Woodrow Wilson International Center for Scholars
Project on Emerging Nanotechnologies

GREEN NANOTECHNOLOGY: IT'S EASIER THAN YOU THINK

KAREN F. SCHMIDT

PEN 8
APRIL 2007

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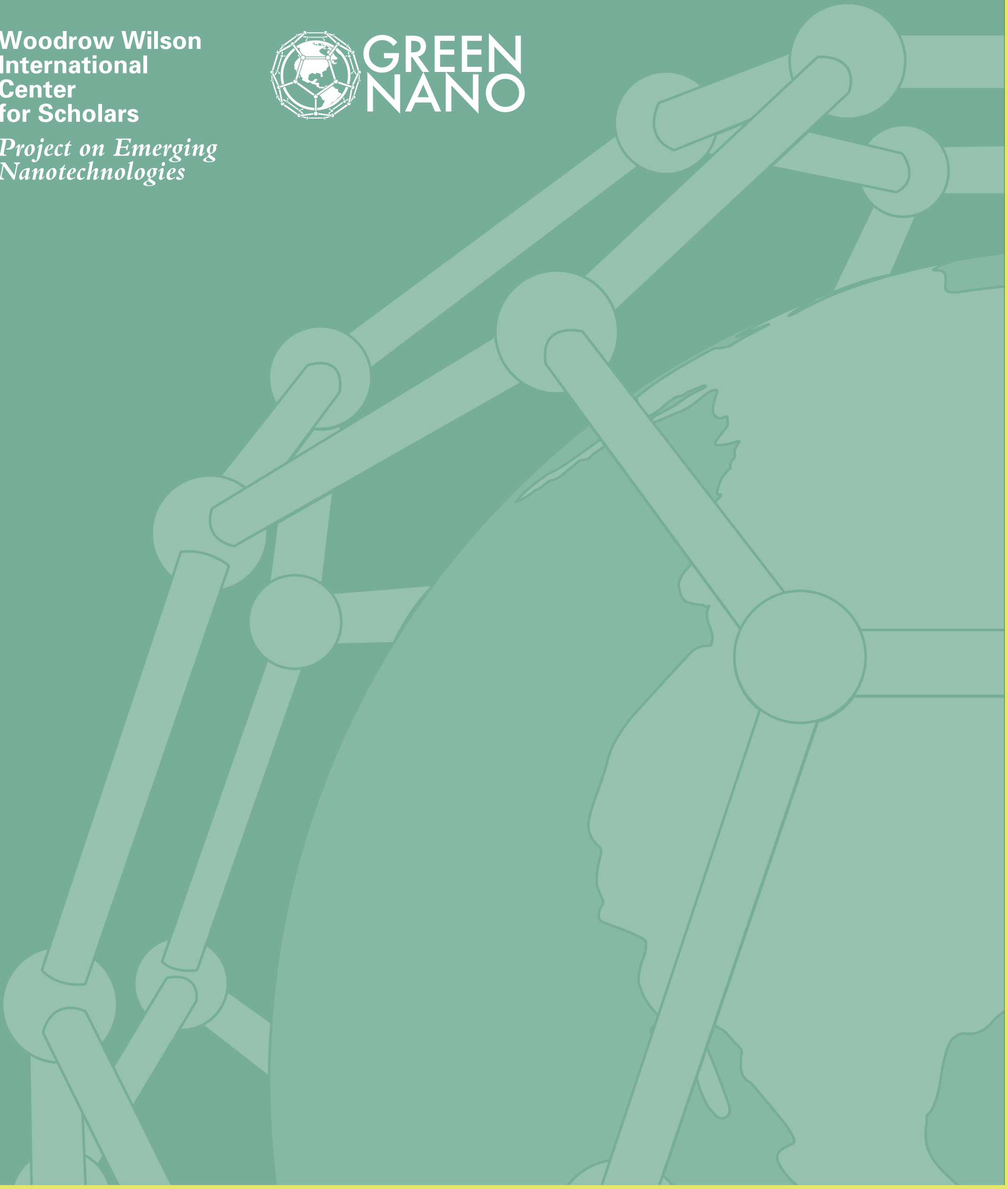
GREEN NANO



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About the Author

Karen F. Schmidt is a freelance journalist and science writer based in California. Her articles have appeared in numerous national and international magazines and journals, including *New Scientist* and *Science*. Her writing focuses on biology, nanotechnology and toxicology, as well as on research and policy issues related to human health and the environment.

