Other effects of fault currents in photovoltaic systems include fire as a result of electric arcs and broken cables, reduced efficiency, and financial loss arising from the cost of replacing damaged equipment.

Typically, fault currents in photovoltaic systems can originate from any of the following sources:

- Photovoltaic modules or strings of modules that are connected in parallel to the faulted string
- Storage batteries in the system
- Backfeeding through grid-interactive inverters.

OVERCURRENT PROTECTION DEVICE (OCPD)

There are a variety of OCPDs used in photovoltaic systems.

» AC switch disconnect

AC switch disconnect which must be double-pole and lockable in the "OFF" position. This device usually separates the load from the inverter output.

Figure 3.27: AC switch disconnect

» Miniature circuit breakers (MCB)

Miniature circuit breakers (MCB) are devices that act like a fuse but have the ability to be switched back on after they are triggered. Circuit breakers on the AC side are different than the ones used on the DC side. Disconnecting a DC load results in a much longer-lasting arc, which is more destructive to the breaker. Therefore, AC circuit breakers cannot be used on the DC side.

Figure 3.28: Double pole MCB

» Fuses

Fuses are the most common form of OPCD. In photovoltaic systems, DC fuses protect wires connected to the battery. In large PV arrays with more than three solar module strings, they are sometimes used to protect the modules and wiring from fault currents, which can occur under certain conditions. The rating should be based on the maximum current, which the string generates.

Figure 3.29: 100 A DC fuse for battery connection

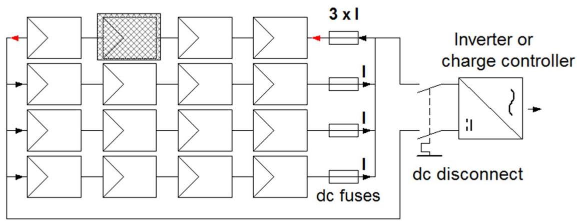


Figure 3.30: Array protected with string fuses and main disconnect

- Battery fuse. A short circuit of the two poles of a battery releases a very high current, the larger the capacity the higher the current. On a big battery, this can easily melt the connected wires and start a fire. Therefore, the battery or battery bank should be protected with a suitable DC fuse. AC fuses cannot be used as they cannot handle a DC spark. For smaller batteries and smaller DC load-currents, automotive fuses can be used; larger currents and battery banks require DC fuses with higher ampere and voltage ratings.

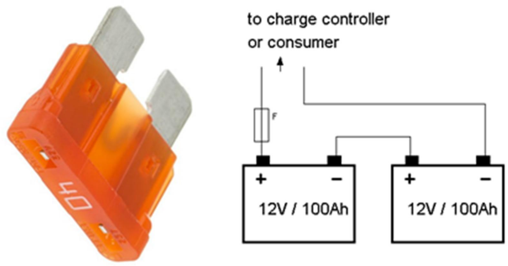


Figure 3.31: 40 A automotive battery fuse for smaller DC loads (left). Diagram showing fuse location (right)

OTHER EQUIPMENT USED WITH OPCD

» Surge protection devices (SPDs)

An SPD is a device which, under normal operating conditions, isolates two connected potentials (e.g. PV+ and PV−) from each other. If a certain voltage is exceeded (e.g. due to a lightning-induced surge), the SPD is triggered and a short-circuit created, thus bringing the potential to zero. This short-circuit, remains as long as the surge persists (e.g. a few microseconds for a lightning strike).

The DC input of charge controllers or inverters is very sensitive to overvoltage. Lightning-induced surges can destroy the device immediately. However, a short circuit of some microseconds is not dangerous for the DC input of a charge controller or inverter and also releases only minimal energy from the battery. For DC equipment, make sure you select and use a DC SPD with the matching voltage to the equipment.

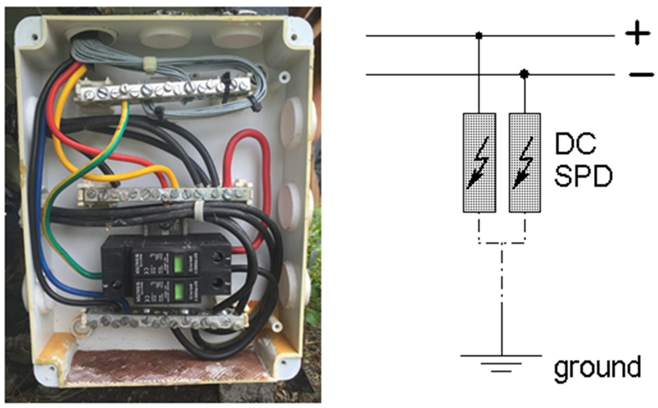


Figure 3.32: PV surge arrestor max 500 V/DC in combiner box (left) and wiring of SPD (right)

The AC output of an inverter is also sensitive to voltage surges that can occur, for example, due to inductive load switching (motors) or lightning-induced surges. Many PV inverters have built-in SPDs, while battery inverters are usually not equipped with SPDs. Some additional equipment/features that are used to protect electrical systems:

- Insulation: All active parts or bodies such as conductors and connectors must be covered with an insulating material, which can withstand several times the nominal operating voltage and which can only be removed by destroying it.
- Enclosures: Enclosures for parts such as switches or sockets must be properly secured. Removal should only be possible with the use of tools. Their protection class must match their application (system voltage, installation environment).
- Spacing: Distribution lines must be installed in a way that people cannot touch them under normal conditions.

The table below explains the ingress protection (IP) rating system published by the International Electrotechnical Commission (IEC).

Table 3.5: Explanation of the ingress protection (IP) rating system

Level	*Protection against solids*	*Protection against liquids*
0	No special protection	No protection
1	Protected from entry by large body parts such as hands (but no protection from deliberate access),as well as solid objects with diameters >50 mm	Protected against condensation
2	Protected from entry by fingers or other objects≤ 80mm in length and 12 mm in diameter	Protected against water droplets deflected up to 15° from vertical
3	Protected from entry by tools, wires, etc., with a diameter ≥ 2.5 mm	Protected against spray up to 60° from vertical
4	Protected against solid bodies > 1 mm (e.g. fine tools, small objects, insects, etc.).	Protected against water spray from all directions
5	Protected against dust that may harm equipment	Protected against low-pressure water jets (all directions)
6	Totally dust-tight	Protected against string water jets and waves
7	*Level 7 does not exist for solids*	Protected against temporary immersion
		Protected against prolonged effects of immersion under pressure

RESIDUAL CURRENT DEVICES (RCD)

Residual current devices (RCD) are devices that monitor current differences between the energised line conductor and the neutral return conductor. If there is an imbalance which exceeds a certain value (mostly 30 mA in domestic use), the RCD disconnects the circuit. Such an imbalance can occur, for example, if a person gets an electric shock due to faulty equipment where the current flows through the body to earth instead of back through the neutral conductor.

Figure 3.33: 80 mA residual current device

LIGHTNING PROTECTION SYSTEM (LPS)

Risk of lightning strikes

Nigeria is located in the tropical belt around the equator, an area with the highest risk of lightning strikes on earth. In Nigeria, each square kilometre is hit by 10 to 50 lightning strikes every year. Buildings with exposed surroundings are far more likely to be hit by lightning than relatively sheltered buildings.

The necessity of lightning protection for the PV system depends on the risk of lightning strikes and the value of the system. A solar home system in an area with a low risk for lightning strikes and a value of no more than NGN 200,000 will not need a NGN 100,000 LPS. Sometimes certain types of buildings require LPS due to their function and due to legal regulations (e.g. public buildings, certain types of industry). If lightning protection is required for a building, the solar PV system must be integrated into the LPS. However, a solar PV system does not increase the risk of lightning striking a building as long as its installation does not change the building's shape significantly.

Note: Damage due to nearby lightning strikes is far more common than damage due to direct lightning strikes. Nevertheless, the damage caused by direct lightning strikes is often significantly more devastating.

» *External lightning protection*

During direct lighting strikes, the function of external lightning protection is to prevent risk to life as well as physical damage to a structure due to lightning current and sparks.

An LPS for external lightning protection consists of:

- Air-termination rod (lightning rod or arrestor)
- Down conductor
- Ground termination system (earth or ground rod)

The LPS for external lightning protection has to lead a lightning strike safely to the ground without causing damage due to heat or sparking.

» *Internal lightning protection*

The function of internal lightning protection is to prevent risk to life and damage of electrical and electronic systems caused by lightning-induced voltages of nearby lightning strikes. An LPS for internal lightning protection consists of:

- Equipotential bonding of all metal housings and structures
- Equipotential bonding of conductors by surge protection devices (SPD)
- Shielding of equipment and conductors against electromagnetic induction
- Appropriate installation site for equipment in order to reduce electromagnetic induction and to prevent flashover from sparks.

» *Measures to protect against lightning-induced surge voltages*

Primary measures against surge voltages are shielding, grounding, equipotential bonding, laying conductors as short as possible and avoiding loops.

Note: Complete equipotential bonding requires the inclusion of all active conductors such as power supply and data lines via surge protection devices.

GROUNDING

There are two ways to ground solar systems:

- **Equipment grounding** means connecting all metal bodies of the equipment to the ground electrode. These include solar panel frames, inverter and charge controller housings, metal junction boxes as well as potential earth conductors on the AC side of the installation. When grounded properly, in the event of lightning strike the induced high voltages on all metal parts of the system are on the same voltage and zero potential to earth. No current flow is possible, which can injure people and damage equipment.

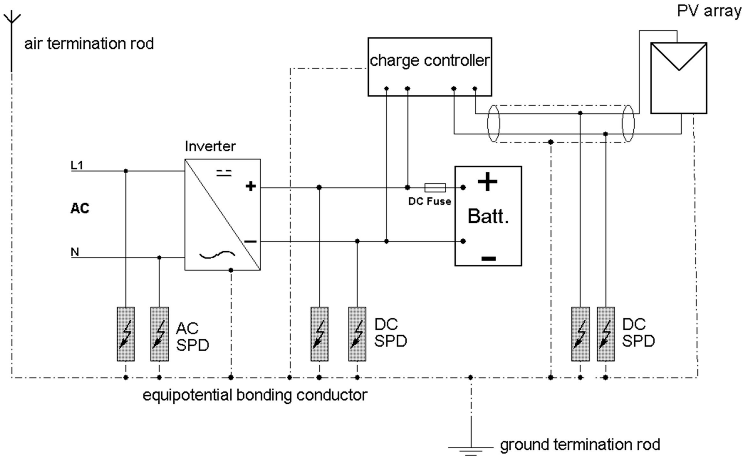


Figure 3.34: External and internal LPS with equipotential bonding of all metal equipment housings, shielded and grounded cable from array to charge controller and AC and DC surge protective devices (surge arrestors)

- **System grounding** of a solar system means connecting either the positive or the negative wire of the battery to ground. System grounding is necessary when manufacturers demand it for the proper function of their equipment. Certain types of PV modules must be negatively grounded, otherwise they lose power output due to the accumulation of electrostatic charge. Also, some protective devices such as DC RCDs will not function without system grounding.

> *Note:* Grounding one of the DC poles increases risk of electric shock during installation and maintenance work on the solar system, as the installer will get an electric shock when touching the opposite pole.

Figure 3.35: Equipotential bonding of module frames

Figure 3.36: Laying a ground electrode through a solid copper band

Figure 3.37: DC surge arrestors

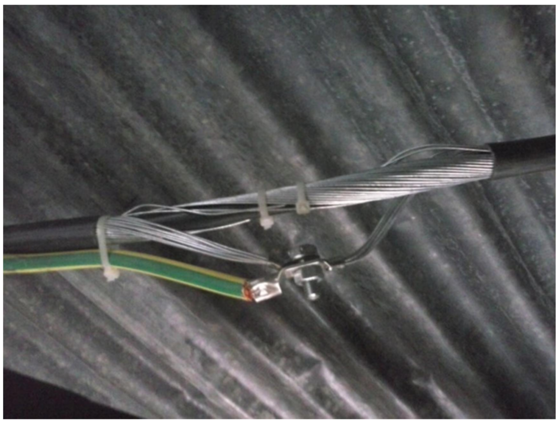


Figure 3.38: Ground connection on cable shield

» *When to ground solar photovoltaic systems*

In locations where the PV array is exposed and could be susceptible to lightning strikes the array should be grounded by connecting the negative terminal to ground. Even for smaller systems such as our example, a bare copper cable of minimum size 10 mm² should be used to connect the metal frame of the PV array to a grounding electrode. If the solar panel array is installed on a roof of a building with an existing lightning arrester, it is usually not required to ground the metal frame of the solar panel array. Otherwise, grounding the metal frame of the solar panel array is necessary.

Figure 3.39: Grounded solar array

4. BASIC SYSTEM SIZING

What this module is about

In order to successfully install a solar photovoltaic system, the system design and selection of components should be in line with best practices. This module teaches students the knowledge required for effective system sizing.

Learning outcomes

At the end of this module, the participant is able to

- Distinguish between DC and AC loads
- Select appropriate components for a solar photovoltaic system

4.1. ELECTRICAL LOADS

In solar powered systems, it is recommended that the energy consumption be kept as low as possible. Investing in extra-low power consuming equipment will significantly reduce the long-term operating cost of the solar system.

Electric loads can be categorised into DC loads and AC loads.

» DC loads

The advantage of DC loads is that no inverter is needed. This increases the efficiency of energy consumption, as DC to AC conversion loss is eliminated. Eliminating the inverter also means less equipment to buy and less potential for failure. The disadvantage is that the availability of DC equipment is limited and DC equipment is often more expensive than standard AC equipment. In addition, most DC equipment is only available for 12 V, although a few products are also available for 24 V.

Figure 4.1: Typical DC solar freezer (left), DC LED lamp (right)

In DC systems, the cable lengths and cross section diameters are critical because low-voltage loads have higher currents and the impact of voltage loss on the cable is higher.

Typical DC loads are energy-saving lamps (CFL), LED lamps, solar fridges and TVs, which often can be used for 12 V DC and 230 V AC. Automotive suppliers offer phone and laptop chargers that use a 12 V battery.

» AC loads

AC loads provide the advantage of AC equipment being commonly available in a wide range of products. Because it is often mass-produced, AC equipment generally costs less than their DC counterparts.

AC equipment can be powered via long cables without a critical voltage drop.

Figure 4.2: AC-powered television (left), energy-saving lamp (right)

The disadvantage of AC loads is that they require an inverter. This decreases the efficiency of energy consumption, because the DC to AC conversion involves an energy loss. The extra piece of equipment also makes the system more costly and less reliable; if the inverter fails, the system is paralysed. Typical AC loads are energy-saving lamps (CFL), LED lamps, fridges, TVs, computers and common household devices.

It is possible to run a combined DC and AC system, where for example some lamps run directly on 12 V and the TV runs on the inverter, which is only switched on when someone uses the TV.

Figure 4.3: AC water pump (inductive load)

4.2. DEVELOPING A LOAD PROFILE

When designing a power supply of any kind, you need to investigate the loads to be supplied. The power supply must be able to provide enough power for the peak load under any conditions and for the required period of time.

» Peak power

This is the sum of the power consumption of all devices that will be operating simultaneously. High surges like the startup power of an induction motor in a fridge have to be considered, as well as the power factor for certain devices. A poor power factor results in higher demands than the real power in watt, which is usually indicated on the device label.

> ***Note:*** Power factor refers to the relationship between real power consumed by the load and the apparent power in the circuit. It is usually expressed as a ratio between 0 and 1. For example, a CLF light bulb could have a power factor of 0.65.

Example: A house is equipped with 11 CFL light bulbs of 14 W (AC), as well as 1 fridge with a compressor motor rated at 100 W (AC).

The CFL light bulbs have a power factor of 0.65; the single phase induction motor of the fridge has a power factor of 0.6.

The total apparent power which has to be generated for the light bulbs is (11 × 14 W)/0.65 = 237 VA.

The total apparent power which has to be generated for the fridge is 100 W/0.6 = 167 VA.

The surge power of the fridge is 167 VA × 7 = 1,167 VA for 0.5 seconds.

The power supply must be able to provide a continuous power of 237 VA + 167 VA = 404 VA.

The power supply must also be able to provide a short-term supply of 237 VA + 1,167 VA = 1,404 VA for 0.5 seconds.

» *Total energy demand*

This is the cumulative sum of energy required by a load over a given period, typically a day. It is calculated by multiplying the continuous power requirement of each load with the number of hours of operation. Standby power consumption must also be considered for devices. It is measured in watt hours (Wh) or VAh when referring to power consumption or power generation, respectively.

Example: In a house, 4 CFL light bulbs operate for 12 hours per day and the other 7 light bulbs for 4 hours per day. The fridge is a modern appliance, with energy class A+ and a compressor runtime of 30%.

The daily efficient energy consumption for the bulbs is 4 × 14 W × 12 h = 672 Wh + 7 × 14 W × 4 h = 392 Wh, for a total of 1,064 Wh.

The daily efficient energy consumption for the fridge is 100 W × (24 h × 30%) = 720 Wh

The total daily efficient energy consumption, which is charged on the electricity bill is 1,064 Wh + 720 Wh = 1,784 Wh.

The daily apparent energy consumption for the bulbs is 1,064 Wh/0.65 = 1,637 Wh.

The daily apparent energy consumption for the fridge is 720 Wh/0.60 = 1,200 Wh.

The total daily apparent energy, which has to be supplied by the solar modules is 2,837 Wh.

» *Power supplied by inverters*

If the electric power is supplied by an inverter, the power conversion from DC to AC is subject to an energy loss. Quality inverters have an efficiency of more than 90%, depending on the operation mode.

Example: An inverter must supply a daily apparent energy of 2,837 Wh with an efficiency of 90%. The total daily energy demand, including energy losses from the inverter, is 2,837 Wh/90% = 3,152 Wh.

