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The Project on
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NANOFRONTIERS

Nanotechnology: Energizing the Future

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Reporting on achievements toward realizing the immense potential of nanotechnology, this newsletter continues and updates the discussion begun at the February, 2006 *NanoFrontiers* workshop, co-sponsored by the Project on Emerging Nanotechnologies, the National Institutes of Health, and the National Science Foundation. Issues provide samplings of recent developments in selected areas—accomplishments that hint at new nanotechnology-enabled tools, products, and applications that can be used for the good of humankind and the planet. This issue focuses on prospective applications of nanotechnology specific to social and environmental needs and economic goals of developing countries. Progress in this fast emerging field of science and engineering suggests that, although far from being a panacea, nanotechnology can provide important tools on the path toward solutions.

*Project on Emerging Nanotechnologies is supported
by a grant from THE PEW CHARITABLE TRUSTS*

1. DOE, "The Nation's Premier Scientific User Facilities for Interdisciplinary Research at the Nanoscale," (http://www.science.doe.gov/news_information/newsroom/2006/nano/index.htm).

2. Lux Research, "The Nanotech Report™: Investment Overview and Market Research for Nanotechnology," 5th Edition, Volume 1. Lux Research Inc., 2007.

3. K Schmidt, "Nanofrontiers: Visions for the Future of Nanotechnology," *Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies*, March 2007 (http://www.nanotechproject.org/process/assets/files/2704/181_pen6_nanofrontiers.pdf).

4. Cientifica Ltd., "Nanotechnologies for Sustainable Energy: Reducing Carbon Emissions Through Clean Technologies and Renewable Energy Sources," May 2007, (http://www.researchandmarkets.com/product/64b2f7/nanotechnologies_for_sustainable_energy)

5. Baker Institute Study Group, "Energy and Nanotechnology: Strategy for the Future," James A. Baker Institute for Public Policy of Rice University, April 2005, (http://www.rice.edu/energy/publications/studies/study_30.pdf).

6. Baker Institute Study Group, "Energy and Nanotechnology: Strategy for the Future."

NANOFRONTIERS

Nanotechnology: Energizing the Future

Introduction

Picture the future of energy, and several images may come to mind. Perhaps you envision more nuclear power plants, snazzy electric cars, or roofs of houses stamped with solar panels. How about a bundle of single-walled carbon nanotubes? It's an unlikely guess, as nanotubes are practically invisible to the naked eye. But considering recent breakthroughs in nanotechnology, that guess may soon be a common one.

Though very tiny, nanotubes—and nanotechnology as a whole—are having huge impacts in the energy discussion. The United States Department of Energy is already operating five new nanoscale science research centers to support the synthesis, processing, fabrication and analysis of substances at the nanoscale.¹ Of the nearly 30,000 scientific papers published on environmental and energy technologies in 2006, roughly 24% involved research on nanotechnology-based approaches, and 89% of those publications were on energy topics.² The science and technology of the extremely small, nanotechnology has the potential to transform the way we produce, store, consume, and conceive of energy.

Realizing this potential, however, is no easy task. Ensuring clean, reliable, and affordable energy to a growing populace is arguably the greatest challenge that policymakers face in the 21st century.³ Fossil fuels currently dominate the world energy market, as their abundance and affordability have yet to be matched by an alternative. Over 70% of electricity in the United States comes from coal and natural gas, and petroleum remains the primary fuel for mobilizing our cars, trucks, and planes.

But fossil fuels carry along significant liabilities for national security and public health. A large portion of

global oil comes from unstable regions of the world, and the health and environmental risks associated with greenhouse gas emissions from hydrocarbon combustion are becoming more and more apparent every day.

