INTEGRATED SOLAR PHOTOVOLTAICS FOR BUILDINGS

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INTRODUCTION

Photovoltaic (solar) cells (Corkish 2004) are semiconductor devices that directly create electric current and voltage from the collection of photons (quanta of light). They convert sunlight to electricity silently and without moving parts, require little maintenance, are reliable, are being sold with warranties of up to twenty-five years, generate no greenhouse gases in operation, and are modular, rapidly deployable and particularly suited to urban rooftops, façades, and similar applications. Hence, they are easily located close to where electricity is consumed.

Solar cells of 15% efficiency covering an area equivalent to just 0.25% of the global area under crops and permanent pasture could meet all the world's primary energy requirements today (Archer and Hill 2001), yet most or all of that area could be otherwise alienated land, such as on buildings, for example. "On any given day, the solar energy falling on a typical oilfield in the Middle East is far greater than the energy contained in the oil extracted from it." (CarbonFree 2006).

However, solar cells remain an expensive option for most power generation requirements, relative to fossil and nuclear sources, especially if the natural environment is attributed little or no value, and relative to some other sustainable options, such as the enhancement of energy efficiency, solar thermal (e.g., solar water heating) or wind energy. Photovoltaics are synergistic with efficiency enhancement and solar thermal use and are usually more easily applied in urban situations than are wind turbines.

Here, we aim to acquaint practising architects, builders, and engineers with the fundamentals of solar photovoltaic energy production and devices and building-related applications (Green 1995; Wenham et al. 2006; Prasad & Snow 2005; Strong et al. 2005; Sick 1996).

BASICS OF SOLAR PHOTOVOLTAICS

Solar cells use semiconducting materials to perform two fundamental tasks: (a) the absorption of light energy to release free charge carriers within the material, and (b) the separation of the negative and positive charge carriers (i.e., electrons and holes) to produce unidirectional electrical current through terminals that have a voltage difference between them (Corkish 2004; Green 1995; Zweibel 1990). The separation function is usually achieved by a p-n junction, the interface of regions of material that have been "doped" with different impurities to give an excess of free electrons (n-type) on one side of the junction and an insufficiency of them on the other (p-type) (Sze 2002). The interface region then has a built-in electrostatic field that sweeps electrons one way and holes the other. A solar cell is, therefore, simply an illuminated, large-area semiconductor diode. Whilst the p-n junction is the most common structure, others, such as metal-semiconductor junctions, are also used.

Figure 1 indicates the main processes. Photons enter the cell volume through the front surface. High energy (blue or violet) photons are absorbed rapidly, close to the cell's front surface, but those from the infrared end of the visible spectrum are weakly absorbed and penetrate more deeply. Each absorption of a photon annihilates the photon and transfers its energy to an electron in the semiconductor, freeing the electron from its parent atom and leaving behind a positively charged vacancy, or "hole."

The electrons and holes are mobile within the cell and will move (a) in response to an electric field ("drift"), or (b) by diffusion to regions of lower con-

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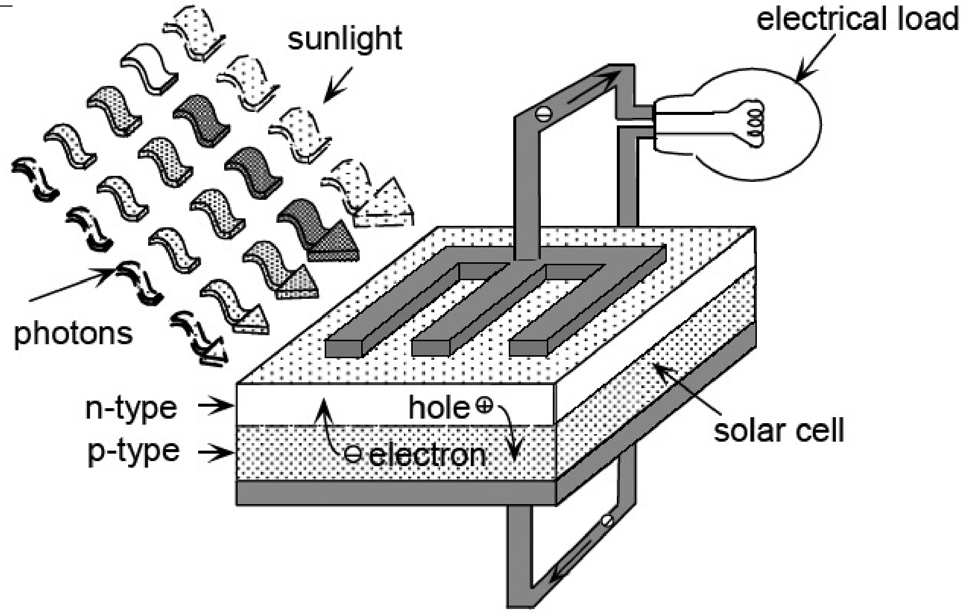
FIGURE 1. Basic operation of a p-n junction solar cell.



centration. They are also prone to recombination with each other. Electron-hole pairs generated near the junction are split apart by the strong electrostatic field there. Minority carriers (electrons in p-type material and holes in n-type material) are swept across the junction, and each crossing of the junction is a contribution to the cell's output current. Minority carriers that are generated too far from the junction to be immediately affected by the junction's electric field can be transported to the junction by diffusion. Metal contacts at the front and rear of the cell allow connection of the generated current to a load. The front contact is normally in the form of a fine metallic grid to reduce blockage of the light's access to the semiconductor. There exist commercial cell designs that avoid the front contact blockage altogether and have both positive and negative contacts on the rear (Sunpower 2006).

However, minority carriers are prone to recombination with the surrounding majority carriers. Recombination can be radiative, the inverse of the optical carrier-generation process that produced the carrier pair, in which the carrier energy is lost in the production of a new photon, or non-radiative, in which the energy is dissipated as heat in the cell. Crystal defects, accidental impurities, and surfaces all promote non-radiative recombination. Most (though not quite all) non-radiative recombination processes are, in principle, avoidable but radiative recombination is fundamental.