She is a former beat reporter, covering chemistry for *Science News,* and a former science features writer for *U.S. News & World Report*, both based in Washington, DC. At *U.S. News & World Report*, Schmidt authored a major cover story on the biology of aging. She began her journalism career as a features writer for the *Santa Cruz Sentinel* in California. She is currently collaborating with a physicist to write and produce a series of podcasts on nanotechnology for The Exploratorium Museum in San Francisco.

Schmidt graduated with a B.S. degree in chemistry/biochemistry, with great distinction, from San Jose State University. She holds a graduate certificate in science writing from the University of California, Santa Cruz. Schmidt has also taught news reporting and writing. Her honors and awards include a Scripps Howard Institute on the Environment Fellowship (2002), a Fulbright Senior Scholar Fellowship in Journalism (2000-2001) and a Society of Environmental Journalists Arizona Fellowship (1996).

Acknowledgements

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Preface

A new generation of highly efficient environmental technologies—from solar technologies and water-purification systems to sensors that detect pollution levels—is becoming a reality as a result of nanotechnology's revolutionary properties and increased investment in this field. As cited in the November 18, 2006 issue of the *Economist*, one of the most significant recent investments in renewable energy went to the nanotechnology-based firm Nanosolar, which received $100 million in funding from venture capitalists in June 2006. Not only are new, clean, energy efficient applications now incorporating nanotechnology, but also some researchers are beginning to integrate green engineering and chemistry principles early on into their production methods for nanomaterials and nanoproducts. Manufacturers have tremendous opportunities to design their production processes in ways that minimize environmental impact at the early stages of development in this nascent (albeit fast-growing) field.

Green nanotechnology involves an approach to risk mitigation in an emerging and important set of industries. It involves three complementary goals: (a) advancing the development of clean technologies that use nanotechnology, (b) minimizing potential environmental and human health risks associated with the manufacture and use of nanotechnology products and (c) encouraging replacement of existing products with new nanoproducts that are more environmentally friendly throughout their life cycles. These approaches not only offer environmental benefits (e.g., reducing fuel use and emissions and cleaning up pollution) but also will help give us greater security (e.g., offering more self-reliability) and help us address public health crises (e.g., alleviating disease and poverty and helping equalize access to clean water), among other benefits. This critically important approach of nanotechnology needs further attention and integration into manufacturing processes, educational curricula and policy efforts. The U.S. government needs a strategy for encouraging and stimulating green nanotechnology.

The Project on Emerging Nanotechnologies, a joint initiative of the Woodrow Wilson International Center for Scholars and The Pew Charitable Trusts, instituted a Green Nano initiative as part of the Project's efforts to encourage responsible development of nanotechnologies. As part of this initiative, our Project hosted a series of science, technology and policy meetings at the Woodrow Wilson Center between February and May 2006, and organized and co-chaired the Nanotechnology and the Environment Symposium at the American Chemical Society meeting in Atlanta, Georgia, in March 2006. This paper reports on the experiences of scientists who apply green nanotechnology in their laboratories and on the perspectives of industry representatives, lawyers and policymakers, who shared their insights at those meetings.

We must learn from the chemists, physicists, engineers and other experts who are making green nanotechnology a reality one lab at a time. Nanotechnologies have the potential to advance as "instruments of sustainability"[1] only if we encourage and witness broad expansion of green nano practices and technologies.

—David Rejeski
Director, Project on Emerging Nanotechnologies

1. Weisner, Mark R., and Vicki L. Colvin. "Environmental Implications of Emerging Nanotechnologies." *Environmentalism & the Technologies of Tomorrow: Shaping the Next Industrial Revolution*. Ed. Robert Olson and David Rejeski. Washington: Island Press, 2005. 41-52.

Foreword

Exciting new technologies with the potential to fundamentally change the way in which we do business do not often occur. Nanotechnology is one of those exciting, albeit infrequent, technological change agents that can influence all industries. Working with matter at the nanoscale or using nanoscale materials to build or improve current products may prove to be as important as moving from the stone age to the bronze, then iron age or harnessing and developing electricity. Nanotechnology holds the potential for pervasive and revolutionary changes. These changes can follow a path leading to waste, pollution and energy inefficiency, or follow a path of green nanotechnology to a more sustainable future. It is our choice while the window of opportunity still remains open.

We are aware of nanotechnology's potential for industry. At the same time, we are aware that producing nanomaterials or the products incorporating these materials may cause damage to the environment or to human health. We also recognize that the novel properties of matter at the nanoscale that make it so exciting to industry and scientists could adversely interact with the environment in novel and unknown ways.