The scientific community, however, already recognizes nanotechnology as a stepping stone out of the fossil fuel era. Experts argue that advancements in this field are key to making energy production and consumption more efficient while providing new ways to harness energy from clean renewable sources. A report released by Cientifica last year estimated that current applications of nanotechnologies would result in a global annual saving of 8 thousand tons of carbon dioxide in 2007, rising to over a million tons by 2014.⁴ In a study by the Baker Institute for Public Policy at Rice University in 2005, the late Nobel laureate Richard Smalley—the renowned "father of nanotechnology"—stressed that "current technology will not be able to meet the need for energy as the century progresses, but stunning new discoveries in underlying core science and engineering will be required to provide an answer."⁵ In Smalley's view, nanotechnology was the clear solution: "Breakthroughs in nanotechnology open up the possibility of moving beyond our current alternatives for energy supply by introducing technologies that are more efficient, inexpensive, and environmentally sound."⁶

“We see a future where vehicles run on electricity and are equipped with clever ways of making electricity on board, making us less dependent on gasoline. It’s the next great paradigm shift in our industry, an opportunity largely due to the rapid advancement in battery cell technology by companies such as A123Systems and LG Chem.”

—Bob Lutz, GM vice chairman of Global Product Development

<http://www.azonano.com/news.asp?newsID=4693>



Improving efficiency, reducing consumption

Scientists and economists alike believe that the first major impacts of nanotechnology on the energy sector will be improvements in the efficiency of current technologies. The transportation sector is already beginning to feel these impacts, with manufacturers weaving carbon nanotubes into the production of structural automobile parts.⁷ The carbon nanotube—an atom-thick cylinder of graphite—is about six times lighter than steel, but it can support weight that is forty times heavier. Companies like Hyperion Catalysis Inc. are already using nanotubes to increase the toughness of plastics for external body parts and fuel system components.⁸ These kinds of enhancements help make our cars lighter, and consequently more fuel efficient, without sacrificing the safety benefits associated with traditional steel cars. Unidym, a leader in the production and application of carbon nanotubes, has also begun to incorporate this technology into the frames of aircraft for increased strength and flexibility.⁹

The chemical side of nanotechnology and energy efficiency, on the other hand, is a bit more abstract. The chemical benefits of nanotechnology come from increased reactivity potential. A substance made up

of nano-sized particles, when compared with the same quantity of that substance at conventional size, has many more points where reactions can occur. Consider the choice between crushed ice and cubed ice: crushed ice, given its higher surface area-to-mass ratio, cools your drink more quickly. Likewise, when catalysts—substances that accelerate chemical reactions—are reduced to the nano-level, the reaction boost is intensified.

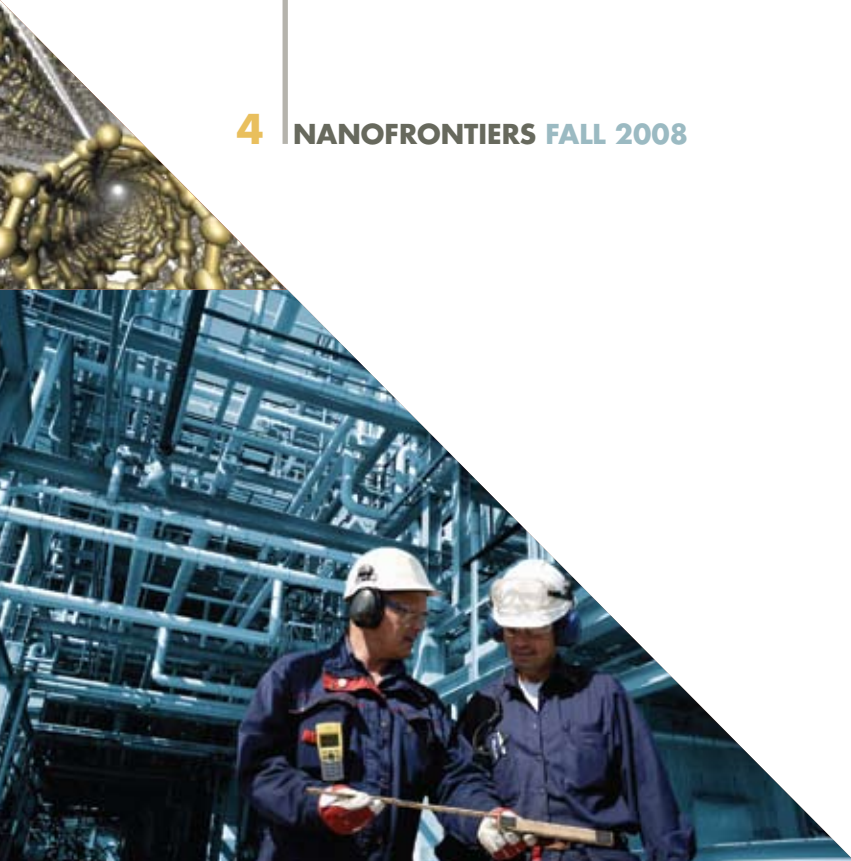
A wide variety of energy consumption activities require catalysts, but the automobile captures the spotlight in the nano discussion. Mazda Motor Corporation, for example, has developed a new automotive catalyst that incorporates precious metal particles—platinum and palladium—at the nano-level. These metals, in their conventional form, are already essential to the process of purifying exhaust gases. But by making them nano-sized, Mazda has reduced the total amount required in automotive catalysts by 70 to 90 percent, while maintaining the same performance quality of these catalysts in the purification process.¹⁰ In addition, a team of engineers from the University of Wisconsin-Madison and the University of Maryland have used nanotechnology to develop a catalyst that

