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Solar Energy Conversion Toward 1 Terawatt

David Ginley (National Renewable Energy Laboratory, USA)
Martin A. Green (University of New South Wales, Australia)
Reuben Collins (Colorado School of Mines, USA)

Abstract

The direct conversion of solar energy to electricity by photovoltaic cells or thermal energy in concentrated solar power systems is emerging as a leading contender for next-generation green power production. The photovoltaics (PV) area is rapidly evolving based on new materials and deposition approaches. At present, PV is predominately based on crystalline and polycrystalline Si and is growing at >40% per year with production rapidly approaching 3 gigawatts/year with PV installations supplying <1% of energy used in the world. Increased cell efficiency and reduced manufacturing expenses are critical in achieving reasonable costs for PV and solarthermal. CdTe thin-film solar cells have reported a manufactured cost of $1.25/watt. There is also the promise of increased efficiency by use of multijunction cells or hybrid devices organized at the nanoscale. This could lead to conversion efficiencies of greater than 50%. Solar energy conversion increasingly represents one of the largest new businesses currently emerging in any sector of the economy.

Introduction

Harvesting energy directly from sunlight using photovoltaic (PV) technology or concentrating solar power (solar thermal energy conversion) is increasingly being recognized as an essential component of future global energy production. The decreased availability of fossil fuel sources and the realization of the detrimental long-term effects of emissions of CO_2 and other greenhouse gases into the atmosphere are driving research and deployment for new environmentally friendly energy sources, especially renewable energy resources. An additional driving force is the increasing worldwide sensitivity toward energy security and price stability. Capturing even a small fraction of the 162,000 terawatts (TW) that reaches the earth would significantly impact the overall energy balance. PV systems, in addition, are portable and well-suited to distributed applications. The large-scale manufacturing of photovoltaics is increasingly economically viable. The rapid expansion of manufacturing capability in PV components and the deployment of concentrating solar power (CSP) systems offers the potential for supplying a significant fraction (10% without need for storage) of our energy demand with minimal environmental impact. (See accompanying sidebar by Mehos for additional detail.) In addition, it is clear that these technologies represent one of the next major high-technology economic drivers eventually succeeding microelectronics, telecommunications, and display industries. Truly achieving this goal will require materials-science-driven cost reductions, not just incremental cost reductions through economies of scale.

In 2004, the average total worldwide power consumption was 15 TW (1.5×10^{13} W), with 86.5% from the burning of fossil fuels, according to U.S. Department of Energy statistics. In 2003, 39.6 quads (1 quad = 1 quadrillion BTU = 1.055×10^9 GJ, 29.9 quad = 1 TW-year) of energy, largely from fossil fuels, was consumed to produce electricity just in the United States. After conversion losses, 13.1 quads of net electrical energy was output by power plants for general consumption.[1] This amount of electricity could be produced by a 100 km × 100 km area of high solar insolation, such as in the desert southwestern United States, covered with solar modules with a power conversion efficiency of 15%. In order to meet the U.S. Department of Energy cost goal of $0.33/W or $0.05–0.06/kWh for utility-scale production, these modules would need to be manufactured at a cost of $50/$m^2$ or less. Goals for solar thermal power are comparable. Although the costs of modules are falling substantially, reaching these objectives with today's technology will require significant improvements in cell performance, as well as in the additional components making up the balance of solar systems. In addition, a variety of new technologies including thin films, thin silicon, organic photovoltaics, multijunction concentrator approaches, and next-generation nanostructured devices have the potential to significantly reduce the cost per watt.

With the recognition of the vast potential of photovoltaic technology, worldwide production levels for terrestrial solar cell modules have been growing rapidly over the past several years, with Japan recently taking the lead in total production volume (**Figure 1**). Current production is dominated by crystalline silicon modules (including both large-grain polycrystalline and single-crystalline materials), which represent 94% of the market. Devices based on silicon wafers, single- or polycrystalline, have been termed "first-generation" photovoltaic technology. These are fairly simple single-junction devices (diodes) that are limited by thermodynamic considerations to a maximum theoretical power conversion efficiency of ~31% under direct AM1.5 sunlight.[2] Solar cells and modules are usually characterized according to the IEC norm[3] under standard test conditions (STC), which correspond to 1 kW/m^2 (100 mW/cm^2) direct perpendicular irradiance under a global AM 1.5 spectrum at 25°C cell temperature. This means that an ideal silicon solar cell operating under direct sunlight converts approximately 30% of the illuminating solar radiation into electrical power, although actual cells suffer from parasitic losses. Current silicon solar cell design represents a considerable evolution beyond that of a simple single-junction device incorporating passivation of the surfaces, light trapping, and sophisticated anti-reflection coatings to help absorb most of

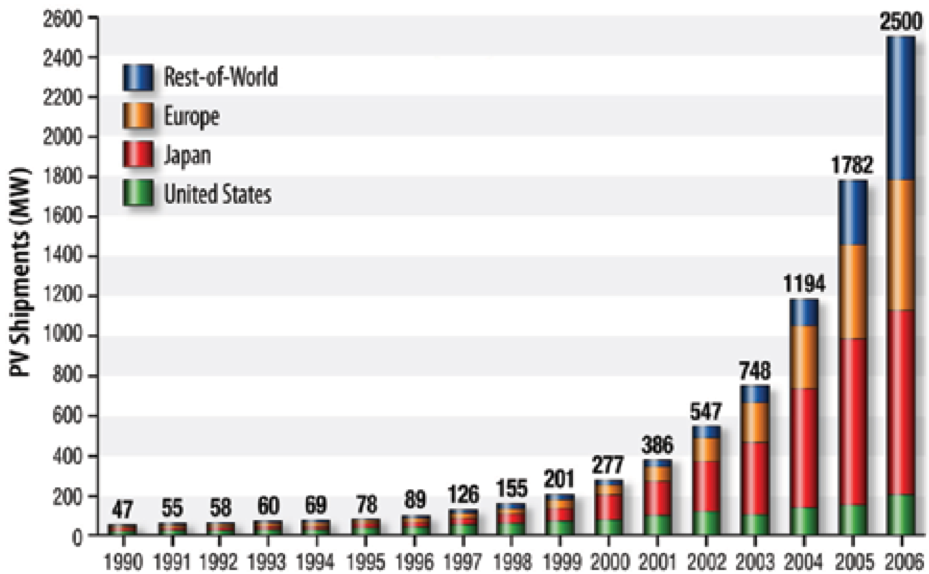

Figure 1. World photovoltaic module production (in megawatts), total consumer, and commercial per country (from *PV News*, Paul Maycock, Editor; February 2004). Most of this production is from crystalline or multicrystalline Si solar cells at present.

the light in the wavelength range accessible to silicon and ensure that each absorbed photon leads to a carrier in the external circuit. **Figure 2** illustrates a Sanyo high-efficiency Si heterojunction with intrinsic thin layer (HIT) solar cell that has an efficiency of up to 22.3%.[4] In fact, for the bandgap of Si, some current cells are pushing against the theoretical limit, so that it is methods to achieve significant cost reductions for the manufacturing of these sophisticated structures that are needed.

The progress in the efficiency of research-scale photovoltaic devices over the past several decades is shown in **Figure 3**. In nearly every technology, better understanding of materials and device properties has resulted in a continuous increase in efficiency. Si, as already noted, is very close to its theoretical limit. In contrast, thin films such as amorphous Si (a-Si), $Cu(In,Ga)Se_2$ (CIGS), and CdTe are all well below their potential maxima, and research efficiencies do not easily translate into production efficiencies. New technologies such as dye cells, organic photovoltaics, and third-generation concepts have just begun and have a long materials and development path ahead. These observations are apparent in the referenced compilation of highest confirmed cell and module efficiencies for many of the PV technologies.[5]

One key to the development of any photovoltaic technology is the cost reduction associated with economies of scale. This has been very evident in the case of crystalline silicon (c-Si) photovoltaics. **Figure 4** shows the decrease in the cost of crystalline silicon photovoltaic modules as the production rate has increased, as well as predicted future costs for both wafer-based c-Si and the emerging technologies to be discussed.[6] The current cost of ~\$4/W_p (W_p = watt peak) is still too high to significantly influence energy production markets. Although it is difficult to determine exactly, best estimates are that costs for wafer-based Si panels will level off in the range of \$1–1.50/W_p in the next 10 years,[7] substantially higher than the \$0.33/W_p target.

Thus, over the past decade, there has been considerable effort in advancing thin-film, "second-generation" technologies that do not require the use of silicon wafer substrates and can therefore be manufactured at significantly reduced cost. Steady progress has been made in laboratory efficiencies as can be seen in **Figure 3** for devices based on CdS/CdTe, $Cu(In,Ga)Se_2$ (CIGS), and amorphous Si. These devices are fabricated using techniques such as sputtering, physical vapor deposition, and hot-wire chemical vapor deposition. Multijunction cells based on amorphous Si and amorphous SiGe alloys have been the most economically successful second-generation technology to date because of their ability to be fabricated at relatively low cost and to be integrated into electronics and roofing materials. These cells, together with other single-junction amorphous Si devices, comprise 6% of the market not dominated by silicon.

However, it is not clear that second-generation technologies are capable of displacing silicon unless they can demonstrate significant cost reductions. The single counterexample has been the recent emergence of CdTe from First Solar,[8] with a compelling low manufacturing cost in the range of \$1.25/W_p. However, there are some residual concerns about the environmental effects of Cd, leading First Solar to adopt a "cradle-to-grave" approach, from sourcing of Cd from mining byproducts through recovery and recycling of Cd from used solar cells.

Although not based on thin films, concentrating solar applications using either photovoltaic cells (typically high-efficiency but costly groups III–V multijunction devices) or solar thermal collectors, take advantage of the relatively low cost of concentrating

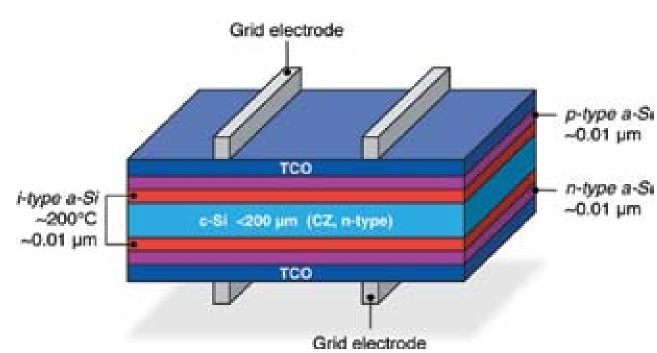

Figure 2. Illustration of the Sanyo heterojunction with intrinsic thin layer (HIT) cell that is based on crystalline Si and has demonstrated a 22% efficiency. TCO means transparent conducting oxide, typically used as a contact, and CZ indicates Czochralski-grown, which means pulled from the melt as a single crystal. The three types of amorphous silicon (a-Si) included in the cell differ in the types of dopants (or impurities) that have been added: *i*-type (or intrinsic) is undoped, *n*-type contains a dopant (such as phosphorous) that increases the number of free negative charge carriers (i.e., electrons), and *p*-type contains a dopant (such as boron) that increases the number of free positive charge carriers (i.e., holes). The types and amounts of impurities in the silicon affect its conductivity and other properties.

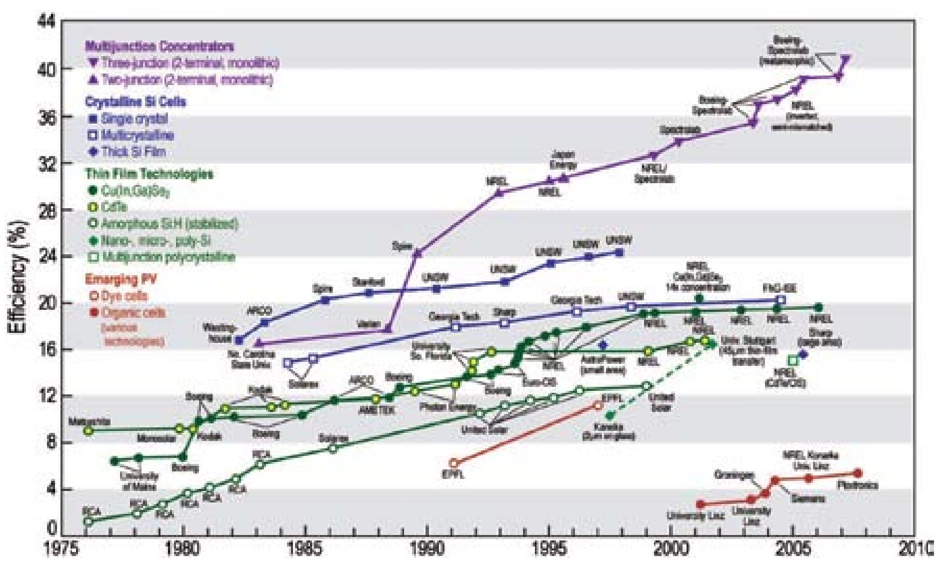

Figure 3. Progress of research-scale photovoltaic device efficiencies, under AM1.5 simulated solar illumination for a variety of technologies (as compiled by Larry Kazmerski, National Renewable Energy Laboratory).

optics to compensate for high-cost converters. These approaches are cost-competitive with most of the thin-film technologies.

