CBCS SCHEME

USN | | | | | | | | | | 17EE832

Eighth Semester B.E. Degree Examination, July/August 2021
Operation and Maintenance of Solar Electric System

Time: 3 hrs. Max. Marks:100

Note: ***Answer any FIVE full questions.***

1 a. Explain the effect of the earth's atmosphere on solar radiation. **(06 Marks)**
b. Define solar altitude, azimuth angle magnetic declination. **(06 Marks)**
c. With the neat graph, explain I–V and P–V characteristics. Mark I_{SC}, V_{OC}, V_{MP}, I_{MP}, M_{PP}. **(08 Marks)**

2 a. Compare Mono crystalline silicon, multi crystalline silicon and Thin film solar cells. **(06 Marks)**
b. List and explain the factors affect the performance of photo voltaic array. **(08 Marks)**
c. In an array 4 solar Panel are connected :
Panel 1 – $V_{mp} = 12V$, $I_{mp} = 6A$, $P_{max} = 100w$
Panel 2 – $V_{mp} = 12V$, $I_{mp} = 6A$, $P_{max} = 100w$
Panel 3 – $V_{mp} = 24V$, $I_{mp} = 6A$, $P_{max} = 200w$
Panel 4 – $V_{mp} = 36V$, $I_{mp} = 10A$, $P_{max} = 360w$
Find total V_{mp}, I_{mp} and P_{max} if it is connected in series and also it is connected in parallel. **(06 Marks)**

3 a. Compare different categories of grid interactive inverters. **(08 Marks)**
b. Explain different techniques to mount PV arrays on roof. **(08 Marks)**
c. What is wind loading? **(04 Marks)**

4 a. Compare net metering and gross metering. **(08 Marks)**
b. Briefly explain types of ground mounting system. **(06 Marks)**
c. Compare basic functions of grid interactive inverters with battery inverters. **(06 Marks)**

5 a. Explain information to be collected during site assessment for PV system installation. **(06 Marks)**
b. Explain use of solar path finder and Horicatcher. **(08 Marks)**
c. Write a note on Portrait and landscape installation. **(06 Marks)**

6 a. Explain the potential sources of shading. **(06 Marks)**
b. List and explain important factors to be considered when choosing system components. **(08 Marks)**
c. What is Fault – current protection? **(06 Marks)**

7 a. What are the issues to be taken care during installation of Grid connected PV system. **(10 Marks)**

b. Explain the system documents to be supplied to the owner after completion of PV installation. **(10 Marks)**

8 a. What are the risk associated with installing PV systems. How risks are classified. **(10 Marks)**

b. Explain the Testing of PV system. **(10 Marks)**

9 a. What are the various costs involved in PV system? Explain in detail. **(10 Marks)**

b. List and explain the strong barriers to PV technology. **(10 Marks)**

10 a. What is feed-in tariff? What are the two different ways of feed in Tariff? Give important features. **(10 Marks)**

b. What are the positive attributes of PV systems need to be considered while marketing. **(10 Marks)**

* * * * *

1. a

The effect of the Earth's atmosphere on solar radiation

The Earth's atmosphere reflects a large amount of the radiation received from the sun – without this protection life could not be sustained on the planet. When solar radiation arrives at the top of the Earth's atmosphere it has a peak irradiance value of 1367W/m^2 (this is known as the solar constant). By the time solar radiation reaches the Earth's surface it has a peak irradiance value of approximately 1000W/m^2. The difference between the solar constant and the peak irradiance value at the Earth's surface is due to the Earth's albedo – the amount of solar energy reflected from a surface on the Earth at that specific location. Light is reflected from Earth in a variety of ways:

- 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.

1b.

SOLAR ALTITUDE:

AZIMUTH:

Solar altitude: The angle between the sun and the horizon; the altitude is always between 0° and 90°.

Azimuth: The angle between north and the point on the compass where the sun is positioned. The azimuth angle varies as the sun moves from east to west across the sky through the day. In general, the azimuth is measured clockwise going from 0° (true north) to 359°.

