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ENVIRONMENT DESIGN GUIDE

PHOTOVOLTAIC CELLS – HOW THEY WORK

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Photovoltaic, or solar, cells are devices that convert the energy of sunlight directly into electricity, with little environmental impact. Since they have no moving parts and use no fuel, photovoltaic cells are highly reliable and have very low maintenance requirements. Initially, their use was largely confined to satellite and remote-area applications, but new technologies and lower costs have opened up markets for urban application, providing power for lights, street signs and buildings, as well as for large-scale power stations. This paper provides background information on the design, operation and characteristics of photovoltaic cells.

Keywords:
crystalline cells, photovoltaics, renewable energy, solar cells

Figure 1 The Olmedilla Photovoltaic Park in Olmedilla de Alarcón, Spain, is one of the world's largest photovoltaic plant.

(Image: Nobesol and Siliken)

1.0 INTRODUCTION

Photovoltaic, or solar, cells are devices that convert the energy of sunlight directly into electricity. Quantum-mechanical interactions between sunlight and current-carrying electrons in the cell's semiconductor material generate electric current in a process known as the 'photovoltaic effect'. This electricity can then be stored in batteries or used directly to power electrical equipment which uses Direct Current (DC), or it can be passed through an inverter and used like grid power for normal Alternating Current (AC) equipment.

Early photovoltaic (PV) cells, developed in the 1950s, were used primarily for satellite applications. They were costly and had low efficiencies. By the 1970s PV cell development had reduced costs and increased efficiencies sufficiently for terrestrial applications to begin. During the 1970s and 1980s these were largely confined to remote-area applications, such as telecommunication links, isolated household power supplies and water pumping. In these applications, the relatively high cost of PV was compensated with high reliability and low maintenance requirements, compared with options such as diesel generators or windmills (Wenham et al. 2006). Over the last decade, PV has been increasingly used in urban areas and one of the fastest growing markets for the technology is now grid-connected PV systems installed on buildings (PVPS 2010).

The worldwide market for PV has been growing rapidly from a rate of 15 to 20 per cent per year in the 1990s to over 100 per cent in 2008. Installations are now over seven gigawatts (GW) per year (EPIA 2010). Japan, USA, Europe, China, Korea and other jurisdictions have all set high targets for PV use, which will see continued growth in demand, the development of new markets, the emergence of new technologies and PV costs reaching 'grid parity' (PVPS 2010). These developments will transform the PV industry and provide new opportunities for energy supply and building design.

Key Point

Technological advances, along with pressure from government bodies responding to environmental concerns, should rapidly increase the product range, cost competitiveness and application of photovoltaics over the coming decade.

2.0 HOW SOLAR CELLS WORK – THE PHOTOVOLTAIC EFFECT

PV cells are made from semiconductor materials such as silicon, which act as insulators at low temperatures and as conductors when heat or energy is available. Semiconductors form the basis of the electronics industry and are used for microprocessors, like those found in personal computers. The 'photovoltaic effect' is a specific response whereby an electric current is produced when the semiconductor material is exposed to light. For instance, the energy contained in photons of light falling on silicon material is transferred to the negatively charged electrons within the silicon, allowing them to move away from the silicon atom, leaving it with a 'hole' or a positive charge. Normally, the free electrons would soon lose their energy as heat and return to a silicon atom. Hence, to be able to use this light induced current, a mechanism is needed to direct the free electrons and form a continuous flow or current of electricity (Wenham et al. 2006).

Modern photovoltaic cells are manufactured with advanced materials to increase their efficiency. Semiconductors can be treated or 'doped' with small quantities of other atoms to form 'p-type' material, with an excess of holes, or negative or 'n-type' material with an excess of electrons. For silicon cells, the most common dopant for 'n-type' material is phosphorous, and for 'p-type', boron. A p-n junction is made by placing 'p-type' material against 'n-type' material, creating an electric field at the junction. When light falls on the cell, the electric field separates the electrons from the holes, creating an electric potential (or voltage) between the p-type and n-type materials. If metallic contacts are placed either side of the composite material to form an electrical circuit, an electric current can be drawn away from the cell in the same way as it can from a battery (Wenham et al. 2006). This current will continue to flow as long as light continues to fall on the cell, as shown in Figure 2.