4.3. LOAD PROFILE

The load profile is the relationship between energy use and time. In a solar PV system, the load profile requires particular attention in reference to power generation, because power is generated by a renewable energy power supply. This supply is limited in its daily generation capacity and its daily power generation.

time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	power consumption in KVA																								daily energy consumption	
mainlodge																		0,8	0,8	0,8	0,8	0,8			4	KVAh
cottages																		1	1	1	1,2	1,2	1	0,5	6,9	KVAh
tank pump										1,5	1,5	1,5	1,5	1,5											7,5	KVAh
pool pump											1,2	1,2													2,4	KVAh
tools									0,5	0,5	0,5														1,5	KVAh
security light	0,6	0,6	0,6	0,6	0,6	0,6													0,6	0,6	0,6	0,6	0,6	0,6	7,2	KVAh
sec. cameras	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	4,8	KVAh
kitchen tools							0,4	0,4	0,4							0,4	0,4	0,4							2,4	KVAh
office								0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5									4,5	KVAh
peak power	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,6**	**1,1**	**1,6**	**2,7**	**3,9**	**3,4**	**2,2**	**2,2**	**0,7**	**1,1**	**0,6**	**2,4**	**2,6**	**2,6**	**2,8**	**2,8**	**1,8**	**1,3**	**41,2**	**KVAh**

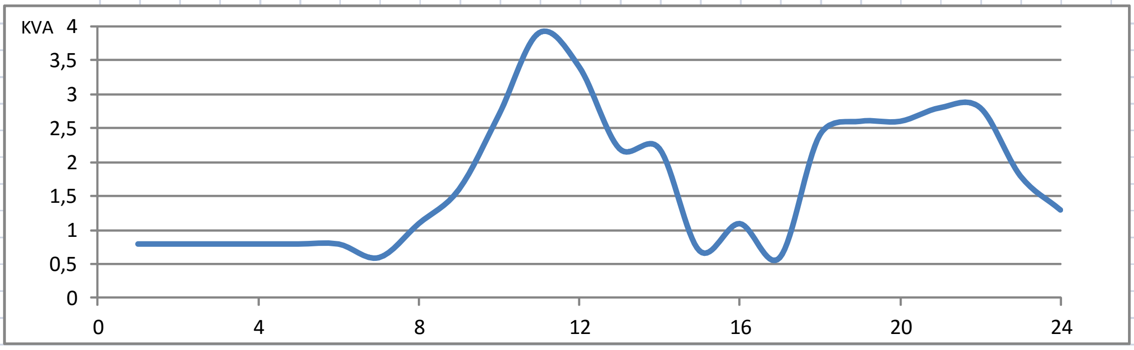


Figure 4.4: Load profile of a label

time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	solar power generation in KW																								daily energy generation	
peak power	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**1,0**	**2,0**	**3,0**	**4,5**	**4,9**	**4,9**	**4,5**	**4,0**	**3,0**	**2,0**	**1,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**34,8**	**KWh**

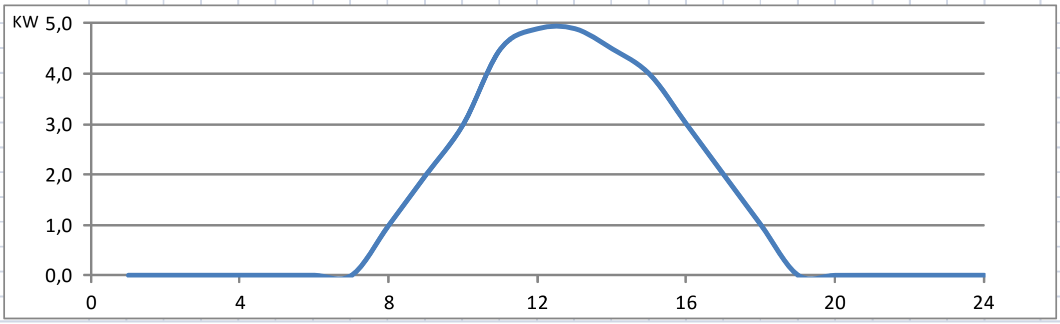


Figure 4.5: Daily energy-generation profile of a 5 kWp solar generator

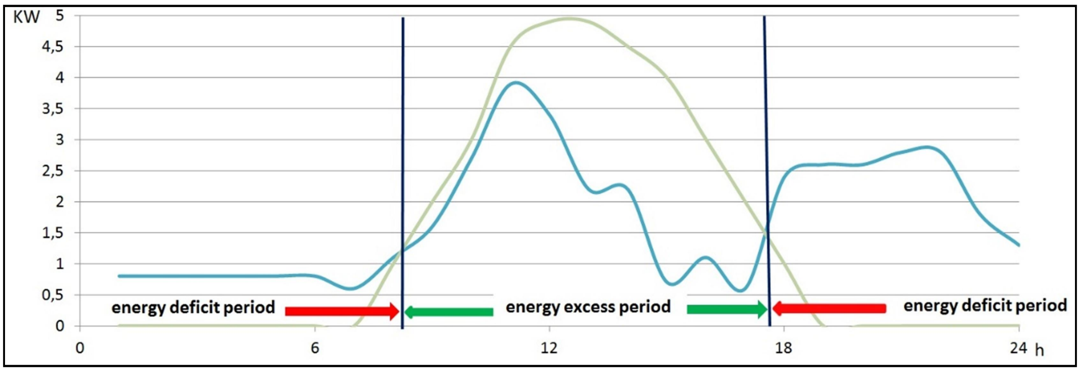


Figure 4.6: Comparison of the load and generation profiles

4.4. LOAD OPTIMIZATION

Load optimisation means using the provided power source in the most efficient way. This can be either done by:

- Reducing electric consumption by eliminating unnecessary loads or replacing electric appliances with more efficient ones. For example, disconnecting electronic devices from the socket to avoid standby consumption or replacing an old fridge with a modern A++ rated appliance.
- Timing electricity consumption to distribute and lower peak loads, which might overload the generator or switching loads at peak hours of electric energy generation. In a solar PV system, for example, this could include switching on a water pump to refill a storage tank at noon when the sun is strongest.

4.5. OFF-GRID SYSTEM SIZING

Important criteria to consider when designing and selecting components for a standalone system include:

- *Lowest life cycle cost:* This is the cost of the system over its lifetime (initial investment, maintenance and replacement costs), which can be up to three times the initial investment cost. Battery life extensions will have a strong impact on reducing this cost.
- *Tolerance of load and insolation variations:* Seasonal climatic variations are key factors as they will determine how much electricity can be generated in the rainy season versus sunny months.
- *Modularity and flexibility:* The system's flexibility and adaptability to various future expansions should be determined. Important questions include: How flexible is the system? Can it be expanded if the loads are increased?
- *Ease of maintenance and repair:* It is important to be able to assess maintenance requirements for selected system components. Are spare components and parts readily available in your region? Is the technology easy to maintain by the consumer?
- *Quality of power supply:* The type of loads to be powered determine the type of inverter (square/modified/pure sine wave) used. For instance, a laser printer will not function if connected to a square wave inverter.
- *Reliability:* The expected system reliability should be considered. A system used to power an entire household or a small business should be 100% reliable.

» Role of the inverter

The inverter is a power device that converts DC to AC for use with conventional appliances. It is important to define what role the inverter plays in the operation of the system.

» Role of the battery

The battery is the primary energy storage device in a standalone system. It has the two main functions:

- Storing energy generated by the solar generator
- Releasing stored energy to the inverter or directly to DC loads when needed

» *Role of the charge controller*

- Regulating the charging and discharging of a battery
- Preventing overcharging
- Preventing deep discharge by disconnecting the load whenever the battery is empty
- Indicating state of charge
- Determining battery maintenance schedule and measures

» *Decision-making algorithm*

When choosing equipment to meet your power requirements, you will need to determine the following:

- Loads to be powered, whether AC, DC or mixed.
- Minimum battery capacity, which is determined by the load requirements. The battery bank stores enough energy to provide power at night and through days with little sun, and will determine your number of days of autonomy.
- Number and type of PV modules required to capture enough solar energy to power the loads and charge the batteries.
- Characteristics of all other components (regulator, wiring, etc.) needed to support the power generated and stored.

Three main steps must be followed to calculate the proper size of a PV system:

» *Estimate the required electrical energy (demand)*

Record the power consumption characteristics of the equipment as well as estimated usage time (i.e. develop a load profile). Then calculate the electrical energy required on a monthly basis. You should consider the expected fluctuations of usage due to the variations between winter and summer, rainy/dry seasons, school/vacation periods, etc. The result will be 12 energy demand values, one for each month of the year.

The calculated power consumption must include the efficiency of the inverter if DC/AC conversion is a factor.

» *Determine the available solar energy (offer)*

Use statistical data for solar irradiation, which are available from meteorological institutes or websites and include the orientation and optimal inclination for PV modules, to determine the available solar energy. Solar energy data is usually stated in monthly intervals, reducing the statistical data to 12 values. This estimation is a good compromise between precision and simplicity.

» *Combine the energy demand and energy offer (result)*

The so-called **worst month** is the month with the least favourable relationship between energy demand and available solar energy. To determine that relationship, divide the energy demand by the available solar energy (peak sun hours). The worst month is the month with the highest result. Solar energy data and energy demand data from that month are used to size the PV system.

For the table below, the solar irradiation data for the site of "Kainji dam" was used.

Table 4.1: Kainji dam solar irradiation data

	jan	feb	mrz	apr	mai	jun	jul	aug	sep	okt	nov	dez	
solar energy	5,73	6,02	6,27	6,13	5,75	5,17	4,65	4,38	4,83	5,39	5,73	5,74	KWh/m²/day
energy demand	11	12	12	12	11	9	9	8,5	9	10	11	11	KWh/day
	1,92	1,99	1,91	1,96	1,91	1,74	1,94	1,94	1,86	1,86	1,92	1,92	
		data used											

February is the month with the least favourable relationship between available solar energy and energy consumption: 6.02 peak sun hours have to cover an energy demand of 12 kWh/day.

Using solar energy data and energy demand data for this month we can calculate:

- Required energy storage capacity of the battery bank
- Energy generation capacity of the solar array and the size, number and type of PV modules
- Required electrical characteristics of the regulator
- Cable length and sections required for electrical connections

SIZING THE BATTERY BANK

The system voltage is determined by the battery bank, which needs to provide enough capacity to supply the energy demand when there is not enough solar radiation. The energy demand is the amount of energy discharged from the battery and provided to the DC loads or converted to AC via an inverter. It includes the DC/AC conversion losses (inverter efficiency).

To estimate the required battery capacity, we need to know the load demand on the solar system in the worst month as well as the desired days of autonomy. When sizing a battery bank in Nigeria, the following should be taken into consideration:

- Batteries should not be discharged by more than 30% of their rated capacity each day (DoD = 30%).
- Total number of days of autonomy should be at least one and can increase depending on the application and required reliability.
- Energy demand should be chosen from the "worst month" according to the definition above.

The total energy required to be stored in the battery bank can be calculated using:

$$E_{battery} = \frac{E_{load} T_{aut}}{DOD}$$

Where

$E_{load} = load\ energy\ demand$

$T_{aut} = days\ of\ autonomy$

Example: The consumer energy demand for a small residence as calculated for the worst month is 12 kWh/day (this includes the efficiency of the inverter).

Battery storage capacity: (12 kWh × 1)/30% =40 kWh.

To determine the battery capacity, we must divide the energy storage capacity by the system voltage.

CHOOSING THE SYSTEM VOLTAGE

The higher the energy demand, the higher the currents from the PV array and from the battery to the loads. Choosing a higher system voltage will enable operation with lower currents and reduce costs related to charge controllers and cables.

Table 4.2: Recommended system voltage based on peak energy demand

Mean daily energy consumption (kWh)	*Peak power for minutes (kW)*	*Peak power for seconds (kW)*	*System voltage not below (V)*
0-2	0-1	0-2	12
2-4	1-2	2-4	24
4-14	2-4	4-8	48
10 and above	4-8	8-16	60

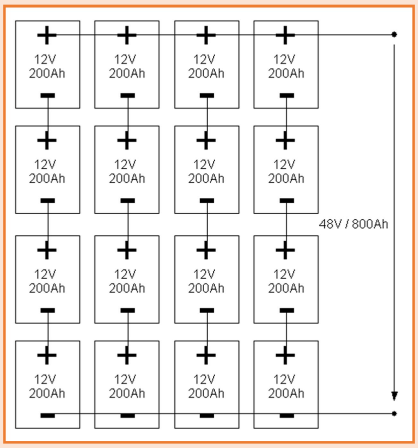
Example: For our solar system to cover a daily energy consumption of 12 kWh, we need a system voltage of 48 V. Battery storage capacity: 40 kWh/48 V = 833 Ah.

CHOOSING THE RIGHT BATTERY TYPE

Consider the following requirements when choosing a battery:

- High capacity
- Low maintenance
- Long cycle life
- Capability to withstand deep discharge up to 80%
- Low self-discharge
- Good ampere-hour efficiency

Example: For our solar PV system we need a battery bank of 48 V/833 Ah. Finding exactly that size will be difficult. We could choose a smaller bank with 48 V/800 Ah and accept a slightly deeper DoD or we could go up to the next available size and choose 48 V/1,000Ah. Opting for the smaller and less expensive configuration, the battery bank would have the following configuration:



However, the alternative to designing a battery bank out of 16 12 V batteries would be a battery bank containing 96 cells, which would provide a much less reliable configuration. As a general rule, it is better to minimise the number of cells when building a battery. The configuration shown below would be the better choice:

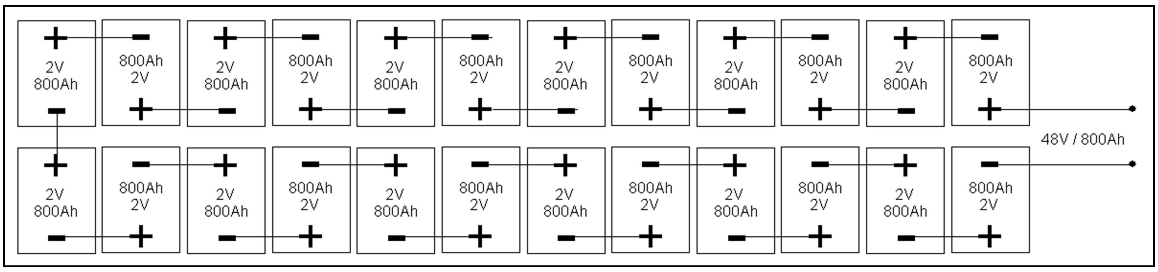


Figure 4.7: Configuration of 48 V 800 Ah battery bank using 2 V 800 Ah batteries

As an added rule of thumb, always try to minimise the number of strings, that is, if a battery with smaller capacity results in a large number of strings in parallel. The above configuration is a single string.

Example: We decide to build the battery bank out of 2 V/800 Ah tubular plate gel batteries to obtain a better lifetime and increased reliability. Part of a data sheet for the "OPZV solar power" series by Hoppecke is shown below. The expected lifetime at 30% DoD will be approx. 3,600 cycles, which is about 10 years, assuming one daily cycle (discharge and recharge).

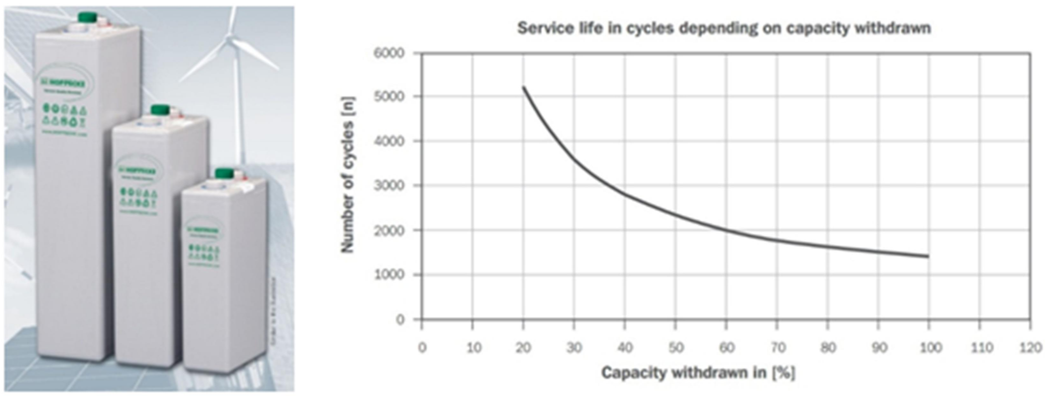


Figure 4.8: Dry cell batteries (left) life cycle of typical 2 V dry cell battery – *Courtesy: Hoppecke*

SIZING THE PV ARRAY (PV ARRAY YIELD CALCULATIONS)

The size of the solar array depends on the energy demand of all electrical consumers, the available solar irradiation at the site of installation and the performance ratio of the solar PV system.

When energy demand varies throughout the year, we choose the data from the *worst month* calculation as described above; the same applies for solar energy availability. When calculating, solar energy we use *peak sun hours*. The performance ratio for a standalone PV system is approximately 65%.

The size (required power) of the solar panel array can be calculated as follows:

- Start by dividing the daily consumer energy demand (kWh) by the performance ratio in order to get the theoretical daily energy output of the solar array (the energy it would generate without any loss).
- Then divide this theoretical energy output (kWh) by the peak sun hours, as these hours specify the period during, which our solar array receives full (1,000 W/m²) sunshine. The result is the array size in kW_P.

Example: Our solar system will be installed in Kainji dam and needs to cover a daily consumer energy demand of 12 kWh. The performance ratio is 65%. The theoretical energy output of the solar array must be 12 kWh/65% = 18.46 kWh

The available solar energy in Kainji dam in the "worst month", i.e. the month with the poorest ratio between available solar energy and energy demand, is 6.02 kWh/m²/day.

The required power of the solar array is 18.46 kWh/6.02 h= 3.066 kW.

CHOOSING THE RIGHT TYPE AND QUANTITY OF PV MODULES

The maximum power voltage (V_{MPP}) of the PV modules must be larger than the nominal system voltage. For proper charging, a battery requires a higher voltage than its nominal voltage. Another concern is the voltage loss due to the high temperatures of solar panels under intense sunlight. Figure 4.9 shows the effect of a voltage decrease on the maximum power point of a PV module with a 12 V nominal voltage, as well as its relationship to battery charging voltage.

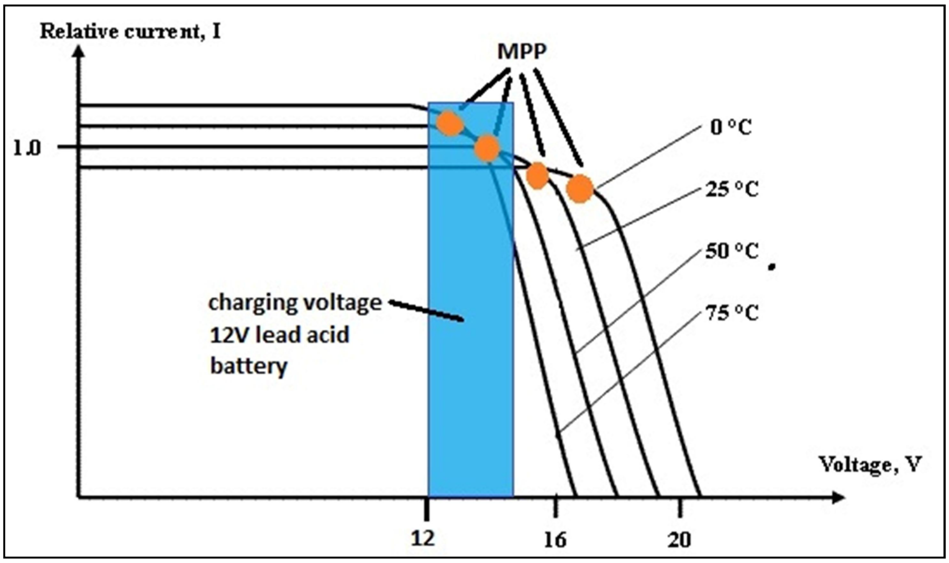


Figure 4.9: Effect of voltage decrease on MPP of 12 V PV module

By combining PV modules in series and parallel, we can obtain the desired voltage and current. When panels are connected in series, the total voltage is equal to the sum of the individual module voltages, while the current remains unchanged. When connecting panels in parallel, the currents are added together while the voltage remains unchanged. It is very important to use similar panels when building an array. It is also advisable to use modules that are as large (i.e. powerful) as possible, as this reduces the number of modules needed to complete the array and makes wiring easier and less costly.

Example: Based on a 48 V system voltage, we want to size a battery bank so it can be charged by the solar PV system. The maximum charging voltage (absorption stage) for this type of battery is approximately 2.45 V per cell. The charging voltage for the whole battery bank is 24 × 2.45 V = 58.8 V.

Due to intense sunlight, the solar panel heats up to 65 °C and the PV modules can reach only 85% of their STC voltages. For proper battery charging, we need PV modules which have a MPP voltage under STC of no less than 58.8 V/85% = 70 V.

The table below serves as a rule of thumb for determining the solar panel voltage according to system voltage.

Table 4.3: MPP voltages to determine system voltage

System voltage	*MPP voltage of solar panel(s)*
12 V	17-19 V
24 V	34-38 V
48 V	68-76 V
60 V	85-95 V

Most PV modules on the market are designed for a system voltage of either 12 V or 24 V. For a system voltage of 48 V, we need to connect two 24 V modules in series, and we will always have an even number of solar modules in the array.

Example: Our 3,066 kWp solar array shall be built of an even number and of as few PV modules as possible. The next even integer is 3,200 Wp. Below you can see part of the data sheet for a "Solarworld SW320XL" PV module. Two of these modules connected in series would result in a maximum power voltage of 73.4 V under STC. Losses due to high temperatures would bring the MPP voltage down to 63.9 V, which is more than it needs to charge the 48 V battery.

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

Maximum power	P_{max}	320 Wp
Open circuit voltage	V_{oc}	45.9 V
Maximum power point voltage	V_{mpp}	36.7 V
Short circuit current	I_{sc}	9.41 A
Maximum power point current	I_{mpp}	8.78 A
Module efficiency	η_m	16.04 %

*STC: 1000 W/m², 25°C, AM 1.5

1) Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 2% (TUV Power Controlled).

