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

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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.

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Thermoelectrics: Direct Solar Thermal Energy Conversion

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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

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

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

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

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-

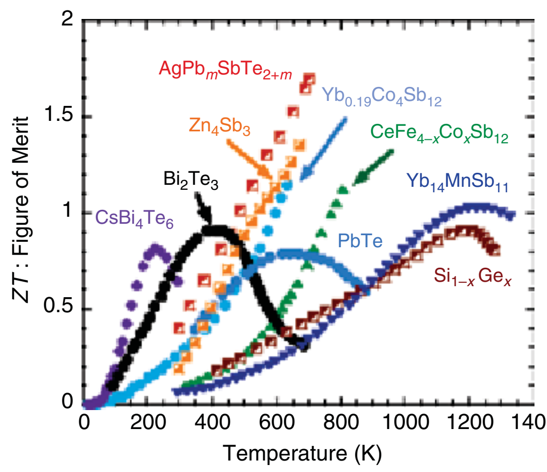

Figure 1. Figure of merit (ZT) as a function of temperature for several high-efficiency bulk thermoelectric materials.