7. Cientifica, “Nanotechnologies and Energy Whitepaper,” *Cientifica.eu*, Feb 2007, (<http://www.cientifica.eu/files/Whitepapers/NanoenergyWhitePaper2007.pdf>).

8. Hyperion Catalysis, “Automotive Applications,” *fibrils.com*, (<http://www.fibrils.com/automotive2.htm>).

9. Unidym, “Unidym Inc. announces the first flight of an aircraft using carbon nanotubes for increased fuselage strength,” April 22, 2008, (http://www.unidym.com/press/pr_080422.html).

10. Mazda Motor Corporation, “Mazda Develops a World-First Catalyst Material Structure for Autos Using Single Nanotechnology,” Oct 1, 2007, (<http://www.mazda.com/publicity/release/2007/200710/071001b.html>).



“The weight, size, safety and performance of these batteries have implications on all transportation, including hybrid buses, trucks and aircraft.”

—David Vieau, A123System's chief executive officer

<http://www.azonano.com/news.asp?newsID=4693>

11. J. Beal, “New nanoparticle catalyst brings fuel-cell cars closer to showroom,” *University of Wisconsin-Madison News*, March 19, 2008, (<http://www.news.wisc.edu/14928>).

12. Lux Research, “The Nanotech Report™: Investment Overview and Market Research for Nanotechnology.”

13. R. Raffaele, “Carbon Nanotube Anodes Being Evaluated for Lithium Ion Batteries,” *NASA*, July 15, 2002, (<http://www.grc.nasa.gov/WWW/RT2001/5000/5410hepp1.html>).

14. R. Ranalli, “Power players,” *The Boston Globe*, Nov 29, 2007, (http://www.boston.com/news/local/articles/2007/11/29/power_players?mode=PF).

15. A123Systems, “Technology: A123Systems' Nanophosphate technology offers unprecedented power, safety and life,” (<http://www.a123systems.com/#/technology/>).

16. A123Systems, “High-power lithium ion batteries,” (<http://www.a123systems.com/hymotion/technology/>).

promises improved efficiency in hydrogen fuel-cells.¹¹ The catalyst—a ruthenium nano-particle surrounded by one to two layers of platinum atoms—improves the key hydrogen purification reaction and leaves more hydrogen available to make energy in the fuel cell.