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.042 %/°C
TC $_{Voc}$	-0.304 %/°C
TC P_{mpp}	-0.43 %/°C
Operating temperature	-40°C to 85°C

Figure 4.10: Electrical and mechanical parameters for solar performance

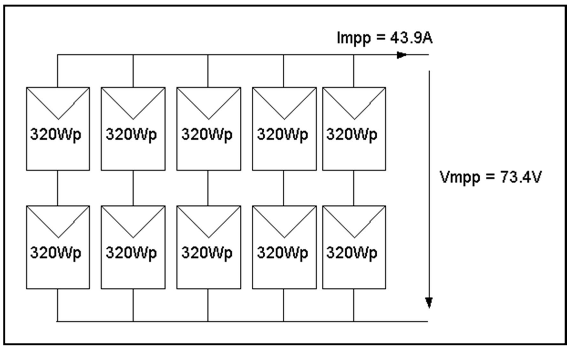


Figure 4.11: Interconnection of PV modules to give required array size

Ten of these PV modules would combine to form a PV array of 3.2 kWp. The maximum current (IMPP) would be of 5 modules in parallel: 5 × 8.78 A = 43.9 A. The resulting array configuration is represented in Figure 4.11.

SIZING THE CHARGE CONTROLLER

The charge controller must be able to control the maximum array current under any conditions. In real-life operating situations, a solar module can generate a much higher current than that specified under STC. Unlike the voltage, the current of a solar module increases only slightly with rising temperatures. Moreover, solar radiation at noon can, in some regions and under certain weather conditions, be much stronger than 1,000 W/m². Therefore, a solar charge controller needs to operate with a current at least 20% greater than the maximum power point current of the array.

Example: Our 3.2 kWp solar array generates under STC a maximum current (I_{MPP}) of 43.9 A. The rating of the charge controller should be at least 43.9 A + 20% = 52.7 A. Below is part of the datasheet for the "Steca Power Tarom" series. The 4055 model is ideal; otherwise the next possible controller would probably be a 60 A controller.

	2070	2140	4055	4110	4140
Characterisation of the operating performance					
System voltage	12 V (24 V)		48 V		
Own consumption	14 mA				
DC input side					
Open circuit voltage solar module	< 47 V		< 82 V		
Module current	70 A	140 A	55 A	110 A	140 A
DC output side					
Load current	70 A	70 A	55 A	55 A	70 A
programmable:					
End of charge voltage	13.7 V (27.4 V)		54.8 V		
Boost charge voltage	14.4 V (28.8 V)		57.6 V		
Equalisation charge	14.7 V (29.4 V)		58.8 V		
Reconnection voltage (SOC / LVR)	> 50 % / 12.6 V (25.2 V)		> 50 % / 50.4 V		
Deep discharge protection (SOC / LVD)	< 30 % / 11.1 V (22.2 V)		< 30 % / 44.4 V		
Operating conditions					
Ambient temperature	-10 °C … +60 °C				
Fitting and construction					
Terminal (fine / single wire)	50 mm² / 70 mm² - AWG 1 / 00				
Degree of protection	IP 65				
Dimensions (X x Y x Z)	330 x 330 x 157 mm	360 x 330 x 157 mm	330 x 330 x 157 mm	360 x 330 x 157 mm	
Weight	10 kg				

Technical data at 25 °C / 77 °F

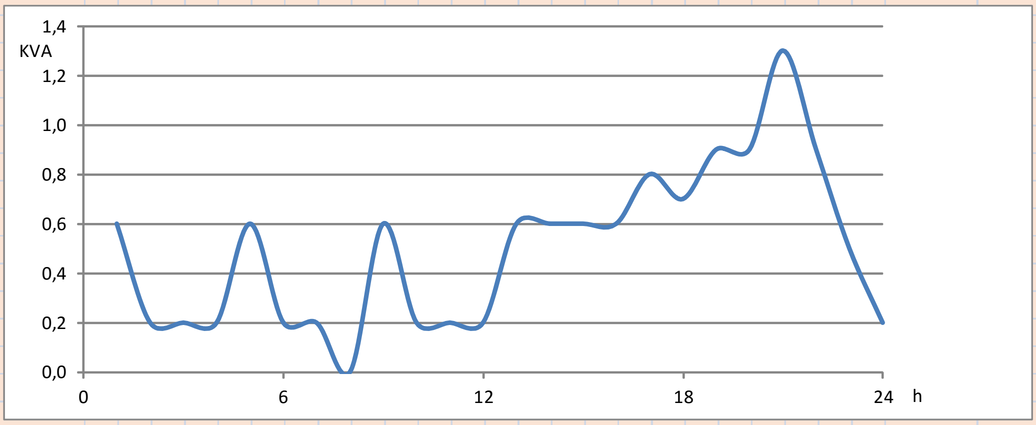
Figure 4.12: Charger controller (left), charge controller data sheet (right)

SIZING THE INVERTER

When choosing an inverter, keep in mind that the inverter's performance will vary with fluctuating power demands. Oversizing an inverter not only leads to inefficient operation but also unnecessary costs. Correct inverter sizing is very important to overall system performance. In addition, the size (or nominal output) of an inverter cannot be upgraded after purchase. In this regard, the inverter is different than modules and batteries, which can be added later should the system design or sizing prove to be insufficient. When choosing a specific inverter, the inverter's output capacity must be matched to the electrical loads it will supply. By choosing which electrical circuits the inverter will power (all circuits or only selected circuits), the power draw of all electrical loads on each circuit can be added together to arrive at the minimum inverter capacity required. Extremely "power-hungry" appliances such as electric water heaters and electric clothes dryers should either be replaced with gas-powered energy-efficient models, or be supplied by a different source (i.e. other than the inverter).

Example: Our daily 12 kWh energy requirement is distributed over the day as shown in the load profile below. The peak occurs at around 9 pm with 1.3 kVA.

time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	power consumption in KVA																								daily energy	
lights																		0,3	0,3	0,3	0,3	0,3	0,3		1,8	KVAh
TV														0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4			3,6	KVAh
fridge	0,4				0,4				0,4				0,4				0,4				0,4				2,4	KVAh
sec. lights	0,2	0,2	0,2	0,2	0,2	0,2	0,2												0,2	0,2	0,2	0,2	0,2	0,2	2,6	KVAh
laptop									0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2									1,6	KVAh
peak power	**0,6**	**0,2**	**0,2**	**0,2**	**0,6**	**0,2**	**0,2**	**0,0**	**0,6**	**0,2**	**0,2**	**0,2**	**0,6**	**0,6**	**0,6**	**0,6**	**0,8**	**0,7**	**0,9**	**0,9**	**1,3**	**0,9**	**0,5**	**0,2**	**12**	**KVAh**



We need an inverter with a minimum continuous power output of 1.4 kVA and a 48 V DC input to supply the high start-up requirement for the fridge during a short peak.
Below is part of the data sheet for the "Steca XPC" series. The 2200-48 model would be the best choice in this case. Its peak power can also easily supply the high start-up power of the fridge motor.

	1400-12	2200-24	2200-48
Characterisation of the operating performance			
System voltage	12 V	24 V	48 V
Continuous power	1,100 VA	1,600 VA	1,600 VA
Power 30 min.	1,400 VA	2,200 VA	2,200 VA
Power 5 sec.	3,300 VA	4,800 VA	4,800 VA
Max. efficiency	94 %	95 %	95 %
Own consumption standby / ON	0.6 W / 4 W	0.9 W / 7 W	1.3 W / 7 W
AC input side			
Input voltage	adjustable: 150 V AC … 230 V AC		
Charging current adjustable	0 A … 45 A	0 A … 37 A	0 A … 20 A
Max. current / power on transfer system	16 A / 3.7 kVA		
Switching time transfer relay	< 20 ms		
DC output side			
Battery voltage	9.5 V … 16 V	19 V … 32 V	38 V … 64 V
Battery monitoring	LVD, HVD, floating and equalisation voltage adjustable by user via optional remote control RCC-01		
AC output side			
Output voltage	230 V AC +0 / -10 % (true sine wave)		
Output frequency	50 Hz +/-0.05 %		
Load detection (standby)	adjustable: 1 W … 25 W		

Figure 4.13: Inverter (left), inverter data (right)

CABLE SIZING AND SELECTION

Cable sizing is an important, yet often neglected, part of system design. Once you know the required quantities of panels and batteries, along with the type of regulators and inverters you want to use, you will need to calculate the length and thickness of the cables to connect the components.

The length of a cable run depends on the location of the installation. Cable lengths should be minimised to reduce power loss and the costs of cabling. The maximum voltage drop on the DC side of a PV installation should not exceed 3%, meaning that no more than 3% should be lost in the distance from the solar modules to the battery. The voltage drop depends on four factors:

- Length of cable
- Current on cable
- Thickness of cable
- Material of cable

The absolute voltage drop can be calculated using the following formula:

$$\Delta V = \frac{2 \text{ x l (length) x I(current)}}{\varkappa \text{ x q}}$$

l = cable length (m), I = current (A), ϰ = conductivity (mS/m), q = cross sectional area of cable (mm^2). The conductivity of copper = 58 mS/m. The voltage drop is calculated as a percentage by dividing the absolute voltage drop over the system voltage. The required minimum cross sectional area of the cable can be calculated using the following formula:

$$A = \frac{2\rho L_{cable} I_{rated}}{\gamma V_{system}}$$

Where:

A =	cross-sectional area of cable (mm^2)
P =	resistivity of copper (0.0179 $\Omega mm^2 m^{-1}$)
L_{cable} =	length of cable run
I_{rated} =	maximum current flowing through a cable (A)
Γ =	maximum power loss allowance (%)

Example: Our 3.2 kWp solar array generates under STC a maximum current (IMPP) of 43.9 A. The cable length from the combiner box to the battery via the charge controller is 12 m.

The required cable thickness is:

(2 × 0.0179 Ωmm^2m-1 × 12 m × 43.9A) / (= 0.3 × 48 V) = 13 mm^2. We need a cable with minimum cross section of 13 mm^2; the available size would be a 2 x 16 mm^2 cable.

With a 16 mm^2 cable, the voltage drop would be:

(2 × 12 m × 43.9 A) / (58 mS/m × 16 mm^2) = 1.14 V.

The voltage drop expressed as a per cent would be 1.14 V / 48 V = 2.4%, which is acceptable.

All equipotential bonding wires running between the metallic bodies of the equipment and to the ground electrode should have a cross sectional area of at least 6 mm^2.

5. SITE PREPARATION

What this module is about

As with all systems, preparations to the site are required before installation. The supervisor in charge of installation should be familiar with and adequately prepare all pre-installation requirements.

Learning outcomes

At the end of this module, the participant is able to

- Plan an installation work schedule
- Understand and explain requirements for PV system installation on different surfaces
- Identify suitable installation points for system components
- Plan to mitigate the effect of inter-row shading

5.1. TAKING MEASUREMENTS

As with any installation job, you need to understand, which measurements are important. As the supervisor in charge of installation, you must be familiar with how to take measurements and interpret the results. For photovoltaic installations, the most important measurements are:

SOLAR IRRADIANCE

This is the quantity of solar resource available at the installation site. For large multi-megawatt systems, this measurement is taken using a pyrometer or a pyrheliometer.

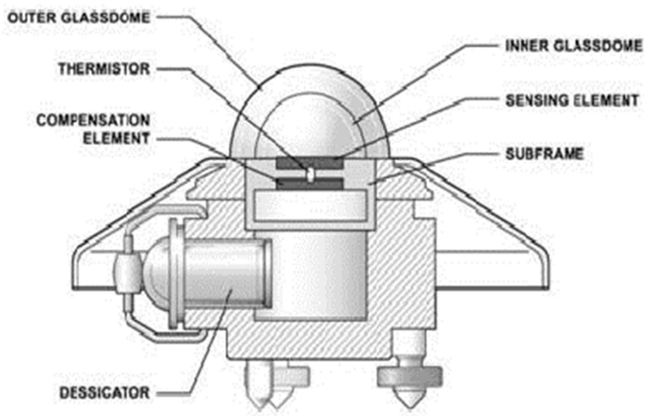


Figure 5.1: Pyrometer (left), Pyrheliometer (right)

Prior to installation, solar irradiance is usually measured for multi-megawatt projects over longer periods of time (i.e. as longitudinal data over 6 to 12 months). For smaller domestic or commercial systems, solar irradiance is mostly measured for system evaluation purposes.

LENGTHS

Knowing how to measure linear distances and lengths is critical for planning the installation of a solar PV system. Some of the linear measurements that you shall be required to take include:

- Length of each cable type to be installed
- Position of the solar PV modules
- Length of shadow cast by modules, trees or other objects

Lengths are measured using a tape measure.

ANGLES

To properly install a solar PV system, you need to be conversant with angles and trigonometry. This is critical when determining parameters such as the angle of inclination and the minimum distance to mitigate shading. Angle measurements can be taken using instruments such as an inclinometer.

CURRENT, VOLTAGE AND POWER

The solar PV system is an electrical power supply system. Your ability to use a multimeter to measure electrical parameters such as current and voltage is critical for your success as a solar PV installation professional.

5.2. SHADE ANALYSIS AND SUN PATH CHART

When you are deciding on the location of your solar PV array, you must always consider the possibility of shading caused by trees and nearby man-made objects such as buildings, poles and telecommunications towers.

The sun chart is a useful tool, which allows system designers and installers to understand the availability of sunshine over the year, as well as to understand the shadow that would be cast by the PV array. The sun chart has two axes; the solar elevation and the solar azimuth.

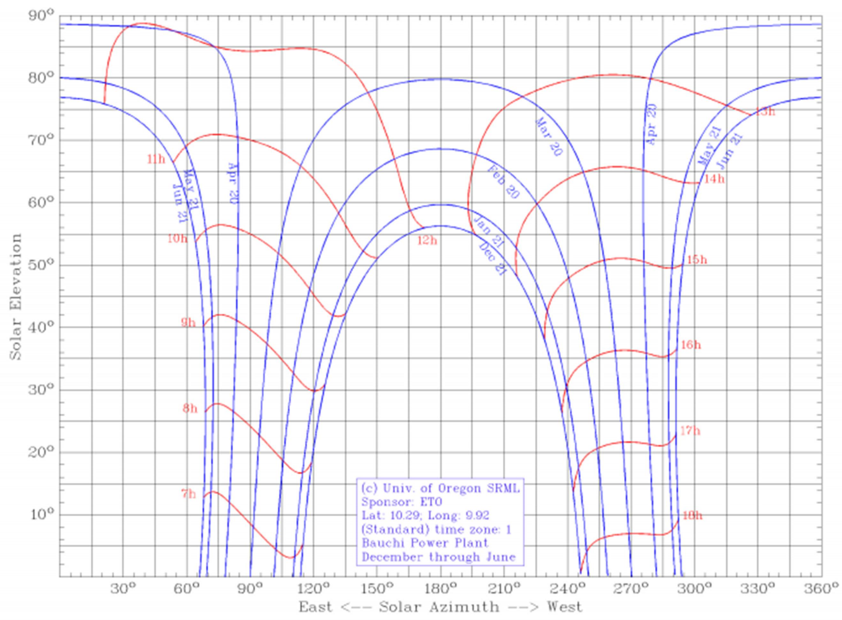


Figure 5.2: Sun chart for Bauchi, Nigeria – *Courtesy: University of Oregon, http://solardat.uoregon.edu*

The sun path chart in Figure 5.2 explains the sun's location in the sky for six months (December to June) in Bauchi, Bauchi State, Nigeria.

The solar azimuth axis (horizontal axis) indicates the sun's direction in the horizontal plane for a given location. The North is assigned an azimuth of 0° while the South is defined by an azimuth of 180°. The East and West, where the sun rises and sets, have an azimuth of 90° and 270°, respectively.

On the other hand, the solar elevation axis (vertical axis) indicates the sun's height over the sky during the day. These two axes are connected via the blue lines, which indicate a particular day of the year in which the values were measured. In this case, the 20th or 21st of every month.

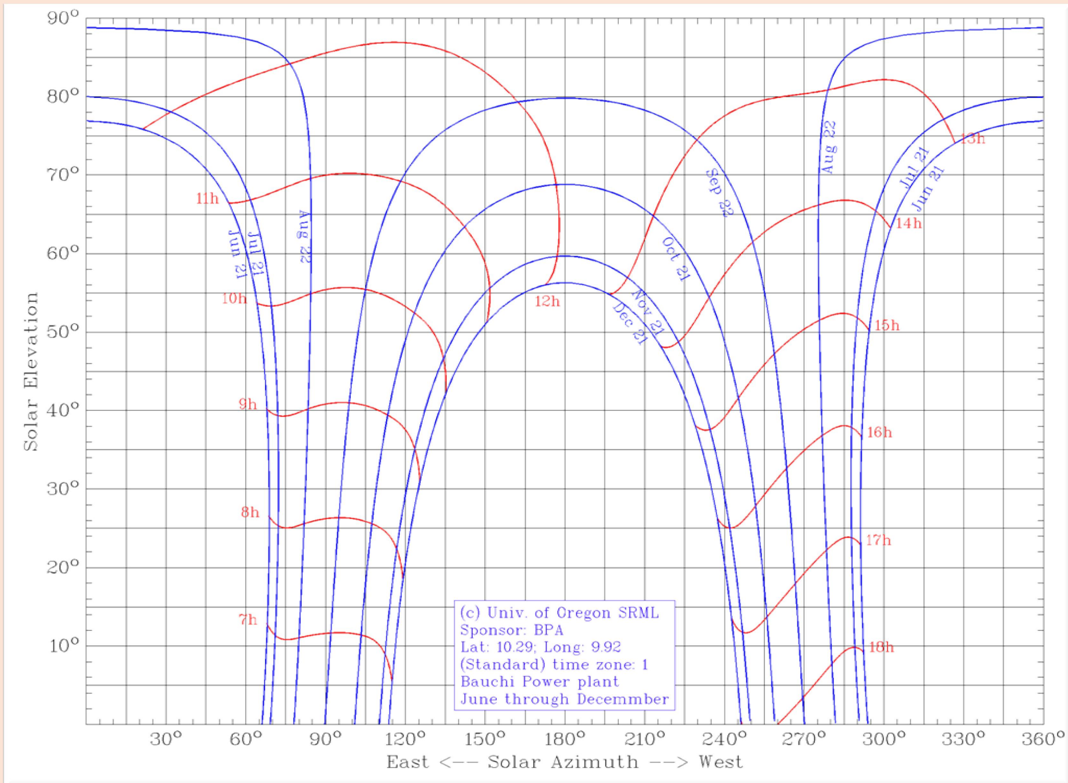
The sun path chart would be incomplete without information on the time of day at which the sun is at a particular location. At the intersection of the red lines, which show the time of day, and the blue lines, which show the day of the year, you can reasonably know the location of the sun all year round. For site planning, however, a sun path analysis instrument such as the solar pathfinder may be used to determine the shading effect of trees and other objects like houses and telecommunications equipment in the vicinity of the PV array.

From the above chart, we can deduce that that at 9 am on April 20, the sun is at an elevation of 40° to the horizontal and at an azimuth of 80° (i.e. located in the Northeast).

Note: This chart refers to the position of the sun in the sky from June through to December. Another chart should be generated for the months July to November.

Example: From the sun path chart below, deduce:

- Solar elevation on October 21 at 3.pm
- Azimuth of the sun on August 22 at 11 am



5.3. ORIENTATION AND INCLINATION OF PV MODULES

To maximise the performance of a solar PV module, it must be installed at the optimum orientation (angle of inclination and azimuth).

- **Angle of inclination**: This is the angle that the solar PV array makes with the horizontal plane to the ground. For Nigeria, you should always use 15^0.
- **Azimuth**: The azimuth is an angular measurement in a spherical coordinate system. The vector from an observer (origin) to a point of interest is projected perpendicularly onto a reference plane; the angle between the projected vector and a reference vector on the reference plane is called the azimuth. The sun is the point of interest, the reference plane is the horizon or the surface of the sea, and the reference vector points north. The azimuth is the angle between the north vector and the perpendicular projection of the sun down onto the horizon. For Nigeria, as a rule, it is advisable to point the solar PV modules facing true south.

