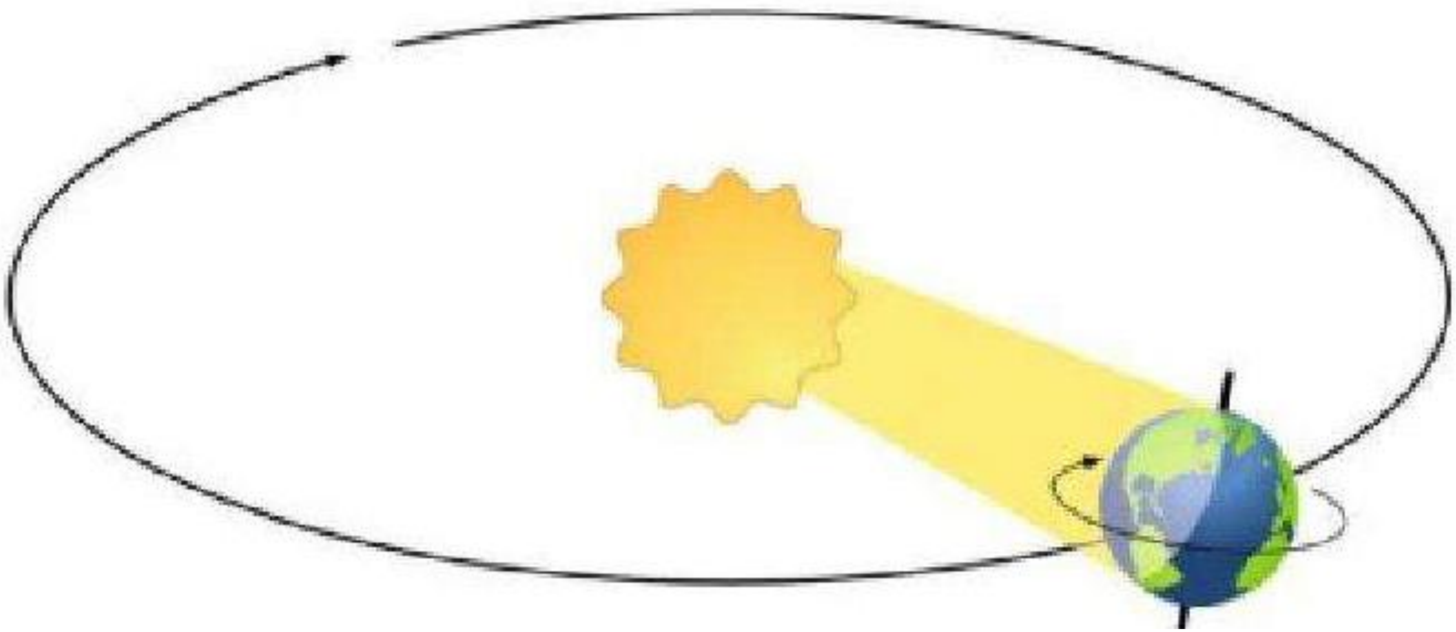
Sun geometry

Because of the Earth's orbit and rotation, the position of the sun relative to a solar array is constantly changing. Designers use several geometrical techniques to design an array that will capture the most solar energy possible. The location of the sun is specified by two angles which vary both daily and annually.



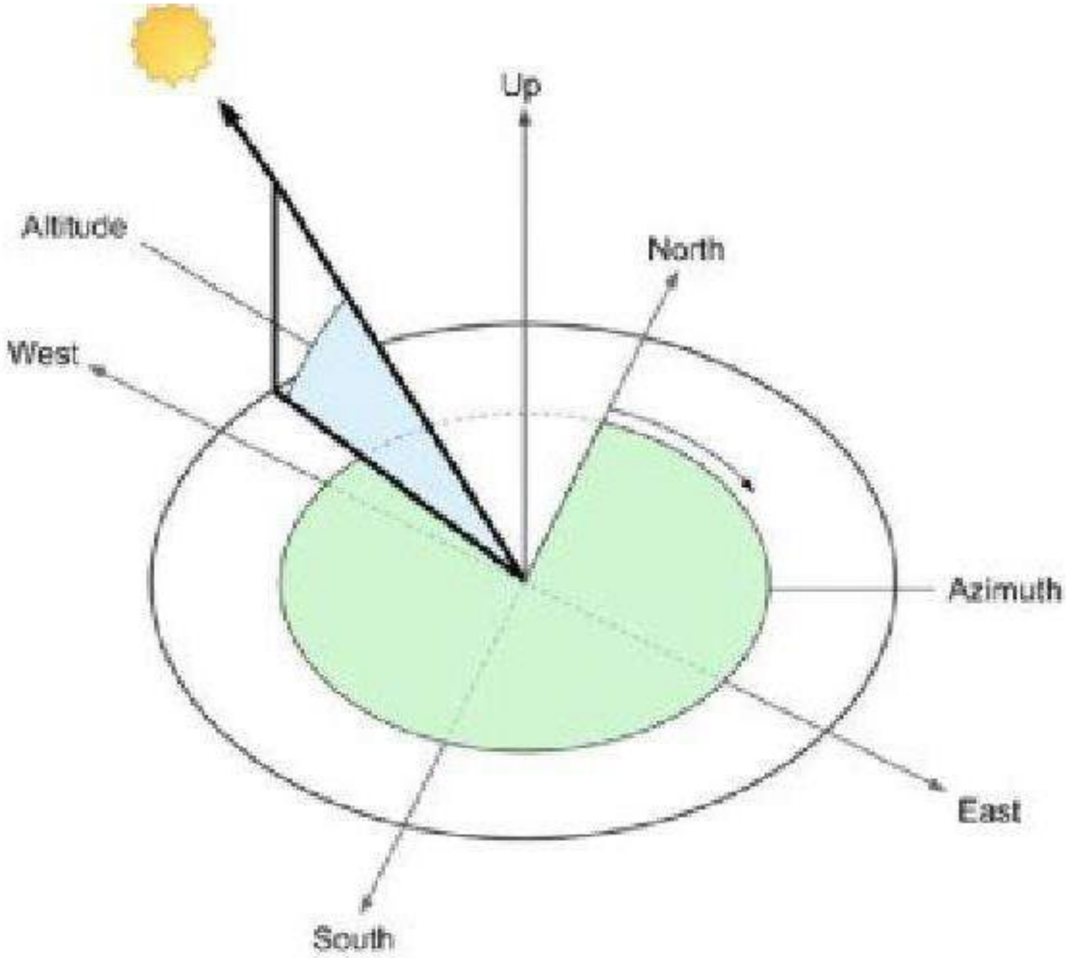
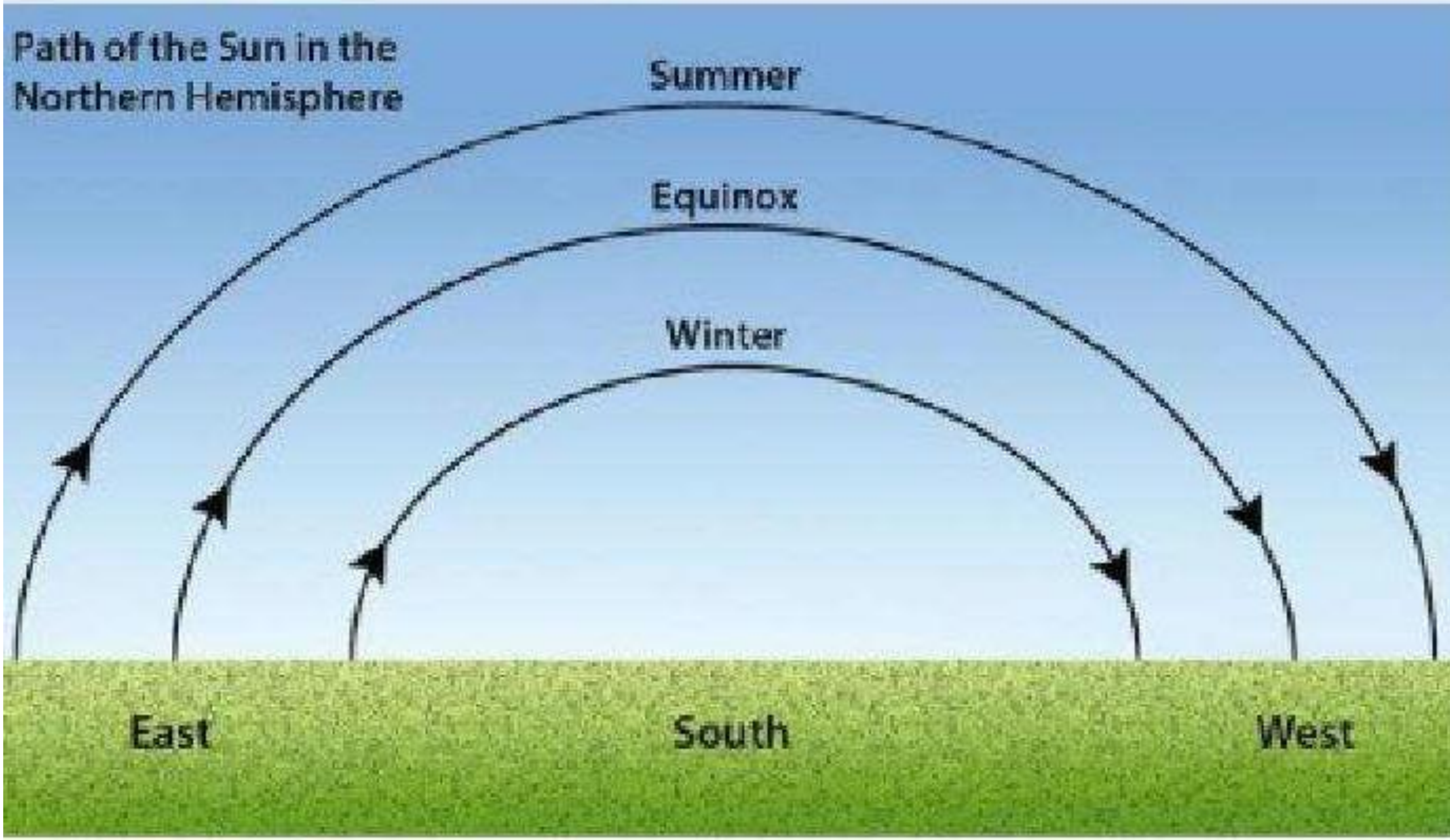


Figure 2.16 The sun's altitude is shown in blue while its azimuth is represented by green

Source: Global Sustainable Energy Solutions



Path of the Sun in the
Northern Hemisphere
Summer
Equinox
Winter
East
South
West

The sunpath diagram is composed of:

- azimuth angles, represented on the circumference of the diagram;
- altitude angles, represented by concentric circles;
- sunpath lines from east to west for different dates in the year;
- time of day lines crossing the sunpath lines;
- location information that refers to latitude.

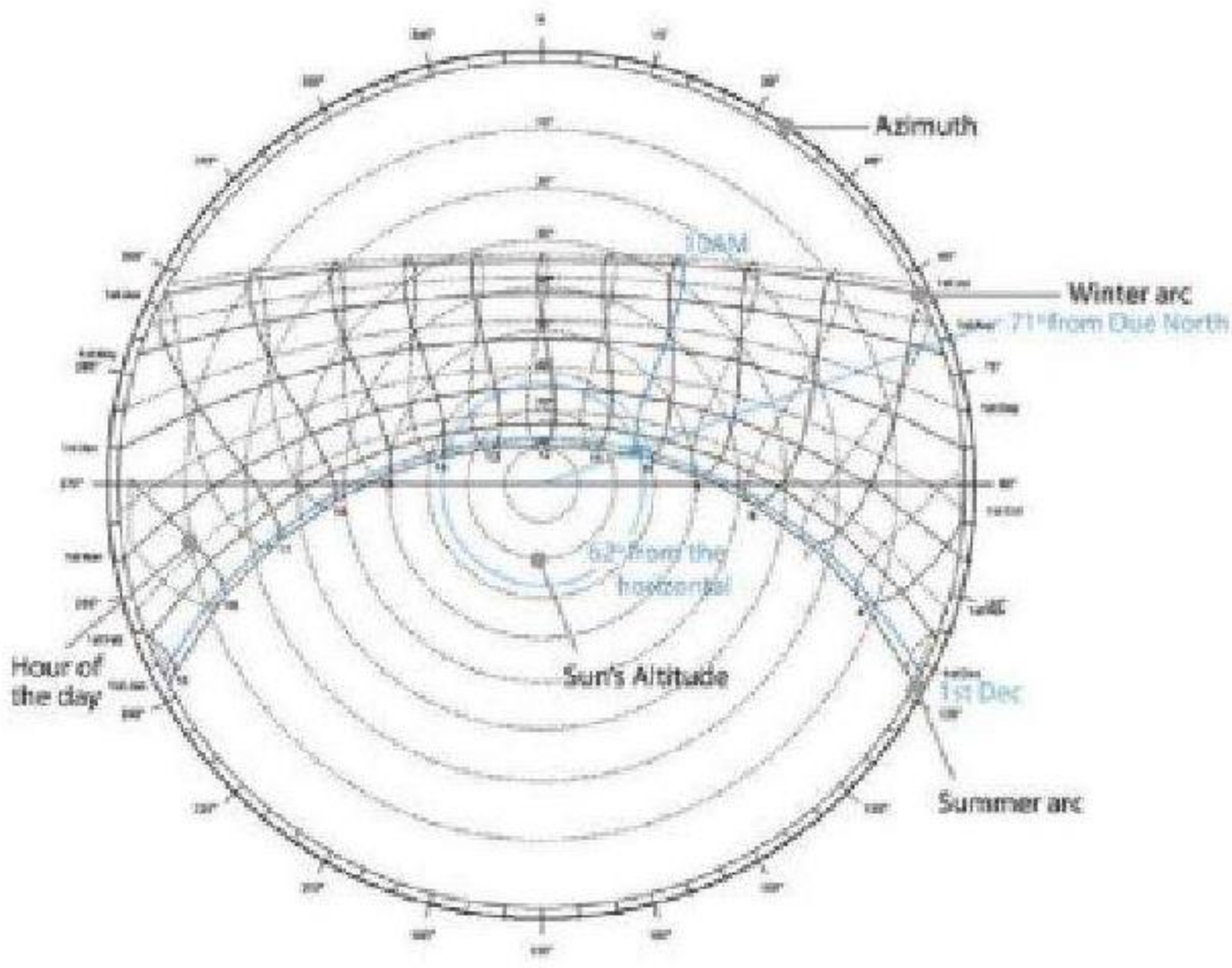
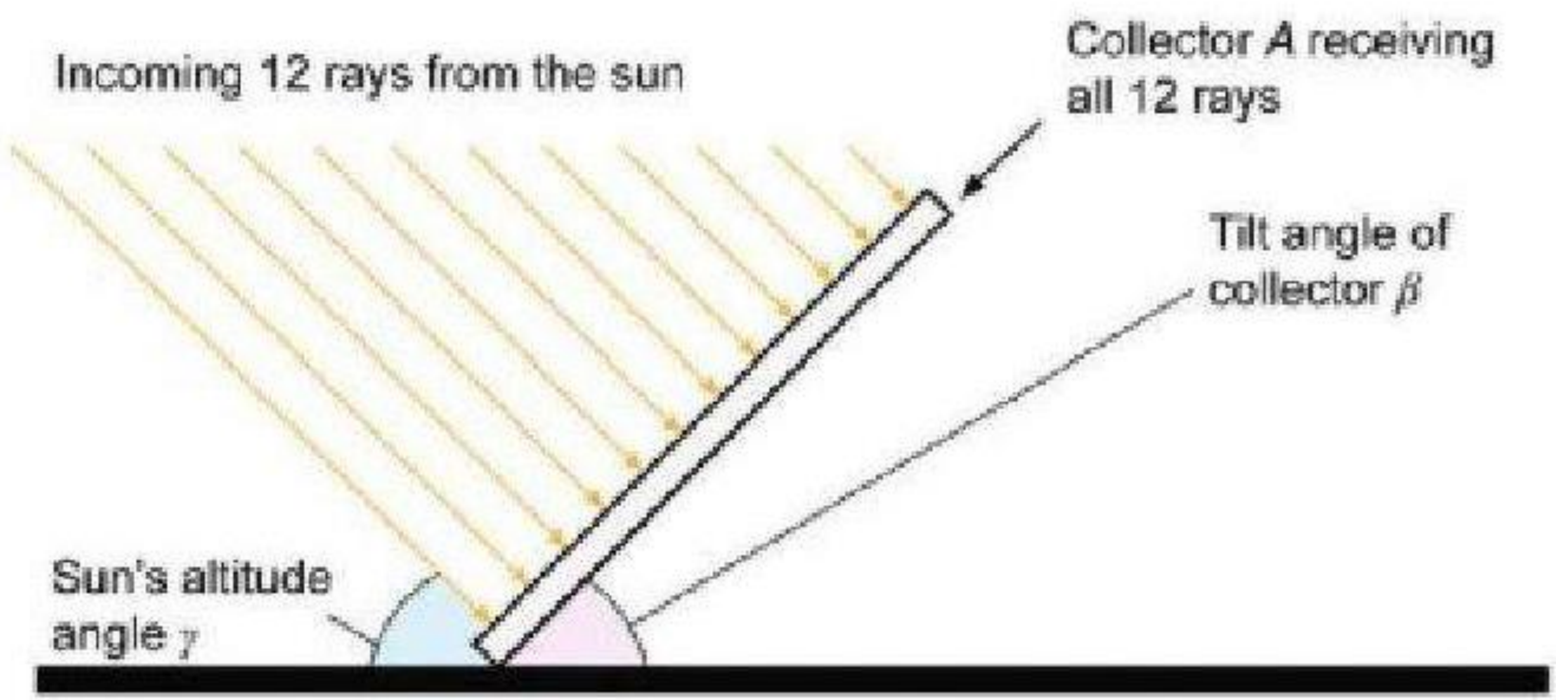


Figure 2.19 Sunpath diagram of Sydney has been used to find the precise location of the sun on 1 December at 10am. 1 December is highlighted on the right of the circle, this line is

The position of a solar module is referred to as its orientation. This orientation of the solar array is very important as it affects the amount of sunlight hitting the array and hence the amount of power produced. The orientation generally includes the direction the solar module is facing (i.e. due south) and the tilt angle, which is the angle between the base of the solar module and the horizontal. The amount of sunlight hitting the array also varies with the time of day because of the sun's movement across the sky.



Incoming 12 rays from the sun

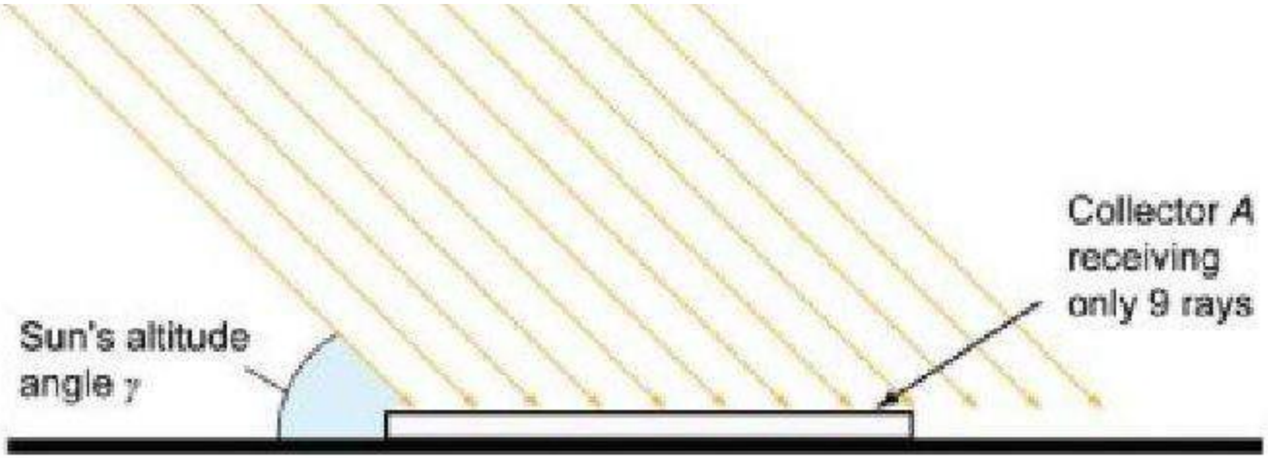


Figure 2.21 If the same collector is laid horizontally on the Earth's surface at the same time as in the image above, the collector only captures 9 rays

Source: Global Sustainable Energy Solutions

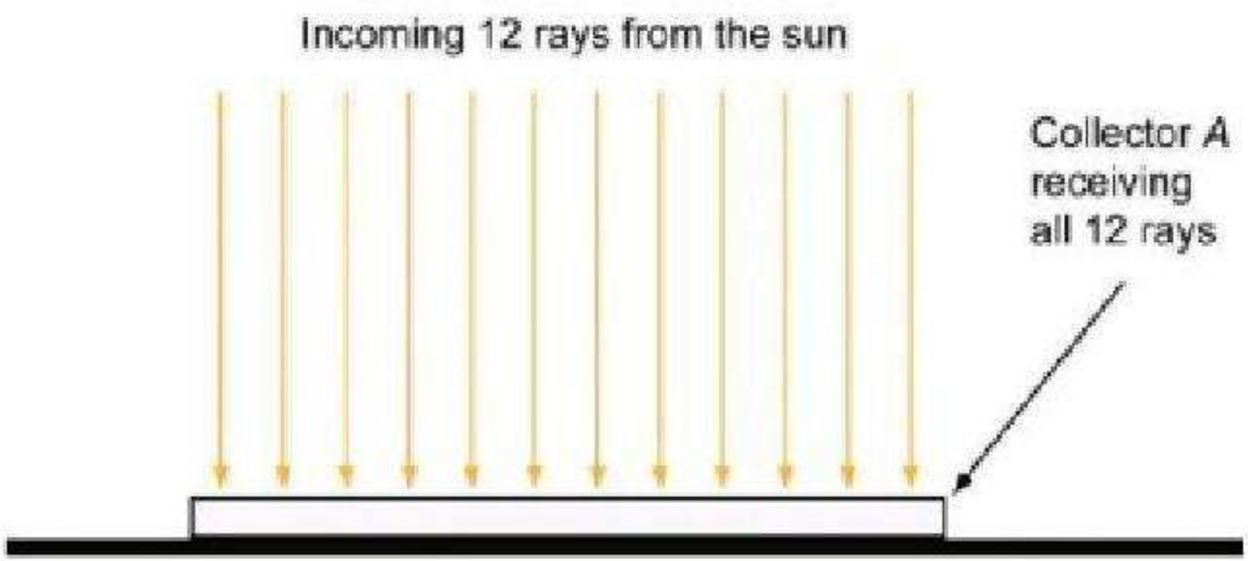


Figure 2.22 A solar array horizontal to the ground will receive the most radiation at solar noon when the sun is directly overhead

Source: Global Sustainable Energy Solutions

Box 2.5 Magnetic declination

When installing a photovoltaic system it is important to consider the magnetic declination of a location (also known as magnetic variation). Magnetic declination is the difference between true north (the direction of the north pole) and magnetic north (the direction in which a compass will point). A solar system should face true north or true south and so the magnetic declination angle of the location should be considered.

In New Orleans magnetic declination is approximately 0° and so the compass would point to true north. In Seattle, however, the magnetic declination angle is approximately 17° east, so when the compass points to 17° east it is in fact facing true north or true north is 17° west. A PV system in Seattle should be installed facing 197° east (or 163° west) so as to face true south.

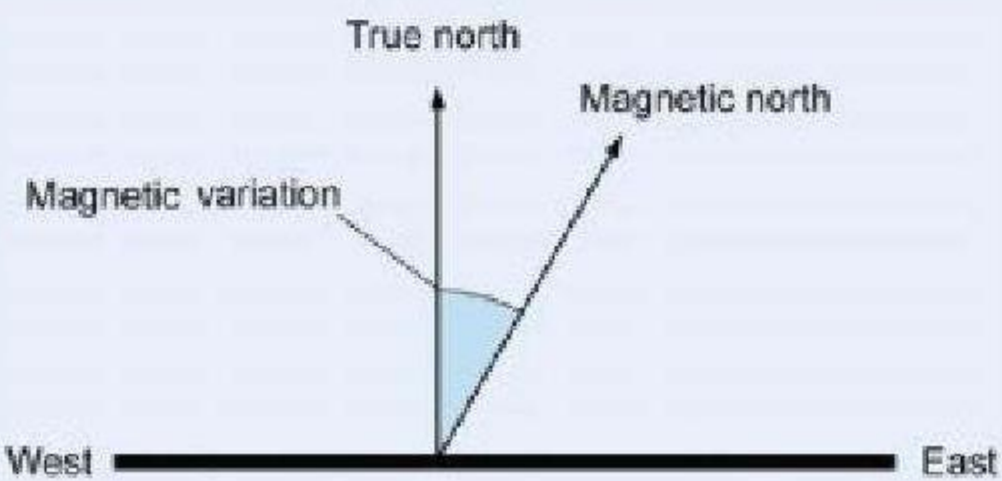
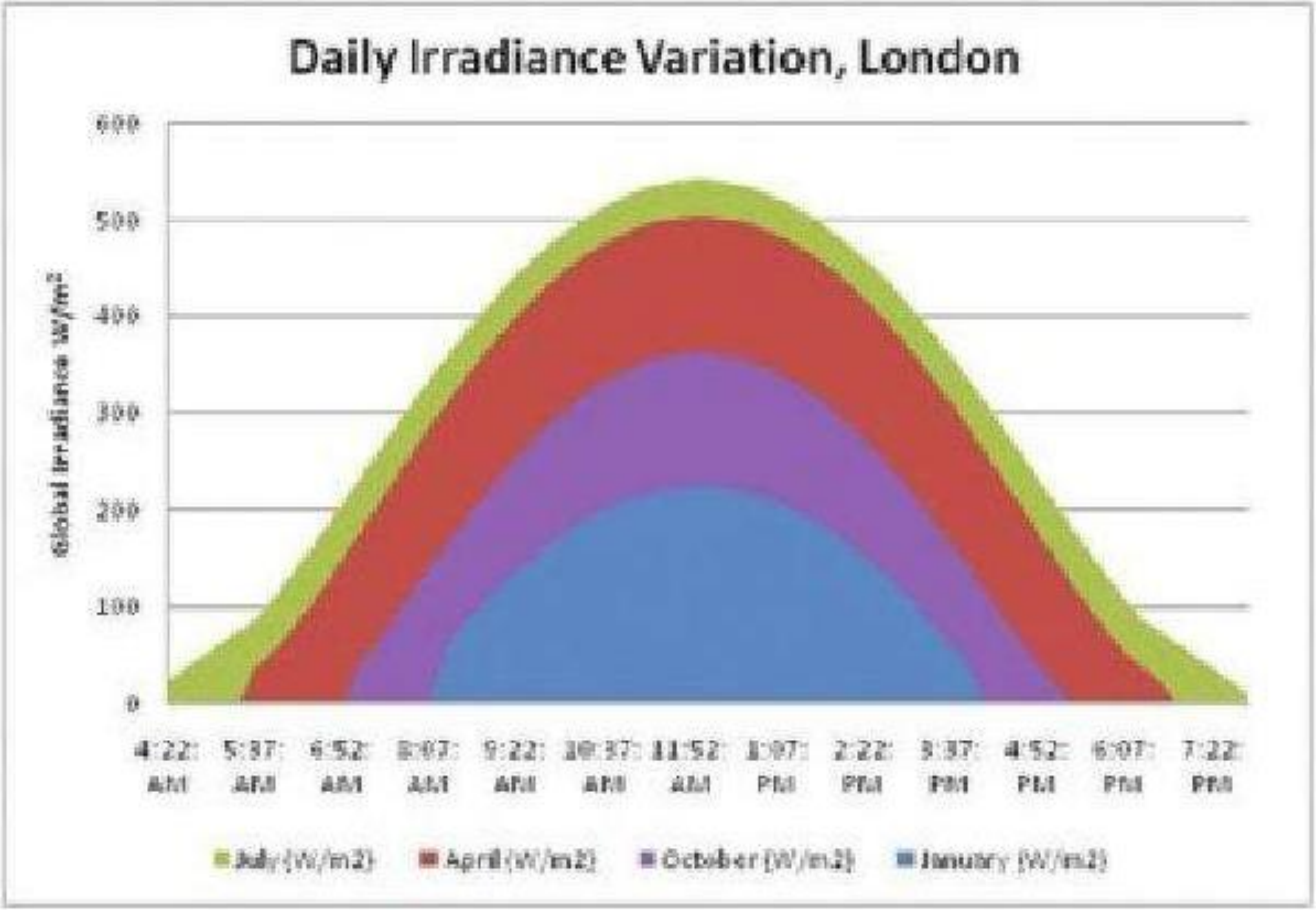


Figure 2.23 Magnetic declination is the bearing between true north and magnetic north

Source: Global Sustainable Energy Solutions

Figure 2.24 In Seattle magnetic north is always 17° east of true north



Daily Irradiance Variation, London
Global Irradiance W/m²
600
500
400
300
200
100
0
4:22: AM
5:37: AM
6:52: AM
8:07: AM
9:22: AM
10:37: AM
11:52: AM
1:07: PM
2:22: PM
3:37: PM
4:52: PM
6:07: PM
7:22: PM
July (W/m2)
April (W/m2)
October (W/m2)
January (W/m2)

Box 2.2 Solar radiation terminology

Peak sun hours (PSH): Daily irradiation is commonly referred to as daily PSH (or full sun hours). The number of PSH for the day is the number of hours for which power at the rate of 1kW/m^2 would give an equivalent amount of energy to the total energy for that day. The terms peak sunlight hours and peak sunshine hours may also be used.

Irradiation: The total quantity of radiant solar energy per unit area received over a given period, e.g. daily, monthly or annually.

Insolation: Another term for irradiation. The amount of solar radiation incident on a surface over a period of time. Peak sun hours (kWh/m^2/day) are a measurement of daily insolation.

Irradiance: The solar radiation incident on a surface at any particular point in time measured in W/m^2.

