CHAPTER 15

PHOTOVOLTAIC MODULES, SYSTEMS AND APPLICATIONS

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> *The best way to predict the future is to invent it.*
> Alan Kay, Apple Computers.

15.1 Introduction

The electricity from photovoltaic cells can be used for a wide range of applications, from power supplies for small consumer products to large power stations feeding electricity into the grid. Previous chapters in this book have discussed the different cell technologies and the optimisation of cell structures to achieve high efficiency of conversion from light to electricity. In this chapter, we will address the aspects that allow us to take those photovoltaic cells and incorporate them into a system delivering a required service.

The chapter concentrates on the use of the most common types of photovoltaic cells, described mainly in Chapters 3–7, and on typical system applications including both stand-alone and grid-connected options. System issues for space cells have already been discussed in Chapter 13 and will not be reconsidered here since they differ substantially from those for terrestrial systems. This is also true of designs for thermophotovoltaic systems, which are considered in Chapter 11. Finally, although some aspects of concentrator systems will be included, readers are referred to Chapter 12 for a fuller discussion of the issues involved in the design of PV systems incorporating high concentration.

In the next section, the construction and performance of photovoltaic modules will be discussed. The individual solar cells must be connected to provide an appropriate electrical output and then encapsulated so as to protect the cells from environmental damage, particularly from moisture. The design of the module depends on the application for which it is to be used and an expansion of those applications in recent years has led to a range of alternative module designs, including the use of coloured cells, variable transparency and different electrical configurations. The section will discuss the variation in module design and their suitability in different scenarios. Finally, module testing including the establishment of rated output and long-term performance will be discussed.

In Section 15.3, the design of PV arrays will be considered, including electrical configuration, optimum tilt angle and orientation, protection from shading and mounting aspects. The variation in performance expected from different array configurations will be discussed.

The next section (15.4) will deal with the whole PV system, commencing with the rest of the system components, usually referred to as the balance of systems (BOS) equipment. The BOS portion of the system differs substantially according to the application and use of the electricity produced by the PV array. This section will discuss the requirements of equipment to be included in a PV system, testing and standardisation, issues of power conditioning and sizing of the PV system to meet the required application. Both stand-alone and grid-connected systems will be considered.

Finally, the widespread adoption of a PV system to provide any given service is dependent upon its economic viability in comparison with alternative supplies. Section 15.5 will consider the issues involved in determining the cost of electricity from a PV system, look at the viability of the system for certain applications and make some projections for the economic future of PV systems.

15.2 Photovoltaic modules

In order to provide useful power for any application, the individual solar cells described in previous chapters must be connected together to give the appropriate current and voltage levels and they must also be protected from damage by the environment in which they operate. This electrically connected, environmentally protected unit is usually termed a photovoltaic module, although it can also be termed a PV laminate when it is supplied without a frame. Figures 15.1a and b show typical module constructions for crystalline silicon and thin film silicon cells respectively.

The module is then used alone or connected in an electrical circuit with other similar modules to form a photovoltaic array. The design and performance of PV arrays will be discussed in Section 15.3.

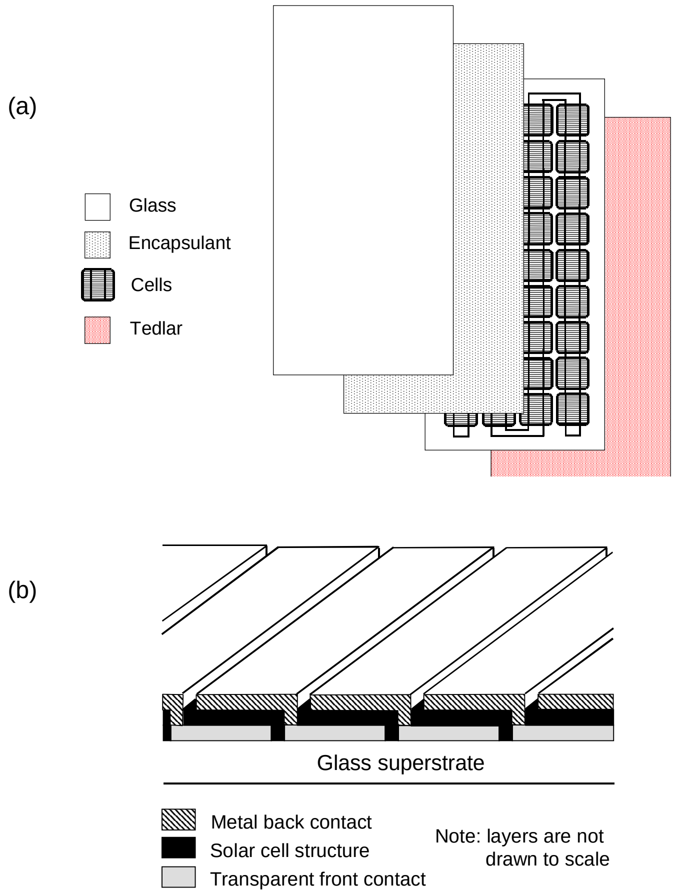

Figure 15.1 a) Schematic of module construction for crystalline silicon cells—exploded view showing the different layers which make up the module; b) schematic of module construction for thin film cells.

Due to the difference in fabrication process, module designs for crystalline and thin film cells, whilst following the same basic principles, differ substantially in several aspects of module construction and design. Indeed, it could be said that the thin film cells are fabricated in modular form, requiring only the encapsulation step after completion of the deposition processes. For simplicity, the crystalline silicon solar cell will be considered initially in each sub-section, since it is presently the most common cell type for power applications. Variations introduced by the use of thin film cells will then be identified.

15.2.1 Electrical connection of the cells

The electrical output of a single cell is dependent on the design of the device and the semiconductor material(s) chosen, but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, a number of cells must be electrically connected. There are two basic connection methods: series connection, in which the top contact of each cell is connected to the back contact of the next cell in the sequence, and parallel connection, in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells.

Series connection

Figure 15.2 shows the series connection of three individual cells as an example and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string (*i.e.* in this case, the voltage output is equal to $3V_{\mathrm{cell}}$).

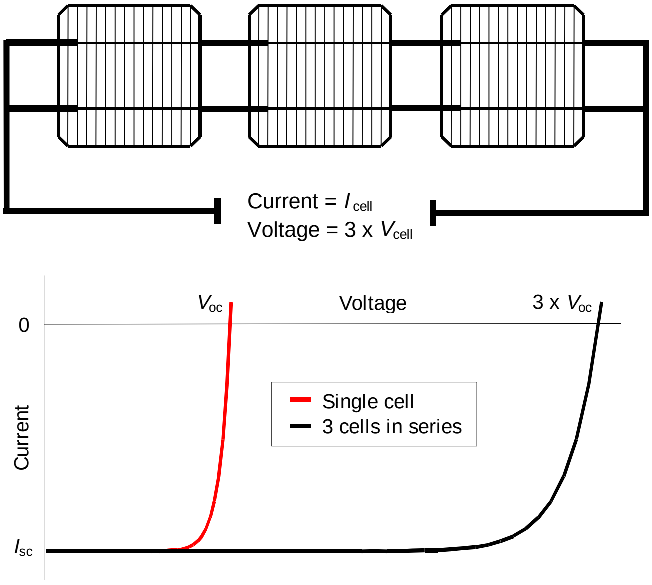

Figure 15.2 Series connection of cells, with resulting current–voltage characteristic.

It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at their maximum power points. This could also happen in the case of partial shading of a string and the effect of this is discussed more fully in Sections 15.3.1 and 15.3.5.

Parallel connection

Figure 15.3 shows the parallel connection of three individual cells as an example. In this case, the current from the cell group is equivalent to the addition of the current from each cell (in this case, 3 I_{cell}), but the voltage remains equivalent to that of a single cell.

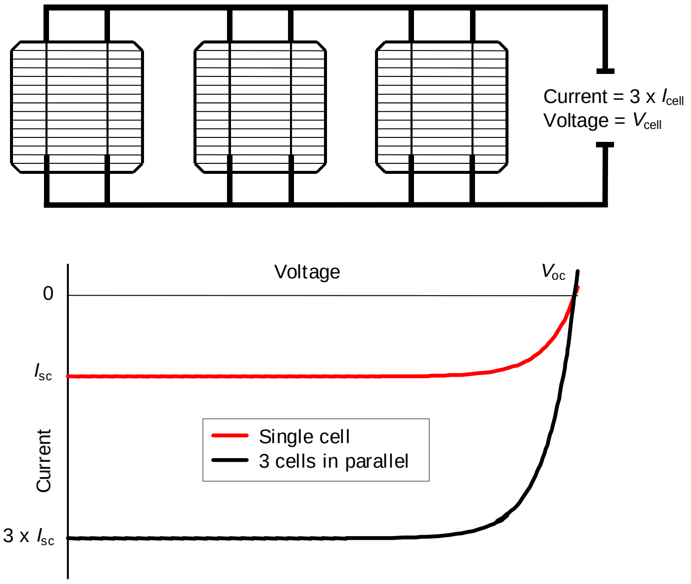

Figure 15.3 Parallel connection of cells, with resulting current–voltage characteristic.

As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum.

Typical module configurations

The electrical connections within a module can be arranged in any desired combination of series and parallel connections, remembering the importance of the matching of the units in any series or parallel string. This means, for example, that parallel connection of series strings should be made using similar strings with the same number and type of cells. The series/parallel configuration will determine the current and voltage values obtained from the module under given illumination and load conditions.

The majority of modules produced in the early 1980s, when the development of module fabrication techniques for crystalline silicon cells reached maturity, were for use in stand-alone applications for the charging of batteries. Thus, the electrical output was required to be appropriate for battery charging under a range of sunlight conditions and this was found to be most readily achieved by the series connection of 34–36 crystalline silicon cells. The series connection of these cells produces an open-circuit voltage of around 18 V (depending on the detail of the cell design) and a maximum power point voltage of around 14–15 V. This provides a voltage above the 12 V required for battery charging over a wide range of sunlight conditions.