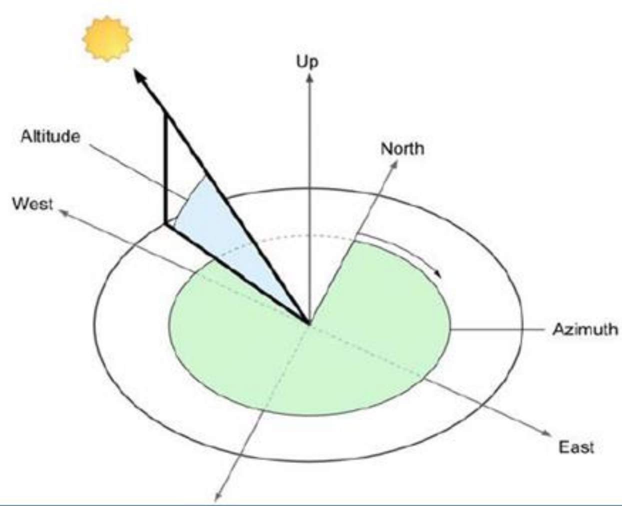

Figure 2.16 The sun's altitude is shown in blue while its azimuth is represented by green

Source: Global Sustainable

1 c.

Graphic representations of PV cell performance

- It is very common for the features of a PV cell to be represented graphically as a current-voltage (or I-V) curve.
- An I-V curve tracks the PV cell's performance and highlights key features such as V_{oc}, I_{sc} and P_{max}.
- A PV cell will always operate along this curve, i.e. at a given voltage; the current produced will always have the same value and vice versa
- A power curve is used to find the maximum power point.
- A power curve plots the voltage along the horizontal axis and the power (current multiplied by voltage) along the vertical axis.
- When this is superimposed on the I-V curve for the same cell, it is very clear where the maximum power point lies

---

- The I-V and power curves are important because it is necessary to know the characteristics of each individual cell when designing a module.
- Connecting cells with dramatically different characteristics together will have a large (generally negative) effect on the power output of the PV module

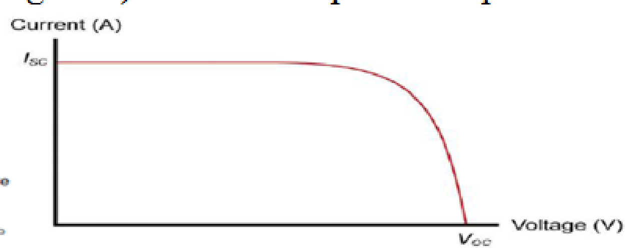

Figure 4.5 V_{oc} and I_{sc} are the *x* and *y* intercepts respectively. Ideally the PV cell operates around the knee of the curve, where the maximum power point is located

Source: Global Sustainable Energy Solutions

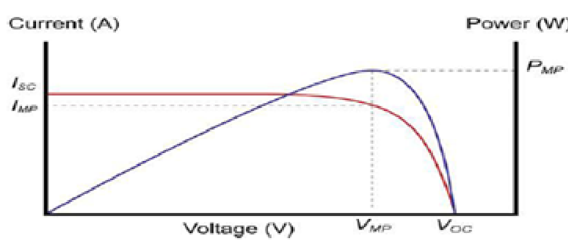

Figure 4.6 P_{mp} is the highest point on the power curve; by extrapolating back to the *x*-axis, V_{mp} can be found. V_{mp} is also on the I-V curve and so the corresponding current can be found for this particular voltage (I_{mp})

Source: Global Sustainable Energy Solutions

2.a.

Monocrystalline silicon

- These solar cells are produced from a single silicon seed crystal placed in a crucible of molten silicon and drawn out slowly while rotating.
- In this manner it is possible to produce a larger pure crystalline silicon ingot, which is then sliced into thinner wafers.
- Monocrystalline silicon solar cells are the most efficient .
- Generally the most expensive, although the higher initial cost may be justified by their increased power output as they are highly efficient compared to other silicon technologies.
- Commercially available solar cells are now being produced with efficiencies of 22.5 per cent and finished modules with efficiencies of 19 per cent.

Multicrystalline/polycrystalline silicon

- Multicrystalline or polycrystalline silicon solar cells are manufactured by block casting molten silicon.
- 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.
- It is still a very popular technique because it is easier and less expensive.

Thin film solar cells/Amorphous silicon cells

- Thin film solar cells are made from materials suitable for deposition over large areas.
- They are less expensive & low cost to manufacture than crystalline solar cells.
- The most common materials are made out of cadmium telluride (CdTe) and copper indium (gallium) diselenide (CIS or CIGS).
- Thin film solar cells are well suited to high volume manufacturing.
- They are made using the chemical vapour deposition (CVD) process, where the material is deposited onto large area materials,
- e.g. coated glass, flexible plastic or stainless steel sheet.

2 b.

Photovoltaic array performance

The performance of a PV array is affected by a variety of factors: the most significant of these (temperature, irradiance and shading) are discussed here.