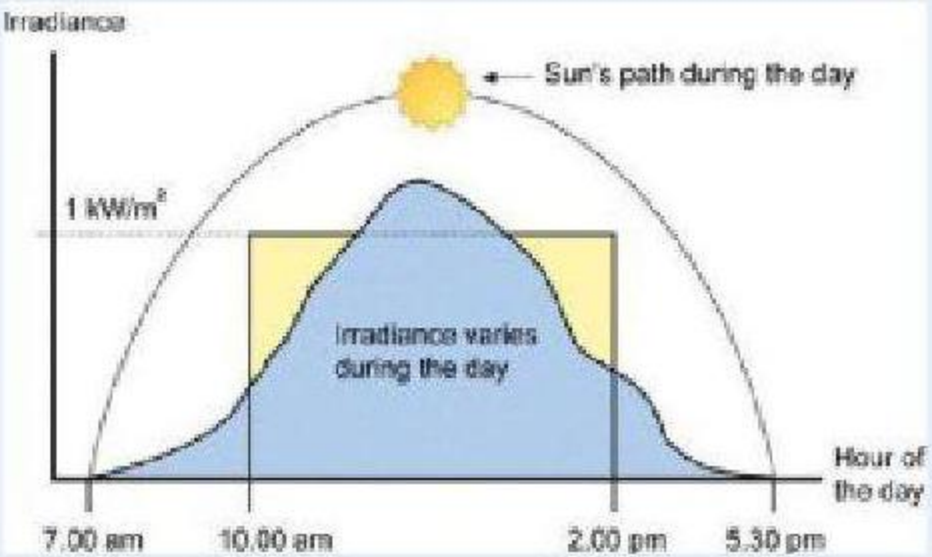


Figure 2.6 Peak sun hours are very useful in system yield calculations (see Chapter 9); one PSH represents 1 hour of radiation at 1kW/m^2. Because the sun does not shine consistently all day the number of peak sun hours will always be less than the number of hours in a day

Source: Global Sustainable Energy Solutions

Example

If sunlight is received at an irradiance of $1000W/m^2$ for 2 hours, $600W/m^2$ for 1.5 hours and $200W/m^2$ for 1 hour, the total radiation received that day is 3.1PSH:

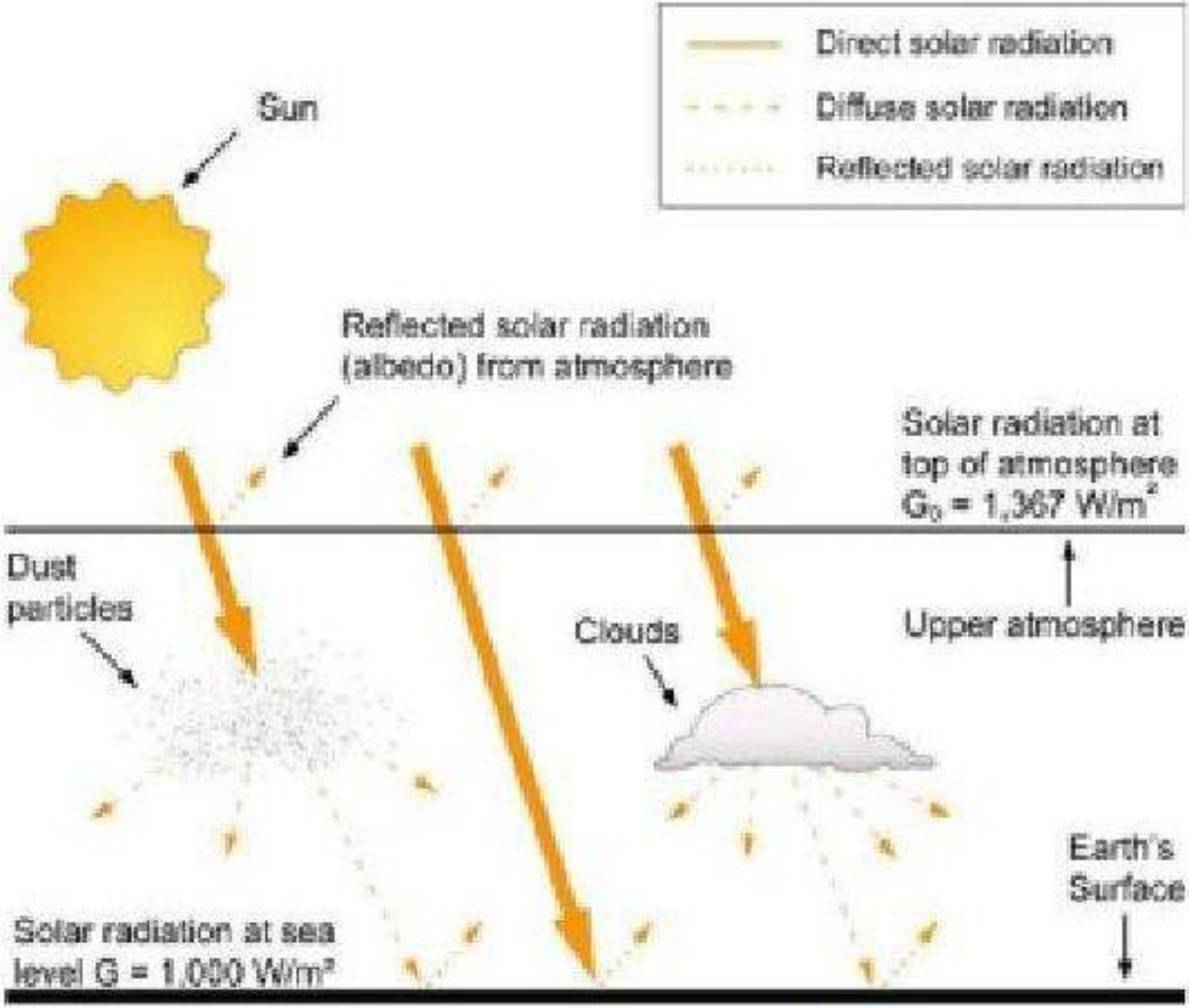
$1000W/m^2 \times 2$ hours + $600W/m^2 \times 1.5$ hours + $200W/m^2 \times 1$ hour = $3100W/m^2/day$

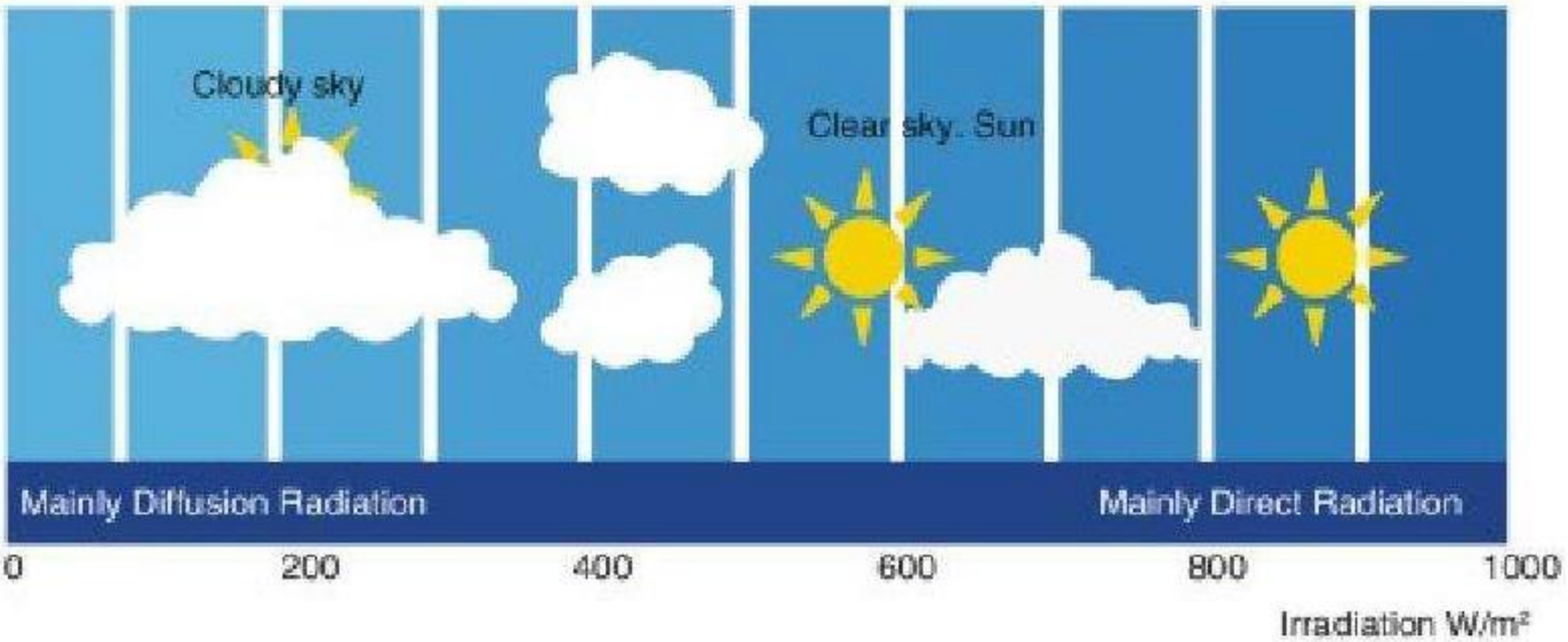
$3100W/m^2/day \div 1000W/m^2/day = 3.1PSH$

The effect of the Earth's atmosphere on solar radiation

- Radiation is reflected off the atmosphere back into space.
- Radiation is reflected off clouds in the stratosphere.
- The Earth's surface itself reflects sunlight.

The average portion of sunlight reflected from the Earth (the Earth's albedo) is 30 per cent. Polar regions have very high albedo as the ice and snow reflect most sunlight, while ocean areas have a low albedo because dark seawater absorbs a lot of sunlight.


Direct solar radiation
Diffuse solar radiation
Reflected solar radiation
Sun
Reflected solar radiation
(albedo) from atmosphere
Solar radiation at
top of atmosphere
G_0 = 1,367 W/m^2
Dust
particles
Clouds
Upper atmosphere
Earth's
Surface
Solar radiation at sea
level G = 1,000 W/m^2



Cloudy sky
Clear sky. Sun
Mainly Diffusion Radiation
Mainly Direct Radiation
0
200
400
600
800
1000
Irradiation W/m²

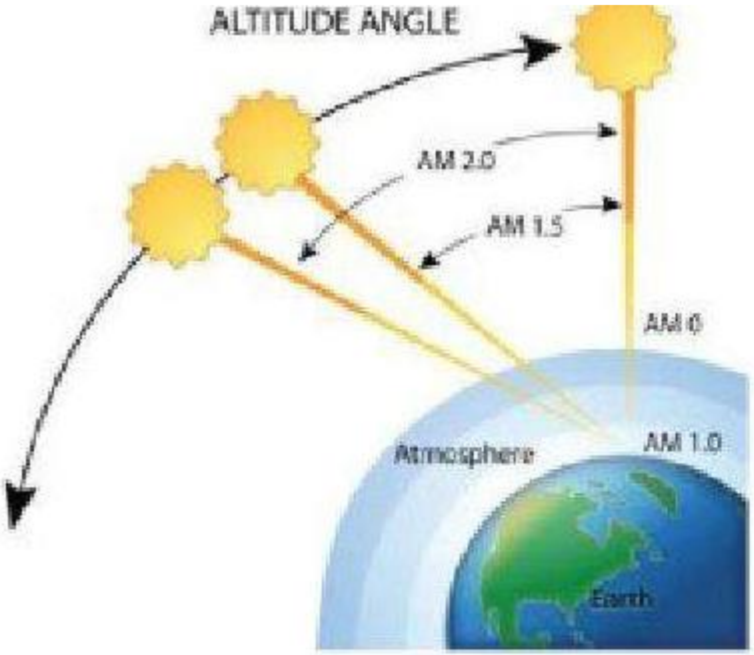


Figure 2.9 From the surface of the Earth, air mass is directly related to the altitude of the sun

Source: Global Sustainable Energy Solutions

Semiconductor devices

Solar cells are made from semiconducting materials. Semiconductors are materials that conduct electricity under certain conditions, so they are neither insulators nor conductors. The most common semiconductor material is silicon. To improve its conductivity, it is often combined with other elements in a process known as doping. Semiconductors are used frequently in electronics, including PV cells, light-emitting diodes (LEDs) and microchips such as those used in computers.

Dye-sensitized solar cells

Dye solar cells are still technologically immature. At the atomic level they operate very differently from other solar cells and do not use silicon. Dye solar cells use titanium dioxide (also used in toothpaste) and coloured dyes; they can be manufactured at a much lower cost than other solar cells and work better in low light. Dye solar cells are transparent and can be produced in many different colours, making them ideal for architectural applications as windows. Dye solar cells also have potential in military applications as they can be made in camouflage patterns.

Figure 3.10 Dye solar cells are available in a range of attractive colours and are transparent so they can be integrated into the facade of a building

Source: Dyesol

Sliver cells

Sliver cells were developed at the Australian National University and are very thin monocrystalline silicon solar cells. They are unique as silicon cells because they are bifacial (they can absorb light from both directions). Sliver technology has achieved cell efficiencies of over 19 per cent and module efficiencies of 13.8 per cent. The technology is in its early stages of commercialization but shows a lot of potential for applications in building-integrated photovoltaics.

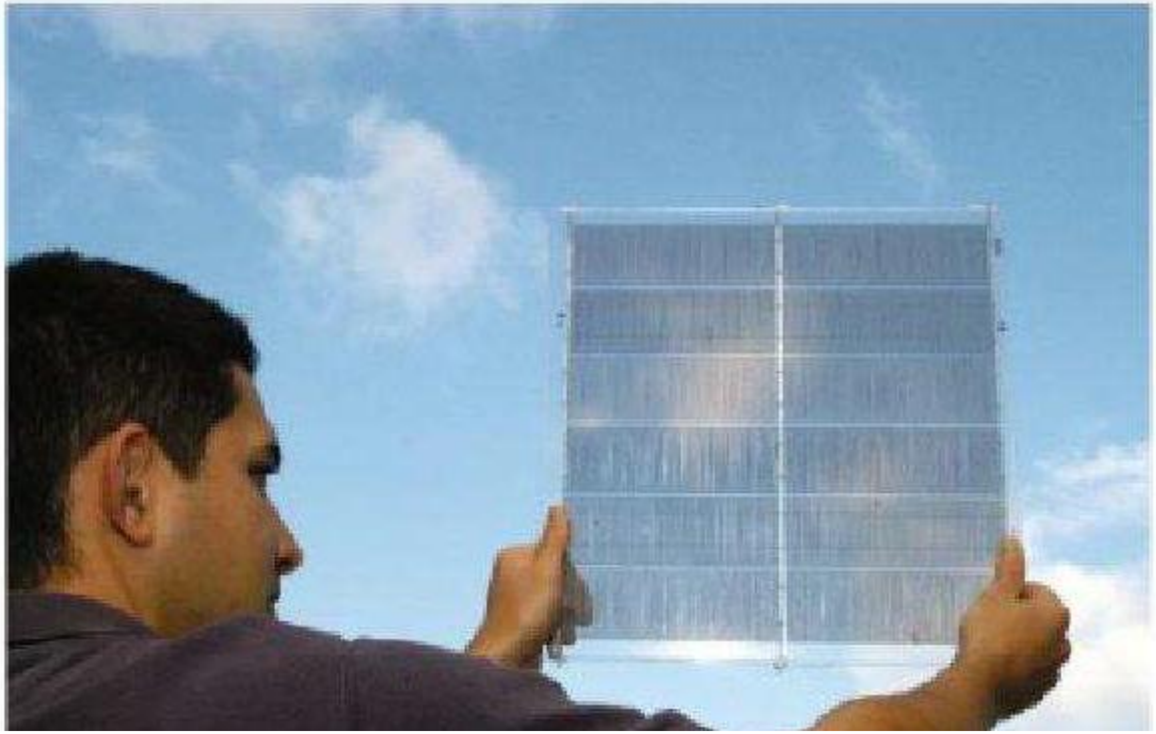


Figure 3.12 Sliver cell are also transparent an flexible

Source: Australian Nation

III-V Semiconductors

III-V or extrinsic semiconductor solar cells use an element from group III of the periodic table and an element from group V (as opposed to silicon which is a group IV element), such as gallium arsenide which is commonly used in space grade solar cells. These solar cells are commonly multi-junction so they are in fact many layers of solar cells, which will collect different colours of visible light. They also frequently use advanced solar concentrator technology to maximize incoming solar radiation. Extrinsic semiconductor multi-junction solar cells are the most efficient and most expensive technology on the market. The highest recorded laboratory efficiency is 41.6 per cent and is held by Spectrolab Inc in the US. Due to their high cost, III-V semiconductor cells are normally used for space applications such as satellites or other big-budget, high-performance, solar-powered devices such as solar planes and solar racing cars (see Figure 3.13).

Solar concentrators

Solar concentrators are used to increase the intensity of light hitting the cell so that it will generate more electricity (the output power produced by a solar cell is dependent on the intensity of light hitting that cell). There are many different kinds of solar concentrators available for a variety of applications, but the most common are lenses or reflective troughs used to focus light.

Box 3.1 Solar cell efficiency

Efficiency is a unitless measurement used to indicate how well a device changes one form of energy (i.e. heat, movement, electricity etc.) into another. Efficiency is mentioned a great deal in connection with solar cells, so it is important to understand what is meant by it and what it actually entails in relation to the operation of the cell. Many different forms of efficiency are used to describe the operation of a solar cell:

- Cell efficiency: The amount of electrical power coming out of the cell per amount of light energy that hits the cell. Usually this is measured at standard test conditions (STC): 25°C ambient temperature and 1000W/m² light intensity. A cell will rarely experience STC in the field so it will rarely perform at its rated efficiency. Efficiency and power output are related as follows:

Efficiency = Power OUT/Power IN

The standard value for power in (irradiance) is 1000W/m². If the cell's efficiency is 22 per cent and it has an area of 0.2m² then:

Power OUT = Efficiency × Power IN

Power OUT = 0.22 × 1000W/m² × 0.2m²

Power OUT = 44W

- Module efficiency: The efficiency of a module is measured the same way as that of a cell, the difference being the inclusion of losses from reflection and shading of the glass as well as a few other minor losses.

Multicrystalline/polycrystalline silicon

Multicrystalline or polycrystalline silicon solar cells are manufactured by block casting molten silicon, so they are not made from a single crystal ingot but rather from one composed of many small crystals, which grow in random orientations as the molten material solidifies. This produces lower efficiencies than monocrystalline cells; however, it is still a very popular technique because it is easier and less expensive. Multicrystalline and monocrystalline silicon solar cells are those most commonly used in PV arrays, and commercially available multicrystalline solar cells can now reach laboratory efficiencies over 18 per cent, with the record for module efficiency being 17.84 per cent.

Thin film solar cells

Thin film solar cells are made from materials suitable for deposition over large areas. They need only be about one micron thick, hence the name thin film (a dot such as '.' covers 615 microns and multicrystalline and monocrystalline silicon solar cells are normally about 300 microns thick).

Table 3.1 Comparison of different solar technologies

Cell material	Module efficiency	Surface area required for 1kWp in metres squared	Surface area required for 1kWp in square feet
Monocrystalline silicon	14–20%	5–7m^2	54–77 ft^2
Polycrystalline silicon	13–15%	6.5–8.5m^2	72–83ft^2
Amorphous silicon thin film	6–9%	11–16.5m^2	110–179ft^2
CdTe thin film	9–11%	9–11m^2	98–110ft^2
CIS/CIGS thin film	10–12%	8.5–10m^2	90–108ft^2

Source: IEA

The most common way to manufacture solar cells is by screen printing, where the metal is simply printed onto the cell. This method is very reliable and is typically applied to solar cells producing efficiencies of about 12–15 per cent. Several factors need to be balanced when using screen printing:

- If there is too much space between the contacts, the cell will be less efficient.
- If the area covered by the contacts is too large, the cell will receive less sunlight and produce less power.
- For the contacts to be effective, the top of the cell often needs to be treated in such a way that its absorbance of high-energy blue light is reduced.

Another method used by manufacturers to achieve solar cell efficiencies over 20 per cent is rear or back contacts. This technology increases the working cell area, allows a simplified automated production and the cell wiring is hidden from view. The most efficient commercially available silicon solar cells use rear contacts (18–23 per cent). There is no metal on the front of the cell, which means the whole cell is producing electricity.

Figure 3.6 The metal contacts on this polycrystalline cell are clearly visible

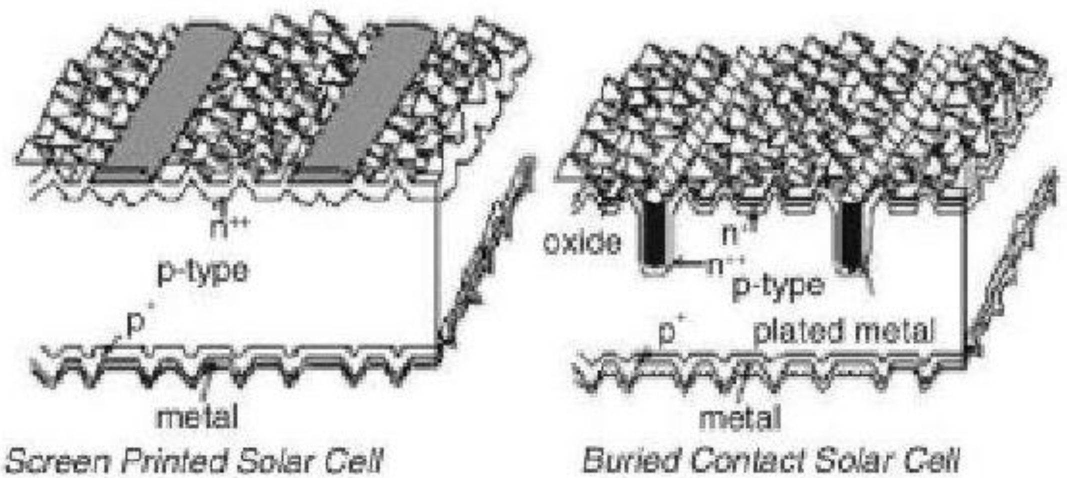


Figure 3.8 BCSC technology is used to manufacture solar cells with much higher efficiencies than those that use screen printing. However, screen printing is still the dominant form of contact manufacturing because of its technical simplicity and cost effectiveness

Source: School of Photovoltaic and Renewable Energy Engineering, University of New South Wales

Standards

The PV industry is growing rapidly, resulting in many new manufacturers producing PV modules. It is important that only quality modules are installed and standards do exist. The most common standards applicable to PV modules are:

- IEC 61215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval.
- IEC 61646 Crystalline thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval.
- IEC 61730 Photovoltaic (PV) module safety qualification – Requirements for construction and requirements for testing.

These standards originate from the International Electrotechnical Commission: www.iec.ch. In many countries a PV module must evidence compliance with either IEC 61215 or IEC 61646 (depending on whether it is thin film or crystalline silicon technology) and IEC 61730.

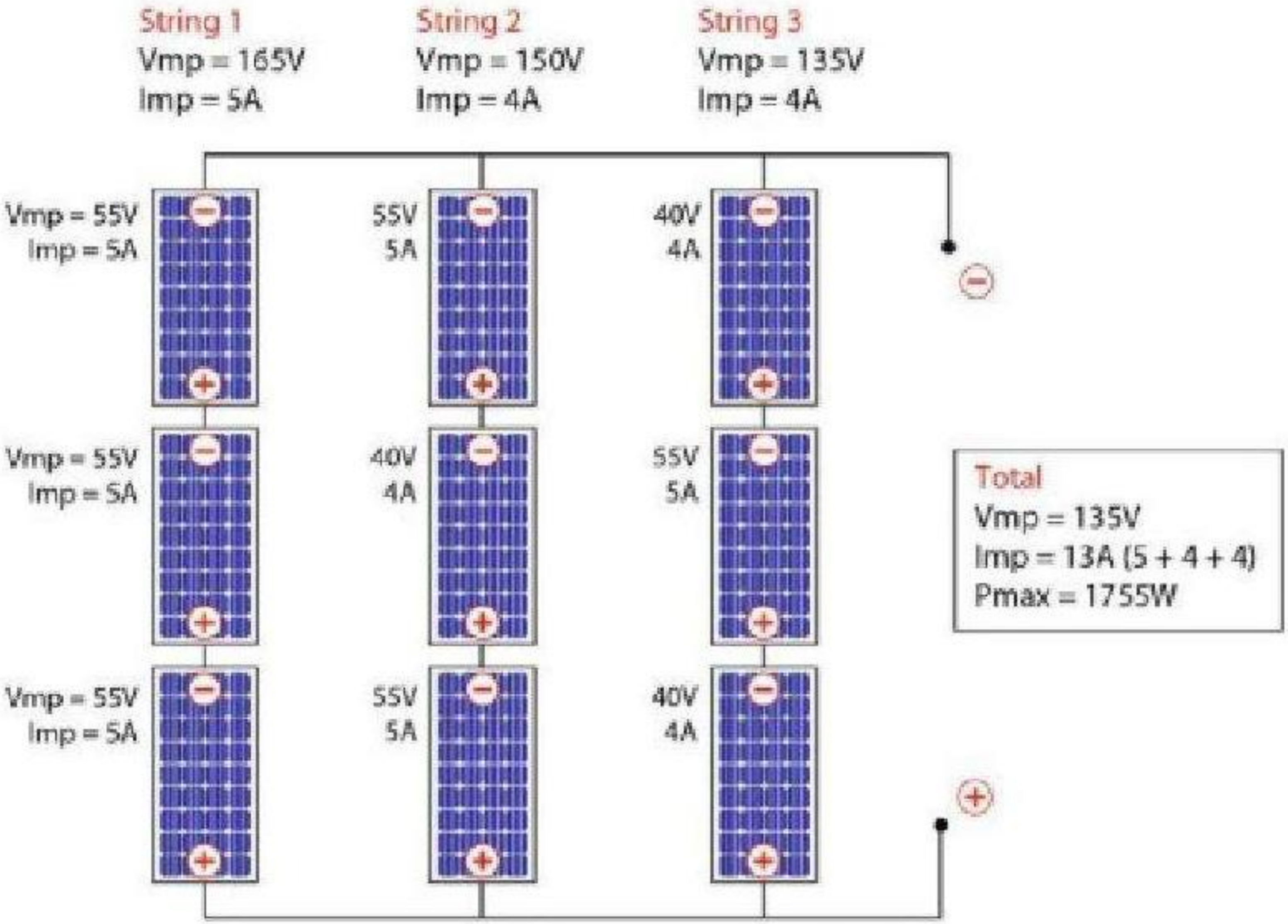


Figure 4.16 To calculate the power output of an array, first calculate the output of each string (as explained previously) and then treat the strings as though they were modules and calculate the power output by adding them in parallel

Irradiance

The amount of solar radiation (sunlight) hitting the cell will largely determine its power output.

The output of a PV array can be estimated using performance data provided by the manufacturer on the data sheet. All arrays have a rated peak power output, i.e. an array can be described as a 1.5kWp array – meaning that PV is installed to provide a 1.5kW peak of power. This output has been determined by the manufacturer using standard test conditions. Using this information and local solar insolation data (see Chapter 2), it is possible to estimate the output of an array.

Example

On a clear sunny day a 2kWp PV array received 6 peak sun hours: the 6 peak sun hours equate to an energy input of 6000W/m^2 per day. Expected output can be determined as follows:

peak power output × peak sun hours = expected output

2kW × 6PSH = 12kWh

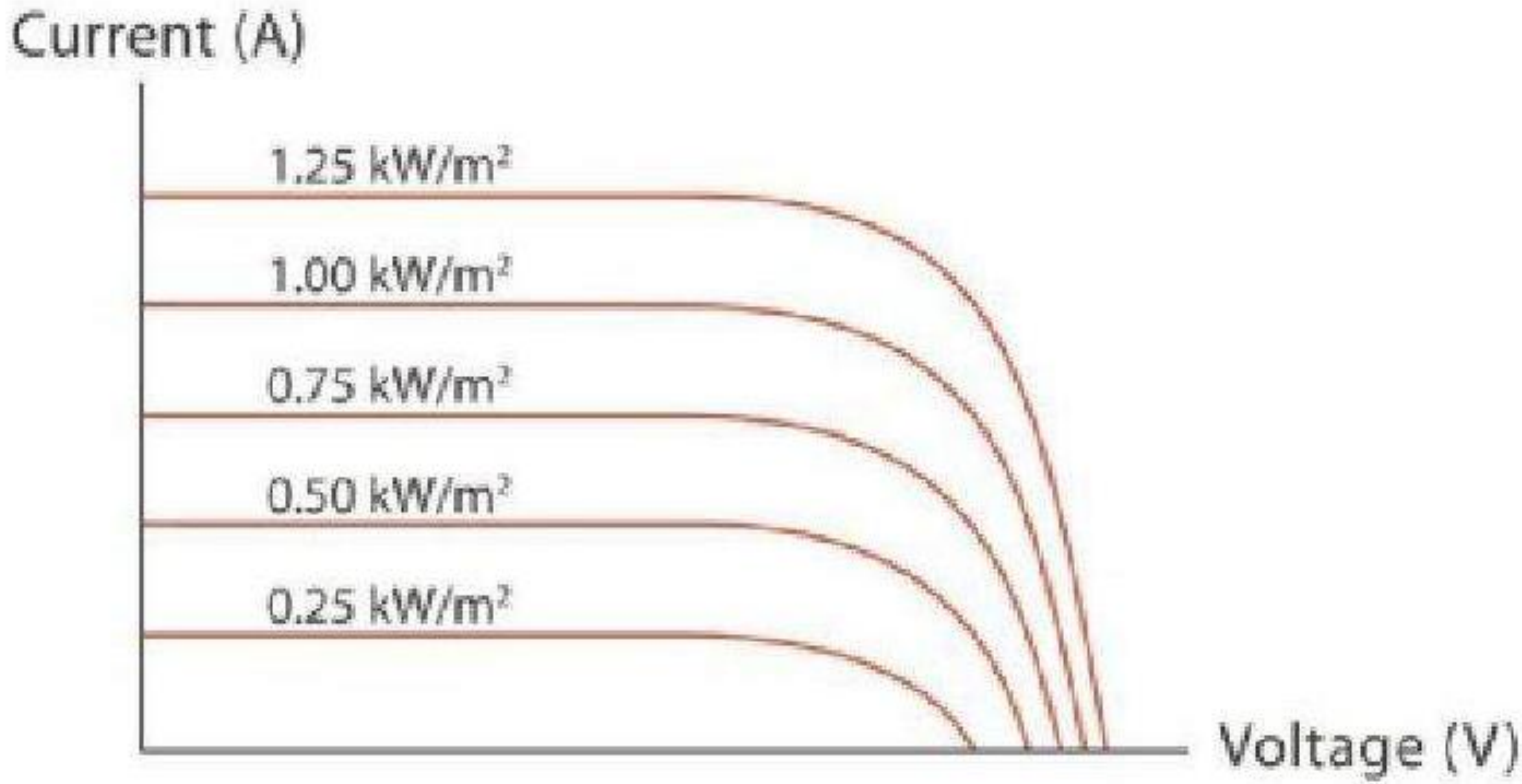


Figure 4.17 The I-V curves for a cell operating at different irradiance values show the increase in power output with irradiance

Table 4.1 Monthly peak sun hours for Sydney, Australia

Month	Average peak sun hours (31° tilt) per day
January	5.38
February	5.11
March	4.84
April	4.42
May	3.87
June	3.90
July	4.04
August	4.68
September	5.33
October	5.51
November	5.44
December	5.57
Average	4.84

Source: NASA

cell temperature = ambient temperature + 25°C

As hot temperatures adversely affect power output, output from a PV array has to be calculated taking the temperature effects into consideration, i.e. derating an array's output based on the operating temperature conditions. Likewise, as

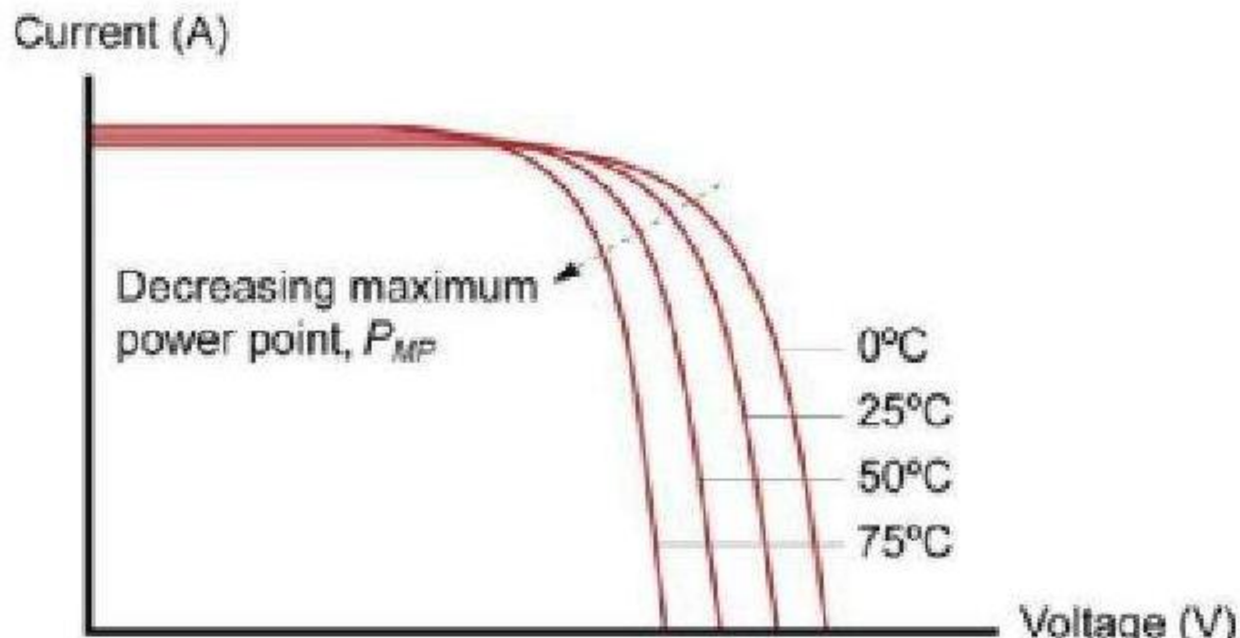


Figure 4.18 As power = current x voltage (I x V), as voltage decreases, power decreases

Source: Global Sustainable Energy Solutions

Shading

PV cells require sunlight in order to produce electricity. If a cell receives no sunlight due to shading it will not produce any power (even a small area of cell

Figure 4.22 Even this small shadow can reduce the amount of electricity a module produces – a small shaded area can, under certain circumstances reduce module output by 80–90 per cent as well as affecting the rest of the array

Shading of the array can lead to irreversible damage. Hot spot heating occurs when a cell is shaded such that its power output is reduced and most of the current being produced by the other (unshaded) cells is forced through that one cell causing it to heat up. This often leads to cell damage (cracking) and can also damage the glass encapsulation.

It is difficult to prevent shading. However, diodes can be used to mitigate temporary shading (i.e. leaves that may have fallen on the array). When a cell is shaded or damaged, a diode can be used to give current another path to follow. It will skip the damaged or shaded cell completely and have minimum impact on the power output of the array. This kind of diode is referred to as a bypass diode and manufacturers typically install one, two or three bypass diodes per module.