Green nanotechnology offers the opportunity to head off adverse effects before they occur. Green nanotechnology can proactively influence the design of nanomaterials and products by eliminating or minimizing pollution from the production of the nanomaterials, taking a life cycle approach to nanoproducts to estimate and mitigate where environmental impacts might occur in the product chain, designing toxicity out of nanomaterials and using nanomaterials to treat or remediate existing environmental problems. Green nanotechnology does not arise de novo; rather, it builds on the principles of green chemistry and green engineering and focuses them through a new lens on the unique and often counterintuitive effects that occur in nanoscale materials.

While at the Woodrow Wilson Center, I sought to advance the understanding and application of green nanotechnology, continuing and expanding work that began at the U.S. Environmental Protection Agency. To this end, the Project on Emerging Nanotechnologies hosted the series of seminars in the spring of 2006 to explore:

(1) what green nanotechnology is and how it changes our approach to this emerging technology;

(2) how industry perceives its role in preventing harm from new technologies, how it can adopt proactive measures and whether "being green" offers competitive advantage;

(3) how environmentally benign manufacturing, green engineering and design for the environment can be integrated into nanoproduct manufacturing, and what tools engineers need to manufacture nanomaterials and products with a low impact on the environment; and

(4) what policy options would be effective for "greening" new technologies.

The time is ripe and advantageous for nanotechnology researchers and developers to apply green chemistry and green engineering principles in their laboratories, design, and production facilities. Please join us in this endeavor to follow a path of green nanotechnology to a more sustainable future.

—Barbara Karn
Visiting Environmental Scientist, Project on Emerging Nanotechnologies

Acronyms Used in This Report

ACS	American Chemical Society
CEO	Chief Executive Officer
DRAM	Dynamic Random Access Memory
ECA	Electrically Conductive Adhesive
EPA	U.S. Environmental Protection Agency
LCA	Life Cycle Assessment
MSN	Mesoporous Silica Nanoparticle
NSF	National Science Foundation
ppb	parts per billion
PRINT	Particle Replication In Non-wetting Templates
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscope
SRAM	Static Random Access Memory
SRC	Semiconductor Research Corporation
TEM	Transmission Electron Microscope
UV	Ultraviolet

I. Introduction

The microelectronics industry once was considered "clean" when compared with heavy industries of the past, but we now know that its environmental impact is far greater than it first appeared. A single dynamic random access memory (DRAM) microchip that weighs a mere 2 grams and goes inside a computer requires 1.7 kilograms of raw material inputs, including chemicals, water and fossil fuels.[1] So, the race is on to develop a memory chip that is faster and cheaper, requires less energy and material inputs and generates less waste than conventional DRAM, selective random access memory (SRAM) and flash memory.

Since 2000, the semiconductor industry has been engaged in nanoscale manufacturing. Semiconductor manufacturers such as Hewlett-Packard are beginning to use nanotechnology to design more energy efficient, longer-lasting chips.[2] And now, though very small in volume, nanomaterials are becoming a part of the waste stream from those factories.[3]

The semiconductor industry is just one of many industries using and producing nanomaterials. According to an inventory maintained by the Project on Emerging Nanotechnologies, nearly 400 company-identified nanotechnology-based consumer products are on the market—ranging from computer chips to automobile parts and from clothing to cosmetics and dietary supplements. This figure does not include more than 600 raw material and intermediate components and industrial-equipment items used by nanotechnology manufacturers who participated in a survey by EmTech Research.[4] Whether from the electronics or other industries, at this early stage of nanotechnology commercialization, little is known about the transport and fate of these nanomaterials in the environment or about their risks to wildlife and people.

Today, a cadre of research scientists and engineers is working to develop cutting-edge methods for green manufacturing of nanoelectronics and other nanoproducts that are more people- and planet-friendly. Take James E. Hutchison, a chemist at the University of Oregon in Eugene, who was interested in gold nanoparticles, which are promising materials for use in new kinds of electronics and medical imaging. The standard way to synthesize gold nanoparticles uses large amounts of toxic solvents that can be flammable and explosive. Hutchison thought there must be a better way, and in fact, he and his students figured out an innovative synthesis method that uses non-toxic solvents, a new catalyst and purification by nanoporous filtration.

Hutchison's technique not only proved to be greener, safer and faster than the old method but also much cheaper. A gram of gold nanoparticles costs just $500 to make using the new method, rather than costing $300,000 using the more resource-intensive and hazardous conventional method. By showing that green synthesis of nanomaterials can boost efficiency and save money, Hutchison says, he has won friends in the electronics industry, including CEOs who once derided all things "green."

"Green chemistry is a terrific way to do nanotechnology responsibly."