INTER-ROW SHADING

When you install a large solar PV array with numerous strings, you always have to consider the possibility of inter-row shading. Inter-row shading occurs when the solar PV module in front casts a shadow on the module behind it.

Figure 5.3: Shadow caused by solar PV modules

When considering the effect of inter-row shading, always include the following criteria:

- **Effective period of operation**: PV modules work in the presence of sunlight. You have to determine the time span during which some shading would be acceptable. It is recommended that if there is shading, it should not occur between 8 am and 4 pm (8 hours).
- **Latitude at which you are installing the PV array**: The latitude (φ) is a geographic coordinate that specifies the north-south position of a point on the earth's surface. Latitude is an angle, which ranges from 0° at the equator to 90° (north or south) at the poles. Lines of constant latitude, or parallels, run parallel to the equator as circles. The latitude affects the location of the sun in the sky at different times, which in turn affects the length of the shadow that could be cast.
- **Size of the solar panels**: The dimensions of the solar PV modules also have a direct correlation with the length of the shadow cast.
- **Orientation of the PV array**: The angle of inclination and azimuth of the array play a major role in the occurrence of inter-row shading. At a larger angle of inclination, there is bound to be a longer shadow cast by the preceding photovoltaic module.

REQUIRED AREA FOR INTER-ROW SPACING

Inter-row shading could drastically reduce the amount of energy that can be obtained from a PV array. To mitigate this effect, you have to interpret the sun path diagram or use industry-accepted rules of thumb - but first you need to identify the following parameters:

- Module length and width
- Required array length, width and area
- Module orientation
- Tilt angle
- Sun path chart

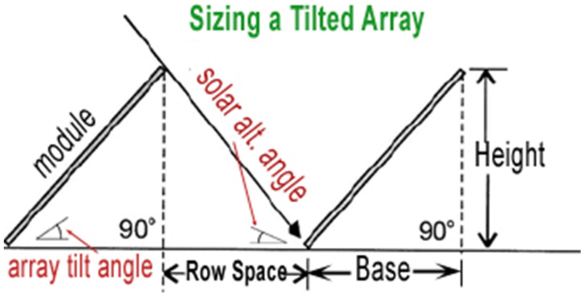


Figure 5.4: Calculating for inter-row shading
– Courtesy: www.thesolarplanner.com/steps_page5b.html

Once you have the above-listed parameters, it becomes a simple case of multiplication to calculate the required distance (based on a rule of thumb) between rows. In Nigeria, a row spacing factor of 1 is generally recommended when determining the space to be used between 8 am and 4 pm. For example, if you have an array (module) table that is 2 m high, the minimum row spacing that is required between that module and the next is 2 m.

In situations where the solar photovoltaic array does not face true south, a more complicated method must be used to determine the required row spacing. Here, you would need to read values off the sun path chart and interpret them using trigonometric laws and principles.

To do this, you must apply the following formulae:

$$Space\ between\ modules = \frac{Mocdule\ height}{\tan(solar\ altitude\ angle)} \times \cos(array\ azimuth)$$

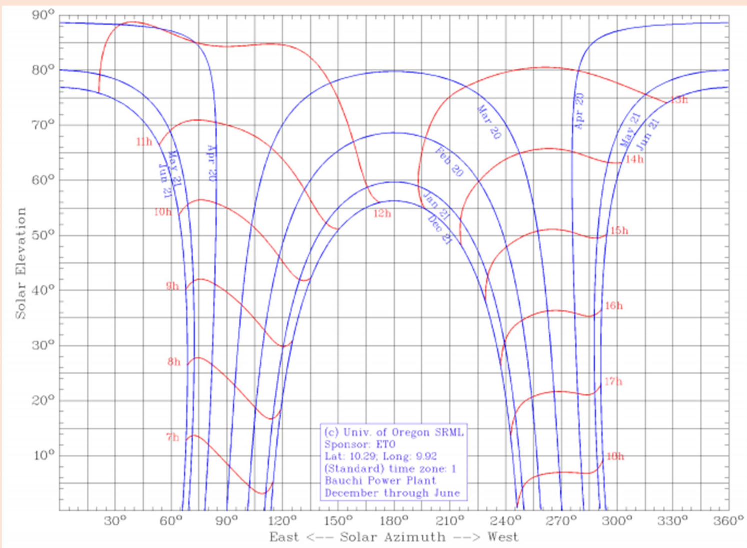
The module height is the vertical distance from the horizontal plane on which all the stands are to the top of the module. It may be calculated using Pythagoras' theorem as follows:

$$Module\ height = Module\ length \times \sin(array\ tilt\ angle)$$

Combining the two formulae above, the space between rows can be calculated as:

$$Space\ between\ rows = \frac{Module\ length \times \sin(array\ tilt\ angle)}{\tan(solar\ altitude\ angle)} \times \cos(array\ azimuth)$$

Example: The figure below shows the sun path diagram of Bauchi, Bauchi State in northeastern Nigeria. Calculate the spacing required if inter-row shading is to be avoided between the hours of 8 am and 4 pm on December 21st, the day when the sun is at its lowest point in the northern hemisphere.



» *Solution*

What we know

- You wish to calculate the spacing between rows of PV arrays in Bauchi State
- Let us assume the effective period of operation is between 8 am and 4 pm
- Bauchi has the latitude 10°17'32''N (geographic coordinates) or 10.29° (decimal coordinates)
- Let us assume that the PV modules to be used are each 1.956 m by 0.991 m. Furthermore, each table (array) has a length of 3.96 m (4 × 0.991 m)

Data we can gather using the sun path chart

Solar elevation angle at 8 am = 18°

Solar azimuth angle at 8 am = 120°

Solar elevation angle at 4 pm = 70°

Solar azimuth angle at 4 pm = 235°

Using the formula above:

At 8 am

$Space\ betweenrows = 3.96 \times \sin(-15°)\text{-}\tan(-18°)\times\cos(-180) = 3.15\ m$

The table below shows the inter-row spacing required to avoid shading for the solar PV array mentioned previously:

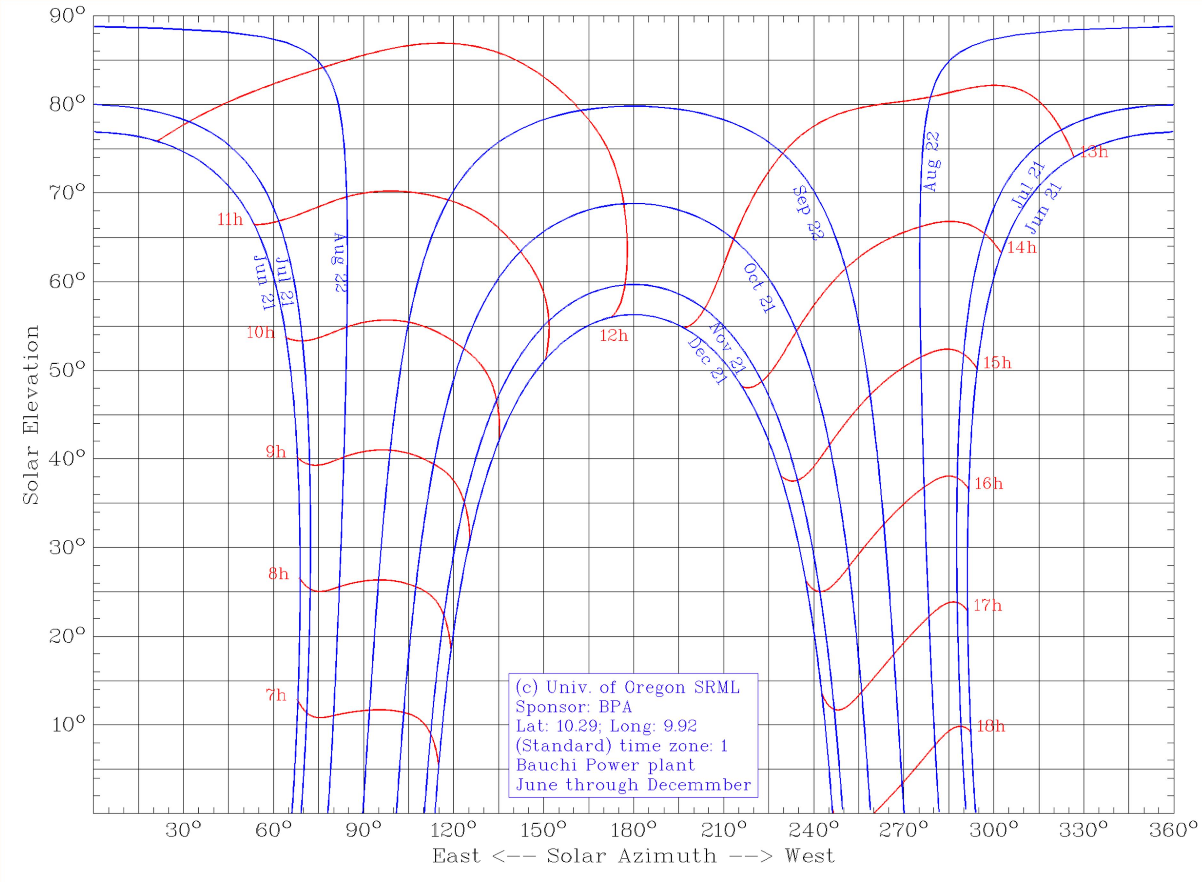
Table 5.1: Required inter-row spacing for Bauchi, NE Nigeria

Time	*Inter-row spacing (21 Dec)*	*Inter-row spacing (20 Apr)*
7 am	11.7 m	4.8 m
8 am	3.15 m	2.0 m
9 am	1.8 m	1.1 m
10 am	1.1 m	0.8 m
11 am	0.8 m	0.3 m
Noon	0.7 m	0.1 m
1 pm	0.7 m	0.2 m
2 pm	0.9 m	0.5 m
3 pm	1.3 m	0.8 m
4 pm	1.9 m	1.4 m
5 pm	4.1 m	2.4 m
6 pm	Infinity (no sunshine)	8.3 m

Once you have calculated the required inter-row spacing, you can now determine how many solar photovoltaic modules you can install in the area available at the site.

From the Table 5.1, you can see that if you design your solar PV array to maximise the solar energy you can harvest in Bauchi, you shall require a substantial amount of space to mitigate inter-row shading. Therefore, there must a trade-off between the solar energy you can harness and the available space.

Exercise: Using the sun path chart below, calculate the minimum row space required for July 21 and October 21?



5.4. INSTALLATION SURFACES

Solar PV modules are commonly mounted in four different ways:

ROOF MOUNTING

Most residential solar PV systems are roof-mounted, especially in urban areas. The roof offers a suitable location for the PV modules when no space is available on the ground.

Roof mounting can be divided into two groups:

- **Flush mounting**: For this type of mounting, the PV modules are installed very close (flush) to the roof. Here, the photovoltaic modules take the orientation (azimuth and inclination) of the roof. Flush-mounted solar photovoltaic modules generally provide the advantage of better aesthetics. A flush-mounted system consists of footings to fasten the system to the roof (to which rails are then fastened), tails to which the photovoltaic modules are fastened and clamps which hold the modules to the rails.
- **Tilt-up mounting**: This type of mounting is used when you have a flat roof. The PV modules are inclined at the ideal orientation to achieve a maximum energy output from the array.

Figure 5.6: Flush-mounted PV modules on a pitched roof

GROUND MOUNTING

This is the easiest type of mounting setup. It can be realised if you have a client with sufficient land who can also afford the cost of laying cables over a few extra metres.

This is similar to the tilt-up system mentioned above; however, the mounting structures are secured via concrete bases or foundations.

Figure 5.7: Ground-mounted solar PV array – *Courtesy: Melissa Van Hoorne, http://blog.solarmicronics.co*

TOP-OF-POLE MOUNTING

This mounting type is more common with street lighting, traffic lighting or other off-grid applications as can be seen across Nigeria. In this system, a hole is dug in the ground and the pole is set in the hole while concrete is poured to surround the pole. This mounting system is generally limited by the maximum amount of PV modules that can be installed.

Figure 5.8: Pole-mounted PV array – *Courtesy: Accutrack Solar System, www.accutrack.com*

BUILDING-INTEGRATED

Commonly called BIPV (building-integrated photovoltaics), this mounting type refers to systems in which PV cells and modules are directly incorporated in building materials such as window glass or roofing tiles.

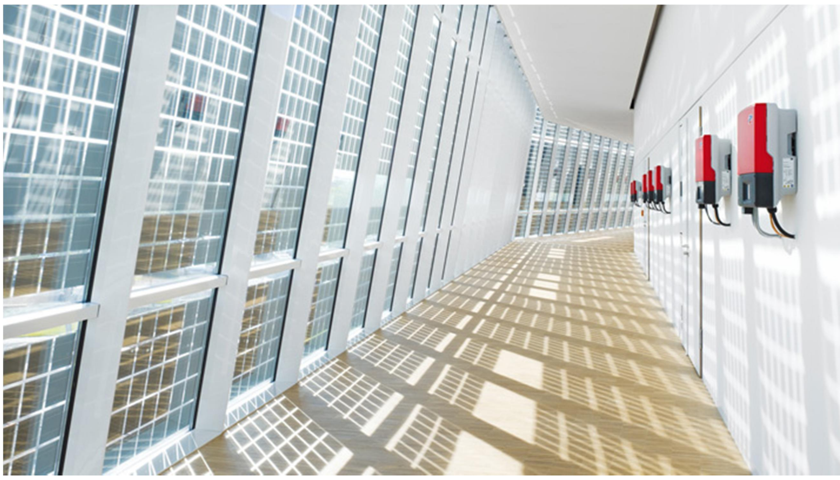


Figure 5.9: PV modules integrated in the windows of SMA GmbH headquarters in Kassel, Germany – *Courtesy: SMA Solar Technology*

Table 5.2: Comparisons of the different mounting techniques

Mounting method	*Advantages*	*Disadvantages*
Roof mounting	▪ Usually provides the best access to sunlight ▪ Utilises "unused" roof space, thereby saving space on the ground ▪ Reduces costs due to proximity to the electrical load centre ▪ Minimises effects of on-site installation	▪ Orientation (azimuth and inclination) of the solar PV array is determined by the existing roof ▪ Less ventilation under the PV modules means operation at higher temperatures ▪ Roof size determines the maximum number of PV modules that can be installed ▪ Maintenance work on the roof could affect the PV modules, e.g. need for removal ▪ Installation could cause leaks in the roof because of holes for proper mounting
Ground mounting	▪ Suitable for all types of solar PV systems ▪ Flexible orientation of PV array ▪ Roof penetration issues are not a problem ▪ Allows for easy maintenance ▪ Easier to install ▪ Panels operate at cooler temperatures than roof-mounted systems due to greater ventilation underneath the solar panel array	▪ Concrete base needs to support the weight of the array ▪ Need for preparation of ground at the installation site (clearing of vegetation, digging of cable trenches, protection from unauthorised personnel, etc.)
Top-of-pole mounting	▪ Operates at cooler temperatures, like ground-mounted systems ▪ Flexible orientation of PV array ▪ Enables flexible seasonal adjustments of the array (automatically or manually), enabling you to increase your energy yield over the year	▪ Fair amount of ground work required prior to this method. Analysis to determine the soil type, wind loading, etc. must be carried out. May add extra costs if the information is not readily available ▪ Need for preparation of ground at the installation site (clearing of vegetation, digging of cable trenches, protection from unauthorised personnel, etc.) ▪ Maximum number of PV modules that can be installed on a pole-mounted structure to minimise risk of storm damage

Mounting method	*Advantages*	*Disadvantages*
Building-integrated photo-voltaics (BIPV)	▪ Solar PV array can be installed in any part of the building ▪ Offers better aesthetics. PV modules can be installed unobtrusively on the building	▪ Expensive when compared to the other mounting techniques ▪ Installed along with the building, so the PV array does not usually have an optimum orientation, potentially leading to energy losses

Note: If you intend to make use of pre-fabricated mounting systems, be sure to read, understand and follow the manufacturer's manual prior to installation. If you fabricate the mounting structure yourself, ensure that it is sturdy enough to withstand the weight of the solar panels and the effect of wind gusts and that it does not pose a threat to life or property in its immediate vicinity. Always be mindful of shading when choosing a mounting system. Plants grow over time and the location in which you place your solar photovoltaic array could be susceptible to shading from subsequent plant growth.

IDEAL SURFACES FOR BATTERIES, INVERTERS AND CHARGE CONTROLLERS

The central requirement for installing batteries, inverters and charge controllers are:

- Clean and dry space/ surface
- Adequate ventilation
- Easily accessible for maintenance

5.5. PLANNING WORK SCHEDULES

Before beginning installation activities, during the site assessment phase it is important to have a clear idea of how many tradesmen are needed to complete the installation within the agreed time frame. Activities to consider include:

- **Equipment delivery to site**

  Before beginning to install system components, ensure that the PV modules, batteries, inverter, charge controller, etc. are available on site or are made available.
- **Identification of installation tasks**

  For you to be able to adequately plan a work schedule and know the type of professionals required, you should identify all necessary tasks to complete the installation of the photovoltaic system.
- **Complexity of each installation task**

  Once you have identified each task, the next step is for you to determine the complexity of each task. This gives you the necessary information to determine the number of personnel that you require to complete the installation job.
- **Required tools and materials**

  Before you begin installation, ensure that all necessary tools and equipment to complete the installation are available on site. For example, you do not want to be in the middle of installation process only to discover that you forgot to order a ladder and are therefore unable to install the PV modules on the roof because it is inaccessible.

6. INSTALLING A SOLAR PHOTOVOLATIC SYSTEM

What this module is about

The proper connection of system components is integral to reliable system performance. This module walks the students through the steps and procedures that are required to successfully install a photovoltaic system.

Learning outcomes

At the end of this module, the participant is able to

- Install photovoltaic system components and systems
- Explain how to wire PV system components, terminate cables and commission systems
- Explain electrical installation tests

6.1. UNDERSTANDING ELECTRICAL DRAWINGS

Electrical work drawings are important to the installer because they help communicate the engineer's design. As a supervisor of electrical installations, you will be responsible for the interpretation of a wide range of electrical drawings and diagrams. Therefore, you must be able to understand different circuit symbols and identify the electrical components that they represent.

TYPES OF ELECTRICAL DRAWINGS

- **Block diagrams** are used to show how principal system components are interconnected. These components are represented by blocks connected by lines to show their relationships.

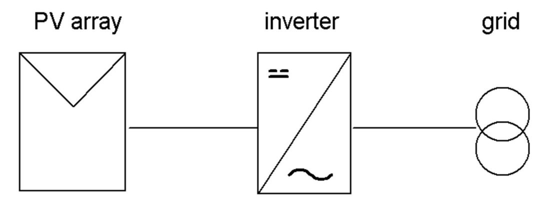


Figure 6.1: Block diagram of a grid-connected PV system

- **Circuit drawings** provide a graphical representation of an electric circuit. They are mostly represented on the layout/floor plans of a building or an installation site.

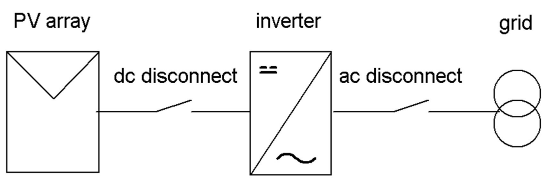


Figure 6.2: SLD of a grid-connected PV system

- **Single-line diagrams (SLD) (or one-line diagram)** are a type of block diagram containing more detailed technical information. On the single-line diagram, unlike the block diagram, all system components are represented. These components appear in the form of internationally standardised schematic symbols.
- **Schematic diagrams** are simplified representations of the system's electrical circuit using standardised symbols. They indicate all system components and their connections, and also provide information such as polarities and electrical specifications.