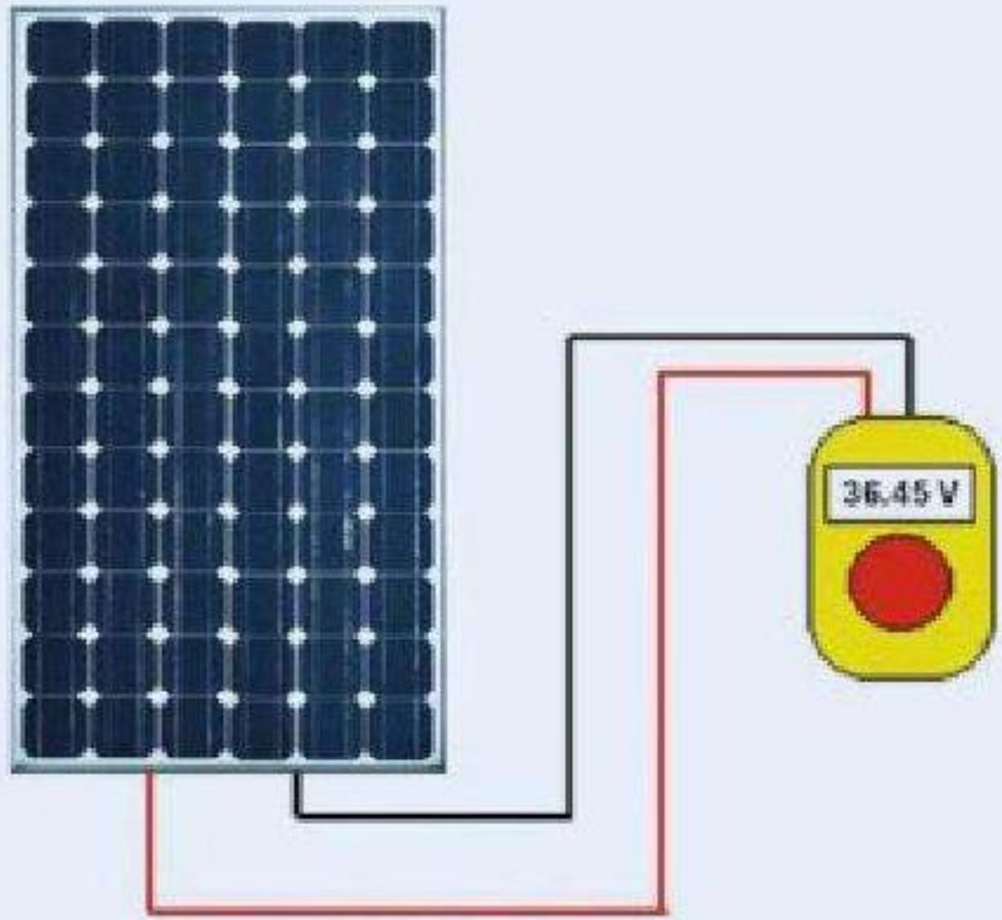


Figure 4.3 Measuring the open-circuit voltage of a module using a multimeter

Source: Frank Jackson

Short-circuit current I_{sc}: The current measured across a PV cell under short-circuit conditions, voltage is zero.

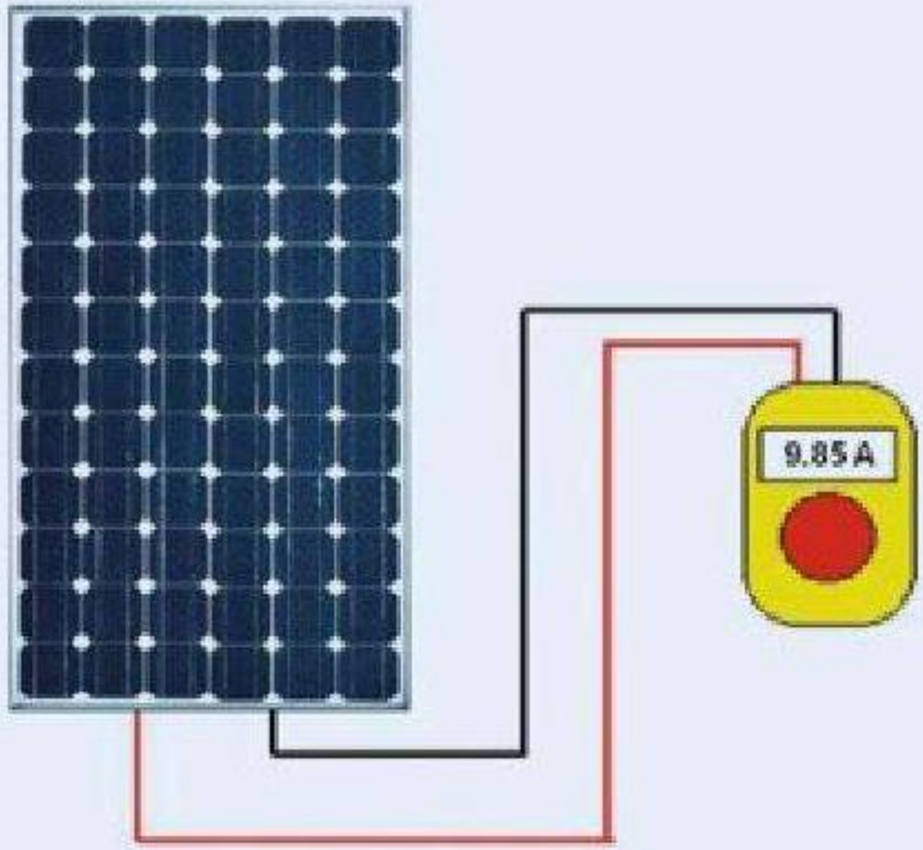


Figure 4.4 Measuring the short-circuit current of a module using a multimeter

Source: Frank Jackson

Maximum power point: The theoretical maximum power output of a PV cell. The maximum power point (P_{max}) is the product of the maximum power point voltage (V_{mp}) and the maximum power point current (I_{mp}).

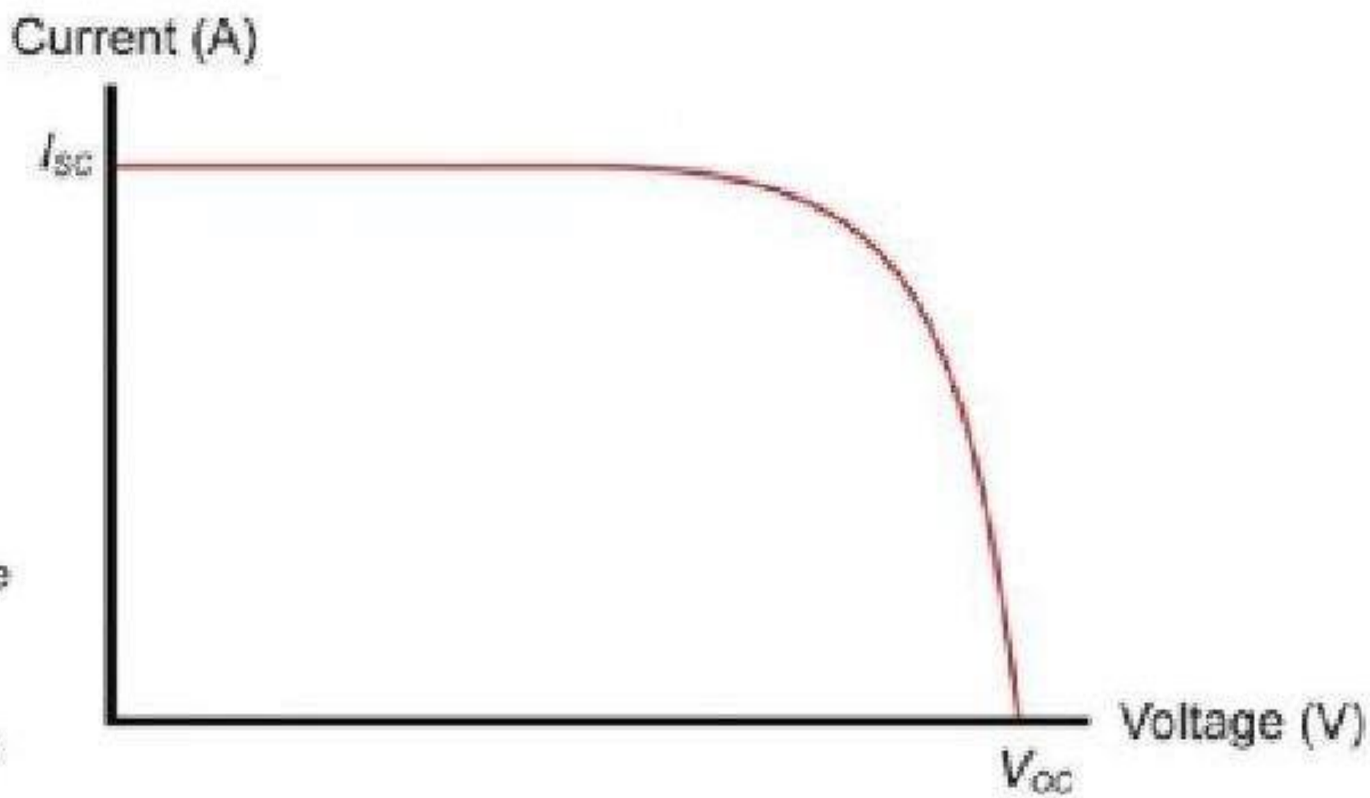
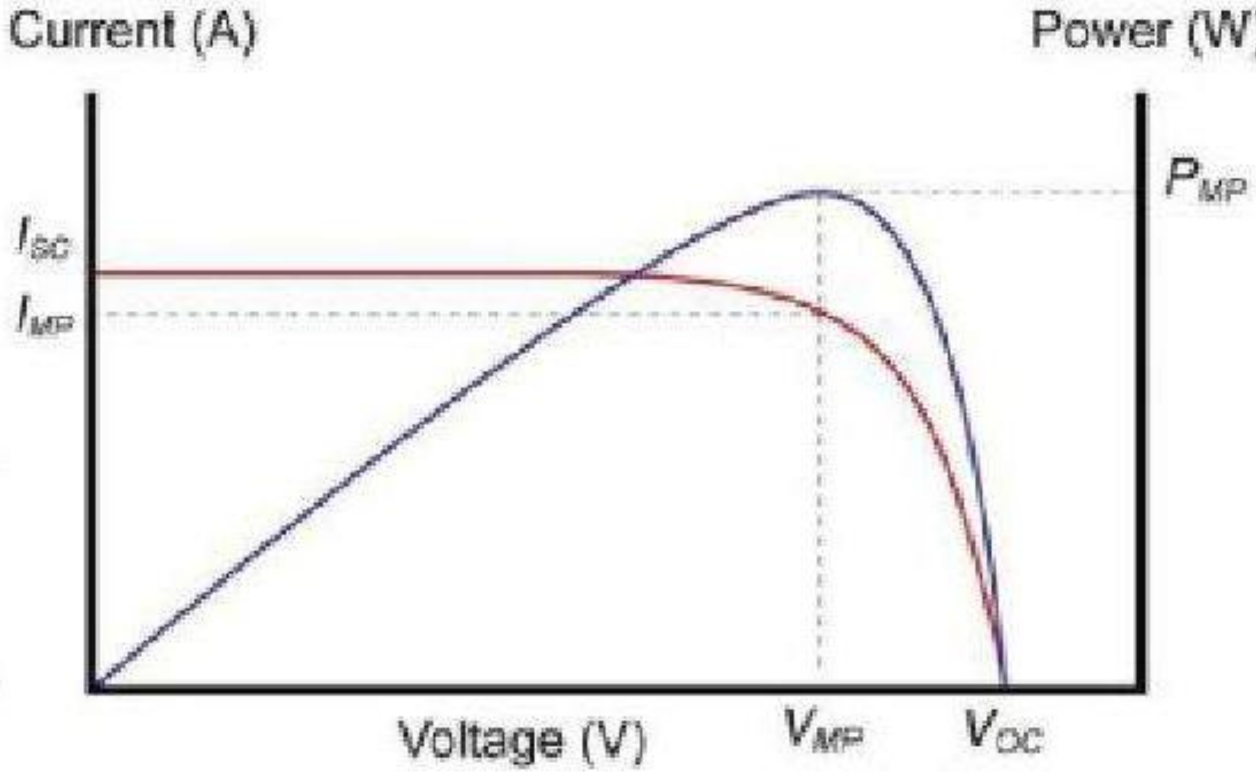


Figure 4.5 V_{oc} and I_{sc} are the *x* and *y* intercepts respectively. Ideally the PV cell operates around the knee of the curve, where the maximum power point is located

Source: Global Sustainable Energy Solutions

Figure 4.6 P_{mp} is the highest point on the power curve; by extrapolating back to the x-axis, V_{mp} can be found. V_{mp} is also on the I-V curve and so the corresponding current can be found for this particular voltage (I_{mp})

Source: Global Sustainable Energy Solutions



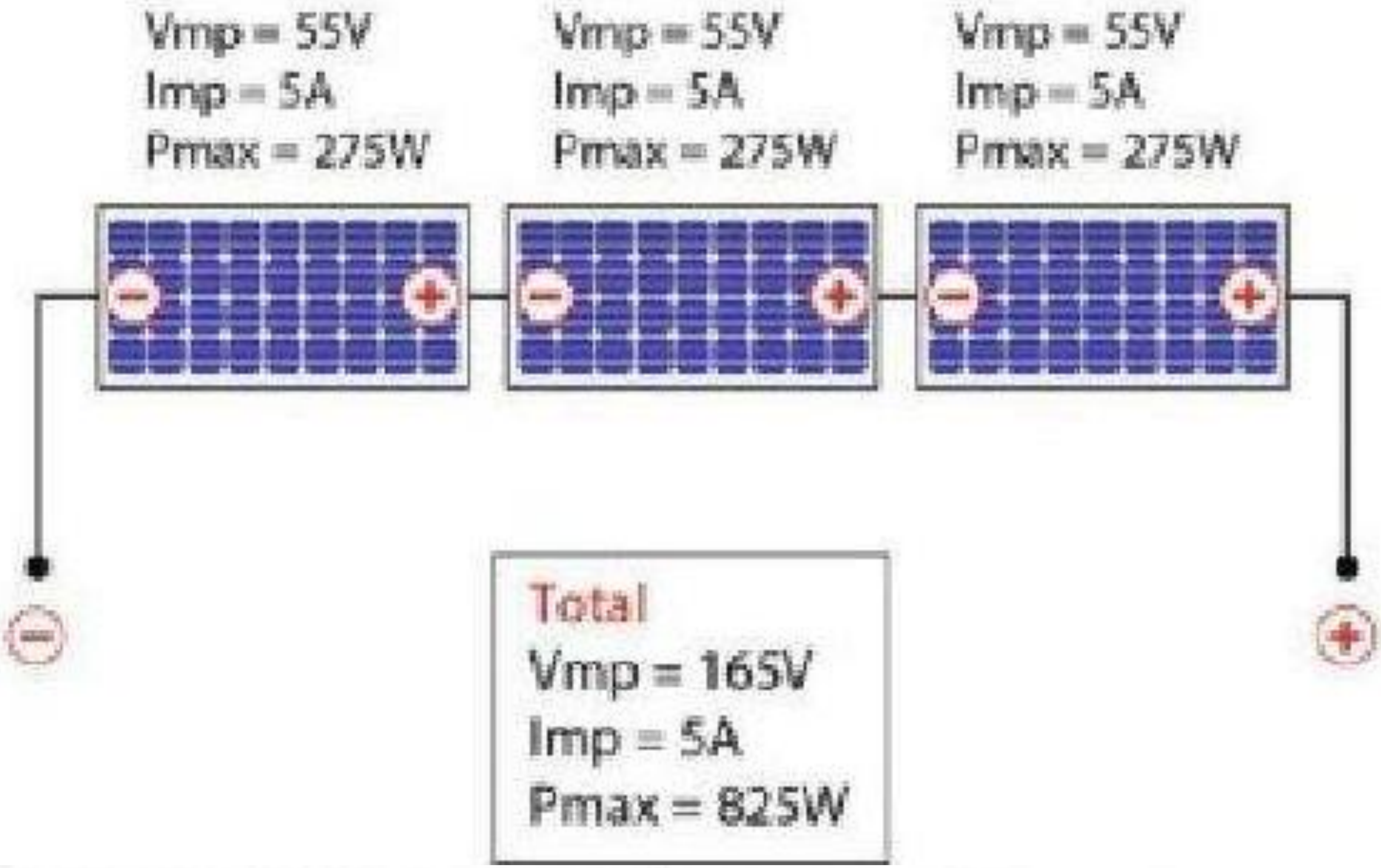


Figure 4.11 When three identical modules are connected in series to form a string their voltages add and the total current is that of one single module. The power output of the string is calculated using $P = I \times V$

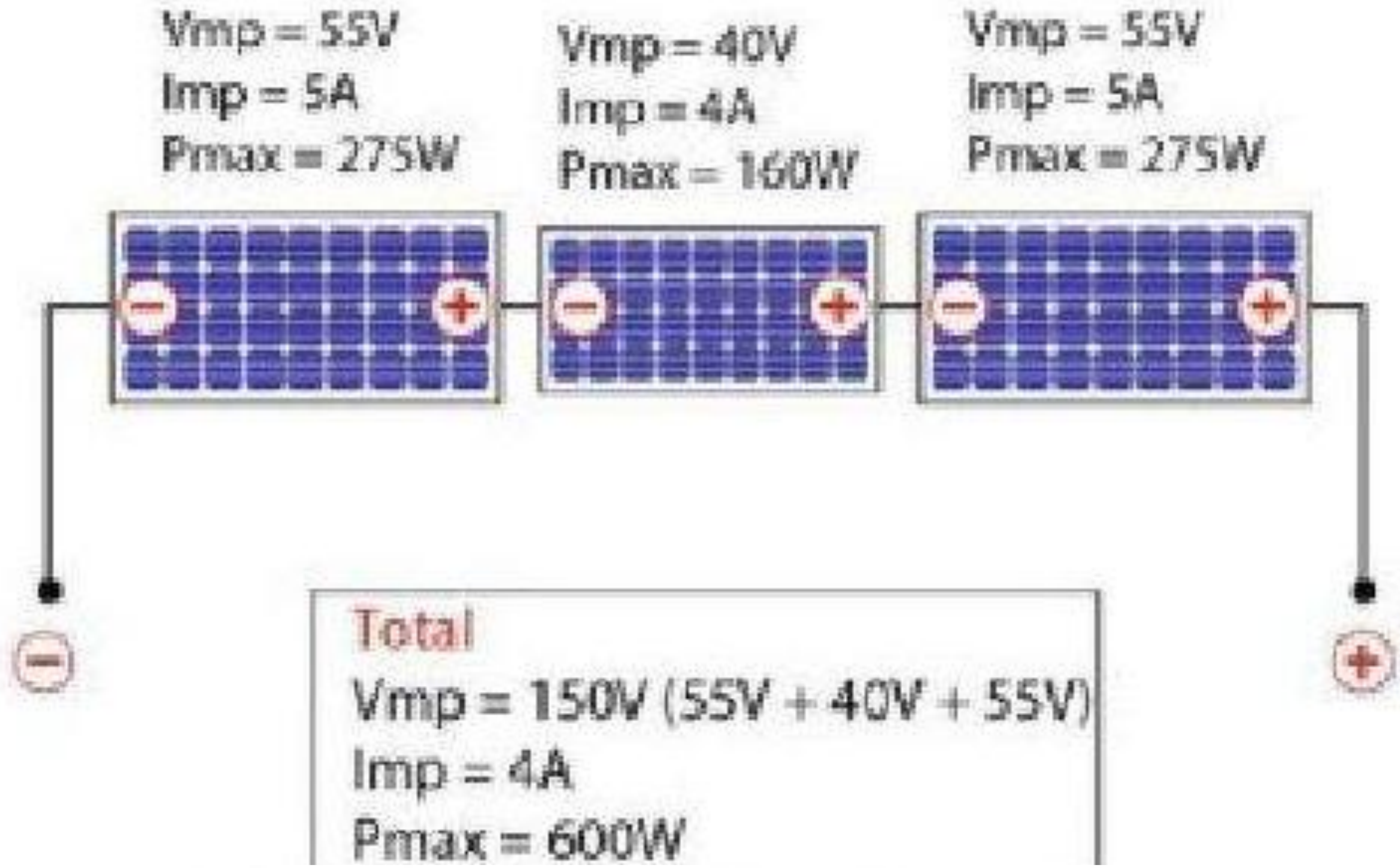


Figure 4.12 When non-identical modules are connected in series the voltages will still add; however, the current of the string will be the lowest current of any single module (in this case 4A). The power output of the string is then calculated using $P = I \times V$

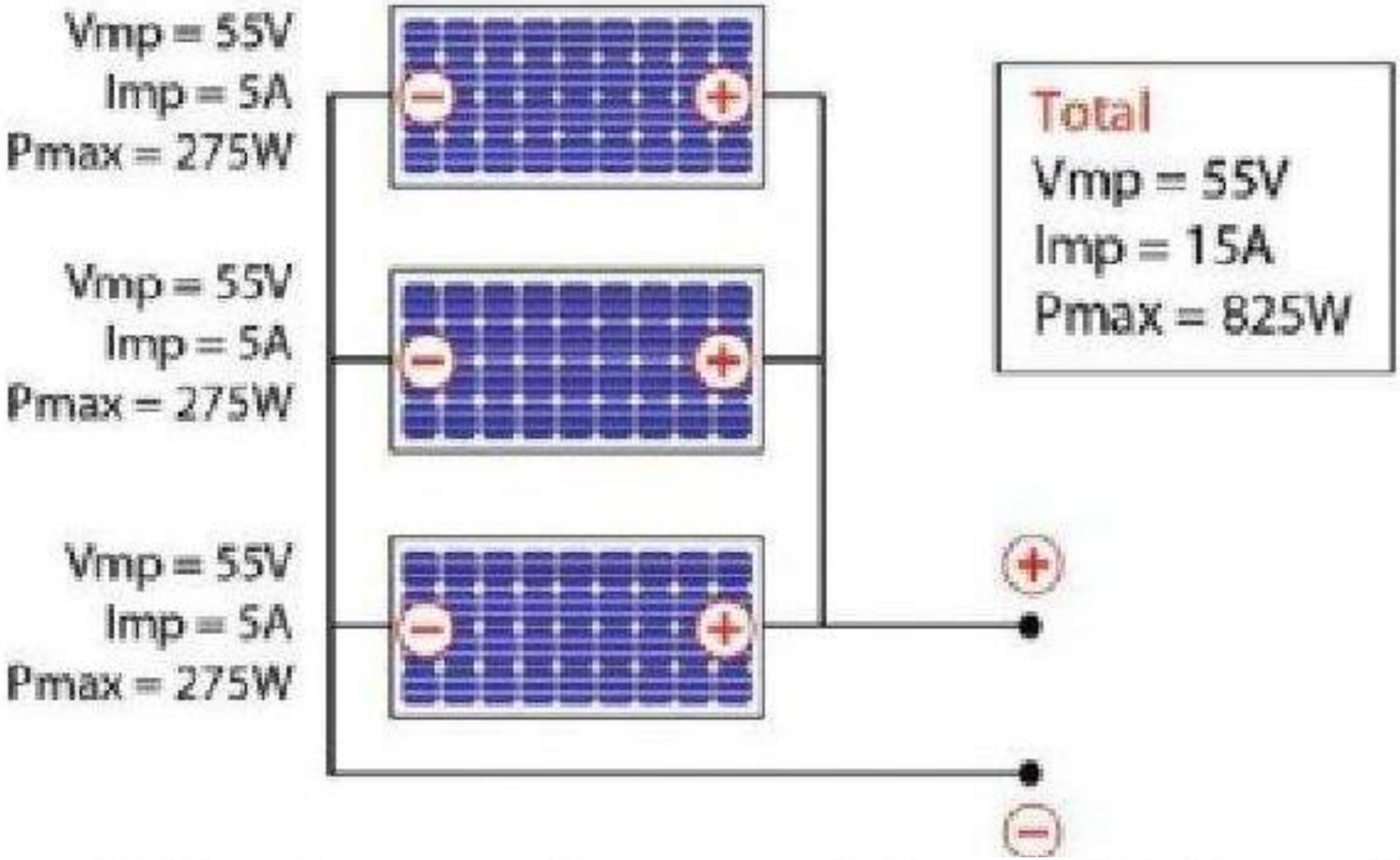


Figure 4.13 Three identical modules are connected in parallel; the total current is the sum of each individual current, while the total voltage is the voltage of a single module. The power is once again calculated using $P = I \times V$

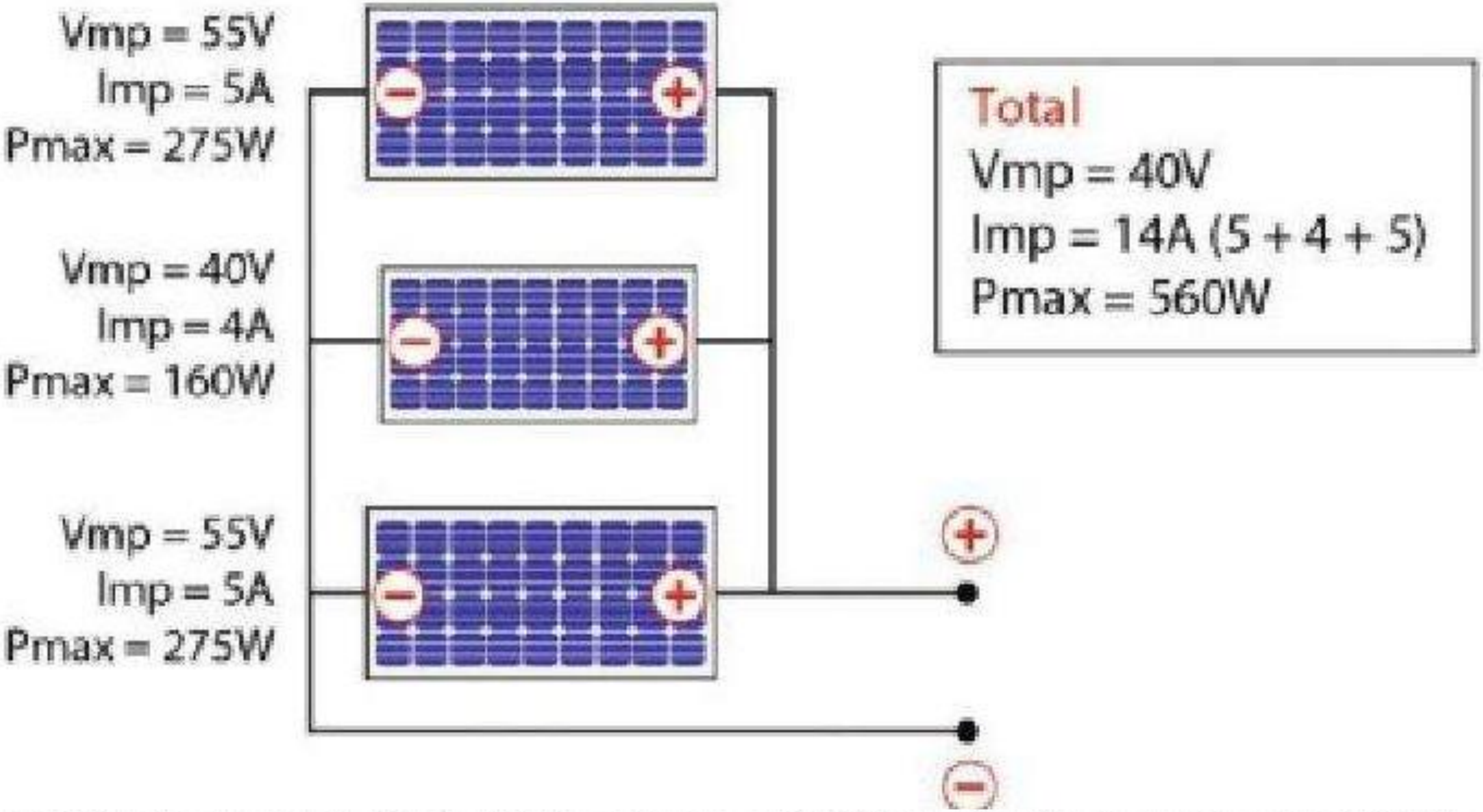
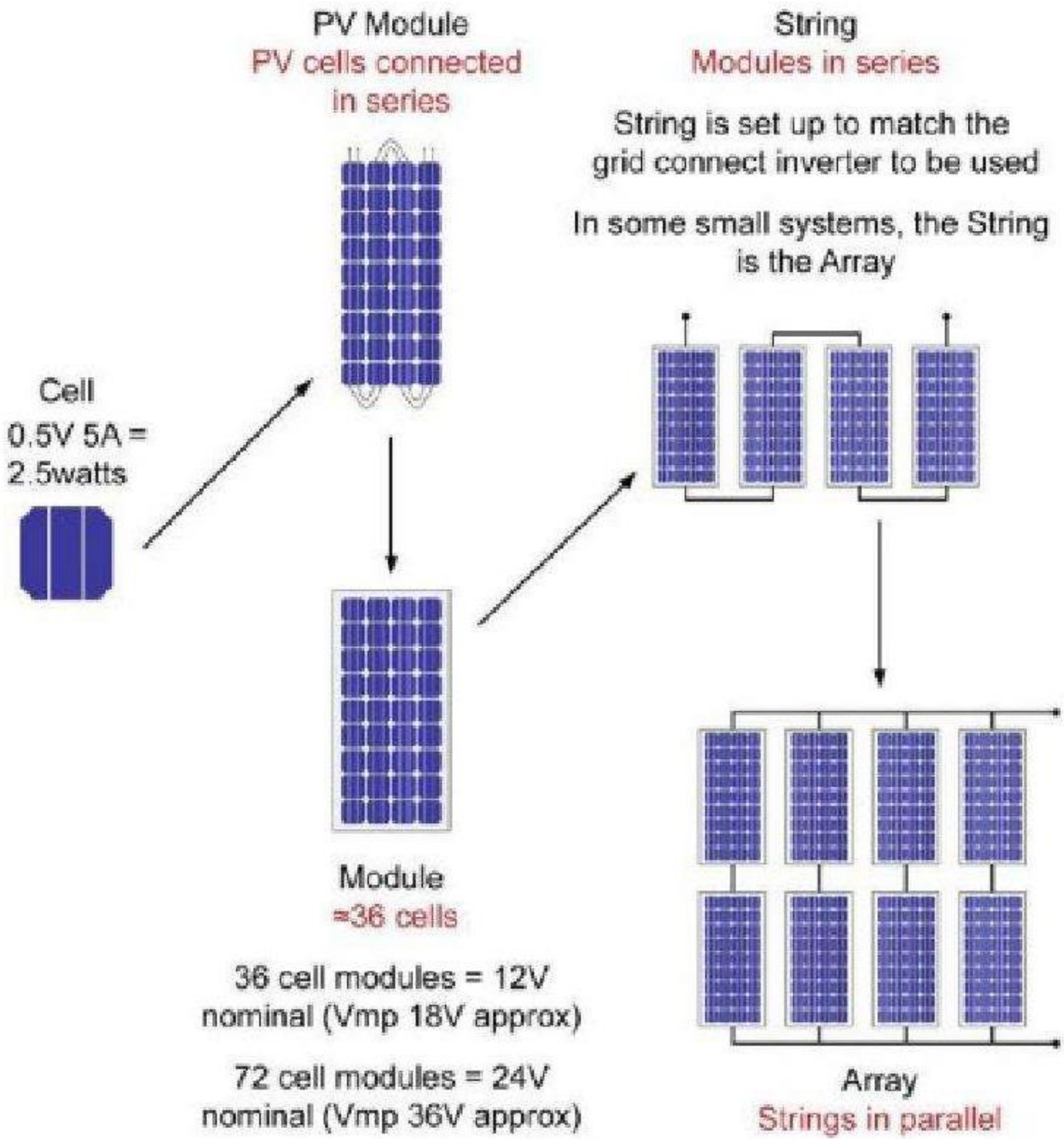


Figure 4.14 When non-identical modules are connected in parallel the currents add while the output voltage is equal to the lowest single module voltage. The power output of the modules is then calculated using P = I x V


PV Module
PV cells connected
in series
String
Modules in series
String is set up to match the
grid connect inverter to be used
In some small systems, the String
is the Array
Cell
0.5V 5A =
2.5watts
Module
≈36 cells
36 cell modules = 12V
nominal (Vmp 18V approx)
72 cell modules = 24V
nominal (Vmp 36V approx)
Array
Strings in parallel