In addition, an emerging set of devices employ organic- or dye-based absorbers/acceptors including the Grätzel cell, organic photovoltaic cells, and a number of third-generation concepts including intermediate-band devices (i.e., devices that use an impurity level in the bandgap of the semiconductor to essentially split the gap to absorb more solar radiation), quantum dot solar cells, and multiple exciton devices. Some of these devices (i.e., the Grätzel cell and polymer-based bulk heterojunction devices) have demonstrated initially attractive efficiencies of >10% and >5%, respectively. Many of these devices can be fabricated with low-cost, solution-based, low-temperature, atmospheric-pressure processing approaches such as spray painting or inkjet printing.

The increasing manufacturing capacity in solar cells depicted in **Figure 1**, coupled with the uncertainties of fossil fuel energy sources, is clearly a significant driver for current photovoltaic technologies. Ultimately, however, there will be limits on how much the costs of current technologies can be reduced. Achieving truly competitive cost and efficiency might require breakthroughs even in mainstay technologies. This is represented by the red, black, and blue "learning curves" in **Figure 4**, where significant technological advances might be necessary to stay on the present trajectory at very high production volumes. This has driven more attention to the concept of third-generation PV technologies, as shown in **Figure 5**.[9,10] Here, the primary focus is on those approaches to solar energy conversion that strive to achieve very high efficiencies by exploiting processes that have smaller losses than a diode-based approach including hot-carrier collection, multiple electron–hole pair creation, and thermophotonics where the theoretical maximum efficiencies are in excess of the 31% Shockley–Queisser limit for a single-junction device. In this case, the allowed cost of the cell can be higher. An alternative is to develop moderate-efficiency devices (~15%) at extremely reduced costs. This is where printable organic solar cell devices and other approaches that are not capital- or energy-intensive might become important. Achieving the goal of <$0.30 per watt will require significant basic and applied science advancements over the next 20 years in a variety of technologies.

As we look to the future of solar energy, it is clear that materials science plays a critical role in this arena—in the near term for the improvement of Si, thin-film, and concentrator technologies and in the next 20–30 years for the development of third-generation technologies. Although the focus here is on cell- and

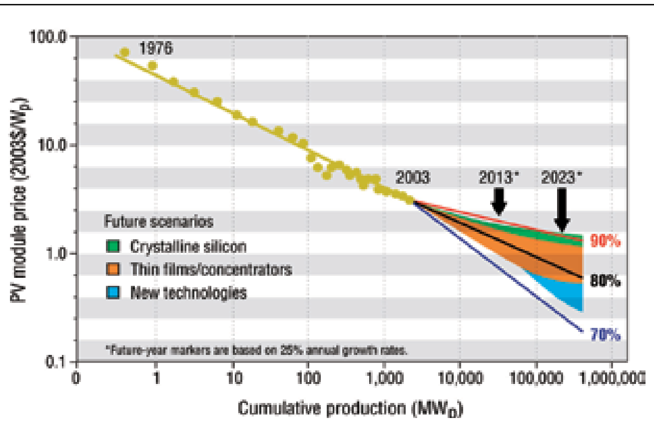

Figure 4. Historical and projected costs for wafer and film c-Si photovoltaic modules versus their cumulative production (in megawatts). Extrapolations for future technologies are also shown (from References 5 and 6). The 70%, 80%, and 90% curves represent learning curves for the technology; the lower the percentage, the more rapid the learning, and the more rapid the price decrease with increasing production.

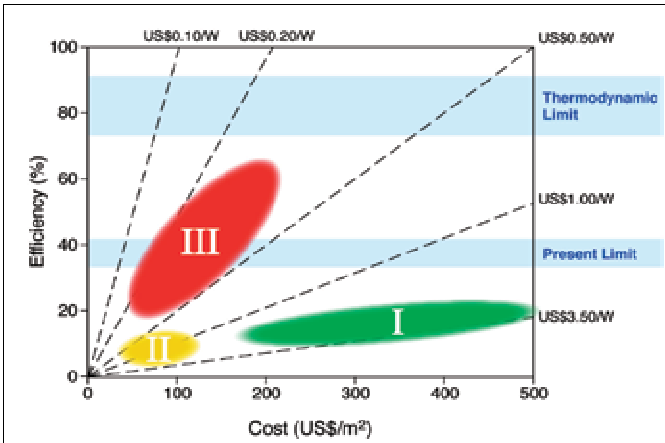

Figure 5. Cost-efficiency analysis for first- (I), second- (II), and third- (III) generation PV technologies (from Reference 9).

device-level materials science, it is important to keep in mind the broad range of materials considerations required for cost-effective solar conversion systems. For example, solar systems must have anticipated installation lifetimes and warranties of up to 25 years. To accomplish this goal, all of the system components must be long-lived, low-maintenance, and stable. This requires solar cell packaging, contacting (bus structures), and support structures to be stable in a wide variety of climates with extremes in temperature, humidity, and wind, for example. Crystalline Si and stabilized amorphous Si have been able to meet these challenges. To date, the other thin-film technologies have not been commercially available long enough to evaluate their lifetimes, making the ability to perform accelerated aging on modules to predict stability a critical emerging area of solar science. Coupled closely to the development of improved cost-effective photovoltaics is the eventual development of low-cost energy storage solutions, as discussed elsewhere in this issue (see the article and sidebar by Whittingham and the article by Crabtree and Dresselhaus). Also, as with all other technologies, PV modules contain valuable materials that will need to be recycled. Such considerations are generating interest in cradle-to-grave or lifecycle approaches by some solar companies (such as First Solar mentioned earlier), whereby they install and will eventually remove and recycle their products. The natural resource needs, environmental issues of the various technologies, and impacts of recycling on the efficacy of technologies that use scarce or toxic materials are also important considerations as the solar energy sector moves forward.

First-Generation Technologies

First-generation technologies are primarily crystalline Si (including large-grain poly- and single-crystalline) materials. **Figure 6** shows a 2 megawatt (MW) system installed at the Sacramento Municipal Utility District power station in Rancho Seco, Arizona.

The current technologies are rapidly evolving toward costs of \$1–2/W_p (see **Figure 4**). Key issues are Si feedstock supply, losses involved in preparing silicon wafers, and the development of lower cost high-throughput processing. To this end, a number of companies are exploring the use of ribbon-based technologies in which crystalline Si is grown as a thin sheet directly from molten Si. This avoids the kerf loss (materials lost by sawing) associated with cutting blocks of polycrystalline silicon or boules of single-crystal Si into wafers. To date, the materials produced by the ribbon approach have not yielded the efficiencies of wafer-based single-crystal materials, but their efficiencies are reasonable for commercial viability. Both the ribbon and boule technologies are striving to achieve thinner cells. A cell that is approximately 30 microns (μm) thick and has an efficiency comparable to that of current cells (which are 100–200 μm thick) would significantly reduce materials costs. Manufacturing such a cell would require new ways to process, contact, and handle such thin materials. For example, contacting could be done by inkjet noncontact printing instead of the screen-print approach currently employed.

Figure 6. Two megawatt system installed at the Sacramento Municipal Utility District power station in Rancho Seco, Arizona.

Second-Generation Technologies

Second-generation technologies are those that have demonstrated practical conversion efficiencies and potentially lower costs per watt than crystalline silicon, but that have no significant market penetration at present. Commercialization of these approaches is typically in the early manufacturing phase. This group represents a fairly broad base of technologies, including thin-film photovoltaics, solar concentrators, solar thermal conversion, and the emerging field of organic photovoltaics that sits between second- and third-generation technologies. The potential for producing power at substantially reduced cost has recently been demonstrated by First Solar for CdTe solar cells, with a reported manufacturing cost of \$1.25/W_p. Some of the key elements of thin-film inorganic PV approaches are summarized here, and further details can be found in a recent *MRS Bulletin* issue.[11]

Amorphous silicon has been the most commercially successful thin-film PV technology to date, with 5–6% of the total PV market. Devices are typically single- or triple-junction designs laid down in multiple layers by vacuum deposition processes such as sputtering and plasma-enhanced chemical vapor deposition (**Figure 7**). The continued development of these multijunction cells is a materials challenge pushing the limits of materials synthesis and processing that is still not fully understood.

Amorphous silicon is attractive because its bandgap is quasi-direct, leading to a larger absorption coefficient and hence thinner absorbing layers and less materials cost than crystalline silicon. That is, Si absorbs light less efficiently near its band edge (indirect gap) than does a-Si, in which absorption turns on very rapidly (direct gap). Alloying with Ge allows absorption to be tuned across a useful range of the solar spectrum as is shown in **Figure 7**.[12] Amorphous Si, however, suffers from a light-induced instability known as the Stabler–Wronski effect that causes the cell efficiency to degrade with time. Although the effect cannot, as yet, be eliminated, the extent of the degradation can typically be reduced to 10–20% of the as-manufactured (not aged) efficiency. Maintaining the initial efficiency of a-Si is one of the great materials science challenges facing this technology. Most of the work to limit this degradation is focused on controlling the hydrogen content and morphology of the film during growth. The same growth techniques used to deposit amorphous silicon can also be used to grow films consisting of nano- or microcrystalline silicon, either with or without an accompanying amorphous matrix, if the hydrogen content and deposition temperatures are changed, for example. These materials show crystalline, regularly ordered regions on a small length scale and usually form at increased process temperature. As grain size grows, the film begins to have more of the characteristics of polycrystalline silicon (also called polysilicon), with the energy gap becoming more indirect, thicker layers being required for complete absorption, and passivation becoming more important. Large-grain-size polycrystalline silicon thin films produced by solid phase crystallization of amorphous silicon are also being explored and are now in production (CSG Solar). In addition, combinations of polysilicon, amorphous silicon, and microcrystalline silicon are being explored to develop low-cost thin-film silicon solar cells on glass that could substantially reduce costs for large-area production.

High-Efficiency Concentrators

The highest efficiency solar cells known are multijunction cells based on GaAs and related groups III–V materials. Here, very sophisticated molecular beam epitaxy or metal–organic chemical vapor deposition (MOCVD) techniques are employed to grow a multilayer structure such as the triple-junction cell illustrated in **Figure 8**. These cells are too expensive for large-area applications but are usually used at the focus of mirrors or lenses that concentrate the solar light by a factor of 50–1,000. For maximum efficiency, the optic collection system must track the sun, which adds mechanical complexity to the system. However, by concentrating the solar energy by up to 500 times, the cost of the cell can be reduced to the point that the cost of the optics dominates. Thus, if inexpensive optics and trackers can be developed, the technology is very competitive with thin-film technologies. This is a significant materials challenge in its own right.

The efficiency of a single-junction device is limited by transmission losses of photons with energies below the bandgap and thermal relaxation of carriers created by photons with energies above the bandgap. The purpose of a multijunction device is to capture a larger fraction of the solar spectrum while minimizing thermalization losses. By stacking cells in order of their bandgaps, with the cell with the largest bandgap at the top, light is automatically filtered as it passes through the stack, ensuring that it is absorbed in the cell most efficiently able to convert it. Another elegant simplification is that, if bandgaps are appropriately selected, all of the cells in the stack will generate close to the same current, so the cells can be simply interconnected in series. **Figure 8** shows how a three-junction cell splits the solar spectrum, leading to a theoretical efficiency of 52% of the incoming energy converted to useful power for this particular combination of materials. The theoretical limit for multijunction devices where the number of junctions can be unlimited is above 60%. The best efficiencies to date have actually been over 40%, as recently reported for Spectrolabon multijunction cells with solar concentration. Achieving much higher efficiencies might require an increase in the number of junctions and/or integration of new absorber materials with more optimal bandgaps into the devices.[13] The added complexity of concentrator systems, which must use tracking and concentrating optics, raises other issues such as appropriate site locations for tracking concentrators and the potential reliability/maintenance questions for active mechanical devices. The concentrator approach also collects little of the diffuse (scattered) solar radiation.