—James E. Hutchison, chemist and Director, Oregon Nanoscience and Microtechnologies Institute's Safer Nanomaterials and Nanomanufacturing Initiative, University of Oregon, Eugene, OR

Many similar stories are now playing out around the country and the world. A growing number of researchers are merging green chemistry and green engineering with nanotechnology, and they

1. Williams, Eric, Robert Ayers, and Miriam Heller. 2002. "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices." *Environmental Science and Technology*. 36: 5504-5510.
2. Reuters. 2007. "HP Claims Advance in Semiconductor Nanotechnology." Reuters. January 16, 2007.
3. Shadman, Farhang. 2006. "Environmental Challenges and Opportunities in Nano-Manufacturing." Presentation given at Green Nanotechnology Event hosted by the Project on Emerging Nanotechnologies at the Woodrow Wilson International Center for Scholars, April 26, 2006.
4. EPA. 2007. *Nanotechnology White Paper*. Science Policy Council, U.S. Environmental Protection Agency. EPA 100/B-07/001. February 2007.

say they see a bright future for a new field known as "Green Nano." Some, like Hutchison, want to help "green up" industries that use emerging nanotechnologies. Others who are working on green technologies—such as solar cells, remediation techniques and water filters—are turning to nanotechnology to achieve their goals of creating better devices to help the environment. These researchers assert that a strong marriage between nanotechnology and green chemistry/engineering holds the key to building an environmentally sustainable society in the 21st century.

To explore this possibility, the Project on Emerging Nanotechnologies at the Woodrow Wilson International Center for Scholars launched a Green Nano Program in February 2006. This initiative aims to advance the development of clean technologies using nanotechnology, to minimize potential environmental and human health risks associated with the manufacture and use of nanotechnology products in general, to apply nano to solve legacy environmental problems, and to encourage replacement of existing products with new nanoproducts that are more environmentally friendly throughout their life cycles.

To promote these ideas and present current research findings, the Wilson Center's Green Nano Program co-organized a four-day symposium at the annual meeting of the American Chemical Society (ACS) in Atlanta in March 2006. Nearly 50 scientists presented their latest research findings, and hundreds of others attended the talks.[5] In addition, four public seminars on green nano took place at the Wilson Center in Washington, DC, during the spring of 2006. At these events, eight speakers representing scientists, engineers and industry and policy experts offered their perspectives and solicited a dialogue.[6] This report summarizes the highlights of the ACS research symposium and the seminar series and provides an overview of the challenges and opportunities of green nano.

Throughout the discussions, participants explored the overarching concepts of green nano and how to define it. For some, it started with the National Nanotechnology Initiative definition of

5. See Appendix B for the ACS agenda.
6. See Appendix A for the event listings and webcast information.

BOX 1: 12 Principles of Green Chemistry

1. Prevent waste: Design chemical syntheses to prevent waste, leaving no waste to treat or clean up.
2. Design safer chemicals and products: Design chemical products to be fully effective, yet have little or no toxicity.
3. Design less hazardous chemical syntheses: Design syntheses to use and generate substances with little or no toxicity to humans and the environment.
4. Use renewable feedstocks: Use raw materials and feedstocks that are renewable rather than depleting. Renewable feedstocks are often made from agricultural products or are the wastes of other processes; depleting feedstocks are made from fossil fuels (petroleum, natural gas or coal) or are mined.
5. Use catalysts, not stoichiometric reagents: Minimize waste by using catalytic reactions. Catalysts are used in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and work only once.
6. Avoid chemical derivatives: Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.
7. Maximize atom economy: Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be few, if any, wasted atoms.
8. Use safer solvents and reaction conditions: Avoid using solvents, separation agents or other auxiliary chemicals. If these chemicals are necessary, use innocuous chemicals.
9. Increase energy efficiency: Run chemical reactions at ambient temperature and pressure whenever possible.
10. Design chemicals and products to degrade after use: Design chemical products to break down to innocuous substances after use so that they do not accumulate in the environment.
11. Analyze in real time to prevent pollution:Include in-process, real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts.
12. Minimize the potential for accidents: Design chemicals and their forms (solid, liquid or gas) to minimize the potential for chemical accidents, including explosions, fires and releases to the environment.

Source: EPA. 2006. "12 Principles of Green Chemistry." U.S. Environmental Protection Agency, June 26, 2006. http://www.epa.gov/opptintr/greenchemistry/pubs/principles.html, accessed January 24, 2007. Adapted from: Anastas, P. T., and J. C. Warner. *Green Chemistry: Theory and Practice*. New York: Oxford University Press, 1998.