When arranged in three or four rows and with the minimum spacing between cells, the module area is around 0.3 m^2 and the module is also suitable for transportation and light enough to be lifted by one or two people for ease of installation. Thus, this design was adopted for most modules of about 10 W or above.

In the case of the thin film module, the same design principle was adopted when battery charging was required. This was accomplished by the series connection of the cells during fabrication. Since the voltage from the amorphous silicon cell is higher than that from a crystalline silicon device, fewer series-connected cells are required to maintain sufficient voltage to charge the battery. However, the cells must be of larger area in order to reach similar current levels.

More recently, larger modules have begun to be produced for building integrated systems and many more cells are incorporated in each module. In these cases, it is possible to have a number of series- and parallel-connected circuits in the same module. In some designs, there can even be more than two terminals with the electrical output from different areas of the module being extracted via different circuits.

Module I–V characteristic

In previous chapters, the *I–V* characteristic of the photovoltaic cell has been described. The module *I–V* characteristic is of a similar shape and can be described by the same equation, where now the parameters of reverse saturation current, diode factor, series and shunt resistances refer to the whole module and are dependent on the type, number and electrical connection method of the cells.

The characteristic is described by the same parameters of open-circuit voltage, short-circuit current, fill factor and maximum power point, where these values now refer to the module rather than the individual cells. Figure 15.4 shows an *I–V* characteristic together with the power curve, to illustrate the position of the maximum power point.

Owing to mismatch between the characteristics of the component cells and to an increased overall series resistance, the module will typically have a reduced fill factor as compared to its constituent cells. Whilst the open-circuit voltage of the module becomes the sum of the voltages from each cell, the module short-circuit current is equivalent to the lowest cell short circuit current (assuming the configuration of all series-connected cells). As we noted previously, the efficiency of the module can be substantially lower than that of the cells from which it is produced if the cells differ significantly in current output.

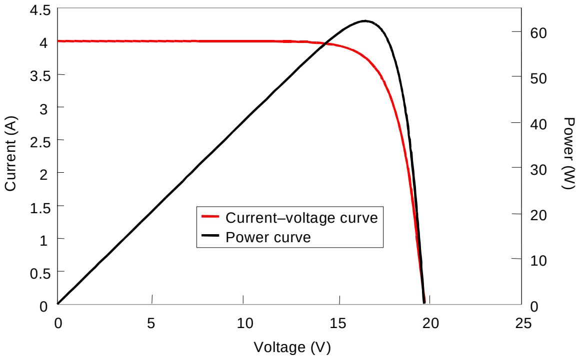

Figure 15.4 Typical *I–V* characteristic of a crystalline silicon module with the variation of power with voltage also shown. This illustrates the position of the maximum power point.

Module rating and efficiency

As with the individual cells, the module output varies with illumination and temperature conditions and therefore these must be defined when considering the power rating of the module. Module testing uses the same Standard Test Conditions (STC) as are used for the measurement of cells, these being a light intensity equivalent to 1 kW m^{-2}, a spectral content corresponding to a standard AM1.5 global spectrum and an operating temperature of 25 C. The test conditions are fully defined in the International Electrotechnical Commission standard number 60904 (IEC, 1987).

In the ideal case, the module rating would simply be the sum of the rating of the individual cells but there are, of course, additional losses that must be taken into account. The most important is the mismatch between the cells, whereby differences in performance will mean that the maximum power point operation of the module as a whole does not coincide with the maximum power point operation of some or all of the cells in the module. The mismatch losses can vary depending upon the operating conditions and whether differences in cell performance are light- or temperature-induced. Where possible, for example for crystalline silicon cells, manufacturers usually batch sort their cells by performance and use cells from the same batch to construct the modules. In this way, mismatch losses are minimised.

The module efficiency is related to the total area of the module in the same way that the efficiency of a cell is related to the total area of the cell. Because it is necessary to have the cells physically separated, the module area is always larger than the sum of the cell areas and therefore the module efficiency is always lower than the cell efficiency. The amount of reduction due to area effects depends on the configuration of the module and is defined by the packing density (ratio of cell area to module area). The packing density is clearly lower for the circular silicon cells produced during the 1970s than for the current pseudo-square cells and this is one of the reasons for increased efficiency in modern modules. Typically, a crystalline silicon module will have a packing density in the range 80–90% and so, if it uses 14% efficient cells, the module efficiency would be around 12%.

For thin film cells, the reduction in efficiency is much lower because the strip cells are only separated by the contact strip. More important in this case is the mismatch between cell performances since it is not possible to sort and select the cells as for the crystalline devices. Since the mismatch arises from variations in the production process across the surface of the module, it is important to control the uniformity of all processes.

The performance of the module is also a function of its operating temperature and hence the rated efficiency is quoted at a standard temperature of 25 C. The module voltage reduces with increasing temperature and, although the current increases slightly, the overall effect is for the efficiency to reduce as the temperature rises. The amount of the change depends on the cell type and structure, with crystalline silicon cells typically losing about 0.4–0.5% of their output per degree Celsius rise. Higher band-gap cells, have a lower temperature coefficient, for example, thin film silicon reduces by about 0.2% per degree Celsius because of the change in voltage. However, thin film silicon modules also exhibit a thermal dependence due to annealing of the light-induced degradation and this acts in the opposite direction. So, their overall temperature coefficient can be zero or even slightly positive over some temperature ranges. This varies with cell structure and operating conditions.

The operating temperature varies as a function of the climatic conditions of ambient temperature and incident sunlight and also depends on the module design and the module mounting. Both these latter factors affect the ability of the module to lose heat and hence determine the operating temperature under given climatic conditions. A measure of the effect of module design is given by the Nominal Operating Cell Temperature (NOCT) of the module, which is measured under defined sunlight, temperature and wind conditions for an open mounting structure.

15.2.2 Module structure

The structure of the PV module is dictated by several requirements. These include the electrical output (which determines the number of cells incorporated and the electrical connections), the transfer of as much light as possible to the cells, the cell temperature (which should be kept as low as possible) and the protection of the cells from exposure to the environment. The electrical connections have already been discussed, so this section will concentrate on the physical protection from the environment and the maintenance of cell operating conditions. Figures 15.5 and 15.6 show typical PV modules.

In modern crystalline silicon modules, the front surface is almost always composed of glass, toughened to provide physical strength and with a low iron content to allow transmission of short wavelengths in the solar spectrum. The rear of the module can be made from a number of materials. One of the most common is Tedlar (see Fig. 15.1), although other plastic materials can also be used. If a level of transparency is required, then it is possible to use either a translucent Tedlar sheet or more commonly a second sheet of glass. The glass-glass structure is popular for architectural applications, especially for incorporation into a glazed façade or roof.

The glass-Tedlar module is usually fabricated by a lamination technique. The electrically connected cells are sandwiched between two sheets of encapsulant, for example EVA (ethylene vinyl acetate), and positioned on the glass sheet which will form the front surface of the module. The rear plastic sheet is then added and the whole structure is placed in the laminator. Air is removed and then reintroduced above

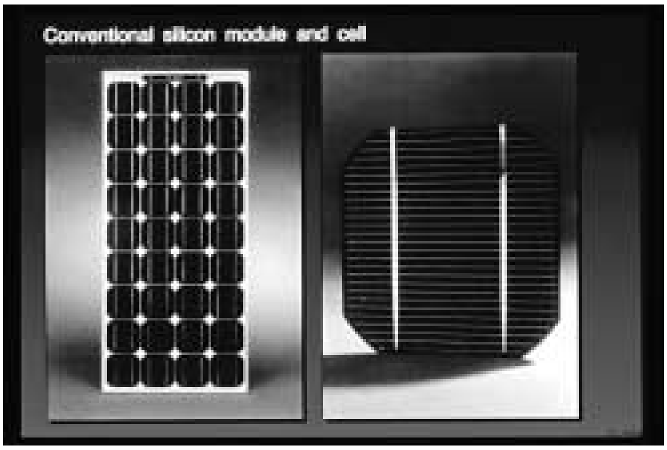

Figure 15.5 Typical crystalline silicon module and cell (photograph courtesy of BP Solarex).

Figure 15.6 Typical thin film silicon module (photograph courtesy of Intersolar Group).

a flexible sealing membrane above the module to provide pressure. The module is heated and the encapsulant melts and surrounds the cells. Additional encapsulant material is included at the module perimeter to ensure complete sealing of the module edges.

The glass-glass construction is more time and labour intensive, since the removal of air must be accomplished without the aid of lamination. Both film and liquid encapsulants can be used. In the case of the liquid encapsulant, this is poured between the glass sheets after the module has been sealed on three edges. The connected cells must be fixed in place before this procedure is undertaken.

In the thin film module, the glass substrate on which the cell is deposited is often used as the front surface of the finished module. Lamination is then carried out in the same way as for crystalline modules although only a single layer of encapsulant is required. Lower temperatures are often used to avoid damage to the cells. Particular care must be taken with edge sealing since all thin film cells are badly affected by the ingress of moisture. In the manufacturing process, a clear gap must be left around the edge of the cell area for proper sealing of the module.

The electrical connections to the module are made via a junction box, usually fixed to the rear of the module, or by flying leads. These typically exit the module through the rear Tedlar sheet. In the case of glass-glass modules, the leads may exit through one edge of the module to avoid drilling holes in the glass sheet. The points at which the electrical connections are brought out of the module are sealed to prevent moisture ingress.

The module will exhibit the highest efficiency when the maximum amount of the light falling on the module is incident upon the cells. Light which is incident on the spaces between cells or at the module edge is either reflected or converted to heat. Since the 1970s, cell shape and spacing has been altered to produce more densely packed modules and hence increase efficiency. Most power modules use the minimum cell spacing, which is accepted to be 2–3 mm between the cell edges. This gap is to prevent any problems with electrical shorting between cells.