Solar Thermal Conversion

Historically, the most prevalent use of solar thermal systems has been flat-plate systems for domestic hot water or heating.

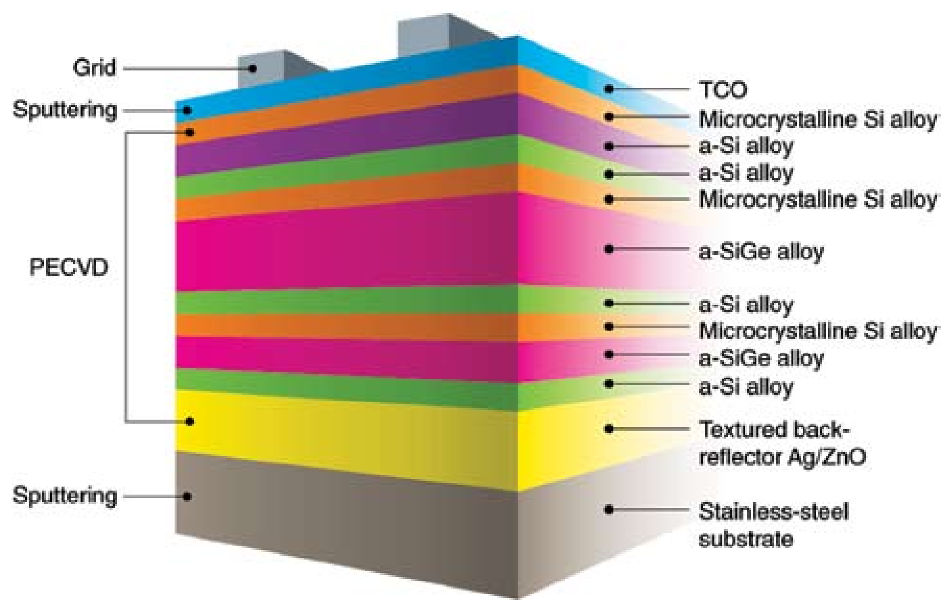

Figure 7. Triple-junction spectrum-splitting amorphous (Si/Ge and Si) and microcrystalline silicon solar cell structure produced on a flexible steel substrate. *Note:* TCO, transparent conducting oxide; PECVD, plasma-enhanced chemical vapor deposition. (From United Solar Ovonic.)

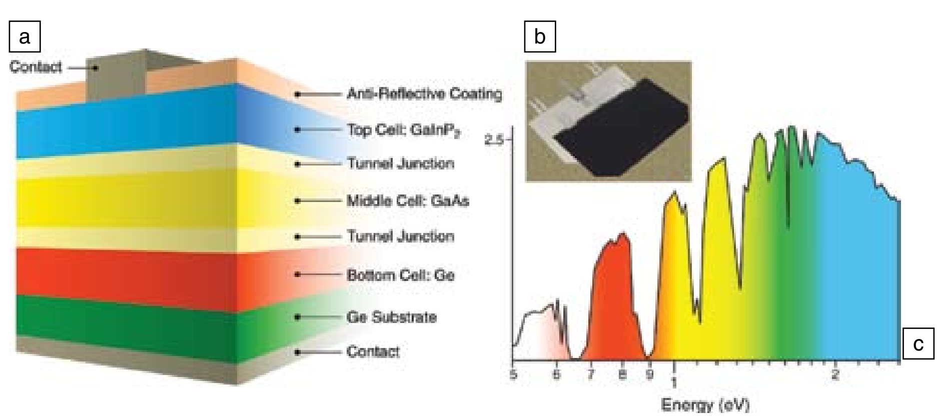

Figure 8. (a) Schematic of a possible configuration for a three- (triple-) junction device and (b) picture of a GaInP/GaAs/GaInAs cell with a demonstrated 31.3% efficiency. (c) Solar spectrum illustrating the basic approach for spectrum splitting by a multijunction cell. A four-junction device with bandgaps of 1.8 eV, 1.4 eV, 1.0 eV, and 0.7 eV would have a theoretical efficiency of >52%.

Worldwide, this is perhaps the largest use of solar energy at present, estimated at up to 88 gigawatts (GW) per year according to an Environment California report. In fact, solar hot water is required for new housing in some countries such as Israel. These systems can be either passive or active. A passive system typically uses no pumps and depends on a gravity feed, as shown in **Figure 9**. These systems represent an important energy-saving technology that can be applied almost anywhere.

More recently, large-area solar thermal systems have emerged as a promising option. Such systems use concentrating collectors for the solar radiation and heat a working fluid to a high temperature; the hot fluid can then be easily stored and utilized later to make steam to turn a turbine to generate electrical power. **Figure 10** shows the solar power tower in California, which uses molten salts as a working fluid to produce 10 MW of power.

Other approaches to central solar thermal power include parabolic dish systems and parabolic trough systems. All of the systems operate at relatively high temperatures, ideally 400°C or higher. This enables *in situ* storage and ready generation of steam. Key materials challenges lie in the development of working fluids for solar collectors that are stable throughout the broad temperature range experienced and have high heat capacities (amount of heat stored per molecule) but are still low in cost. New working fluids include polysilicones, nanostructured fluids, and molten salts. The other major area is the development of high-efficiency optical coatings for mirrors and for the absorption of solar energy. Estimates are that solar thermal electrical power production could be up to 7 GW by 2015. (See the sidebar by Tritt et al. for further information.)

Figure 9. Passive solar hot water system on a residential roof top.

Figure 10. Solar 2 power tower in Barstow, California. The plant uses a combination of 60% sodium nitrate and 40% potassium nitrate as a working fluid and heat storage medium.

High-Efficiency Thin Films

Figure 11 shows typical cross sections of polycrystalline $Cu(InGa)Se_2$ (CIGS or CIS with no Ga) and CdTe solar cells. Laboratory efficiencies for the former are approaching 20% (**Figure 3**),[14,15] and a large number of companies around the world are developing a variety of manufacturing approaches aimed at low-cost, high-yield, large-area devices that maintain laboratory-level efficiencies.

Materials challenges exist regarding each layer of these devices, as well as the interactions between layers, beginning with the search for improved transparent conducting oxide (TCO) contacts. Such contacts need to be made from low-cost, plentiful elements; have high conductivities and high transparencies in the visible spectrum; and allow for easy electrical isolation of devices.

Another example is provided by the thin CdS contact layer in both devices that also functions as a window for solar radiation. Because CdS absorbs in the blue wavelength range, it is important that this layer be thin. When the layer is too thin, however, pinholes between the TCO contact and the absorber layer create short circuits. This is especially problematic for CdTe cells, in which diffusion of sulfur into the CdTe layer during post-growth annealing further decreases the CdS layer thickness. The inclusion of thin buffer layers between the TCO and the CdS, such as a highly resistive transparent oxide, improves efficiency.[15,16] The exact role of the buffer layer, whether it simply introduces resistance into short circuits or changes the interfacial energetics, is not well understood, and optimization of this interface is a critical need. As can be seen in **Figure 11**, although the absorbing CIGS and CdTe films are thin (ideally 1 μm and 5 μm, respectively), the grain size for efficient devices is a large fraction of the thickness. In the case of CdTe, this large grain size is achieved by a post-deposition annealing in the presence of $CdCl_2$ and oxygen, which promotes low-temperature grain growth. Finding controllable and manufacturable methods for performing this annealing treatment, or, better still, for incorporating it directly into the growth process, is an active area of research and development. The highest efficiency CIGS films are produced by physical vapor deposition, in which the grain microstructure is defined by a complex evolution from Cu-rich to In- and Ga-rich phases dur-

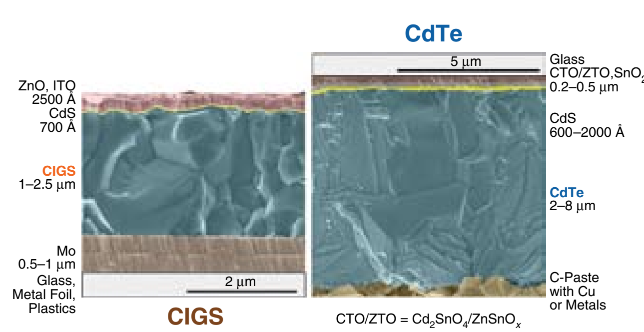

Figure 11. Cross-sectional scanning electron microscopy images of a $Cu(InGa)Se_2$ (CIGS) solar cell (left) and a CdTe cell (right). The absorber layers are 1–2.5 and 2–8 μm thick, respectively. CTO (cadmium tin oxide) and ZTO (zinc tin oxide) are transparent conducting oxides used as transparent electrical contacts to the solar cell.

ing growth.[17] Reproducing this growth path with other more manufacturable deposition options is a major challenge. Incorporation of Na^+ ions, which occurs naturally as an aspect of growth on soda lime glass substrates, is also important to optimizing the CIGS device efficiency. Although there is no definitive explanation for the beneficial effects of Na, Na is believed to reduce the resistivity of the film and possibly increase the grain size.[18] The defect structures at the grain boundaries in both CIGS and CdTe are just beginning to be understood and are believed to play a dominant role in both minority carrier lifetime and carrier collection. Other absorber layer materials and processing issues that affect cell costs include the need to lower growth and processing temperatures which presently exceed 500°C for the highest efficiency films, and the desire to use thinner films without loss of absorption. The latter goal requires methods for increasing the optical path length through back-reflection, texturing, or light trapping.

For the back contact, significant challenges exist in understanding and improving the electronic and structural characteristics of these layers in both CIGS and CdTe devices. Delamination issues, for example, in CIGS cells are typically correlated with problems in the molybdenum back contact layer. Finally, we note that, although both CIGS and CdTe technologies have demonstrated good operating lifetimes, both are sensitive to moisture. They are presently protected by being sealed between glass plates. A thin-film encapsulation approach that provides a moisture barrier without compromising efficiency could be a significant advance. Beyond the simple thin-film cells depicted in **Figure 11** is the potential to combine thin-film materials, Si, a-Si, CIS, and CdTe to form tandem cells that capture more of the solar spectrum, analogously to the previously mentioned multijunction concentrator structures. Such an approach would place even more stringent requirements on understanding and controlling the interfaces between dissimilar materials.

Organic Photovoltaic Cells

As detailed in a recent *MRS Bulletin* issue,[19] organic photovoltaics (OPV) represents a rapidly emerging device technology with the potential for low-cost non-vacuum-processed devices. OPV devices have rapidly moved from very low efficiency to efficiencies obtained by Plextronics and Konarka of 5.4% and 5.2%, respectively, as documented by the National Renewable Energy Laboratory (NREL). The key is that these devices combine polymers, small molecules, and inorganic nanostructures to build an excitonic-based structure. An excitonic solar cell first goes through an excited bound electron–hole state that subsequently generates charge carriers (which can do work in an external circuit) by decomposing at an interface. The charge carriers are then collected conventionally. Although the excitonic mechanism is different from the conventional PV mechanism, the theoretical efficiency is the same as for conventional semiconductor devices, with a cost structure similar to that for plastics processing, leading to the potential for significant reductions in cost per watt. The development of materials for OPV systems is being leveraged by the emergence of an organic electronics industry based on displays (organic light-emitting devices, OLEDs) and transistors.[20,21] A key aspect of OPV technology is that the organic small-molecule and polymer materials that are being investigated are inherently inexpensive; typically have very high optical absorption coefficients (very thin films work); are compatible with plastic substrates; and can be fabricated using high-throughput, low-temperature approaches by low-capital-cost roll-to-roll processes.[22] Thus, if efficiencies are comparable to or even slightly lower than those of existing technologies, there might be compelling cost arguments favoring OPV devices. Another important aspect of organic materials is their versatility. Organics exhibit a remarkable flexibility in the synthesis of basic molecules, allowing for alteration of a wide range of properties, including molecular weight, bandgap, molecular orbital energy levels, wetting properties, structural properties (such as rigidity, conjugation length, and molecule-to-molecule interactions), and doping. The ability to design and synthesize molecules and then integrate them into organic–organic and inorganic–organic composites provides a unique pathway in the design of materials for novel devices. Additionally, with the abilities to alter the color of the device, fabricate devices on flexible substrates, and potentially print them in any pattern, OPV cells can be integrated into existing building structures and into new commercial products in ways impossible for conventional technologies.