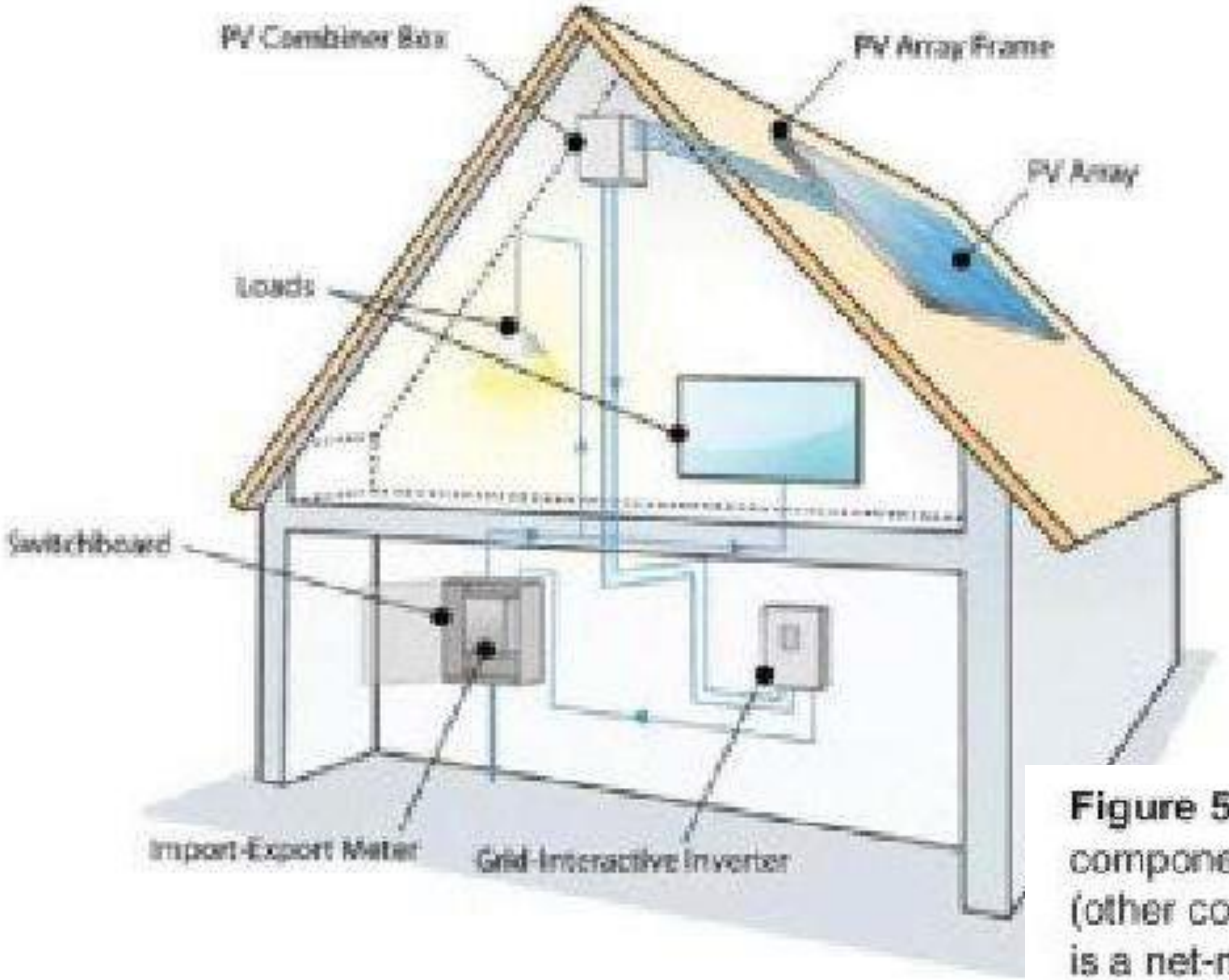


Figure 5.1 The primary system components are shown in this diagram (other configurations are possible). This is a net-metering arrangement where the electricity generated by the PV array and converted to AC by the grid-interactive inverter is either used on site or exported to the grid

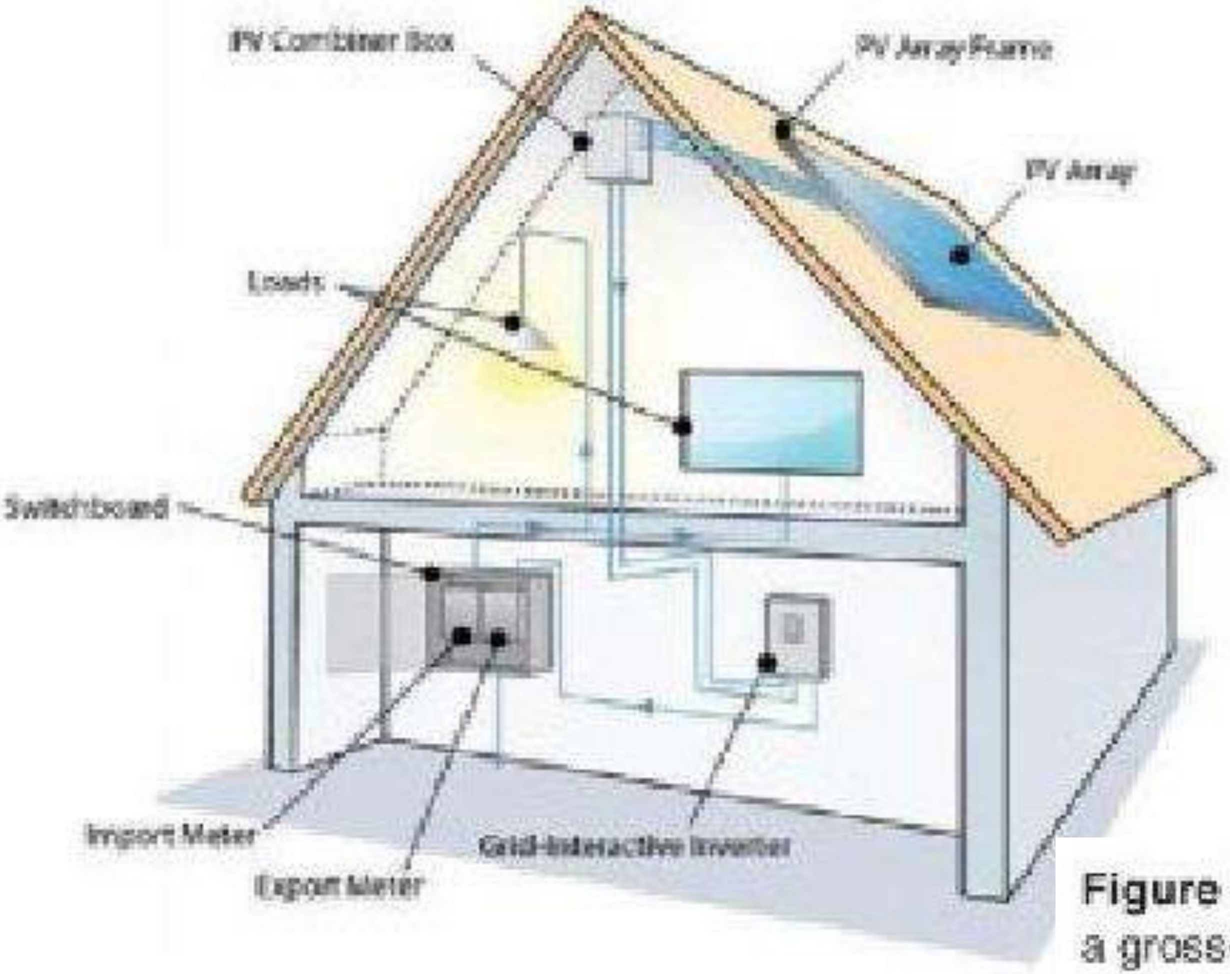


Figure 5.2 Alternative PV system using a gross-metering arrangement where all the power generated by the PV array is exported to the grid and all the power required by the loads is imported from the grid

Modular inverters

Modular inverters (also known as micro-inverters) are small transformer-less inverters (some will have an isolating transformer to minimize DC injection currents) designed to be mounted on the back of the PV module.

Over the years there have been a number of modular inverters manufactured in the range 100–300W. This product has re-emerged during 2009 for the grid-connect PV market. Two main advantages of the modular inverter are that they remove the requirement for DC cabling from the array as each module has an AC output and these AC cables can be paralleled at each module and then connected to the grid at the appropriate location. These inverters are also small and easy to handle, and they have the advantage of being modular (just like PV modules), which means that more modules and inverters can be added to the system in future at minimum cost.

Table 5.1 Inverter types and characteristics

Inverter type	Modular	String	Multi-string	Central
Power range	100–300W	700–11,000W	2000–17,000W	10,000–300,000W
MPPT	Yes	Yes	Multiple	Multiple
Typical efficiency	95%	93–97%	97%	97%
Advantages	No DC cabling; easy to add more modules	Readily available	Multiple MPPTs; readily available	Lower $/W cost; one location for maintenance
Disadvantages	Replacing a faulty inverter can be difficult	Only one MPPT		No redundancy if inverter fails

Inverter protection systems

Grid-connected inverters will only work if the AC grid is functioning and is within the grid's predetermined operating conditions. If these conditions are not met, the grid-connected inverter will disconnect and will not output any power from the PV array at all. The inverter is set up to mirror the function of the grid itself. The MPPT software in these inverters allows the PV output to be optimized to best match the grid specifications at the time of power output. Grid-interactive inverters will typically incorporate two types of protection: active and passive. Both forms have the inverter switch off on over/under frequency or over/under voltage. This protection is intended as self-protection for the inverter if extreme conditions occur and protection for the grid itself, so the inverter will disconnect if it cannot see the grid, e.g. if there is a blackout.

Self-protection

Inverters incorporate protection mechanisms for a variety of problems:

- Incorrect connection: if an inverter is incorrectly connected to the PV array (e.g. with reverse polarity) it will not work and will in most cases be damaged. Even though some inverters protect against incorrect connection, the warranty for most inverters does not cover such damage.
- Temperature: inverters are sensitive to temperature variation and manufacturers will specify a temperature range within which they must operate. Some inverters reduce their power output or turn themselves off when temperature increases past the manufacturer's operating specification. Although the inverter might have over-temperature protection, it is important that the inverter has sufficient ventilation and cooling; over-temperature can cause damage to the inverter.

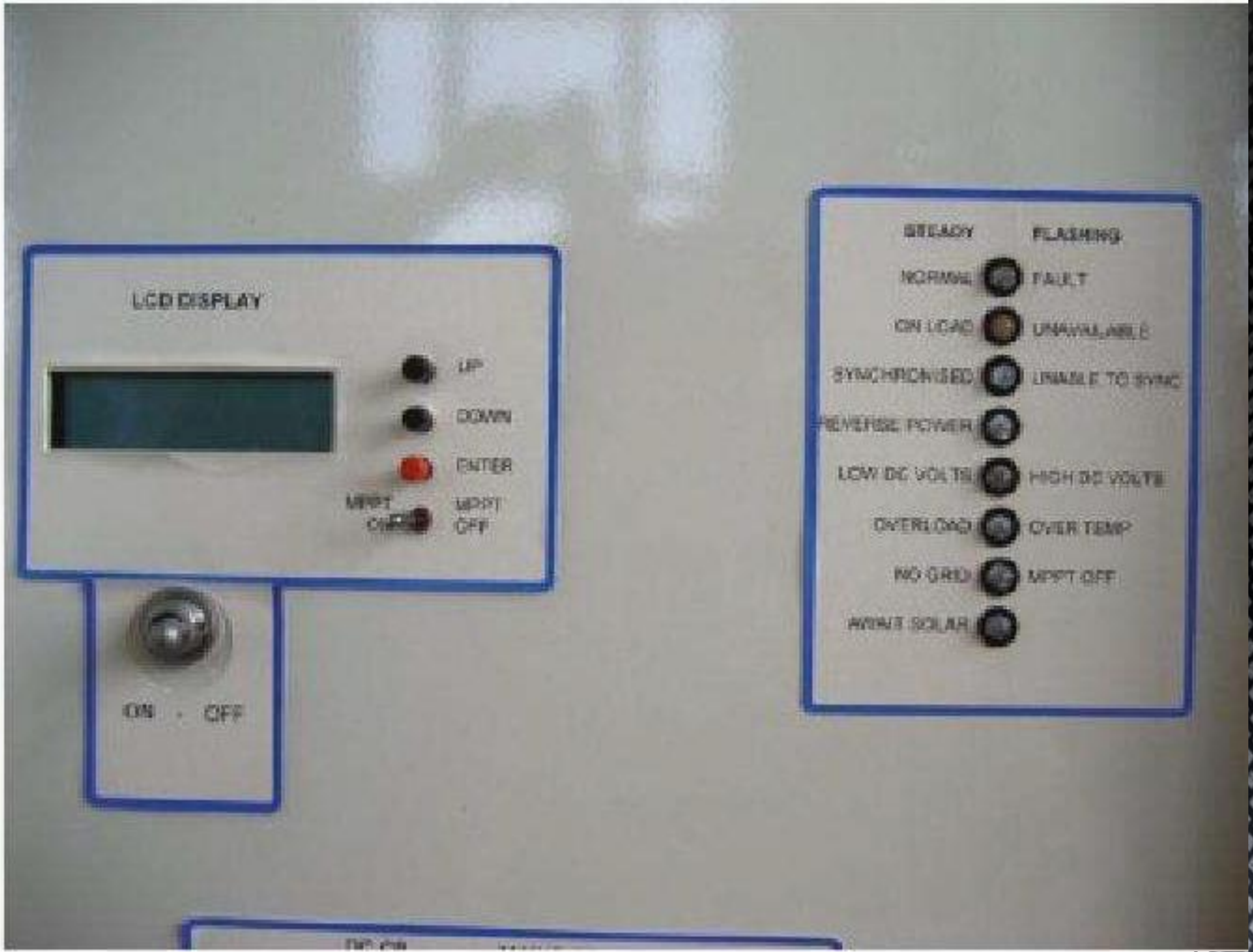


Figure 5.18 The front panel of an inverter will commonly display array faults

Source: Global Sustainable Energy Solutions

- DC voltage too high: all grid-connected inverters will have a specified voltage range within which they operate correctly. Some inverters switch off to protect their electronics if the maximum DC voltage they can tolerate is exceeded, but the inverter could still be damaged; other inverters have no such protection.

Grid protection

Grid-interactive inverters must be able to disconnect from the grid if the supply from the grid is disrupted or the grid itself is operating outside the preset parameters (e.g. under/over voltage, under/over frequency). In both these cases, the inverter disconnects to avoid continuing to output power to the grid when the grid itself is not operating.

Balance of system equipment: System equipment excluding the PV array and inverter

In addition to the PV array and inverter, a system requires a variety of other components in order to function. These are known collectively as the balance of system equipment (BoS) and often must comply with local and/or national codes and regulations. The BoS equipment is composed of the components required to connect and protect the PV array and the inverter. This equipment includes cabling, disconnects/isolators, protection devices and monitoring equipment. The key balance of systems components are given below, and are described in further detail:

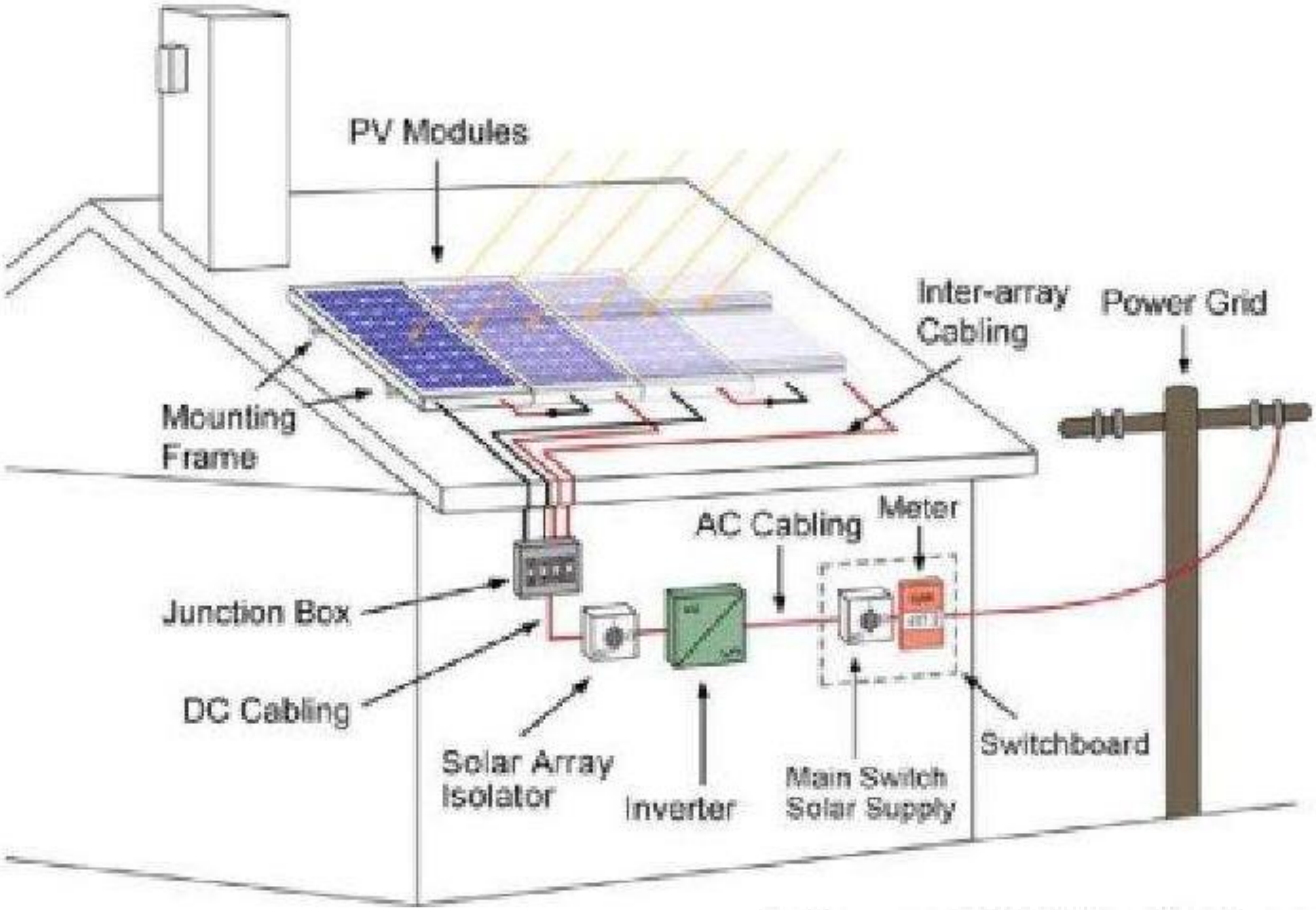
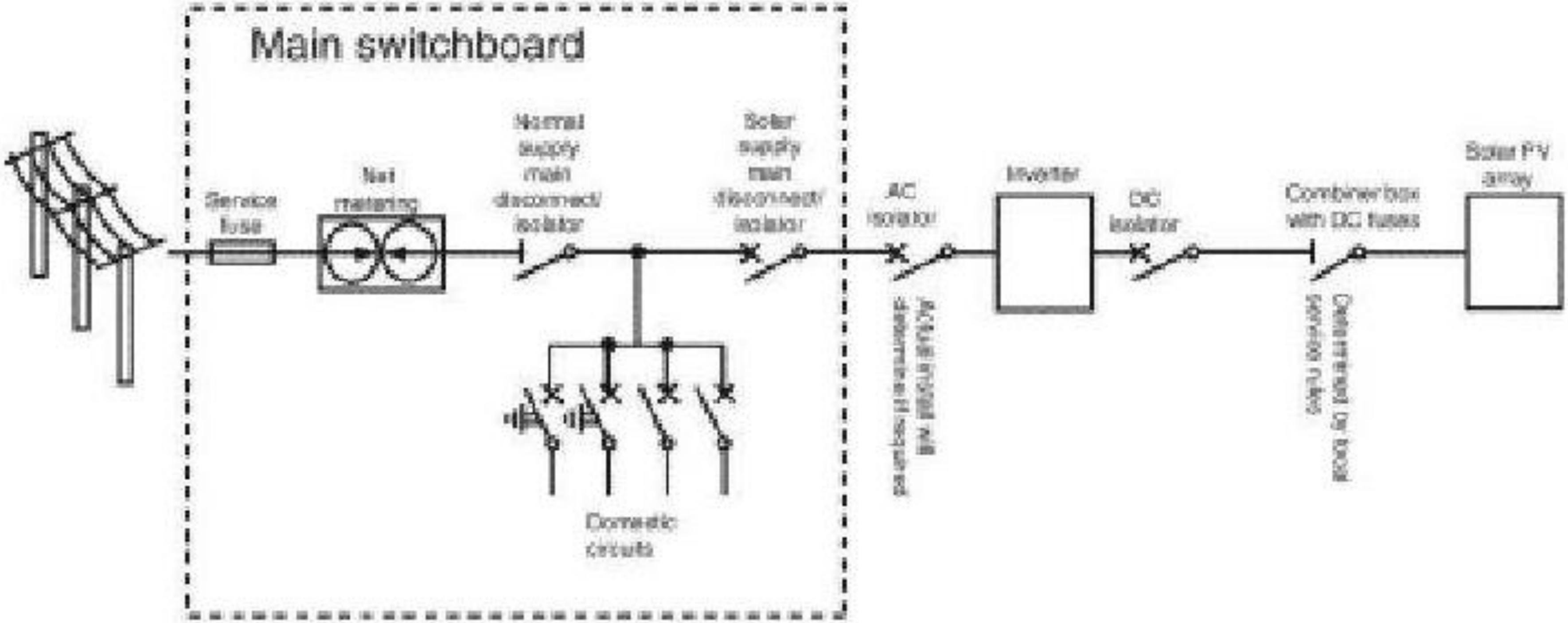
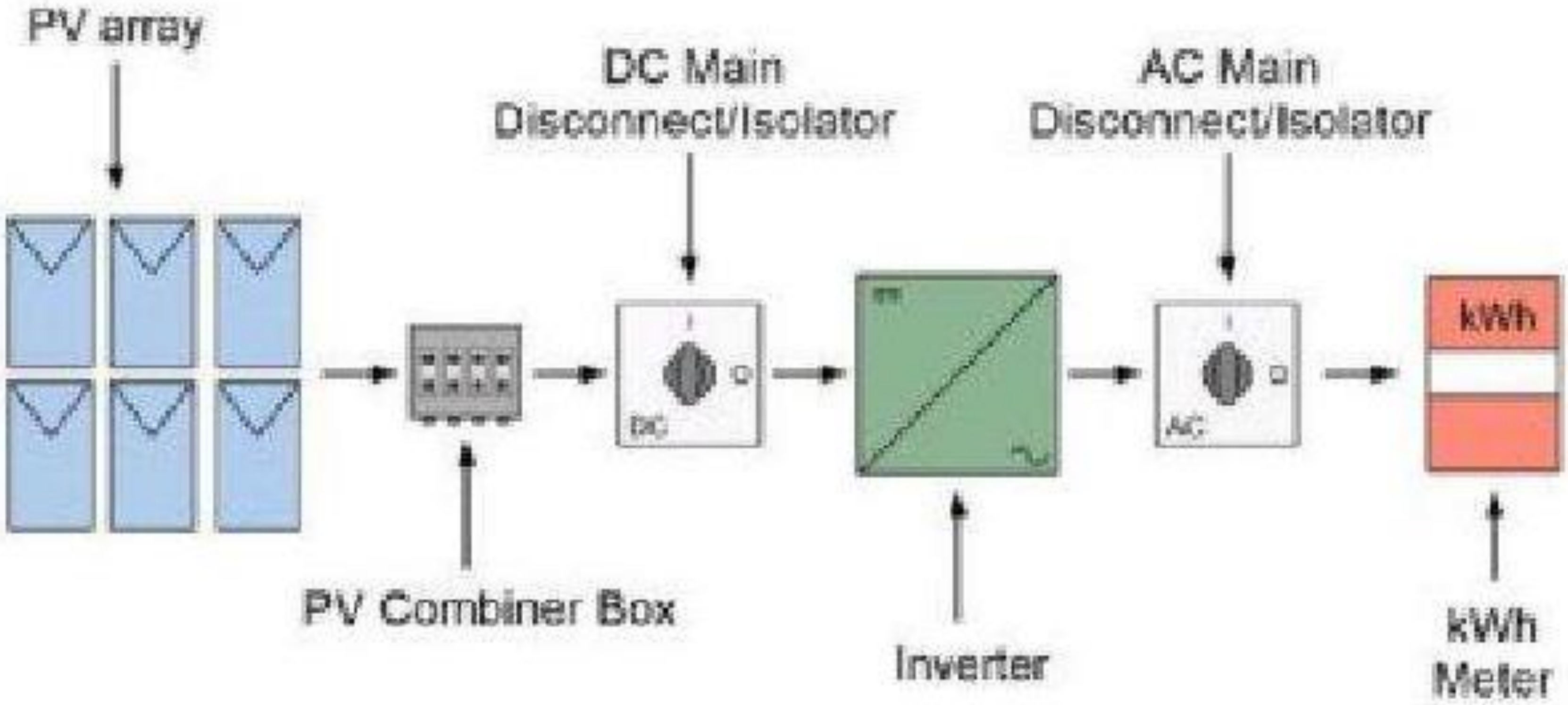
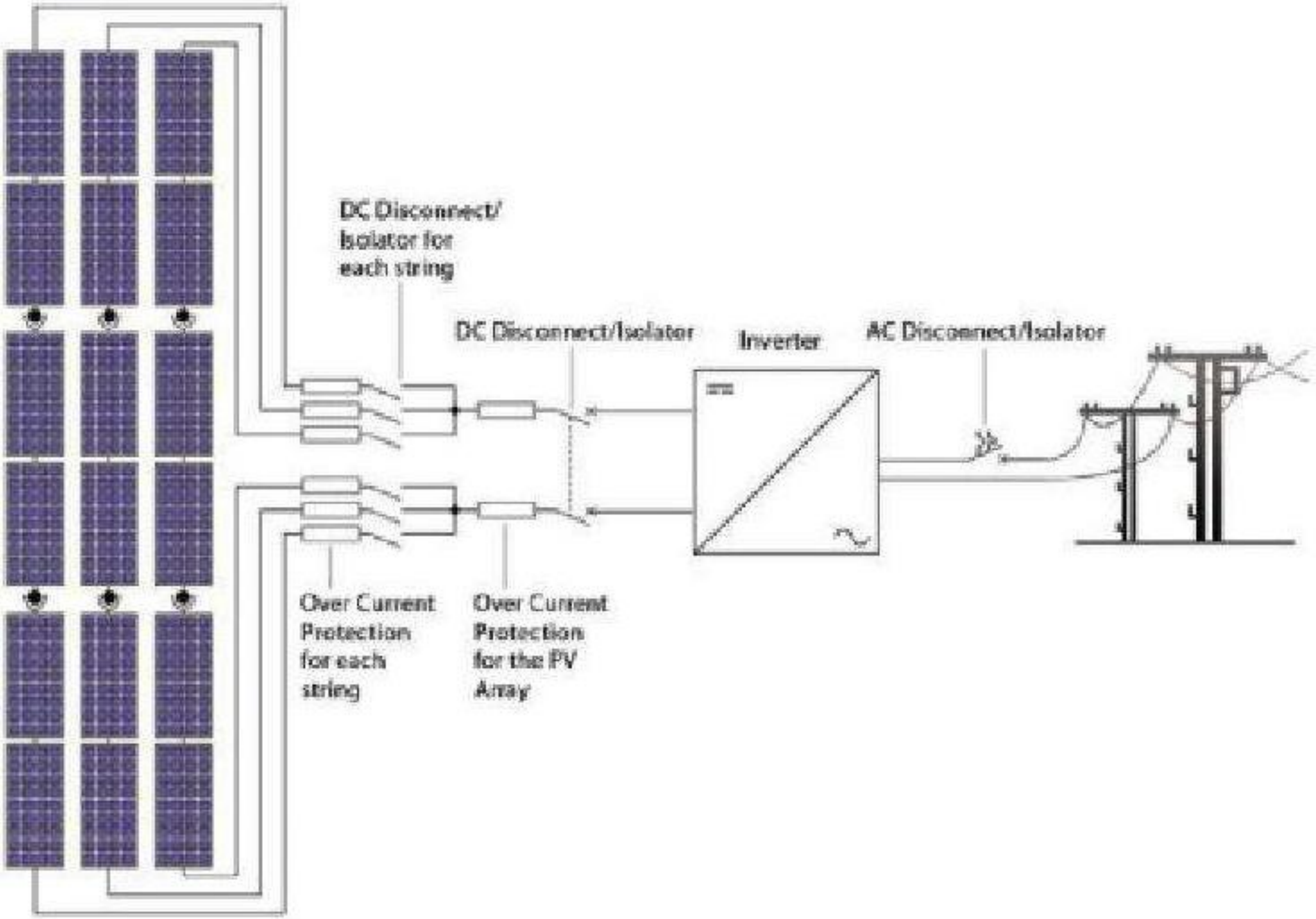


Figure 5.19 Key balance of system components shown excluding grounding/ earthing


Main switchboard
Service fuse
Net metering
Normal supply main disconnect/ isolator
Solar supply main disconnect/ isolator
AC isolator
Inverter
DC isolator
Combiner box with DC fuses
Solar PV array
Domestic circuits


PV array
DC Main
Disconnect/Isolator
AC Main
Disconnect/Isolator
kWh
PV Combiner Box
Inverter
kWh
Meter


DC Disconnect/ Isolator for each string
DC Disconnect/Isolator
Inverter
AC Disconnect/Isolator
Over Current Protection for each string
Over Current Protection for the PV Array

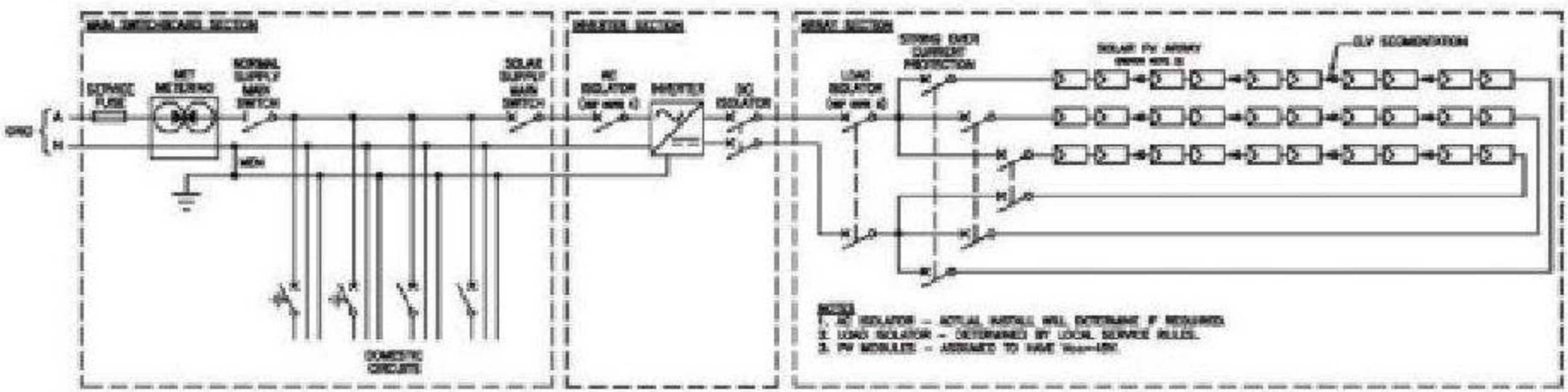


Figure 5.29 Schematic showing main disconnect/isolators and over-current protection. ELV segmentation is explained in Chapter 8

Inverters

Photovoltaic arrays produce DC, while the typical electricity grid is AC and most electrical devices operate on AC power. To ensure that the power produced by a PV array will flow into the grid, it is necessary for an inverter to convert the DC power produced by the PV array to AC power.

The circuit design of inverters makes this conversion possible: the alternating current is created by the inverter's switching mechanisms, which rapidly open and close the circuit. Transformers, discussed later in the chapter, are then used to increase the voltage to the level required by the grid.

There are two main types of inverters: battery or power inverters, which use batteries as their power source, and grid-interactive inverters, which are used in grid-connected PV systems.

Battery inverters

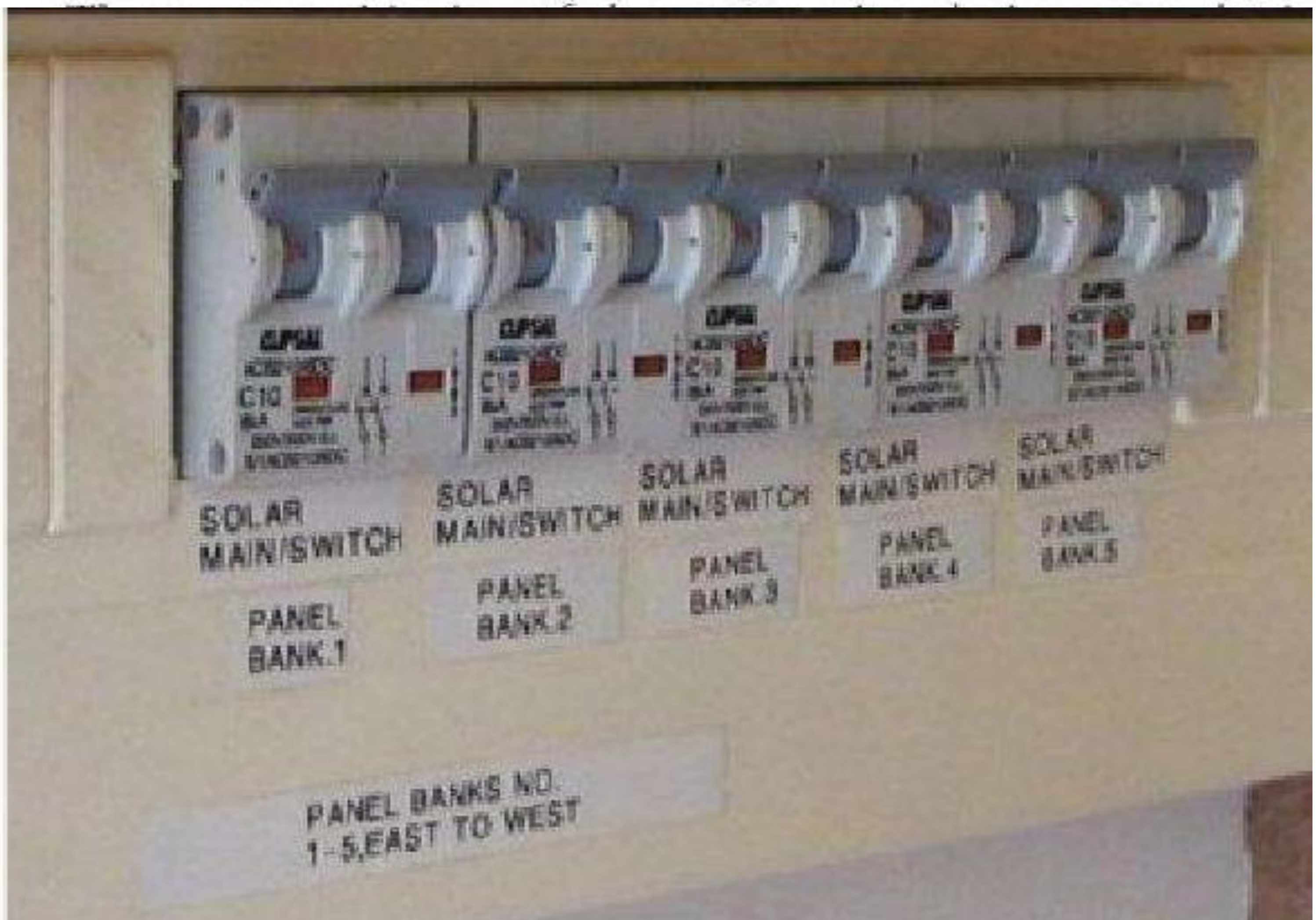
Many people are familiar with using an inverter when operating standard AC appliances from DC power sources, such as a car battery or larger storage batteries. The inverter takes the DC battery power and converts it to AC for use in AC circuits and loads. These inverters are usually referred to as battery inverters or power inverters. Battery inverters have a wide range of applications and are used in stand-alone PV systems; they are very different from the type of inverter used in grid-connected systems (see Chapter 1). Normally these inverters range from 1kW to 5kW continuous output.

