Solar Energy Cost Breakthrough Ahead?

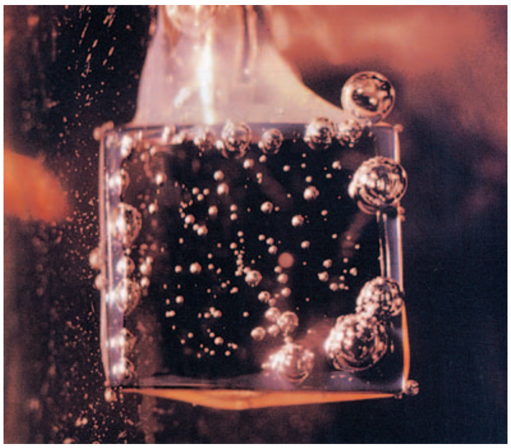
Scientists Chart New

Researchers look to cutting-edge advances for the solar technologies of tomorrow.

By Nathan S. Lewis, Ph.D., and George Crabtree, Ph.D.

SOUTHERN CALIFORNIA EDISON

Technology advances in high-temperature solar thermal systems could enable energy-conversion efficiencies in excess of 60 percent, revolutionizing the cost competitiveness of solar energy systems.



To be a source of primary power, solar electricity must have convenient, cost-effective energy storage. One line of research focuses on constructing an "artificial leaf" that directly produces solar fuel the way plants do, but more efficiently.
Left, A photoelectrochemical cell used in research studies on the storage of solar energy in a chemical fuel. Here, hydrogen gas is produced by light shining on the surface of solid silicon immersed in a liquid solution of hydrochloric acid.

Horizons

Last April, 200 scientists convened in Bethesda, Md., to address "Basic Energy Research Needs for Solar Energy Utilization." From left, George Crabtree, workshop co-chair; Patricia Dehmer, U.S. Department of Energy Office of Basic Energy Sciences; and Nathan S. Lewis, workshop chair.

The sun is the champion of all energy sources. Sunlight has provided, through photosynthesis, the energy from which all of our fossil resources were formed, as well as the energy that sustains life on earth and powers the wind, the tides, hydrological flows and the climate. At present, global primary energy consumption amounts to about 410 x10^{18} joules (410 exajoules) per year, which is equivalent to an average thermal power consumption of 13 trillion watts, or 13 terawatts (TW). The sun provides a staggering 120,000 TW of power to the earth, far more than humans could ever reasonably envision using. In fact, more energy from sunlight strikes the earth in one hour than all of the energy consumed by humans in an entire year!

Solar electricity in 2004 was a $7.5 billion business and is growing in excess of 30 percent per annum, but it still accounts for less than 0.1 percent of total global electricity supply. Solar fuels, in the form of plant, vegetable and agricultural-waste biomass, provide the primary energy source for over a billion people. Yet solar fuels obtained from sustainable (modern, renewable) biomass account for less than 2 percent of total global energy supply. Solar thermal heating provides approximately 0.006 TW of power, amounting to about 0.04 percent of total global energy consumption. Clearly, solar energy is underutilized given its enormous potential to be a carbon-neutral, renewable, secure energy source.

Remarkable technology advances are being experienced in all aspects of solar energy conversion, including solar electricity, biomass and low- and high-temperature solar thermal conversion systems. However, it is no secret that in many applications, especially in primary power generation, using fossil fuels is still cheaper (at least in costs directly borne by the consumer) than using the sun.

Last April, to foster the next generations of technology that will enable even more widespread use of solar energy, the U.S. Department of Energy Office of Basic Energy Sciences convened a workshop in Bethesda, Md., to address "Basic Energy Research Needs for Solar Energy Utilization." Almost 200 scientists from around the world, by invitation only, seized this opportunity to lay the groundwork for a redoubled R&D effort to support new methods of using and converting solar energy. The outcome of this workshop was an authoritative report that reviewed the state of solar energy utilization technology, identified the key technological barriers that prevent solar energy usage from growing even more rapidly, and, in anticipation of a significant increase in R&D support for solar energy, identified 13 priority research directions designed to help move notions from the minds of laboratory researchers into technologies, and ultimately products, for the energy consumer. The report, "Basic Research Needs for Solar Energy Utilization," may be downloaded at www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf. *(See "Solar Leaders Identify Research Priorities," p. 54, September/October* SOLAR TODAY.*)*

Solar energy-conversion systems fall into three categories according to their primary energy product: solar electricity, solar fuels and solar thermal systems. Workshop participants considered the potential of all three approaches.