A number of key issues must be overcome for the ultimate success of OPV technology. One is the development of red absorbing molecules to utilize more of the solar spectrum without losing open-circuit potential. It is also necessary to develop optimized interfaces at the nanoscale that allow for exciton decomposition, charge transfer and optimization of the morphology of the organic constituent. Additionally, a key materials issue faced by the organic electronics community in general is the stability of the organic materials. It is encouraging that, for instance, automotive paints contain chromophores that are similar to molecules commonly used in OPV devices and that organic light-emitting displays are demonstrating acceptable lifetimes under high injection currents. Device degradation pathways stem largely from changes in morphology, loss of interfacial adhesion, and interdiffusion of components, as opposed to strictly chemical decomposition. Thus, careful design, prudent materials engineering, and improved encapsulation should substantially improve device lifetimes. In fact, the issue of encapsulation is important to all PV technologies and is becoming an increasingly active area of research. Development of encapsulants that are stable for 10–25 years with no yellowing and no diffusion of oxygen or water, that have low initial costs, and that are easy to process is a significant challenge. Increasingly, as for the OPV devices themselves, researchers are considering nanomaterial/polymer composites for sealants in which both elements scavenge impurites and slow diffusion. There are also efforts to develop new polymers with very little diffusion or photosensitivity to be the top and bottom layers for flexible PV devices.

Third-Generation Technologies

The term "third-generation photovoltaics" originally was coined to describe an "ultimate" thin-film solar cell technology. Features specified included high efficiency (derived from operating principles that avoided the constraints upon the performance of single-junction cells) and the use of abundant, nontoxic, and durable materials. In general usage, however, the term has been applied to any advanced photovoltaic technology ranging from organic cells to three-junction multijunction concentrator cells.

The multijunction approach discussed earlier is one of the best known and most investigated approaches meeting the aim of improving on the performance of single-junction cells. Efficiency ideally is limited merely by the number of cells in series; however, practical considerations tend to limit devices to between three and five junctions. Although the best cells do not meet the original definition of third-generation technology because they are not thin films and they use toxic and nonabundant materials, these disadvantages are not as severe in solar concentrating systems.[23] Such concentrating systems closely resemble solar thermal electric systems, particularly dish-Stirling and power tower concepts, although the photovoltaic conversion unit is simpler, is potentially more reliable, and now has higher conversion efficiencies. (Note that a dish-Stirling system generates power by using parabolically arranged mirrors to reflect sunlight onto a small focal receiver, thereby heating a gas chamber connected to a piston and drive shaft. The drive shaft powers a generator that produces electricity to be distributed to a grid.)

The multijunction cell approach is also being extended to much less expensive and more exploratory materials systems. The approach potentially has the same efficiency advantages, for example, in organic and dye-sensitized solar cells, but in this case, the difficulty is finding a stable, low-bandgap cell that uses similar/compatible materials. Combinations of these materials with inorganic cells that have a lower absorption threshold have worked well, but such devices violate the basic guideline that the best cells need to be on top in a stacked cell design. Another multijunction approach explores the use of quantum confinement to increase silicon's bandgap and hence allow implementation of a higher temperature "all-silicon" tandem cell.[24] By embedding Si quantum dots in a matrix of silicon oxide, nitride, or carbide, an increased optical bandgap has been demonstrated (**Figure 12**). Transport of photogenerated carriers is determined by dot density because, the closer the dots, the easier it is for carriers to tunnel between them. Stacks of either one or two of these quantum dot cells on top of a thin-film Si bottom cell have been proposed, with the effective bandgap of each cell determined by dot size.

Figure 13 shows the thermodynamic limiting efficiency for multijunction designs as well as a range of other options suggested as possible third-generation approaches. For diffuse sunlight, the thermodynamic limit on the terrestrial conversion of sunlight to electricity is about 74%, although the limit for conversion approaches that are time-symmetric is somewhat lower at 68%. A multijunction cell with a large number of cells in the stack can theoretically approach this limit, with limiting efficiency steadily dropping as the number of cells in the stack decreases, bottoming out at 31% for a single cell. (The best single laboratory cells made from Si or GaAs reach about 80% of this limiting efficiency.)

Hot-carrier cells also have close to the maximum theoretical performance potential. Rather than introducing complexity by stacking a large numbers of cells as in the multijunction approach, hot-carrier designs transfer the complexity to their operating physics (**Figure 14**). Although hot-carrier cells could be implemented as "simple" two-terminal devices and would almost certainly be very thin because of operating requirements, these requirements are severe. Unlike conventional cells, where photoexcited carriers quickly thermalize with the cell atomic lattice, a hot-carrier cell has to be designed so that the carriers are collected before this thermalization occurs. This suggests small transport distances and techniques for reducing the interaction between the carriers and the host lattice. Progress in nanostructural engineering aimed at controlling lattice vibrational properties might provide some opportunities here. Increasing the challenge further is the fact that careful attention has to be paid to the interface between the hot carriers and the outside world. Ideally, transfer should occur over only a narrow range of energies to prevent cooling of the hot carriers, again providing practical challenges. Resonant tunneling through quantum dots has been suggested as one way of meeting this requirement.

Next in efficiency in **Figure 13** come the thermal approaches. A limiting efficiency of 54% applies to diffuse light conversion using such approaches. For direct sunlight conversion, such as for the concentrating solar power systems discussed earlier, this limiting efficiency jumps to 85% (but this value applies to only the fraction of the available light that is direct). The multiple processes in series in this case, as well as temperature constraints, limit practical efficiencies to only a fraction of this value.

Three other classes of approaches are also included in **Figure 13**. The first is based on multiple-step excitations between different energy levels deliberately introduced into a material. Again, nanostructures are being investigated as a means of introducing different ranges of available energies within a material so that two-step excitations are possible. The limiting efficiency is identical to that possible using optical upconverters, which could be placed at the rear of a cell.[25] In this case, two low-energy photons, which are not able to cause excitations in the cell individually, can be combined in the upconverter in two-step excitation to produce one higher energy photon, which the cell can use. There is also some advantage in using down-conversion,[26] where one high-energy photon produces two (or more) lower energy photons prior to the light entering the cell.

The final option shown in **Figure 13** is impact ionization (see also **Figure 15**) but also includes multiple exciton generation (MEG), an approach that has created much recent interest. Evidence for the creation of up to eight excitons from a single photon has been found in PbS, PbSe, PbTe, CdSe, and InAs quantum dots, with more recent work

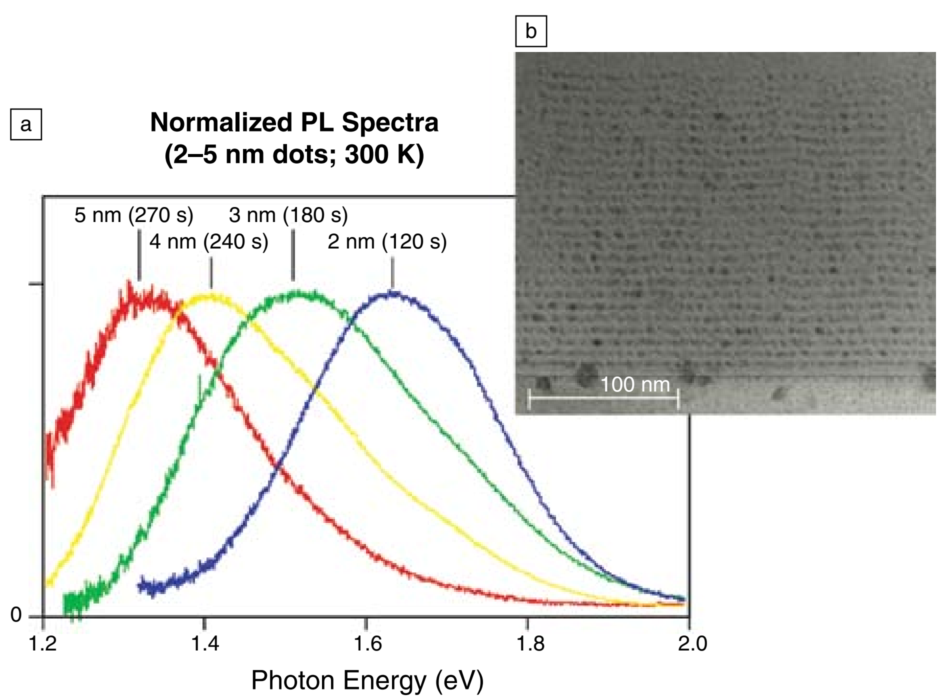

Figure 12. Silicon quantum dots in an oxide material (micrograph) and resulting photoluminescence (PL) spectra as a function of quantum dot diameter. (a) Different particle sizes and associated PL wavelengths and (b) high-resolution transmission electron microscope image of the 5-nm particles for illustration. Numbers in parentheses represent lifetime in microseconds.

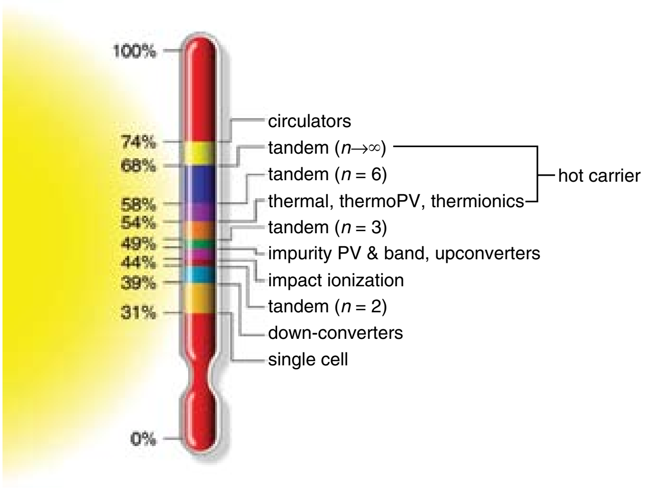

Figure 13. Third-generation options and thermodynamic limits on their efficiency. Upconverters include multi-excitonic approaches. *Note: n* is the number of cells in the stack.

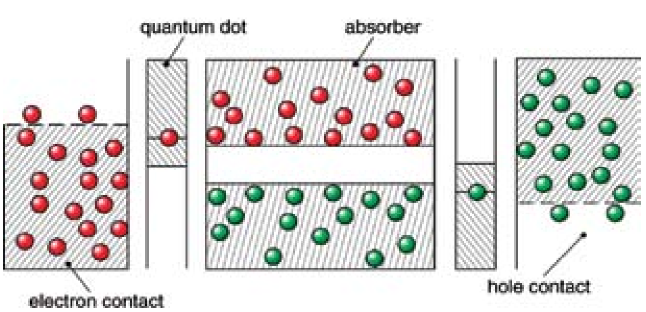

Figure 14. Hot-carrier cell schematic. Special properties are required for both the absorption volume and the carrier collection contacts.

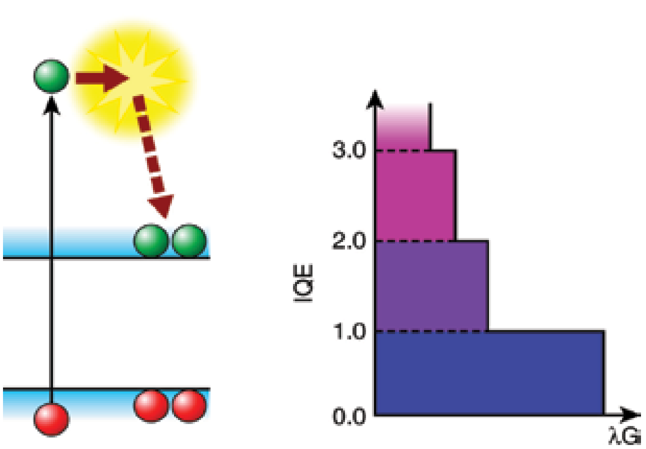

Figure 15. Impact ionization whereby more than one carrier pair is created by an incident photon (left), leading to the ideal internal quantum efficiency (IQE) as a function of excitation wavelength (λG) (right).

showing MEG in Si quantum dots as well.[27] What is now needed is a way of converting these multiple excitons to electrons doing useful work.