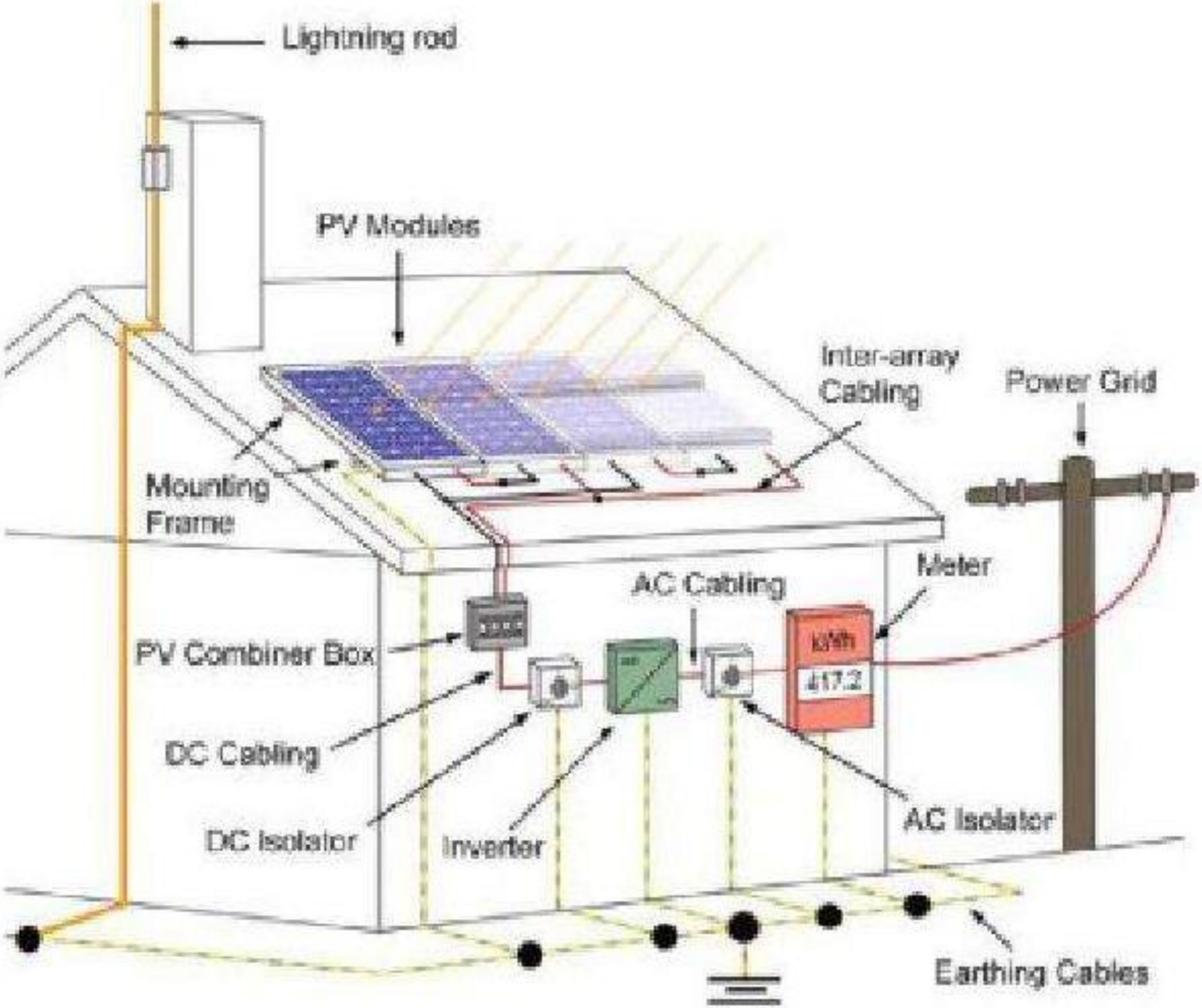
Grid-interactive inverters

This type of inverter, also known as a grid-tied inverter, is used in grid-connected systems and many different models are currently available. They receive the DC input from the array and match it to the AC output required by the utility grid. The inverter will only function when the grid is present and is working within a specific voltage and frequency range. Whether an inverter-charger feeds power back to the grid will be determined by the operating specifications of the unit itself, e.g. a US manufacturer of inverter-chargers has one model which is used only with mains or DC power input and cannot export to the grid and another model which has a software change to allow the inverted AC power to be exported to the grid.

Lightning and surge protection

Lightning and surge protection may or may not be required, depending on the system and local codes. If it is required then the devices may be required on both the DC side of the inverter (protecting from strikes on the array) and on the AC side of the inverter (protecting from strikes on the AC power grid).

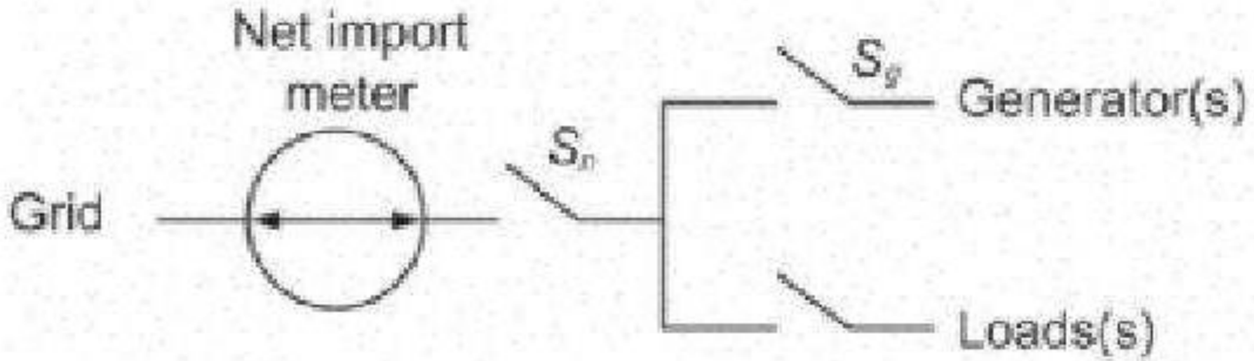




Lighining rod
PV Modules
Inter-array
Cabling
Power Grid
Mounting
Frame
Meter
AC Cabling
kWh
417.2
PV Combiner Box
DC Cabling
DC Isolator
Inverter
AC Isolator
Earthing Cables

Net metering

Net metering is a method by which a utility measures the difference between the consumption of a site and the generation at the site. In a typical residential system the electricity produced by the system will be exported to the grid during peak sunlight hours (usually 10.00am to 3.00 or 4.00pm) and the consumer will import electricity from the grid for use in the evening. If the generated energy is less than the consumed energy, then there is no net export and the customer pays the utility for the difference. If the generated energy is more than the consumed energy there is a net excess generation (NEG), the utility may pay the customer for their NEG or roll it over to offset the next month's bill. Net metering is widely used and is very common in the US where many states' utilities must make net metering available to customers with grid-connected PV systems.



The process of testing a PV system to confirm that it is producing electricity and interacting correctly with the electricity grid is known as system commissioning. Before an installer leaves the system to the customer it should be tested and inspected to ensure that the system is compliant with national and local standards and regulations, that all components have been safely installed and that all components are functioning as expected. Many utilities have rules or procedures that must be followed during the system commissioning process and in some cases the utility may wish to conduct a commissioning inspection. These requirements should already have been discussed with the utility when the interconnection agreement is made (see Chapter 10).

Commissioning procedures vary widely throughout the world and are largely dictated by national codes and standards.

- US: Article 690 of the National Electric Code (NEC) outlines inspection and testing requirements for PV systems. The Institute for Electrical and Electronics Engineers (IEEE) standard is also used: IEEE 1547 Standard for interconnecting distributed resources with electric power systems.
- International Electrotechnical Commission: The IEC provides international standards, IEC 62446 Grid-connected photovoltaic systems – Minimum requirements for system documentation, commissioning tests and inspection. This standard is intended to provide a template for electricians.
- UK: BS 7671 is the British wiring regulation and PV systems including inspection and testing requirements are covered in Section 712. The local distribution network operator (DNO) may also require various tests and documentation.
- Australia and New Zealand: The Australia and New Zealand Standards (AS/NZS) cover the commissioning of photovoltaic systems in AS/NZS4777

Final inspection of system installation

Before the PV system is commissioned, a final inspection should be undertaken to ensure the system is ready to be tested. If any issues are identified they should be addressed before any part of the system is switched on and/or tested. The equipment and installation should be checked to ensure that:

- Equipment and components are not damaged.
- The system matches the design documents and all equipment has been correctly connected according to the wiring diagrams.
- Equipment and components comply with local safety standards and are suitable for use in a utility-interactive PV system.
- The site has been left clean and tidy and presents no hazards for the general public.
- The signs and warning labels required by local codes are present.

Testing

Following a visual inspection of the system, testing should be undertaken in accordance with the prevailing national codes. National codes may require installers to ensure that the following points are compliant prior to system testing:

- There is no voltage at the output of the PV array (and at the output of each string if there is more than one). This may be achieved by leaving one of the module's interconnects disconnected/unplugged.
- Any fuses have been removed and all circuit breakers are in the 'off' position.
- The AC and DC main disconnects/isolators are in the 'off' position; local codes may also require them to be tagged or locked for the duration of the testing procedure.
- All components, i.e. the inverter, are switched off.

- continuity between adjacent system components;
- resistance of cable insulation;
- measurement of array and string open-circuit voltage (a large difference in the open-circuit voltage of identical strings or an open-circuit voltage very different to that expected may indicate a problem;
- measurement of array and string short-circuit current (hazardous – see box below);

Commissioning

Commissioning will be the first time the complete system is switched on and able to feed electricity into the grid. As already mentioned this process is normally covered in great detail by national codes and standards, with which any electrician undertaking PV system commissioning should be very familiar. The following table outlines the necessary post-commissioning tests to ensure the system is functioning with the grid and operating as expected. It is particularly important that the PV system disconnects and reconnects to the grid in accordance with local standards. This is required to ensure that an islanding situation does not occur (see Chapter 5).

Box 11.5 Commissioning test sheet

Refer to system manual for the inverter and follow start-up procedure	
System connects to grid	☐
When inverter, AC main disconnect/isolator and DC main disconnect/isolator have been turned on and inverter start-up procedure followed:	
Voltage at DC input of inverter	V
Voltage within operating limits of inverter	☐
Voltage at AC output of inverter	V
Input power of the inverter (if available)	W
Output power of the inverter (if available)	W
Output power as expected	☐
System disconnects from grid when inverter AC isolator turned off	☐

Conducting a site assessment or site survey is an important step in the design and installation of a system. During the site assessment the installer should collect all the necessary information required to optimize system design and plan for a time-efficient and safe installation. A site assessment aims to determine the location of the PV array, the roof specifications, the amount of shading, the available area and other considerations.

Location of the PV array

In most urban areas the array is located on the roof of a building, or in cases where there is a large, clear area of ground that will not be shaded (by trees or nearby buildings) it may be desirable to use a ground-mounted system. Mounting structures are discussed in Chapter 6. There are many options available and these often depend on the angle and orientation of the roof or ground.

Roof specifications

- Orientation: as discussed in Chapter 2, the ideal orientation is where a module receives maximum sunlight (this is true south for the northern hemisphere or true north for the southern hemisphere). Unfortunately when a PV array is installed on a roof its orientation is governed by the direction of the roof. Using a compass and magnetic declination data (as

- Tilt angle: in most systems the tilt of the modules will follow the tilt angle (or pitch) of the roof. The tilt angle should be measured using an inclinometer or an angle finder; it may also be available on architectural drawings of the building. The optimum tilt for a system is equal to the latitude of that location. In cases where the pitch of the roof is not equal to the optimum tilt angle the PV array's energy yield will be affected.

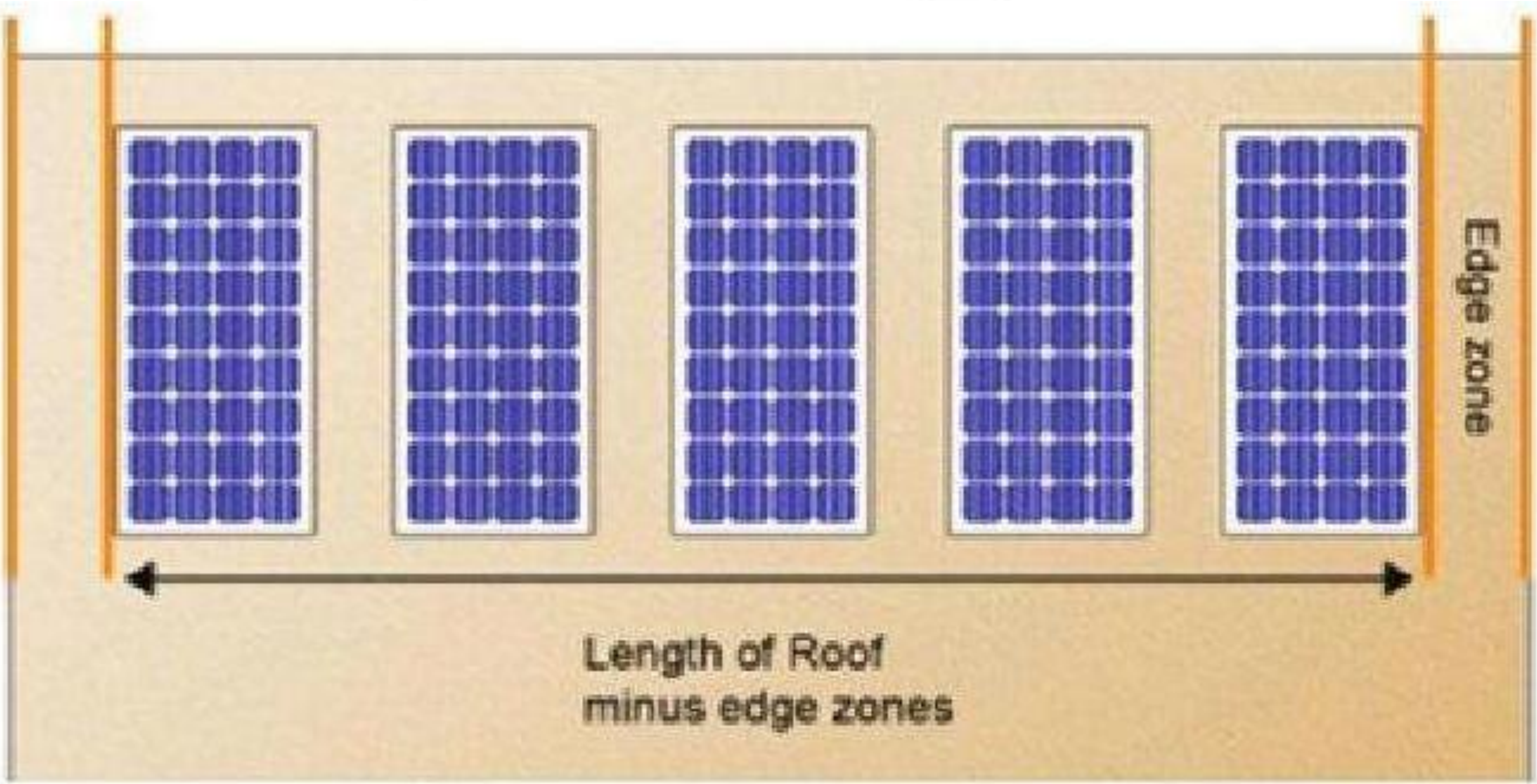


Figure 7.16 Example of calculating the number of columns in a portrait installation

Locating balance of system equipment

The location of the solar array has already been covered in this chapter. While on site, the location of all other equipment must be determined. This includes the location of:

- PV combiner box (if required);
- Inverter: the inverter should be located somewhere where it is easily accessible, protected from direct sunlight and well ventilated.

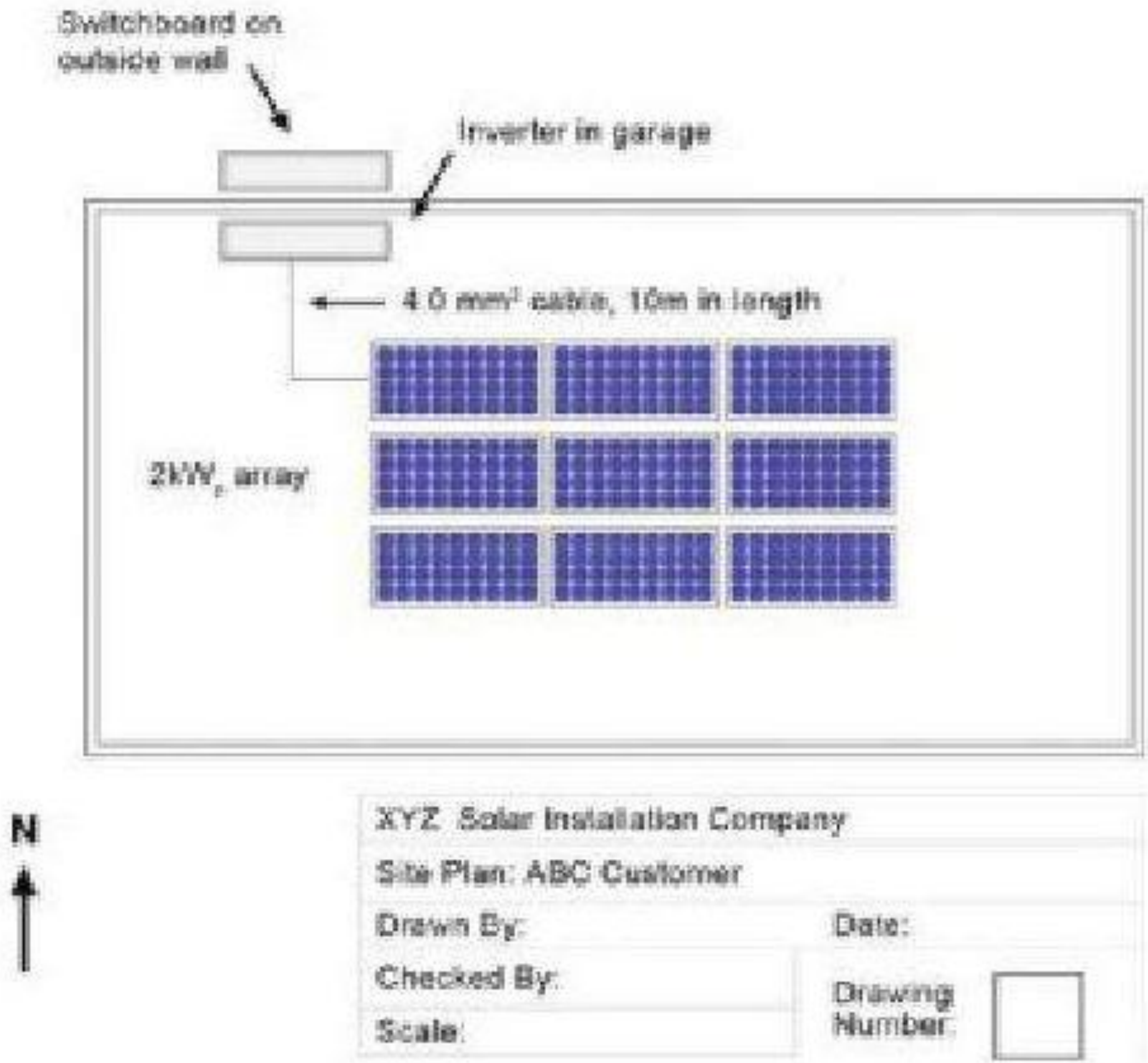
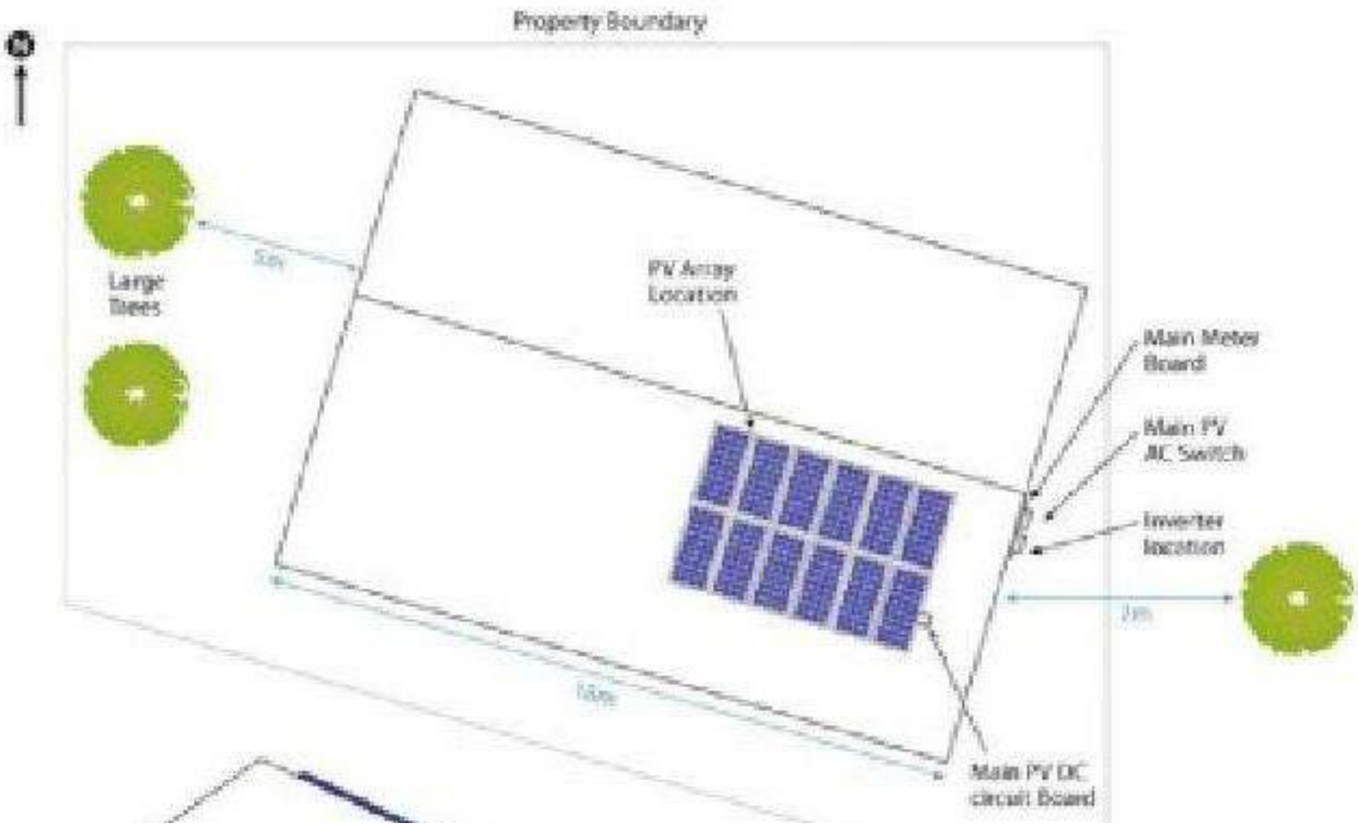
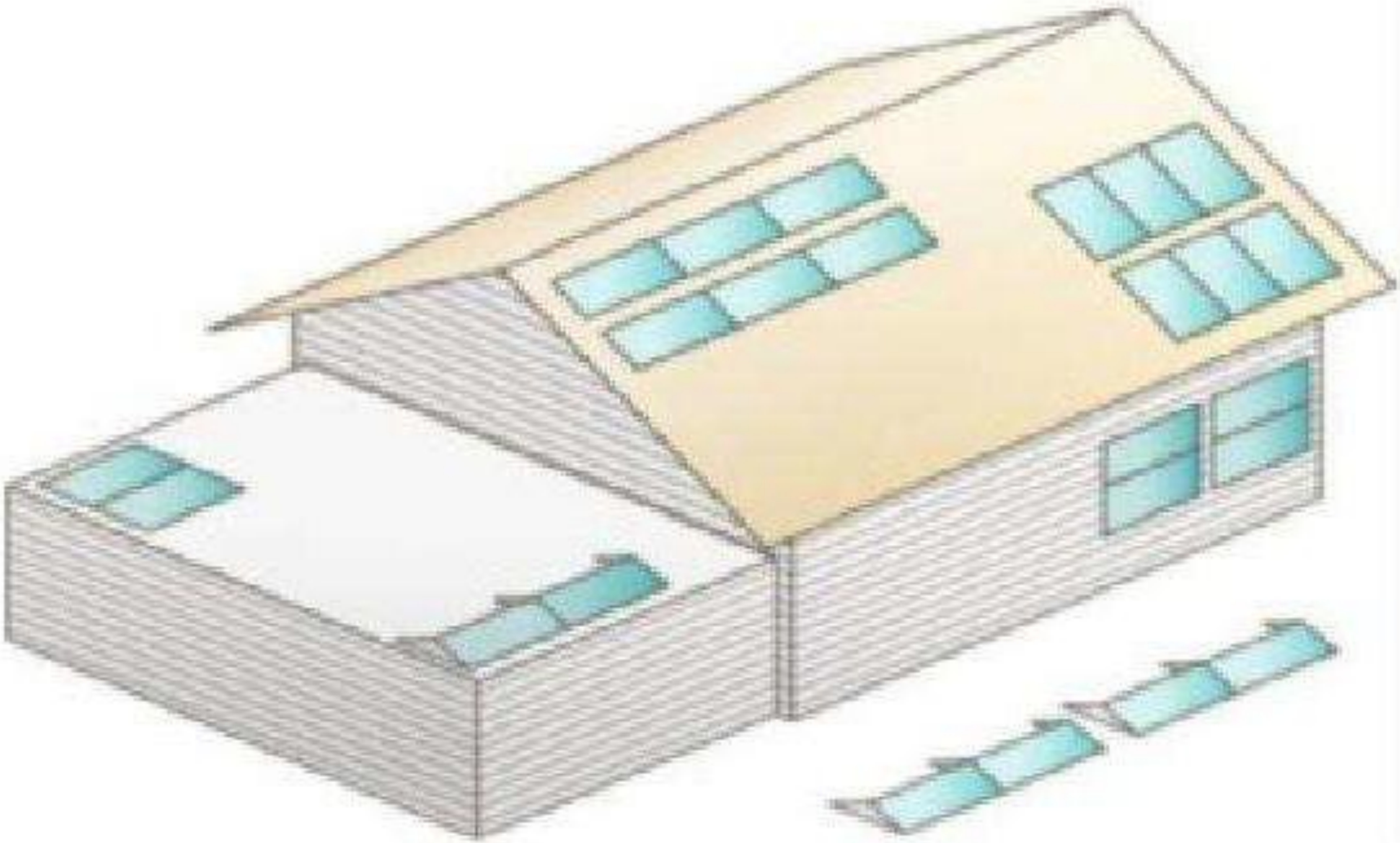


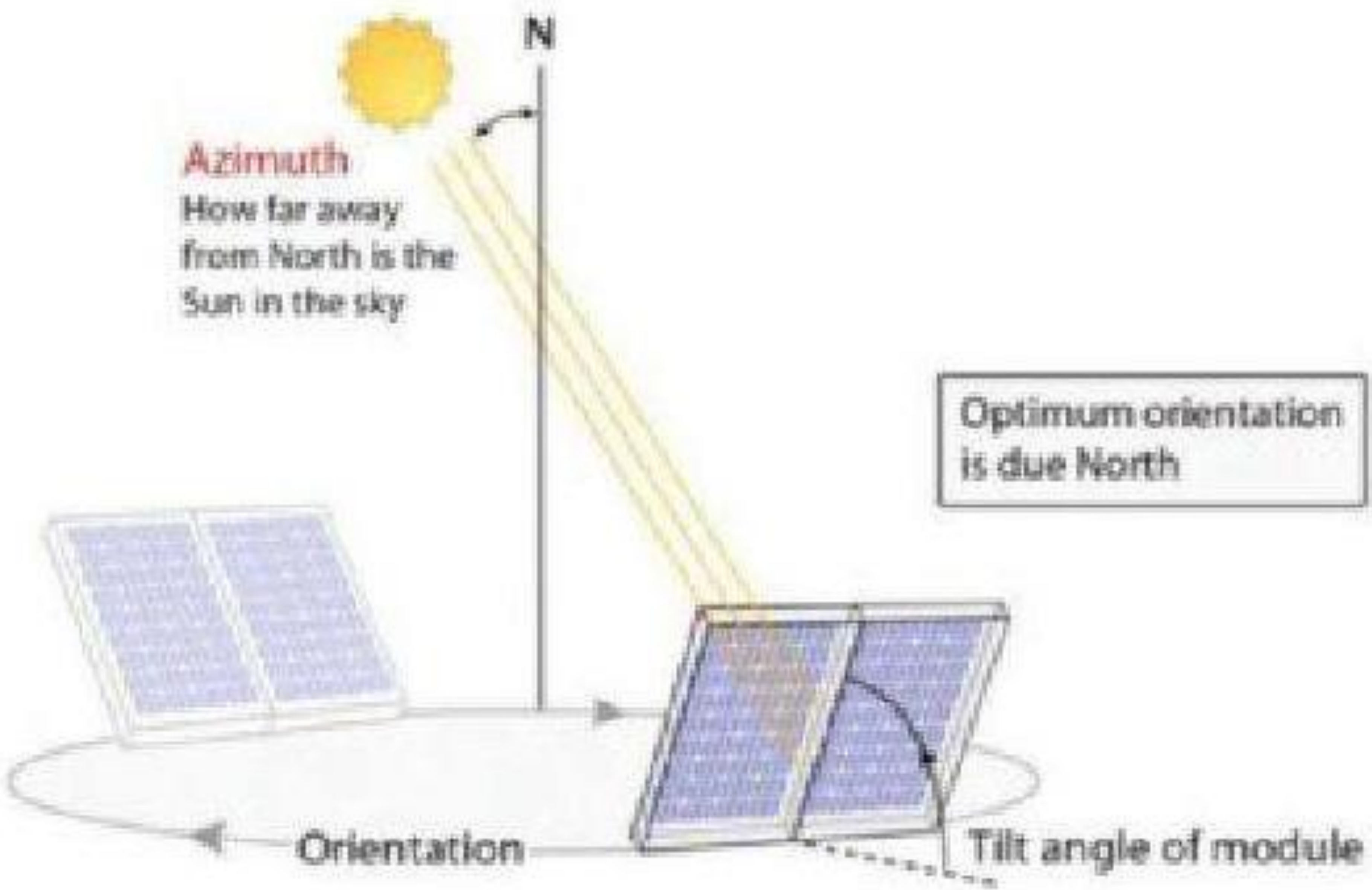
Figure 7.21 Example of site plan for a PV installation

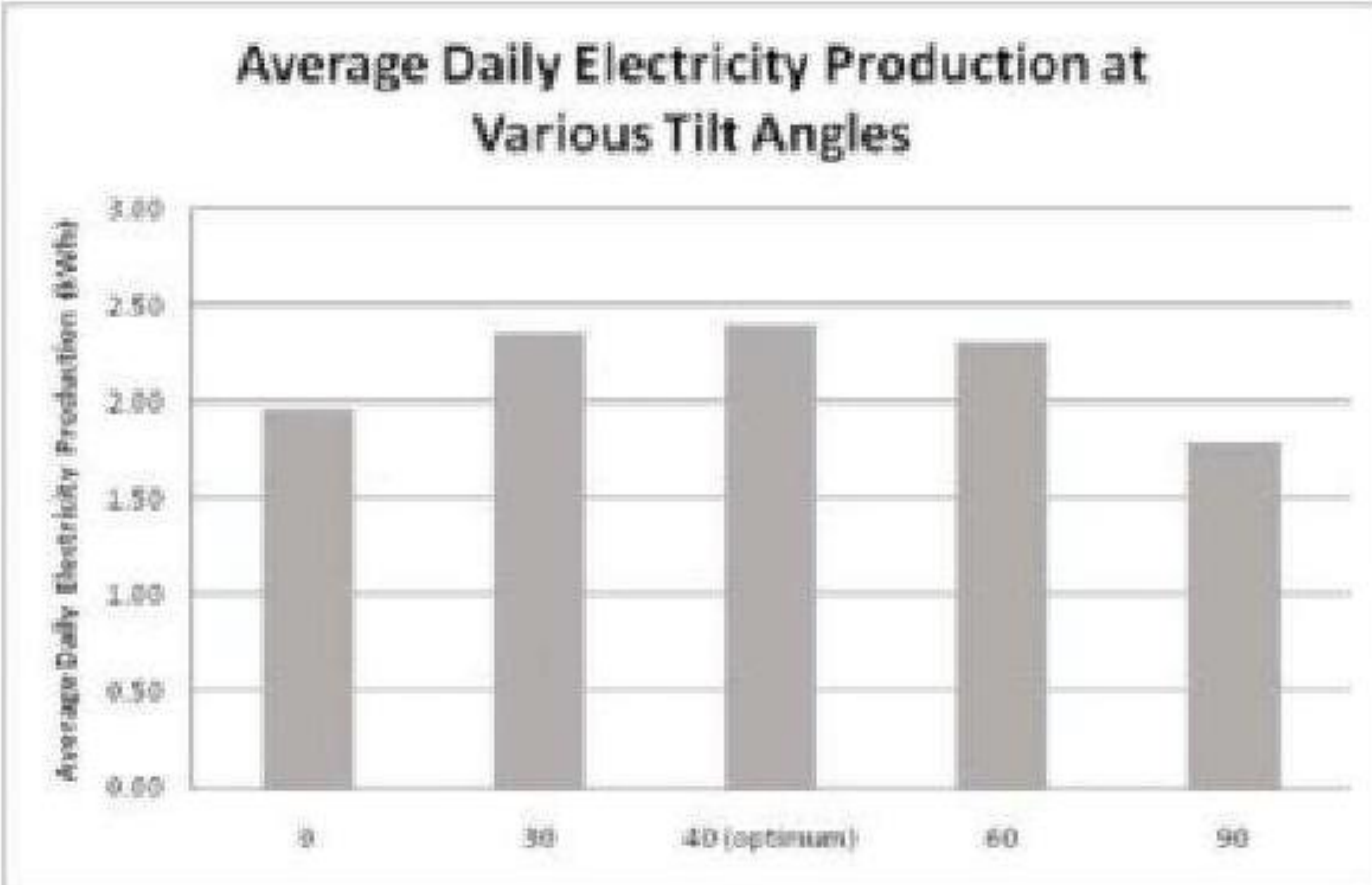
Site plan

Before installing the system, installers need to complete a site plan detailing any buildings, solar obstructions, access pathways and the physical layout of the site. It is necessary to overlay the designed system onto this drawing. The site plan should include dimensions such as roof lengths, cable lengths, position of components and distances between buildings.