The most common shape of monocrystalline silicon cell is pseudo-square, where the cell is cut from a circular wafer and is square apart from the cut-off corners (see Fig. 15.5). Polycrystalline silicon cells are often truly square, depending on the manufacturing technique of the material. Thin film cells are deposited in strips, usually of around 1 cm in width and running the length of the module, although dimensions can vary depending on cell properties.

In operation, the module is often at a temperature in the region of 50–80 C when operating in good sunlight conditions and for an ambient temperature of 25–30 C. Whilst these operating temperatures are not excessive, the difference in thermal expansion of the various components must be taken into account. Also, allowance must be made for the higher temperatures experienced during manufacture, albeit for a much shorter time. The cell stringing allows for some differential expansion in the length of ribbon between each cell. The electrical connection is also made in two places on each cell (often referred to as double tabbing) to allow for any problems with thermal expansion and other stresses during manufacture or operation. This is shown schematically in Figs. 15.2 and 15.3.

The ideal module would also provide good heat transfer in order to keep the cell temperature as low as possible. However, the encapsulant is required to provide electrical isolation and physical protection, so a high heat transfer coefficient is not always possible. The operating temperature is also influenced by the exterior materials of the module, with glass-glass structures usually running at a higher temperature than the glass-Tedlar module under similar conditions. The colour of the rear Tedlar film also has some influence. For example, a module with a white Tedlar backing will reject more heat than one with a black Tedlar backing, so allowing it to operate at higher efficiency.

The module is often provided with a metal frame in order to make it straightforward to fix to a support structure, although this is less usual for building integrated applications.

15.2.3 Variations in module design

Module design varies according to the electrical output required and the application of the PV system. Considerable variation in size, shape, colour and cell spacing has been introduced in recent years to accommodate the consumer market, especially where the modules are incorporated directly into the product, and the building integration market, where appearance is of particular importance. It has also been possible to design modules which have additional functions, such as the semi-transparent modules that can be used as shading devices and to influence light patterns inside buildings.

The choices available are mainly in terms of power rating, size and shape of cell, colour of cells and/or backing sheets, level of transparency, cell spacing and size and shape of module. Since production volumes are lower, non-standard features tend to increase the module cost.

The colour of the crystalline silicon cell is altered by variation of the thickness of the anti-reflection coating on the top surface of the cell. This can dictate the wavelength of light which is predominantly reflected from the cell and hence its colour. Of course, light which is reflected cannot contribute to the generation of electricity and so the cell efficiency is reduced in comparison to the traditional cell. The output is reduced by between 10 and 25% compared with the usual dark blue cell, depending on the cell colour chosen (Mason *et al.*, 1995).

For thin film modules, the cell colour cannot be changed since there is no anti-reflection coating. To alter the transparency of the modules, the semiconductor film is thinned to allow some light to be transmitted through the cell whilst the rear contacts and the backing sheet are transparent. Again, efficiency is reduced owing to the lower absorption of light. Thin film cells can also be made on flexible substrates, such as metal or plastic sheets, for use in consumer products or for roofing.

The choice of module structure and design is very dependent on the application in question with output, appearance, cost, compatibility with other components and durability being the issues to consider.

15.2.4 Module testing

The electrical output of the module is tested under Standard Testing Conditions as described earlier. The measurement under STC provides the module rating in peak watts (W_p) and defines the module efficiency. The testing method requires control of module temperature, light spectrum and illumination uniformity.

It is also important to assess the effectiveness of the module construction in protecting the cells from the environment, since this determines the lifetime of the module in operation. Again, testing conditions have been defined for accelerated life testing. These include thermal cycling, hail impact, humidity-freeze, mechanical twist and electrical isolation tests and are detailed in IEC standard 61215 for crystalline silicon modules (IEC, 1993). Whether a module meets the standard is determined by setting maximum limits for change in output and visual faults after each test. For thin film silicon modules, the output reduces during the initial weeks of operation and so the accelerated life testing should be carried out after the module output has stabilised. The IEC standard 61646 sets out the requirements for the pre-test stabilisation, the environmental tests and the limits of change of performance (IEC, 1996).

15.3 The photovoltaic array

A PV array consists of a number of PV modules, mounted in the same plane and electrically connected to give the required electrical output for the application. The PV array can be of any size from a few hundred watts to hundreds of kilowatts, although the larger systems are often divided into several electrically independent sub-arrays each feeding into their own power conditioning system.

15.3.1 Electrical connection of modules

As with the connection of cells to form modules, a number of modules can be connected in a series string to increase the voltage level, in parallel to increase the current level or in a combination of the two. The exact configuration depends on the current and voltage requirements of the load circuitry fed by the system output. Matching of interconnected modules in respect of their outputs can maximise the efficiency of the array, in the same way as matching cell output maximises the module efficiency.

If there is one shaded module in a series-connected string of modules, it can then act as a load to the string in the same way as a shaded cell does in an individual module. As with the cell, damage can occur due to heating by the current flowing through the module. The severity of the problem varies according to the number of modules in the string (and hence the potential power drop across the module) and the likelihood of partial shading of the string (which depends on system design and location). Where the shading situation may cause damage to the module, bypass diodes can be included. The bypass diode is connected in parallel with the module and, in the case of the module being shaded, current flows through the diode rather than through the module.

This use of bypass diodes adds some expense and reduces the output of the string by a small amount, owing to the voltage that is dropped across the diode. For some large modules, the bypass diodes are incorporated into the module structure itself at the manufacturing stage and several diodes may be used, each protecting different sections of the module. This integration reduces the need for extra wiring, although it makes it difficult to replace the diode in the case of failure. The use of bypass diodes should be decided on a system-by-system basis depending on the likelihood of partial shading of a string and the power level of the string.

In systems where shading may reduce the output of one of the strings substantially below that of the others, it can also be advantageous to include a blocking diode connected in series with each string. This prevents the current from the remainder of the array being fed through the shaded string and causing damage.

The use of blocking or bypass diodes reduces the output of the system slightly but does provide protection. The choice of whether to use blocking or bypass diodes depends on the design of the system and the need for protection from shading or other aspects.

15.3.2 Mounting structure

The main purpose of the mounting structure is to hold the modules in the required position without undue stress. The structure may also provide a route for the electrical wiring and may be free standing or part of another structure (*e.g.* a building). At its simplest, the mounting structure is a metal framework, securely fixed into the ground. It must be capable of withstanding appropriate environmental stresses, such as wind loading, for the location. As well as the mechanical issues, the mounting has an influence on the operating temperature of the system, depending on how easily heat can be dissipated by the module.

15.3.3 Tilt angle and orientation

The orientation of the module with respect to the direction of the Sun determines the intensity of the sunlight falling on the module surface. Two main parameters are defined to describe this. The first is the tilt angle, which is the angle between the plane of the module and the horizontal. The second parameter is the azimuth angle, which is the angle between the plane of the module and due south (or sometimes due north depending on the definition used). Correction of the direct normal irradiance to that on any surface can be determined using the cosine of the angle between the normal to the Sun and the module plane.

The optimum array orientation will depend on the latitude of the site, prevailing weather conditions and the loads to be met. It is generally accepted that, for low latitudes, the maximum annual output is obtained when the array tilt angle is roughly equal to the latitude angle and the array faces due south (in the northern hemisphere) or due north (for the southern hemisphere). For higher latitudes, such as those in northern Europe, the maximum output is usually obtained for tilt angles of approximately the latitude angle minus 10–15 degrees. The optimum tilt angle is also affected by the proportion of diffuse radiation in the sunlight, since diffuse light is only weakly directional. Therefore, for locations with a high proportion of diffuse sunlight, the effect of tilt angle is reduced.

However, although this condition will give the maximum output over the year, there can be considerable variation in output with season. This is particularly true in high-latitude locations where the day length varies significantly between summer and winter. Therefore, if a constant or reasonably constant load is to be met or, particularly, if the winter load is higher than the summer load, then the best tilt angle may be higher in order to boost winter output.

Prevailing weather conditions can influence the optimisation of the array orientation if they affect the sunlight levels available at certain times of the day. Alternatively, the load to be met may also vary during the day and the array can be designed to match the output with this variable demand by varying the azimuth angle.

Notwithstanding the ability to tailor the output profile by altering the tilt and azimuth angles, the overall array performance does not vary substantially for small differences in array orientation. Figure 15.7 shows the percentage variation in annual insolation levels for the location of London as tilt angle is varied between 0 and 90 degrees and azimuth angle is varied between –45^{o} (south east) and +45^{o} (south west). The maximum insolation level is obtained for a south-facing surface at a tilt angle of about 35 degrees, as would be expected for a latitude of about 51^{o}N. However, the insolation level varies by less than 10% with changing azimuth angle at this tilt angle. A similarly low variation is observed for south facing surfaces for a variation of +/- 30 degrees from the optimum tilt angle.

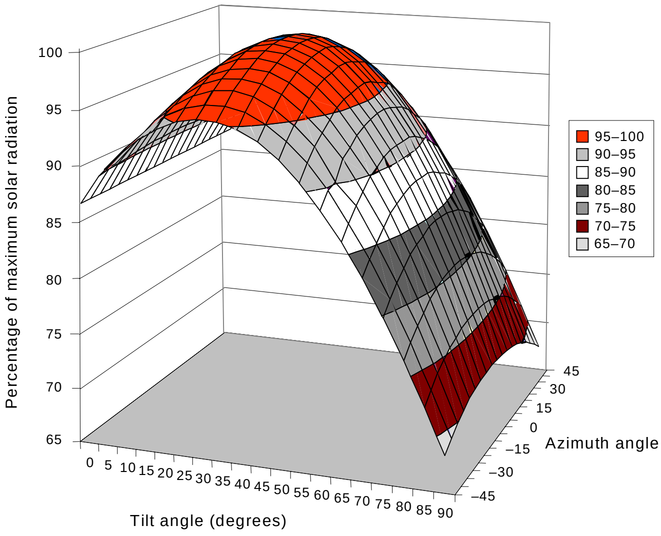

Figure 15.7 Percentage variation of annual sunlight levels as a function of tilt angle and azimuth angle. The calculations were carried out for the location of London using Meteonorm Version 3.0.

