

Is Downsizing to Atomic Scale One Way Forward? Nanotechnology for Energy

by Trudy E. Bell

globally each year, humans now consume close to 500 quadrillion Btu for all purposes [Fig. 1]. That translates to some 85.6 billion barrels of oil per year.¹ Of that total, the U.S. alone consumes about 20 percent (just under 100 quads per year); U.S. energy costs run about a trillion dollars per year, or about 10 percent of the GDP.² All totals are expected to keep growing, not only because of growth in world population (currently nearly seven billion and counting³), but also because of the rapid global spread of industrialization.

A growing number of scientists and engineers are exploring and tweaking material properties at the atomic scale to create *designer materials*, which might ultimately increase the efficiency of current energy sources or make new energy sources practical on a commercial scale. At the nanoscale, some materials have different physical properties (strength, conductivity, reflectivity, chemical reactivity, etc.) than they do in bulk. Many nanoscale materials can spontaneously self-assemble into ordered structures. Nanostructured materials also have enormous surface areas per unit weight or volume, so that vastly more surface area is available for interactions with other materials around them. That is useful because many important chemical and electrical reactions occur only at surfaces and “are sensitive to the shape and texture of a surface as well as its chemical composition,” explained Dr. James A. Dumesic, *WI A '71*, Steenbock professor of the chemical and biological engineering department at the University of Wisconsin–Madison.

Catalysts: a “holey” successful story

Two centuries before the word “nanotechnology” was coined, in 1756 a Swedish mineralogist named Baron Axel

F. Cronstedt (1722–65) discovered a fascinating new class of silicate minerals, which seemed to froth or boil when heated in a blowpipe flame. He named the mineral a zeolite, from the Greek words meaning “to boil” (zeo) and “a stone” (lithos). In the 1930s, scientists realized that zeolites were a subset of porous solids that became known as molecular sieves,

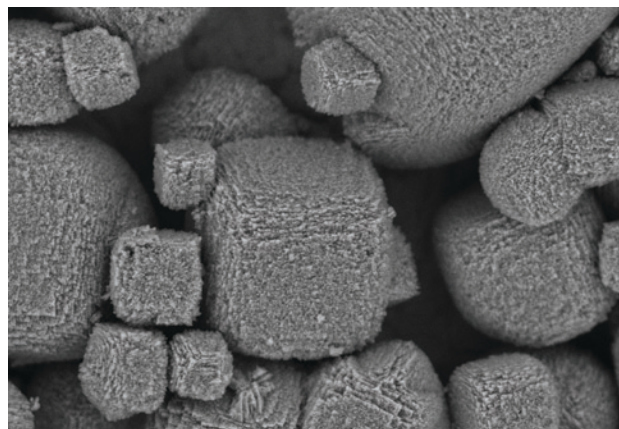
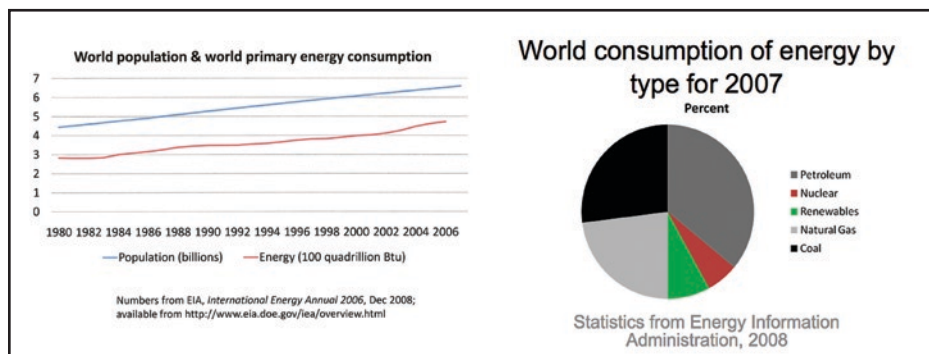


Fig. 2. Zeolites, non-metallic silicates that are one class of molecular sieves, are essential to the petroleum industry (e.g., cracking crude oil to produce gasoline). This particular zeolite, made of sodium with a nanoscale template, is unusual because it has a wide range of pore sizes (1 to 50 nanometers) to assist its function as a catalyst. —Ryong Roco, Korea Advanced Institute of Science and Technology

which could separate gases on the basis of molecular size. In the 1950s, Union Carbide inorganic chemists discovered ways to synthesize zeolites on a commercial scale. Today, synthetic zeolites are central to chemical processing and waste treatment, and are crucial as catalysts in refining petroleum to break down the long-chain hydrocarbon molecules in crude oil into smaller molecules of useful lighter liquid fuels such as gasoline.