The result of the above processes is a light-generated current (i.e., electrons flow out of the cell into the circuit from the n-type contact and back into the cell through the p-type contact). The light-generated current is approximately independent of the voltage across the cell. Unfortunately, the normal diode current, which would remain even in the dark at the same contact voltage, may be thought of as simultaneously flowing in the opposite direction to the light-generated current. That dark current (solid line in Fig. 2) increases strongly with the voltage and at some voltage, known as the open circuit voltage (V_{oc}), completely cancels the light-generated current. As a result, we see the typical current-voltage characteristic shown as a dashed line in Fig. 2. The (forward) dark current is added to the (reverse) light-generated current to make the resultant current negative for a range of positive voltage, in which the cell generates power. Power is zero at zero volts and at $V_{oc,}$ with maximum power being produced near the

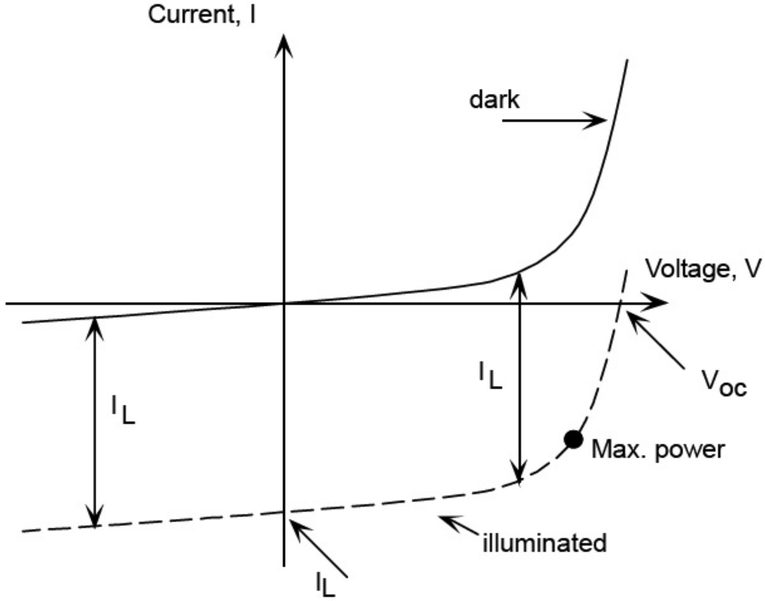


FIGURE 2. Conceptual current—voltage characteristic for a solar cell.

"knee" of the curve. The electrical load connected to the cell should be chosen to keep the operating point close to the optimum "knee" point during normal operation.

PHOTOVOLTAICS TECHNOLOGIES AND RESEARCH DIRECTIONS

There is a wide range of different solar cells materials and approaches in production, under development, or having been proposed (Corkish 2006). It may help to categorise the field as comprising three generations of technology. The first includes "bulk" or "wafer" cells, made from layers of semiconductor material thick enough to be self-supporting, usually up to 0.3 mm. This generation, which dominates current markets, is exemplified by single and multicrystalline silicon cells, and commercial production cells currently have efficiencies of around 10–18%. Cost reductions for such cells will eventually be limited by the costs of the wafers. The second generation aims for lower cost at the expense of efficiency by using thin layers of active material. A rigid substrate or superstrate provides mechanical support for the semiconductor, which is deposited rapidly over large areas. Unlike the wafer-based cells described above, which are mechanically and electrically connected together to form weatherproof solar modules that produce convenient voltages and currents, the thin film materials are deposited on large areas of sub/superstrate and subsequently patterned (commonly by lasers) to form multiple cells. Hence, the basic production unit is the module, rather than the individual cell. The four important thin film technologies are amorphous silicon, polycrystalline silicon, cadmium telluride, and copper indium diselenide. Current production efficiencies are 4–9%. Thin film cells are a growing challenge to the first generation cells' current dominance, especially in the current global shortage of silicon wafers (Schmela 2005a). Third generation approaches intend to eventually combine high efficiency and low cost. One type of cell that approaches the third generation criteria (Green 2003) is the tandem cell. Tandem cells are already commercially available as both low-cost, low-efficiency amorphous silicon-germanium and, at the other performance extreme, high-efficiency cells made from elements of Groups III and V of the Periodic Table, known simply as III-V cells (Yamaguchi 2005). The latter are used almost exclusively for space applications.

As indicated by Fig. 3, cell production has been growing at or above 30% p.a. for several years, with 67% reported for 2004 (Schmela 2005b). During 2004/05 the demand for photovoltaics exceeded the global production capacity of purified polysilicon for the production of wafers (Corkish 2006). Up until 1998, the silicon photovoltaics industry

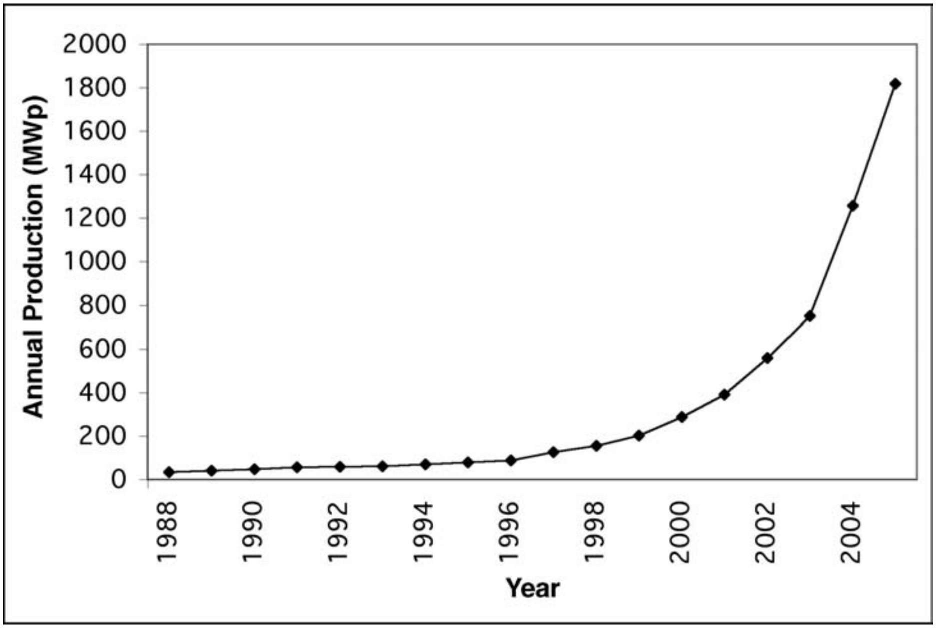


FIGURE 3. Growth in global cell production.
Data is sourced from industry magazines, Photon International and Renewable Energy World.

was able to rely on off-specification material that was effectively waste of the electronics industry. This amounted to 2–3 thousand tons per year. However, the rapid growth of photovoltaics in recent years has resulted in demand exceeding that supply, and shortages are occurring until new capacity comes on line in 2006/07 (Schmela 2005a). This shortage, along with the inherently high energy and financial costs of wafers, has motivated increased interest in both saving silicon in first generation technologies by, for example, use of thinner wafers and using wafers in new ways (Weber at al. 2004), and in crystalline silicon (Basore 2005) and non-silicon, thin-film technologies.