The final aspect to consider when deciding on array orientation is the incorporation in the support structure. For building-integrated applications, the system orientation is also dictated by the nature of the roof or façade in which it is to be incorporated. It may be necessary to trade off the additional output from the optimum orientation against any additional costs that might be incurred to accomplish this. The aesthetic issues must also be considered.

15.3.4 Sun-tracking/concentrator systems

The previous section has assumed a fixed array with no change of orientation during operation. This is the usual configuration for a flat-plate array. However, some arrays are designed to track the path of the Sun. This can account fully for the sun's movements by tracking in two axes or can account partially by tracking only in one axis, from east to west.

For a flat-plate array, single-axis tracking, where the array follows the east-west movement of the Sun, has been shown to increase the output by up to 30% for a location with predominantly clear sky conditions. Two-axis tracking, where the array follows both the daily east-west and north-south movement of the sun, could provide a further increase of about 20% (Lepley, 1990). For locations where there are frequent overcast conditions, such as northern Europe, the benefits of tracking are considerably less. It is usually more economical to install a larger panel for locations with less than about 3000 hours of direct sunshine per annum. For each case, the additional output from the system must be compared to the additional cost of including the tracking system, which includes both the control system and the mechanism for moving the array.

For concentrator systems, such as those described in Chapter 12, the system must track the Sun to maintain the concentrated light falling on the cell. The accuracy of tracking, and hence the cost of the tracking system, increases as the concentration ratio increases.

15.3.5 Shading

Shading of any part of the array will reduce its output, but this reduction will vary in magnitude depending on the electrical configuration of the array. Clearly, the output of any cell or module which is shaded will be reduced according to the reduction of light intensity falling on it. However, if this shaded cell or module is electrically connected to other cells and modules which are unshaded, their performance may also be reduced since this is essentially a mismatch situation.

For example, if a single module of a series string is partially shaded, its current output will be reduced and this will then dictate the operating point of the whole string. If several modules are shaded, the string voltage may be reduced to the point where the open-circuit voltage of that string is below the operating point of the rest of the array, and then that string will not contribute to the array output. If this is likely to occur, it is often useful to include a blocking diode for string protection, as discussed earlier.

Thus, the reduction in output from shading of an array can be significantly greater than the reduction in illuminated area, since it results from

- the loss of output from shaded cells and modules;
- the loss of output from illuminated modules in any severely shaded strings that cannot maintain operating voltage; and
- the loss of output from the remainder of the array because the strings are not operating at their individual maximum power points.

For some systems, such as those in a city environment, it may be impossible to avoid all shading without severely restricting the size of the array and hence losing output at other times. In these cases, good system design, including the optimum interconnection of modules, the use of string or module inverters and, where appropriate, the use of protection devices such as blocking diodes, can minimise the reduction in system output for the most prevalent shading conditions.

15.4 The photovoltaic system

A PV system consists of a number of interconnected components designed to accomplish a desired task, which may be to feed electricity into the main distribution grid, to pump water from a well, to power a small calculator or one of many more possible uses of solar-generated electricity. The design of the system depends on the task it must perform and the location and other site conditions under which it must operate. This section will consider the components of a PV system, variations in design according to the purpose of the system, system sizing and aspects of system operation and maintenance.

15.4.1 System design

There are two main system configurations – stand-alone and grid-connected. As its name implies, the stand-alone PV system operates independently of any other power supply and it usually supplies electricity to a dedicated load or loads. It may include a storage facility (*e.g.* battery bank) to allow electricity to be provided during the night or at times of poor sunlight levels. Stand-alone systems are also often referred to as autonomous systems since their operation is independent of other power sources. By contrast, the grid-connected PV system operates in parallel with the conventional electricity distribution system. It can be used to feed electricity into the grid distribution system or to power loads which can also be fed from the grid.

It is also possible to add one or more alternative power supplies (*e.g.* diesel generator, wind turbine) to the system to meet some of the load requirements. These systems are then known as 'hybrid' systems. Hybrid systems can be used in both stand-alone and grid-connected applications but are more common in the former because, provided the power supplies have been chosen to be complementary, they allow reduction of the storage requirement without increased loss of load probability, as discussed in Section 15.4.7. Figures 15.8–15.10 show schematic diagrams of the three main system types.

15.4.2 System components

The main system components are the photovoltaic array (which includes modules, wiring and mounting structure), power conditioning and control equipment, storage equipment (if required) and load equipment. It is particularly important to include the load equipment for a stand-alone system because the system design and sizing must take the load into consideration. By convention, the array components are split into the photovoltaic part (the PV modules themselves) and the balance of system (BOS) components. The remainder of this section provides a brief discussion of the most common system components and their role in the system operation, with some examples of typical performance. Note that there are many different options for BOS equipment, depending on the detail of the system, and it is only possible to give a general overview here.

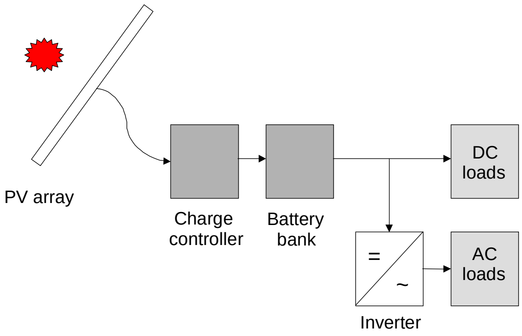

Figure 15.8 Schematic diagram of a stand-alone photovoltaic system.

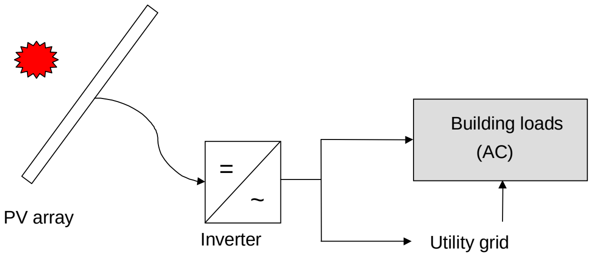

Figure 15.9 Schematic diagram of grid-connected photovoltaic system.

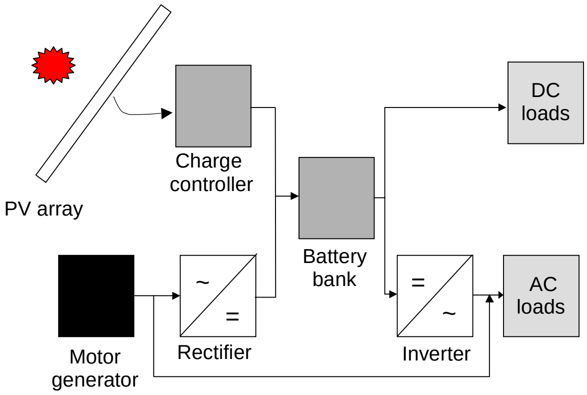

Figure 15.10 Schematic diagram of hybrid system incorporating a photovoltaic array and a motor generator (*e.g.* diesel or wind).

The photovoltaic array

The PV array is made up of the PV modules themselves and the support structure required to position and protect the modules. Cabling and interconnections are sometimes included in the definition although here they are discussed in a later section. The array has already been discussed in Section 15.3.

Power conditioning

It is often advantageous to include some electrical conditioning equipment to ensure that the system operates under optimum conditions. In the case of the array, the highest output is obtained for operation at the maximum power point. Since the voltage and current at maximum power point vary with both insolation level and temperature, it is usual to include control equipment to follow the maximum power point of the array, commonly known as the Maximum Power Point Tracker (MPPT). The MPPT is an electrical circuit that can control the effective load resistance which the PV array sees and thus control the point on the I–V characteristic at which the system operates. There are a number of ways in which the optimum operating point can be found but an MPPT often operates by checking the power levels on either side of the present operating point at regular intervals and, if a gain in power is observed in one direction, then the MPPT moves the operating point in that direction until it reaches the maximum value. For grid-connected systems, the MPPT is often incorporated into the inverter for ease of operation, although it is possible to obtain the MPPT as an independent unit.

When DC loads are to be met, it may be necessary to include a DC–DC converter to change the voltage level of the output of the array to that required for input to the load. It is also usual to include charge control circuitry where the system includes batteries, in order to control the rate of charge and prevent damage to the batteries.

Inverter

If the PV system needs to supply AC loads, then an inverter must be included to convert the DC output of the PV array to the AC output required by the load. As with PV systems, inverters can be broadly divided into two types, these being stand-alone and grid-connected (sometimes referred to as line-tied).

The stand-alone inverter is capable of operating independently from a utility grid and uses an internal frequency generator to obtain the correct output frequency (50/60 Hz). By contrast, the grid-connected inverter must integrate smoothly with the electricity supplied by the grid in terms of both voltage and frequency. The output voltage of the inverter is chosen according to the load requirements, *e.g.* 220–230 V single-phase for European domestic appliances. However, if the electricity from the PV system is to be fed directly into the supply of a large office building, for example, a 415 V three-phase output may be chosen. The input voltage depends on the design of the PV array, the output characteristics required and the inverter type. Stand-alone systems commonly operate at 12, 24 or 48 V, since the system voltage is determined by the storage system, whereas grid-connected inverters usually operate at significantly higher voltages (over 110 V).