Catalysts (by definition) are materials that turn a raw material into a desired product without being consumed themselves; in refineries, most catalysts are solids (fine granules) through which liquids or gases are flowed. Catalysts vastly accelerate chemical reactions that occur naturally or facilitate the reactions at lower temperatures. Catalysts also make possible reactions that do not occur in nature at all. The best catalysts efficiently

Fig. 1. According to the U.S. Department of Energy’s energy information administration, 482.5 quadrillion BTUs of energy were consumed globally in 2007, with more than 86% from fossil resources. This consumption represents an increase of 21% from the 2000 usage rate.



and quickly convert a raw material into a specific product with minimal waste heat or unwanted byproducts.

Today's zeolites are ceramic-like solids permeated with millions of nanometer-sized pores so they have surface areas of 500 to 1,000 square meters per gram [Fig. 2]. Nanostructured catalysts are so fundamental to energy production that a National Science Foundation report described them as "the engines that power the world at the nanometer length scale."⁴ "Catalysts are nano-reactors," declared Robert J. Davis, professor and chair of the chemical engineering department of the University of Virginia in Charlottesville. Nanotechnologists have found that placing a single atom of aluminum inside each pore of a silicate zeolite can speed up the chemical reaction or tailor the end product. Other nano-tricks to boost a catalyst's efficiency include arranging individual atoms to expose certain crystal faces, creating nanoscale junctions between two different materials where reactions occur best; deliberately including pores, corners, or defects; and fine-tuning the sizes of the pores.

Nanotechnologists are searching for new catalysts to improve the energy efficiency of cracking fossil fuels. The world's supplies of light, sweet crude oil—the most desirable type free of sulfur—are getting low; remaining stores of heavier crude oil have sulfur, so new catalysts are needed to remove the sulfur as well as to create cleaner-burning fuels. Additional new catalysts are needed for converting coal to diesel and other liquid transportation fuels. Also, most existing catalysts—such as the one in every automobile's catalytic converter—rely on precious metals, notably platinum, because the transition metals have an optimal configuration of electrons available in their outer orbitals for

desired chemical reactions. Precious metals, however, are both expensive and scarce, a growing concern as industrializing countries demand more automobiles. So the search is on for cheaper substitutes.

Nanotechnology for renewables

New catalysts are also imperative if biofuels such as ethanol or methanol from green plants are to be mass-produced on a commercial scale. The chemistry of biofuels radically differs from the chemistry of fossil fuels, explained Dumesic. Fossil fuels are oil-based: coal, crude oil, and natural gas are hydrocarbons, composed almost entirely of carbon and hydrogen (with reduced chemical formulas of C, CH₂, and CH₄, respectively). Biofuels, however, are water-based: their raw material is basically sugar water, or carbohydrates, composed not only of carbon and hydrogen but also of oxygen (with a reduced chemical formula of CH₂O). So catalysts are needed to turn plant sugars into fuels. Moreover, different types of plant matter require different catalysts: for example, corn kernels and sugar cane are rich in sugar, but tougher cornstalks and leaves—so-called cellulosic plant material—are not. Yet, cellulosic material rather than fruit makes up the bulk of most plants. So the search is also on for catalysts that can break down tough but cheap and abundant cellulosic plant material.

Other researchers are devoting attention to fuel cells, with an eye to the prospect of an eventual *hydrogen economy*. Fuel cells—long used on spacecraft—react hydrogen with oxygen to produce electricity, with the sole exhaust product being nonpolluting water. Fuel cells are compact and very efficient: those routinely used in spacecraft have efficiencies of up to 60 percent, compared to 25 percent efficiency for the best gasoline engines. But major technical challenges still face a hydrogen economy "if we're serious about replacing the gasoline in cars," said Dr. George W. Crabtree, *ILL* '67, senior scientist and associate division director at Argonne National Laboratory in Argonne, IL. Chief among them are: storing hydrogen, purifying hydrogen, devising membranes for fuel cells, and producing enough hydrogen on a commercial scale from water instead of from natural gas to support a hydrogen economy genuinely independent of fossil fuels [Fig. 3].