Battery Power

Energy storage is the next part of the nano-energy equation. Batteries are the most fundamental and convenient method of energy storage: they are lightweight, portable, and often rechargeable. Storage capacity, lifetime, and safety are the measure of battery quality, and each category can be improved with nanotechnology. Nano-porous materials enable faster discharge in battery electrodes; carbon nanotubes can enhance their efficiency and conductivity; and ceramic nanoparticles can improve safety profiles by expanding the range of battery operating temperatures.¹² But the hard science of batteries, for many, is the less interesting part of the story. What can nano-enabled batteries actually do?

Nano-enabled batteries have already begun to emerge in portable electronics. Manufacturers are utilizing the surface area advantage of carbon nanofibers and nanotubes in lithium-ion batteries to create batteries that supply energy for longer periods of time with the same amount of electrode material.¹³

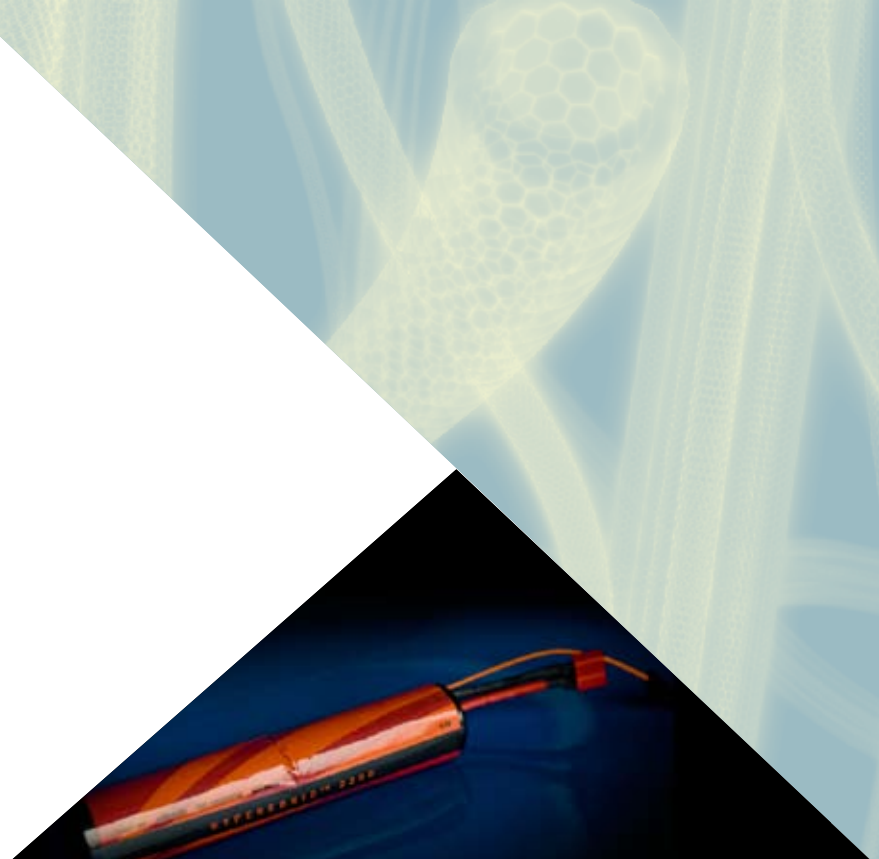
Mobile phones, power tools, and iPods have already been granted longer lives, but improvements in the storage capacity of larger batteries, such as those used to power vehicles, are well underway.

To date, the development of safe and commercially viable electric vehicles has been slowed by the limitations in battery power and range.¹⁴ Current hybrid models incorporate nickel metal-hydride batteries, because conventional lithium-ion batteries, though lighter and more efficient, tend to overheat and explode when used to power vehicles. However, A123Systems, a private start-up firm based in the U.S., has developed a more stable lithium-ion battery. Using electrode technology and low-impedance nanophosphates developed in labs at the Massachusetts Institute of Technology, A123Systems has created cells and electrodes that give batteries higher voltage and longer lifespans, promising greater overall range and safety in vehicular use.¹⁵ Indeed, A123Systems has already developed a conversion module to upgrade the Toyota Prius from a standard hybrid-electric vehicle to a plug-in hybrid-electric vehicle, allowing consumers to achieve mileage results as high as 100 mpg.¹⁶ Other major players in the automotive sector, including General Motors and Chrysler, have already jumped on the nano-battery bandwagon.