BOX 2: Principles of Green Engineering

The following green engineering principles were developed through discussions of approximately 65 engineers and scientists during the week of May 19, 2003, at the Sandestin Resort in Destin, Florida at the "Green Engineering: Designing the Principles" conference, sponsored by Engineering Conferences International.

1. Engineer processes and products holistically, use systems analysis and integrate environmental impact assessment tools.
2. Conserve and improve natural ecosystems while protecting human health and well-being.
3. Use life cycle thinking in all engineering activities.
4. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
5. Minimize depletion of natural resources.
6. Strive to prevent waste.
7. Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.
8. Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability.
9. Actively engage communities and stakeholders in development of engineering solutions.

Source: EPA. 2006. "What Is Green Engineering." U.S. Environmental Protection Agency, March 31, 2006. http://www.epa.gov/oppt/greenengineering/pubs/whats_ge.html, accessed January 12, 2007.
Note: For other important principles of green engineering, see Anastas, P.T. and J.B. Zimmerman. 2003. "Design through the Twelve Principles of Green Engineering." *Environmental Science and Technology*, 37(5): 94A-101A.

nanotechnology: the study and control of matter in the dimension of 1 to 100 nanometers. In this size range, matter takes on new and interesting properties—for instance, while bulk metals are not very chemically active, nanoparticles of metals are often highly catalytic. Properties such as color, electrical conductivity and magnetism can potentially be tuned by changing the size and shape of nanoparticles. Nanotechnology offers myriad new materials and methods for scientists and engineers to exploit in new applications.

For other participants, green nano started with a definition of what it means to be "green." They talked about the philosophy embodied in "green chemistry," which is defined by 12 principles, detailed in Box 1, that include such goals as preventing waste, maximizing the incorporation of raw materials, exploiting catalysis and minimizing the use of toxic chemicals.

"Green engineering" likewise seeks to avoid harming the environment, but, as Box 2 indicates, focuses more on the design of products and processes—for instance, making them more energy efficient and building them out of biodegradable materials. The green approach relies on Life Cycle Assessment (LCA), a way of examining all of the impacts that a particular product has on the environment. This approach requires that the engineer consider the product's manufacture, its use over many years and its ultimate resting place and decomposition. Ideally, an LCA looks at such things as the impacts of mining or manufacture of the raw materials, factory emissions released during production, the waste materials disposed of, and the product's fate at a landfill, a recycling center or elsewhere. Another approach to LCA, suggested by one speaker, would be to examine each step in the product's life span for opportunities to make better choices for the environment.

Green chemistry/engineering might seem like an odd mate for nanotechnology, but, in fact, both respect and seek to emulate natural processes. The goal of green chemistry/engineering is to make industries function more like ecosystems or like cells, in which benign materials are used wisely, wastes are recycled and energy is used efficiently. As it turns out, biological systems accomplish this feat by exploiting properties that occur in the nanodimension. Indeed, the cell is the quintessential "green nano factory," one speaker emphasized. It uses natural ingredients at room temperature to assemble nanostructures, carries out its chemical reactions in water rather than in harmful solvents, employs smart controls with feedback loops, conserves energy and reuses wastes. So, it should be no surprise that many researchers view nanotechnology and green chemistry/engineering as capable of working hand-in-hand to produce environmentally sustainable products and processes.

A marriage of nanotechnology with green chemistry/engineering serves two important purposes. First, emerging nanotechnologies could be made clean from the start. As several speakers noted, it would be foolhardy to build a new nanotechnology infrastructure from an old industrial model that would generate another set of environmental problems. While nanotechnology might never be as green as Mother Nature, adopting a green nano approach to the technology's development ultimately promises to shift society into a new paradigm that is proactive, rather than reactive, when it comes to environmental problems.

"We are on an unsustainable path. It is not as though nanotechnology will be an option; it is going to be essential for coming up with sustainable technologies."

—Paul Anastas, Director, ACS Green Chemistry Institute, Washington, DC

FIGURE 1: Green Chemistry in Action. Dr. Kei Saito, research professor at the Center for Green Chemistry at the University of Massachusetts, Lowell, prepares the dye-encapsulated nanoscale polymeric micelle solution.

(Photo from John C. Warner, Center for Green Chemistry)

Second, green technologies that benefit the environment could use nanotechnology to boost performance. In other words, nanotechnology could help us make every atom count—for example, by allowing us to create ultra-efficient catalysts, detoxify wastes, assemble useful molecular machines and efficiently convert sunlight into energy. It could potentially contribute to long-term sustainability for future generations, as more green products and green manufacturing processes replace the old harmful and wasteful ones.