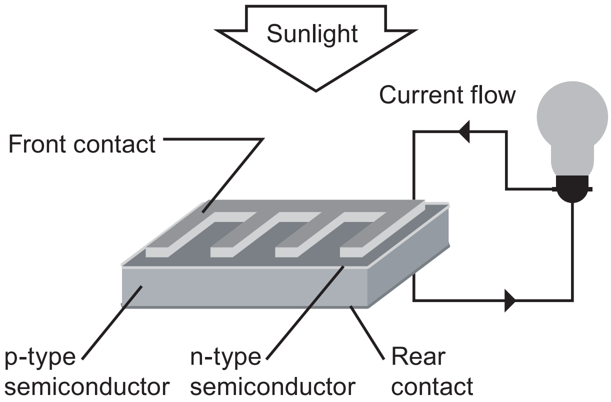


Figure 2 Operation of a typical crystalline photovoltaic cell

2.1 Photovoltaic Modules

In order to achieve useful voltages and currents, individual PV cells are connected together into PV modules of different sizes and shapes. Modules form the building blocks for PV systems and range in size from a square millimetre to over 4 m², depending on the end-use application. The most common modules are around 1 m².

Since individual silicon cells produce around 600 millivolts (mV), cells are connected in series to produce the desired voltage. For instance, for a 12 V battery charging system, 36 cells are typically used. Similarly, under peak sunlight 100 milliwatt (mW/cm²) cells produce around 30 milliamperes (mA/cm²) and so are connected in parallel to reach the desired current (Wenham et al 2006).

Because each individual cell is connected in series, the current output of a module is limited by the current output of the lowest performing cell and hence it is important to match cell characteristics when placing them in a module. Similarly, when connecting an array of modules to an inverter, the overall output will be limited by the lowest performing module. For this reason, it is important to make sure that sections of a module or an array are not performing poorly, due to breakage or shading, as their performance will limit the overall system performance (Wenham et al. 2006).

Most modules have some bypass diodes to limit the impacts of poorly performing cells, while a good system designer will predict shadowing and other mitigating factors and wire modules accordingly with bypass diodes or use dummy modules to optimise array output (Gaiddon et al. 2009).

Key Point

The performance of a solar array is limited by the performance of the poorest performing module. In designing arrays, care needs to be taken to ensure the array is well constructed, has uniform solar access or is appropriately wired to minimise the effects of partial shading.

Figure 3 Surfaces incorporating PV cells can provide shade while generating electricity.

(Image: courtesy DOE/NREL)

Corrosion of electrical contacts is one of the causes of module failure. Early modules were made by sandwiching cells between sheets of glass which served to protect the cells from moisture and breakage, while also being an electrical insulator. Most modules now use a glass front cover with a polymer rear (such as a polyvinyl fluoride sheet). This is cheaper to produce and results in lighter modules. If partial light transmission is required, such as for atria or windows, double glass modules may still be preferred (Prasad and Snow 2002). The opaque crystalline cells are spaced apart when they are encapsulated, to allow the desired light level, as shown in Figure 3.

Aluminium module frames are common in stand-alone arrays to provide rigidity and support, with aluminium being a lightweight and corrosion-resistant material. However, modules used in building applications typically are butted together without individual frames (Prasad and Snow 2002).

2.2 AC or DC?

The power output from a PV cell is in the form of direct current (DC) and is often used to charge battery banks. Many small appliances, for instance those you would normally run off a battery, use DC electricity at 12 V. However, grid electricity in Australia is supplied as alternating current (AC) at 240 V. For ease of use in household applications, or for grid inter-connection, the PV output must be converted from low-voltage DC to the higher AC voltage via an inverter. PV power supplied through an appropriate inverter can be used in the same way as grid electricity, for any standard electrical appliances. Australian Standards AS4777 Grid Connection of Energy Systems via Inverters and AS/NZS5033 Installation of Photovoltaic (PV) Arrays must be followed when installing and connecting a PV system to the electricity grid. Once connected, the PV system owner can use power from the PV system when it is operating, or from the grid when there is no sun. They can also send electricity in excess of their needs back into the grid for others to use.