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.

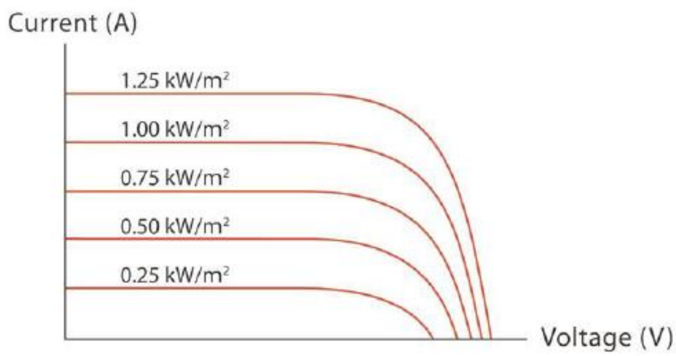

Figure 4.17 The I-V curves for a cell operating at different irradiance values show the increase in power output with irradiance

Source: Global Sustainable Energy Solutions

Temperature

Not only does the solar radiation hitting the modules produce electricity, it also heats up the modules. It is not uncommon for a PV module to reach 70°C on a sunny day in a temperate climate. As temperature increases, the open-circuit voltage decreases rapidly while the short-circuit current increases slowly. Power output is voltage multiplied by current and so will decrease as well. When designing systems, engineers will often use the following approximation (depending on local design codes and guidelines):

cell temperature = ambient temperature + 25°C

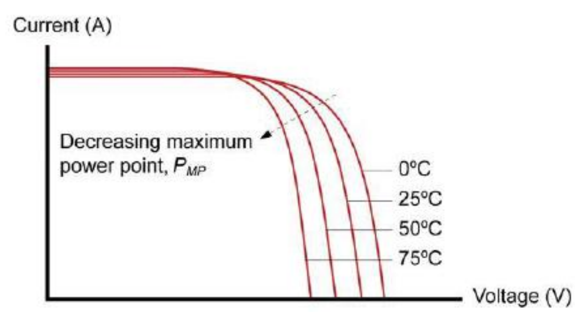

Figure 4.18 As power = current x voltage (I x V), as voltage decreases, power decreases

Source: Global Sustainable Energy Solutions

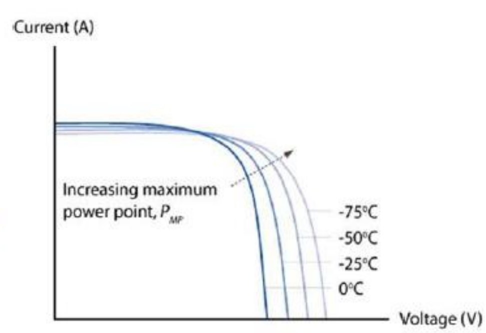

Figure 4.19 In areas that experience extremely cold temperatures, the voltage increases as the ambient temperature decreases

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

shading can result in a large reduction in power output). Cells in modules are normally connected in series, so when one or several cells are shaded, the current output of the module will be reduced. If the module is part of an array, then the current output of the array will also be reduced. This will also occur if a cell is damaged and unable to produce power.

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.

3 a.

Grid-interactive inverters

- 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.

Mainstream inverter technologies

1. String inverters
2. Multi-string inverter
3. Central inverter
4. Modular inverters

String inverters

- String inverters are used in small systems ranging from 1kWp to 11kWp.
- String inverters will all have one maximum power point tracker (MPPT) and the DC input voltages could vary from extra low voltage (ELV) right up 1000 volts DC (low voltage, LV).
- String inverters can be connected in a variety of ways as shown in Figures

Multi-string inverter

- A multi-string inverter is a single inverter appliance, but it has a number of MPPT inputs.
- Therefore the PV array can be divided into multiple strings and a suitable combination of strings connects to each one of the inverter's MPPT inputs.
- These inverters have the advantage that if the modules are facing different directions then the array could be divided into strings so that modules in the same string are all facing the same direction

Central inverter

- A central inverter is very similar to the string inverter with multiple strings – the difference is that central inverters are generally used for a large system (>10kWp).
- In these systems the array could be divided into a number of sub arrays, each comprising a number of strings.
- In some systems there is just one large inverter suitable for the whole array or the single central inverter might be a single enclosure housing several smaller multi-string inverters combining to represent a single, electrical output.
- In others there will be a number of inverters, for example 5 × 20kW inverters for a 100kW system.