Researchers are already taking the first baby steps toward this green nano vision. At the ACS meeting, they unveiled a wide variety of innovative efforts to revolutionize both products and processes. Some aim to re-engineer and reduce the environmental impacts of products—everything from computer chips to automobile bodies to batteries. Others are trying to directly help the environment by creating new kinds of solar cells, remediation methods and water filters. Researchers examining manufacturing processes described ways of making existing processes more efficient and less hazardous, and outlined new green methods (discussed in the following sections) for use in producing nanomaterials and other nanoproducts.

While Hutchison's work shows how green chemistry could benefit nanoelectronics, another powerful example that was discussed at the meeting shows how nanotechnology could spur the green engineering of cars. For instance, fuel economy could be boosted by building auto bodies out of lightweight nanomaterials, by using nanosensors to monitor fuel use and by running on nano-enhanced fuel cells. Tailpipe emissions could be cut through the increased use of nano-engineered catalysts and sensors. The amount of cleaning solvents used could be reduced by putting self-cleaning nanocoatings on car exteriors. The number of tires going to landfills might decline if embedded nanomaterials helped tires wear better and last longer.

Nano-enhanced green cars are likely to be popular with those consumers who prefer to spend less money at the gas pump and less time washing their cars and replacing worn tires. People might feel these cars are safer to drive in bad weather because the coated windshields improve visibility during rainstorms. At the same time, such vehicles could broadly benefit society by helping to prevent air pollution, reduce energy use and minimize waste. *That* is the green nano vision.

> "Nanotechnology offers us the opportunity to make products and processes green from the beginning. We simply cannot let this opportunity pass by."
>
> —Barbara Karn, Visiting Environmental Scientist, Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, Washington, DC

II. Clean and Green Nanotechnology

All kinds of nanoproducts are now making their way into the marketplace—everything from sunscreens to tennis rackets and from lens cleaners to clothing. Some of these products contain nanomaterials, such as carbon nanotubes, nanoparticles of silver and nanoparticles of zinc oxide. Others are made from processes involving nanotechnology—for instance, one process creates nanosized whiskers in cotton fibers, making the fabric stain-resistant.

The Wilson Center searched the Internet for products that manufacturers identified as "nano" and found more than 380 items currently available to consumers. The Center published these results in a Nanotechnology Consumer Products Inventory, which can be viewed at http://nanotechproject.org/44. Many more nanoproducts are in use in industry, research laboratories and biomedical applications. Lux Research estimates that by 2014, nanotechnology will be incorporated in manufactured goods worth $2.6 trillion and will provide 10 million jobs.[7]

The number of nanoproducts will continue to grow, but concerns about potential impacts of nanotechnology on the environment, human health and safety have not yet been fully addressed. Little is known about the risks of nanomaterials, including their toxicities, their potential for emissions and human exposure, their fate in the environment and their possible ecological impacts. Research studies to clarify the risks and benefits of nanotechnology are ongoing, but many results are still years away.

One way to circumvent these unknown risks is to design and make nanoproducts as clean and green as possible from the start. Because nanotechnology is still in its early days and the infrastructure is under construction, the opportunities for pollution prevention are tremendous, many participants noted. Green product design, and green methods for synthesis and manufacturing, could be incorporated now into the new industrial models that are being developed. Indeed, scientists at the ACS Green Nano Symposium showed many examples of how green chemistry and engineering principles can be used to minimize the environmental impact and potential risks of a wide range of nanoproducts.

Moreover, participants said it was easy to envision green strategies for nanotechnology because there are some inherent advantages. With greater ability to manipulate matter and tailor properties, it should be possible to make materials and products with reduced toxicity, increased durability and improved energy efficiency. As for processes, the power of nanotechnology might allow scientists to synthesize materials and devices from the bottom-up, instead of the top-down, as is currently done. This kind of molecular manufacturing would resemble what is done in the cell and theoretically would ensure that more raw materials are incorporated into the final product, rather than being lost as waste. Likewise, the ability to make and control nanoscale patterns promises to maximize the use of raw materials. However, this manufacturing would likely be at a slower production rate, and a new model of more distributed manufacturing may be required.

"Scientists with expertise in different areas need to come together. The green chemist needs to learn that a process that takes three days will never be used commercially. And the engineer needs to learn which chemicals will be harmful and should be avoided."

—Julie Chen, engineer and Director, Nanomanufacturing Center of Excellence, University of Massachusetts, Lowell, MA

"Nanotechnology and green chemistry have an intimate relationship and great potential to do good."

—John C. Warner, chemist and Director, University of Massachusetts Center for Green Chemistry, Lowell, MA

7. Lux Research. 2006. *The Nanotech Report™: Investment Overview and Market Research for Nanotechnology. 4th Edition, Volume 1.* New York: Lux Research Inc.