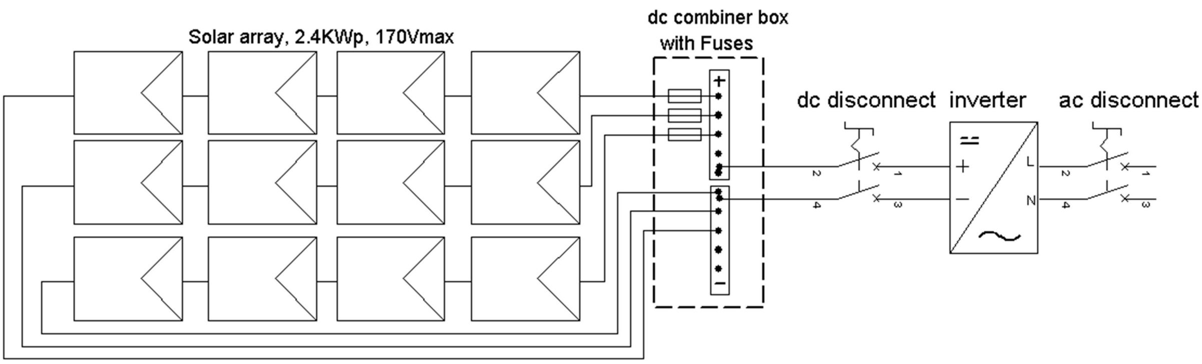


Figure 6.3: Schematic diagram of a grid-connected PV system

- **Wiring diagrams** are a simplified representation of the system's electrical circuit using standardised shapes. The wiring diagram shows how to make connections between different components and provides additional information such as polarities and the relative arrangement of devices and terminals.

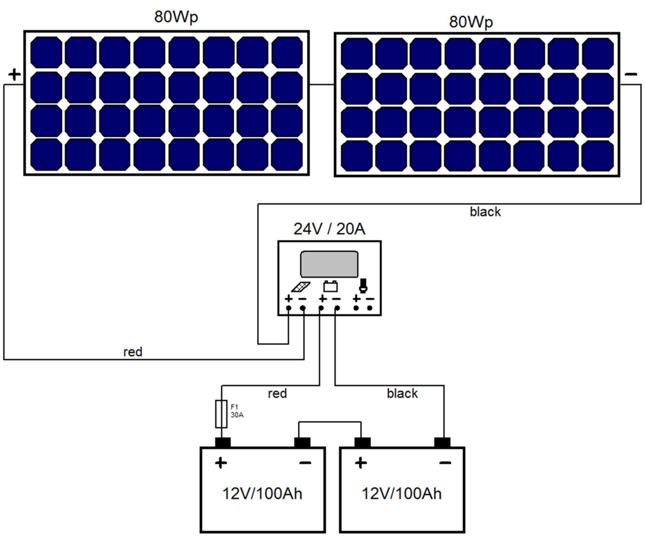
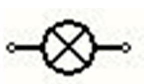
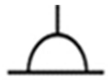
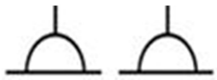
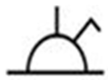
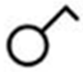
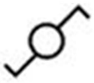
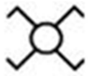
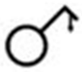
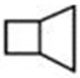
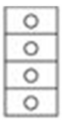


Figure 6.4: Wiring diagram of an off-grid PV system

» *Commonly used symbols in electrical drawings*

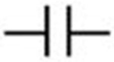
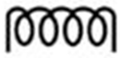
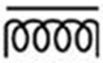
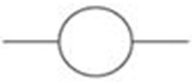
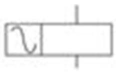
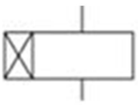
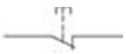
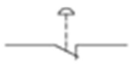
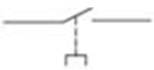
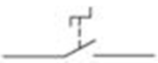
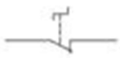
Figure 6.1: Symbol used in domestic circuit diagram

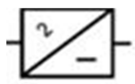
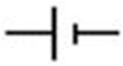
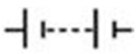
Symbol	Description	Symbol	Description
	Lamp (Standard)		Lighting outlet position – general symbol
	Fluorescent luminaire		Wall mounted luminaire
	Self-contained emergency lighting luminaire		Emergency lighting luminaire (or special circuit)
	Machine, general symbol *function, etc.		Load, general symbols *details

Symbol	Description	Symbol	Description
	Motor starter, general symbol *indicates type		Socket-outlet, general symbol
	Twin socket-outlet, general symbol		Switched socket-outlet
	Twin switched socket-outlet		Switch, general symbol
	Two way switch, single pole		Intermediate switch
	Pull switch, single-pole		microphone
	loudspeaker		Antenna, general symbol
	Machine, general symbol *function M=Motor G=Generator		Generator, general symbol
	Indicating instrument, general symbol *function V = Voltmeter A = Ammeter etc.		Integrating instrument or energy meter *function Wh = Watt hour VArh = Volt ampere reactive hour
	Plug male		Coax plug male
	Wire connection (Two wires)		Wires crossing (Not connected)
	Terminal block		Noiseless earth
	Chassis earth		Socket (plug female)
	Slow operating relay *Delay on		Wire connections (crossed)

Symbol	*Description*	*Symbol*	*Description*
	Terminal connector		Earth connection
	Protective earth		Equipotentiality

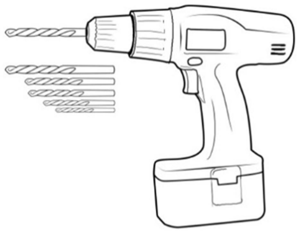
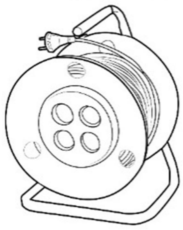
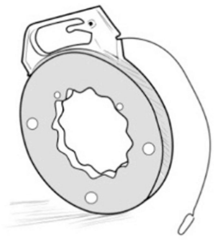
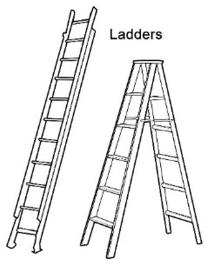
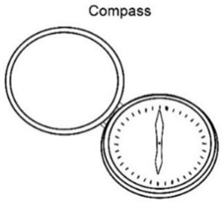
Table 6.2: Symbols used in schematic and wiring diagrams

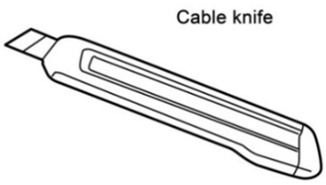
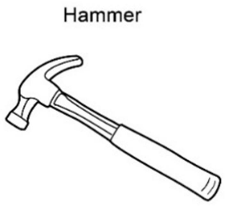
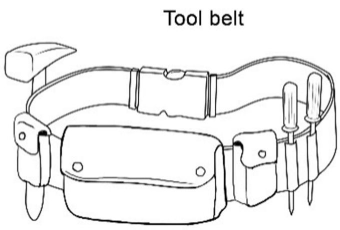
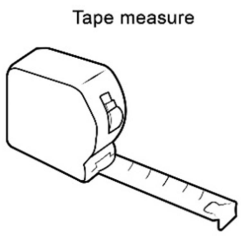
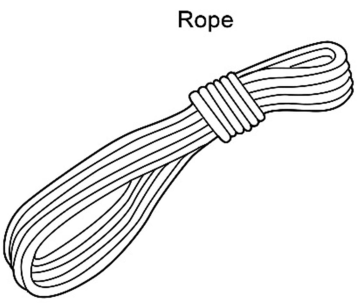
Symbol	*Description*	*Symbol*	*Description*
	Capacitor, general symbol		Inductor, core, winding or choke
	Inductor, core, winding or choke with magnetic core		Semi-conductor diode, general symbol
	Contractor coil		Relay to AC supply
	Slow release relay. Delay off		General relay (DC supply)
	Slow operating relay. Delay on		Mechanically latched relay
	Normally open PB (N/O)		Normally closed PB (N/C)
	Emergency stop PB (N/O) indication contact		Emergency stop PB (N/C)
	Pull switch (N/O)		Pull switch (N/C)
	Turn/rotary switch (N/O)		Turn/rotary switch (N/C)
	Normally open contact (N/O)		Change over or two contact Made position

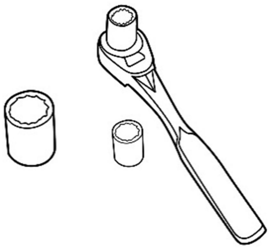
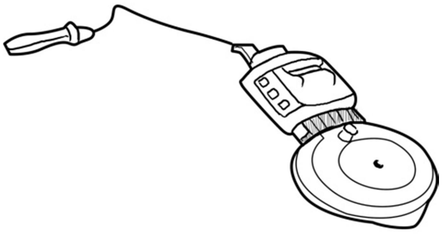
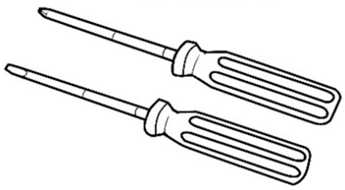
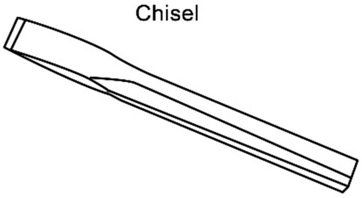
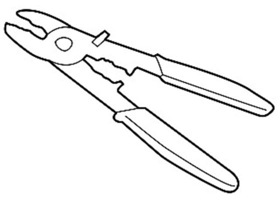
Symbol	*Description*	*Symbol*	*Description*
	Limit switch (N/O)		Flow switch (N/O)
	Time delay (N/O) Delay on closing		Thermal switch – overload (N/O)
	Temperature switch (N/O)		Pressure switch (N/O)
	Normally closed contact (N/C)		Fused switch open contact (N/O)
	Limit switch (N/C)		Flow switch (N/C)
	Time delay (N/O) Delay on re-opening		Thermal switch-overload (N/C)
	Temperature switch (N/C)		Pressure switch (N/C)
	3-phase winding-star		Rectifier
	Inverter		Primary cell – long line positive, short line negative
	Battery		Fuse link, rated current in amperes
	Notes: (1). If the direction of change is not obvious, it may be indicated by an overhead on the outline of the symbol. (2). A symbol or legend indicating the input or output quantity, wave front, etc. may be in each half of the general symbol to show the nature of change		

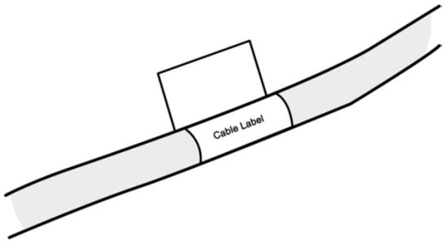
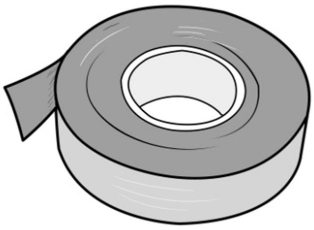
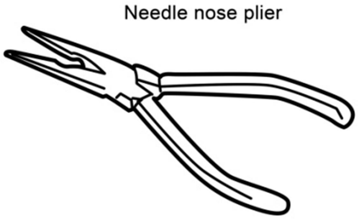
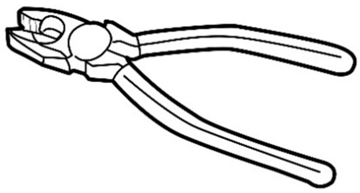
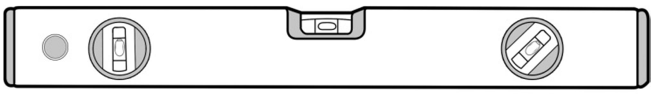
6.2. REQUIRED TOOLS AND EQUIPMENT

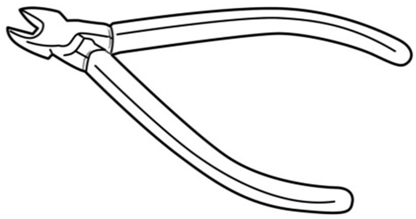
There are a variety of tools and equipment used in the installation of photovoltaic power systems. A selection is included below.

Tool	Function
 Power drill with appropriate drill bits	Drilling holes in surfaces
extension cord 	Connecting electrical installation equipment to a power supply
 Cable fishing tape	For running cables in conduits
	For work requiring access to high places
Compass 	Determining the azimuth of the solar photovoltaic array

Tool	Function
	For basic arithmetic calculations
	Cutting cable insulations to terminate them
	Hammering nails
	Carrying basic installation tools. To be worn around the waist
	Measuring distances
	Protecting workers; functions as a line when working on elevated surfaces (above 2 m)

Tool	Function
Ratchet wrench 	Screwing in nuts and bolts
Electricians chalk line 	Making straight-line markings on installation surfaces
Screw driver set 	Fastening screws
Chisel 	Punching holes in the installation surface, used together with a hammer
crimping tool 	Terminating cable lugs

Tool	Function
	Measuring electrical parameters
	Identifying cables and their respective circuits after installation
 Electricians tape	Insulating cables with broken insulation
Needle nose plier  Line man's plier 	Holding cables
 Spirit Level	Determining whether a surface is straight or slanted

Tool	Function
	Cutting long wires
	Fastening conduits and equipment to mounting surfaces

6.3. INSTALLING THE PHOTOVOLTAIC ARRAY

You cannot have a functional system without solar PV modules. Knowing where and how to install the PV array can make the difference between proper system performance and system failure.

HANDLING PV MODULES

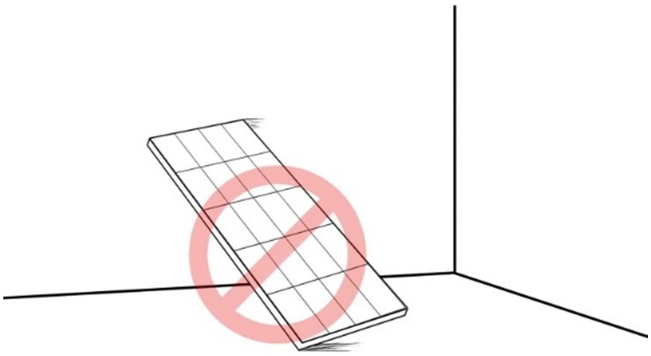
Solar photovoltaic modules are manufactured to withstand difficult weather conditions. Their aluminium frames and tempered glass covering further provide strength. However, they could be damaged if they are not handled properly during transportation and installation.

It is important to note the following when handling and transporting solar PV modules:

- Until installation, always **transport the modules in their original packaging** to prevent damage.

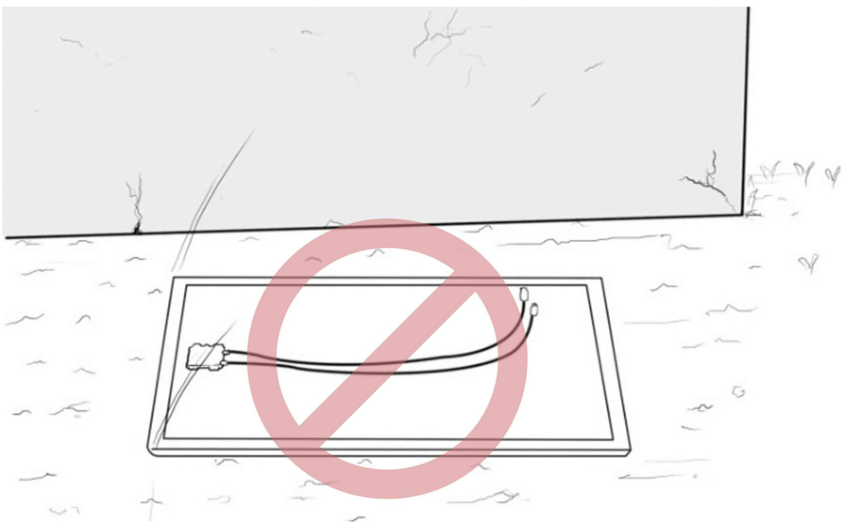
- Inappropriate handling may break the module.

- Hard objects can strike the back of a module and cause permanent damage.
- When one cell is broken, the whole solar PV module is unusable or permanently compromised and its use is limited to a low value and lower power application.
- Store PV modules in a cool dry place.
- Protect the PV modules against scratches and similar damage.
- Do not rest a PV module unprotected on its edges, as this can damage its frame.

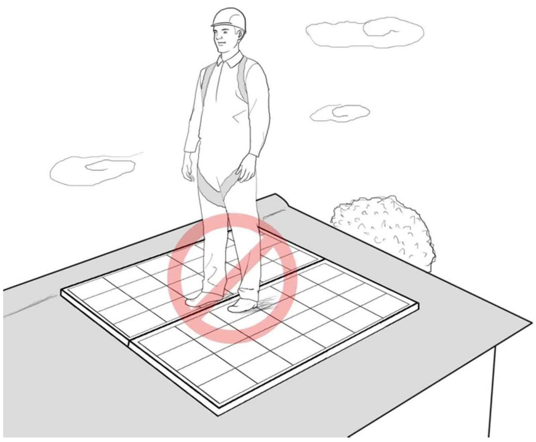


- Ensure the solar PV modules do not bow under their own weight.
- Never move or lift the PV modules using the cables or at the junction box.

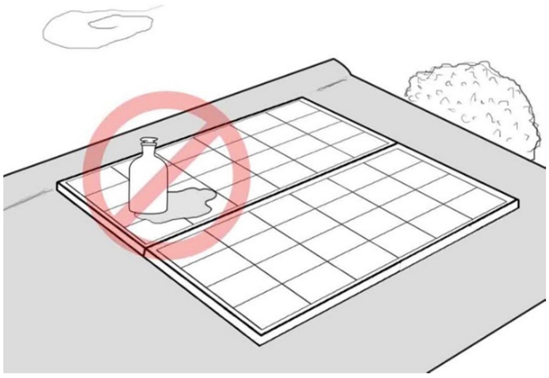
- Do not lay the solar PV module face down on any surface.



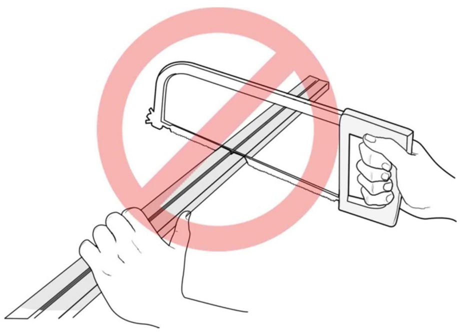
- Do not subject the face of the PV module to mechanical stress
- Do not stand on the PV modules



- Do not drop or place objects on the PV module
- Do not expose the solar photovoltaic module to chemicals



- Do not immerse the solar photovoltaic module in liquids
- Do not install modules when it is raining
- Do not cut or modify parts or rails of the solar photovoltaic module. If you must drill holes in the frame, drill from the base or from the side and avoid damaging the solar cells.