Modular/micro/hybrid inverters

- Modular inverters (some will have an isolating transformer to minimize DC injection currents) designed to be mounted on the back of the PV module.
- 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.

3 b.

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**

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.
- A horizontal railing system is then attached to these brackets and modules are secured to the railing through the use of module clamps.
- In this way the railing elevates the modules above the roof surface and allows for increased air circulation under the array.

Pitched roof mounts for metal roofs

- Working on a metal roof poses safety risks due to the conductivity of metal.
- Dissimilar metals must not come into contact as this could cause galvanic corrosion, damage the roofing material and mounting system, and pose a significant safety risk to occupants of the building.
- Galvanic corrosion can be prevented by inserting a rubber separator between dissimilar metals, a technique known as galvanic isolation (also referred to as galvanic insulation).
- Certain types of metal roofs can also use mounting techniques that do not require the system to penetrate the roof material.
- These techniques are particularly popular in locations where there is frequent rainfall and the roof must be absolutely watertight

Rack mounts

- Rack mounts (also referred to as tilt-ups) are used when the roof slope or orientation is far from the best; they are most commonly used on flat or low-angle roofs.
- Rack mounts utilize most of the same mounting hardware as pitched roof mounts, but differ chiefly in that they include a triangular-shaped support structure to elevate the array and increase its tilt angle.
- If installed on a flat roof, there is often no need for scaffolding and in some circumstances no need for a harness (check local working-at-height legislation).
- Despite ease of installation, this mounting option typically involves extra engineering costs because of the additional weight of the structure on the roof as well as the greater exposure to wind loading forces

3c.

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.

4. a.

Metering

- An electricity meter records the electrical energy in kWh consumed by the loads within the building where the meter is connected.
- The meter records the number of units of energy consumed and a unit is typically 1kWh.
- The electricity consumer is then charged for this electricity based on the price set for that consumer.
- Electricity distributors will often have different rates for residential homes, industrial and/or commercial consumers

- **Types of metering**
- Net metering
- Gross metering

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

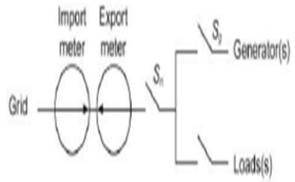

Figure 5.39 Diagram of a net import meter using two meters – one to measure import and other to measure export. The NEG can be calculated simply by subtracting the number on the export meter from the number on the import meter

Source: Global Sustainable Energy Solutions

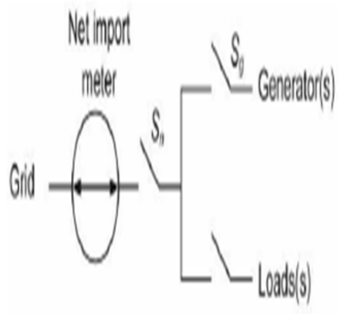

Figure 5.38 Diagram of a net import meter able to run in both directions

Source: Global Sustainable Energy Solutions

After PV installation, following conditions can occur

Day time : we don't have excess energy to feed to grid
we have excess electricity generated from PV
Night time: We have to access energy from grid
We have enough energy stored in batteries and don't need grid supply

Gross metering

- Gross metering is a method used by utilities to measure the entire solar energy production and electricity consumption separately for a site.
- Gross meters either have two spinning discs (one for consumption and one for production) or two mechanical meters installed, which only operate (or rotate) in one direction.
- The export meter records the amount of electricity generated by the PV system exported to the grid during the day, while the import meter records the exact amount of electricity consumed from the grid.

4b.

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.

Ground rack mounts

Similar to roof-rack mounts, ground-rack mounts allow flexibility in orientation and tilt. Ground-rack mounts are a fixed tilt mounting system and often use a pre-engineered steel or aluminium array frame to securely hold the modules in place. Modules are normally clamped or bolted onto the frame, which is fixed in a concrete foundation. Where the installation site wind conditions and soil are suitable, earth screws or driven piers may be suitable replacements for a concrete foundation.

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.

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.

4c.

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.

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.

All grid interactive inverters perform these basic functions:

- Convert the DC power from the PV array into AC power that can be used by appliances on site or fed back into the grid via the meter. Without a grid-interactive inverter it is impossible to export the electricity produced by a PV system into the grid.
- Ensure that the power being fed into the grid is at the appropriate frequency and voltage. If the inverter is unable to convert the DC power to match the grid's appropriate frequency and voltage, it will not release electricity to the grid.
- Use 'maximum power point tracking' (MPPT) to ensure that the inverter is finding the maximum power available from the PV array to convert to AC.
- The inverter has inbuilt active and passive safety protections to ensure that the inverter shuts itself down when the grid is not operating within acceptable voltage and frequency tolerances. This is discussed here in the section on inverter protection systems.