Take just one of those issues, hydrogen storage: one surprising fact about hydrogen is that, unlike most gases, it's most densely stored not if it is liquefied, but if it is bound to a solid structure (fortunate, because significant energy is needed to cool and pressurize hydrogen enough to liquefy it). Chemically bound in a solid

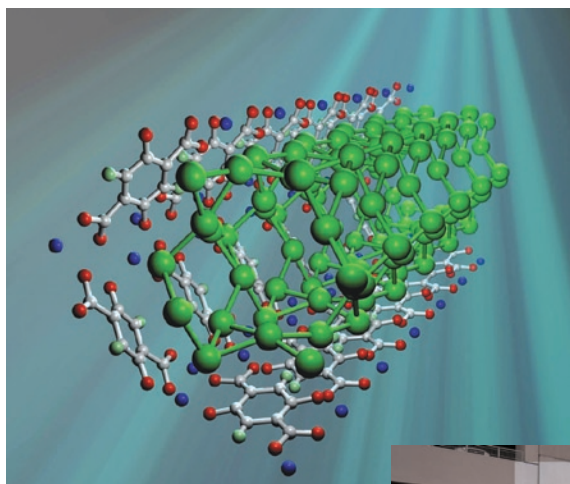


Fig. 3. A metal-organic molecular framework could be one solid useful for storing hydrogen—*NIST*. Shown also are a zero-emission, hydrogen-fuel-cell bus in the Connecticut transit district—*NREL*, and a robot arm filling a hydrogen car at Munich Airport—*BP*.

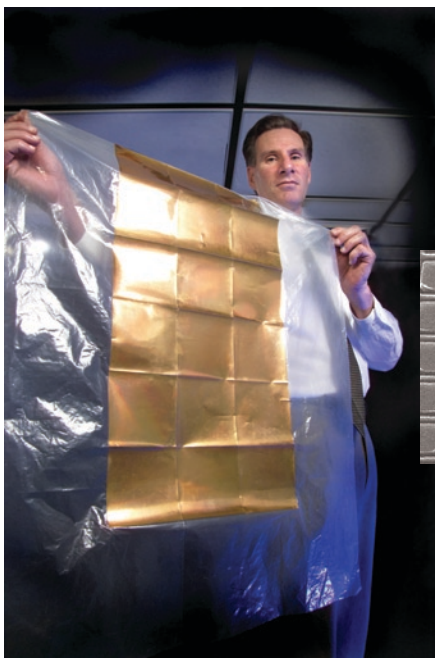
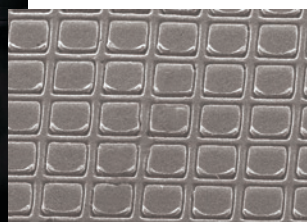


Fig. 4. Steven Novack at DOE's Idaho National Laboratory holds a sheet of flexible plastic printed with gold nanoantennas (close-up). The nanoantennas collect solar infrared, not only directly from the sun during the day, but also heat reradiated by the earth at night, and so offer the possibility of operating at nighttime as well.¹⁰ —DOE Idaho



hydride, hydrogen atoms can be densely packed at room temperature.

The challenge is designing a hydride that will release the hydrogen quickly when a driver accelerates. One structure under investigation is core-shell nanoparticles: spherical nanoparticles coated with a catalyst. When a hydrogen molecule (H_2) lands on the coating, the catalyst splits the molecule into two hydrogen atoms, which diffuse into the core. Because the nanoscale particles are so small and have high surface area, the atomic hydrogen remains near the surface. The process can be thermally reversed when the hydrogen is needed. "So the hydrogen might be stored in a tank already seemingly densely packed with 'nano-sand,' which also reduces any explosion risk," Crabtree said. For fastest release, other investigators are looking at compounds that "physi-sorb" hydrogen: instead of the hydrogen being chemically bound into a compound, hydrogen atoms or molecules are attracted by electrostatic or Van der Waals forces just to sit on the surface or inside molecular cages until released. For either approach to be practical for hydrogen storage, however, "we'd like to get 10 percent storage by weight," Crabtree said.

Meantime, "more solar energy strikes the earth on a single day than the world uses annually—which is why the sun is so appealing as an ultimate energy source," said Michelle V. Buchanan, associate laboratory director of physical sciences at the Oak Ridge National Laboratory, TN. So in the photovoltaic community, converting solar photons into electrons cheaply enough to compete with fossil fuels remains a research challenge. "With traditional single-crystal silicon solar cells, the best reported maximum efficiency from visible light is 24.7 percent," said Dan Holladay, advanced technologies manager at Sematech in Austin, TX.⁵