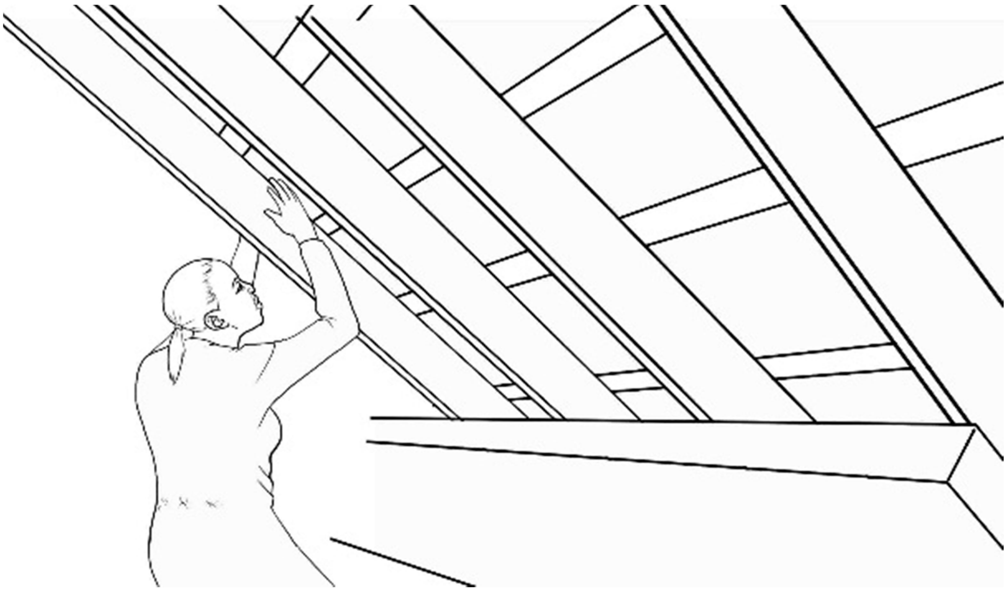


- Completely cover solar photovoltaic module with opaque materials when installing and wiring to halt production of electricity
- Do not use chemicals on solar photovoltaic module when cleaning
- Do not wear metallic jewellery, which may cause electrical shock
- Do not touch cable electrical contacts

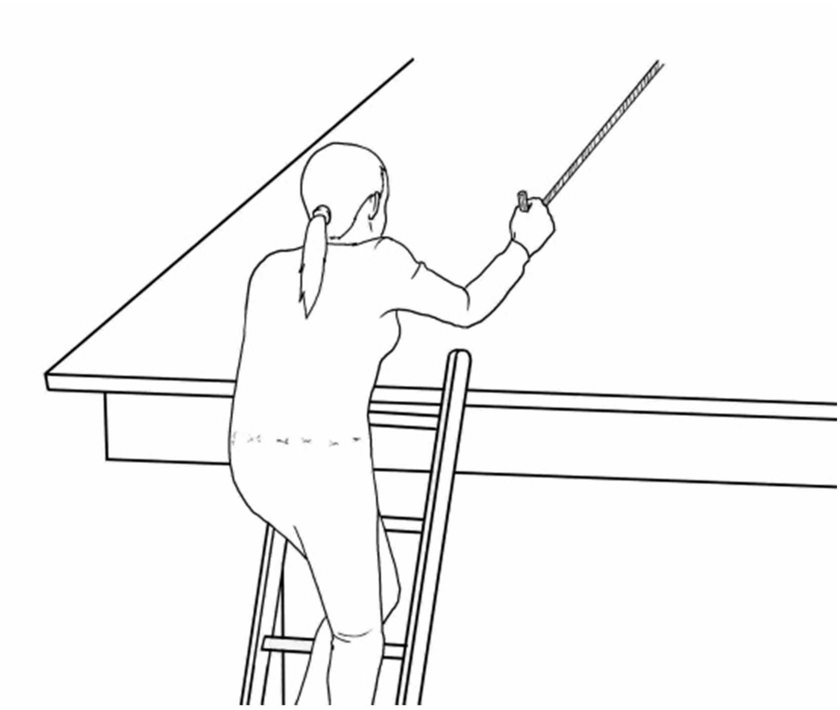
PREPARING A SHINGLE ROOF FOR INSTALLATION

In earlier chapters, we already identified the ideal orientation for installation of PV modules. Which is South facing with an inclination of 15°. You must ensure that the area you plan to install the modules are also free from obstructions such as trees and skylight, etc.

- Locate rafters or trusses on the inside of the roof

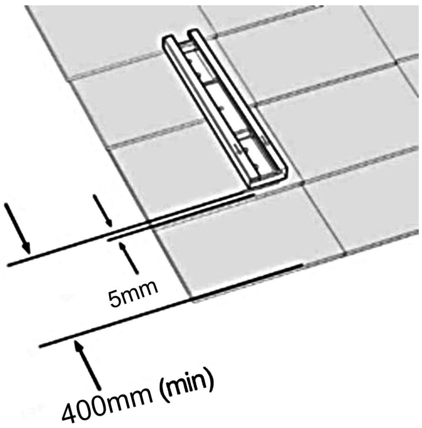


- Locate and measure the locations of the rafters in the attic or at the outside eave, and transfer measurements to the roof

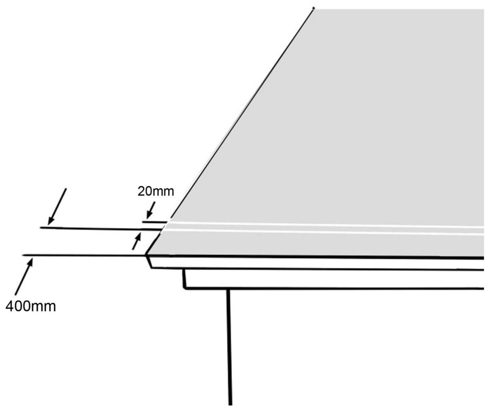


- If you are unable to locate the rafters, alternatively you may scan the roof with a high-sensitivity stud finder

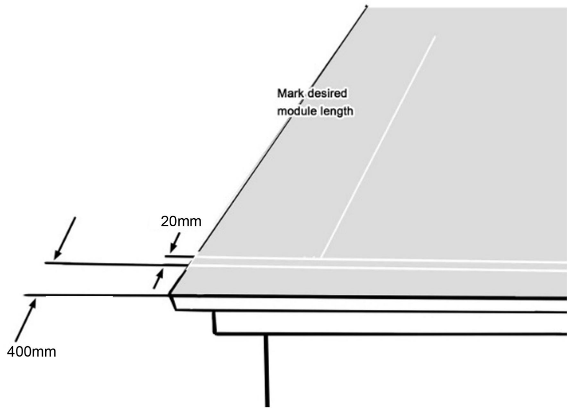
- Measure up at least 400 mm from the eave. Snap a chalk line. This marks the location of the bottom edge of the slider. This line needs to be at least 5.5 mm away from the nearest front edge of shingles.



- Measure up 20 mm from the chalk line and snap a new chalk line. This marks the location of the bottom edges of the PV modules.

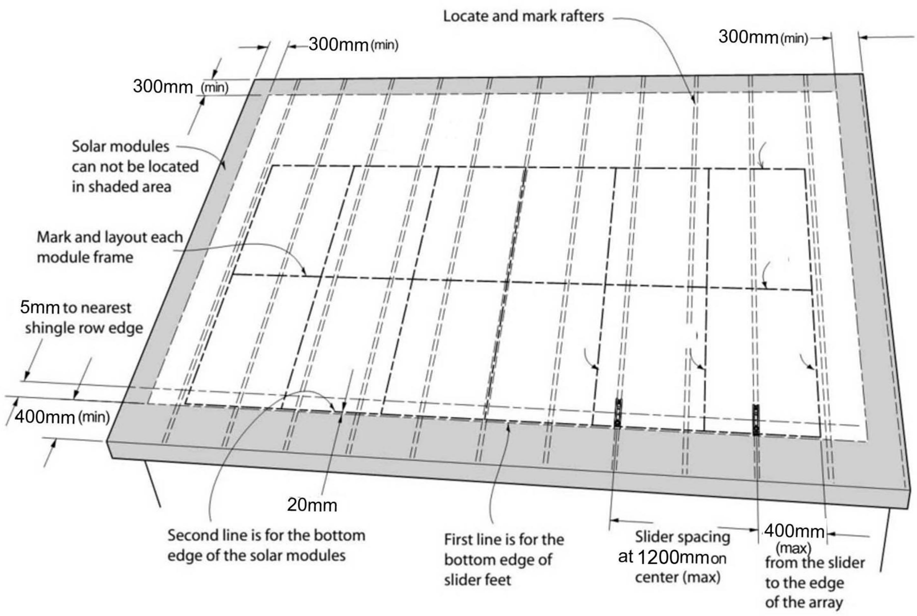


- Measure up from the solar panel chalk line to the desired module length to form the array.

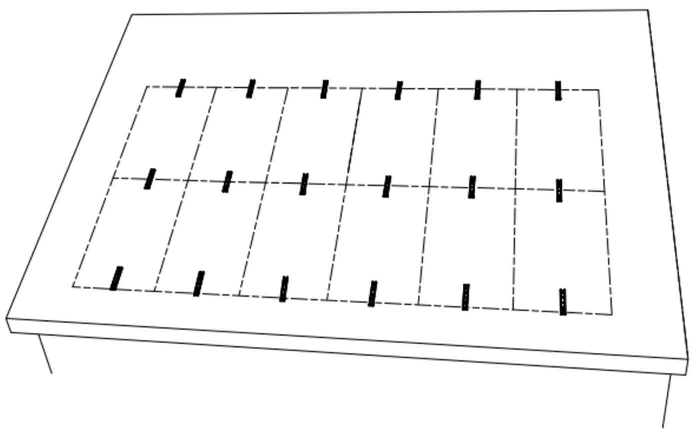


USING PRE-FABRICATED MOUNTS TO INSTALL SOLAR PV MODULES

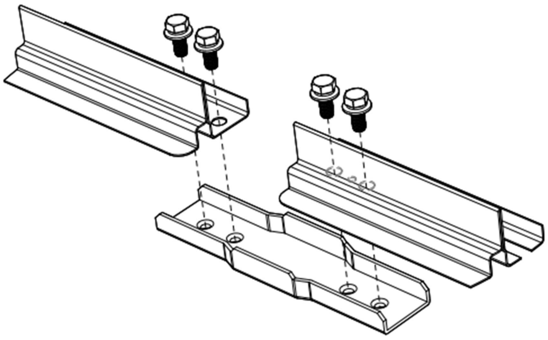
- Before installing the sliders, check the layout of the rails and splices.



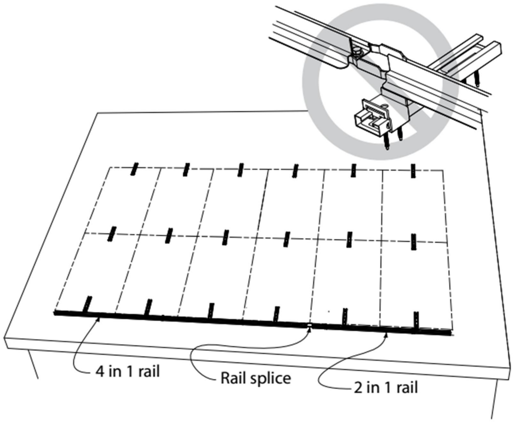
- Place all sliders in the desired locations



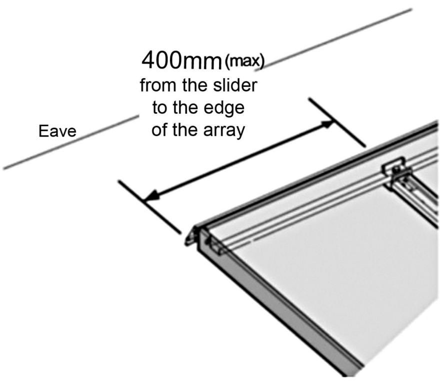
- Place rails with splices into position. Ensure slider locations do not overlap with splices.

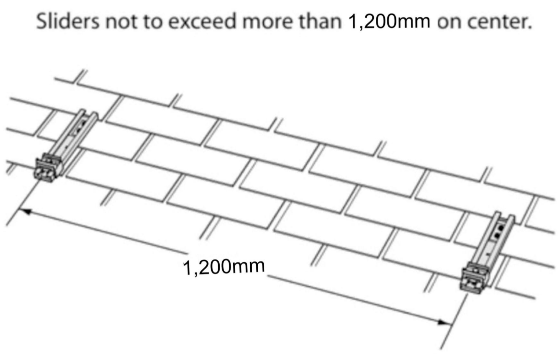


- If these overlap or seem too close
  - Shift rails horizontally or
  - Move sliders to the next rafter or remove splices to switch the long and short rails to opposite sides.
  - Reattach splices after switching the rails and recheck for overlap.



- **Caution**: The maximum distance from the slider to the edge of the array is approximately 400 mm.





- Installing a standard slider assembly

Each adjustable slider is equipped with pre-installed butyl sealant pads. A protective cover must be removed prior to installation on the roof. A hole is located at the centre point of the slider. It can be used as the sight window for locating the slider on the previously snapped chalk line.

There are two arrows located at one end of the slider. The arrows should be pointing towards the eave of the roof. The arrows indicate the location of indents on the slider that prevent the standard slider bottom bracket from falling out.

Place the slider assembly in the measured location and install the self-drilling screws at the upper and lower locations.

Arrows on the standard slider assembly should point to the eave.

CONNECTING PV MODULES

Cables on the DC side of a solar system, whether grid-connected or off-grid, require particular attention, since voltages on the DC side are usually low and the current high. For example, if a 4 kW off-grid solar array feeds via a 10 m long cable of 2 × 6 mm² into a battery at 48 V system voltage, the voltage drop is 7% which means a 7% power loss.

Figure 6.5: MC4 connector, female (left) and male (right)

Ideally, the voltage drop on the DC side should not exceed 3%. Cables can account for a big part of the investment, especially if the solar array is far away from the battery or inverter. Stepping up to a higher system voltage can reduce required cabling and, therefore, costs.

Solar panels often come with a length of wire with a so-called MC4 (multi-contact 4 mm²) connector. These connectors are weatherproof and easy to plug together. There is a male and a female connector (for positive and negative connections), which makes it very easy to connect solar modules in series.

Figure 6.6: Wiring of solar modules with MC4 connectors

However, the pre-mounted MC4 connectors can only be used to connect solar panels in series.

When a parallel connection is required, you will need to cut off the MC4 connector (male or female) and use a common cable connector (screw connector).

When connecting solar PV modules, always observe the following rules:

- Be aware that a solar array generates close to its full voltage even with minimal sunlight

- Choose a main feeder cable from the array to the charge controller to keep the voltage drop below 3%
- Avoid unnecessary cable lengths
- Use screw connectors for all connections. Splicing is very unreliable, since tight connections are difficult to assure and twisting weakens the wires. Splicing also complicates the disconnection of wires, which can be necessary for maintenance and troubleshooting.
- Connect solar module cables to the charge controller feeder cable inside a junction box or DC combiner box.
- Observe the colour code, positive = red, negative = black.
- Junction boxes must be protected from rain, preferably inside the roof.
- Secure the cable and protect it from mechanical stress and impact from objects such as debris, hail, etc.

Figure 6.7: Feeding of module wires through a conduit into the roof

Figure 6.8: Connection of module wires in the junction box

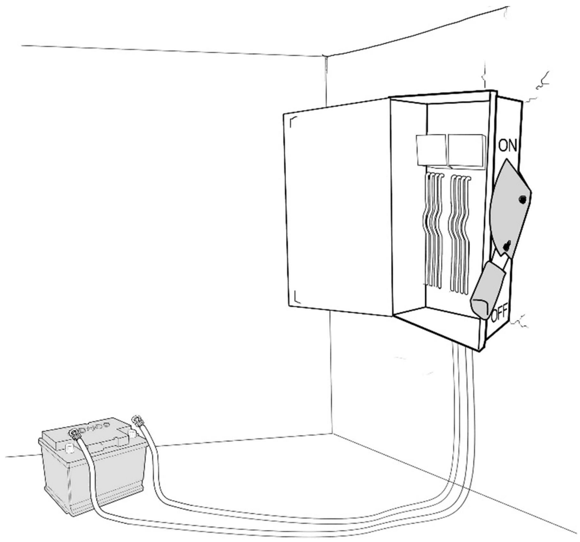
6.4. INSTALLING THE BATTERY BANK

Batteries are the most volatile component in a photovoltaic system. Work done on batteries always poses a risk and maximum care must be taken to avoid all forms of injury.

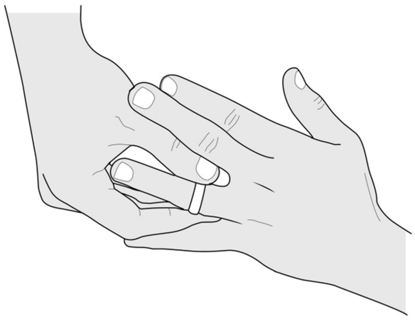
Figure 6.9: 48 V battery bank in a solar hybrid system
– Courtesy: www.solarconnections.com.au

PRECAUTIONS WHEN WORKING WITH BATTERIES

- Care should always be taken to prevent arcing at or near battery terminals. Always open the main DC disconnect switch between the batteries and the inverter prior to servicing or working on the battery bank.



- Battery banks can store voltages with very high current potential. These higher potentials can create electrical arc hazards. Metal tools and personal jewellery can create arcing on batteries that lead to severe burns or battery explosions. Remove personal jewellery and only use appropriate tools when working on batteries.



- Always wear eye protection when working on liquid lead-acid batteries.

- Currents on the battery cables can be very high in normal operation. Choose the correct cable size and the right connectors to connect batteries.


Figure 6.10: Poor connection (left) and good connection (right)

- A short circuit on the battery terminals can result in an enormous release of energy with strong sparks. Batteries must be protected from mechanical impact (falling objects, etc.). The installation must also allow some airflow, as batteries generate warmth during use.

Figure 6.11: Batteries protected in vented battery box

6.5. INSTALLING THE INVERTER AND CHARGE CONTROLLER

Most inverters do have a fan for cooling. Nevertheless, because inverters and charge controllers can get very hot during operation, you should always provide enough space for a cooling airstream when choosing the installation site. Never cover ventilation slots.

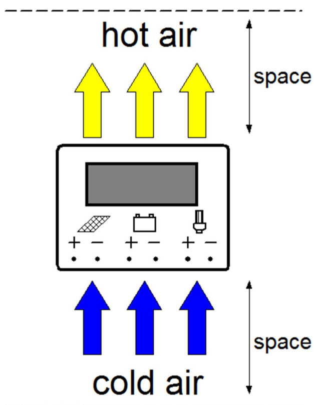


Figure 6.12: Cooling in a charge controller

The inverter can draw high currents from the battery during operation. For example, a 24 V/2,000 VA inverter might draw 2,000 VA/24 V = 83 A under full load. The connector wires from the inverter to the battery must be strong enough to handle the maximum current.

Table 6.1: Required cable sizes for DC side cabling of inverter

Inverter wattage	***Battery voltage***		
	12 V	***24 V***	***48 V***
	Wire cross-section		
150	10 mm^2	6 mm^2	-
250	16 mm^2	6 mm^2	-
500	35 mm^2	10 mm^2	-
1,000	50 mm^2	25 mm^2	-
1,500	50 mm^2	35 mm^2	-
2,000	70 mm^2	50 mm^2	-
2,500	95 mm^2	70 mm^2	50 mm^2
3,000	-	95 mm^2	50 mm^2
3,500	-	95 mm^2	70 mm^2
4,500	-	-	70 mm^2

Many inverters are immediately destroyed when connected with the wrong polarity. If the label does not say 'polarity protected', you should assume it's not. Always observe the following rules when installing an inverter:

- Read the manual
- Mind the specified ventilation space around the charge controller according to the manual
- Use the battery connection cables which are usually supplied with the inverter. Otherwise, use 16 mm^2 cables.
- Check if the voltage rating matches the battery
- Mind the polarity
- Make sure all connections are tight

Always observe the following rules when installing a charge controller:

- Read the manual
- Check if the voltage and current ratings match the solar array
- Mind the specified ventilation space around the charge controller according to the manual.
- Mind possible setup options for different battery types
- First, connect the battery
- Second, connect the solar array
- Make sure all connections are tight

Note: If the solar array is connected before the battery, the charge controller might sustain damage due to overvoltage.

6.6. CONNECTING THE SYSTEM COMPONENTS

» DC connections

When connecting components on the DC side of a PV system, you must connect the negative (-) terminal before the positive (+) terminal.

» AC connections

When connecting components on the AC side of a PV system, you may connect them as you usually connect equipment when wiring a house.

CIRCUITS IN A SOLAR PHOTOVOLTAIC SYSTEM

A solar photovoltaic system consists of a number of circuits, which are identifiable by the system components that they interconnect.