It is clear that new materials, particularly nanomaterials, are closely linked to current third-generation research efforts. The flexibility offered by nanomaterials in the engineering of critical materials properties might allow for the eventual implementation of even the more challenging of these approaches.

Summary

As discussed herein, the solar power industry, both PV and thermal technologies, is on track to become an increasingly significant component of future global energy supplies. Although the industry is currently based on Si, ultimately, Si might not be able to meet long-term cost goals, opening the door to thin films and solar thermal conversion. Significant materials challenges exist for these technologies as well, but they are nearing manufacturability on a large scale, as evidenced in the recent growth of CdTe production. New high-efficiency or low-cost technologies such as multijunction and organic-based devices are advancing rapidly and might have second- and third-generation embodiments. Finally, new very high-efficiency approaches to solar energy conversion offer the potential in the extended time frame to produce devices that can convert much larger portions of the solar spectrum. Given the anticipated market growth, nearly all of these approaches will have to be investigated in parallel to meet the demand.

Given the length of this article, the discussions of various solar technologies were of necessity brief, and adequate credit could not be given to all of the many leading scientists who have contributed to this field. For more information, interested readers are referred to the works previously cited as well as to the following resources on specific aspects of solar technology and the references cited therein: Si and thin-film inorganic photovoltaics,[28–31] organic photovoltaics,[32,33] third-generation photovoltaics,[34,35] and solar thermal electricity.[36]

References

1. Energy Information Administration, *Annual Energy Review 2003* (EIA, 2004; www.eia.doe.gov/emeu/aer/contents.html) (accessed January 2008).
2. W. Shockley, H.J. Queisser, *J. Appl. Phys.* **32** (3), 510 (1961).
3. International Electrotechnical Commission, “IEC Norm” (IEC-904-3, 1989).
4. S. Taira, Y. Yoshimine, T. Baba, M. Taguchi, H. Kanno, T. Kinoshita, H. Sakata, E. Maruyama, M. Tanaka, *Proceedings of the 22nd European Photovoltaic Solar Energy Conference and Exhibition, Milan, Italy*, **4**, 932 (September 2007).
5. M.A. Green, K. Emery, D.L. King, Y. Hishikawa, W. Warta, *Prog. Photovoltaics: Res. Appl.* **15** (1), 35 (2007).
6. T. Surek, *J. Cryst. Growth* **275** (1–2), 292 (2005).
7. R.M. Margolis, Presented at NCPV Solar Program Review Meeting, Denver, CO, 2003.
8. D. Eaglesham, “First Solar, Inc. Announces 2006 Fourth Quarter and Year-end Financial Results” (First Solar, Phoenix, AZ, 2007; http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=229824) (accessed January 2008).
9. M.A. Green, *Physica E* **14** (1–2), 65 (Amsterdam, The Netherlands, 2002).
10. M.A. Green, *Photovoltaics for the 21st Century: Proceedings of the Electrochemical Society* **2001–10**, 3 (2001).
11. A. Slaoui, R.T. Collins, *MRS Bull.* **32** (3), 211 (2007).
12. B. Yan, G. Yue, J.M. Owens, J. Yang, S. Guha, *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, HI*, **2**, 1477 (2006).
13. F. Dimroth, S. Kurtz, *MRS Bull.* **32** (3), 230 (2007).
14. M.A. Contreras, M.J. Romero, R. Noufi, *Thin Solid Films* **511–512**, 51 (2006).
15. X. Wu, *Solar Energy* **77** (6), 803 (2004).
16. M.A. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon, R. Noufi, *Prog. Photovoltaics: Res. Appl.* **7** (4), 311 (1999).
17. J. AbuShama, R. Noufi, Y. Yan, K. Jones, B. Keyes, P. Dippo, M. Romero, M. Al-Jassim, J. Alleman, D.L. Williamson, *Cu(In,Ga)Se_2 Thin-Film Evolution During Growth from (In,Ga)$_2$$Se_3$ Precursors* (Mat. Res. Soc. Symp. Proc. Vol. **668**, Warrendale, PA, 2001).
18. A. Romeo, M. Terheggen, D. Abou-Ras, D.L. Batzner, F.J. Haug, M. Kalin, D. Rudmann, A.N. Tiwari, *Prog. Photovoltaics: Res. Appl.* **12** (2–3), 93 (2004).

19. S.E. Shaheen, D.S. Ginley, G.E. Jabbour, *MRS Bull.* **30** (1), 10 (2005).
20. G. Collins, *Sci. Am.* 74 (2004).
21. D.M. de Leeuw, *Phys. World* **12** (3), 31 (1999).
22. S.E. Shaheen, R. Radspinner, N. Peyghambarian, G.E. Jabbour, *Appl. Phys. Lett.* **79** (18), 2996 (2001).
23. G. Hering, *Photon Int.* **10**, 92 (2006).
24. M.A. Green, in *Future Trends in Microelectronics: Up to Nano Creek,* S. Luryi, J. Xu, A. Zaslavsky, Eds. (Wiley Interscience, New York, 2007), p. 391.
25. T. Trupke, M.A. Green, P. Wurfel, *J. Appl. Phys.* **92** (7), 4117 (2002).
26. T. Trupke, M.A. Green, P. Wurfel, *J. Appl. Phys.* **92** (3), 1668 (2002).
27. M.C. Beard, K.P. Knutsen, P. Yu, J.M. Luther, Q. Song, W.K. Metzger, R.J. Ellingson, A.J. Nozik, *Nano Lett.* **7** (8), 2506 (2007).
28. R.W. Miles, G. Zoppi, I. Forbes, *Mater. Today* **10** (11), 20 (2007).
29. R. Messenger, D.Y. Goswami, H.M. Upadhyaya, T.M. Razykov, A.N. Tiwari, R. Winston, R. McConnell, in *Energy Conversion*, D. Yogi Goswami, F. Kreith, Eds. (CRC Press, Boca Raton, FL, 2007), p. 20.
30. M. Green, *J. Mater. Sci.* **18** (Suppl. 1), S15 (2007).
31. *MRS Bull.* **32** (3), (2007).
32. A.J. Mozer, N.S. Sariciftci, in *Handbook of Conducting Polymers*, T.A. Skotheim, John Reynolds, Eds. (CRC Press, Boca Raton, FL, ed. 3, 2007), vol. 2, p. 10.
33. *MRS Bull.* **30** (1), (2005).
34. G. Conibeer, *Mater. Today* **10** (11), 42 (2007).
35. A. Luque, A. Marti, A.J. Nozik, *MRS Bull.* **32** (3), 236 (2007).
36. D. Mills, *Solar Energy* **76** (1–3), 19 (2004). □

Another Pathway to Large-Scale Power Generation: Concentrating Solar Power

Mark Mehos (National Renewable Energy Laboratory, USA)

CSP's Great Potential

Photovoltaics is not the only means of using sunlight to generate electricity. Another major solar technology is called "concentrating solar power" or CSP. CSP technologies use concentrating optics to generate high temperatures that are used to drive conventional steam or gas turbines. CSP is generally considered a central generation technology, rather than a source of distributed generation. That is, a large amount of power is generated in one location, with transmission and distribution to the various points of use, rather than generating small amounts of the power at numerous points of use. Because of this feature, CSP is predominantly a utility-scale source of power.

A 2005 study commissioned by the Western Governors' Association (WGA) looked at the solar resource and suitable available land in seven southwestern U.S. states (California, Arizona, Nevada, Utah, Colorado, New Mexico, and Texas) and calculated a capability of generating up to 6,800 gigawatts (GW) using CSP technologies—almost seven times the current electric generating capacity of the entire United States. It should be noted that this Geographic Information Systems (GIS) analysis determined optimal CSP sites with high economic potential by excluding regions in urban or sensitive areas (e.g., national parks), regions with low solar resource (e.g., those with insufficient hours of daily direct-normal radiation), and regions where terrain would inhibit the cost-effective deployment of large-scale plants (e.g., terrain that had more than a degree or two of slope). Other factors considered included land ownership, road access, local transmission infrastructure capabilities, and state policies and regulations. The WGA study found that, with a build out of only 2–4 GW of CSP, the technology will be competitive with conventional natural-gas-fired combined-cycle plants with a cost of less than $0.10 per kilowatt-hour. With increasing capacity and further research and development in thermal storage, CSP can be competitive with future coal-based generation, especially when considering the cost and performance impact of carbon constraints on future plants.

However, the southwestern United States is not the only area with great potential for CSP. Projects are under way in Spain and Northern Africa (e.g., Egypt, Algeria, and Morocco), with additional projects planned for Israel, the Middle East, Northern Mexico, and Australia. In total, over 40 utility-scale CSP plants are in construction or under various stages of development worldwide. These projects will lead to significant deployment in other regions with high solar resources, which includes areas with extended periods of sunny skies and relatively few clouds.

Three Basic CSP Systems

The three main types of concentrating solar power systems are parabolic trough systems, dish/engine systems, and power tower systems. Variants of these systems are also being considered, such as the compact linear Fresnel reflector system, which uses flat, rather than parabolic, mirrors with a Fresnel lens to concentrate the solar thermal energy.

Parabolic trough systems concentrate the sun's energy through long, rectangular, curved mirrors (see **Figure 1**). The mirrors are tilted toward the sun, focusing sunlight on a receiver,

Figure 1. Aerial photograph of Acciona's Nevada Solar One, a 64 MW parabolic trough power plant near Las Vegas, Nevada, that covers 280 acres (*Credit:* Acciona Solar Power). Inset: Closeup of an individual parabolic trough unit at Kramer Junction, California, showing the curved mirror and the receiver (*Credit:* Henry Price).

which is a special tube that runs along the focal line of the trough, with heating oil flowing through the receiver. The hot oil is then used to boil water in a conventional steam generator to produce electricity. Alternatively, water can be boiled directly in the receiver using a direct-steam receiver. As with towers, parabolic trough systems can use thermal storage, thus giving the systems the flexibility to dispatch electricity coincident with peak utility loads, which often occur late in the evening. Currently, parabolic trough systems are the most commercially developed technology, but the other technologies are also starting to see commercial deployment.

A dish/engine system uses a mirrored dish, similar to a very large satellite dish. The dish-shaped surface collects and concentrates the sun's heat onto a receiver, which absorbs the heat and transfers it to a gas within a Stirling engine (i.e., a closed-cycle regenerative hot-air engine) or gas turbine. The heat allows the gas to expand against a piston (Stirling engine) or power a turbine to produce mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity.

A power tower system uses a large field of mirrors to concentrate sunlight onto the top of a tower, where a receiver is located. This focused sunlight heats a working fluid such as molten salt or water/steam flowing through the receiver. Similar to oil in a parabolic trough receiver, the salt in a tower receiver is used to generate steam (using heat exchangers) to generate electricity through a conventional steam generator. Molten salt can be stored in tanks, allowing separation of the collection of solar energy from the generation of electricity. This is an important consideration for many areas of the U.S. southwest, where the peak utility loads often occur after the sun has set in the evening. Future low-cost storage options should allow both troughs and towers to operate as baseload plants, potentially displacing coal-based generation.

Energy, Security, and Environmental Benefits of CSP

As CSP generates electricity, it also generates significant benefits related to energy, security, and the environment. First, as the WGA study determined, CSP can provide a huge capacity of electrical generation within the southwest U.S states. This utility-scale power is generally considered intermediate-load generation (capacity factors in the range of 30–70%), although advances in thermal storage as mentioned previously will provide baseload status in the future. Second, the "fuel" for these systems is sunlight—a domestic resource in all countries. Therefore, CSP technologies bolster energy security by not requiring imported fuel and decreasing the use of other conventional fuel sources such as coal and natural gas. Finally, the environmental impact of CSP is also low, both in the manufacturing of the systems and during normal operations.

Materials-Related CSP Issues

The main challenges related to materials research and development (R&D) are in the areas of optical materials (i.e., absorbers and reflectors) and heat-transfer/storage fluids. In advanced absorber materials, the important factors are high absorbtivity, low emissivity, and good performance at high temperatures. In advanced reflectors, key factors are high reflectivity, high durability, and low cost.