2.3 Impacts Associated with Cell Manufacture

While in operation, PV arrays have little environmental impact, however their manufacture does usually involve the use of fossil fuels, and therefore associated embodied greenhouse gas emissions. The direct and indirect energy used in the manufacture of the most common PV modules typically results in an energy 'payback period' (i.e. the period of operation required before the output of the cell exceeds the energy required to manufacture it) of less than two years (de Wild-Scholten 2009). The energy payback time and the greenhouse impacts depend of course on the production process, the encapsulation (encasement) and framing used (virgin aluminium has very high embodied energy) and the end-use location. However most PV modules operate for 20 to 30 years, so over their lifetime they can produce 10 to 30 times the energy used in their manufacture (Richards and Watt 2007). A kWh of electricity from a PV system will typically have a greenhouse gas impact less than three per cent of that for a kWh of Australian coal-generated electricity (based on de Wild-Scholten 2009).

In addition, new silicon-cell production techniques and new thin-film products are continuing to reduce energy requirements, while PV manufacturers are increasingly installing PV on their factory roofs, so that the fossil fuel and thus embodied carbon in PV products is decreasing.

In addition to minimising carbon dioxide emissions due to fossil fuel use, there have been recommendations for the reduced use of other greenhouse gases, such as SF6, which is used in some thin film processes.

PV manufacture requires the extraction and provision of the raw materials used in their construction. The environmental impact associated with cell manufacture is therefore dependent on the materials used, as well as impacts associated with processes of converting these materials into PV cells. A number of different semiconductor materials can be used to make PV cells including silicon, gallium arsenide, cadmium telluride and copper indium di-selinde. Standard chemical handling codes, including procedures for emergency release of dangerous chemicals, combined with efficient recovery and recycling of waste materials are required to ensure there is little or no health or environmental impacts from the manufacture and use of PV cells. See for instance IEA-PVPS Task 12: PV Environmental Health and Safety (www.iea-pvps-task12.org).

Laws in many countries stipulate the safe disposal of PV modules containing toxic materials, such as cadmium, and require the provision for recovery of used modules. For cadmium telluride modules, recovery and recycling practices are being arranged by the manufacturers (First Solar 2010). Silicon is not a toxic material and requires no special disposal methods. Nevertheless, the PV industry is developing a recycling system for all PV modules (PV Cycle 2009).

2.4 Photovoltaic Cell Efficiencies

The most important determinant of the power output from a PV cell is the amount of sunlight it receives. The efficiency with which a PV cell can use the energy in sunlight is affected by a number of factors, some of which are determined by the characteristics of the cell material, others by ambient conditions, such as temperature and humidity levels, and others by the cell design (Wenham et al. 2006).

The efficiency of PV cells has increased significantly over the past decades, as shown in Figure 4. For silicon cells since the 1950s, laboratory efficiencies are up by 24 per cent and commercial efficiencies are up by 19 per cent in the conversion of solar radiation to electrical energy. In operation, these figures can drop by five to 10 per cent with higher operating temperatures and the build up of dirt on the surface of the array (Wenham et al. 2006). Although not normally required, in particularly polluted inner urban or dusty rural conditions, where natural rainfall cannot be expected to wash the modules, arrays may require periodic cleaning.

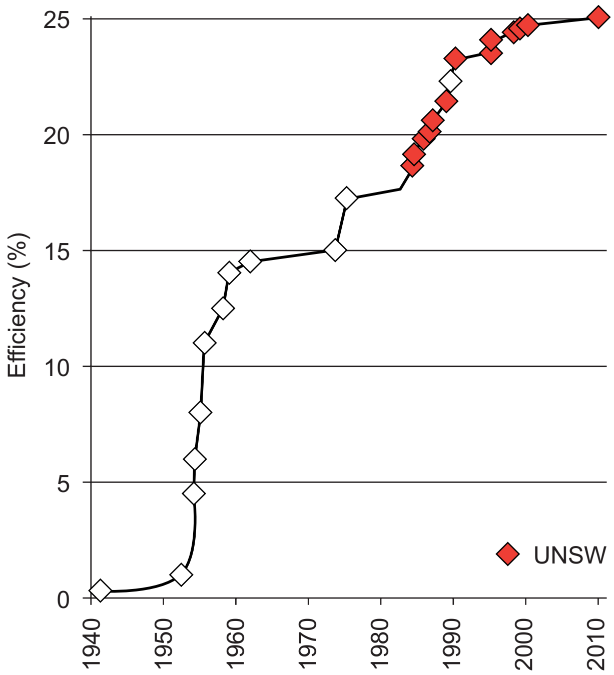


Figure 4 Trend in silicon cell efficiencies

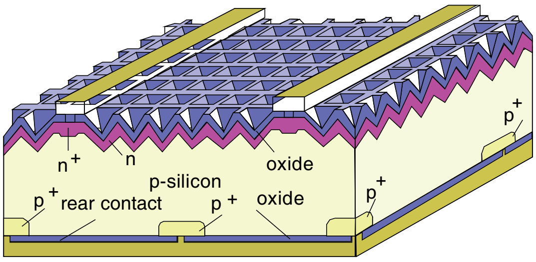
(Source: Prof. Martin Green, ARC Photovoltaics Centre of Excellence, UNSW)