An important figure of merit on which solar cells and modules (see below) are compared is their efficiency. Record efficiencies for research cells and modules using different technologies are published regularly (Green et al. 2006). Commercial efficiencies tend to be a few percentage points lower (Kreutzmann 2005). Another, more commercially important but less precisely defined, figure of merit is the cost per peak Watt (W_p). This recognises that efficiency is only of prime importance in some applications and for many potential users, the capital cost and the cost of the resultant electricity are more useful measures on which to base decisions. Hence, technologies that are less efficient but cheaper per unit area are able to compete in the market.

Active solar cell research topics at present include advances in top contact design for wafer cells, use of n-type rather than p-type wafers, crystallisation of amorphous silicon on glass, texturisation of glass for better absorption of light in thin deposited layers of silicon, and a group of advanced future possibilities for high efficiency devices that rely on silicon nanocrystals in benign matrices (Centre for Advanced Silicon Photovoltaics and Photonics 2005).

PHOTOVOLTAIC MODULES

Wafer solar cells are rarely used individually but are normally interconnected and encapsulated in arrays of (commonly 36) series-connected cells to provide a useful output voltage (the quasi-standards have become the voltage suitable for charging 12 and 24 Volt batteries) and to protect them from the environment (Corkish et al. 2006; Wenham et al. 2006). Solar modules are often used in harsh and remote locations, so they must be capable of extended, reliable, maintenance-free operation. They must be able to withstand dust, salt, wind, snow, rain, humidity, hail, birds, pollutants, and temperature variations and ultraviolet light. The front cover must maintain high transmission in the optical wavelength range. Moisture penetration is responsible for many module failures, with condensation on the cells and circuitry causing short or open circuits. The most vulnerable sites are at the interfaces between different materials and the materials used for bonding are required to maintain adhesion under operating conditions.

Materials engineering of photovoltaic modules has allowed their development over the last half century into a highly reliable product. Advances in cover glasses, some with UV absorbing ingredients, encapsulants and sealing techniques have all contributed to reducing persistent problems. However concerns remain, particularly with inexperienced manufacturers and where standards are not complied with (see Appendix E of Wenham et al. 2006, for a listing of many relevant standards). Module lifetimes of around 20 years or more are commonly offered by manufacturers of modules of silicon wafer cells, and the industry is seeking 30-year lifetimes. Encapsulation failure is a major contributor to solar module life expectancy (King 2000).

Commonly used encapsulants are ethylene vinyl acetate (EVA), Teflon, and casting resin (Brand 2005; Ecofys 2004). EVA is usual for standard modules and is applied in a vacuum chamber, as is Teflon, whose use avoids the need for a front cover glass. Resin encapsulation is sometimes used for large modules intended for building integration. Polyvinyl butyral (PVB) is commonly used in laminated glass in the construction and vehicle industries for its adhesion and durability, but an historical problem of clouding after moisture absorption caused its abandonment as a photovoltaics encapsulant. However, modern formulations of PVB are not subject to this problem, and its use in modules is being reconsidered (Diefenbach 2005), especially for modules with glass front and rear covers, such as in building integration applications. PVB modules are not yet commercially available (Kreutzmann 2006).

Tempered, low-iron, rolled, sheet glass is generally used for the top surface because it is relatively cheap, strong, stable, transparent, impervious and has good self-cleaning properties (i.e., rinses it effectively). Tempering helps the glass withstand thermal stress. Low iron glass with anti-reflective coatings, applied by caustic processes or dip coating, allows transmission of up to 96% of the incident light.

Polyvinylfluoride (e.g., Tedlar), polyethyleneterephtalate, or Mylar are commonly used for the rear of the module, to act as a moisture barrier. Alternatively, glass is used for the rear as well as the front, particularly for laminates for building integration that require transparency between cells.

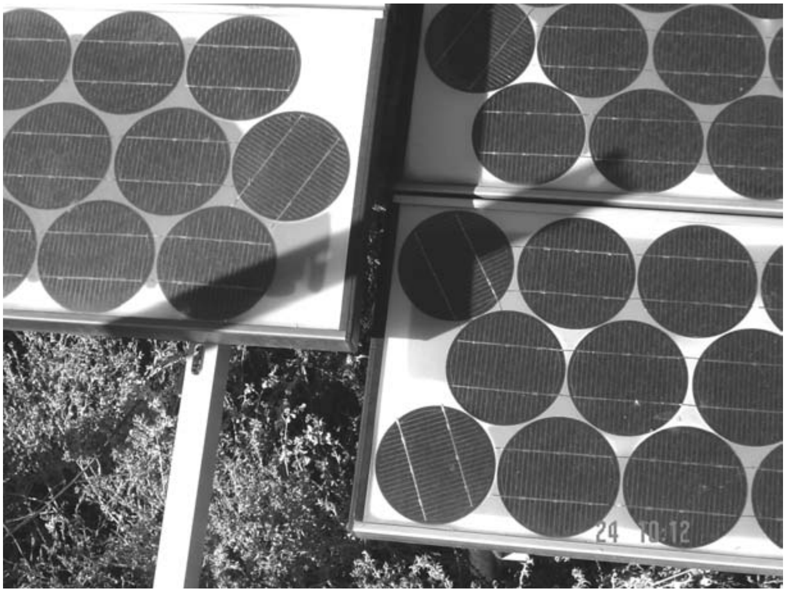
Many modules, particularly those with the longer warranty periods, have their edges protected by aluminium frames, which also help protect against twisting and other stresses to the glass; however, frames are commonly excluded from laminates for architectural uses.