Despite these advantages, nanotechnology will nevertheless have impacts on the environment because making nanoproducts will still require water, energy, chemicals and raw materials, one speaker noted. Indeed, the total product package, not just the part that is nano, is what counts. Consider that electronic gadgets, such as MP3 players, have a nanocomponent that is a minuscule part of the device, and nanofibers in composites often make up only a small fraction of the total material. This is the case today. However, in the future, the nanomaterials contained in products might be a greater part of the whole and will therefore require more careful consideration as raw materials.

A thorough LCA should be conducted for all new nanoproducts, suggested **Satish Joshi**, an engineer at Michigan State University in East Lansing. Joshi analyzed the environmental impact of a material that is an attractive alternative for plastics in automobile parts: a polymer-layered silicate nanocomposite. He found that its use would lower overall vehicle greenhouse gas emissions, but require more water during production. Joshi is now altering the composite material, comparing its properties and measuring its biodegradability, which is another potential advantage. Thinking about a product's life cycle is important, but getting all the data needed for the analysis has proven difficult, he said. Joshi suggested that more data on the environmental impacts of products should be gathered and made publicly available.

Ideally, such assessments could help many industries "clean up and green up" their products and manufacturing processes. Over the long term, a new industrial ecology might emerge if nanomaterials made by green synthesis replaced existing materials in products, if new nanoproducts were designed using green engineering principles, and if cleaner nano-based manufacturing processes were adopted. It is still early, but research in these areas is expanding, as the ACS Symposium showed. Some of the current research on clean and green nanotechnology is summarized in the following sections.

Green Nanoelectronics

- New, greener methods for layering semiconductor materials to make microchips are being developed, according to **Farhang Shadman**, director of the National Science Foundation-Semiconductor Research Corporation (NSF-SRC) Engineering Research Center for Benign Semiconductor Manufacturing, University of Arizona in Tucson. His group is working on making nanofilms and on putting materials precisely where they want them to go. The process they use—called selective deposition—promises to maximize use of raw materials and minimize waste.

FIGURE 2: Image of silver nanostructure from the Buriak Research Group of the Department of Chemistry, University of Alberta, and the National Institute for Nanotechnology.

(Images from Buriak Research Group)

- A green approach to patterning nanoscale metal features on surfaces is being developed by **James E. Hutchison**, a chemist at the University of Oregon in Eugene. The process—called biomolecular nanolithography—builds patterns from the bottom up with the help of a DNA scaffold. He said it uses fewer steps, incorporates more material and requires less water and solvents than traditional top-down lithography.

- Simple aqueous dipping reactions can be used to create nanoscale patterns on the surfaces of semiconductors and could make massively parallel manufacturing of microchips possible, according to **Jillian Buriak**, a chemist at the University of Alberta in Edmonton. Her lab uses room-temperature galvanic displacement reactions—requiring only metal salts, a semiconductor wafer and water—to make complex nanoscale metal architectures. With a couple benign additives, the researchers can alter the morphology, size and shape of the hybrid nanoparticle/semiconductor materials. They control the patterns with the help of small amounts of benign block copolymers.

- A newly developed nanomaterial could replace the tin-lead solders widely used as interconnects in electronic products, said **Yi Li**, a chemist at Georgia Institute of Technology in Atlanta. Her lab is investigating alternative materials called electrically conductive adhesives (ECAs), which are lead-free and can be produced with less energy and in fewer steps. The group enhanced the performance of ECAs by adding nanosilver fillers and molecular monolayers to create an environmentally friendly nanocomposite for use in interconnects.

- It should be possible to build better solid-state lithium-ion batteries with nanofibrous anodes and nanofibrous cathodes synthesized by templates, according to **Fan Xu** of the University of Florida in Gainesville. She described her group's experiments to design and build three-dimensional nanostructured batteries, which promise high capacity to store energy.

"The best way to reduce risks is to design and engineer those risks out of products before the problems arise."