2.5 Semiconductor Material

The electrons in different semiconductor materials differ in the amount of energy required to release them from their host atom, referred to as their band gap energy. Although silicon is the most common solar cell material, its band gap of 1.1 electron volts (eV) is lower than the 1.4 to 1.6 eV required for the most efficient use of the energy available in the solar spectrum. Other cell types, including gallium arsenide, with a band gap of 1.4 eV and copper sulfide, 1.2 eV, are closer to the optimum (Green 1992). Many PV cell types use a number of layers of different materials to increase efficiency by capturing energy from a broader spectral band.

2.6 Operating Temperature

The performance of a PV cell is affected by its operating temperature. Operating temperature is determined by the ambient temperature, as well as by the thermal performance of the PV module housing (Green 1992). As most cells are less than 20 per cent efficient, some of the remaining energy and light is converted to heat, and thus modules usually operate at higher than ambient temperature. This can sometimes be up to 50°C higher, causing significant reductions in the power output of the PV system. The power output of a crystalline silicon cell in full sunshine drops by 0.4



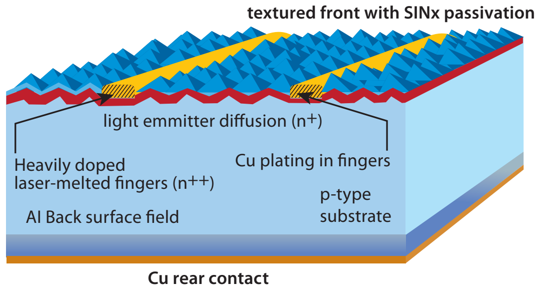


Figure 5 Two 'first-generation' crystalline silicon solar cells: left, UNSW world record holding passivated emitter, rear locally diffused (PERL) cell with inverted pyramids and surface mounted contacts; right, laser doped selective emitter (LDSE) cell with surface passivation and laser melted fingers

(Source: ARC Photovoltaics Centre of Excellence, UNSW)

to 0.5 per cent for every degree C increase in operating temperature over 25°C (Green 1992). Other cell types, such as amorphous silicon, are not as temperature sensitive.

For PV use in buildings, minimising operating temperature is an important design issue, since the rear of the PV array may not be naturally ventilated (Wenham et al. 2006). For PV used as a roof element, the typically high temperatures in the roof cavity can reduce output, as well as placing stress on PV system components (Prasad and Snow 2002).

Key Point

PV arrays using crystalline silicon cells become less efficient upon heating, therefore consideration needs to be given to venting excess heat from array housings when designing PV installations. Elevating panels off surfaces by 50 to 70 mm to allow for air movement can alleviate this, though it can create potential nuisance from birds and other pests, as well as potentially increased wind loading.

2.7 Cell Structure

There are many ways of constructing a PV cell which impact on its efficiency. The blue colouring of most solar cells is due to an antireflection coating on the top of the cell, usually a nitride. This increases the amount of light absorbed into the cell, and hence available for use (Wenham et al. 2006). The increasing market for PV in buildings has led to an interest in the development of cells of different colours. A wide range of colours is possible, but performance is typically lower than for conventional blue cells.

Light absorption can also be increased by texturing the cell surface. Texturing silicon results in pyramid or inverted pyramid surfaces, maximising the potential for absorption of reflected rays of light (Wenham et al. 2006). Cell structures developed at the University of NSW now produce some of the most efficient commercial silicon cells worldwide. Figure 5 shows some of the latest cell structures.

3.0 PHOTOVOLTAIC CELL TYPES

There are a range of PV technologies falling under the general classifications of crystalline silicon, or thin-film, cells.