N
Azimuth
How far away from North is the Sun in the sky
Optimum orientation is due North
Orientation
Tilt angle of module

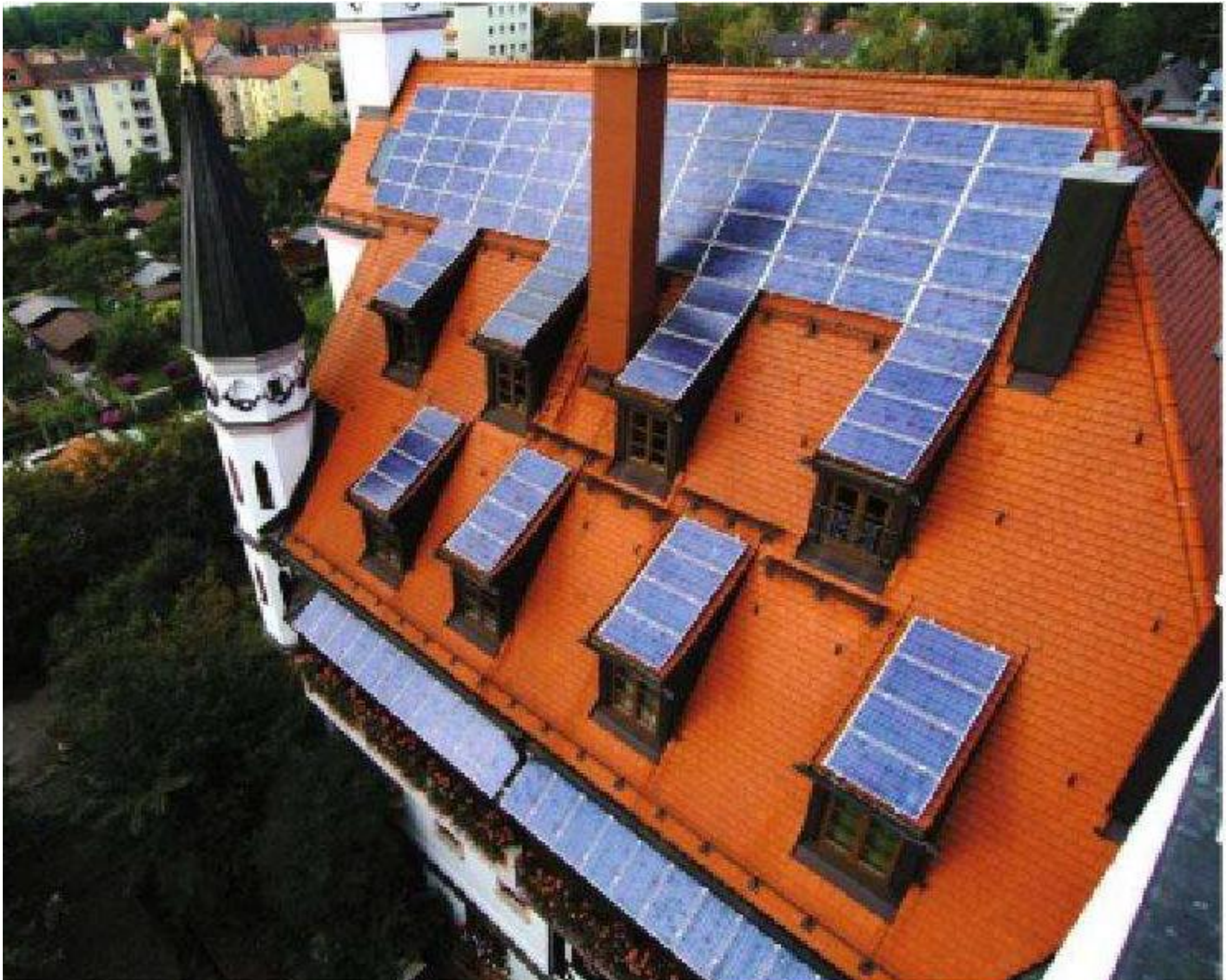

Average Daily Electricity Production at Various Tilt Angles
Average Daily Electricity Production (kWh)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
30
40 (optimum)
60
90

Is the site shade-free?

As explained in Chapter 3 shading on a PV array can significantly decrease its output. Some sources of shading such as dust, dirt and bird droppings are unavoidable and must be cleaned off regularly. Any permanent source of shading needs to be identified during the site survey. Potential sources of shading may include:

- Trees and vegetation: it is important to bear in mind that trees that do not shade the PV array at the time of the site assessment will grow and may shade the PV array in a few years, so this should be discussed with the owner before installation. The owner may agree to prune the tree regularly and ensure it does not shade the array. If this is not possible, for example, if the tree is on a neighbouring property, another location should be considered, or the neighbour may be consulted.
- Other buildings, including neighbouring properties or buildings on site. Be aware that new buildings may be constructed, shading areas currently suitable for arrays.

Figure 7.4 Poorly chosen site where trees are shading the PV array



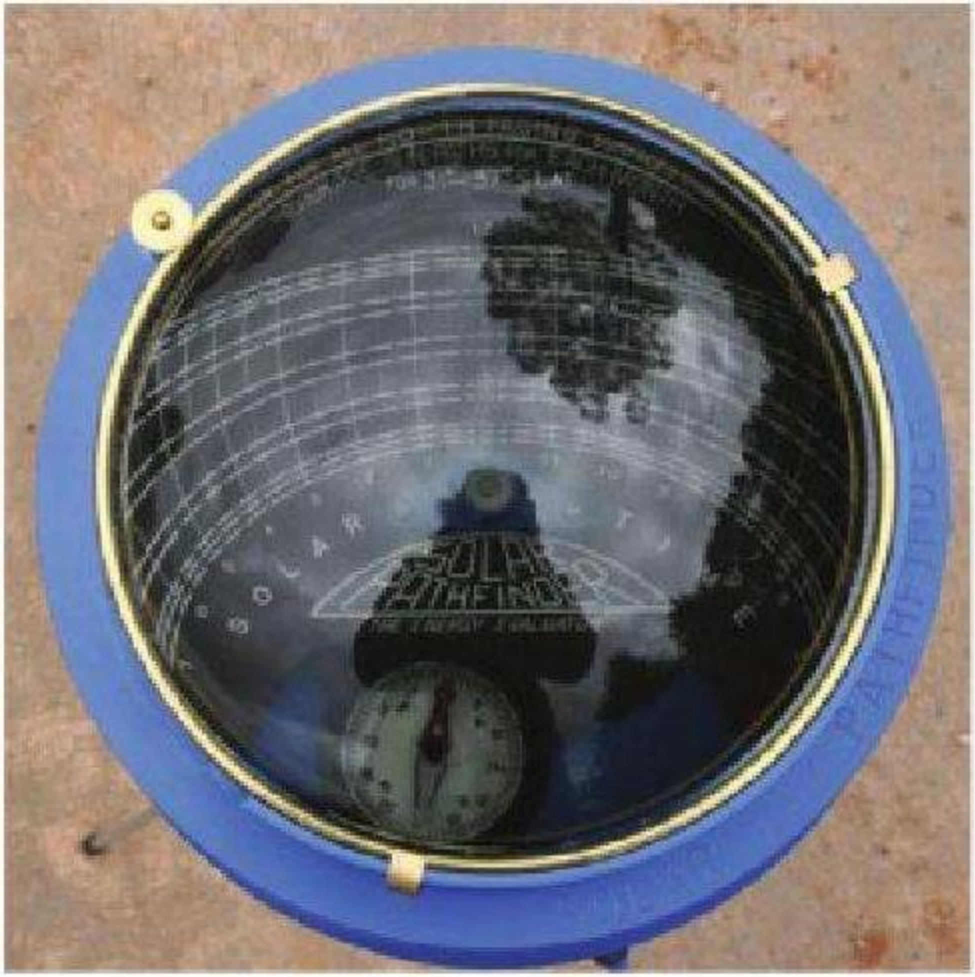


Figure 7.7 Solar Pathfinder, showing trees to the north and to the right shading the site

Source: Global Sustainable Energy Solutions

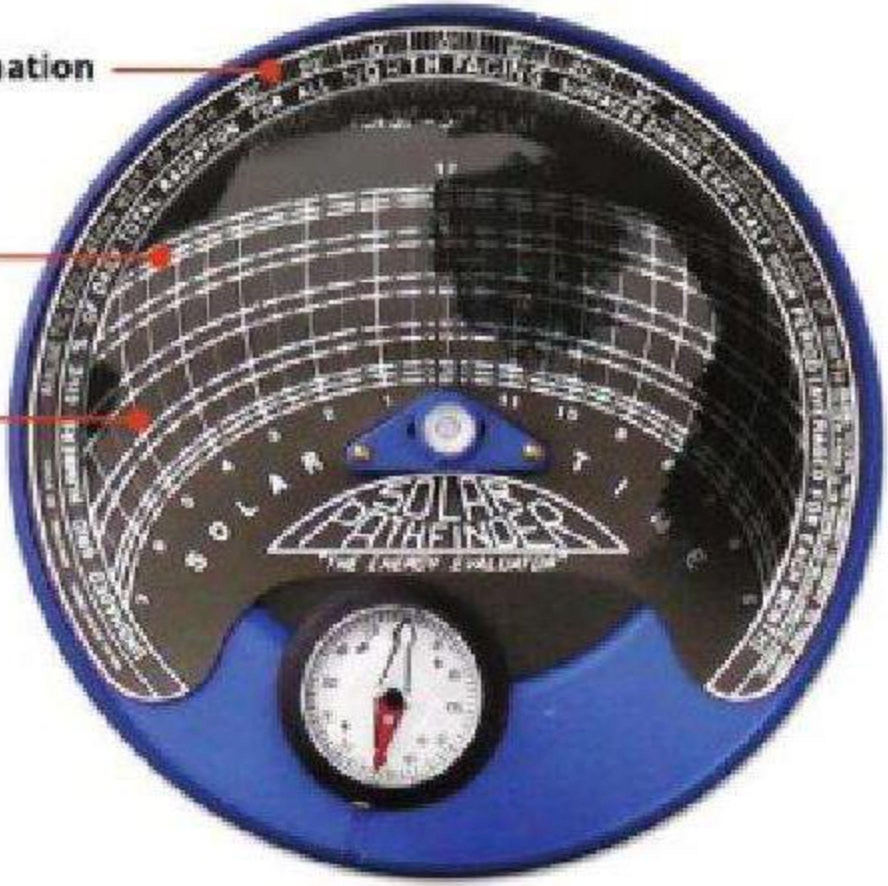


Figure 7.8 Example of a sunpath diagram with the shading traced on it; it is important to use the correct sunpath diagram for the latitude of the site

Source: Global Sustainable Energy Solutions

The most important aspect of system maintenance is performance monitoring, which will ensure that when a problem arises it can be identified and corrected before serious damage occurs (shading causing hot spot heating, for example). It will also give the user records of year-round system performance, which will help performance comparison in the future.

PV array maintenance

PV arrays have no moving parts and therefore operate for many years, often without issues. However, regular maintenance is still important to ensure a PV array is operating safely and efficiently. Common maintenance tasks include cleaning the modules and mechanical and electrical checks. It is recommended that PV modules are maintained only by suitably trained service personnel.

It is also common practice to monitor PV systems. Although it is normal for power output to degrade over time, a large difference between measured and expected values indicates a problem to be tackled. The most common form of monitoring is checking electrical parameters such as output voltage and current, which can be compared with what is expected from the design and what was measured during the commissioning process, to determine whether there is a problem or not. Many modern inverters include monitoring functions, or external monitoring equipment may be used (see Chapter 5). In some cases the environment may also be measured (temperature), as this helps designers see a correlation between environmental conditions and system yields. The temperature of the modules may be monitored to ensure it is within the designed system range (see Chapter 9).

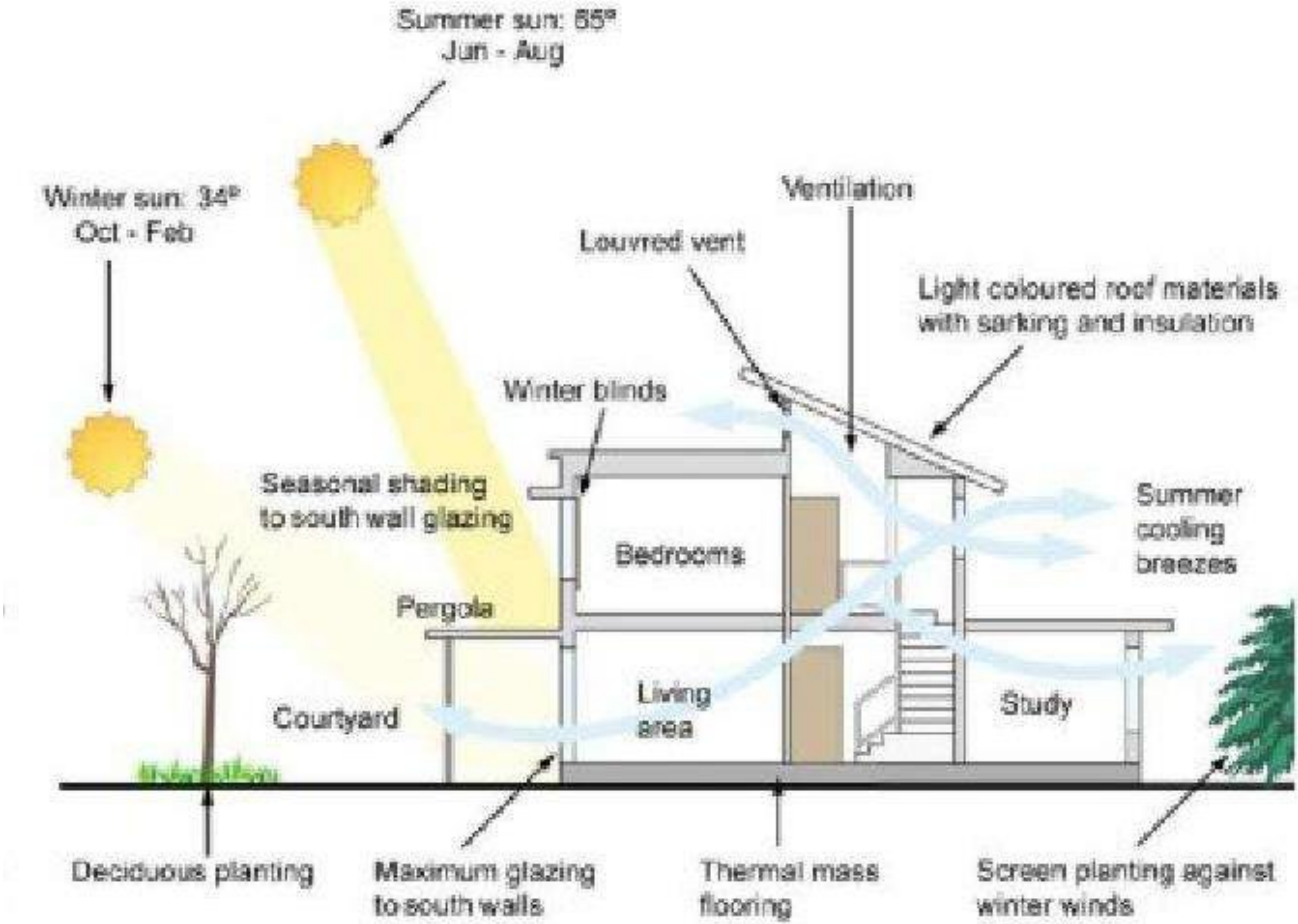
Table 12.1 Recommended maintenance for PV array

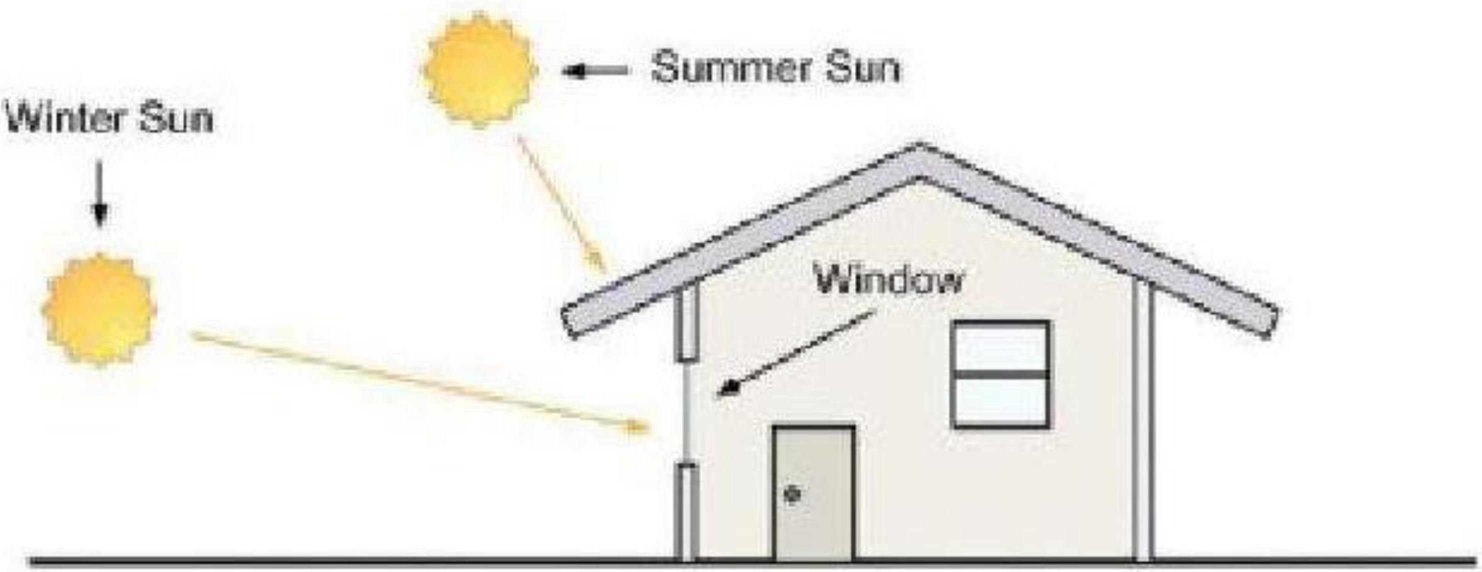
Activity	Frequency
Clean modules	As required
Check mechanical security of the array structure	Annually
Check all cabling for mechanical damage	Annually
Check output voltage and current of each string of the array and compare to the expected output under existing conditions	Annually
Check electrical wiring for loose connections	Annually
Check the operation of the PV DC main disconnect/isolator (only after AC main disconnect/isolator has been switched off)	Annually

Passive solar design

Passive solar design refers to designing a building in order to utilize the sun's energy as much as possible. It varies significantly throughout the world, the basic idea being to keep the sun's rays out of the house in the summer and to trap the sun's rays inside the house during winter and so to minimize the need for artificial cooling and/or heating.

- Deciduous trees and vines are useful because if planted in a location exposed to direct sunlight, they will shade the area in summer, but in winter they lose their leaves allowing the sun's rays to come in and warm the area.
- Eaves and pergolas can be designed to shade windows during the summer (when the sun is high in the sky) but allow sunshine in during winter (when the sun is low in the sky) to warm the building. The eaves should also be lightly coloured so they will reflect the sun's rays in summer. If they are a dark colour the material will absorb the sun's rays and heat up.


Summer sun: 65º
Jun - Aug
Winter sun: 34º
Oct - Feb
Ventilation
Louvred vent
Light coloured roof materials with sarking and insulation
Winter blinds
Seasonal shading to south wall glazing
Bedrooms
Summer cooling breezes
Pergola
Living area
Study
Courtyard
Deciduous planting
Maximum glazing to south walls
Thermal mass flooring
Screen planting against winter winds



Figu
desig
sumr
wind
warn

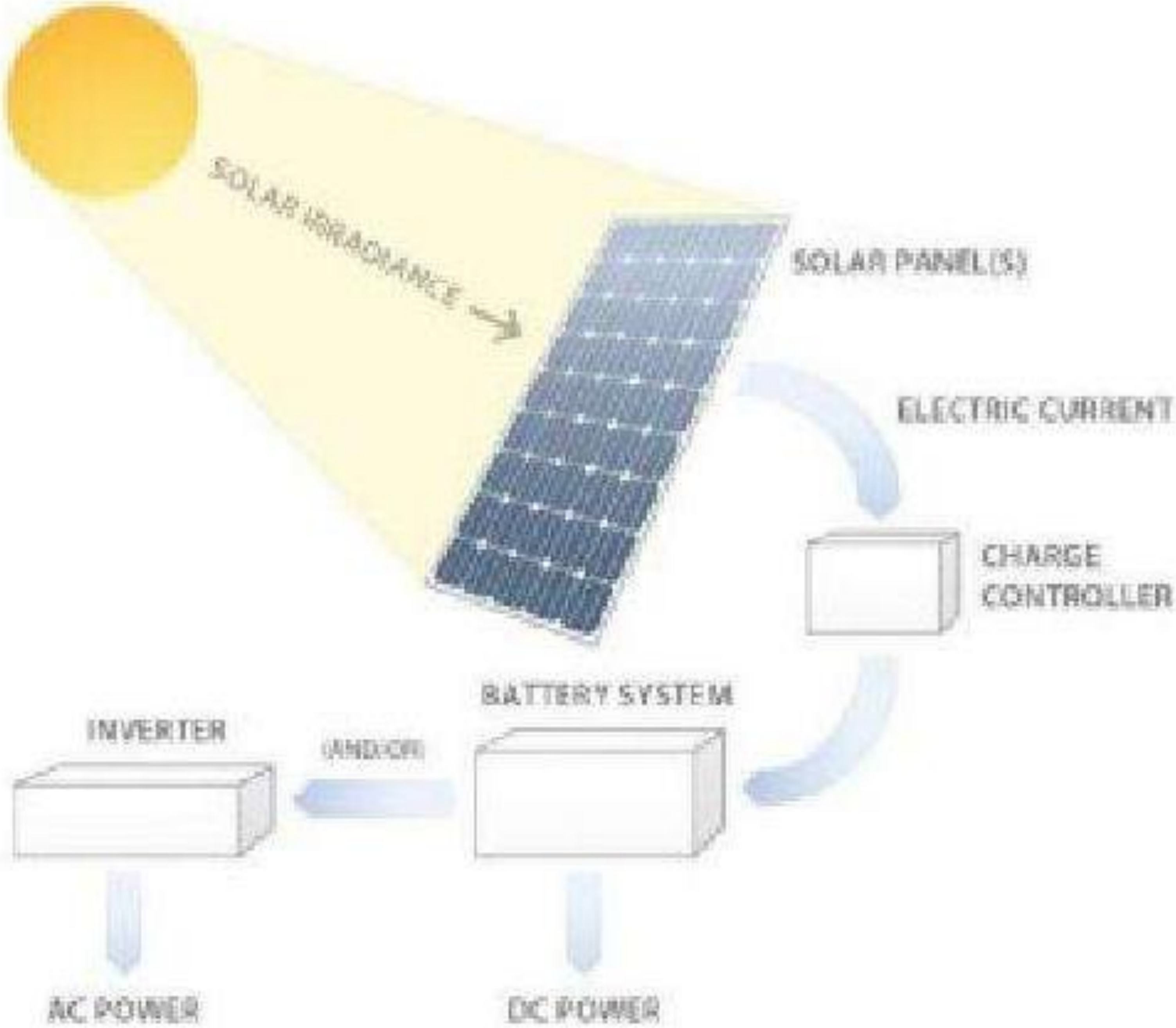
Sourc
Soluti

Windows allow for cooling breezes in summer and can be closed in the winter to seal in warm air. These should be positioned according to local wind direction, i.e. if summer winds commonly blow from the northeast, windows should be placed on the north side of the building and on the east side of the building to capture the breeze.

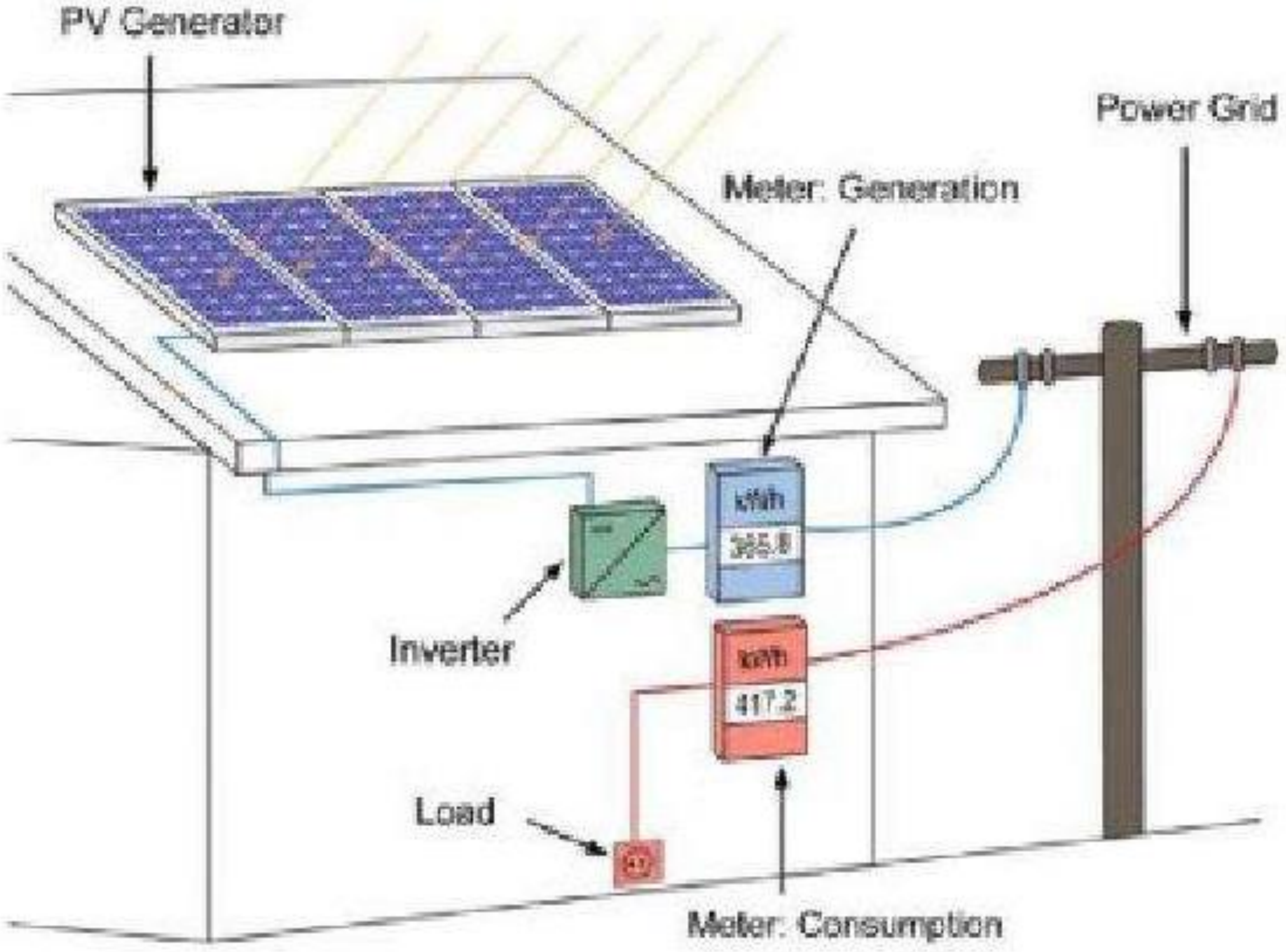
Thermal mass and insulation is important for maintaining the building at a comfortable temperature despite fluctuations in outside temperature. This can be as simple as closing curtains in winter to stop heat escaping through the windows.

What is a solar electric system?

Solar energy is harnessed by using solar electric systems, also known as photovoltaic (PV) systems. The word photovoltaic is derived from the Latin words *photo* (light) and *voltaic* (energy). PV devices capture the energy in sunlight and convert it into electricity – that is, they use light energy. Solar electric systems should not be confused with solar thermal systems which use the sun's energy to heat a substance (typically water). Electric and thermal systems are very different in appearance and operation, as Figure 1.3 shows. There are several different types of solar electric systems, discussed below. This book focuses on solar electric systems that feed electricity back into the grid (grid-connected solar electric systems).


SOLAR IRRADIANCE
SOLAR PANEL(S)
ELECTRIC CURRENT
CHARGE
CONTROLLER
BATTERY SYSTEM
INVERTER
(AND/OR)
AC POWER
DC POWER

The major components of a grid-connected PV system include the PV array, inverter and the metering system. In addition to these major components are the necessary cables, combiner boxes, protection devices, switches, lightning protection and signage.



Central grid-connected PV systems

The existing electricity system typically consists of central power stations using a variety of fuel sources such as coal, gas, water (hydro) or diesel that provide power to end-users via transmission lines and a distribution system. The power stations directly connect to the transmission lines and the power produced by the power stations is consumed by end-users at their actual location in factories, businesses and homes.

Distributed grid-connected PV systems

As the name suggests, these grid-connected PV systems are distributed throughout the electricity grid. This is the most common type of PV system and hence the focus of this book. There are typically two types of system: commercial and residential.

Commercial systems are generally greater than 10kWp and are located on buildings such as factories, commercial businesses, office blocks and shopping centres. The power generated by these systems is typically consumed by the loads within the building, so no excess power is exported to the electricity grid.

Residential systems refer to those installed on homes and are generally smaller than commercial systems, typically between 1 and 5kWp. The power generated by these systems is first consumed by any loads operating in the house during the day; excess power is fed into the grid providing electricity to nearby buildings.

Roof mounting systems

For homes or businesses using a grid-connected PV array, the most common installation is the rooftop mounting system. Its most important role is to securely and safely attach the solar array to the roof. Aside from safety there are three other important factors to consider when choosing a roof mounting system: the amount of solar radiation the module will receive in that position, ventilation of the module and the overall aesthetics of the PV system.

The amount of solar radiation the module receives (the module's solar access) will directly affect the power it produces and therefore should be optimized by using a mounting system that secures the array at optimal orientation and tilt angle for that location. In cases where attaching modules at the angle and direction of the roof will not yield this result, installers may consider using a mounting system that can elevate the modules to face the optimum tilt angle and orientation and so improve the modules' power output.