Single modules are used only in very low power applications (less than 100W), and modules are usually interconnected, in various series and parallel arrangements, into arrays (Wenham et al. 2006). The overall voltage of the array is primarily determined by the number of modules in series, and the electrical current is primarily determined by the number in parallel. An anti-intuitive and surprising aspect of photovoltaic arrays is that, unless protection is built in, blocking or shading the sunlight from a relatively small area of the total array can have a profound effect on the whole array's electrical output (Wenham et al. 2006, Sect. 5.4). This is because each module, and indeed, each cell, in a series-connected array section (known as a "string") must carry the same current as all the others. Hence, the complete shading of even a single cell in one of the modules of a large string of illuminated modules could reduce the electrical output of the entire string to zero. Furthermore, electrical power produced by all the illuminated cells could be dissipated as heat in the shaded cell, causing overheating and permanent failure of the module that contains it (Wenham et al. 2006, Sect. 5.5). Bypass diodes are normally connected around small blocks of series-connected cells (commonly across each 18 cells, or two per nominally 12V module) to protect the overall system output from dramatic reduction due to accidental shading of a small fraction of the array (Standards Australia 2005). Bypass diodes are a "blunt instrument" that protect the array and prevent excessive output reduction but still cannot allow the collection of electrical energy from the bypassed section of cells. Hence, care should be taken to avoid partial shading effects due to bird droppings (Fig. 4), overhanging trees, structural elements, adjacent buildings, parts of the same building, etc. (Fig. 5).

A less dramatic form of the same problem occurs if modules of different cell technology or even modules

FIGURE 4. Locating an antenna directly above the photovoltaic modules that power this earthquake monitor has provided an ideal perch for birds to generate partial shading on the glass front cover below.

FIGURE 5. Accidental shading of a (non-building-integrated, in this case) photovoltaic array has a negative impact on output that far exceeds the fractional area of the array that is shaded. This array was installed on a sheep station in outback Australia in 1985 and still drives a water pump. An installation error resulted in one section being set proud of the adjacent section, causing a row of cells in the right-hand section to be shaded each morning. Additionally, the mounting structure had been further secured by metal fencing stakes, the shadow of one of which can be seen on parts of all three modules seen on the photograph.



of the same cell technology with different current rating, or differently oriented modules receiving different insolation, are connected in series. The output of the string is essentially restricted to that generated in the worst-performing cell in the string. Module manufacturers take care to match cells with similar output in each module, thereby minimising the impact of the poorer cells, and array designers should ideally match the current ratings of modules in strings (although this would be difficult to justify economically unless there was a large variation in the modules being used in the project) and certainly should avoid the series interconnection of dissimilar modules.

Similarly, strings with lower voltage, perhaps due to use of a different cell technology, fewer cells, fewer modules, or different temperature in operation, will drag down the voltage and the available power of other strings to which they are connected in parallel (Wenham et al. 2006).

Thin film solar technologies, including amorphous silicon, are usually deposited as large area film on supporting substrates or superstrates, and the film is then cut, with a laser for example, into individual cells that are then electrically interconnected in the module. This manufacturing method tends to result in cells that are long and narrow, rather than the circular, square, or quasi-square shapes that are common for crystalline silicon cells. The long, narrow shape of the thin film cells tends to make these modules more tolerant of partial shading, simply because the whole of a cell is less likely to be shaded.

Suppliers of modules and other system components and services are listed in various industry directories, such as that maintained, for example, by James & James (2006).

BALANCE OF SYSTEM

The components of photovoltaic systems other than the photovoltaic modules themselves are commonly termed "balance of system." The two main modes of application of photovoltaics are in stand-alone and grid-connected systems (Wenham et al. 2006). Stand-alone systems include those that power satellites, remote communications systems, navigational aids, railway crossings, road and emergency signage; cathodic protection against corrosion, consumer products, battery charging for boats, campervans, lights, solar home systems, refrigeration for medicines and vaccines in remote areas, water pumping and purification, solar powered vehicles, lighting, remote monitoring, remote flow metering, electric fences, remote gates, and village community power supplies. Grid-connected systems, on the other hand, are required to feed power into an electricity distribution grid.

The balance of system for all systems usually includes design and installation costs mounting structures (fixed or sun-tracking), wiring, switches, circuit breakers, connectors, lightning protection, metering, alarms, etc. Stand-alone systems commonly include chemical (battery) storage of energy, and, if so, battery charge regulation to optimise charging and prevent overcharging and automatic load disconnection to prevent excessive discharging. Inverters may be included to convert the direct current electricity that is characteristic of photovoltaics and batteries to alternating current, as is expected by many electrical loads. Water pumping applications often do not have battery storage but may incorporate storage of pumped water.

Grid-connected systems do not normally include storage of any form but require special inverters that convert the direct current from the photovoltaics to alternating current at the same voltage and frequency as the grid, with restricted harmonic content, and are able to automatically synchronise with the grid. They also need to automatically disconnect from the grid at times that the grid is otherwise unpowered to avoid the phenomenon of "islanding" that can conceivably threaten the safety of electrical grid maintenance staff (Krampitz 2005).

COSTS

Several guides are available for costs of photovoltaic modules and systems. For example, prices for modules and systems are monitored and reported in the countries that participate in the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS 2005). Those data are available free of charge. More timely information is available from various commercial organisations, such as, for example, Solarbuzz (2006).

Prices are tending to increase at present as a result of the temporary shortage of purified polysilicon and wafers (Schmela 2005a).

PHOTOVOLTAICS IN BUILDINGS

Building integrated photovoltaics (BIPV) has been defined as "the harnessing of solar power technologies as a part of, or attached to, the external building skin" (Prasad and Snow 2005). However, more restrictive definitions are also in common use, such as: "A BIPV system operates as a multifunctional building construction material; it generates energy and is part of the building envelope." (Eiffert 2003). In this article we adopt a definition somewhat between those two and consider photovoltaics that are used as part of the building envelope and photovoltaics mounted on buildings, but only where they perform a building function other than power generation. Most commonly, the additional building function is shading. We do not include the simple use of buildings as structures to support the mounting of photovoltaics.

We note that energy efficiency measures incorporated into buildings are almost always more cost effective ways of improving building energy performance and should normally be included in preference to BIPV (Strong et al. 2005). Passive systems, such as solar access, shading, thermal insulation, and natural ventilation and lighting, taking into account the climate of the site, should be used before calling on "active" systems such as photovoltaics. Solar thermal water heating is usually a more economical option for reducing demand for purchased energy than are photovoltaics. Control systems can be used to reduce energy demand by restricting unnecessary energy use and optimising natural inputs.

BIPV is a confluence of engineering and architectural design (Prasad et al. 2005). Seven architectural criteria (Table I) have been espoused by the IEA PVPS Task 7 (Schoen 2001).