Nanotechnology Is Focus of Next-Gen Electric Systems

A key figure of interest in solar electricity is, of course, the cost per peak watt. Because the total solar energy striking a given area of land over a 30-year period is known, we can readily calculate the total output of solar electricity from that area at any given efficiency. The sale price of this electricity output must at least allow for recovery of the initial materials and installation costs of the panels, along with the balance of systems cost. At the present installed module cost of a few hundred dollars per square meter, and with 10 to 15 percent module energy-conversion efficiency, to recover the system costs over a 30-year-system lifetime, the electricity must be sold at approximately $0.30 per kilowatt-hour *(see figure 1)*. Generation II systems, which would provide much lower cost per peak watt, are being developed either from advanced silicon cells or from thin-film materials including amorphous silicon, cadmium telluride, copper-indium-gallium-diselenide or organic semiconductors. A longer-term goal is Generation III materials, which would have even more favorable cost per peak watt, and which would enable a price point for solar electricity that would be competitive with fossil-fuel-derived electricity costs.

Scientists envision several paths for achieving the Generation II and Generation III regimes. In one approach, the industry expands capacity and rides the learning curve using improvements in the existing solar electricity technologies *(see "Photovoltaic*

Industry Pushes the Limits," page 20, for one manufacturer's approach). In a second approach, R&D on innovative disruptive technologies is performed in parallel with efforts to improve the existing technologies. Nanotechnology offers a dizzying set of possibilities that could lead to both Gen II and Gen III technologies.

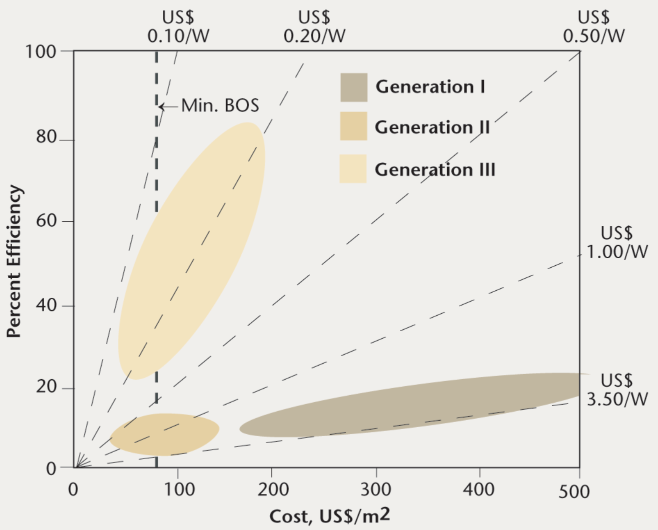
The ultrahigh efficiencies of Gen III technologies require a new paradigm in which little heat is generated during light absorption, and almost all of the sunlight is converted into electrical energy. These so-called nonthermalized absorber materials, or hot-carrier collectors, in principle can be realized by using nanoparticles or nanostructures as the light absorber, because the energy levels in such systems are spaced far enough apart to prevent the electrons from producing heat before they get collected by the wires at the ends of the solar cell.

Gen II systems' moderate efficiencies at ultralow cost can possibly be achieved by use of organic, plastic materials in solar cells. These materials also offer the ability to produce conformal materials that can be rolled up and unrolled like carpet onto roofs and in back yards, and would facilitate other near-effortless installations of solar panels.

Finally, nanotechnology offers the possibility of making materials out of so-called interpenetrating networks, which resemble the structure of the pigment and binder in paint. Such materials could enable a "solar paint" technology that literally could be deployed on any surface on which one wanted to paint a solar converter system.