The shape of the output waveform is important because some loads can overheat or be damaged if a square wave output is used. True sine wave or quasi-sine wave (or modified sine wave) outputs are generally more costly but are much more widely applicable. Most modern stand-alone inverters provide a modified sine wave output, whilst grid-connected inverters should have a sine wave output with a very low harmonic content.

In recent years, the module-integrated inverter has been developed. This is a small inverter designed to be positioned on the rear of a module and converting the electrical output from that single module. Hence, this module–inverter combination is sometimes referred to by the term “AC module”. These modules are designed for grid-connected applications, particularly where the system is building-integrated. It allows AC power to be produced at the module level and has some advantages in system design such as the use of AC wiring for most of the power transmission and reduced losses for non-uniform systems (*e.g.* where there is shading). It is also expected to lead to a reduction in overall inverter cost when production levels are sufficiently high.

Inverters for PV systems are designed to have high conversion efficiency (usually >90% at maximum). The efficiency varies with the operating point of the inverter, but is usually reaches its maximum between 30 and 50% of rated capacity and shows only a small decrease as the power level increases. However, the efficiency generally reduces substantially at power levels below about 10% of full power.

In locations in the middle and north of Europe, the performance at low light levels (and hence low power levels) can have a significant effect on the overall system efficiency. Thus, it is usual to size the inverter at about 75–80% of the array capacity so that high inverter efficiencies are maintained at lower power levels. This means that the very high power levels are sacrificed since they are out of the range of operation of the inverter, but the balance of low and high power operation is usually such that it is more advantageous to use a reduced inverter size. This may not be the case for systems that experience a significant proportion of high power levels due to cold, clear weather conditions.

When the inverter is grid-connected, it must be ensured that the system will not feed electricity back into the grid when there is a fault on the grid distribution system. This problem is known as islanding, and safeguards are required in order to provide protection for equipment and personnel involved in the correction of the fault. Islanding is usually prevented by closing down the inverter when the supply from the grid is outside certain limits. The allowable limits vary from country to country but are usually around +/–2% in voltage and frequency. Requirements for prevention of islanding for systems are detailed in the connection regulations for each country. A good discussion of all aspects of grid connection has been prepared by Task V of the Photovoltaic Power Systems Programme of the International Energy Agency (IEA, 1998).

Storage

For many PV system applications, particularly stand-alone, electrical power is required from the system during hours of darkness or periods of poor weather. In this case, storage must be added to the system. Typically, this is in the form of a battery bank of an appropriate size to meet the demand when the PV array is unable to provide sufficient power. The design and operation of batteries is discussed in detail in Chapter 14.

Load equipment

The nature of the load equipment will determine the need for and suitability of the power-conditioning equipment and the capacity of both the PV system and the storage. The first consideration is whether the load or loads use DC or AC electricity. In the former case, the loads can be operated directly from the PV system or battery storage whereas AC loads will require an inverter to be included in the system.

Where the system is grid-connected, loads are almost always AC but for autonomous systems, a choice can be made. This choice will depend on the availability, cost and performance of the DC and AC versions of the load equipment. For example, it is possible to obtain high-efficiency DC fluorescent lighting which, by virtue of its superior performance compared with AC lighting, results in a smaller capacity requirement for the PV system and hence, usually, reduced costs. In the case of water pumping, the choice between DC and AC pumps depends on the nature of the water supply (*e.g.* deep borehole or surface pump).

The requirements of the load in terms of voltage and current input range will influence the type of power conditioning included in the system and the load profile will determine the relative sizes of the PV system and the storage, if used. System sizing in accordance with load details is discussed in more detail later in the chapter.

Cabling and switching equipment

The array cabling ensures that the electricity generated by the PV array is transferred efficiently to the load and it is important to make sure that it is specified correctly for the voltage and current levels which may be experienced. Since many systems operate at low voltages, the cabling on the DC side of the system should be as short as possible to minimise the voltage drop in the wiring. Switches and fuses used in the system should be rated for DC operation. In particular, DC sparks can be sustained for long periods, leading to possible fire risk if unsuitable components are used.

15.4.3 System sizing

It is important to determine the correct system size, in terms of both peak output and overall annual output, in order to ensure acceptable operation at minimum cost. If the system is too large, it will be more expensive than necessary without increasing performance levels substantially and therefore the system will be less cost-effective than it could be. However, if too small a system is installed, the availability of the system will be low and the customer will be dissatisfied with the equipment. Again, the cost-effectiveness is reduced.

Although many of the same principles are included in the sizing process, the approach differs somewhat for stand-alone and grid-connected systems. In the first instance, stand-alone systems will be discussed. The first step is to gather the relevant information on the location and purpose of the system.

Location information includes

- Latitude and longitude;
- Weather data—monthly average sunlight levels, ambient and maximum temperatures, rainfall, maximum wind speeds, other extreme weather conditions;
- Constraints on system installation—tilt angle, orientation, risk of shading;

Information on system purpose includes

- Nature of load or loads;
- Likely load profile—daily, annual variation (if any);
- Required reliability—ability to cope with loss of load (for example, clinic lighting requires a higher level of reliability than a lighting system for a domestic house);
- Likelihood of increase of demand—many systems fail because they are sized for an existing load, but demand increases soon after provision of the PV supply.

If an autonomous system is required, the PV system must provide sufficient electricity to power the loads even under the worst conditions. Thus, system sizing is usually carried out for the month that represents the worst conditions in terms of the combination of high load levels and low sunlight conditions. Note that this is not necessarily the month that has the lowest sunshine or the highest load, but that for which the combination represents worst case.

For a given system design, the average electrical output in the sizing month can be calculated from the average daily insolation level (usually expressed in $\mathrm{kWh\,m^{-2}}$) taking into account the number of modules, their rated efficiency, the efficiencies of all control and power conditioning equipment, the efficiency of any storage system, mismatch losses, wiring losses and the operating temperature. For an autonomous PV system, the average daily electrical output should match or exceed the average daily load. If this is not the case, then the PV array size must be increased.

The battery storage allows for variations in the load level during the day and the provision of power at night. The battery bank must be sized to accommodate the average daily need for electricity which cannot be directly supplied by the PV system and so that this results in only a shallow discharge of the batteries.

So far, we have considered only average values for load and sunlight levels. The daily sunlight levels can vary substantially and the battery storage must also allow for providing power in periods of unusually poor weather conditions. The length of the period to be allowed for is determined by consideration of local weather conditions (*i.e.* the probability of several days of poor weather) and the importance of maintaining power to the load. Clearly, if the system is used for medical purposes or communications, loss of power could have serious consequences, whereas for other situations, such as powering domestic TV or lighting, it is merely an inconvenience. Since an increase in the period for which supplies can be maintained involves an increase in the size of the PV array and/or battery bank and hence an increase in system cost, this aspect is an important part of the sizing exercise. Supply companies tend to refer to this by many different terms, including reliability, availability and loss-of-load probability.

Clearly, the sizes of the PV array and battery bank are linked, and an increase in the size of one can often allow a decrease in the size of the other. The sizing operation is usually an iteration of the problem to find the most cost-effective solution, taking into account the requirements and preferences of the user. Most companies have their own computer programs for performing this iteration and also use their experience to determine the parameters which should be input for any given case. It is also possible to purchase sizing software from several companies.

For a grid-connected system, it is not usually necessary to meet a particular load but only to contribute to the general electricity supply. Some systems are designed to feed all their output into the electricity grid whilst others (*e.g.* most building integrated systems) are designed to meet some of the load in a local area with the rest of the requirement being supplied by the grid. These latter systems only feed power back into the grid when their output exceeds the demand of the load. The system sizing is therefore not often governed by the size of the load, but by other constraints such as the area available for the system and the budget available for its purchase and installation.

Therefore, most sizing packages are used to determine potential output and to compare different options of system location and design, rather than optimising system size as such. Not all sizing packages are suitable for building-integrated applications, because they do not take account of the higher operating temperatures or the shading levels which can be experienced. However, more complex system simulation programs, taking these factors into account, have been developed in recent years (see, for example, Reise and Kovach, 1995).

The accuracy of the output of any simulation will depend on the accuracy of the data which is input, as with all such systems. However, since there is a natural variation in insolation levels depending on climatic conditions, this must also be taken into account in the use of results from a simulation. If average insolation data are used, as is most common, then an average output will be obtained as a result. This is strictly speaking only the average value over the period represented by the input data rather than a prediction of what any future values will be. Thus it is possible to obtain practical results from a system which are significantly different from the simulation results of the design process, simply because of normal climatic fluctuations.

15.4.4 System operation

The output of any PV system depends mainly on the sunlight conditions but can also be affected by temperature, shading and the accumulation of dirt on the modules. The overall system performance is usually represented by the efficiency, which is defined as the ratio of the electrical output to the load (in kWh) to the sunlight energy input (also in kWh) over the surface of the array in the same period. In general, this overall efficiency results from several processes to which individual efficiency values can be assigned, *e.g*. the conversion of sunlight to DC electricity, the conversion of DC to AC by the inverter.

The system yield is also a useful parameter. This expresses the annual output (or that over another defined period) as a function of the nominal rating of the system and is in units of kWh/kW_p. This allows comparison of systems in different locations. However, since this parameter does not explicitly include the sunlight level received over the period, account must be taken of whether the level was above or below average if the yield is to be used for a critical assessment of system performance.

Another often-quoted parameter is the performance ratio, which is either given as a percentage or as a number between zero and one. Essentially, this parameter expresses the performance of the system in comparison to a lossless system of the same design and rating at the same location. It provides a measure of the losses of the system, but, because the sunlight level is included in the calculation, it becomes independent of sunlight conditions. Thus, it allows the comparison of system design in different locations. The performance ratio (PR) is calculated from the following formula:

$$\begin{aligned}\text{PR} = {} & \text{system output over period} / (\text{average daily irradiance} \times \text{array rating} \\ & \times \text{number of days in period} \times \text{monitoring fraction})\end{aligned}$$

where all parameters are values for the same period, the system output is in kWh, the average daily irradiance is in kWh m^{-2} and the array rating is in kWp. The monitoring fraction is the fraction of the period considered for which monitoring data are available and have been used to determine the values of the other parameters. The formula makes the assumption that average conditions are experienced for the time when data are not collected and so care must be taken with the use of PR values calculated for monitoring fractions less than 0.9.