Nanotechnology may help to both raise the efficiency and lower the costs of tapping solar energy. Large single crystals of silicon are costly to grow. Cheaper solar cells may be built from amorphous and microcrystalline silicon; although such technologies are less efficient than single-crystalline silicon (best reported is 12-to-14 percent), the manufacturing processes are about half the cost. Non-silicon thin-film materials

such as cadmium telluride or $CiGS$ (copper indium gallium selenide) are also cheaper because they can be deposited on steel, glass, or other inexpensive rigid substrates, and have attained an efficiency of 19.1 percent. Researchers are also exploring making organic (plastic) thin-film solar cells that are optically transparent (so they can cover windows) and flexible (so they can wrap around curved shapes), to be able to collect solar energy from the entire surface of an office building rather than just

from its roof. One crucial technical challenge with flexible solar cells, however, is creating an impervious vapor barrier to prevent water molecules from diffusing inside and lowering the efficiency.

Another approach is boosting efficiency at all wavelengths. "The sun has a huge amount of energy in the infrared that is not captured with existing single-junction solar cells," explained Paul Maycock, consultant with PV Energy Systems Inc. in Williamsburg, VA. The heart of any solar cell is the $p-n$ junction, a narrow semiconductor layer where solar photons give rise to electron-hole pairs that flow as current; on either side of the junction are different semiconductor materials, one doped to be n -type to collect the electrons that flow in one direction and the other doped to be p -type to collect the holes that flow in the opposite direction. Depending on the choice of semiconductors, the $p-n$ junction can absorb solar photons at a specific wavelength. "Multijunction thin-film solar cells stack several $p-n$ junctions in thin layers so that a solar cell can efficiently produce electricity from a spectrum of wavelengths, including the infrared," Maycock said. Last year (2008), experimental multijunction photovoltaic cells attained efficiencies greater than 40 percent.

Potentially even more efficient may be quantum dot solar cells, "which absorb solar infrared and create electron-hole pairs from thermal gradients," Maycock continued. In theory, nanoscale quantum dots of various sizes and chemical compositions could be optimized to harvest solar radiation of all wavelengths from infrared to ultraviolet. "Quantum dots are one of my favorite areas on paper although no one yet has built a prototype," said Maycock. "The practical challenge is figuring out how to wire all the quantum dots together to collect current. But it's very good physics."

Energy storage

Intermittent sources of power, such as sun and wind, benefit by being paired with a medium for storing energy for use at night or when the wind has died. Batteries and capacitors store energy directly; energy may also be converted into chemical fuels, salts, or hydrogen.

Batteries store and release electrons *chemically*: when the battery is charged, the positive and negative terminals have a completely different chemical composition than they do when the battery is discharged. Ions (such as lithium ions

in a lithium-ion battery) flow through a liquid electrolyte—one direction to charge, the other direction to discharge; electrons are released to an outside circuit while discharging or taken in while charging. Because chemical reactions take time, batteries are best for operating a device that draws relatively low power steadily over a long time (hours or days). Similarly, rechargeable batteries also require time (usually at least an hour) to recharge. Nanotechnology is improving the design of finely layered “intercalation compounds” for storing high densities of lithium ions, minimizing the distances the lithium ions must travel, allowing for faster charging and discharging. Nanotechnology is also making possible the design of “truly big lithium-ion batteries—the size of a tractor trailer—already being tested in applications where they improve the efficiency of the electric grid,” said Dr. Yet-Ming Chiang, MA B '80, Kyocera professor of materials science and engineering at the Massachusetts Institute of Technology and a co-founder of A123 Systems, a developer of advanced batteries in Watertown, MA.

In contrast to a battery, capacitors store and release

charge *physically*: positive and negative charges just line up on the surfaces of the terminals, held there by electrostatic forces. As a result, a capacitor can charge and discharge very quickly (seconds). Capacitors are excellent for operating any device that requires high power in a short burst. New types of capacitors, often called *ultracapacitors* or *supercapacitors*, store the greatest charge by using a nanostructured double-layer structure [Fig. 5].

In addition, because the internal structure of a battery and a capacitor can be similar, researchers are also investigating methods for using nanostructured oxide materials to combine the best characteristics of both in “pseudocapacitors that can both deliver high power fast (like a capacitor) but also sustained over time (like a battery),” added Dr. Bruce S. Dunn, professor of materials science and engineering at the University of California, Los Angeles.

Not to be overlooked for energy storage is hydrogen. “Hydrogen is misunderstood. It is not a source of energy, but a storage medium,” said Buchanan. “There is no free hydrogen on the earth. We can’t mine hydrogen or stick a pipe into the ground and get hydrogen out. We have to make it from something else. Hydrogen has a very high energy density. So it may prove to be a convenient way to store energy as an alternative to batteries.”