One way to reduce the cost of parabolic trough technology is to increase the operating temperature of the solar field from 400°C to 500°C or higher. Therefore, a materials-related challenge is to develop new, more efficient selective coatings for the absorbers that have both high solar absorbances and low thermal emittances at 500°C. Moreover, although the absorbers are likely to be used in an evacuated environment, the coatings need to be stable in air in case the vacuum is breached.

Selective absorber surface coatings can be categorized as intrinsic, semiconductor–metal tandems, multilayer absorbers, metal–dielectric composite coatings, textured surfaces, or selectively solar-transmitting coatings on a blackbody-like absorber. Intrinsic absorbers use a material having intrinsic properties that result in the desired spectral selectivity. Semiconductor–metal tandems absorb short-wavelength radiation because of the semiconductor bandgap and have low thermal emittance as a result of the metal layer. Multilayer absorbers use multiple reflections between layers to absorb light and can be tailored to be efficient selective absorbers. Metal–dielectric composites—cermets—consist of fine metal particles in a dielectric or ceramic host material. Textured surfaces can produce high solar absorbances by multiple reflections among needlelike, dendritic, or porous microstructures. Additionally, selectively solar-transmitting coatings on a blackbody-like absorber are also used but are typically found only in low-temperature applications. To achieve the stated properties of high absorbance and low emittance at high temperatures, CSP research has focused on multilayer cermets.

For reflectors, environmental concerns are causing researchers to explore new designs for manufacturing mirrors. For example, some scientists are studying thin-glass mirrors with copper-free reflective surfaces that use lead-free paints. This basic mirror construction is radically different from the historical constructions, and outdoor durability must be determined and any problems mitigated to achieve a commercially viable product. Scientists are also developing mirrors using a silvered polymer commercial laminate construction. Another option is front-surface reflectors that use a silvered substrate protected by an alumina hardcoat deposited under high vacuum by ion-beam-assisted deposition. All of these reflectors must be able to be produced at low cost and must maintain high specular reflectance for lifetimes of 10–30 years under severe outdoor conditions.

Further materials R&D is also needed in thermal energy storage, which includes developing advanced thermal storage materials and improving heat-transfer fluids. Note that the electricity generated by CSP can be stored in technologies discussed elsewhere in this *MRS Bulletin* issue, such as batteries and flywheels (see the article and accompanying sidebar by Whittingham). However, storage in the realm of CSP specifically refers to effectively storing *thermal* energy in the system, which is much more efficient and cost effective than other forms of storage at this time. This stored thermal energy can then be used to generate electricity at a later time, when the solar resource may not be available. Materials with improved heat-capacity characteristics will extend the storage capabilities and overall generating efficiency of CSP systems.

Castable ceramic and high-temperature concrete are being tested for solid-media, sensible-heat storage systems (i.e., systems in which the addition or removal of heat results in a change in temperature). Other scientists are pursuing the development of improved phase-change materials such as high-temperature nitrate salts to allow large amounts of energy to be stored in relatively small volumes (for example, see the article and sidebar by Judkoff and Bonfield, respectively, in this issue).

For further information on CSP technology, the interested reader can consult References 1–7.

References

1. D.M. Blake, L. Moens, D. Rudnicki, H. Pilath, *J. Solar Energy Eng.* **128** (1), 54 (2006).
2. U. Hermann, D. Kearney, *J. Solar Energy Eng.* **124** (2), 145 (2002).

3. C.E. Kennedy, "Review of Mid- to High-Temperature Solar Selective Absorber Materials" (NREL Report TP-520-31267, NREL, Golden, CO, 2002; www.nrel.gov/csp/troughnet/pdfs/31267.pdf) (accessed January 2008).
4. C.E. Kennedy, H. Price, "Solar Engineering 2005: Proceedings of the 2005 International Solar Energy Conference" *(ISEC2005), 6–12 August 2005, Orlando, Florida* (NREL Report CP-520-36997, American Society of Mechanical Engineers, New York, 2006; www.nrel.gov/csp/troughnet/pdfs/36997.pdf) p. 749 (accessed January 2008).
5. C. Kennedy, K. Terwilliger, M. Milbourne, "Development and Testing of Solar Reflectors" (NREL Report CP-520-36582, NREL, Golden, CO, 2005; www.nrel.gov/docs/fy050stify05osti/36582.pdf) (accessed January 2008).
6. L. Moens, D. Blake, "Advanced Heat Transfer and Thermal Storage Fluids" (NREL Report CP-510-37083, NREL, Golden, CO, 2005; www.nrel.gov/docs/fy050stify05osti/37083.pdf) (accessed January 2008).
7. R.G. Reddy, Z. Zhang, M.F. Arenas, D.M. Blake, *High Temp. Mater. Processes* **22** (2), 87 (2003). □

Thermoelectrics: Direct Solar Thermal Energy Conversion

Terry M. Tritt (Clemson University, USA), **Harald Böttner** (Fraunhofer Institut für Physikalische Meβtechnik, Germany), and **Lidong Chen** (China Academy of Sciences, China)

Introduction

The field of thermoelectricity began in the early 1800s with the discovery of the thermoelectric effect by Thomas Seebeck.[1] Seebeck found that, when the junctions of two dissimilar materials are held at different temperatures (ΔT), a voltage (V) is generated that is proportional to ΔT. The proportionality constant is the Seebeck coefficient or thermopower: $\alpha = -\Delta V/\Delta T$. When the circuit is closed, this couple allows for direct conversion of thermal energy (heat) to electrical energy. The conversion efficiency, η_{TE}, is related to a quantity called the figure of merit, ZT, that is determined by three main material parameters: the thermopower α, the electrical resistivity ρ, and the thermal conductivity κ. Heat is carried by both electrons (κ_e) and phonons (κ_{ph}), and $\kappa = \kappa_e + \kappa_{ph}$. The quantity ZT itself is defined as

$$ZT = \frac{\alpha^2 \sigma T}{\left(\kappa_e + \kappa_{ph}\right)} \quad (1)$$

where σ is the electrical conductivity. In addition, the thermoelectric efficiency, η_{TE}, is given by

$$\eta_{TE} = \eta_C \left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}} \right) \quad (2)$$

where η_C is the Carnot efficiency, $\eta_C = (T_H - T_C)/T_H$ and T_H and T_C are the hot and cold temperatures, respectively. Thus, a significant difference in temperature (large ΔT) is also needed to generate sufficient electrical energy, and the infrared (IR) region of the solar spectrum can supply the needed hot temperature, T_H. This is important because IR radiation generates only waste heat in conventional semiconductor-based solar photovoltaic cells.

It was not until the mid-1900s, when semiconductor materials research became prevalent, that thermoelectric materials and devices became more important.[2,3] Semiconducting materials permit band tuning and control of the carrier concentration, thus allowing optimization of a given set of materials. A thermoelectric couple is made up of *n*-type and *p*-type materials, and in a thermoelectric device, many of these couples are then connected electrically in series and thermally in parallel. The thermal-to-electric energy conversion is a solid-state conversion process that is quiet, has no mechanical parts, and provides long-term stability. Thermoelectric devices can be used either for cooling (Peltier effect) or for power generation (Seebeck effect).[4] Thus, heat (typically waste heat) can be converted directly into useful electrical energy. Thermoelectric materials and devices was the theme topic of the March 2006 issue of *MRS Bulletin*, and readers are referred to the articles therein for more detail.[4]

Current thermoelectric materials, as shown in **Figure 1**, have $ZT = 1$, and new materials with ZT values of 2–3 are sought to provide the desired conversion efficiencies. The current materials exhibit conversion efficiencies of 7–8% depending on the specific materials and the temperature differences involved. With regard to solar energy conversion, thermoelectric devices will likely utilize the IR spectrum of solar radiation as shown in **Figures 2 and 3**. For example, a thermoelectric power conversion device with $ZT = 3$ operating between 500°C and 30°C (room temperature) would yield about 50% of the Carnot efficiency. As shown in **Figure 4**,[5] a value of ZT>4 does not sig-

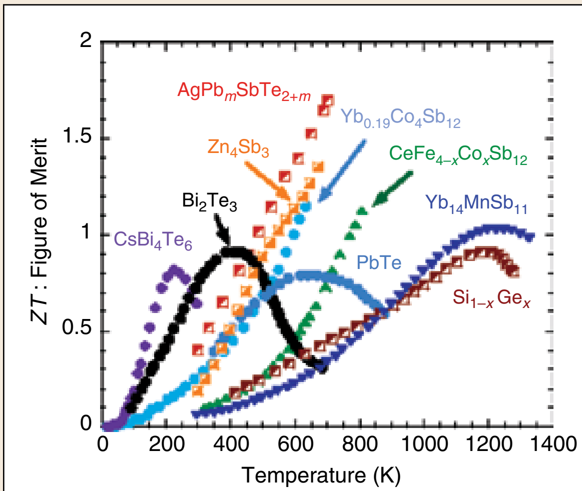

Figure 1. Figure of merit (ZT) as a function of temperature for several high-efficiency bulk thermoelectric materials.

	Wavelenth	Spectrum	%
Photovoltaic	~200–800nm	UV & visible light	58
Thermoelectric	~800–3000nm	IR	42

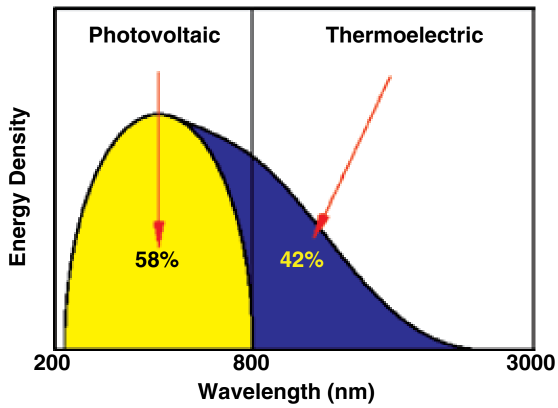

Figure 2. Sun radiates energy as a 6000 K blackbody radiator with part of the energy in the ultraviolet (UV) spectrum and part in the infrared (IR) spectrum.

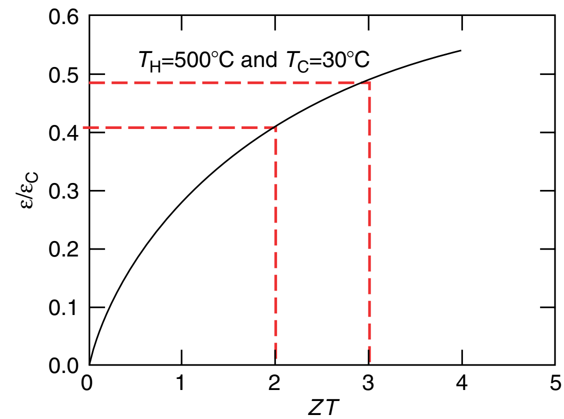

Figure 4. Ratio of the thermoelectric efficiency to the Carnot efficiency ($\varepsilon/\varepsilon_C$) as a function of the figure of merit, *ZT*. The maximum efficiency or Carnot efficiency is given by $\varepsilon_C = (T_H - T_C)/T_H$ = (773 K–300 K)/(773 K) = 61%. (*Source:* Reference 5, Figure 5a.)

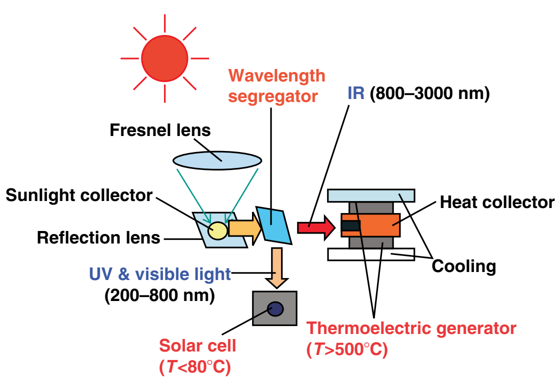

Figure 3. After the solar energy is concentrated, it can be converted into electricity through both photovoltaics (UV spectrum) and thermoelectrics (IR spectrum).

nificantly increase the conversion efficiency over that of a material with ZT = 2–3.[5] Therefore, we believe that the "Holy Grail" of thermoelectric materials research is to find bulk materials (both *n*-type and *p*-type) with a *ZT* value on the order of 2–3 (efficiency = 15–20%) with low parasitic losses (e.g., contact resistance, radiation effects, and interdiffusion of the metals) and low manufacturing costs. With respect to solar energy, these materials would need to operate at about 1000 K (~700°C). The solar energy conversion process could be envisioned as shown in **Figure 3**, where a high-efficiency solar collector turns the sunlight (from the IR spectrum) into heat that is then transformed by the thermoelectric devices into usable electricity. In addition, the solar energy could be stored in a thermal bath and transformed into electricity through thermoelectrics when the sun was not shining.