“This is an important milestone in our battery development. Proving out our unprecedented battery technology for a large-scale operation like a Navy destroyer paves the way for a safe, less costly, and environmentally sustainable substitute for turbines that use increasingly costly imported oil.”

—Terry M. Copeland, chief executive officer
of Altair Nanotechnologies

<http://www.marketwire.com/press-release/Altair-Nanotechnologies-Inc-NASDAQ-ALTI-897177.html>



KEY ENERGY STORAGE COMPANIES

NAME	COUNTRY	COMMENT
Showa Denko	Japan	Incorporates multi-walled carbon nanotubes into lithium battery electrodes
Altair Nanotechnologies	U.S.	Using nanostructured electrodes to create lithium-ion batteries; supplying batteries to the U.S. Navy for back-up turbines
Evonik	Germany	Developing battery electrodes and separators based on nanoparticle technology; has strong ties to the automotive industry in Germany and is aiming to supply electric and hybrid-electric vehicles
Columbian Chemicals	U.S.	Produces nano-enhanced catalysts for electrode membrane, direct methanol, and phosphoric acid fuel cells
NanoDynamics	U.S.	Manufacturing nickel, copper and silver nanoparticles for applications including fuel cells

Lux Research, “The Nanotech Report™: Investment Overview and Market Research for Nanotechnology,” pp 144.



"This is the world's lowest-cost solar panel, which we believe will make us the first solar manufacturer capable of profitably selling solar panels at as little as 99 cents a watt."

—Martin Roscheisen, chief executive officer of Nanosolar

<http://www.guardian.co.uk/environment/2007/dec/29/solarpower.renewableenergy>

Nano in the Auto

17. Chevrolet, "Concept Chevy Volt," Jan 2008, (<http://www.chevrolet.com/electriccar/>).

18. "Jeep Renegade," *Jeep.com*, (http://www.jeep.com/en/autoshow/concept_vehicles/renegade/).

19. "Electric Doblò: 300km driven in one day," Newteon Ecofriendly Vehicles, (http://www.newteon.com/www2/en/Actualites/Actu_Newteon/Doblo_Electrique%3A_300km_parcourus_en_un_jour_20071015255/).

20. J Losh, "A New (Good) Look for Electric Cars," *Time*, July 28, 2008, (<http://www.time.com/time/business/article/0,8599,1827090,00.html>)

- Chevrolet has introduced what it calls a new kind of electric vehicle—Concept Chevy Volt—which incorporates the battery developed by A123Systems into its rechargeable electric drive system.¹⁷ The Chevy Volt concept car is designed to use zero gasoline and produce zero emissions for daily commutes of up to 40 miles.
- The 2008 Jeep Renegade Concept car developed by Chrysler combines a nano-enhanced lithium-ion battery pack with a small-displacement BLUETEC diesel engine. This combination, according to Chrysler, will help the Renegade achieve a fuel economy of more than 110 miles per gallon.¹⁸
- Micro-Vett, a leader in Italian electric vehicles, has released the Fiat Doblò, a regular size five-seat station wagon that can travel over 180 miles in one day using a lithium-ion battery pack. The battery pack can be recharged in less than 10 minutes.¹⁹
- A new electric sports car out of the UK—the Lightning GT—contains 30 batteries made of lithium-titanate nanoparticles that boast a range of over 185 miles and take only 10 minutes to recharge.²⁰

“You’re talking about printing rolls of the stuff—printing it on the roofs of 18-wheeler trailers, printing it on garages, printing it wherever you want it. It really is quite a big deal in terms of altering the way we think about solar and in inherently altering the economics of solar.”