Engineering issues include maintaining the integrity of the building envelope and the optimisation of energy collection, which includes the effect of temperature on photovoltaic performance. From a photovoltaic systems engineering point of view, siting and orientation of photovoltaics should take into account the shading issues discussed above and also the geographically-dependent apparent path of the sun across the sky (Iqbal 1983). The apparent solar trajectory can be indicated in the form of polar or cylindrical sunchart diagrams. The latter are particularly useful for visualising the shading effects of nearby objects (Quaschning and Hanitsch 1995) and a free online calculator is available (University of Oregon 2003). Other design tools are listed by Gutschner et al. (2005) and Argul et al. (2003). From a structural engineering point of view, a BIPV system must perform its assigned tasks as part of the building (e.g., being part of the waterproof and windproof building envelope, shading, etc.) reliably and should be constructed in a way to withstand wind and other loads.

Electrical power output of fixed photovoltaic arrays is maximised over a year by tilting them towards the equator at the site's latitude angle to the horizontal. However, there are often good reasons to orient them otherwise. These could include the avoidance of shading, an intention to optimise output in a particular season or time of day, such as to offset peak power loads due to air conditioning, or the need to conform to building surfaces whose orientation is otherwise restricted. Orientation on façades at low, especially tropical, latitudes is particularly challenging. Misalignment from tilting towards the equator by about 15° is usually acceptable.

Maintenance and cleaning are additional design issues. Modules oriented at low angles to horizontal,

TABLE 1. Seven architectural criteria outlined by the IEA PVPS Task 7 (Schoen 2001; Strong et al. 2005, 2005).

1. NATURALLY INTEGRATED
   The PV system is a natural part of the building. Without PV, the building would be lacking something; the PV system completes the building.
2. ARCHITECTURALLY PLEASING
   Based on a good design, does the PV system add eyecatching features to the design?
3. GOOD COMPOSITION
   The colour and texture of the PV system should be in harmony with the other materials. Often, also a specific design of the PV system can be aimed at (e.g., frameless vs. framed modules).
4. GRID, HARMONY, AND COMPOSITION
   The sizing of the PV system matches the sizing and grid of the building.
5. CONTEXTUALITY
   The total image of a building should be in harmony with the PV system. On a historic building, tiles or slates will probably fit better than large glass modules.
6. WELL-ENGINEERED
   This does not concern the watertightness of PV roof, but more the elegance of design details. Have details been well conceived? Has the amount of materials been minimised? Are details convincing?
7. INNOVATIVE NEW DESIGN
   PV is an innovative technology, asking for innovative, creative thinking of architects. New ideas can enhance the PV market and add value to buildings.

as would be the optimum for energy collection at low latitudes, will not be easily self cleaned by rainfall, at least without special surface treatments, and a minimum tilt angle of 10° is sometimes recommended for Australian installations (Standards Australia 2002).

The main modes in which photovoltaics have been incorporated into buildings are (Strong et al. 2005; von Aichberger 2004; Kreutzmann and Schmela 2005):

- Integrated roofing
- Curtain walls for vertical and inclined façades
- Rainscreen cladding
- Fixed and moveable solar shading

Integrated Roofing

Mounting on sloping roofs is a common and well established method of installing photovoltaic modules and many aesthetically pleasing examples exist (Fig. 6), but they are excluded from the scope of this article according to our definition, above.

There are also several examples of integration of photovoltaics into, rather than on, the roof profile but with the waterproofing task being satisfied by another layer below, as in the example of the Sydney Olympic Village (Prasad and Snow 2005). On the other hand, there is a range of methods currently available in which the photovoltaic modules perform the normal functions of roofing materials (Reijenga 2005; von Aicheberger 2003, 2004). This method tends to produce a more aesthetically pleasing outcome but faces the additional challenges of having the photovoltaics in intimate contact with the attic space, which can reduce the photovoltaics performance through heating (see below) and the necessity to maintain reliable waterproofing.

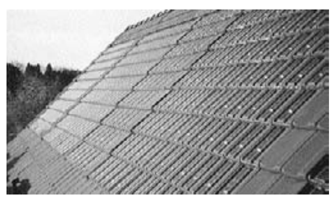
FIGURE 6. One of two sections of a 40 kW grid connected photovoltaic array mounted above the curved, corrugated metal roof of the "Quadrangle Building" at the University of New South Wales, Sydney. In this example, the photovoltaic modules were retrofitted and are not part of the building envelope. (UNSW Facilities Management 2006)

A wide range of products for integrating photovoltaics into sloped roofs have entered the market in recent years, particularly in Europe (von Aicheberger 2003, 2004). They range from roof tiles of "standard" profiles containing small photovoltaic arrays, through systems to fit custom or non-specific sizes of photovoltaic laminates (essentially modules without frames) as roof elements, to direct lamination of photovoltaic cells onto sheets of roofing material. This is a rapidly evolving field, with many options available, for which the reader may consult product reviews such as that by von Aicheberger (2003, 2004) or IEA-PVPS Task 7 (http://www.task7.org/Public/lausanne/part3proda.pdf or http://www.pvdatabase.com/search_form.cfm). We provide here only a brief, illustrative overview. In all cases, reliable watertight transitions to the surrounding roofing material, with which it is integrated, are necessary, as is compliance with local building codes.

Products that seek to mimic normal roofing tiles or shingles allow excellent aesthetic integration, but they tend to be expensive and face the barrier that roofing tile profiles and sizes are not consistent across the world or even within countries. They have the advantage that roofing installers can install and connect such products without significant additional training.

Frameless solar module laminates are used by several companies for fixing to roof battens with screws or

FIGURE 7. Example of a photovoltaic roof tile for BIPV. (Source: www.starunity.ch/deutsch/frame_d.htm)



clamps. The example system shown in Fig. 8 uses special spacers to join adjacent laminates, forming a waterproof barrier (Erling undated). A perforated metal batten at the bottom of the array allows air to flow up the rear surfaces of the modules, cooling them. This particular system, unlike some others, is able to use laminates of unspecific size and manufacturer. Thin film cells can also be incorporated into roof shingles (Fig. 9).

A great number of arrays has been mounted on flat roofs either by roof-penetrating fixtures or by gravity mounting (Reijenga 2005), although there have been serious structural engineering challenges in some cases (Siemer 2004). It is interesting diversion to note that stones used as top covering on residential and commercial roofs have been blamed for fracturing tempered glass front covers of modules by being propelled by storm winds up the inclined faces of modules and dropped onto the row of modules behind (King et al. 2000).