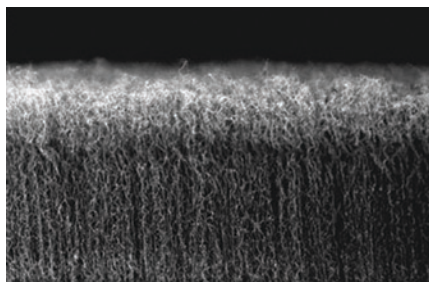


Fig. 5. Forest of ultralong (250 microns) carbon nanotubes grown on an aluminum electrode is key to high-energy storage capacity of an ultracapacitor designed at the Massachusetts Institute of Technology. Ultracapacitors could store energy from any rapidly changing intermittent source such as wind. —Riccardo Signorelli, TX A '02, MIT; NREL

Power from efficiency

“We should use energy we now just throw away,” declared Dr. Mark E. Davis, KY A '77, Warren and Katharine Schlinger professor of chemical engineering at the California Institute of Technology in Pasadena (and, incidentally, the older brother of the University of Virginia’s Robert Davis). “Coal-fired power plants are only about 35 percent efficient: nearly two-thirds of the energy in the fuel burnt is not recovered as generated electricity. A lot of this wasted energy is heat that may be discharged into a river—or in the case of a nuclear reactor sent to a cooling tower.” Some of the wasted heat starts out at high temperatures—above 800°C with nuclear and solar thermal. That’s high enough to thermochemically split water into oxygen and hydrogen. “The only carbon-free source for producing hydrogen is water,” Davis declared. “Thus, to have a *clean* hydrogen economy in the future, hydrogen must come from water instead of from natural gas, as most does today.” Thus, some engineers are investigating co-generation—reclaiming heat energy to produce hydrogen.

Even low-grade heat—heat at temperatures usually considered too low to be useful—can reduce energy demand, as shown in a demonstration heat pump us-



ing a zeolite developed by Davis’s former student Takahiko Takewaki, senior researcher at Mitsubishi Chemical Corp. in Tokyo. The heat pump takes advantage of the fact that some zeolites act as a desiccant: they strongly adsorb—that is, attract to their surfaces—molecules of water vapor, amounting to a significant fraction of their weight. The adsorption is an exothermic reaction and gives off heat. Furthermore, the process is completely reversible: when low-grade heat is added, the saturated zeolite desorbs (releases) the water vapor and is thus regenerated (dried) so it can repeat the cycle. The complete cycle between adsorption and desorption functions like the condenser and evaporator in an air conditioner. The heat pump uses a novel proprietary nanoscale zeolite desiccant that Mitsubishi calls AQSOA, plus just plain water, “to provide air conditioning without using any chlorofluorocarbon coolant, which is known to be harmful to the earth’s ozone layer,” Takewaki explained.

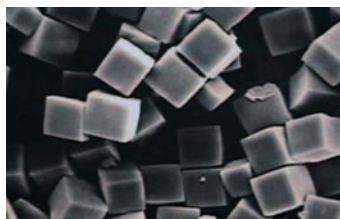
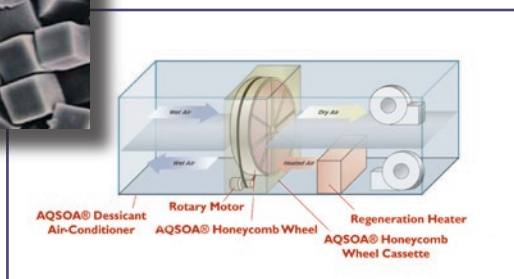


Fig. 6. Novel nanoscale inorganic zeolite dessicant (inset) called AQSOA adsorbs moisture from air; solar-thermal collectors concentrate the sun's heat to dry and regenerate the zeolite. In a new Mitsubishi adsorption heat pump, the adsorption and desorption cycles act like the condenser and evaporator in an air conditioner. Such a solar air conditioner cools a demonstration apartment building and shopping center in Tokyo, conserving electricity. —Mitsubishi



The moisture-laden AQSOA zeolite dessicant is regenerated when exposed to pipes full of hot water at a temperature 140°F (60°C), standard for steaming hot tap water; the water itself is heated by rooftop solar-thermal collectors. Because of the use of solar thermal, the system draws significantly less power from Tokyo's electrical grid than standard

air conditioning. Demonstration AQSOA adsorption heat pumps are now air conditioning a residential apartment building and a shopping center in Japan, and the technology is commercially available from Mitsubishi Plastics, Inc.⁶