5. a

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 discussed in Chapter 2) installers should determine the orientation that the roof is facing and its bearing from the ideal orientation. The orientation of the roof will be the same as the orientation of the modules and will be required for energy yield calculations.
- 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.

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.

5b.

1. Solar Pathfinder

- It is used to determine the extent of shading at the intended PV installation site.
- It is used to identify objects which will cause shading and the times of year when shading will occur.
- A Solar Pathfinder requires a sunpath diagram for the latitude of the location. This diagram is then placed inside the Pathfinder
- the entire Pathfinder must be rotated so that the needle at the base points to magnetic north. The transparent dome is then placed over the top of the Pathfinder.
- When the Pathfinder is placed at a given location, the objects surrounding it will cast a shadow on the dome and the outline of these shadows is then traced onto the sunpath diagram in wax pencil to determine when the array in that location will be shaded.
- If no shadow is cast on the Solar Pathfinder the site will be shade-free all year. The horizontal arcs represent the sun's path across the sky for each month of the year. Vertical lines represent the hours of the day

HORIcatcher

- The HORIcatcher is another widely used digital tool.
- A digital camera is mounted above a horizon mirror;
- the photos taken are then uploaded and used with associated software to calculate the irradiation available at the location.

5c.

Portrait installation

Traditionally PV modules were mounted in portrait, with mounting rails installed across the roof. First, the number of rows that can be installed must be calculated by dividing the width of the roof by the length of the module. The edge zone must be factored in and deducted from the width of the roof before the calculation takes place.

The number of columns can then be calculated by dividing the length of the roof minus the edge zones by the width of the module.

The number of rows and columns must then be multiplied to obtain the maximum number of modules for that roof area.

Landscape installation

Many mounting systems can now be used to mount modules in landscape. First, the number of rows that can be installed must be calculated by dividing the width of the roof by the width of the module. Remember to deduct the edge zone from the width of the roof.

The roof length should be reduced by the edge zone size and then the number of columns is calculated by dividing the length of the roof by the length of the module. The number of modules along the length and the width are then multiplied to determine the total.

6 a.

- 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.
- Components of the building on which the array is to be installed; chimneys, TV aerials, satellite dishes and other sections of roof could all shade the array if it is not located properly. The user should be made aware that future rooftop installations should not shade the array at any time.
- The natural landscape: mountains or hills may shade a solar array, particularly when the sun is low in the sky.

6b.

Choosing system components

An important part of system design is choosing components that are appropriate for the system and environment. This chapter lists important factors to consider when choosing system components, while Chapter 9 discusses matching the array and inverter. Chapter 6 covers choice of mounting system.

Modules

Choosing and ordering the appropriate modules is very important. They are usually the most expensive part of the system and it can be a costly error if the incorrect product is chosen. This choice should not only be governed by the performance, efficiency and cost of the module but also by the conditions under which it will operate. The factors affecting the choice of module are discussed below, while sizing the system is outlined in Chapter 9.

Particular environmental conditions that will affect module choice should have been identified during the site assessment and are briefly summarized below:

- 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.

Mounting structure

Once the system's modules have been selected, designers must determine how they will be mounted. This decision depends not only on the type of module but also on the installation site and the local environment. This information is covered in Chapter 6. Environmental characteristics such as frequency of heavy rainfall, proximity to the coast (and hence corrosive environment) and local wind-loading requirements play an important role in deciding what type of mounting system to use. The designer may also have to consider the customer's aesthetic requirements for the PV system.

Inverters

The main types of inverters, as discussed in Chapter 5, are: central, multi-string, string and modular. When selecting an inverter it is important to consider the following:

- The peak rating of the PV array: the maximum PV array rated power an inverter can handle will be given on the data sheet. As a rough guide, this should be similar to the peak rating of the PV array, but more complex calculations are required to ensure safety and these are shown in Chapter 9.
- Whether all the PV modules have the same tilt angle and direction: if the modules are to be at different tilt angles or facing different directions, it is generally better to divide the system into a number of different strings and use a multi-string inverter or a single string inverter on each string. Typically

Cabling

Cabling is covered in further detail in Chapter 10. It is important that the cable chosen is appropriate for use in a PV system (i.e. UV-resistant for outdoor use) and appropriately sized for the expected currents and voltages of the system. Cable sizing is covered extensively by local codes, which should always be followed as there is a lot of variation between different countries. The sizing of the cable will often vary with its position (i.e. a string cable may be sized

Voltage sizing

Each cable will have a maximum voltage rating (available from the manufacturer) and this must never be exceeded; sizing standards vary between countries.