However, the use of photovoltaic modules to watertight and insulate layers is more closely compliant with our restricted definition of BIPV in this paper. One system, intended for either retrofitting or for a new roof, avoids roof penetration with interconnecting modules backed by "tongue-and-groove" extruded polystyrene boards (Fig. 10). Another roofing product combines amorphous silicon, deposited onto large, thin metal substrates, with a traditional roofing foil and can be installed in a similar way to normal roofing foil. These roof-integrated products do not benefit from the cooling effect of air flow over the rear surfaces that is enjoyed by the non-integrated roof-mounted arrays. Note, however, that the performance of amorphous sil-

FIGURE 8. Photovoltaic laminates integrated into a residential roof with the aid of proprietary frames and showing a perforated metal batten to encourage air flow behind the modules. A corner of a solar thermal water heater is visible at left. (Source: PV Solar Tiles Pty. Ltd.)

FIGURE 9. Amorphous silicon thin-film photovoltaic roofing shingles. (Source: Unisolar)

FIGURE 10. Interconnecting module system for flat roofs. (Source: PowerLight)

icon modules is less seriously degraded by temperature increases than that of crystalline silicon.

Integrated Façades

Photovoltaic modules on vertical surfaces of buildings can sometimes replace expensive alternative cladding materials at similar cost and can protect underlying surfaces from sun-induced damage. They enjoy high visibility, often an important factor in justifying their cost. However, there are serious challenges with respect to solar access and optimal orientation, except at very high latitudes, and shading by other structures in dense cities. Façades using crystalline silicon photovoltaics need ventilation to keep them cool.

Many examples exist of the use of photovoltaic laminates in curtain wall façades, in which they have an airgap behind, usually not ventilated in order to prevent condensation (Fig. 11). Coloured effects can be created by modifying the anti-reflective coating on cell front surfaces, though at some cost in performance (Fig. 12). Sloped façades allow both novel architecture and improved solar access for photovoltaics (Reijenga 2005; Kreutzmann and Schmela 2005)

Eaves (Fig. 13), sunscreens and louvres offer excellent opportunities for the incorporation of air-cooled photovoltaics on the walls of buildings while performing a useful building function in addition to generating electricity. A fine example of this is the Children's Museum of Rome (Fig. 14) (Prasad and Snow 2005), in which movable photovoltaic screens formed from glass-glass laminates are adjusted to control shading of the south wall. Products are available for simpler, fixed sunscreens (Reijenga 2005).

Skylights and atria are an opportunity for dramatic application of photovoltaics in buildings (Fig. 15). Lighting control is possible through varying the fractional cell area in custom-made laminates, and semi-transparent thin film modules allow a different effect. Local building codes restrict the range of choice for these applications.

TEMPERATURE

The negative impact of rising cell temperature (Emery 1996) on electrical output is not always adequately considered in BIPV applications. Power output from crystalline silicon solar cells decreases approximately 0.4–0.5% per °C, but amorphous silicon cells are less dramatically affected (Shima 2005). While module

FIGURE 11. PV curtain wall example. (Source: Shüco)

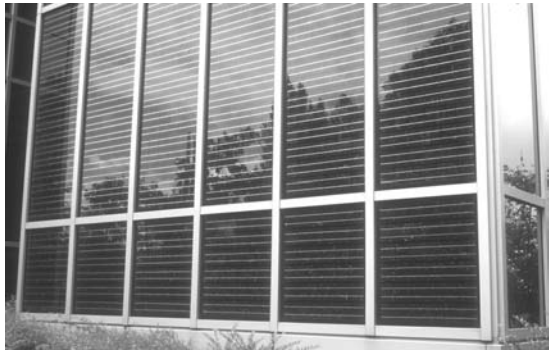


FIGURE 12. Coloured surface effects on multicrystalline silicon solar cells, shown at an industry exhibition.

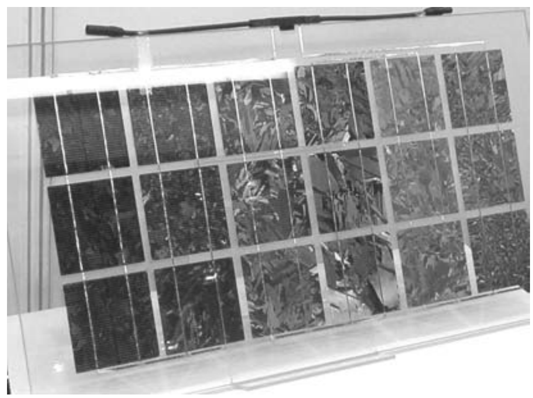


FIGURE 13. BIPV window shading at the CSIRO Division of Energy Technology, Newcastle, Australia.

FIGURE 14. Photovoltaic canopies at the Children's Museum of Rome move to control shading on the south wall.

FIGURE 15. Skylight roof at the Children's Museum of Rome.

ratings are usually at the standard test condition of 20°C, the temperature can far exceed that in operation. The usual approach to minimising the modules' temperature rise is to allow or encourage air flow behind them. For example, Fig. 8 shows a metal roof batten that has been perforated to provide a convective air inlet along the bottom edge of a roof-integrated array. The temperature rise for various situations has been modelled mathematically (Guiavarch and Peuportier 2006) and tested experimentally (Brinkworth and Sandberg 2006). The latter found that, due to the additional turbulent mixing and enhanced heat transfer to the air, typical structural members, somewhat anti-intuitively, can enhance cooling.

Brinkworth and Sandberg (2006) propose, as a rule of thumb, that the airgap, *a,* should be sized such that the duct between the roof and the modules has hydraulic diameter:

$$D = L/20$$

where L is the duct length, D is defined by (Kutz 1998)

$$D = 1.3\frac{(ab)^{0.625}}{(a+b)^{0.25}},$$

and b is the array width. For typical installations, an air gap of around 140 mm is adequate (Brinkworth and Sandberg 2006).

While it is commonly considered, and found in applications, that heat is a problem in BIPV installations, it is also possible to make a virtue of necessity by capturing the heat for water or space heating or other uses (Crawford et al. 2006). For one example, the system in Fig. 8 can be enhanced by a layer of insulation sagging under the module rears, inside the attic space, forming ducts to ventilate the heated air to the ridge of the roof. Conventional ducting and fan forcing collects the hot air for space heating or for enhancing domestic water heating. Another example of a BIPV product that produces both electricity and heat as outputs is the recently released "Complete Solar Roof" (Solarcentury 2006).

SYNERGIES IN BUILDING APPLICATIONS

Apart from the obvious benefits of power generation, possible heat collection and shading, there is significant potential for other synergies with BIPV. Perhaps the most important in developed nations in temperate climates is the ability to temporally match peak loads of grid feeders or of buildings. This potential if often over-stressed since many loads, particularly domestic dwellings with air conditioning, experience peaks on days of high insolation but with load peaks a few hours later than the insolation peak at midday. However, industrial and commercial peak loads are often well suited to peak photovoltaic output (Watt et al. 2003). Aligning photovoltaic modules away from the equatorial direction shifts the time of peak output (Watt et al. 2003).