- **Solar source circuit**: This refers to the interconnection between PV modules. It terminates at the PV combiner box.
- **Solar output circuit**: Circuit between the combiner box and the DC disconnect, which is used to isolate the solar panel array from the rest of the system.
- **Charge controller input circuit**: Interconnection between the DC disconnect and the charge controller (solar panel array and battery bank).
- **Charge controller output circuit**: Interconnection between the charge controller and DC loads.
- **Inverter output circuit**: Interconnection between the inverter and the main distribution board

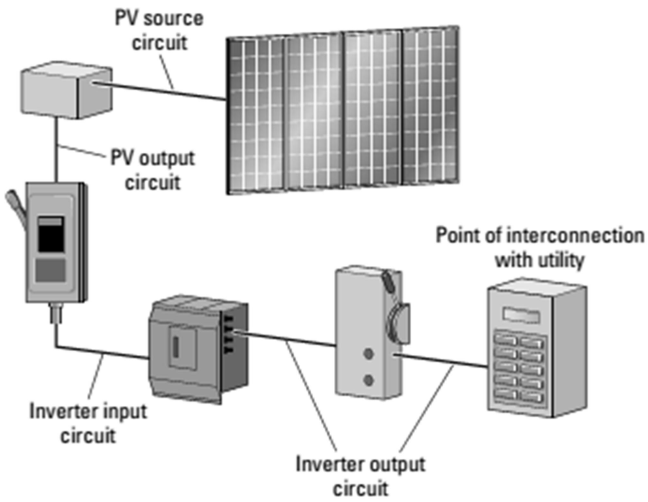


Figure 6.13: Circuits in a grid-connected solar system with no battery bank – *Courtesy: Ryan Mayfield, Photovoltaic design and installation for dummies, Wiley, 2010*

6.7. STEP-BY-STEP INSTALLATION

It is important to prepare the site before starting to install components. Site preparation includes the following steps:

- Confirm the location where the PV modules will be installed.
- Confirm that there is no shade or shade-causing feature, which could interfere with the irradiance that the solar panel array receives. This might include trees, buildings or other man-made structures such as electricity poles.
- Develop a safety plan to be implemented once installation work begins.
- Determine the installation location of system components and cable routes.

- Prepare equipment and tools to be used during installation and ensure that they are available before installation work begins.
- Prepare the installation diagrams, i.e. a single-line diagram or wiring diagram, which shows the interconnection between system components.
- Install conduits (pipes and trunkings) along the planned cable route.
- Install cables in conduits.
- Label all cables according to circuits.
- Install solar panel mounting systems.
- Install system components in the pre-determined locations.
- Mount PV modules on structures at an appropriate angle (15^0) and orientation (facing south).
- Connect PV modules according to desired series/parallel connection.
- Connect batteries according to desired series/parallel connection.
- For an AC system, connect batteries to the inverter (input side). Ensure that the inverter output switch is in the OFF position.
- Ensure that the main distribution board (MDB) breaker is in the OFF position.
- For an AC system, connect the inverter output to the home distribution board. Take care to ensure that only relevant circuits are connected.
- Connect the battery bank to the charge controller.
- If the system consists of DC loads, connect the loads to the charge controller.
- Connect the solar photovoltaic array to the charge controller
- Switch on the inverter
- Turn on all switched off breakers on both the AC and DC sides.

6.8. COMMISSIONING

Once installation is completed, before your client takes ownership of the system, it is important that you commission the system. Commissioning is the process of assuring that all the components of the photovoltaic system have been installed and tested and are fully operational according to the requirements of the owner.

COMMISSIONING REQUIREMENTS AND ACTIVITIES

Commissioning of a solar photovoltaic system comprises the following activities:

» Visual inspection

Visual inspection activities must be completed before and after the system is energised. This visual check ensures that:

- Number of PV modules connected in series and in parallel is correct
- All modules are properly wired
- PV array mount is properly fastened
- All cable conduits are properly installed
- All cables are properly terminated and appropriately labelled.

» *Electrical inspection*

DC SIDE

On the DC side of the installation, you must verify the following:

- Polarity of all cables (positive and negative)
- Open-circuit voltage of each array string
- Short-circuit current on each array string
- Voltage and readings at the critical connection points (junction boxes, disconnects and at the inverter) in the system
- Correct operating voltages and system current as specified for system design
- Wire insulation and resistance
- Effectiveness of grounding connections

AC SIDE

Once you have verified that the DC side meets all requirements, you need to inspect the AC side. This is done by measuring AC voltages along the circuit. Start at the inverter as this is the origin of the AC circuit in your PV system (ensure that the AC disconnect and MDB breaker are in the “OFF” position). If this voltage measurement is as expected, then:

- Switch “ON” the AC disconnect and measure the output voltage and current from there.
- Switch “ON” the main breaker on the MDB and measure the output voltage and current from there.

At this point, if all is as expected, then you may declare the system technically sound. However, commissioning is not complete. You must now proceed with documentation.

» *Documentation*

You must document the procedure for installation, commissioning and maintenance for the system owner. This can easily be done by creating a manual with all relevant information. Make sure that all documentation is simple, clearly presented and easy to understand.

The manual must include the following information:

- Date of commissioning
- Contact numbers in the event of system failure
- Emergency contact numbers
- Basic maintenance schedule for the system owner

FILLING IN A JOB CARD

The job card is to be filled in by you the installer and handed over to the customer with the photovoltaic system. In the job card, important information pertaining to installation and maintenance activities should be included. The job card should also include:

- **Site details**: Clearly state the installation location as well as the name and contact details of the owner.
- **Equipment details**: Indicate all installed equipment as well as quantities and locations. Maintenance requirements may be included if necessary.

- **Installer details**: Name and contact details (telephone numbers, email address and physical address) of the installer should be clearly and visibly stated on the job card.
- **Declaration by the installer**: Ensure that the installation strictly adheres to relevant electrical installation codes in Nigeria.

installation of solar electric system			Job nr.:
company name:	client name:		
company adress:	client adress:		
installer name:	installation site:		
installation date:			
technical details			
the solar electric system is designed to:			
solar module specifications:		qty:	
charge controller specifications:		qty:	
battery specifications:		qty:	
inverter specifications:		qty:	
combiner box:		qty:	
battery fuse:		qty:	
surge protective devices:		qty:	
other equipment:		qty:	
other equipment:		qty:	
other equipment:		qty:	
other equipment:		qty:	
documentation handed over			
manual for charge controller		system logbook	
manual for inverter		maintenance guide	
manual for batteries		troubleshooting guide	
The installer assures that the system is fully functional according to its intended design and in accordance with the regulations of the Nigerian electricity regulatory comission :		date:	
		sign:	
the client confirms that the system is fully functional according to its intended design and to have received all relevant documentation and instructions to operate the system		date:	
		sign:	
if technical assistance is required contact:			

Figure 6.14: Typical job card

7. MAINTENANCE AND TROUBLESHOOTING

What this module is about

Once installation of the photovoltaic system is complete, it is important that the system is adequately and periodically maintained to minimise the possibility of failure. In the event of a failure, the installer must be able to diagnose the problem, provide and implement a solution. This module describes the maintenance activities for a photovoltaic system as well as solutions for common faults that the installer may encounter while at work.

Learning outcomes

At the end of this module, the participant is able to

- Understand and describe factors that can lead to system faults
- Diagnose and correct system faults
- Understand and describe the testing procedure for PV system components
- Use appropriate tools, equipment and materials for system maintenance and repair
- Outline the maintenance procedure for PV system components

7.1. MAINTENANCE

There is a common misconception that PV systems do not require any sort of maintenance. This notion is false. As with any other electrical system installation, a PV system should be maintained periodically to ensure safe and reliable functioning.

Maintenance, when done correctly, helps you identify avoidable problems that could lead to system failure. If you notice a fault during routine maintenance, you will proceed with troubleshooting or, in other words, systematic corrective actions.

Maintenance for PV systems can be classified into mechanical maintenance and electrical maintenance. These maintenance categories include the following tasks:

- Visual inspection of components and wiring systems
- Evaluation of structural attachments and weather sealing
- Cleaning and removal of debris around arrays
- Battery maintenance
- Measuring electrical characteristics and verifying system performance
- Replacement of failed or faulty system components

CATEGORIES OF PV SYSTEM MAINTENANCE

» Mechanical maintenance

This refers to maintenance activities involving the support structures of the solar system. Such structures include the PV array mounts, as well as the mounting structures of all the other system components.

» *Electrical maintenance*

To ensure optimal system performance, you have to measure the electrical characteristics of the PV system from time to time. You must be able to carry out basic measurements using a digital multimeter.

SPECIFIC MAINTENANCE ACTIVITIES FOR SYSTEM COMPONENTS

» *PV array maintenance*

Maintenance activities for the PV arrays are generally mechanical. You will be expected to tighten bolts that fasten the array to the mounts, remove leaves that may fall on the PV array, remove dust which accumulates on the surface of the PV array, etc. Specifically, PV array maintenance activities could include:

- **Debris removal:** Periodically remove any debris, leaves or trash around the PV array. Debris presents a fire hazard as well as a drainage problem. It can lead to mildew and insect problems, ultimately causing cable damage.
- **Shade control:** Blockage from the sun results in energy loss. Therefore, you want to ensure that a solar PV array is not shaded by any natural or man-made objects. Objects such as trees or shrubs, which were not present at the time of installation could be a major cause of shade. Regularly trim all plants which could cast a shadow on your PV array.
- **Soiling**: PV modules collect dust and are soiled over time, especially in arid and semi-arid regions where rainfall is infrequent. Things like bird droppings and engine emissions can also accumulate on the surface of the PV module. This can lead to a reduction in array output of up to 20%. Therefore, periodic cleaning of the PV modules is essential.
- **Weather sealing and structural maintenance:** All equipment that is exposed to the elements should be inspected regularly for signs of weathering. Regularly inspect all points where the solar PV array is attached to a building for signs of water leakage and initiate necessary repairs immediately.

> ***Recommendation***
> PV system inspection should be done quarterly.

» *Battery bank maintenance*

Battery maintenance is the most critical aspect of any off-grid or hybrid solar PV system. To maximise the battery lifespan, monthly maintenance must be carried out on the battery. Battery maintenance tasks depend on a number of factors such as the type of electrolyte and manufacturer. These tasks include:

- Inspecting and cleaning the battery racks and battery terminals. Battery racks should be inspected for structural integrity and any dust removed at every maintenance interval. Always check for and remove any corrosion.
- Inspecting the battery disconnects, over current devices and wiring connected to the battery bank.

- Electrical protective devices are the only safeguard on the PV system to protect the user from electrocution. You must check these devices to ensure that they are fully functional.
- Measuring voltage across the battery bank. The voltage flowing across a battery bank is an important indicator of the state of charge of the battery bank.
- Checking terminations and connecting cables. If the connecting cables are not firmly connected and terminated, the partial contact could result in arcing, which could melt the battery casing and lead to fire.
- Topping up the electrolyte with distilled water (wet cell battery)

Table 7.1: Expected voltmeter readings for 12 V batteries

SoC	*Type of battery*		
	Gel	*Absorbed glass mat (AGM)*	*Wet cell*
100%	12.95 V	>12.8 V	12.60 V
75%	12.74 V	12.55 V	12.36 V
50%	12.54 V	12.30 V	12.10 V
25%	12.34 V	12.20 V	11.90 V
0%	12.10 V	12.00 V	11.80 V

PRE-MAINTENANCE ACTIVITIES

Before you begin maintenance work on a battery bank, you must perform the following procedures:

- Isolate the battery bank by disconnecting the input (supply) from the solar PV array and the output from the electrical load.
- If working on dry cell batteries, ensure that the terminals are clean.
- If working on wet cell batteries, ensure that the caps of each individual cell are tightly sealed to prevent dirt from entering the cells.
- First aid kit. Make sure that a kit is always on site and fully stocked.
- Ensure that a mixture of baking soda and water is close by when working on wet cell batteries in case of acid spills.

PRECAUTIONS TO TAKE WHEN WORKING WITH BATTERIES

When working with batteries, follow all relevant safety rules and regulations. These include:

- Always wear safety goggles when undertaking battery maintenance.
- If working on wet cells, wear protective gloves that are resistant to battery acid solution.
- If working on wet cells, always have a mixture of sodium bicarbonate (baking soda) and water at hand to treat acid burns.
- Always use tools with insulated handles when undertaking battery maintenance.
- Do not smoke or light a fire near batteries.

> *Recommendation*
>
> Battery inspection should be performed monthly.

» *Inverter and charge controller maintenance*

The inverter and charge controller are system components, which are mostly installed indoors and which rarely have moving parts except the inbuilt cooling fan. Required maintenance activities include the following steps:

- Tighten all electrical connections and terminals connected to the inverter system.
- Wipe all accumulated dust from vents and surfaces using a dry cloth.
- Visually examine all indicators and displays to ensure that the PV array is charging the battery bank.
- With the use of a multimeter, measure the voltages and currents for the system components.

> ***Recommendation***
>
> Inverter and charge controller inspection should be done quarterly.

» *Maintaining cables and connections*

Take care to inspect all cables in the system, ensuring that you do not omit any from your periodic maintenance. Tasks to be carried out include:

- Inspect all panels and boxes for rodent infestation and tighten all connection points.
- Inspect the efficacy of switches and breakers. Switch them on and off, looking for sparks. There should be no spark.
- Check for signs of corrosion or burning on the cables and at their connection termination points.
- Where possible, visually inspect all conduit pipes and trunkings for wear and tear.
- Ensure all grounding connections are intact.

Figure 7.1: Rodent bites on a cable

> ***Recommendation***
>
> Inspection of cables and connections should be done quarterly.

DOCUMENTING MAINTENANCE ACTIVITIES

As a PV installation professional, you must always document all maintenance activities that you carry out on the PV system. Important documentation items include:

- **Maintenance schedule**, which shows the maintenance frequency and dates, the type of maintenance, involved components and responsible technician.

- **PV array log sheet**, which shows the maintenance date, condition of the PV array, condition of the PV array mounting structure, condition of the cabling, array output voltage and array output current.
- **Battery inspection log sheet**, which shows the date, battery serial number, condition of terminals and connections, voltage level of the batteries in the bank, and action(s) taken.

7.2. TROUBLESHOOTING

Over the lifetime of the PV system, some faults may develop, which you will need to diagnose and rectify. The method you choose depends on a variety of factors such as the type of fault as well as the system type and age.

Before getting into more detailed troubleshooting, talk to the system owner or operator and ask the following questions. They might provide a quick, easy answer to the problem:

- Has the weather been cloudy recently? Less sunlight means the system will generate less energy than the load consumes.
- Is the system a new installation? Failure(s) in a new system can be caused by faulty components or improper installation.
- Have there been any recent modifications to the system wiring?
- Have you added any new loads which were not part of the original system design?
- How old are the batteries?

COMMON SOLAR SYSTEM FAULTS

PROBLEM: LOW BATTERY STATE OF CHARGE

Indications:

- Low voltage on battery
- "Battery low" indicator of the charge controller is "ON"
- Inverter not functioning (automatic low voltage disconnect)

Possible cause	*Solution*
Faulty connection between PV modules and charge controller	▪ Check and fix connection to PV modules. ▪ Check breakers and disconnect switches.
Faulty connection between charge controller and battery	▪ Check for broken wires or loose connections.
Disconnection between PV modules in array. Disconnection in junction/combiner box	▪ Check module-to-module wires. ▪ Check breakers and disconnect switches.
Insufficient power coming in from PV modules	▪ Make sure modules are clean. ▪ Check for shading. ▪ Check all module-to-module wires; check Voc and Isc of whole array and individual modules.
Battery electrolyte is low	▪ Add distilled water to cell.
Defective battery or cell	▪ Check state of charge of each cell; if there is a significant difference (>0.5 V) between cells the battery needs to be replaced (only possible for single-cell batteries).
Loose or corroded battery terminal	▪ Clean and tighten battery terminals.

Possible cause	Solution
Blown battery fuse	▪ Check correct rating. ▪ Check for a short circuit. ▪ Replace the fuse.
Overuse of the system	▪ Leave appliances and lamps off to allow battery recharging or recharge the battery by other means. ▪ Check and inquire about connected loads and runtime.
Battery will not accept charge	▪ Consider the battery age and history. ▪ Replace battery if old or damaged.
Voltage drop between module and battery too high	▪ Calculate voltage drop. ▪ Replace cable with higher diameter if necessary.
Incorrect setup of charge controller	▪ Consult the manual; change setup accordingly.
Defective charge controller	▪ Check operation of charge controller. ▪ Measure voltages and currents; disconnect and reconnect. ▪ Replace the charge controller.

PROBLEM: NO SOLAR CHARGE

Indications:

- Low voltage
- Charging indicator of charge controller remains "OFF" while sun is shining
- No current in cable from solar modules to charge controller

Possible cause	Solution
Faulty connection between solar modules and charge controller	▪ Check and fix connection to solar modules. ▪ Check breakers and disconnect switches.
Faulty connection between charge control-ler and battery	▪ Check for broken wires or loose connections.
Disconnection between modules in array. Disconnection in junction/combiner box.	▪ Check module-to-module wires; check breakers and disconnect switches.
Thick coating of soot or dust on the module	▪ Clean module with water and soft cloth.
Broken module	▪ Check for broken cells, broken glass or poor connection inside module; replace solar module.

PROBLEM: NO AC POWER ON INVERTER OUTPUT

Indications:

- Appliances are not running
- Power indicator of inverter remains "OFF"
- Fault indicator on inverter is "ON"

Possible cause	Solution
Inverter switched off	▪ Locate ON/OFF switch. ▪ Switch ON.
Short circuit in AC circuit or AC load	▪ Disconnect all circuits and loads from inverter output. ▪ Disconnect DC input from inverter. ▪ Reconnect DC input. ▪ Check output. ▪ Check loads and load circuits. ▪ Reconnect AC loads one by one.
Inverter overloaded	▪ Disconnect all circuits and loads from inverter output. ▪ Disconnect DC input from inverter. ▪ Reconnect DC input. ▪ Check output; check power ratings of all AC loads. ▪ Reconnect AC loads one by one.
Inverter overheated	▪ Disconnect all loads from inverter output. ▪ Shut down inverter and allow to cool down. ▪ Check ventilation. ▪ Check power ratings of AC loads. ▪ Reconnect AC loads one by one.
Low battery voltage	▪ Check battery voltage. ▪ Follow troubleshooting section “low battery state of charge”

» Fault finding and troubleshooting steps

Table 7.2: PV system troubleshooting checklist

	Task	Check
1	Ask the customer when he/she first noticed the fault.	
2	Ask the customer to explain what he/she has noticed in as much detail as possible.	
3	Carry out a visual check of the PV system for any mechanical damage.	
4	Ensure that you have the system circuit diagram at hand.	
5	Check all disconnects, circuit breakers and fuses in the PV system. Ensure that they are in the “ON” position and/or fully functional.	
6	Check the wiring and electrical cables for poor or loose connections.	
7	Check for earth/ground leakage.	
8	Check the PV array connections for damage or disconnections.	
9	Check the charge controller indicator for proper functioning.	
10	Measure voltages and current entering and leaving the charge controller and verify that the values meet design expectations.	
11	Check the inverter indicator for proper functioning.	
12	Check that the inverter is connected to the AC circuit of the building.	
13	Measure voltages and current entering and leaving the inverter and verify that the values meet design expectations.	
14	Check that the terminals of the battery are properly connected.	
15	Measure the voltage and current of the battery bank.	
16	If working with wet cell batteries, check the specific gravity of the electrolyte.	

8. ENTREPRENEURSHIP AND CUSTOMER RELATIONS

What this module is about

Before selling and installing any photovoltaic system, steps such as advertising, marketing and customer communication are necessary. The supervisor must be able to communicate and engage with the customer in a way, which is comfortable for both the supervisor and the customer. The supervisor must also be informed about the financial implications of the proposed system.