—Dan Kammen, founding director of the Renewable and Appropriate Energy Laboratory at the University of California at Berkeley

http://www.popsi.com/popsi/flat/bown/2007/green/item_59.html

On the glow

In the long-run, we will likely see a stronger presence of nanotechnology in the energy production process.²¹ The future of energy production begins with a well-known source: the sun. The sun provides more energy to the Earth than all fossil fuels combined. From sunlight, total energy available to the Earth is about 3850 zettajoules (3.85 million trillion joules) per year.²² To put that figure into perspective, worldwide energy consumption was 0.471 zettajoules in 2004, which amounts to just 0.01 percent of the solar energy striking the Earth’s surface. In effect, a solar power plant constructed across one percent of the Sahara Desert, working at maximum efficiency, could satisfy the world’s electricity demand.²³

Photovoltaic (PV) cells convert beams of sunlight directly into electricity. Some of the more common uses of PV today include calculators with liquid crystal displays (LCD), roadside emergency telephones, satellites, and spacecraft. PV-installed solar panels can also be attached to houses and buildings and connected to a transmission grid or an energy storage device, such as a battery. Currently, the most affordable form of PV cell is bulk crystalline silicon, but it tends to have high materials cost and low capital efficiency. Thin-film

PV—commonly referred to as the second generation of PV—is beginning to attract a lot of market attention with its lower production costs, but it still has lower module efficiency than silicon cells.²⁴ Though solar energy is renewable and almost pollution-free, low efficiency—which raises the cost of production—remains its greatest weakness. Fortunately, advancements in nanotechnology may solve this problem.

Nanosolar—a leader in solar cell technology—is using nanotechnology to reduce waste in solar cell production. The company has developed a proprietary ink that allows for simpler and higher-yield printing in depositing the solar cell’s semiconductor, which is the first step in the panel production process.²⁵ Engineers at General Electric have also been tinkering with a third generation of PV cells, which incorporates new energy conversion mechanisms—nanocomposites and quantum wires—that promise both the low-cost benefits of thin-film and the high efficiency of silicon PV cells.²⁶ Nanocomposites can add to the electrical and thermal conductivity of solar cells, and quantum wires—wires spun from carbon nanotubes—are lighter in weight and conduct electricity more efficiently than conventional copper wires.²⁶

21. Cientifica, “Nanotechnologies and Energy Whitepaper,” (http://www.cientifica.eu/index.php?option=com_content&task=view&id=61&Itemid=106).

22. V Smil, “Energy at the Crossroads,” OECD, May 17, 2006, (<http://www.oecd.org/dataoecd/52/25/36760950.pdf>).

23. “Ten Facts About Solar Energy,” *Solel*, (<http://www.solel.com/faq/>).

24. J P Lynch, “2007: The Year of the Thin Film PV Stock,” May 2, 2007, (<http://www.renewableenergyaccess.com/rea/news/business/story?id=48359>).

25. “The Third Wave of Solar Power,” *Nanosolar*, (<http://www.nanosolar.com/technology.htm>).

26. L Tsakalakis, “GE Looks at Nano to Power Next-Gen Solar in Historic R&D Labs of Thomas Edison,” *Nano Science and Technology Institute*, Sept 24, 2007, (<http://www.nsti.org/news/item.html?id=187>).



“Future solar cells will exploit solar energy better as the distance of energy transportation in the solar cell will be shorter and thus lessen the loss of energy”

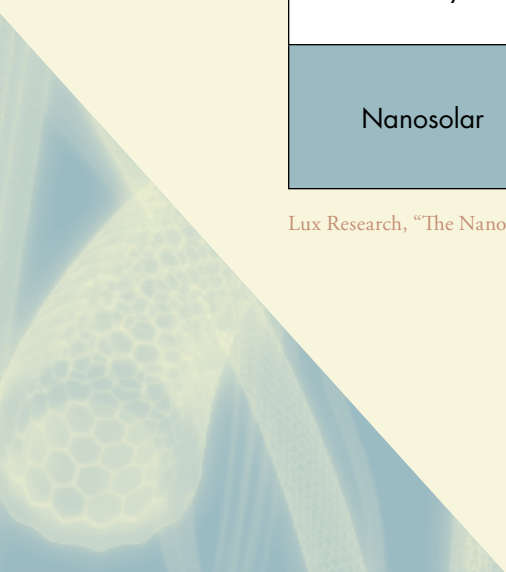
—Dr. Martin Aagesen, director of SunFlake Inc.