Photovoltaics on buildings are an ideal way to locate electricity generation close to loads, thereby making it more valuable (Chowdhury and Sawab 1996). Urban location of generation avoids resistive transmission losses and loads on transmission infrastructure. Photovoltaics, and especially well integrated BIPV, are rarely the object of rejection by urban communities, unlike many alternative means of electricity production.

SUMMARY

Building integration of solar photovoltaics is a field that is, while still in its infancy, one with huge potential for the alignment of engineering and architectural values. This overview introduces photovoltaic technologies and many of the ways for their integration into buildings. Some emphasis is placed on aspects that have sometimes been insufficiently understood in past implementations of BIPV: partial shading and other mismatching of modules and the impact of temperature and the need to design for cooling.

REFERENCES

Archer, M.D. and R. Hill, editors. 2001. "*Clean Electricity from Photovoltaics,"* London: Imperial College Press.

Argul, F.J., M. Castro, A. Delagado, J. Carpio, and J. Peire. 2003. "Software Modelling of Grid-Connected Photovoltaic Buildings." *Progress in Photovoltaics* 11 (2003): 255–73.

Basore, P.A. 2005. "Crystalline Silicon on Glass Device Optimization." 31st IEEE Photovoltaic Specialists Conference, Lake Buena Vista, Florida, 3–7 January 2005.

Brand, B. 2005. "The Latest Module Wrap. Market Survey on Laminators." *Photon International* 8/2005, 66–82.

Brinkworth, B.J. and M. Sandberg. 2006. "Design Procedure for Cooling Ducts to Minimise Efficiency Loss Due to Temperature Rise in PV Arrays." *Solar Energy* 80, no.1, 89–103.

CarbonFree. 2006. "Farming Renewable Energy," abstract available online at www.carbonfree.co.uk/cf/report_farming.htm.

Centre for Advanced Silicon Photovoltaics and Photonics. 2005. Annual Report 2004, www.pv.unsw.edu.au/research/annualreports.asp.

Chowdhury, B.H. and A.W. Sawab. 1996. "Evaluating the Value of Distributed Photovoltaic Generations in Radial Distribution Systems." *Ieee Transactions on Energy Conversion* 11, no. 3 (1996): 595–600.

Corkish, R. 2004. "Solar Cells," "*Encyclopedia of Energy,"* 545–57: Academic Press.

———. (2006). "Photovoltaic Materials," "*Encyclopedia of Chemical Processing,"* 2129–38. Taylor & Francis, USA.

Corkish, R. , S.R. Wenham, M.A. Green, A.B. Sproul, J. Cotter, A.G. Aberle, and A. Bruce. 2006. "Materials Engineering Education in Two New Engineering Degree Programs at the Centre for Photovoltaic Engineering," in press, *Journal of Materials Education* 28 (1) 59–71.

Crawford, R.H., G.J. Treloar, R.J. Fuller, and M. Bazilian. 2006. "Life-Cycle Energy Analysis of Building Integrated Photovoltaic Systems (Bipvs) with Heat Recovery Unit." *Renewable and Sustainable Energy Reviews* 10, no. 6 (2006): 559–75.

Diefenbach, K.H. 2005. "New Old Foil. The Return of Laminated Glass Modules with PVB," *Photon International,* April 4, 2005, 78–79.

Ecofys. 2004. German Solar Energy Society and *Planning and Installing Photovoltaic Systems: A Guide for Installers, Architects, and Engineers,* London: Sterling; VA: Earthscan.

Eiffert, P. 2003. "Guidelines for the Economic Evaluation of Building-Integrated Photovoltaic Power Systems," Golden: National Renewable Energy Laboratory, Report Number NREL/TP-550-31977.

Emery, K., J. Burdick, Y. Caiyem, D. Dunlavy, H. Field, B. Kroposki, and T. Moriarty. 1996. "Temperature Dependence of Photovoltaic Cells, Modules, and Systems," In *Proceedings of 25th IEEE Photovoltaic Specialists Conference, Washington, 13–17 May 1996,* 1275–78. New York: IEEE.

Erling, P. (undated). "Installation picture manual," www.members.optusnet.com.au/pvsoleng/ms_pvcf1.html?./ms/installation_pm.html. Accessed March 2006.

Green, M.A. 1995. "*Silicon Solar Cells," Advanced Principles and Practice,* Centre for Photovoltaic Devices and Systems, UNSW Sydney, Australia.

———. 2003. "*Third Generation Photovoltaics: Ultra-High Efficiency at Low Cost,"* Springer Series in Photonics, New York: Springer-Verlag.

Green, M.A., K. Emery, D.L. King, Y. Hisikawa, and W. Warta. 2006. "Solar Cell Efficiency Tables (Version 27)," *Progress in Photovoltaics: Research and Applications* 14, no. 1 (2006): 45–51.

Guiavarch, A., and B. Peuportier. 2006. "Photovoltaic Collectors Efficiency According to Their Integration in Buildings," *Solar Energy* 80, no.1: 65–77.

Gutschner, M., P. Lund, and M. Snow. 2005. "Bipv Potential and Design Tools." In *Designing with Solar Power. A Source Book for Building Integrated Photovoltaics (Bipv),* edited by Deo Prasad and Mark Snow, 184–216. Mulgrave, Australia: The Images Publishing Group and Earthscan.

International Energy Agency Photovoltaic Power Systems (IEA PVPS) programme, Task 1: Exchange and dissemination of information on photovoltaic power systems, "Trends in photovoltaic applications. Survey report of selected IEA countries between 1992 and 2004, September 2005," www.oja-services.nl/iea-pvps/products/rep1_14.htm

International Energy Agency Photovoltaic Power Systems (IEA PVPS) programme, Task 7: Photovoltaic power systems in the built environment, www.oja-services.nl/iea-pvps/tasks/task7.htm.