Current sizing

Cables will also have a maximum current rating which may not safely be exceeded. For example, in the UK and Australian standards, DC cables in a PV system must be rated to carry at least $1.25 \times I_{sc}$. This means that string cables must be rated to $1.25 \times I_{sc}$ of the module and the DC main array cable must be rated to carry $1.25 \times I_{sc}$ of the array (I_{sc} of the array = I_{sc} of the module × number of parallel strings in the array). In the US the standard is slightly different and DC cables must have a minimum current rating of $1.5625 \times I_{sc}$, i.e. the string cables will be rated at $1.5625 \times I_{sc}$ of the module and the DC main array cable will be rated at $1.5625 \times I_{sc}$ of the array.

Monitoring

The choice of inverter might also include the possible monitoring options, such as a wireless display that the customer can use inside the home to monitor system performance, or the ability to monitor electricity production and consumption at a site using multiple inverters at a large facility. Bluetooth is also a feature that some customers are now requesting, allowing wireless monitoring on a computer, PDA or mobile phone. Monitoring is covered in further detail in Chapter 12.

System protection

The design of the protection system is important to ensure the safe operation of the PV system. There are many potential reasons for a PV system to fail. Natural threats such as lightning, flooding or strong winds can destroy system components or cause dangerous system operation. National codes typically require many types of protection in PV systems for safety; over-current protection, lightning and surge protection and a means of disconnection are all common requirements. The details of what protection measures are required are set out in national codes which should always be followed. The hardware commonly used as system protection devices is covered in Chapter 5.

Over-current protection

All circuit over-current protection, both AC and DC, is designed to protect the components and cables in which it is installed from damage due to overload currents or short circuits. The size of the over-current protection is determined by the type of device used and the maximum current which can be safely passed through the circuit elements. National codes will outline how over-current protection should be designed and sized. In the UK and Australia (and many other parts of the world) all sizing is based on the short-circuit current of the

6c.

Fault-current protection

It is important to note that there is a limit to the amount of current that can pass in either direction through a PV module without damaging it. This is known as the 'maximum series fuse rating', 'reverse current rating' or 'over-current protection rating' and is stated on the module data sheet. If a fault occurs within one string it is possible that the current from the other strings will feed into the faulty string. If this current exceeds the maximum series fuse rating the module is likely to suffer damage. This is normally only a problem for arrays with multiple strings, i.e. the sum of the currents of all the non-faulty strings exceeds the maximum series fuse rating. To prevent this occurring, string fuses or miniature circuit breakers (MCBs) are often used, and these must be rated for use in a DC PV system.

To determine whether fault-current protection is necessary, designers need to know the short-circuit current of the array and the modules' maximum series fuse rating. National codes normally specify what is required and should always be consulted. For example, in the UK string fuses are required whenever the reverse current rating of the modules (I_r) is less than the combined short-circuit current of all the strings minus one multiplied by 1.25, shown as follows: $I_r < \{I_{sc} \times (\text{number of strings } -1) \times 1.25\}$. As a rule of thumb, string fuses are required in all arrays of four or more strings, and the fuses used must meet the following requirements:

- Fuses must be fitted to both the positive and negative string cable.
- Fuses must be rated for DC (see Chapter 5 regarding the difference between AC and DC fuses).
- Fuses must be rated: (V_{oc} × number of modules in the string × 1.15).
- Fuses must have a tripping current (I_{trip}) of less than $2 \times I_{sc}$ or less than 2 × current-carrying capacity of the string cable (whichever value is lowest should be used).
- If the system does not have string fuses, then the string cable should have a minimum current rating of $I_{sc} \times (\text{number of strings } -1) \times 1.25$.

7a.

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.

The array and array frame should be inspected to ensure that they have been installed correctly and are suitable for the location. This includes checking that the frame is sturdy, is appropriately rated for local wind and snow conditions, and has been installed so that any roof penetrations are properly sealed and weatherproofed (see Chapter 6).