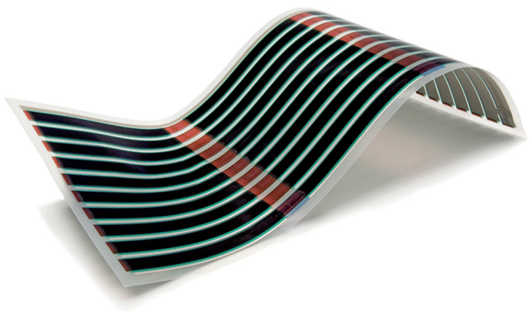
3.1 First-Generation Cells

Crystalline silicon cells currently account for around 80 per cent of the world PV market and dominate the power module market. They are considered the 'first generation' of PV cells. In 2009, 38 per cent of cells were made from single crystal silicon (Hirshman 2009). These large crystals are pulled from a silicon melt and sliced into wafers which can be as thin as 120 micrometres (m) wide (Corkish 2006). The high purity results in few cell defects and hence relatively high efficiencies (typically around 15 per cent, but up to 19 per cent for commercial cells). Lower-cost multi or polycrystalline silicon cells are sliced into wafers from a cast of silicon crystals (Corkish 2006). The multiple crystal boundaries lower cell efficiencies (typically to around 13 per cent). Crystalline silicon cells and modules are highly stable and can last 25 years or more. A drawback with crystalline silicon cells is that their power output in full sunshine begins to drop with operating temperatures over 25°C.

3.2 Second-Generation Cells

Thin film cells are formed by depositing a thin layer of semi-conductor material onto a substrate. They are referred to as 'second-generation' cells. While the manufacturing costs can be significantly lower, this is offset by the reduction in cell efficiency, and hence the increase in area required to achieve the same output. They also tend to have a shorter lifespan.

Cadmium Telluride cells made up nine per cent of the world's PV market in 2009 (Hirshman 2009) and are used in many larger-scale PV power plants. Amorphous silicon cells are available in power modules, but dominate the consumer product market in watches,



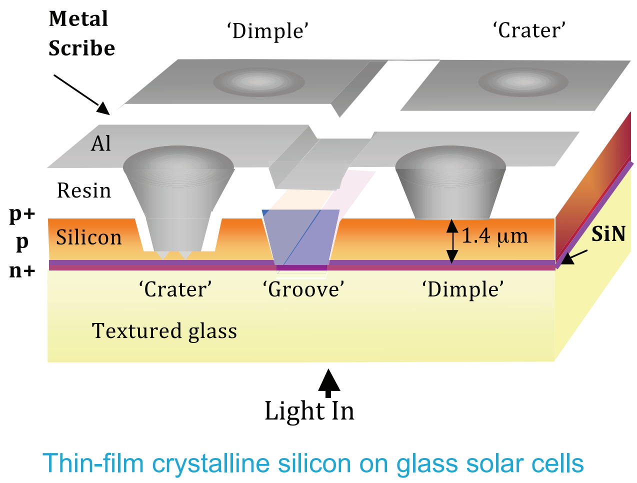


Figure 6 'Second-generation' solar cells use thin layers of photoactive layers bonded to a substrate which can be glass, plastic or metal. Left, Konarka Power Plastic; right, Crystalline Silicon on Glass (CSG)

(Images: Power Plastic, courtesy DOE/NREL; CSG, ARC Photovoltaics Centre of Excellence, UNSW)

calculators, torches and other devices. An example of a flexible thin film module and a thin film cell schematic is shown in Figure 6.

3.3 Third-Generation Cells

The silicon wafers used in crystalline cells account for a large portion of the PV system cost. Hence, reducing material requirements by adopting thin-film technologies offers potentially large cost reductions and is the focus of much of the current PV research and development (IEA 2010). Over the last few years, a number of large thin-film facilities have commenced production. They include improved amorphous silicon cells, thin-film crystalline cells and cadmium telluride cells (Hirshman, 2009). However wafer based cells are likely to continue to dominate the PV market for at least the next decade, particularly in applications where reliability and long life are critical factors.