International Energy Agency Photovoltaic Power Systems (IEA PVPS) programme, Task 7: Photovoltaic power systems in the

built environment, Review of PV Products, www.task7.org/Public/lausanne/part3proda.pdf.
International Energy Agency Photovoltaic Power Systems (IEA PVPS) programme, Task 7: Photovoltaic power systems in the built environment, Project and Product Browser, www.pvdatabase.com/search_form.cfm.
Iqbal, M. 1983. *An Introduction to Solar Radiation*. Toronto: Academic.
James and James. 2006. REW Suppliers Database, www.jxj.com/suppands/renenerg/, (accessed 13 March 2006)
King, D.L., M.A. Quintana, J.A. Kratochvil, D.E. Ellibee, and B.R. Hansen. 2000. "Photovoltaic Module Performance and Durability Following Long-Term Field Exposure," *Progress in Photovoltaics: Research and Applications* 8 (2000): 241–56.
Krampitz, I. 2005. "Islands and Continents. Can PV Grid Connection Standards Be Harmonized?" *Renewable Energy World* 2005, 71–73.
Kreutzmann, A. 2006. "Solar Modules 2006, Market survey with over 500 products." *Photon International,* Feb 2, 2006, 70–93.
Kreutzmann, A. and M. Schmela. 2005. "Anything Is Possible. Facade-Integrated Pv Systems Remain a Niche Market." *Photon International,* November 2005, 74–84.
Kutz, M., ed. 1998. Mechanical Engineers' Handbook (2nd Edition). John Wiley & Sons. Online version available at: http://www.knovel.com.wwwproxy0.nun.unsw.edu.au/knovel2/Toc.jsp?BookID=584&VerticalID=0.
Moshfegh, B. and M. Sandberg. 1998. "Flow and Heat Transfer in the Air Gap Behind Photovoltaic Panels," *Renewable and Sustainable Energy Reviews* 2, no.3: 287–301.
Prasad, D. and M. Snow, eds. 2005. "*Designing with Solar Power", A Source Book for Building Integrated Photovoltaics (BiPV)*. Mulgrave, Australia: The Images Publishing Group and Earthscan.
Prasad, D., M. Snow, and M. Watt. 2005. "Best Practice Guidelines for Solar Power Building Projects in Australia" 61. Sydney: The Centre for a Sustainable Built Environment, University of New South Wales.
Quaschning, V. and R. Hanitsch 1995. "Quick determination of irradiance reduction caused by shading at pv-locations," in *13th European Photovoltaic Solar Energy Conference,* pp. 683–686.
Tjerk, R. and D. Ruoss. 2005. "Technologies and Integration Concepts." In *Designing with Solar Power. A Source Book for Building Integrated Photovoltaics (Bipv),* edited by Deo Prasad and Mark Snow, 22–52. Mulgrave, Australia: The Images Publishing Group and Earthscan.
Schmela, M. 2005 a. "Mapping the Silicon World. Solar and Silicon Industry Discuss Feedstock Supply." *Photon International,* May 2005, 24–35.
Schmela, M. 2005 b. "Super Sonic Solar Market." *Photon International,* March 2005, 66–82.
Schoen, T., D. Prasad, D. Ruoss, P. Eiffert, and H. Sørensen. 2001. "Task 7 of the Iea Pv Power Systems Program—Achievements and Outlook," In *17th European Photovoltaic Solar Energy Conference*. Munich: WIP-Munich.
Shima, M., M. Isomura, K. Wakisaka, K. Murata, and M. Tanaka. 2005. "The Influence of Operation Temperature on the Output Properties of Amorphous Silicon-Related Solar Cells," Solar Energy Materials and Solar Cells 85 (2005): 167–75.
Sick, F. and T. Erge. 1996. "*Photovoltaics in Buildings: A Design Handbook for Architects and Engineers,*" London: James & James Ltd.
Siemer, J. 2004. "Solar for Big Roofs," *Photon International,* Issue 9, 2004, September 2004, 18–24.
Solarbuzz. 2006. Solar module price environment, www.solarbuzz.com/moduleprices.htm.
Solarcentury. 2006. "Solarcentury Launch World's First Complete Solar RoofTM at Interbuild 2006 following DTI recognition," News Release, 20 March 2006, www.solarcentury.co.uk/news/newsitem.jsp?newsid=432 (Accessed 1 April 2006).
Standards Australia. 2002. Stand-alone power systems Part 2: System Design Guidelines, AS 4509.2.
Standards Australia. 2005. Installation of photovoltaic (PV) arrays, AS/NZS 5033.
Strong, S., D. Lloyd-Jones, D. Prasad, T.H. Reijenga, and D. Ruoss. (2005), "Designing with Solar Power," *Renewable Energy World,* May–June 2005, 140–49.
Strong, S. and D. Prasad. 2005. "Building Design and Environmental Concepts." In *Designing with Solar Power. A Source Book for Building Integrated Photovoltaics (Bipv),* edited by D. Prasad and M. Snow, 10–21. Mulgrave, Australia: The Images Publishing Group and Earthscan.
Sunpower. 2006. (www.sunpowercorp.com/html/).
Sze, S.M. 2002. "*Semiconductor Devices, Physics and Technology.*" 2nd ed. New York, USA: Wiley.
University of Oregon. 1995. Sun path chart program, http://solardat.uoregon.edu/SunChartProgram.html
UNSW Facilities Management. 2006. "Quadrangle Building Photovoltaic System," http://www.energy.unsw.edu.au/NewsInfoPVproject.shtml
von Aichberger, S. 2003. "Discrete Power. Market Survey on Solar Roof Tiles." *Photon International,* Issue 9/2003, November 2003, 42–55.
von Aichberger, S. 2004. "Beauty Has Its Price. Market Survey on Building-Integrated Solar Modules." *Photon International,* November 2004, 54–71.
Watt, M.E., M. Oliphant, H. Outhred, and R. Collins. 2003. "Using Pv to Meet Peak Summer Electricity Loads," Paper presented at the Destination Renewables–ANZSES 2003, Melbourne.
Weber, K.J., A.W. Blakers, and M.J. Stocks. 2004. "A Novel Low-Cost, High-Efficiency Micromachined Silicon Solar Cell," *IEEE Electron Device Letters* 25, no. 1: 37–39.
Wenham, S.R. et al. 2005. "2004 Annual Report," Centre for Advanced Silicon Photovoltaics and Photonics, University of New South Wales www.pv.unsw.edu.au/research/annualreports.asp
Wenham, S.R., M.A. Green, M.E. Watt, and R.P. Corkish. 2006. "*Applied Photovoltaics,*" 2nd ed.: Centre for Photovoltaic Engineering, Sydney, Australia.
Yamaguchi, M., T. Takamoto, K. Araki, and N. Ekins-Daukes. 2005. "Multi-Junction III-V Solar Cells: Current Status and Future Potential," *Solar Energy* 79, no.1: 78–85.
Zweibel, K. 1990. "*Harnessing Solar Power : The Photovoltaics Challenge,*" New York: Plenum Press.