Learning outcomes

At the end of this module, the participant is able to

- Understand marketing mechanisms and how to merchandise products in the field of PV systems
- Advertise products, skills and motivate the customer to have the proposed products installed
- Compute basic life cycle cost analysis (LCCA), levilised cost of energy (LCOE), payback periods

Before you install a solar system, there has to be communication and interaction with a potential or current customer. You will most likely be in a position where you have to re-introduce solar PV systems to them all over again. At this time, you perform a variety of roles simultaneously. You are the marketer, salesman, customer service executive and engineer. The customer's decision to purchase or upgrade a system will greatly depend on your interaction with that customer.

8.1. MARKETING AND SALES

Marketing refers to all activities that you engage in to assist potential customers to purchase your product and services. To successfully market your product, it is important that you understand the environment in which you are operating. You need to identify what is the customer's personal motivation. Is it financial, emotional, prestige-related or due to environmental concerns? Everyone has a reason for purchasing a product and solar PV systems are no different in that respect.

When selling a solar PV system, you are not only selling an electric power system. You are also selling the idea of the need for environmental sustainability, that is, that the earth needs to be looked after as well. However, this idea is often not enough to close a sale. Closing the sale of a solar PV system is about more than just stating facts to the customer. It is about how the customer feels about you and your product as well. Your ability to connect with the customer on a subconscious or emotional level plays a far more relevant role than you might imagine in determining your success.

When making a pitch to a potential customer, you need to have a clear idea of the sort of benefits the customer may receive. Explaining technical information or how an inverter works is not the same as explaining potential benefits. What is important to customers is what they stand to gain by purchasing your product, in this case a solar PV system.

MARKETING YOUR PRODUCT

» Developing a marketing concept

It is always useful to develop a marketing concept before you begin to engage with potential customers. Having this type of plan can save you sleepless nights, money and time. A well-developed marketing concept is based on four principal aspects:

Company: An analysis of your company's ethos is very important. You need to decide on a number of questions: What is important to your company? What are your company's strengths and weaknesses? The answers will go into determining the image and subsequent reputation of your company.

Product: Understanding the importance of your product and communicating it to the customer are crucial elements of successful marketing. Consider the following questions: How does this product benefit my customers? What are its weaknesses compared to the products of my competitors? For example, a grid-connected solar PV system benefits customers by providing quiet electricity even when there is a failure from the grid, thus reducing noise pollution when compared to a generator.

Market: The importance of understanding the market cannot be overstated. You need to conduct a market analysis and consider the following questions:

- Which brands dominate the market and why?
- Who are your most important competitors and what is their marketing strategy?
- Which groups of customers are able and willing to pay for your products?

Marketing: You also need to decide:

- Who will do your marketing? Should you involve a marketing company or are you able to do it yourself?
- What resources are available to you for marketing? Marketing can be very expensive if poorly planned and ineffective.

It is important to understand that you need the customer's trust to build a close business relationship. For all of your marketing activities, your focus should always be on the customer and not the product.

» Marketing tools

These are the means you can use to communicate with potential customers. Your choice of tools will depend on factors such as available resources, your target audience, etc. These tools include:

- Face-to-face contact involves direct interaction with the customer.
- Telephone contact does not require direct interaction, but it is also demanding. This method is best used as a follow-up to a previous discussion with the customer.
- Organising events or participating in trade fairs gives you the opportunity to showcase and advertise your product and its benefits to various potential customers at the same location. This is ideal for your company as it allows you to interact with many customers within a short time frame.
- Sending emails is another method to generate attention and interest in your product, which can prompt customers to contact you to make a purchase.

- TV and print media are the best options to reach a large number of people within a wider geographical area.

SELLING YOUR PRODUCT

» Creating the bridge

This is the most important aspect of selling solar PV products. No matter the mode of communication, you need to create a "bridge" to your potential customer. Below are a simple set of guidelines, which would help you cross the "bridge" faster.

- Note the names of the potential customers and address them by name often.
- Introduce yourself clearly by stating who you are and where you are from.
- Explain how you know the customer. It could be through a friend, a chance meeting or even a cold call. Ensure the customer knows how and why you find them interesting.
- If it is a follow-up contact, always introduce yourself in a familiar tone. Phrases like "Nice to see/talk to you again" are helpful in this regard.
- Explain to the customer why you are contacting them. You need to state your business here.
- Make sure to ask if it is a good time for the customer to talk.

» Crossing the bridge

At this point, you need to get a sense of and understand the customer's needs. Your questions always have to be honest, direct and open. In this phase, you have the opportunity gather as much information as possible on the needs of the customer.

Open questions encourage the customer to be more involved in your conversation, as they are forced to think more about their responses. For you, this is a gold mine. You may find out that the customer is interested in another one of your products, which can then become an add-on to your original sale. Closed questions, in contrast, are questions that require a definitive answer. Questions that can be answered with a "yes" or "no" (or a different set of clear alternatives) are closed questions and should be avoided.

Always have a list of questions prepared before you meet with the customer. People often tend to ask closed questions when they are under pressure or they are meeting someone for the first time. Avoid this by preparing well. **Have your list of open questions at hand**.

Remember this is a conversation and not a lesson. Keep the technical information at a minimum and listen to the customers. Let them talk and give them time to imagine scenarios for the things you are discussing. Your goal is to understand the customers. The more they talk, the more information you are able to gather.

As a last word, always be on the lookout for other opportunities that may arise from your conversation with the customer.

> ***Note:*** That crossing the bridge could take you more than one meeting with the customer.

» *After the bridge*

Now the customer has warmed up to you. The conversation is flowing and you are aware of the customer's needs. It is time for you to begin to offer solutions to meet those needs. The following points should guide you on how to navigate this part of the conversation.

- Start with the benefits of your solutions. The customer wants to know "what is in it for them". You have identified their needs; now take the time to explain specific ways that your solution can help.
- Use customer-oriented words and phrases. Use terms that the customer is comfortable with. For example, if the customer uses "energy-saving bulbs" instead of "LED lamp", you should adopt the customer's phrases while explaining the differences in layman's terms.
- Give the customer a show. Where possible, a presentation, which demonstrates your product being used helps to solidify the image you wish to create in the mind of the customer. If you are unable to do this with some system components, share letters of recommendation from satisfied customers, show pictures of installation work you have done, etc. Make the customer feel at ease with the knowledge that you thoroughly understand the technology.

CLOSING THE DEAL

You have crossed the bridge and the customer seems to be interested in purchasing a system. This is what you have been working towards, and you are very excited. You should be! After all, you have worked hard to reach this point. Now, **slowly** shift to the business aspect of things.

Below is a list of helpful pointers to help you know when the customer is ready to purchase a system:

- The customer uses affirmative phrases (phrases of assent). For example, "That means I will have uninterrupted electricity?"
- The customer asks questions about choices. For example, "Do you think I should get a bigger battery bank because of my load?"
- The customer refers to a project and asks delivery-related questions. For example, "What will be the total cost?" or "How long will it take to complete the installation?"
- The customer is eager to interact with the equipment. For instance, you show the customer a working system or a component and they want to take a second look.

When you are confident about the customer's readiness to purchase the system, you need to eliminate any obstacles that could prevent the purchase. Ask questions such as: "Do you have any other questions that I may clarify?", "What else can I do for you?" Take care not to sound overly confident, as it can be a turn-off for customers. Most customers prefer to feel that they have put you through your paces before making payments. Do not make them feel otherwise.

» *Agreeing on a price*

Everything appears to be going well and you are eager to make the sale. However, before you bring up the topic of price, remember that you are selling a product and not a price. Don't be in a hurry to start talking about money. Instead, make sure that the customer is aware of all the benefits they will receive by purchasing your product. Save the financial part for the very end. If the customer does bring it up, try to buy time until you have fully explained all benefits.

» Managing expectations

You have agreed on a price and the customer expects you to install a system according to the terms of the deal. Make sure that the client understands what the system can do and how it functions. It makes no sense to sell a 5 kW system when the customer expects it to perform like a 10 kW system. It is your responsibility to ensure that the customer fully grasps the possibilities of the system.

AFTER THE DEAL

» Customer relationship management

Now you have agreed on a price and the system. Before installing the system, ensure that the customer understands the type of system that you have agreed on, as well as the estimated time it will take to install completely.

You must ensure in all your dealings with the customer that you are direct and honest and that you deliver on all agreed points. If there are any changes on your end, for whatever reason, you must inform the customer immediately.

Once installation is completed and you have handed over the system to the customer, ensure that you explain the need for maintenance to the customer, ideally providing the customer with an abridged manual for tasks that are end-user friendly.

8.2. SIMPLE ECONOMIC CALCULATIONS

SYSTEM COSTING

The initial costs of a solar system often seem high in relationship to the energy demand they are supposed to cover, especially when compared to the investment cost of a diesel generator equipped to do the same job. However, it is no longer a secret that when considering the long-term costs such as reliability, cost-effectiveness and noise, a solar system is clearly the winner in this comparison. Prices for solar modules have declined over the past three decades. This is largely due to the improved commercialisation of PV modules, as well as the use of more advanced technologies in the production chain.

The average price for photovoltaic modules in Nigeria is about NGN 300 per watt.

Costing a system can be done under several aspects:

- Initial investment: This is the total cost of all components plus installation.
- Running costs: Applies to paid labour for maintenance work such as cleaning and other service activities, battery changes and other scheduled replacements, repair or exchange of faulty components, system checks.
- Cost versus generated energy: This is the cost of the entire system over its lifetime compared to the amount of electrical energy it generates during the same time.

- System lifespan: Solar systems are usually assigned the lifetime of the solar modules, which is at least 20 years.

Example: Cost of total investment

Please note that prices stated below are as of 8 March 2016.

For our 3.2 kWp solar system we want to estimate the costs for the total investment, lifetime, daily operation (running costs) and energy generation:

Initial investment			
Item	***Qty***	***Unit cost (NGN)***	***Total costs (NGN)***
Solar module 320 Wp	10	96,000	960,000
Battery OPzV 2 V/800 Ah	24	120,000	2,880,000
Charge controller, Steca, 48 V/55 A	1	90,000	90,000
Inverter, Steca, 48 V/1.6 kVA	1	100,000	100,000
DC combiner box incl. circuit breakers	1	30,000	30,000
Cable 2 ×16 mm²/m	12	1,500	18,000
Mountings for solar modules	10	2,500	25,000
Connectors, fasteners (lump sum)	1	15,000	15,000
Labour	1	40,000	40,000
		Sum total	**NGN 4,158,000**

Running costs over 20 years			
Weekly cleaning	1040	NGN 500	NGN 520,000
Quarterly system check	80	NGN 4,000	NGN 320,000
Replace faulty charge controller	1	NGN 90,000	NGN 90,000
Replace faulty inverter	2	NGN 250,000	NGN 500,000
Replacement of batteries	1	NGN 2,880,000	NGN 2,880,000
		Sum total	**NGN 4,310,000**
		Total cost	**NGN 8,468,000**
		Annual cost	NGN 423,400
		Monthly cost	NGN 17,641.67
		Daily cost	NGN 1,160
		Daily energy generation	12 kWh
		Cost / kWh	NGN 96.67

Note: A battery-based standalone solar power supply system cannot compete with the energy price of the utility grid. The most expensive part is the energy storage. Unlike the prices for solar modules, battery prices are not decreasing, nor are they expected to change in the near future, barring a ground-breaking new technology or manufacturing process.

Example: Instead of our 3.2 kWp solar system, we consider another power source and calculate the costs of energy generated by a petrol-driven 2 kVA generator:

Power generation by petrol-driven 2 kVA generator, 10-year lifespan	
Initial investment	NGN 140,000
Replacement after 20 years (4 replacements)	NGN 560,000
Maintenance over 20 years @ NGN 240,000/a	NGN 4,800,000
Petrol over 20 years @ 25 l/day for 24 hrs	NGN 26,100,000
Total life cycle cost	**NGN 31,600,000**
Daily costs	NGN 4389
Cost per kWh @ 38 kWh/ day	NGN 114.3

Note: When compared, the initial investment in a petrol-driven generator does not vary more than 5% from an investment in a solar power supply system; however, the daily running expenses for the 20-year period and the cost per kilowatt hour of electricity generated turn out to be 2 to 3 times higher than the corresponding costs for the solar generator.

Solar photovoltaic system projects often require high capital investments. As is the case with all projects and investments, the associated risks and potential rewards should also be considered.

FINANCIAL FORECASTING TOOLS

Financial forecasting tools support decision-making and provide the project developer with vital information for planning. It is common to adopt a multi-criteria approach by including two or more of the following financial analysis tools in the financial planning for your project.

» *Life cycle cost analysis (LCCA)*

A LCCA takes into account the present value of all the costs associated with an investment option over its lifetime; that is, the total cost of ownership over a given period. This includes the costs for acquisition (capital and installation costs), replacement, operations and maintenance (O&M), fuel, conversion and/or decommissioning at end of life. The advantage of LCCA is that it is a familiar tool for decision makers and economists. It also provides options to include time preferences and/or the opportunity cost of capital.

If...	*It means...*	*Then...*
LCC > 0	Net income IS NOT generated over the project lifespan.	It is advisable to reject the project.
LCC < 0	Net income IS generated over the lifespan of the project.	It is advisable to accept the project.
LCC = 0	No gain, no loss. The project breaks even over its lifespan.	No clear rule. Base your decision on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

The project with the lowest (or negative) life-cycle cost is more favourable; this means it generates net income. The project with a zero life-cycle cost breaks even; its costs equal its income. The project with the highest positive life-cycle cost (greater than zero) is a failure as it does not generate net income.

» ***Cost-benefit analysis (CBA)***

Prior to erecting a new facility or taking on a new project, prudent developers will conduct a cost-benefit analysis as a means of evaluating all potential costs and revenues once the project is complete. A cost-benefit ratio (CBR) is normally calculated where only recurrent income sources are considered as benefits.

If...	***It means...***	***Then...***
CBR > 1	Costs exceed benefits	It is advisable to reject the project.
CBR < 1	Benefits exceed costs	It is advisable to accept the project.
CBR = 1	Benefits and costs are equal	No clear rule. Base your decision on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

Formula:

$$CBR = \sum_{t=0}^{n} \frac{[(C_n + M_n + F_n - R_n) \div I_n]}{1 + r^n}$$

Where C_n = capital cost at time n

M_n = operations and maintenance cost at time n

F_n = fuel cost at time n

R_n = residual cost at time n

I_n = income at time n

n = time span

r = discount rate

Example: Comparison between lifetime cost and cost-benefit ratio

For a lifespan of n = 120 months (10 years) and an assumed equivalent discount rate r = 0.5% per month, the discount factor $D_{nr} = [[1-(1+r)^{-n}]/r\} = \{[1-1.005^{-120}]/0.005\} = 90.073$. Compare the lifetime costs and cost-benefit ratio of the two projects below:

	2 kW water turbine	***20 kW solar PV plus battery storage***
Average installed capacity	1,460 kWh/month	14,600 kWh/month
with average availability	0.75	0.07
giving average monthly output	1,095 kWh/month	1,022 kWh/month
worth savings of	NGN 43,800/month	NGN 40,900/month
Capital cost (at start of project)	NGN 3,000,000	NGN 2,500,000
including fees, control system, electrical connections, etc.	including civil works	including energy storage (batteries) and inverter
O&M costs (including insurance, maintenance, spares, etc.)	NGN 1,500/month	NGN 4,000/month
Capital cost C (at start of project)	NGN 3,000,000	NGN 2,500,000
Lifetime net expenditure (OD_{nr})	NGN 1,500 × 90.073 = NGN 135,100	NGN 4,000 × 90.073 = NGN 360,300
Lifetime net income (ID_{nr})	NGN 43,800 × 90.073 = NGN 3,945,200	NGN 40,900 × 90.073 = NGN 3,684000
Lifetime Cost LC = [C + (O – I)] (negative cost indicates net gain)	NGN 3,000,000 + NGN 135,100 -NGN 3,945,200 = -NGN 810,100	NGN 2,500,000 +N 360,300 – NGN 36,840 = -NGN 823,700
CBR = [(C + O)/I] (CBR < 1 indicates net benefit)	[(NGN 3,000,000 + NGN 135,100)/NGN 3,945,200] = 0.795	[(NGN 2,000,000 + NGN 360,300)/NGN 36,840] = 0.776

Based on both LCCA and CBR, the solar PV project is marginally better and would be recommended.

» *Payback period (PP)*

Payback period is the time it takes for an investment to generate an amount of income or cash equal to the cost of the initial investment. The shorter the payback period, the better the investment is deemed to be. Developers and investors use payback period to make quick judgments about a particular investment or capital purchase. It is calculated as:

PP = Capital cost ÷ Annual savings

Example: Calculation of payback period for project A and B

Project A (wind turbine) has an investment cost of NGN 1,171,500 while project B (solar PV) costs NGN 1,092,000. Both have the same savings from reduced diesel generator use which is 70% of current spent = NGN 60,000. Assuming either of the two projects will repay initial investment costs with savings from reduced diesel generator use over time, determine which project to choose based on payback period.

Project A: Wind turbine

Calculations		***Remarks***
Investment required	NGN 1,171,500	Per installation
Savings from reduced diesel generator consumption	NGN 54,000	Assuming diesel generator usage is reduced to one-tenth of NGN 60,000
Payback period	22 months	Assuming investment financed by savings

Project B: Solar PV

Calculations		***Remarks***
Investment required	NGN 1,092,000	Per installation
Savings from reduced diesel generator consumption	NGN 54,000	Assuming diesel generator usage is reduced to one-tenth of NGN 60,000
Payback period	20 months	Assuming investment financed by savings

The preferred project with the lowest payback period is project B, solar PV.

» *Levelised cost of energy (LCOE)*

LCOE is the ratio of the net present value (NPV) of total investment/capital costs, fuel costs, operating and maintenance costs of a system to the NPV of the total electricity generated by the system over its economic lifespan. It allows for comparisons to be made between different technology sources based on the electricity cost.

The LCOE gives the price of electricity required for a project where revenues would equal costs, including a return on the capital invested equal to the discount rate. An electricity price that surpasses the LCOE would yield a greater return on capital, while a price below it would yield a lower return on capital, or even a loss.

CONSIDERATIONS WHEN MAKING A FINANCIAL ANALYSIS

When conducting financial analysis for a project, it is advisable to adopt a multi-criteria approach to provide different valuation mechanisms that can inform your investment decision.

» *Financial statements*

In addition to the financial forecasting tools described above, for certain categories of projects, permitting agencies require project developers to provide projections of the following financial statements for the duration of the license or a minimum of five years.

» *Profit and loss (P&L)*

The P&L or income statement reports the financial performance of an entity or project in terms of net profit or loss over a specified period of time. It takes the difference between the income and expenses to present either a profit or a loss.

Advantages	*Disadvantage*
An updated profit and loss account is a useful tool for measuring performance and expenditures: ▪ It can tell you where you're losing money, where you're making it, and how to improve performance. ▪ It can help you identify trends and predict future performance.	▪ As with all financial statements, a disadvantage is that the information provided depends largely on the accuracy of the data used to generate the statement.

» *Cash flow forecasts*

The cash flow statement presents the cash inflow and outflow over a period of time.

Advantages	*Disadvantage*
▪ It shows the actual cash position available. ▪ It helps in making projections regarding the future liquidity position, thereby allowing for arrangements to be made in advance for any shortfalls.	▪ On its own, a cash flow forecast only shows the cash position and not the company's actual profit and loss.

» *Balance sheet*

The balance sheet is a statement of financial position presented at a given date. It captures the position of assets, liabilities and equity of an entity or project.

Advantages	*Disadvantages*
▪ It allows investors to develop a well-informed opinion of the risk and return prospects. ▪ Financial ratios can be calculated using various balance sheet items to obtain a very thorough summary of the financial health of the company in question by analysing its cash position, working capital, liquidity and leverage. ▪ Balance sheet items allow you to assess a company's asset turnover rates, a measure of how efficiently a company uses its assets, as well as key profitability and return measures such as return on equity.	▪ Balance sheets present a snapshot of the financial position at a given point in time; its figures can be misleading. ▪ Many balance sheet items, such as fixed assets, are reported at their historical cost basis, the purchase amount of an asset, which often has little to do with the more meaningful fair market value.