Meantime, at the consumer end, what about those fans in a desktop blowing away heat generated by the electronics? Could some of that wasted heat also be turned back into useful power? That question is the focus of research on thermoelectric generators for energy scavenging. Usually a good conductor of electricity is also a good conductor of heat. But to reclaim heat for electricity, it's necessary to find a good electrical conductor that is a *poor* thermal conductor so the heat can be confined to one place for harvesting phonons—nanoscale quanta of vibrational energy, analogous to photons of light. Experimenters at the Office of Naval Research, the University of California, Santa Cruz, and elsewhere are designing nanostructured solid-state thermoelectric materials for converting heat back into electricity, silently and with no moving parts, taking advantage of reversible physical phenomena discovered a century and a half ago (the Peltier effect or the Seebeck effect).

Other gains are being sought by increasing the efficiency of electricity use. For example, lighting alone consumes

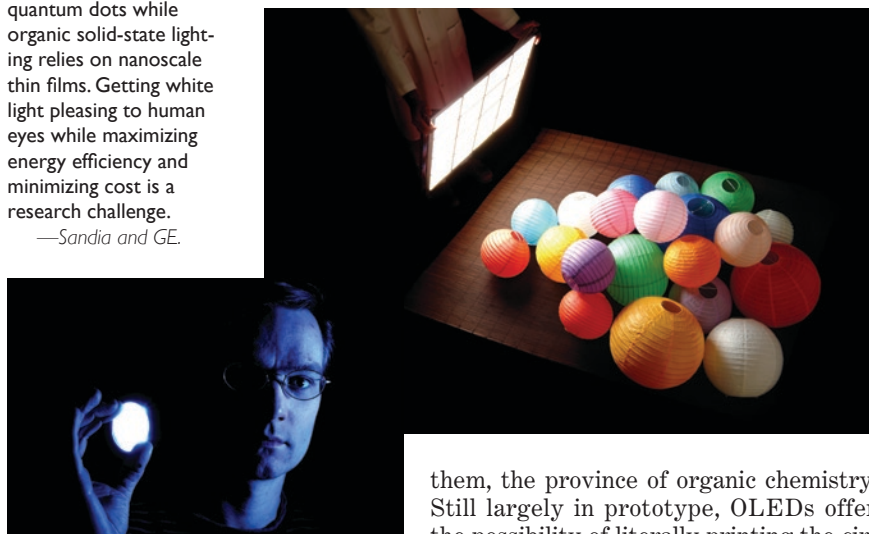
more than 22 percent of the electricity generated in the U.S. Because an incandescent bulb is basically a blackbody radiator, fundamental physics dictates that “95 percent of the power to it is radiated as heat rather than light,” making incandescents only 5 percent efficient, noted Anil Duggal, advanced technology leader of the organic electronics project at General Electric Global Research in Albany, NY. The best fluorescent bulbs—the long tubes—are perhaps 20 or 25 percent efficient. Compact fluorescents fall in the middle because “spiraling the fluorescent tube drops the efficiency to 16 or 17 percent,” added Jerry A. Simmons, deputy director of the physical, chemical, and nanoscience center at Sandia National Laboratories in Albuquerque, NM.⁷

Solid-state lighting based on light-emitting diodes, however, is significantly more efficient than fluorescents [Fig. 7]. Inorganic white-light LEDs are now commercial in flashlights, traffic signals, and automobile and bicycle headlights and tail lights. But for residential lighting, one hefty challenge faces developers: getting white light pleasing to human eyes while not compromising energy efficiency and keeping costs low (“people are reluctant to pay \$20 for a light bulb,” noted Simmons). Efficiently reproducing the spectrum of sunlight requires controlling the composition and structure of the semiconductor layers at the nanoscale as well as devising new phosphors.⁸ Ultimately, “we think solid-state lighting can be more than 50 percent efficient. In fact, that’s a government target⁹ and Sandia is looking at the potential to go even higher,” Simmons said.

A newer kid on the block is thin-film organic light-emitting diodes or OLEDs. Being developed at General Electric, Universal Display Corporation, University of North Texas, and elsewhere, OLEDs are called “organic” because they employ polymer materials with carbon in

Fig. 7. Inorganic solid-state lighting relies in part on nanoscale quantum dots while organic solid-state lighting relies on nanoscale thin films. Getting white light pleasing to human eyes while maximizing energy efficiency and minimizing cost is a research challenge.