In the longer term, a range of new materials and technologies are expected to provide low cost 'third-generation' PV products. Some of these, such as nano silicon cells (Figure 7), aim to combine the high efficiencies of crystalline products with the low manufacturing cost of thin films. Others, such as organic cells, use entirely different processes and may form the basis of very low-cost PV products, even if efficiencies remain relatively low. These technologies may compete with the 'power modules' of generation 1 and 2, described above, or provide a new range of PV applications built into consumer products, clothing or building materials and replacing batteries in a wide range of appliances. Hence, the emphasis may be on integration, aesthetics and low cost more than on efficiency and long life. The IEA (IEA 2008) expects third-generation PV to account for a third of the market by 2030 and a half by 2050.

4.0 THE AUSTRALIAN PHOTOVOLTAIC MARKET

Photovoltaic cells and systems have a wide variety of applications, including satellites, navigation beacons, microwave repeater stations, cathodic protection, electric fences, lighting, watches, vaccine refrigerators, water pumps and purifiers, electric vehicles, off-grid domestic and community power supplies and grid-connected buildings and power stations.

In Australia, telecommunication applications such as microwave repeater stations, remote telephones, navigation aids and signalling systems have provided the largest PV market over the past three decades (Watt and Wyder 2010). Remote household power supplies and water pumping markets have developed rapidly over the last decade. PV is a cost-effective power supply option in these off-grid markets.

A new market in grid connected PV systems is now emerging (Watt and Wyder 2010). The two grid-connected applications of most interest at present are for central-generating power stations and building-integrated systems. The market for grid applications has now overtaken the off-grid market and is the fastest growing sector. Total installed capacity is over 180 MW and is expected to be over 2 GW by 2020 (Watt 2010).

4.1 Remote-Area Power Supply Systems

The high capital and maintenance costs of grid extensions to remote households and communities means that off-grid remote-area power supply (RAPS) systems are a cost-effective option in many areas of Australia.

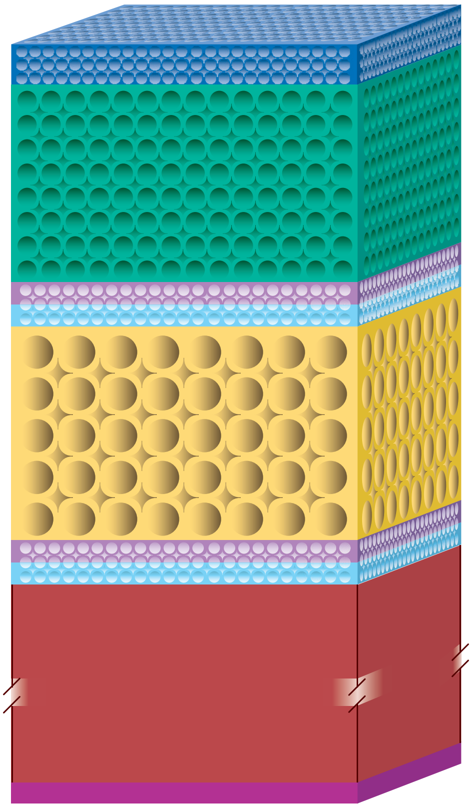


Figure 7 'Third-generation' solar cells aim to provide the high efficiency of crystalline cells and the lower material cost of thin films. In this schematic, cells of different bandgaps controlled by quantum dot size are stacked on top of a third cell made of bulk silicon.

(ARC Photovoltaics Centre of Excellence, Uni of NSW)

The development over the last 20 years of sine-wave inverters, which produce grid-equivalent AC power in the relatively small size range (2 to 20 kW) typically needed for these applications, has led to a rapid development of this market. Power supply quality can now be equivalent to grid supply, while reliability in remote areas is often higher (Wenham et al. 2006). Complete systems can be purchased from PV distributors and from some electricity utilities. Most modern RAPS systems use one or more energy sources to provide power to battery banks or directly to the source of electrical demand. AC power is provided to the demand from the battery bank via an inverter. Photovoltaic arrays and diesel generators are the most common energy sources for RAPS, with micro-hydro systems and wind generators used where conditions are suitable. PV systems are also widely used without inverters for DC applications such as water pumping, remote telecommunications and navigation aids (Wenham et al. 2006).

Standard consumer electrical appliances can be used with RAPS, although to maximise cost effectiveness an emphasis is always placed on minimising electrical loads and using energy-efficient appliances. It can also be useful to schedule the use of large appliances, either to even out the load or to coincide with diesel generator operating times (Wenham et al. 2006). Load management can be undertaken automatically by a RAPS control system.