Thermoelectric Applications

Thermoelectric applications are broad. Thermoelectric materials had their first decisive long-term test with the start of intensive deep-space research. During the Apollo mission, thermoelectric materials were responsible for the power supply, and currently, radioisotope thermoelectric generators (RTGs) are the power supplies (~350 W) used in deep-space missions beyond Mars. Recently, the Cassini satellite was launched with three RTGs using ^{238}Pu as the thermal energy source and SiGe as the thermoelectric conversion material.[5] Smaller self-powered systems such as thermoelectric-powered radios were first mentioned in Russia around 1920; a thermoelectric climate-control system in a 1954 Chrysler automobile shows the scope of this technology. Currently, millions of thermoelectric climate-controlled seats that serve as both seat coolers and seat warmers are being installed in luxury cars. In addition, millions of thermoelectric coolers are used to provide cold beverages. Even wristwatches marketed by Seiko and Citizen and biothermoelectric pacemakers are being powered by the very small temperature differences within the body or between a body and its surroundings.

Thermoelectric materials were previously used primarily in niche applications, but with the advent of broader automotive applications and the effort to utilize waste-heat-recovery technologies, thermoelectric devices are becoming more prominent. The rising costs of fossil fuels have helped spawn a program between the Energy Efficiency and Renewable Energy office of the U.S. Department of Energy and several automotive manufacturers to incorporate thermoelectric waste-heat-recovery technology in the design of heavy trucks. Indeed, without such systems, more than 60% of the primary energy of fossil fuels is lost worldwide as unusable waste energy; the loss is as high as 70% in some automobiles.

This field of thermoelectrics also covers forthcoming applications and markets for remote "self-powered" systems for wireless data communications in the microwatt power range, as well as automotive systems and deep-space probes in the intermediate range of hundreds of watts. Researchers hope to produce systems of several kilowatts using waste heat energy from stand-alone woodstoves and also transform the huge amounts of waste energy from industrial furnaces and power plants.

The Future of Thermoelectric Materials

The future expansion of thermoelectric energy conversion technologies is tied primarily to enhanced materials performance along with better thermal management design. The best thermoelectric material should behave as a so-called phonon–glass–electron–crystal; that is, it should minimally scatter electrons, as in a crystalline material, whereas it should highly scatter phonons, as in an amorphous material. Materials researchers are now investigating several systems of materials including typical narrow-bandgap semiconductors (half-Heusler alloys), oxides, and cage-structure materials (skutterudites and clathrates).[4] More exotic structures that exhibit reduced dimensionality and nanostructures have been the focus of much recent research, including superlattices, quantum dots, and nanodot bulk materials. Also, recent progress in nanocomposites, mixtures of nanomaterials in a bulk matrix, has generated much interest and hope for these materials.[4] The emerging field of these thermoelectric nanocomposites appears to be one of the most promising recent research directions. Such nanocomposites could allow for higher ZT values by reducing thermal conductivity while maintaining favorable electronic properties. With new higher efficiency materials, the field of harvesting waste energy through thermoelectric devices will become more prevalent.

The most stable, long-term, and readily available worldwide energy source is that of solar energy. The issue has always been low-cost transformation and storage. Other alternative energy technologies such as fuel cells, wind energy, and thermoelectrics will provide some assistance in meeting our future energy needs. Many hybrid systems will be needed, and thermoelectrics is able to work in tandem with many of these other technologies, especially solar as it can use the heat source provided by solar radiation. Over the past decade, thermoelectric materials have been developed with ZT values that are a factor of 2 larger than those of previous materials. Another 50% increase in ZT (to $ZT \approx 3$) with the appropriate material characteristics and costs will position thermoelectrics to be a significant contributor to our energy needs, especially in waste heat or solar energy conversion. The likelihood of achieving these goals appears to be within reach in the next several years. Furthermore, some contribution from many of these alternative energy technologies such as thermoelectrics will be needed in order to fulfill the world's future energy needs.

References

1. T.J. Seebeck, *Abh. K. Akad. Wiss.* 265 (Berlin, 1823).
2. A.F. Ioffe, *Semiconductor Thermoelements and Thermoelectric Cooling* (Infosearch, London, 1957).
3. H.J. Goldsmid, R.W. Douglas, *Br. J. Appl. Phys.* **5**, 386 (1954).
4. T.M. Tritt, M.A. Subramanian, *MRS Bull.* **31** (3), 188 (2006); six articles and all references therein.
5. J. Yang, T. Caillat, *MRS Bull.* **31** (3), 224 (2006).
6. S. Maneewan, J. Hirunlabh, J. Khedari, B. Zeghmati, S. Teekasap, *Solar Energy* **78**, 495 (2005).

Off-Grid Solar for Rural Development

Wole Soboyejo (Princeton University, USA) and **Roger Taylor** (National Renewable Energy Laboratory, USA)

The World Bank estimates that over two billion people on the planet live their daily lives without access to basic, reliable electric services.[1] Rural populations in Africa, Latin America, Asia, and island nations need clean water, health services, communications, and light at night. Small, simple, solar electric systems are part of the solution—increasing the quality of life, often at a cost that is less than what is presently being spent for kerosene, dry-cell batteries, and the recharging of automotive batteries that must be lugged to the nearest town on a weekly basis (see **Figure 1**).

Better technology through advanced materials can reduce costs and improve both the performance and reliability of solar electric systems, but in the field, nothing is "maintenance-free." A loose connection or a dry battery can quickly disable the most sophisticated system. The success of solar systems in remote areas depends not only on competitive cost, but also on the human infrastructure needed to deploy and maintain the systems. Work over the past two decades in pilot deployments of solar photovoltaic (PV) systems has highlighted a few issues that must be addressed if solar PV is to provide the promise of cost-effective, reliable energy solutions in remote regions.[2]

Figure 1. In the village of Irapura, Ceara, Brazil, homes were fitted with 50 W solar panels for night lighting, television, and radio. A battery stores electricity generated by the solar panel for use at night. (*Photograph by Roger Taylor.*)

Although PV panels are close to maintenance-free, PV systems are not; therefore, a maintenance support infrastructure needs to be established and nurtured. This issue must be addressed from the very conception of a project. This support infrastructure need not be complex, but it does need to be functional and appropriate for the size, complexity, and sophistication of the systems deployed. A training program with documentation that is matched to the local capabilities, regular refresher courses, planning for personnel turnover, a spare-parts inventory, component resupply, and funds for preventive and problem maintenance must all be addressed.

In small stand-alone systems for homes, schools, health clinics, water pumping, and other applications, strong efforts need to be made to decouple the concepts of electricity sales measured in pennies per kilowatt-hour from fee-for-service monthly payments. Many rural customers are already paying $5–15/month for basic energy services that can be better met with stand-alone renewable energy systems (and without subsidies). It is often difficult to convince electric utilities and other local officials to think about an energy-services approach where customers pay a flat fee-for-service—for lighting, refrigeration, or communications, for example—instead of a per-unit price per metered kilowatt-hour.

Rural electrification generally consists of power line extension or diesel mini-grids based on an annual budget for installations. The concept of life-cycle cost analysis, which equitably compares capital-intensive versus operating-expense-intensive technologies, is still uncommon in small consumer transactions. The concept of life-cycle costing needs to be integrated into the training of officials charged with rural electrification.

Energy-efficient end-use applications/appliances are critical to economically sized renewable energy systems. Investing in energy efficiency has much more economic value than adding generation capacity to meet the demand of inefficient appliances. It is important that a complete systems-engineering approach be maintained, attempting to deliver the best end-use service for the least overall system life-cycle cost.

The most important factor for successful implementation is a supportive, positive attitude by the rural electrification officials. The existence of a champion for solar-based rural electrification, who is in a position of authority, is required to maintain momentum during and after installation. There is no substitute for a dedicated, influential, local champion.

In order to sustain a newly implemented rural electricity system, an administrative system needs to be developed and sustained. Many rural villages have formed cooperatives for fishing, agriculture, and other economic development activities. The specific electricity administrative solution will be regional or village-dependent or both. Although a number of models have been successful, care is needed in matching the administrative system to the village social dynamics.

Renewable energy solutions for village power applications can be economical, functional, and sustainable. Pilot projects are an appropriate step in the development of a commercially viable market for renewable rural solutions. Moreover, a significant number of rural electrification projects are under way that employ various technologies, delivery mechanisms, and financing arrangements. These projects, if properly evaluated and communicated—so that their lessons are incorporated in future projects and programs—can lead the way to a future that includes a robust opportunity for cost-effective, renewables-based village power systems, bringing modern electric services to rural populations at a cost that is competitive with or less than those of both central-station generation and stationary diesel generators.

In an effort to explore the sustainable application of solar energy in rural settings, a number of applications have been explored recently by the U.S./Africa Materials Institute (USAMI) at Princeton University, Princeton, New Jersey, and the Global Development Network (GDN), based in New Delhi, India. These include community-based solar energy approaches at an ecotourism lodge in Il Motiok, Kenya; rural electrification of the Aang Serian School in Eluai village, Monduli District, Tanzania; and a solar refrigeration project for cooling and preserving vaccines during transportation to remote and rural parts of Kenya that cannot be reached by land rover. The last project was undertaken in close collaboration with the Art Center College of Design, Pasadena, California. In all cases, the projects have been designed to provide electricity to people living on less than a dollar a day. Hence, sustainability was considered carefully in the design and installation of the systems.

In the case of the ecotourism lodge in Il Motiok (**Figure 2**), a community-based solar system was provided to a women's group that had set up an ecotourism lodge to attract local and international tourists to a remote off-grid region in the Laikipia district in Kenya. The solution involved the use of high-efficiency crystalline solar cells, a charge controller, and two locally made 100 amp-hours (Ah) deep-cycle batteries that were used to develop a small station for the charging of solar lanterns (light-emitting devices or LEDs). Each charge was found to provide up to five days of lighting for local families in the local village. The lanterns were also used by guests who come largely from Europe and North America to enjoy the wildlife and local culture in the Laikipia plateau. The system is sustainable because the local people derive income from the ecotourism lodge. They also charge a small fee to charge cell phones that are now a common feature of life in most parts of rural Africa. Above all, the local managers of the charging station were trained in solar maintenance and installation after the system was installed. This provided a much better alternative to driving 2 h to the nearest town, Nanyuki, to charge the solar lanterns and cell phones for local use.

Figure 2. Solar-powered light-emitting devices that provide five days of light after each charge at the Ol Gaboli Community Lodge, an ecotourism lodge in Il Motiok, Kenya.

The experience of the Noonkodin Secondary School, which is run by the Aang Serian Community, is also of some interest. This is a school that was established to provide high school education to the nomadic Maasai and Hazabe people within the context of their local cultures and indigeneous knowledge. Photovoltaic systems (**Figure 3**) were installed to provide electricity to the boarding house, classrooms, and homes of the teachers and headmaster. The local people and the staff at the school were also trained to maintain the system, which provided rural electrification for the first time to the people of the village. As income is earned from the school, the system can be maintained to provide for the long-term electricity needs of the school and the local community.

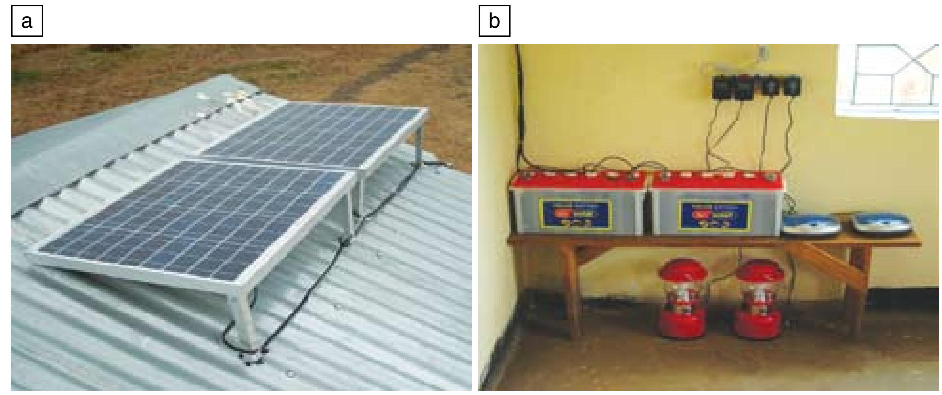

Figure 3. Solar electric power at the Aang Serian Community School in the village of Eluai in Monduli District, Tanzania: (a) crystalline silicon solar cells on the roof of one of the school buildings and (b) solar lanterns (light-emitting devices) and compact disc players powered by deep-cycle batteries at the school.