The inverter should be inspected prior to commissioning to ensure that it is securely mounted and all electrical connections in and out of the unit are firm. The location of the inverter should also be considered during this inspection to ensure that it is accessible for maintenance and emergency disconnection, has been appropriately weatherproofed, and that allowances have been made to ensure sufficient ventilation. Weatherproofing can be verified by checking the IP or NEMA rating of the inverter (see Chapter 8 for further information about this). Ventilation should also be checked against the manufacturer's recommendations.

The wiring and electrical components should also be inspected. The inspection should ensure that all wiring and components are securely installed and adequately protected against mechanical and environmental damage. It should be ensured that they are fully operational, are correctly sized and installed in accordance with standards and regulations. All disconnects/isolators must be easily accessible in case of an emergency.

This inspection process should be documented and a copy of the documentation should be left with the customer for their records.

7b.

System documentation

At the completion of the installation the owner should be supplied with a system manual that includes information on the system. Local codes generally specify the documentation that should be provided; however, a general guide is given below.

- List of equipment supplied: the system manual should include a full itemized list of all the components that have been installed including PV modules, inverters, array frames, PV combiner boxes, string isolators, fuses or circuit breakers and the DC and AC main disconnects/isolators. The list should include the quantities of equipment items used.
- System diagrams: a basic circuit diagram and a wiring diagram should be included in the manual. Architectural drawings or the site plan showing the major components are also useful.
- System performance estimate: the manual should include the expected yield of the system as calculated by the designer. It may also include information on local financial incentives (see Chapter 13) and what these mean for the system in terms of income and/or savings on electricity bills. It is also important to emphasize that this is purely an estimate and some variation from year to year is common.
- Operating instructions for the system and its components: the manual should include a brief overview of the system, the function of each of the main components and how the system operates. Any information important to that particular system should be included in the manual. It is important to explain to the owner that the system will turn off when the grid fails, i.e. when there is no power available from the grid.

8 a.

Health, safety and environment (HSE) risks

There are several key risks associated with PV installations; these include working at heights, manual handling (lifting and moving heavy objects) and risks from working with electricity. Installers should conduct a risk assessment of each site and determine the site-specific risks in their site assessment. They should review this work before commencing the installation.

Local environment

Any features of the local environment that will affect equipment selection must be identified; these may include:

- Local temperature range: equipment will only operate within a specified temperate range, which is given on equipment data sheets. It is also important to know the local temperature range when designing the PV array (as discussed in Chapter 9).

- Corrosive conditions such as salt in the atmosphere: when a system is to be installed in an environment exposed to salt, such as within 1km of the coast, suitable salt-tested modules should be chosen that are certified to IEC 61701 – Salt mist corrosion testing of photovoltaic (PV) modules.
- Snow: in regions subject to heavy snow loads, the solar module to be installed should be rated to withstand the increased downwards pressure caused by the potential accumulated snow loads on the face of the PV module. The higher load capacity rating of 5400Pa for PV modules to be used in these areas is only an optional compliance under IEC 61215.

8a.

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.

After the safety requirements outlined in the local codes have been fulfilled, testing may be undertaken. Each component is switched on and each isolator closed individually, beginning at the array and ending at the loads (i.e. appliances). Testing is done in this order for safety; it reduces the risk of hazards and equipment damage should any problems occur. At each step the system is tested by measuring the system parameters using meters and the displays on various components (i.e. the inverter display will show important data about the system). If at any stage the system begins to operate outside the expected parameters then electricians must identify the problem and address it before testing can continue. Common parameters that are tested include:

- 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;

9a.

PV system costing

The costs associated with the individual components of the PV system need to be analysed in order to estimate the full cost of the system. System costs will vary significantly depending on the area and the local PV market (larger markets with many different companies operating tend to offer lower prices due to high competition). The main costs associated with a PV system are as follows:

- Capital costs: The upfront purchase of all system equipment including PV modules and balance of system equipment makes up approximately 80 per cent of total system costs. The modules are the most expensive item by far, but inverters can still be costly; grid-interactive inverters range from US$500/kW to US$2000/kW. Smaller inverters generally used in residential applications are in the more expensive end of the spectrum because they are smaller. In areas where utilities are obliged to offer free net metering (as is the case in most US states) to customers with a PV system a new meter can be acquired free of charge, but in areas where the policy does not exist (i.e. Australia) it is often necessary to purchase a new meter with the system. The remaining 20 per cent of system cost is for the actual installation (excluding a small ongoing maintenance cost).
- Maintenance costs: 1 per cent of system cost is comprised of maintenance costs. Maintenance should be undertaken every 6–12 months; if the modules and inverter have been installed correctly then maintenance costs should be minimal. The array should last at least 20 years, and most modules are covered by a 20–25 year warranty so if premature failure does occur it is often possible to replace or repair the modules free of charge. The inverter is likely to require repair during its lifetime; inverters generally carry a 5–10 year warranty with an option to extend the warranty a further 5–10 years.
- Replacement costs: PV modules are expected to last at least 25 years and most system components are expected to last at least 20 years. Some system components may not last as long as the panels and will require replacement. Inverters have warranties that commonly last 5–10 years but can mostly be repaired should they fail beyond this period. Terminal failure of a correctly installed and properly sized inverter is uncommon, but possible. The designer should ask the manufacturer about the expected life of the inverter they are installing in the system. If it is less than the expected life of a system, then a replacement should be accounted for in costing. Other components may require replacement: monitoring equipment, bypass diodes, cable, plugs/sockets etc. Protection from the elements and wildlife will increase the lifetime of this equipment and hence reduce these costs.

9b.

- High capital costs: the high capital cost of a system can be a major deterrent for investment or render a PV system unattainable for some people. Rebates and green loan programmes are attempting to address this.
- Lack of public knowledge and advertising: there are many myths surrounding PV such as it being too expensive to even consider putting on a home and that the amount of energy produced by the system is less than the energy consumed in its manufacture. The PV industry needs to be proactive about education to dispel these myths.
- Lack of industry: The grid-connect PV industry is still very much in its infancy in most parts of the world. There are a limited number of companies providing training and installation, and standards and regulations are still being developed.
- Lack of planning: As already discussed the amount of solar radiation a module receives is strongly affected by its orientation, but the installation is often governed by the orientation of the roof. When many towns were planned and built the roof orientation was not considered with respect to future PV installations.
- Utility regulations based on mains supply: Most electricity markets are unaccustomed to dealing with distributed generation, i.e. small-scale PV. Sometimes people seeking to install a small rooftop PV system have been required to complete the same paperwork as those planning to connect a large-scale coal-fired power station to the grid. Over time utilities are becoming more accustomed to dealing with distributed generation and streamlining the process of interconnection.
- Well-integrated fossil fuels: Well-established systems that favour fossil fuels are a key barrier to PV. Despite PV's numerous advantages, fossil fuels remain a more cost-effective option. Policies that put a price on the environmental damage of fossil fuels, such as emissions trading schemes and carbon taxes

10 a.

Feed-in tariffs

A Feed-in tariff (FiT) is a monetary reward for feeding electricity generated by PV into the grid. It can either be equal to the retail electricity rate or greater than this rate (known as an enhanced FiT). FiTs are usually financed by a levy added to all electricity bills. Small-scale PV is generally most successful in locations that have FiTs, such as Germany; however, it is important for these FiTs to be stable in order to encourage sustainable growth in the industry. In both Spain and Australia there have been recent cases where an FiT was introduced by the government but removed within a year. FiTs can be structured in two different ways:

- Gross FiT: All electricity generated, regardless of whether it is used in the customer's house or not, receives the FiT.

or

- Net FiT: Only electricity that is exported to the grid receives the FiT. Some net FiTs are time-of-use FiTs, i.e. if the customer is away from home during the day while the PV system is producing electricity, then the customer receives the FiT (even if they use more energy at night than they produced during the day). Other net FiTs go by the total amount of energy produced vs. the amount consumed; i.e. when it was consumed is irrelevant.

10b.

PV has many unique features among electricity-generating technologies that contribute to its popularity today:

- PV is reliable and low-maintenance; it contains no moving parts and the modules are robust, often coming with a 20–25 year guarantee.
- PV is good for the environment. Some people may suggest that a PV system cannot generate enough energy in its lifetime to equate to the amount of energy required in its production; this is not accurate. The energy required is retrieved in 2–7 years, depending on the system components, design, installation and its location. In addition this energy is clean and renewable, and will further reduce greenhouse gas emissions. PV modules are also recyclable.
- Grid-connected PV systems are easy and quick to install. PV's modular nature also makes it very easy to work with, installations can be of any size without any major manufacturing changes and modules can usually be added or removed during the lifetime of the installation.

- PV can represent a good investment: a system can add value to the building where it is installed and many of the financial incentives available such as FiTs are legislated for a certain period of time.
- PV is useful as a public demonstration of commitment to sustainability and reducing greenhouse gas emissions. This may be desirable for a company marketing itself as green because PV is an easy and highly visible way to make a statement and reduce a company's carbon footprint.