Figure 1

Solar Electric System Module Efficiency, Area Cost and Cost per Peak Watt



Breakthroughs in solar module efficiency enable lower electricity cost-per-peak-watt even if the module cost remains fixed or increases slightly. The dashed lines reflect constant cost-per-peak-watt values. Including a balance of systems cost (BOS), a cost of $3.50 per peak watt increases to a system cost of about $6.00 per peak watt, which amortizes to an electricity sale price of about $0.30 per kilowatt-hour over a 30-year system lifetime. Current solar electricity modules fall in the green Generation I region, whereas Generation II systems would offer moderate efficiency at low cost, and Generation III systems (in the light yellow zone) would offer ultra-high efficiencies at moderate areal cost.

Source: "Basic Research Needs for Solar Energy Utilization" report, U.S. Department of Energy Office of Basic Energy Sciences

Best Energy Storage May Mimic the Leaf

Of course, the sun has a nasty habit: It stops shining locally every night. So solar electricity can never be a source of primary power without convenient, cost-effective energy storage. Probably the most attractive technological approach is to borrow a page from Mother Nature, who performs storage by making and breaking chemical bonds.

In photosynthesis, sugars and oxygen are the solar fuels formed from water and carbon dioxide. In some cases, bacteria instead split water into the solar fuels hydrogen and oxygen. But even the fastest-growing crops like switchgrass on average convert only 0.3 percent of the incident solar energy into stored chemical fuel energy. Biomass in its present forms therefore requires large land areas to produce a lot of energy. One approach is to improve the machinery of plants and bacteria through breeding or biotechnology, enabling them to grow faster. Another approach is to artificially redirect the natural photosynthetic machinery of plants or bacteria to make more desirable chemical fuels such as ethanol or hydrogen, instead of lignocellulose. A third line of research focuses on constructing an "artificial leaf" that directly produces solar fuel the way plants do, but more efficiently.

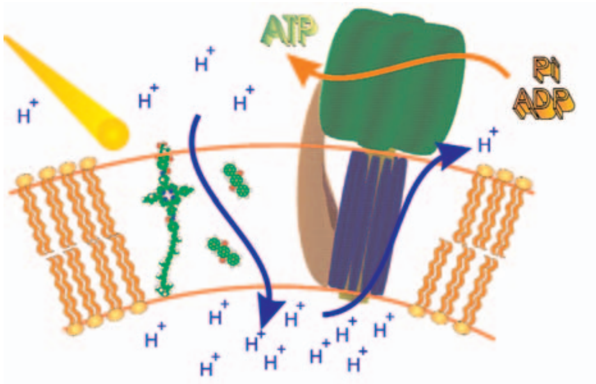
An artificial leaf requires components to capture, convert and store sunlight. The components that capture the sun can be either pigments, such as chlorophylls that are used in nature, or synthetic organic or inorganic molecules that efficiently absorb the incident light. The conversion systems that separate the excited-charge states produced by the pigments can be semiconducting particles, an array of precisely configured complex molecules (mimicking the reaction center of photosynthesis), or some combination thereof *(see figure 2)*. Several such systems have been tested in the laboratory, with some achieving peak efficiencies of 10 percent in sunlight.

Advances in chemistry promise designer systems that will combine these functions into one system that can be self-assembled using simple, wet chemical process steps. A fascinating advantage of such systems is their ability to directly manipulate electrical charges into forming chemical bonds, thereby directly forming fuels the way a plant does, with none of the wiring, inverter and accompanying electrical-current infrastructure that are major components in conventional solar cell systems. However, at present only natural systems contain low-cost catalysts that are efficient at converting such charges into stored chemical fuels. Scientists have developed some molecules that mimic these natural catalysts, but further research is needed to understand how to combine these single-step electrical-charge events into a full artificial photosynthetic system capable of splitting water into hydrogen and oxygen, or reducing carbon dioxide into fuels like methanol, ethanol and/or sugars.

Clearly, solar energy is underutilized given its enormous potential to be a carbon-neutral, renewable, secure energy source.