—Sandia and GE.



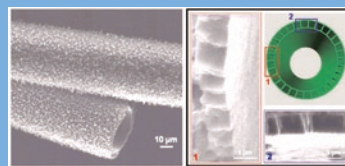
them, the province of organic chemistry. Still largely in prototype, OLEDs offer the possibility of literally printing the circuitry in layers from 30 to 100 nanometers thick on a flexible transparent plastic backing that could be shipped in rolls to offer inexpensive lighting over large

areas, such as an entire wall. One main technical challenge facing OLEDs is the same as that facing organic thin-film photovoltaic devices: the need for an effective vapor barrier, essential for attaining the goal of offering a lifetime of 20,000 hours, comparable to what is standard today for fluorescent bulbs.

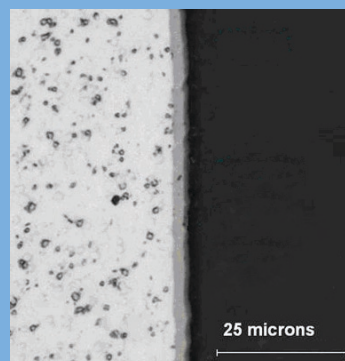
Regardless of the specific nanotechnology or the specific energy application, finding either new sources of power or new efficiencies will “require new breakthrough technologies,” declared Buchanan. “Now is the right time to invest attention and resources.” Added Chiang: “By addressing global issues of energy supply, the great scientific excitement over nanotechnology that we saw last decade may now be justified by widespread societal impact.”

Recent readings—energy applications/nanotechnology:

- *Application of Nanotechnologies in the Energy Sector*, Hessian Ministry of Economy, Transport, Urban, and Regional Development (volume 9 of the series Aktionslinie Hessen-Nanotech), August 2008. www.hessen-nanotech.de/mm/NanoEnergy_web.pdf
- *Energy Frontier Research Centers: Tackling Our Energy Challenges in a New Era of Science*; Department of Energy, Office of Basic Energy Sciences, 2008. www.sc.doe.gov/bes/EFRC.html (scroll partway down for this brochure plus 10 related reports)
- *Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings*, National Science and Technology Council, Committee on Technology; Report of the Subcommittee on Buildings Technology Research and Development, October 2008. www.bfrl.nist.gov/buildingtechnology/documents/FederalRDAGendaforNetZeroEnergyHighPerformanceGreenBuildings.pdf
- “Harnessing Materials for Energy,” special issue, *MRS Bulletin*, Materials Research Society, vol. 33, no. 4, April 2008. www.mrs.org/s_mrs/sec_subscribe.asp?CID=10867&DID=200925
- *Nanoscience Research for Energy Needs: Report of the National Nanotechnology Initiative Grand Challenge Workshop March 16–18, 2004*. www.nano.gov/nni_energy_rpt.pdf
- *Nanoscale Science, Engineering, and Technology in the Department of Energy: Research Directions and Nanoscale Science Research Centers*; Department of Energy, Basic Energy Sciences, 2004. www.sc.doe.gov/bes/brochures/files/NSRC_brochure.pdf
- “Nanotechnology: Energizing the Future,” *NanoFrontiers* (newsletter of the project on emerging nanotechnologies of the Woodrow Wilson International Center for Scholars), Issue 3, Fall 2008. www.nanotechproject.org/process/assets/files/7045/nanofrontiers3energy.pdf
- *New Science for a Secure and Sustainable Energy Future: A report of a subcommittee to the basic energy sciences advisory committee*, Department of Energy, December 2008. www.sc.doe.gov/BES/reports/files/NSSSEF_rpt.pdf
- *Think Efficiency: How America Can Look Within to Achieve Energy Security and Reduce Global Warming*, American Physical Society, September 2008. Download-



Jumbo (1 cm long) carbon nanotube possesses strong electrical conductivity, and has mechanical properties similar to carbon fibers although with 1/20th the density—potentially valuable for high-strength lightweight materials. Reducing the mass of an automobile or aircraft can increase fuel efficiency. Thus, research is being focused on developing strong, lightweight nanocomposite materials, not only to shave mass from the bodies of vehicles, but also from electrical wiring, turbine blades, and the engine block and drivetrain, without compromising crashworthiness or safety. —Sandia/LANL