15.4.5 Operation and maintenance

Because of its lack of moving parts and simple connections, a PV system generally requires little maintenance. However, it is necessary to ensure continued access to sunlight, by cleaning the panels at appropriate intervals, by refraining from building any structures that could shade the panels and by cutting back any branches or other vegetation that could cover the system. The electrical connections should also be checked at regular intervals to eliminate any problems, *e.g.* corrosion, loose connections. If included in the system, the battery bank may need regular maintenance according to the type chosen.

The requirement for cleaning is often overestimated by those with little experience of PV systems. In most cases, it can be assumed that 3–5% of performance will be lost if the system is only cleaned annually, with up to half of that loss being experienced within a few weeks of cleaning. However, the losses incurred and thus the requirement for cleaning are very dependent on location and are best determined from practical applications operating under similar conditions. For example, if there is the possibility of dust or sandstorms causing accumulation on the modules, perhaps in a desert area, then more frequent cleaning will be required. This can also be the case for systems installed in industrial areas close to sources of airborne pollutants. For building integrated systems on houses in many parts of Europe, it may not actually be necessary to clean the systems, since the action of rainwater on the inclined panels removes surface dust.

Most operational problems occur as a result of poor maintenance of the BOS components (including loads and batteries) or allowing the array to become obscured or damaged. This latter problem indicates a lack of understanding of the operation of the system and there is a need for education of users to ensure that they operate the system correctly. This is also demonstrated by system failures arising from the addition of loads that were not included in the original system sizing. In this case, the combination of the PV and storage system cannot meet the increased demand and there is a danger of damage to the batteries from deep discharging.

The costs of operation and maintenance will vary with application, since they are dependent on the ease of access and the requirement for cleaning, the remoteness of the system and any replacements that may be required. However, they are generally not more than a few percent of the system cost per annum.

15.4.6 Photovoltaic applications

The wide range of applications in which photovoltaic systems are employed cannot be covered in depth in this chapter and so two particular examples will be discussed. These are remote area power supplies (RAPS) and building-integrated photovoltaic (BIPV) systems and they represent two of the major markets for photovoltaics, both now and in the future. They also provide examples of stand-alone and grid-connected applications respectively.

Remote area power supplies (RAPS)

These systems supply electrical power to a wide variety of loads remote from any utility distribution grid. The systems range in size from a single module powering a Solar Home System (SHS) to a few kilowatts of PV supplying a local area grid network. The systems are autonomous and so must include energy storage of some sort to supply power in the absence of sunlight. The economics of storage dictate that, for larger systems and for those where high reliability is paramount, some of the energy storage will be in the form of fuel for an internal combustion engine. In locations where the seasonal availability of wind energy is complementary to that of the solar irradiance, it is often cost-effective to include a wind turbine in the hybrid system.

In a small, non-critical system, such as an SHS, a PV module charges a battery during the day, and the power is used at night for a few high-efficiency lights and a radio or small TV. A charge controller ensures that the battery is not overcharged or deep-discharged, to provide as long a battery lifetime as possible. System sizing is simple, using estimates of average daily usage of the loads, and, in the absence of 10 years of solar data in most locations, estimates of solar irradiance and its variability. In order to keep costs as low as possible, a standard system is sold to all users, although richer households may purchase a “2 module system”, *i.e.* double the standard system. The reliability of the systems depends to a large extent on the users observing the remaining battery charge from indicator lights on the charge controller and modifying their usage accordingly. A longer than average period of low irradiance will result in a loss of power to the loads, but this is an inconvenience to the users rather than a threat to life or to the system.

Some autonomous systems are part of safety-critical networks, for instance in aircraft navigation aids or telecommunication systems. In these cases, it is permitted to lose power to the loads only one day in 10 years, and the system design must guarantee this very low loss-of-load probability (LOLP). Even if there were long-run, accurate solar data for the site, it must be remembered that the stochastic variability of solar irradiance is such that past data are only an average predictor for the future, and once in 10 year events are not predictable (Lorenzo and Narvarte, 2000). It is always possible to oversize the PV array and battery to give such a LOLP in an average 10 year period, at a high cost, but even then there is no guarantee that a 1-in-100 year low or worse will not occur in the first year of operation. The cost-effective solution is to include additional charging from a small internal combustion engine, usually a diesel, with a fuel store large enough to need refilling only on visits to the site for periodic maintenance of the electronic systems. The PV array and battery system are sized so that the engine is run at full power for about 1 hour/day, to keep it in good condition.

The third major category of RAPS provides power for a local network, on a farm or for a small community. The PV array is sized to provide the daytime load with some battery charging, with an internal combustion engine, run intermittently, to maintain battery charge for night-time loads. On sites with a good wind regime, a wind generator can also be used. Where the wind generation and solar generation are not coincident in time, the triple hybrid can be the most cost-effective solution. Depending on the wind and solar resources at the site and the load/duration curve, either a wind/diesel or solar/diesel can be the optimum solution, so it is important not to overlook alternative solutions.

The PV/diesel hybrid system is used in many parts of the world as an alternative to grid extension. In Australia, farms and small communities in the outback are supplied with a RAPS system in a standard container unit. All parts are transported in the container, which, on location, becomes the base for the system. The PV array is mounted on the roof, with the diesel engine, batteries and all power conditioning and controls mounted inside the container. The daytime load is supplied by the PV system, with the diesel engine as a back-up charger for the supply of night-time loads. The diesel engine is run at full power for at least one hour per day, to maintain it in good condition without excessive use of fuel. The fuel tank is sized so as to need refilling only at long intervals, so reducing the transport cost of the fuel.

It is usual in these systems for the daytime load to be supplied direct from the PV array, through the inverter to the load. This avoids routing power through the battery, with its consequent losses. Daytime charging of the battery occurs whenever PV output exceeds demand. The PV array is sized to meet the daytime load, usually in the worst-case scenario. The battery is sized to give 1 or 2 days of autonomy and the diesel is sized so as to charge the battery at C/5 or C/10 rates of charge.

In a situation where fuel and maintenance are readily available, an autonomous diesel engine will generate electricity more cheaply than an autonomous PV system. Only where fuel and/or maintenance costs are high will the use of PV become cost-effective. This is frequently the case for navaid or telecommunication systems, which are often located in remote sites, accessible only by helicopter. Fuel and maintenance costs can then be very high and a PV/diesel hybrid is the most cost-effective solution. Refuelling and diesel maintenance takes place during the scheduled maintenance visits for the electronics and is therefore at marginal cost. The larger PV/hybrid systems are replacements for grid extension. At remote sites with small loads far from the existing grid, it is cheaper to install a PV/diesel system than extend the grid. Fuel transport costs and uncertain maintenance make a hybrid system more attractive than a straight diesel system and this will increasingly be the case as PV costs fall.

Remote area power supplies make use of the fact that sunlight is freely distributed to all sites, however remote (at least in the sunbelt). The challenge in system design is to match the power output to the load as far as possible, and maintain a very high availability for safety-critical systems, whist keeping costs as low as possible. Storage is essential for any system that has a night-time load, and while battery storage remains expensive it will be cheaper for systems over $500W_p$ or so to include a diesel engine.

Building-integrated photovoltaic (BIPV) systems

One of the fastest growing sectors of the photovoltaic market is the building integrated photovoltaic system. This is an ideal application for the use of photovoltaics in an urban environment and takes advantage of the distributed nature of sunlight and of the electrical load. The benefits of the BIPV system can be summarised as follows:

(a) in common with other PV systems and most renewable energy technologies, it has a lower environmental impact than production of electricity from conventional fuels;
(b) the electricity is generated at the point of use, so reducing the impacts and costs of distribution;
(c) there is a possibility of offsetting some of the cost of the PV array by the amount which would have been paid for the building material it has replaced;
(d) the system does not require additional land area, since building surfaces are used to accommodate the array.

The PV modules can be integrated in several different ways, for example to replace roofing tiles, in place of façade material or as sunshades. Figure 15.11 shows an example of façade integration, but there are many different ways of including the PV array in the building design.

The principle of the technical system design is similar to that for other PV applications, but there are some additional aspects to be taken into account. In contrast to the RAPS systems described in the previous section, the BIPV system is rarely sized to meet a particular load but often contributes to the electricity requirement of the building as a whole. It may be designed to match the general load profile or to provide higher output levels when, for instance, air conditioning is required, but it does not need to be an autonomous system since most of the buildings also have a grid supply.