Figure 2

Schematic of an Artificial Photosynthetic Assembly

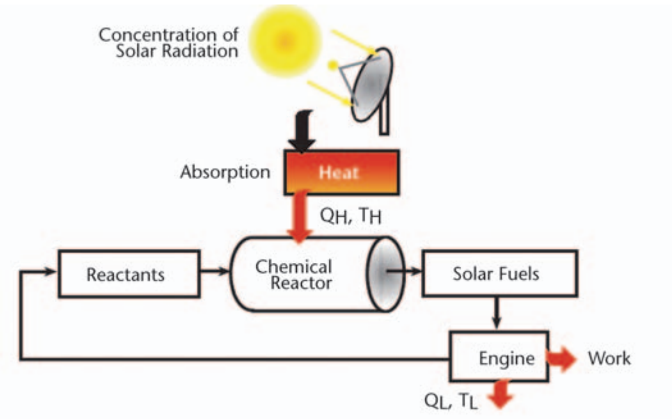


A three-part organic molecule absorbs the light and then transfers charges in a stepping-stone fashion across a membrane. Reactions of the resulting separated charges are used to drive the formation of high-energy chemical fuels in a mode analogous to the operation of a leaf.

Source: Devens Gust, Thomas A. Moore, Ana L. Moore, Arizona State University. For more information see Steinberg-Yfrach et al. *Nature* (London) 392, 1998: 479–482

Figure 3

General Conceptualization of a Solar-Driven Thermochemical Cycle



Source: "Basic Research Needs for Solar Energy Utilization" report, U.S. Department of Energy Office of Basic Energy Sciences

Thermal Innovations Target High Efficiency

The third option for increasing solar energy utilization is solar thermal technology — at low temperatures for space- and water-heating, or at high temperatures for generating electricity and/or fuels. After all, traditional energy systems use heat as the primary entry point for energy flow through burning fossil fuels or through uranium fission in nuclear reactions. The heat produced is then used directly or converted to mechanical energy in heat engines and from mechanical energy to electrical energy through turbines. The sun can provide the initial heat driving these energy-conversion chains, replacing fossil and nuclear fuels.

Advances in solar thermal technology will be enabled by new materials such as thermoelectrics or thermophotovoltaics for converting thermal energy into electrical energy, as well as by new processes for converting high-temperature heat from solar collectors into chemical fuels such as hydrogen from water *(see figure 3)*. In addition to providing integrated storage, high-temperature solar thermal systems offer the potential for ultrahigh efficiencies. In fact, these systems could allow energy-conversion efficiencies in excess of 60 percent, which would revolutionize the cost competitiveness of solar energy systems.

The R&D Stage Is Set

All of these research areas — solar electricity, solar fuels and solar thermal systems — will benefit as advances in nanotechnology and biotechnology enable scientists to design materials with new physical, chemical and electronic properties. Advances in density functional theory now make it possible to screen hundreds of target materials on a computer and develop only the most promising one for the application at hand. Computational prescreening dramatically cuts materials development costs and can be applied broadly, for example to new thermal properties, new light absorbers for photovoltaics, and materials that exhibit new physical properties such as facilitating nonthermal carrier capture for advanced solar electricity-generating applications.

Participants in the April workshop identified the above research directions as key amongst the 13 priority research directions for bringing disruptive, next-generation and beyond-the-horizon concepts to fruition for solar energy utilization. These research priorities complement the industry's ongoing efforts to commercialize existing solar energy technologies and transition incipient processes into the mainstream. If government and industry devote generous R&D funds and these efforts develop according to their promise, we indeed will see something new under the sun — innovations that will enable society to more fully realize the potential of solar energy to power the planet. ●

Nathan S. Lewis, Ph.D., and George Crabtree, Ph.D., co-chaired the April 2005 Workshop on Basic Research Needs for Solar Energy Utilization organized by the U.S. Department of Energy Office of Basic Energy Sciences. Lewis is the George L. Argyros Professor of Chemistry at the California Institute of Technology. His research involves artificial photosynthesis to enable solar energy conversion to directly form chemical fuels. Contact Lewis at nslewis@caltech.edu. Crabtree is a senior scientist at Argonne National Laboratory and director of its Materials Science Division. His awards include the Kamerlingh Onnes Prize for his work on the properties of vortices in high-temperature superconductors. Contact Crabtree at crabtree@anl.gov.