Engine wear due to internal friction increases energy consumption. Shown here is an ultrahard boron-aluminum-magnesium-ceramic (BAM) coating on steel substrate 2-3 microns thick, just one type of wear-resistant boride nanocoating, developed at DOE's Ames Laboratory, IA. Other methods of reducing wear (not shown) are commercial high-performance lubricants and fuels that contain nanostructured materials, such as inorganic fullerenes of tungsten disulfide. In essence, the fullerenes act like nanoscale ball bearings that coat moving surfaces with a protective “tribofilm” that reduces friction even beyond what a fluid lubricant can provide—indeed, can protect moving surfaces for some time even should the lubricant be lost. —DOE Ames

able from www.aps.org/energyefficiencyreport/report
 • *WTEC Panel Report on International Assessment of Research and Development in Catalysis by Nanostructured Materials* (Baltimore, MD: World Technology Evaluation Center, Inc., January 2009), <http://wttec.org/catalysis/CatalysisFinalRpt-6Feb2009-BW-lowres.pdf> (accessed April 13, 2009) [a 21-MB download]

Notes (All URLs accessed May 2009)

1. According to the U.S. Department of Energy's energy information administration, *International Energy Annual 2006* (posted, Dec. 19, 2008), Table E.1., in 2006 the world consumed 472 quadrillion Btu of energy in all forms = 1.29 quadrillion Btu/day in 2006. Since 2001, the amount of energy consumed in the world has been growing between 8 and 15 quadrillion Btu annually, so it is reasonable that by the end of 2009 the amount might top 500 quadrillion Btu/year = 1.36 quadrillion Btu/day. 1 quad = 10^{15} Btu. One barrel of crude oil is 42 U.S. gallons and packs 5.8×10^6 Btu. So the world's daily energy consumption of 1.36 quads corresponds to 230 million barrels per day, or 85.6 billion barrels per year (see EIA's calculators at www.eia.doe.gov/kids/energy-facts/science/energy_calculator.html).
2. Estimates from DOE Lawrence Berkeley Laboratory, <http://eetd.lbl.gov/l2m2/>.
3. According to the U.S. Census population clock at www.census.gov/main/www/popclock.html, estimate was 6.78 billion as of May 12, 2009.
4. Mark E. Davis and Don Tilley, *Future Directions in Catalysis: Structures that Function on the Nanoscale*, (National Science Foundation Workshop Report, NSF Headquarters, June 19–20, 2003) 2004, www.che.caltech.edu/nsfcatworkshop/NSF%20FinalRept%202004.pdf (accessed April 14, 2009), 15.
5. All the photovoltaic efficiencies cited are given in Martin A. Green *et al.*, "Solar Cell Efficiency Tables (Version 32)," *Progress in Photovoltaics: Research and Applications* 16: 435–440, 2008, www.iee.ac.cn/fckeditor/userfiles/file/tyndc/reference/19918874827996.pdf.
6. A patent granted to Takewaki and colleagues on September 9, 2008, can be found online at www.patentgenius.com/patent/7422993.html. According to another reference "Heat-Generated Cooling Opportunities," by Terry J. Hendricks, Valerie H. Johnson, and Matthew A. Keyser of the U.S. National Renewable Energy Laboratory in Golden, CO, "the adsorption of zeolites is very strong, thereby providing a family of materials . . . permitting extremely high efficiencies for adsorption heat pump cycles with air-cooled condensers . . . Another advantage of zeolite systems is that they allow heating and cooling at the same time." See page 7 of the paper online at www.nrel.gov/vehicle-sandfuels/ancillary_loads/pdfs/heat_cooling.pdf.
7. Just how much energy could be saved, even just from specialized niche applications (exit signs, traffic signals, holiday lighting), is calculated in detail in *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications* (prepared for

- the building technologies program, Office of Energy Efficiency and Renewable Energy, U.S. DoE), October 2008, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_october2008.pdf. To accelerate development and adoption of solid-state lighting, the DOE launched the *L Prize* for products to replace the inefficient 60-watt incandescent bulb and PAR 38 halogen lamps: see www.lightingprize.org.
8. "Research challenges to ultra-efficient inorganic solid-state lighting," Julia M. Phillips *et al.*, *Laser & Photonics Reviews* 1, 307–333 (2007).
 9. Specifically, DOE's target is by 2025 to develop solid-state lighting that is 50 percent efficient with a spectrum that accurately reproduces sunlight. See *Multi-Year Program Plan FY'09-FY'15: Solid State Lighting Research and Development* (prepared for the Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy), March 2009, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf, 23.
 10. Announced by DOE's Idaho National Laboratory at https://inlportal.inl.gov/portal/server.pt?open=514&objID=1269&mode=2&featurestory=DA_101047.

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