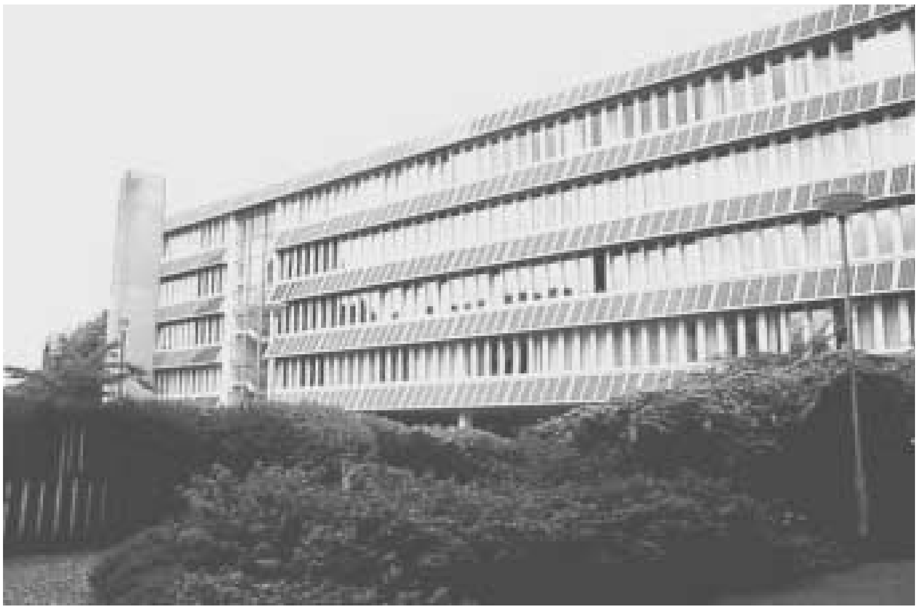

Figure 15.11 Example of facade integration of photovoltaics. The photograph shows the 40 kWp PV façade on Northumberland Building at the University of Northumbria. The PV array is integrated into the rainscreen overcladding. This system was installed in 1994 and is one of the early examples of façade integration (photograph courtesy of University of Northumbria).

However, the area available for the BIPV array may be constrained by building design, shading from surrounding structures or owner preference. Thus, the system size is often dictated by the nature of the building rather than its electrical loads. The visual aspect of the system is also important and this often affects the choice of module type, location and detailed integration method. Finally, the system design must take into account ease of installation, maintenance and operation and compliance with building regulations.

A fully integrated BIPV array performs at least two tasks, the generation of electricity for use in the building and the protective functions of the external building element, but arrays can also be designed to perform additional functions. The most common function is shading, by louvre systems on the exterior of the building, by designing the cladding so as to provide shading to the windows at high Sun positions or by the use of semitransparent PV elements for a roof or façade, where the cells provide the shading. Figure 15.12 shows an example of the use of semitransparent

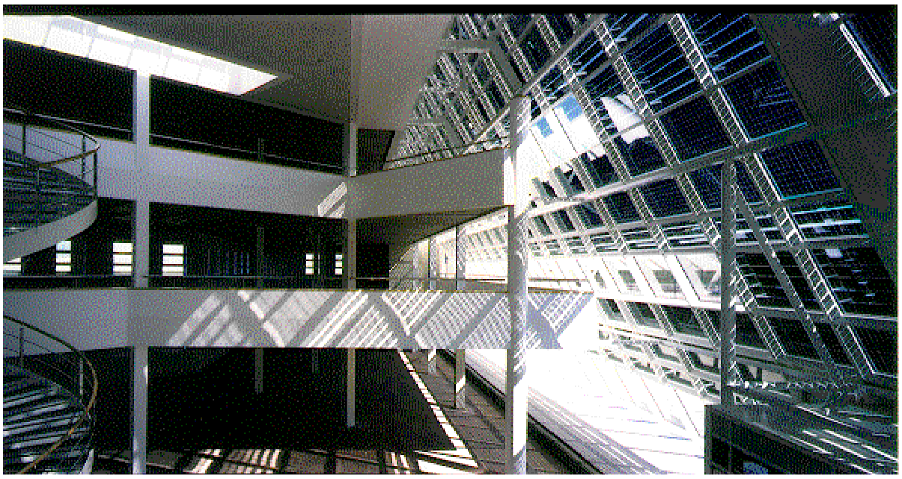

Figure 15.12 Example of the use of photovoltaic modules to influence indoor lighting patterns. The Solar Office at the Doxford International Business Park in Sunderland, UK, has a 73 kWp array formed from semi-transparent PV modules. The cell spacing is varied to create the light effects in the inner atrium (photograph courtesy of Akeler Developments Ltd.).

modules in a glazed façade, where the cells provide both visual stimulation by variation of the arrangement pattern and shading to reduce solar gain and glare.

The heat at the rear of the modules can also be used in some cases. Even in the most efficient modules, only about 15% of the light falling on the module is turned into electricity and, whilst a few percent is reflected, the rest is absorbed as heat. This results in a module operating temperature that can be 25–50 C above ambient temperature. Reducing the operating temperature by removing some of the heat is advantageous in terms of increasing system efficiency and a double benefit can be obtained if the heat is useful for another purpose.

Because of the rather large area of the module and the relatively modest temperature differential between the module and ambient temperatures, it is not usually cost effective to use forced air or fluid flow to extract the heat unless there is a direct use for that heated air or fluid. However, the heat can be used to assist natural ventilation within the building by taking in cold air at the bottom of the building. As this air is heated behind the PV façade, it rises and pulls in more cold air to replace it. Examples of such ventilation systems include the Doxford Solar Office in the UK (Lloyd Jones *et al.*, 1998) and the Mataró Library in Spain (Lloret *et al.*, 1997).

Even for a system where no use is made of the heat, care must be taken to ensure that the PV array operating temperature remains at an acceptable level. For most stand-alone systems, there is free air movement around the array and so some cooling is effected. This is not the case for a BIPV system which forms part of the building fabric. The design must include adequate ventilation around the modules if significant losses in efficiency are to be avoided.

Most BIPV systems are grid-connected, with the conventional electricity supply meeting any shortfall between the BIPV electrical output and the building demand. The system must conform to safety regulations for connection, as discussed previously. Arrangements can be made to sell back any excess production from the BIPV system to the electricity supply company. There is a wide range of tariffs offered for this electricity, ranging from the replacement generation cost (*i.e.* the cost for production of the same amount of electricity by the electricity company, not including distribution costs and overheads) to several times the normal electricity rate, where a scheme to promote BIPV exists (for more information, see Haas, 1998).

Despite the possibility of offsetting part of the cost of the system in respect of the building materials replaced, the electricity generated by a BIPV system still costs several times what conventional electricity would in most cases. Only where the BIPV system performs several important functions and/or replaces expensive cladding materials does the electricity cost become competitive. However, costs are predicted to fall with increasing market size, as discussed more extensively in the next section, and BIPV systems are expected to become widespread in urban areas over the next 20–30 years. They could contribute significantly to world energy supply before 2050.

Several countries (*e.g.* Germany, the Netherlands and the USA) have major promotion schemes for BIPV, stimulated by environmental concerns over global warming and pollution. Most of the current BIPV projects are for technical demonstration, but there are now some commercial projects based on the return expected from an enhanced environmental image and more energy-conscious approach to operation.

15.5 Costs of PV components and systems

The generation of electricity from PV systems is unlike that of other systems in that the cost of generation is only weakly dependent on the size of the system. This is a result of the modularity of PV systems, and such differences as do exist at present arise mainly from sales, installation and maintenance costs rather than hardware costs. These costs will fall as the throughput of PV systems in the supply, installation and maintenance chains increases with increased sales.

The manufacture of PV cells, modules and other components is, however, similar to that of any other product, in that mass production of identical units results in very significant reductions in unit cost. The PV industry is at a very early stage of its development at the present time. The total world market in 1999 was a little over 200 MW_p, which is tiny compared with that for conventional electricity generating plant or compared with the potential PV market within the next decade or two. The costs of PV modules and components have been reduced considerably over the past 20 years or so, both by technical advances and by the benefits of scale in production, but there are very significant further gains to be made, even if there were to be no substantial advance in PV technologies in the next 20 years.

The cost of manufacturing a PV module consists of the material, labour, capital and energy costs. The purchase price of a module is, of course, higher since it must also include marketing and sales costs, the profits to manufacturer and supplier and the costs of management, R&D and other overheads. The price of materials falls as they are purchased in tonnes rather than kilogrammes, whilst large-scale production uses machinery rather than labour, so that the labour costs/unit also fall. It is clear from similar industries that the price of equipment/unit output falls significantly as the throughput rises. The capital cost of equipment to make 1 million modules per year is much less than 10 times the cost of equipment to make 100,000 per year, the equipment would occupy much less than 10 times the space and it would use much less than 10 times the energy. It is also the case that large companies can borrow money more cheaply than small ones, so the capital repayments/unit of borrowing become smaller as the PV industry grows, further reducing the capital costs of manufacture.

There have been a number of calculations of the manufacturing cost as a function of annual output. Table 15.1 below shows the calculations of Hynes and Hill, up to 100 MW_p per annum (Hill, 1993) and the calculations of Bruton *et al.* for 500 MW_p per annum for wafer silicon and 60 MW_p per annum for thin film cells (Bruton *et al.*, 1997).

The overhead costs per unit also fall as the annual output increases so the price of a module falls with increasing scale of production, although not necessarily in a simple relationship to manufacturing cost. It is clear from Table 15.1 that wafer silicon modules can reach a cost of around $\$1/W_p$ in large-scale production. Most of the benefits of scale have been reached at an output of 100 MW_p per annum but the expansion to 500 MW_p per annum does bring further useful cost reductions. It is probable that replication of these plants and operational experience of the production processes could bring further reductions in manufacturing cost.

Table 15.1 The manufacturing cost of PV modules as a function of annual output

Cell material	**Module manufacturing cost (US$/W$_{p)}$**				
	1 MW$_p$	**10 MW$_p$**	**60 MW$_p$**	**100 MW$_p$**	**500 MW$_p$**
Single-crystal Si	4.7	2.2		1.4	1.0
Polycrystalline Si	4.7	1.9		1.2	
Thin-film materials	3.3	1.8	1.0	0.6	

The three thin film materials (amorphous silicon, cadmium telluride and copper indium diselenide) all have equal manufacturing costs within the accuracy of these calculations. The manufacture of thin film modules is more amenable to mass production than that of wafer silicon, since the integrally-interconnected module is the production unit, rather than individual wafers which must then be interconnected. There are already manufacturing plants, for coated-glass windows, for instance, which have an output of 1 million square metres per year. Some of these windows have more thin film layers than would be needed in a thin film PV module, so it is possible to make reasonably accurate predictions of the cost of production for such modules.