Ground mounting systems

Ground-mounted PV systems have two main applications; they are commonly used on residential or commercial properties where rooftop mounting is not a viable option and there is plenty of free ground space, or for very large-scale PV installations. Ground-mounted systems have many advantages: first the tilt angle and orientation is not constrained by the slope or direction of a roof or facade and so the array can be installed at the optimum tilt angle and orientation; they offer the installer the ease of constructing a system at ground level, and avoiding work at heights. Working without ladders and lifts saves time for an installation in some cases, although ground-mounted systems may also require civil engineering, trenching and storm water management. The additional costs of material, labour and engineering associated with ground-mounted PV arrays might not be economical for many small- or medium-sized grid-connect systems.

Figure 6.13 Large ground-rack mounted installation

Pole mounts

Pole mounts are popular for systems requiring fewer modules. The main advantage of these systems is that they are an inexpensive option because they do not require many installation materials and they are usually adjustable so the installers can change the tilt angle seasonally to keep the array at the optimum tilt angle for a larger part of the year.

Figure 6.15 Pyramid-style pole mount, which also uses a sun-tracking system

Sun-tracking systems

Sun-tracking systems are mechanisms that turn the array to ensure it is always facing the sun and thereby operate the solar modules at peak power for a longer period of time each day. These systems are much more expensive. However, where space is limited or the value of the increased energy harvest is high, the additional cost of the tracking system may be justified over the life of the project.

Most tracking systems use sun-seeking sensors or a computer to calculate the position of the sun and move the array accordingly using motors and gears. There are two main types: single-axis trackers and dual-axis trackers. A single-axis tracking system moves the solar modules through one axis from east to west to follow the sun's path over the course of the day, whereas a dual-axis tracking system follows the sun's path along two axes: like the single-axis tracking system it will follow the sun's path throughout the day, and it also makes adjustments in tilt angle to account for changes in the sun's altitude over the year (i.e. in winter the sun is much lower in the sky so the modules will be tilted at a steeper angle).

Figure 6.16 Sun-tracking system: the arrays rotate throughout the day to face the sun

Wind loading

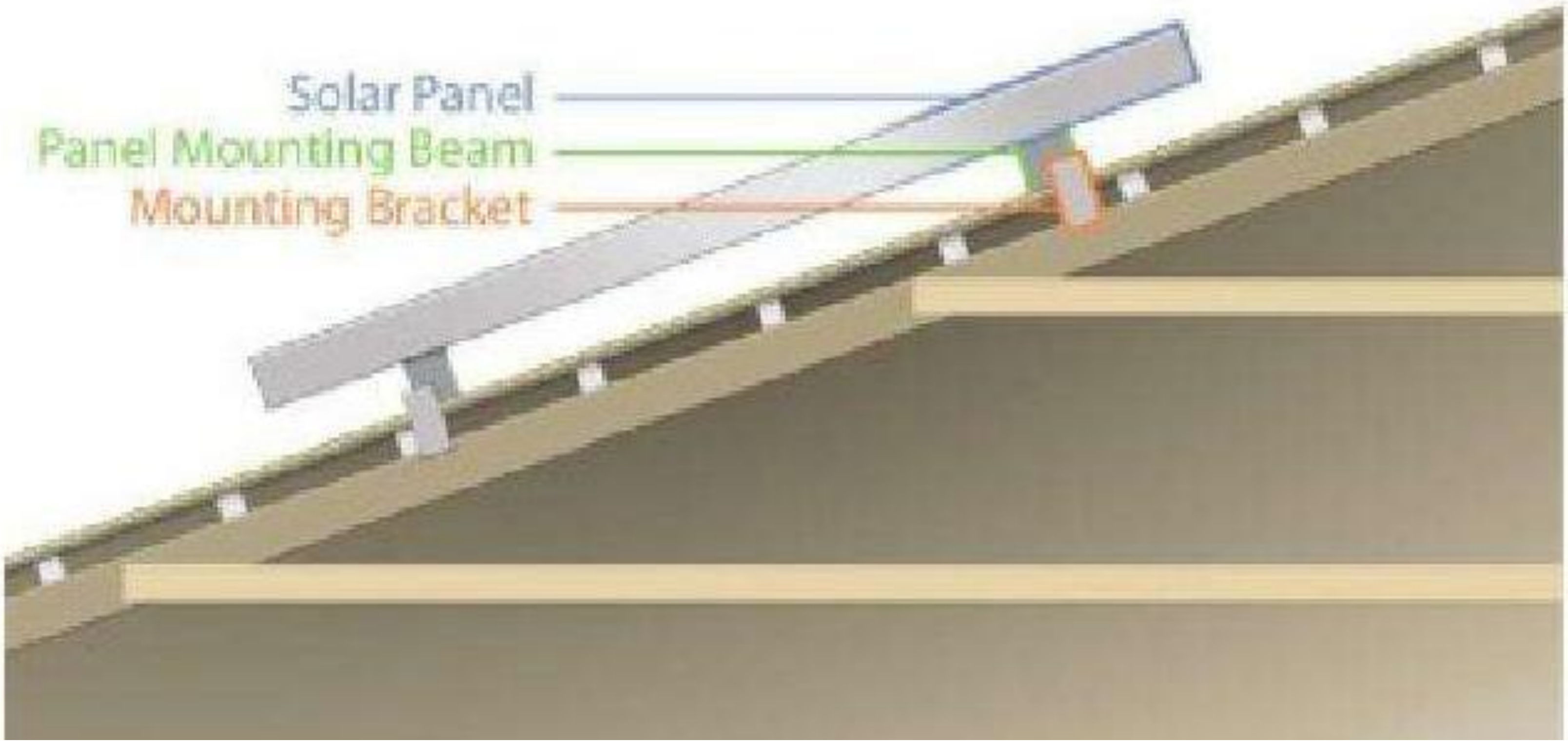
Wind loading describes the wind forces experienced by a solar module, including a suction or uplift force on the module when the wind blows across the array and downward or lateral stresses on the module caused by strong winds. A PV array is not mounted safely unless it can withstand the wind loading forces expected at the site. Wind speeds vary widely throughout the world and so it is important to ensure that the module and mounting system selected are suitable for use at the site. The module's installation manual or data sheet specifies the module's maximum load rating and should be consulted before final module selection.

Figure 6.1 This mounting scheme allows good ventilation. Mounting panels closer to the roof increases operating temperature and thereby lowers system performance

Figure 6.2 This mounting scheme will not permit good airflow

Pitched roof mounts

Pitched roof mounts are the most common roof-mounted system because they are versatile, easy to install and relatively inexpensive. These systems are typically mounted just above the roof surface at the same orientation and tilt angle as the roof. Pitched roof mounts are normally attached to the roof's structural members, e.g. the rafters, through the use of lag bolts or fixing brackets.



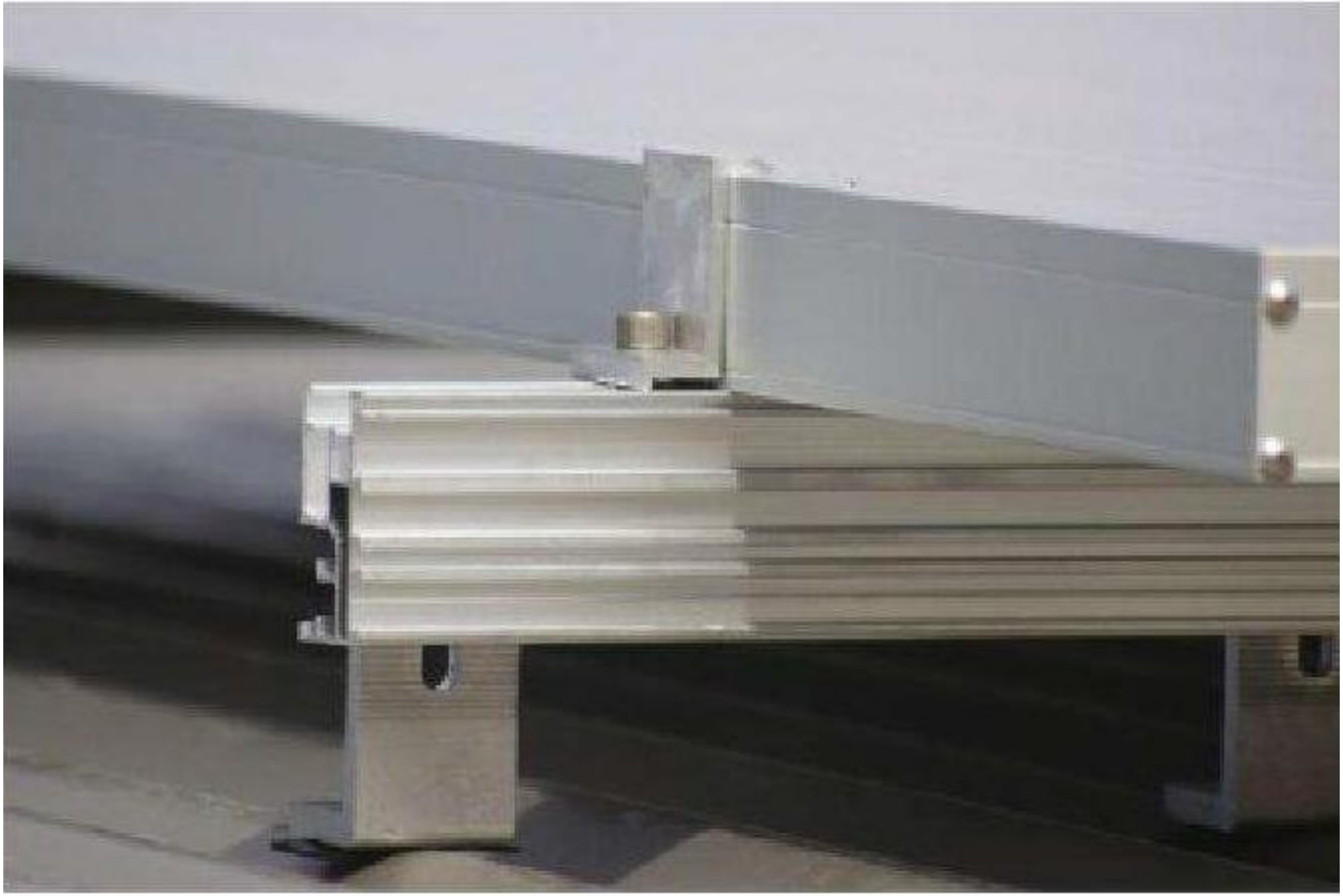


Figure 6.4 Example of a pitched roof mounting system clearly showing the module clamp

Design brief

Before any components are selected it is necessary to consult the client regarding their needs and expectations from the system. The amount of money the client is willing to pay for the system will affect the size of the system, as will the metering system. Different metering systems are discussed in Chapter 5: when gross metering is used, the system installed is often as large as possible to capitalize on the gross metering returns; when net metering is in place, the consumer may choose a smaller system and decide to invest more money in energy-efficiency measures on site so as to minimize local electricity consumption and maximize the energy exported.

Mechanical protection

As PV arrays are often located as high as possible to prevent shading and interference from external agents, they are often subject to high levels of wind loading. As such, the support structure for these arrays should conform to the local building code and any national standards or regulations regarding wind loading. Wind loading is covered in Chapter 6.

Array protection

Array protection is dependent on local codes and varies by country. As there are no other sources of DC current (i.e. no batteries are connected), array fault-current protection is not typically required in grid-connected PV systems without batteries. National codes do, however, normally require the installation of a load-breaking disconnection device between the array and the inverter. This is called the PV array main disconnect/isolator. It is normally located near the inverter and is typically required to be lockable so when maintenance is being carried out the array can be safely disabled. This disconnect/isolator must

Extra low voltage (ELV) segmentation

Another reason for dividing arrays into sub-arrays may be so that the module string can be broken down into ELV segmentation. Most PV arrays operate with their voltage in the range 120–500V DC. It may be desirable to split the array into ELV sub-arrays with V_{oc} of less than 120V in order to make the array safer and reduce the risk of electrocution. National codes generally address ELV segmentation; for instance in Australian/New Zealand Standard 5033: 2005, ELV arrays do not require fault-current protection or disconnection devices on individual strings, whereas LV arrays must have a suitable method of disconnection into ELV segments.

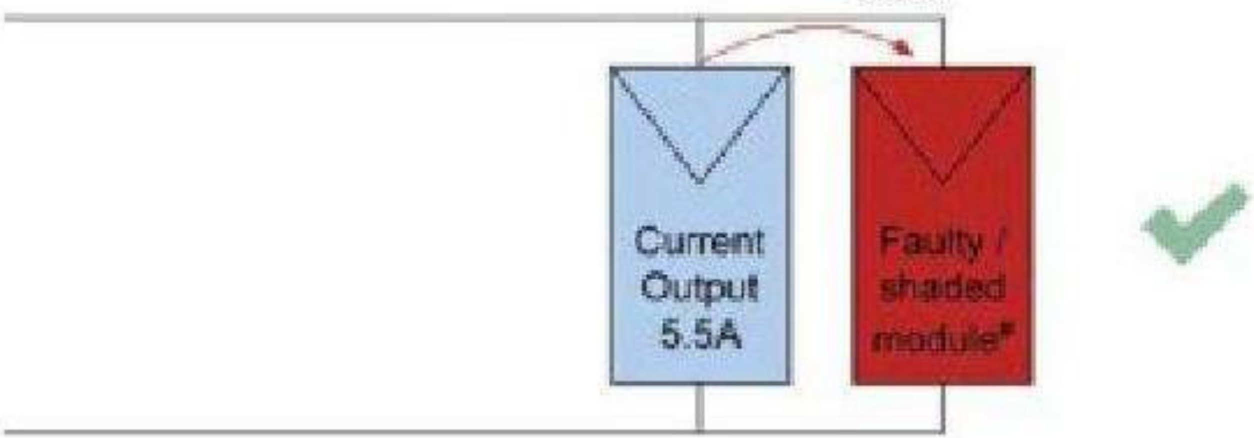
- Local temperature range: Installations in a hot climate require modules with low temperature coefficients in order to minimize the decrease in power output caused by an increase in temperature. PV modules' operating temperature range is specified on the data sheet – it is important to ensure that the installation location's temperature range is within that of the PV module selected.
- Atmospheric salt in coastal environments: Modules installed within 1km of the coast should comply with IEC 61701 – Salt mist corrosion testing of photovoltaic (PV) modules.
- Heavy snow: For snowy areas it is important to install a module that has a load capacity rating of 5400Pa; this will be specified on the data sheet.

String fuse protection: When is it required and when not?

Example:

Module:	**Sunshine Model S185**
Isc:	**5.5A**
Maximum series fuse rating*:	**15A**

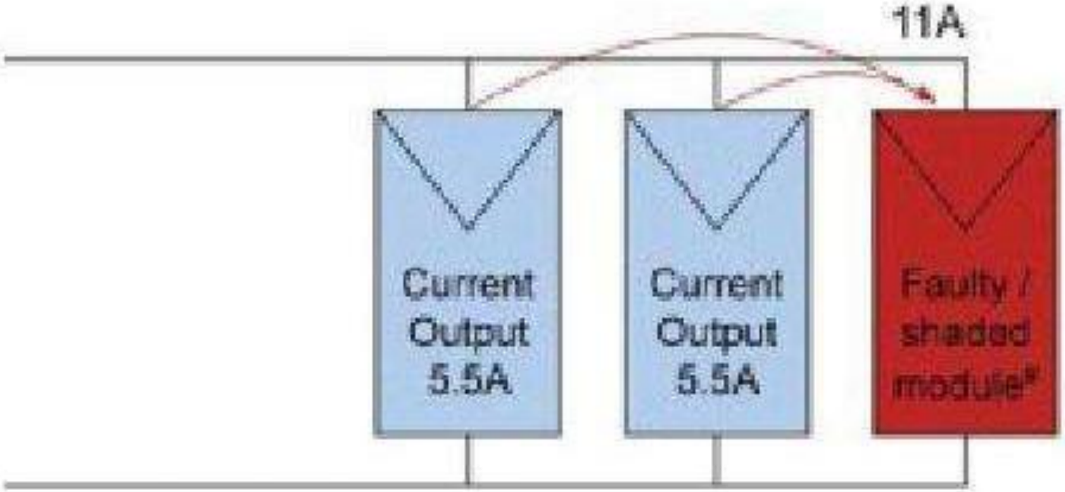
Case One: 2 Parallel Modules : One is shaded or faulty



Maximum fault current 5.5A.

Conclusion:
No fault protection required.

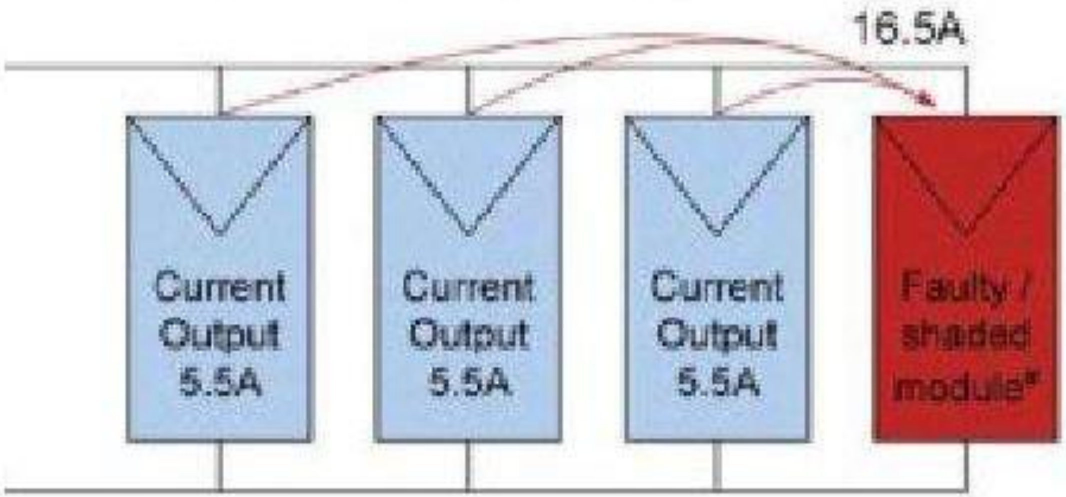
Case Two: 3 Parallel Modules : One is shaded or faulty



Maximum fault current 11A.

Conclusion:
No fault protection required.

Case Three: 4 Parallel Modules : One is shaded or faulty



Maximum fault current 16.5A.

Conclusion:
Fault protection required

Matching voltage specifications

There are two voltage specifications that need to be met. The first is that of the module itself: most manufacturers specify a maximum system voltage on their data sheet. A PV array's voltage must not exceed the maximum system voltage for the modules it is using.

The second voltage figure is the maximum input voltage of the inverter which must not be exceeded: this figure is normally lower than the module's maximum system voltage and hence of greater concern. This figure is highlighted in the following extract from an inverter data sheet (Figure 9.3).

Calculating the maximum number of modules in a string

First the maximum inverter input voltage is multiplied by 0.95 to account for the 5% safety margin	600V × 0.95 = 570V
The maximum inverter voltage should be divided by the maximum module voltage (as previously calculated to determine the maximum allowable modules in a string)	570V/33.84V = 16.84 modules

This figure should always be rounded down for safety and so the string can only have 16 modules.

Calculating the minimum voltage

Minimum voltage will occur at a cell temperature of 65°C and is calculated as follows:	
The temperature coefficient (V) per °C is calculated for module V_{pm}/V_{mp}	$-0.00485 \times 24V = -0.1164V/°C$
Calculate the difference between the cell temperature and STC	$65°C - 25°C = 40°C$
Then multiply this by the V_{mp} temperature coefficient	$40°C \times -0.1164V/°C = -4.66V$
Take this last figure away from the rated V_{mp} (minimum voltage figure is calculated for maximum temperature conditions)	$24V - 4.66V = 19.34V$

Calculating the minimum number of modules in a string

The minimum module voltage is multiplied by the voltage drop expected across the DC cables (1%)	19.34V × 0.99 = 19.15V
The minimum inverter input voltage should be multiplied by 1.1 to account for the 10% safety margin required	268V × 1.1 = 294.8 V
Finally, the minimum number of modules in the string is calculated by dividing this figure by the minimum module voltage	294.8V/19.15V = 15.39

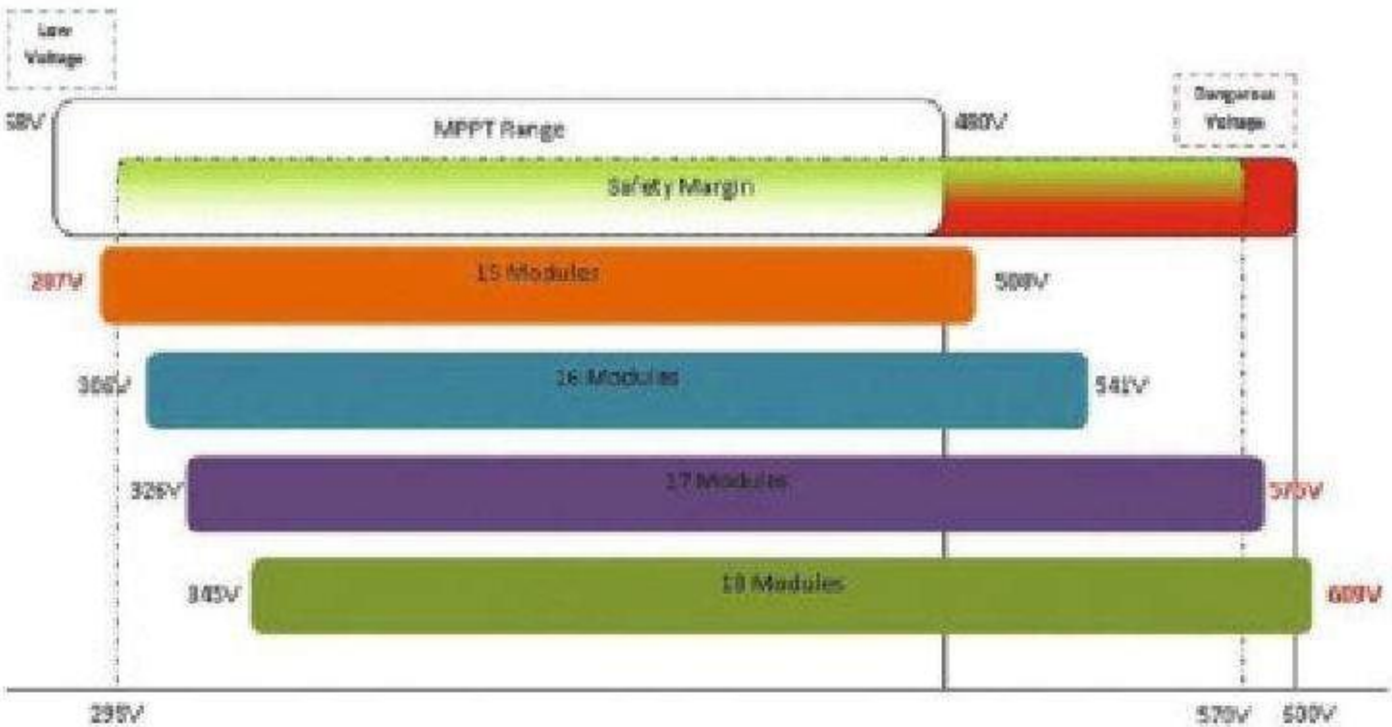


Figure 9.9 Each string must be 16 modules

Source: Global Sustainable Energy Solutions

Matching current specifications

Inverter manufacturers generally give the following ratings in terms of current:

- Maximum DC input current: maximum DC current that the inverter can process;
- Maximum AC output current: maximum AC current that the inverter can deliver.

Table 9.2 SMA Sunny Boy 3000 technical data

Technical data	Sunny Boy 3000
Max input current/per string	12A/12A
Number of MPP trackers/strings per MPP tracker	1/3
Max output current	15A

Source: SMA Solar Technology AG

Matching modules to the inverter's power rating

Most inverter manufacturers give a number of ratings for their inverters in terms of power. Common ratings include:

- Maximum PV array rated power: Maximum rated power of the PV array, usually in kWp or Wp;
- Maximum DC input power: Maximum amount of DC power that the inverter can convert to AC (this is generally lower than the maximum PV array power, because of losses in PV arrays);
- Maximum AC output power: Maximum amount of AC power that the inverter can produce.

Example 1: Sydney, Australia

The de-rating factor for the Sharp modules (specifications given on page 131) installed in Sydney (average ambient temperature 23°C (73.4°F)) is calculated as follows:

From the ambient temperature the cell temperature is calculated	23°C + 25°C = 48°C
The difference between the cell temperature and the standard testing conditions (STC, 25°C) is then be calculated	48°C – 25°C = 23°C
If the temperature coefficient is given in %/°C it must be converted to a decimal	0.485%/°C = 0.00485
Temperature coefficient is multiplied by the difference between cell temperature and STC	0.00485 × 23 = 0.11155
To calculate f_{temp} this figure must be subtracted from 1	f_{temp} = 1 – 0.11155 = 0.88845
Therefore the resultant temperature efficiency is 88.8%	

Example 2: Berlin, Germany

The de-rating factor for the Sharp modules installed in Berlin (average ambient temperature 9.8°C (49.64°F)) is calculated as follows:

From the ambient temperature the cell temperature is calculated	9.8°C + 25°C = 34.8°C
The difference between the cell temperature and the standard testing conditions (STC 25°C)	34.8°C – 25°C = 9.8°C
The temperature coefficient is given in %/°C and converted to a decimal	0.485%/°C = 0.00485
This number is then multiplied by the difference between cell temperature and STC	0.00485 × 9.8 = 0.04753
To calculate f_{temp} this figure must be subtracted from 1	f_{temp} = 1 – 0.04753 = 0.95247
Therefore the resultant temperature efficiency is 95.25%	

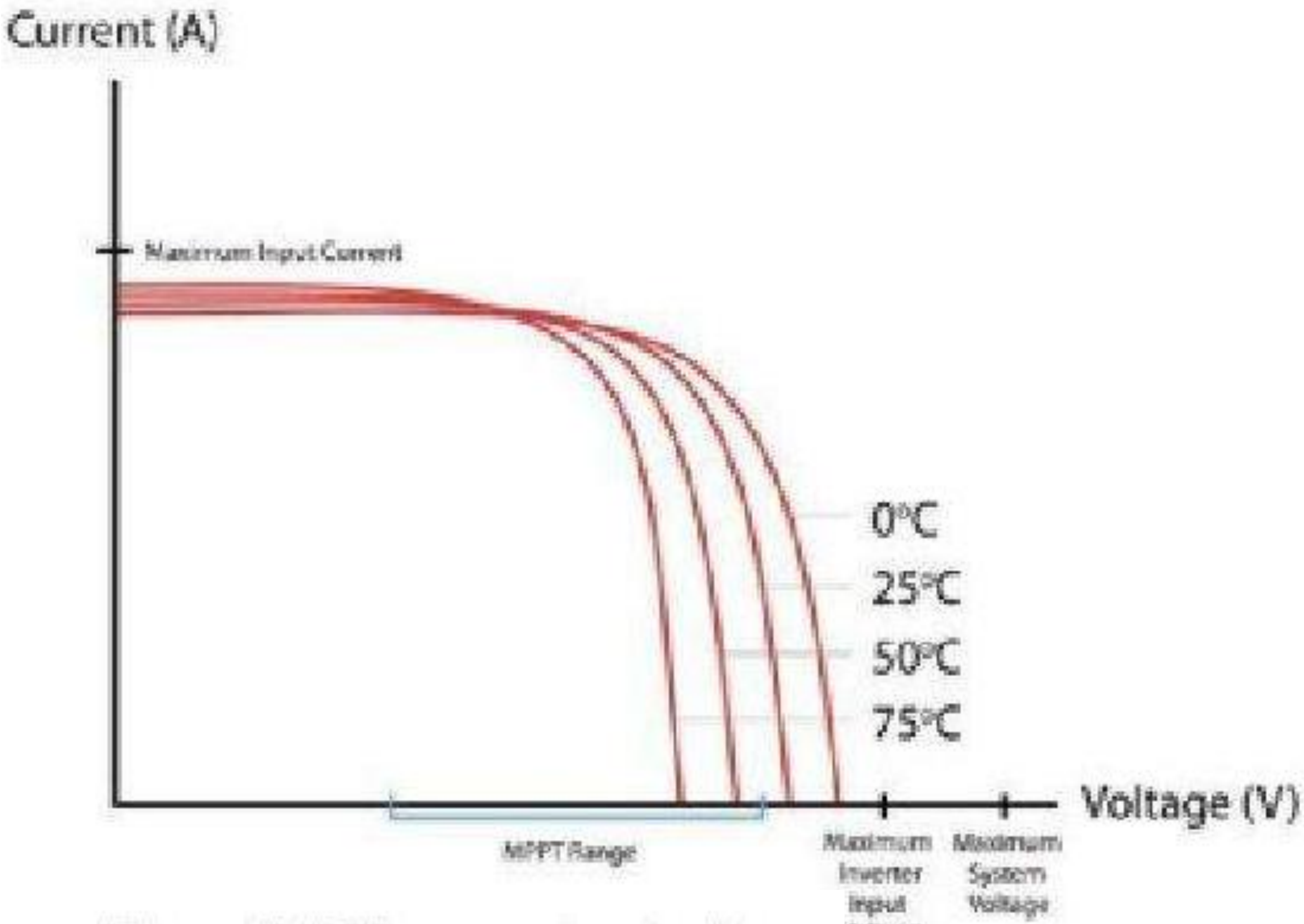


Figure 9.3 The current and voltage of a PV cell or module varies with temperature, so it is important that the PV system operates safely at all temperatures the PV modules can be expected to experience (see Chapter 4)

Example 1: Sydney, Australia

In Sydney the ambient temperature can vary from 0°C to 50°C (32°F to 122°F), so the maximum and minimum cell temperatures are as follows:

Ambient temperature 0°C =	Minimum cell temperature = Minimum ambient temperature	= 0°C
Ambient temperature 50°C =	Maximum cell temperature = 50°C + 25°C	= 75°C

Example 2: Berlin, Germany

In Berlin the ambient temperature can vary from –10°C to 30°C (14°F to 86°F), so the maximum and minimum cell temperatures are as follows:

Ambient temperature of –10°C =	Minimum cell temperature = minimum ambient temperature	= –10°C
Ambient temperature of 40°C =	Maximum cell temperature = 40°C + 25°C	= 65°C

$$Voltage_{at\ X°C} = Voltage_{at\ STC} - [\gamma_V \times (T_{X°C} - T_{STC})]$$

--

If the temperature is lower than 25°C:

$$Voltage_{\ at\ X°C} = Voltage_{at\ STC} + [\gamma_V \times (T_{X°C} - T_{STC})]$$

where:

$Voltage_{\ at\ X°C}$ = voltage at the specified temperature (X°C) in volts;
$Voltage_{\ at\ STC}$ = voltage at STC, i.e. the rated voltage in volts;
γ_V = voltage temperature coefficient in V/°C (absolute value);
$T_{X°C}$ = cell temperature in °C;

T_{STC} = temperature at standard test conditions (i.e. 25°C) in °C.

Note: The second formula as stated is not strictly correct but is a simplification of the concepts; however, it produces the correct answer for the operating conditions specified.

Example 1: Sydney, Australia

Ambient temperature of 0°C =	Corresponding module cell temperature = 0°C	= 0°C
Ambient temperature of 50°C =	Corresponding module cell temperature = 50°C + 25°C	= 75°C

Calculating maximum voltage

The module's maximum voltage (V_{oc}) is present at the minimum cell temperature which in this case is 0°C; it is therefore important to use the open-circuit voltage (V_{oc}) and adjust this figure according to the temperature coefficient when calculating the maximum voltage. From the data sheet it can be seen that the open-circuit voltage (V_{oc}) at standard test conditions is 30.2V, therefore:

The difference between the cell temperature and 25°C is calculated	0°C −25°C = −25°C
This figure is then multiplied by the temperature coefficient to calculate the increase in voltage	−25°C × −0.104V/°C = 2.60V
Finally the maximum voltage can be calculated	30.2V + 2.60V = 32.80V

Calculating minimum voltage

The module's minimum voltage will occur when the cell is hottest, i.e. at a cell temperature of 75°C. This figure is calculated using the maximum power voltage (V_{pm} or V_{mp}) and corresponding temperature coefficient. A temperature coefficient is not given for maximum power voltage, so the temperature coefficient for maximum power should be used as an approximation – this is given in per cent/°C on the data sheet and so must be converted to V/°C:

Temperature Coefficient		
Temp. Coefficient of P_{max}	−0.485	% / °C
Temp. Coefficient of V_{oc}	−0.104	V / °C
Temp. Coefficient of I_{sc}	0.053	% / °C

The temperature coefficient should be converted into a decimal	–0.485% = –0.00485
The temperature coefficient (V) per °C is calculated for module V_{pm} or V_{mp}	–0.00485 × 24V = – 0.1164V/°C
Use this information to calculate the minimum voltage as follows:	
Calculate the difference between the cell temperature and STC	75°C – 25°C = 50°C
Multiply this by the V_{mp} or V_{pm} temperature coefficient	50°C × –0.1164V/°C = –5.82V
The voltage de-rating is subtracted from the V_{mp} = minimum array voltage	24V – 5.82 V = 18.18V

Calculating the minimum number of modules in a string

An outline of voltage drop calculations is given in Chapter 10.