The size of the PV arrays used in RAPS systems vary, but are typically around 2 to 5 kW for a household system. This can be added to over time, to gradually reduce diesel usage. The array can be placed on a roof, if the orientation is suitable, or on a ground-mounted frame. Some systems allow manual or automatic tracking to maximise solar exposure, which is best perpendicular to the panel face. Tracking the daily sun movement from east to west is one option, while north-south tracking or seasonal adjustment of the array is also possible (Siemer 2008). A dual-axis tracker will do both, which can increase an array's output by around 30 per cent.

4.2 Grid-Connected PV Systems

Grid supplied electricity can be supplemented or displaced by the inter-connection of a PV array with the consumer mains. The array can be independently sited, installed on top of an existing roof or used in place of a section of the roof, wall, window or skylight of a building (Prasad and Snow 2002). The only system components needed are the PV array, an inverter and meters which measure grid-supplied power and on-site power generated by the PV array. The latter can be used on-site or fed back into the grid. The grid acts as a battery bank, taking up power produced by the PV array which is excess to the owner's needs, or supplying power when the PV output is not sufficient to meet the load. However in developing countries, or other areas where grid power is unreliable, a battery bank may be added.

For urban use, installation of PV on buildings has the advantage of using a renewable energy source with no extra space requirements, no on-site noise or fumes and the potential to enhance the visual impact of the building. The market for building integrated PV is growing rapidly in Europe, Japan and the US, with many specific products now available (Gaiddon et al. 2009). In Australia, the first large-scale application of PV on buildings was at the suburb used as the Athletes Village for the 2000 Olympic Games, where over 600 houses where fitted with 1 kW PV rooftop systems (Gaiddon et al. 2009). Other large-scale projects in Australia to date include the 1.2 MW system planned for the University of Queensland's St. Lucia campus, the 305 kW system on the roof of the Crowne Plaza in Alice Springs (Watt 2009), and the 1 MW system on the roof of the Adelaide showgrounds, which is shown in Figure 8.

5.0 INNOVATION

Solar car races over the past decade have captured the imagination of the public and provided a high-profile showcase for some of the world's highest efficiency PV cells, including those made in Australia by the University of NSW. In Australia, the bi-annual Darwin to Adelaide race of 3000 km (World Solar Challenge) has been run since 1987 (Roche et al. 1997) and now

Figure 8 1 MW roof-mounted PV system at Adelaide Showgrounds, using cadmium telluride solar cells
(Image: First Solar)

sees entries from around the world and cars reaching average speeds over 100 km per hour (Global Green Challenge 2010).

In addition to stimulating the development of increasingly efficient PV cells, the car races have facilitated the development of innovative electric vehicle concepts, including improved batteries, motors and car designs. Many of these developments are now being applied in the rapidly developing electric vehicle market, which is itself being driven by expected oil supply constraints and the demand for zero-emission vehicles in urban areas (Better Place 2010 and Boyle 2009). In more conventional vehicles, particularly for off-road use, PV is used as a DC power source for fans or other appliances.

Other innovative uses of PV which are under development or already appearing on the market include lightweight power packs for mobile phones and laptops, stand-alone PV street and other lighting, and clothing or bags with integrated PV to provide appliance power supply for people on the move.

As PV prices come down, it is increasingly being considered as an option for conventional power stations. Many PV systems in the 5 to 50 MW size range have recently been installed overseas (PVPS 2010), while the Australian Government has called for expressions of interest for a 150 MW PV power station to be built by 2015 under its Solar Flagships Program (Australian Government 2010).

6.0 CONCLUSION

Over the past 30 years, PV module costs have fallen from around US $30 per peak Watt (Wp) to under US $2/Wp, with some less than US$1/Wp. In real terms, this price decrease is even more dramatic. World production of PV will continue to rise rapidly over the coming years, with new large-scale production facilities emerging in China, Korea, the US, Europe and other parts of the world. Some of these facilities will be producing new thin-film PV products, others more efficient and cheaper crystalline product. All expect to reach economies of scale in manufacture which will allow continued significant cost reductions. At the same time, markets for specialised products, such as building elements and PV-powered appliances, are emerging, which will further facilitate development of the PV market. The photovoltaics industry is set to change from one catering to a small, specialised, high-cost market to one providing a wide range of affordable products. The future for PV has never looked brighter.

Key Point

Photovoltaic system prices are falling rapidly with the introduction of new technologies and major new production facilities.

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