http://nano.ku.dk/english/news/solar_cells_of_the_future/

KEY SOLAR CELL COMPANIES

NAME	COUNTRY	COMMENT
Dyesol	Australia	Developing dye-sensitized solar cells (Gratzel cells) from nano-sized titanium dioxide; reports cells have 12% efficiency under some conditions
Stion	U.S.	Working on high-efficiency thin-film solar cells, likely based on silicon and germanium quantum dots
Nanosys	U.S.	Developing advanced nanowire structures, called “tetrapods,” and other nanomaterials for printed photovoltaic panels
Nanosolar	U.S.	Developing nanoparticles into solar cells at 15% efficiency; has broad, exclusive license technology developed at Sandia National Laboratories

Lux Research, “The Nanotech Report™: Investment Overview and Market Research for Nanotechnology,” pp 154.





Researchers in university labs are also discovering new nano ways to harness energy from the sun. Berkeley's interdisciplinary Energy and Resources Group is developing a type of "solar paint," a photosensitive nano-solution that could be applied on walls, cars, or boats and convert sunlight into energy like a conventional solar panel.²⁸ Dr. Martin Aagesen, researcher at the University of Copenhagen and director of SunFlake Inc., has used molecular beams to create a perfect crystalline structure he calls a "nano flake." This structure has the potential, if embedded in a solar panel, to convert up to 30 percent of solar energy into electricity—about three times the efficiency of current panels. "The potential is unmistakable," Dr. Aagesen says. "We can reduce the solar cell production costs because we use less of the expensive semiconducting silicium in the process."²⁹

The estimated market size of nano-enabled solar cells was \$2.1 million in 2006. But with continued investments in research and development, according to Lux Research, it will reach \$1.2 billion by 2011.³⁰

ADDITIONAL RESOURCES

Project on Emerging Nanotechnologies, Nanotechnology in China: Ambitions and Realities (webcast and materials for program held Feb. 6, 2007):
www.nanotechproject.org/104/

Project on Emerging Nanotechnologies, Using Nanotechnology to Improve Health in Developing Countries (webcast and materials for program held Feb. 27, 2007):
www.nanotechproject.org/106

Meridian Institute Projects on Nanotechnology (including Global Dialogue on Nanotechnology and the Poor; Nanotechnology, Water, and Development; and *Nanotechnology and Development News*):
www.merid.org/nano/

Millennium Project, Task Force on Science, Technology, and Innovation (The Task Force's report contains a detailed overview of nanotechnology and relevant applications in Chapter 4, "Platform technologies with wide applicability.")
www.unmillenniumproject.org/reports/tf_science.htm

United Nations Environment Program (For an overview of prospective benefits and a discussion of potential environmental impacts, see "Emerging Challenges, Nanotechnology and the Environment," in the *Geo Year Book 2007*):
www.unep.org/geo/yearbook/yb2007/

27. J. Wolfe, "Big Energy Turns to Tiny Nanotech," *Forbes.com*, July 24, 2004, (http://www.forbes.com/2003/07/24/cz_jw_0724soapbox.html).

28. "Solar Paint and Other Solar Surprises," *Environmental News Service*, Nov 12, 2007, (<http://www.ens-newswire.com/ens/nov2007/2007-11-12-094.asp>).

29. "Solar cells of the future," Nano-Science Center, University of Copenhagen, Dec 5, 2007, (http://nano.ku.dk/english/news/solar_cells_of_the_future/).

30. Lux Research, "The Nanotech Report™: Investment Overview and Market Research for Nanotechnology."

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