The expected voltage drop across the DC cables should be included in this calculation: 1% voltage drop is assumed, so the minimum voltage should be decreased by the assumed 1% voltage loss (therefore the voltage figure is multiplied by 0.99)	18.18V × 0.99 = 17.99V
The minimum inverter input voltage (from data sheet) should be increased by the 10% safety margin required (therefore the voltage figure is multiplied by 1.1)	268V × 1.1 = 294.8 V
Finally, the minimum number of modules in the string is calculated by dividing this figure by the minimum module voltage	294.8V/17.99V = 16.39 modules
At least 17 modules must be connected in series to form a string	

Calculating the maximum number of modules in a string

First the maximum inverter input voltage is reduced to account for the 5% safety margin (therefore the maximum voltage figure is multiplied by 0.95)	600V × 0.95 = 570V
The maximum inverter voltage should be divided by the maximum module voltage (as previously calculated to determine the maximum allowable modules in a string)	570V/32.8V = 17.38 modules

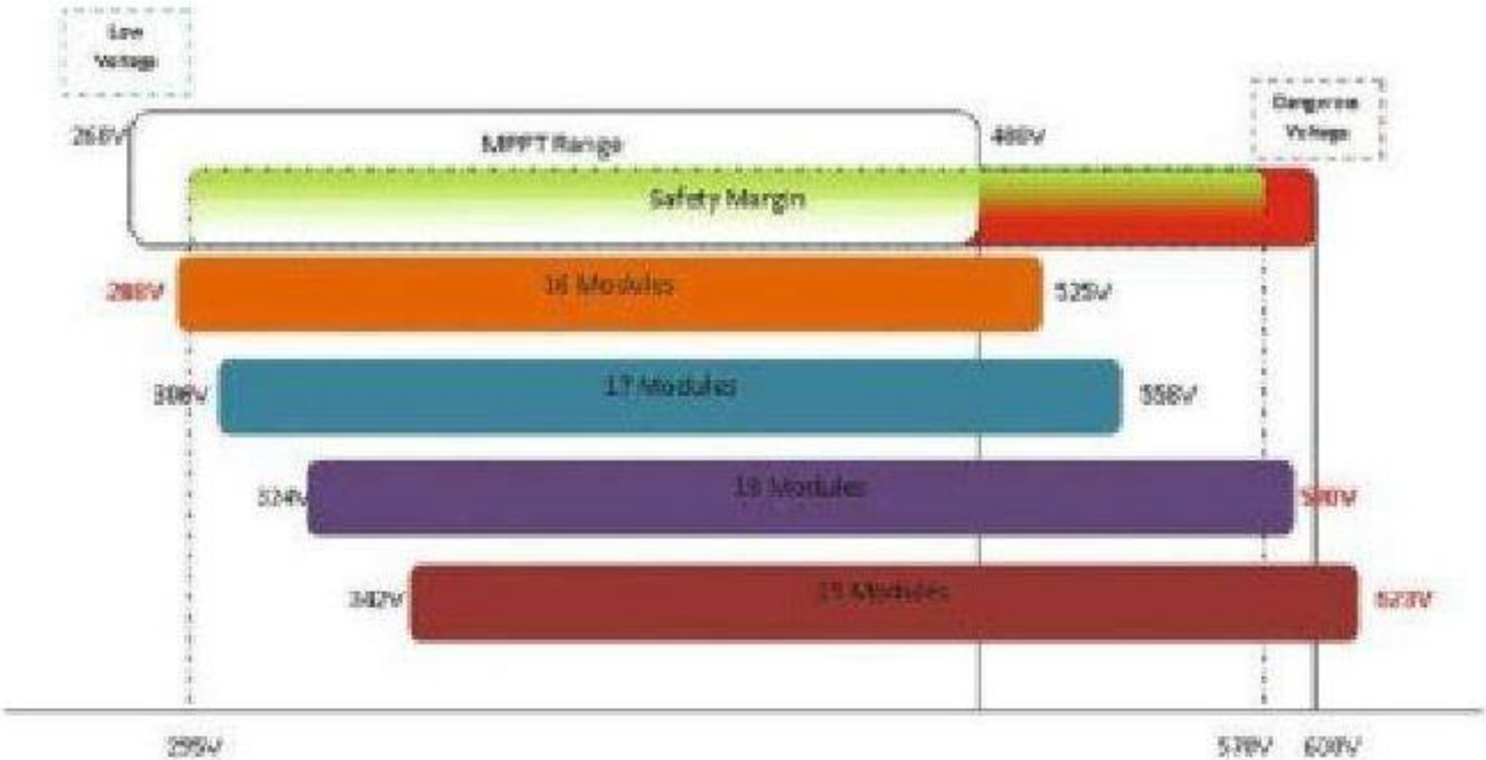


Figure 9.8 Four possible string lengths using the Sharp modules. It can be seen that if there are 16 or fewer modules the voltage range of the string falls below the safety margin and the inverter will turn off on very hot days when the voltage drops below the MPPT range. If there are 18 or more modules the voltage will exceed the inverter's maximum DC input voltage on cold days, damaging the inverter

PV array installation

It is highly advisable that PV installers take time to carefully plan the precise location of the array before deciding on the installation methodology. This is commonly done by measuring the available installation area and marking the boundaries of the array(s) as well as the location of the mounting system's attachment points on the installation area, i.e. the roof, using a string or chalk line. The next step is to install the attachment hardware (array mounting structure) to secure the mounting system to the roof. If mounting on a rooftop, care should be taken to ensure that attachment screws are securely embedded into the rafters or other structural supporting members to provide maximum attachment strength.

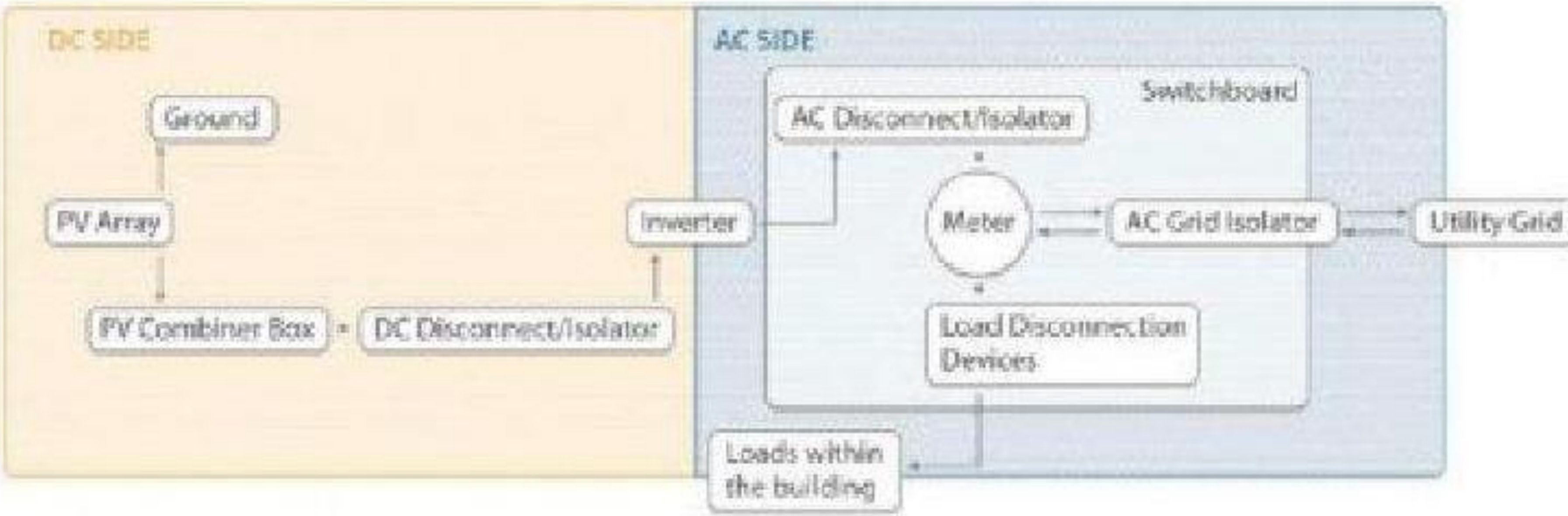
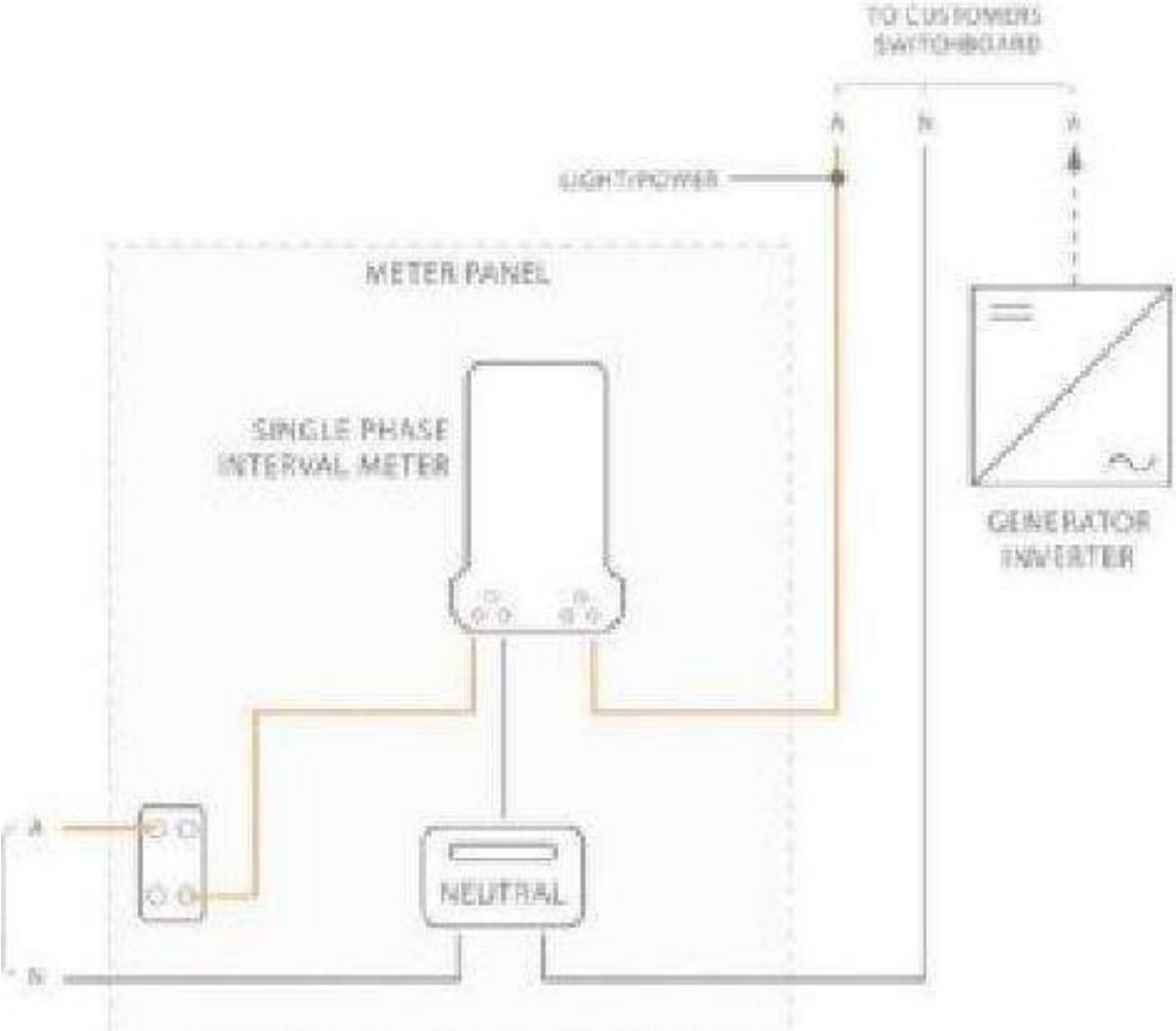


Figure 10.9 Summary of the connection of components of a grid-connected PV system using net metering


TO CUSTOMERS
SWITCHBOARD
LIGHT/POWER
METER PANEL
SINGLE PHASE
INTERVAL METER
GENERATOR
INVERTER
NEUTRAL

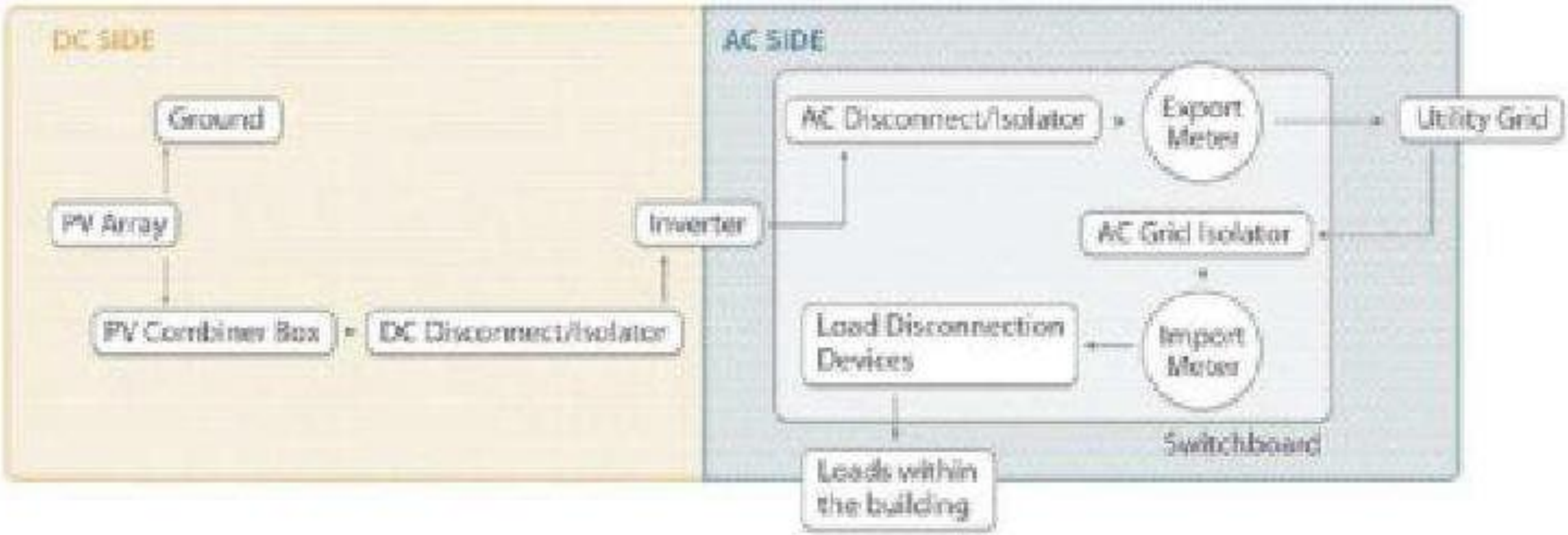


Figure 10.11 Summary of the connection of components of a grid-connect PV system using gross metering

Source: Global Sustainable Energy Solutions

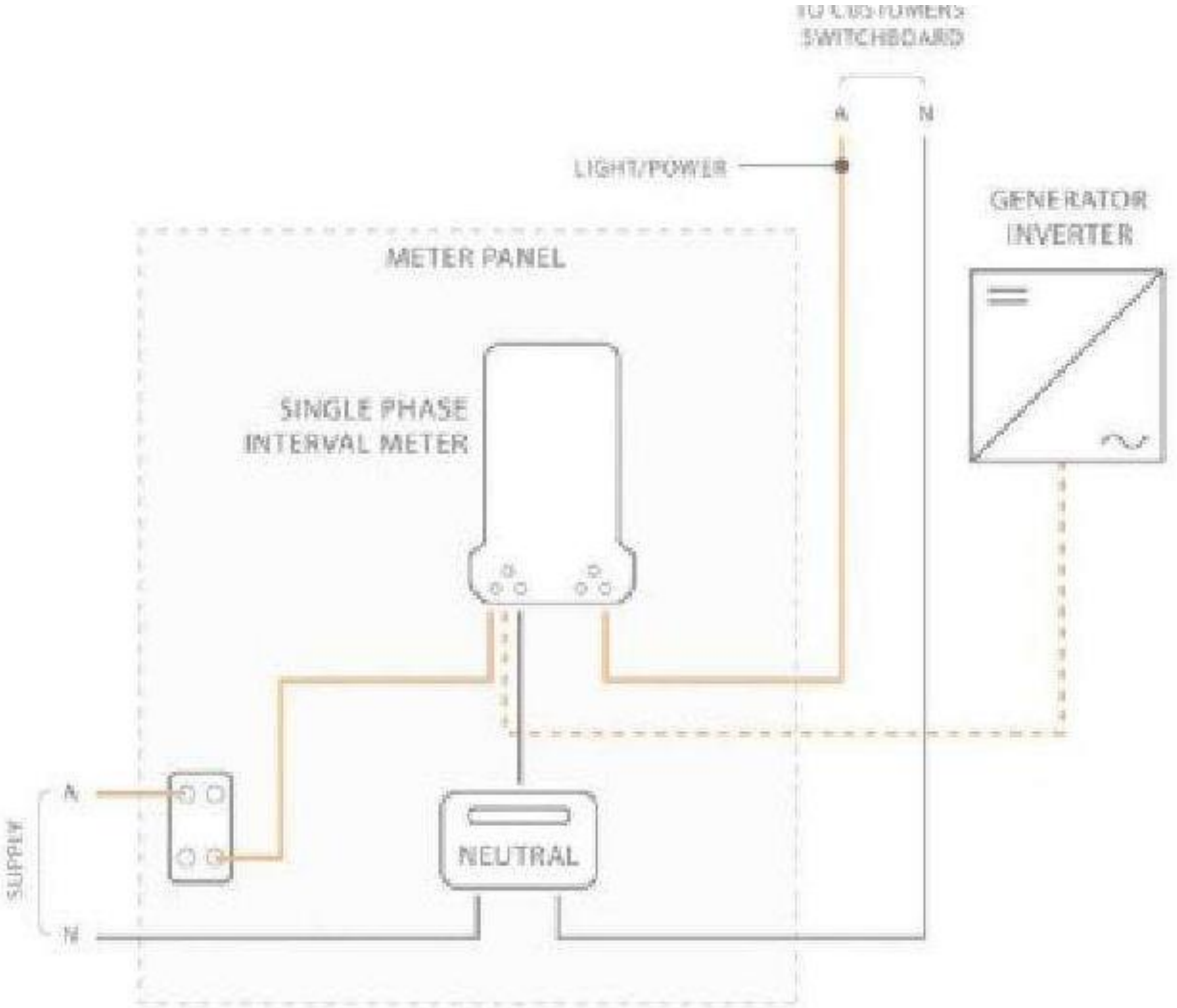
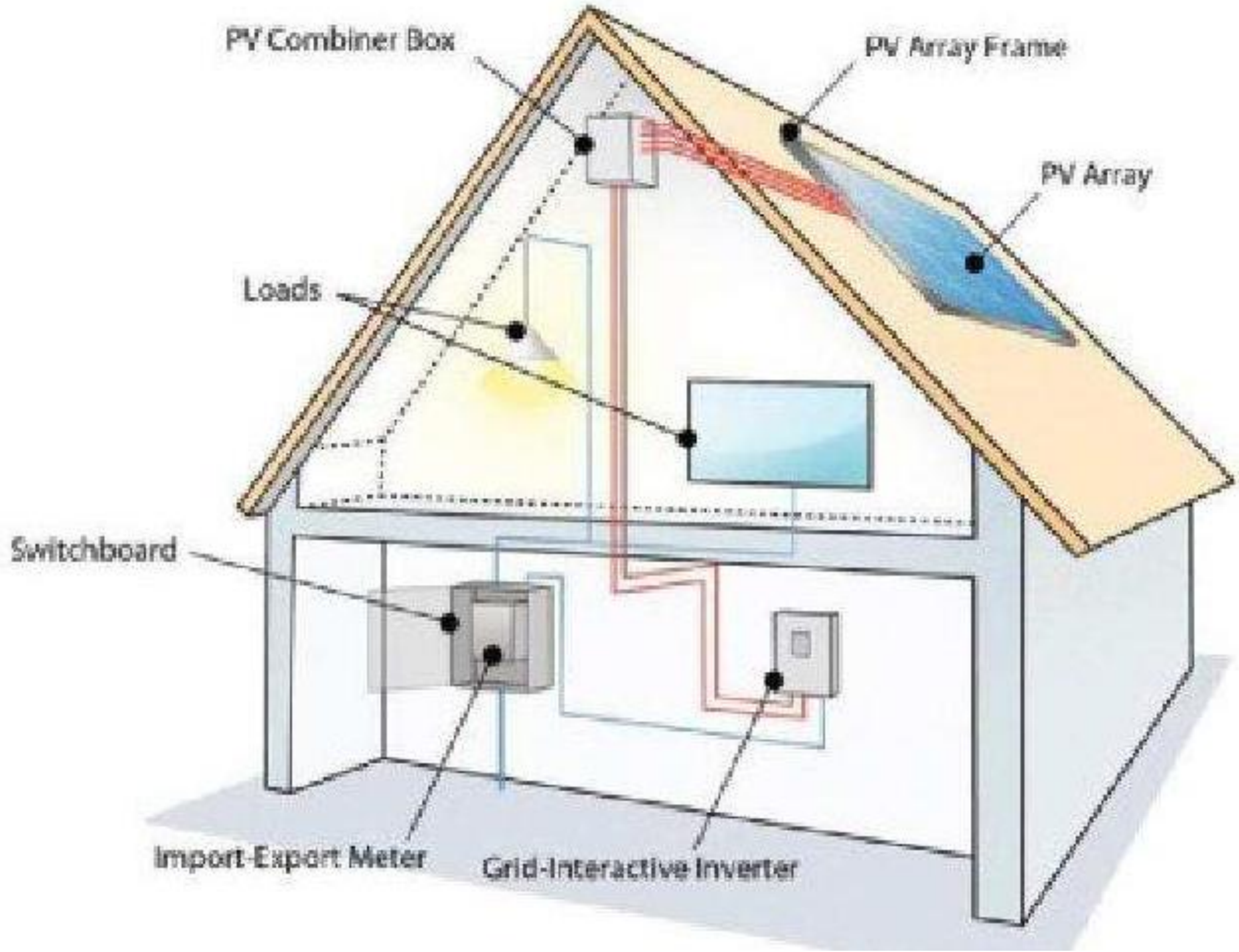


Figure 10.12 Wiring diagram showing a gross-metering arrangement where all power produced by the PV system is exported to the grid

Source: Global Sustainable Energy Solutions

- Electrical diagram: A simplified diagram showing the PV array configuration, wiring system, over-current protection, inverter, disconnects, required signs and AC connection to building. The wiring diagram should have sufficient detail to identify the electrical components, the wire types and sizes, number of conductors and conduit type (if needed). It should also include electrical information about PV modules and inverter(s). In addition, it should include information about utility disconnecting means (required by many utilities).
- Site plan: An architectural diagram showing the location of major components on the property. Major components of the PV system could include the array, inverter, isolation/disconnect switches, point of connection to the utility service panel. It is good practice to include major buildings/ structures on the installation site, as well as property boundaries. This drawing need not be exactly to scale, but it should represent the relative location of components on the installation site (see Chapter 7).
- Calculation sheet: Includes relevant calculations and notes related to the PV array design such as temperature-corrected maximum power and open-circuit voltage, maximum rated power, maximum power and short-circuit current. It should also list information related to the inverter such as voltage, current and power ratings, as well as calculations related to over-current protection devices.


PV Combiner Box
PV Array Frame
PV Array
Loads
Switchboard
Import-Export Meter
Grid-Interactive Inverter

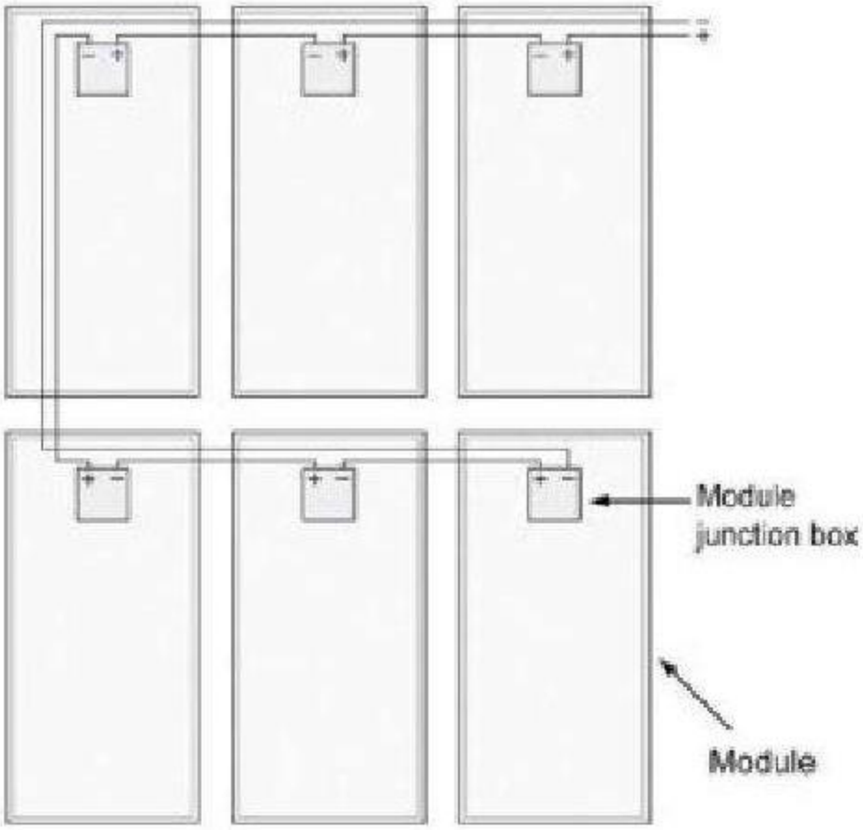


Figure 10.2 Example of correct PV wiring where conductive loops have been reduced

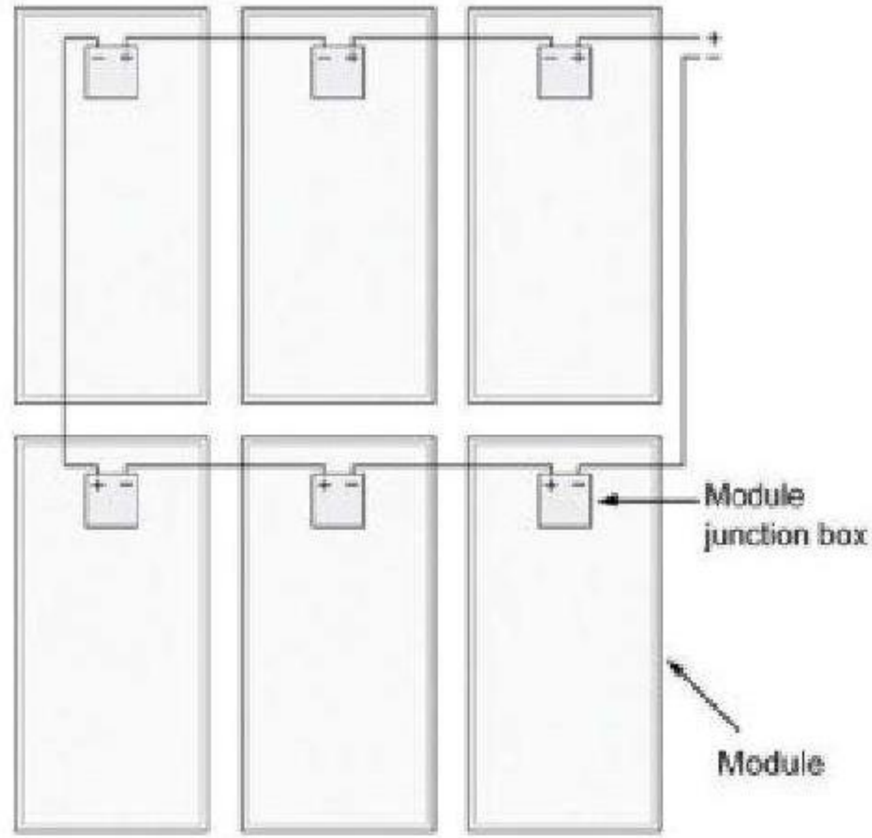


Figure 10.3 Example of incorrect PV wiring where the wiring is a conductive loop

Figure 10.4 Photograph of a conductive loop

The length of cabling route is 15m from the PV array to inverter; copper cabling (resistivity of copper is 0.0183Ω/m/mm²) is used with a cross-sectional area of 2.5mm² and it must carry a current of 5A. According to Ohm's law, voltage drop is calculated as:

Voltage drop = 2 × length × current × resistance (2 accounts for 2 cables, 1 +ve and 1 –ve)

Here resistance = resistivity/area, so

Voltage drop = (2 × length [in metres] × current [in amps] × resistivity [in Ω/m/mm²])/area [in mm²]

Voltage drop = (2 × 15m × 5A × 0.0183Ω/m/mm²)/2.5mm²

Voltage drop = 1.098V

If the voltage at the maximum power is known, then the voltage drop as a percentage can be calculated; if the voltage at maximum power is known to be 155V then the voltage drop is calculated as follows:

Voltage drop (%) = Voltage drop/voltage at maximum power × 100%

Voltage drop (%) = 1.098V/155V × 100%

Voltage drop (%) = 0.71%

Therefore if this voltage drop is sustained in a $10kW_p$ installation, the power loss sustained will be 71Wp, meaning the installation has effectively been reduced to 9.929kWp PV installed before any other system de-ratings are applied (see Chapter 9 for system de-ratings).

US installers often deal with American wire gauge (AWG) cable sizes. It is necessary to convert these gauges into the equivalent mm^2 value for use in the above formula. Conversions are given in Table 10.1

Table 10.1 US wire gauge conversion table

AWG	Size in mm^2
14	2.00
12	3.31
10	6.68
8	8.37
6	13.30
4	21.15
2	33.62
1	42.41
0	53.50

Figure 10.6 An electrician installs a small white PV combiner box next to the array

Source: Global Sustainable Energy Solutions

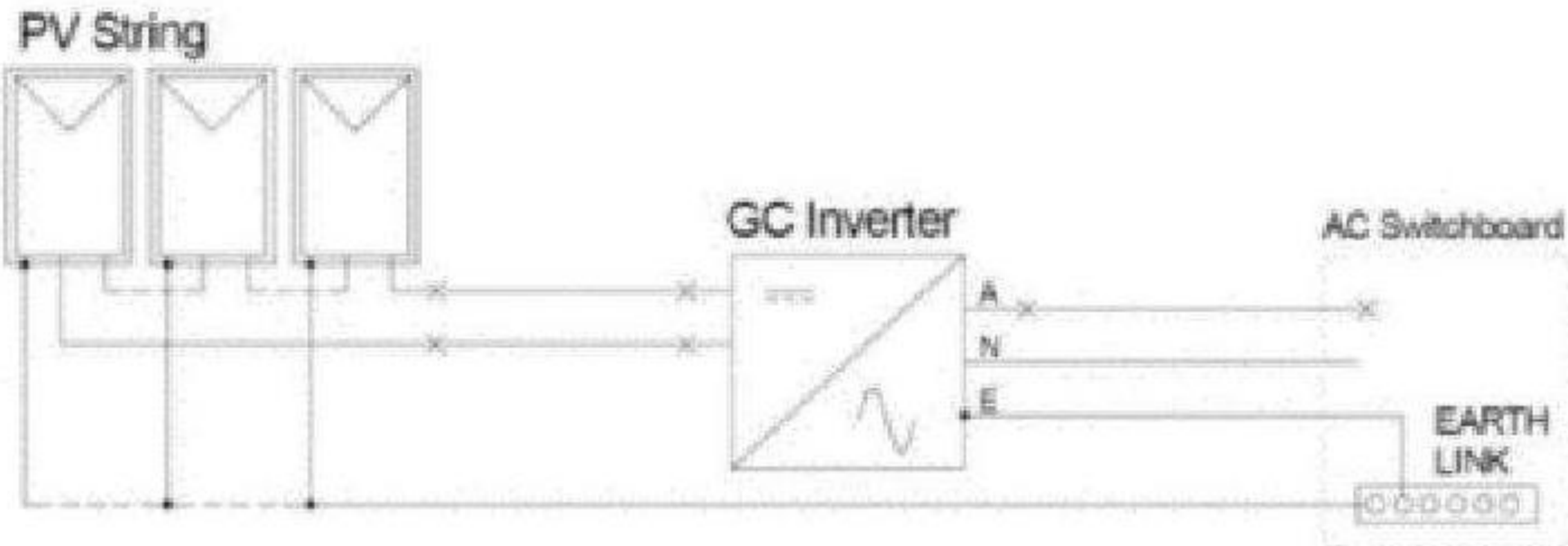


Figure 10.7 It is common practice to ground each component of the PV system separately so that if one is removed the others will remain grounded, i.e. the earth of the array is not connected to the earthing wire from the inverter. The technique shown in this diagram is compliant with Australian National Standards. Techniques vary so local standards should always be consulted