Table 15.1 shows that the benefits of scale in production are reached at lower annual output than for wafer silicon and that almost all of the benefits are reached at 100 MW$_p$ per annum. The lower material and energy usage and the reduced number of process steps give the thin film modules a cost advantage at most production volumes, provided that their efficiency is above 10% and the overall yield of the production processes is above 85%. This combination of criteria has been very difficult to achieve to date, but the learning curve for both suggests that they will be achieved in the reasonably near future. The basic problem is the achievement of sufficient uniformity across the entire module, but this is a problem of thin film deposition technology rather than some fundamental problem of device physics. It is therefore amenable to production engineering solutions and the “tweaking” of the deposition conditions.

Table 15.1 does not give costs for the thin polycrystalline silicon devices, which are being actively investigated at present and produced by at least one manufacturer. There are reports that these devices have been produced in research laboratories in the form of integrally-interconnected modules. If such modules can be produced with a high yield then they could give a product with the price of a thin film module and the efficiency of a wafer silicon module. There are at present insufficient details to allow any independent assessment of the probability of this being achieved.

The estimates of manufacturing cost given in Table 15.1 assume that production is at one plant, or at least at one site. No one plant is likely to produce the entire world output of PV modules, although the rise in the world market does lead to an increase in the size of production plant. An analysis of the growth of both the world market and the size of “state-of-the-art” production plant shows that the largest plants are designed for an output of about 10% of the likely world market when the plant is fully on stream.

At the present time, a ‘state-of-the-art’ plant is around 20 MW_p per year for a world market of around 200 MW_p per annum (1999). On this basis, it can be predicted that plant sizes of 100 MW_p per annum will be built when the world market approaches 1 GW_p per annum, whilst a 500 MW_p per annum plant will appear when the world market exceeds 5 GW_p per annum. Since almost all of the benefits of scale in production have been achieved at 500 MW_p per annum, it seems likely that further increases in the market would lead to replication of this size of plant in locations which minimise distribution costs. The PV industry is therefore at the very interesting stage where an increase in the market leads to falling production costs, whilst falling prices lead to an increase in the world market. The economic consequences of this benign cycle are dealt with by Anderson in Chapter 17 of this book, in his calculation of the economically efficient investments required to bring PV to commercial viability.

The cost of a PV system is the sum of the costs of the hardware (modules and BOS components), and the costs of transport, system design, installation and maintenance. The price paid by a customer also includes the mark-up of the wholesaler and retailer in many instances, and often must include taxes and duties. These mark-ups are very dependent on the throughput of systems and on competition and are likely to fall in the future.

As shown above, module costs can confidently be predicted to fall significantly as the scale of production rises. The costs of many of the BOS components are also subject to the same laws of production economics as those of the modules and large-scale production of identical units will lead to significant cost reductions. For some applications and some components, this is already happening, and is likely to continue. For charge controllers in Solar Home Systems, for instance, increasing the production to 1 million per annum would reduce their price significantly. However, the use of 2 million batteries in these Solar Home Systems would not add very significantly to the world battery market, and the price of storage will not be greatly reduced unless there is some technological change.

The non-hardware costs also have benefits of scale. The unit cost of transport is lower for a container load than for a small number of modules or systems. Spreading design costs over large numbers of systems reduces the cost to each system, whilst the installation and maintenance of many systems/year in one locality reduces the cost per system. The increasing market for PV systems will therefore lead to a reduction in all of the system costs, again giving a benign cycle.

One of the most interesting applications for PV is on buildings, where Building-Integrated PV (BIPV) systems can effectively result in no additional cost. When PV modules are integrated into the structure of a building, they have a dual function. They act as a building element, replacing a conventional roof or façade, as well as being a generator of electricity. On houses, the BIPV system replaces roof tiles, which are of relatively low cost. On commercial office buildings, however, the BIPV system replaces the cladding elements that ensure both the weather-tightness of the building and its physical appearance. Conventional cladding systems vary widely in cost, but for luxury cladding, such as polished stone, the cost can be over £1000/m^2 (US$ 1500/m^2). Where a BIPV system replaces such cladding, the cost of the building is lower with PV than with the polished stone, and the owner of the building gets electricity generation at no additional cost.

Property developers use expensive cladding for prestige, and companies buy or occupy such buildings to enhance their public image. With the increase in “green” awareness, a BIPV façade on a building can make a very significant public statement for the owners and occupiers of the building, and the image value can justify its classification as a luxury cladding. As the cost of PV modules falls, then BIPV systems can replace cheaper conventional cladding at zero additional cost, and the market for BIPV will expand greatly. The cost of electricity generated by a BIPV system is greatly influenced by the avoided cost of the conventional cladding that is replaced by the PV. Table 15.2 shows the cost of electricity from PV costing £2/W_p (US\$3/W_p) for a range of cladding under the assumptions specified.

It is clear from Table 15.2 that PV laminates costing £2/Wp and replacing conventional cladding costing £300/m^2 or more can generate electricity at a cost below the retail price from a utility. The electricity is a free by-product if the PV replaces cladding costing £350/m^2 or more. A modest insolation level, reasonable for UK facades, was chosen to demonstrate that the economic use of BIPV is not only possible for regions with high sunlight levels. Competitive electricity costs would be reached at higher module and/or BOS costs for locations with higher sunlight levels.

Table 15.2 The cost of electricity generated by a BIPV system for a range of cladding costs

Laminate cost £/m^2	**Cladding cost £/m^2**	**Net PV cost Laminate–Cladding £/m^2**	**£/W$_p$**	**System cost Net PV + BOS £/W$_p$**	**Electricity cost p/kWh**
280	100	180	1.3	1.8	27
280	150	130	0.9	1.4	22
280	200	80	0.6	1.1	18
280	250	30	0.2	0.7	10
280	300	–20	–0.14	0.36	5
280	350	–70	–0.5	0	0

Assumptions: PV laminates: efficiency 14% cost £2/W$_p$; BOS costs £0.5/W$_p$; insolation 700 kWh m^{-2} yr^{-1}; discount rate 8%; lifetime 30 years.

Two of the assumptions made in the calculations in Table 15.2 are quite challenging for the PV industry. The PV laminates for BIPV are not usually the standard laminate, but are often of glass/glass construction and frequently of non-standard sizes, to fit in with the architectural design. They are not usually manufactured in large quantities and at present are typically 2–3 times the cost of standard laminates. If the BIPV laminates are made from silicon wafers, then this part of the cost will benefit from the world scale of manufacture, and the growth of the BIPV systems market will provide some benefits of scale to the manufacture of the BIPV laminates. The production of thin film laminates at the sizes required for the BIPV market could give low costs in terms of £/m^2, although probably with a reduced power output from a given facade.

The second challenge is to reduce BOS costs to £0.5/W$_p$. The development of module inverters, which could be made in millions, is a major step forward, and both reduces wiring costs and increases the annual output of arrays that are not simple planar, unshaded structures. There is a pressing need for a major concerted research and development effort in BOS components. However, it is clear from calculations similar to those in Table 15.2 that, even today, when BIPV laminates cost £4/W$_p$ and BOS costs are £2/W$_p$, there is a range of conventional claddings whose cost is equal to or greater than the BIPV system cost and whose replacement by PV would give electricity as a free by-product. In these niche markets, PV is cost-effective now and this should be the target of a campaign of education and demonstration to architects, property developers and all others in the building industry.

15.6 Conclusions

PV cells have social and commercial value only when they are used in a system to provide a service. This chapter has given a brief overview of the technical and economic considerations that allow the cells to provide such a service.

PV cells may be incorporated directly into a product, for example in solar calculators, and add value to that product to the extent that their use is commercially viable. In most cases, the cells are contained in a PV module, interconnected to give an output which is directly usable, for battery charging for example, and protected against damage. The PV module is the standard commercial product from which PV systems are built. This chapter has described the construction of PV modules and their quality assurance testing, which has resulted in a product with an assured output, reliability and lifetime when operating in all of the world's varied climatic conditions. It is these developments in module performance that have provided the basis for the expanding market for PV throughout the world.

A PV module is an electricity generator and requires additional equipment if it is to provide a useful service. This chapter has also discussed the range of other equipment needed in PV systems to provide the various services required by users. These include the electronics needed to give optimal operation in small DC systems, large AC systems and hybrid systems for safety-critical operations. In this book, it is possible to give only a brief overview of the equipment and its design criteria, but detailed discussions can be found in the proceedings of the regular international photovoltaics conferences and in other books devoted to system design (for example, Sick and Erge, 1996).

This chapter has also discussed the economics of PV module production and application, particularly in building-integrated PV systems. It is well known that PV is cost-effective in remote locations. It is much less well understood that there are segments of the commercial building market where PV façades are already commercially viable and provide an opportunity for the PV industry. The sectors of the building industry must be alerted to this fact, through demonstrations and education, but first the PV industry itself needs to become fully aware of the opportunities within these niche markets.

It is clear from the discussions in this chapter that PV is in the midst of benign cycles, where increased sales lead to larger scale production, which leads to lower costs, which leads to increased sales. The targets for low-cost production can be met almost entirely by this increasing scale of production, which follows from increased sales. Technological improvements in the solar cells are an additional bonus, although much remains to be done in bringing laboratory-scale performance to commercial production, and the potential for fundamental improvements is significant, as discussed in many other chapters of this book.

Photovoltaics has the potential to become a major electricity generation technology in the next few decades. It will fulfil this potential only if it is recognised that technical success with cells or modules is a necessary but not sufficient criterion for commercial success. It is the PV systems that provide the services for which users will pay, and these must be designed and implemented to the same level of quality and performance as the modules themselves. Whilst the ways to achieve this are known, they are not always carried out in practice and the development of standards for component quality, system design and installation method is addressing some of these problems. Another crucial area is in marketing and the PV industry will have come of age when the PV community pays as much attention to this aspect of the business as it presently does to the technology.

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