In the area of global health, solar energy provides a crucial means of preserving vaccines in rural off-grid areas. Because of the high energy consumption associated with refrigeration, novel system designs are needed to develop sustainable solutions for transporting vaccines to places that cannot be reached by the most rugged of land rovers. In such cases, the vaccines are often transported on camels on missions that can last up to seven days. In the case of the Mpala Clinic in Mpala, Kenya, a small group of nurses and local doctors provides healthcare to a population of about 150,000 people. Much of the community-based care and vaccination of children, therefore, requires the preservation of vaccines. This motivated the development of a solar-powered refrigeration system that is powered by both flexible and rigid solar cells (**Figure 4**). The system, which includes a special camel saddle, was designed jointly by a team from the Art Center College of Design and the USAMI researchers.

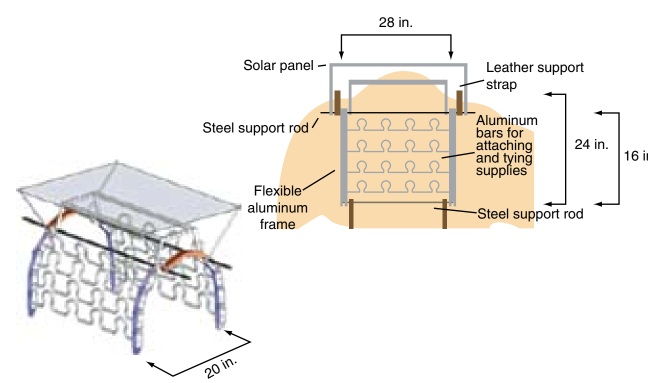

Figure 4. Solar-powered refrigerator for vaccine storage and preservation during transportation on camels to remote areas. (Courtesy of Patrick Kiruki and Marianne Armatullo of the Art Center College of Design, Pasadena, California.)

Larger scale rural electrification programs have been carried out by the Solar Electric Company of India (SELCO). This company has worked with banks to provide financing schemes to enable rural people to pay for solar systems in remote villages. Such approaches have enabled village economies to grow through stimulation of nighttime trading by the provision of solar electrification. They have also enabled off-grid rural people to enjoy the benefits of solar energy at rates that can be sustained by the local economies. This has been sufficient to stimulate the sustained growth of SELCO for more than a decade.

Similar models are being explored in Nigeria, where a recent collaboration between the U.S. and Nigerian academies of science has investigated the concepts that could stimulate the establishment of science-based industries in Nigeria. Funded by the Gates Foundation as a pilot program, the group of U.S. and Nigerian scientists worked with local entrepreneurs, government representatives, and academics to explore the feasibility of establishing an off-grid solar company that could provide energy in an environment where power cuts are frequent in the urban areas, and often unavailable in the rural areas.

The U.S./Nigerian study essentially recognizes that the long-term viability of such off-grid solar companies requires the connection of solar energy to a successful business model. Furthermore, the business model must include financing schemes through banks or community savings groups; social entrepreneurship by local companies; the integration of maintenance costs into the financing and sales agreements; and the development of local technical expertise that can install, maintain, and replace these systems over the projected system life of about 20 years.

Although these examples show how current solar energy technologies are improving the lives of off-grid rural and rural/urban people, much work is needed to develop the materials technologies that could dramatically reduce the costs of solar energy. In the short term, the lowest cost per kilowatt-hour can be achieved by the use of amorphous solar energy systems provided by thin-film deposition technologies.[2,3] However, the current–voltage characteristics of these systems are often designed to provide relatively low currents (about 1 A). Hence, it is often necessary to have a greater number of amorphous solar cells (than crystalline solar cells) to provide the required amount of charge.

In the medium to long term, there is much hope that the so-called balance of system costs could be reduced by advances in battery and charge controller technologies, as well as the devel-

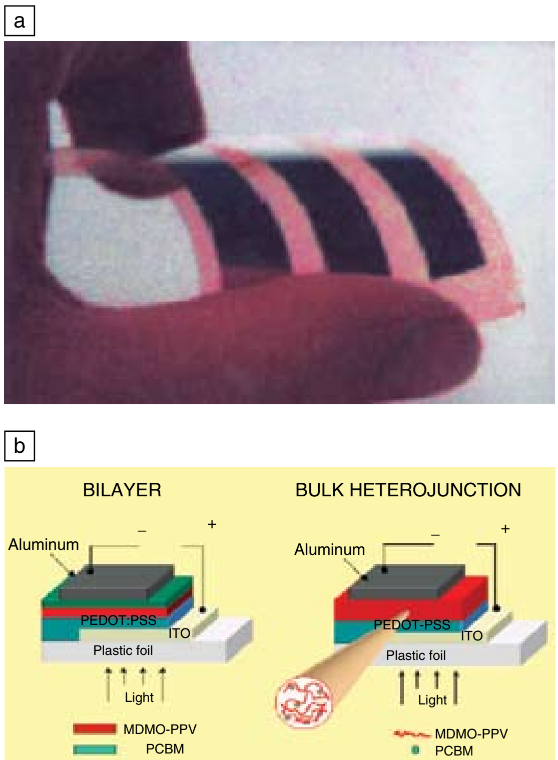

Figure 5. Organic electronic structures for rural and urban lighting: (a) flexible organic solar cells and (b) schematic of possible layered structure. *Note:* MDMO-PPV, poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)-*p*-phenylenevinylene]; PCBM, [6,6]-phenyl C61 butyric acid methyl ester; PEDOT:PSS, poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate).

opment of organic electronic structures that could provide the potential for low-cost solar energy. In the long term, such advances have the potential to reduce the cost of solar cells by a factor of 10. Such a reduction could greatly facilitate the global applications of solar energy in both the developed and the developing world. However, additional research is needed to improve the efficiencies of the solar cells and the stability of the organic electronic structures for rural and urban electrification (**Figure 5**).[4] Ongoing materials research efforts in this area are motivated by issues related to charge transport across bilayers and bulk heterojunctions and polymer/interfacial stability. This is especially true for organic solar cells and organic light-emitting devices, which are essentially solar cells run in reverse.

Before closing, it is important to note that recent advances in research have resulted in a rapid increase in the efficiencies of organic solar cells from about 1% to 6%.[5] If the current trend continues, it is likely that organic electronic structures could soon become competitive alternatives to commercial silicon-based solar cells that have efficiencies between 5% and 15%. This has motivated an integrated research effort in the global materials community.

Acknowledgments

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References

1. *Improving Lives: World Bank Group Progress on Renewable Energy and Energy Efficiency in Fiscal Year 2006* (World Bank Group, Washington, DC, December 2006).
2. M. Hankins, *Solar Electric Systems for Africa* (Commonwealth Science Council, London, 1995).
3. T. Otiti, W.O. Soboyejo, *Perspect. Glob. Dev. Technol.* **5**, 69 (2006).
4. S. Forrest, P. Burroughs, M. Thompson, *IEEE Spectr.* **37** (August 2000).
5. K. Kim, J. Liu, M.A.G. Namboorthiry, D.L. Carroll, *Appl. Phys. Lett.* **90**, 16311 (2007). ☐

The 3 GW Initiative

Tim Palucka (Science Writer, USA)

California continues its tradition of leading the United States in environmental stewardship through the California Solar Initiative (CSI), a $3.3 billion program established in January 2006. The goal is to generate 3 GW of electricity by 2017 through photovoltaic methods by installing solar cells on the roofs of existing and new residential and commercial buildings (see **Figure 1**).[1] CSI will “reduce our output of greenhouse gases by 3 million tons,” California Governor Arnold Schwarzenegger said in a speech given in October 2006. “That is equivalent to taking one million cars off the road.”

Although specific materials technologies are not mandated by the program, photovoltaic systems “are expected to be the common technology to receive incentives” according to the *CSI Handbook*.[2] The fact that incentives paid to participants are based on the amount of electricity generated will motivate consumers to adopt the most efficient solar cell technologies, thus increasing the performance level of the “common technology.” This should result in significant market pressure to drive competition between photovoltaic cell manufacturers to produce the highest quality product.

Figure 1. California homes and commercial buildings with rooftop photovoltaic solar cells installed as part of the California Solar Initiative. *Credit:* Sacramento Municipal Utility District, www.smud.org (accessed January 2008).

The current list of approved products includes 861 photovoltaic modules from 44 companies worldwide.[3] Approved modules are primarily amorphous Si, single-crystalline and multicrystalline Si, and thin-film CdTe devices. Prior to approval, all photovoltaic modules are tested according to PVUSA Test Conditions (PTC), which yields a wattage rating based on 1000 W/m^2 solar irradiance, 20°C ambient temperature, and a wind speed of 1 m/s. PTC measurements for the 861 approved modules range from 9.9 W to 1545.5 W. In addition, critical system components must have been commercially available for at least one year to be eligible for the program.

CSI's initial provisions called for a one-time, up-front rebate called the Expected Performance-Based Buydown (EPBB). The payment was to be made based on the calculated capacity of each system's electricity production, taking into account such variables as the amount of incoming sunlight in a particular geographic region, the efficiency of the installed solar panels, the tilt of the roof, and estimates of shading effects.

On August 24, 2006, however, the California Public Utilities Commission revised this system in favor of a Performance-Based Incentives (PBI) plan.[4] PBI called for monthly payment of incentives to owners of systems with a capacity of 100 kW or more based on the actual metered amount of electricity produced. (The EPBB plan is still in effect for systems smaller than 100 kW.) Current incentive levels are $2.50 per generated watt for residential and commercial participants, with rates scheduled to decrease according to a fixed schedule over the 10-year lifetime of the program.

The early success of the CSI effort is evident in the fact that 1157 projects valued at 9.4 MW in generated electricity and $25 million in incentives have already been completed. In addition, there are currently 5,109 applications for installation of photovoltaic systems that would generate 160.5 MW of electricity and $320 million in incentives. The pace of applications is accelerating, starting with approximately 200 in January 2007 and increasing to over 1200 in the month of August alone as the program becomes more widely known.

Ten percent of the $3.3 billion has been set aside for low-income and affordable housing.[5] In addition, the California Energy Commission is in charge of a 10-year, $400 million New Solar Homes Partnership, to encourage new home builders to include solar energy capabilities in their designs.[6] The fact that new home builders are not *required* by CSI to include solar cells in their designs continues to be a point of debate among Californians.

References

1. California Energy Commission, "Go Solar California!" (California Energy Commission, Sacramento, CA; www.gosolarcalifornia.ca.gov) (accessed January 2008).
2. California Public Utilities Commission, *California Solar Initiative Program Handbook* (California Public Utilities Commission, Sacramento, CA, September 2007; www.gosolarcalifornia.ca.gov/documents/CSI_HANDBOOK.PDF) (accessed January 2008).
3. California Energy Commission, "List of Eligible Photovoltaic Modules" (California Energy Commission, Sacramento, CA; www.consumerenergycenter.org/cgi-bin/eligible_pvmodules.cgi) (accessed January 2008).
4. California Energy Commission, "Performance-Based Incentives and New Incentive Levels Starting in 2007" (California Energy Commission, Sacramento, CA; www.gosolarcalifornia.ca.gov/csi/performance_based.html) (accessed January 2008).
5. California Energy Commission, "Solar for Low-Income Households" (California Energy Commission, Sacramento, CA; www.gosolarcalifornia.ca.gov/csi/low-income.html) (accessed January 2008).
6. California Energy Commission, *New Solar Homes Partnership Guidebook* (California Energy Commission, Sacramento, CA, adopted July 11, 2007, posted July, 24, 2007; www.gosolarcalifornia.ca.gov/documents/index.html) (accessed January 2008). □