—Barbara Karn, Visiting Environmental Scientist, Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, Washington, DC

Green Synthesis of Nanomaterials

- A green method for making water-soluble carbon nanotubes—which have promising applications in thin films, electronics, composite materials and drug delivery—was described by

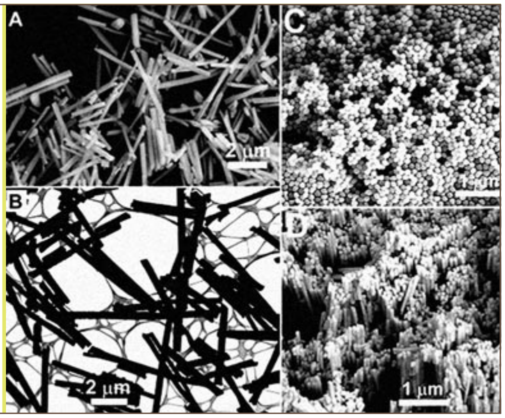

FIGURE 3: Nanorods. (A) Typical scanning electron microscope (SEM) micrograph of barium tungstate ($BaWO_4$) nanorods. (B) Representative transmission electron microscope (TEM) image of $BaWO_4$ nanorods and SEM images of $BaWO_4$ nanorod arrays: (C) top-view and (D) tilt-view.

(Images from Stanislaus Wong, State University of New York in Stonybrook and Brookhaven National Laboratory)

Somenath Mitra, a researcher at the New Jersey Institute of Technology in Newark. The technique allows a variety of functional groups to be added to the nanotubes to tailor them for different applications. To spur the synthesis reactions, Mitra's group uses microwave energy. The new technique generates products in minutes, rather than days, and requires less energy and fewer chemicals.

- Metallic nanorods and nanowires—potentially important for applications in optics and electronics—can be synthesized using green chemistry, according to **Catherine J. Murphy**, a chemist at the University of South Carolina in Columbia. She described how to produce gold and silver nanorods, as well as silver nanowires, using reactions in water, at room temperature and by employing cheap surfactants to exert some control over size and shape.

- Quantum dots—semiconducting nanocrystals—might soon be made using green chemistry, said **Xiaogang Peng**, a chemist at the University of Arkansas in Fayetteville. Quantum dots hold promise in medical imaging, solar cells and sensing and electronic devices, but the most useful kinds—such as cadmium selenide—are highly toxic. Peng's lab is investigating ways to synthesize quantum dots using less toxic compounds, and he expressed hope that zinc chalcogenide nanocrystals doped with transition metal ions could effectively replace cadmium selenide nanocrystals.

- A new method for synthesizing metallurgical nanomaterials could save energy while giving scientists greater control of nanostructure and morphology, as well as greater access to metastable phases at low temperatures, said **Raymond Schaak**, a chemist at Texas A & M University in College Station. Intermetallic compounds and alloys are useful in magnets, batteries, catalysts, computer memory, thin films and robotics. Schaak described his lab's "metallurgy in a beaker" method, which involves mixing nanoparticles in water at low temperature and in the presence of a catalyst.

- Green synthesis of metal oxide nanostructures is possible, according to **Stanislaus Wong**, a chemist at State University of New York in Stonybrook and Brookhaven National Laboratory. He described his lab's methods for making crystalline ceramics—potentially useful in electronics, computer memory and biomedical and environmental applications—using a low-temperature, molten-salt synthesis method.

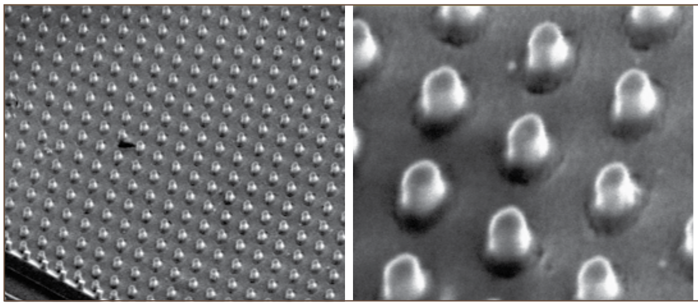

FIGURE 4: Nanoscale titanium dioxide pattern. 200-nanometer titanium dioxide (TiO_2) particles developed with the PRINT method to make photovoltaics.

(Images from researchers in the DeSimone Lab)

Green Nanomanufacturing

- The fabrication of relatively large quantities of organic nanostructures is now possible using a new method that combines tools from microelectronics manufacturing and organic chemistry, according to **Joseph DeSimone**, a chemist at the University of North Carolina, Chapel Hill. His general purpose "molding" technique, called Particle Replication In Non-wetting Templates (PRINT), enables the rapid, error-free reproduction of nanoparticles of any shape. Moreover, functional groups can be added to tailor nanomaterials for biomedical applications. DeSimone described how his team developed and scaled up the method and added a way to efficiently harvest the products. His team has successfully fabricated nano- and micro-particles containing bioactive compounds. PRINT, he said, is a low-waste, green method that can be used to manufacture a broad range of organic nanoparticles.

- Nanofibers made from starches and proteins could be manufactured using electrospinning technology, says **Jochen Weiss**, a researcher at the University of Massachusetts at Amherst. He described his group's latest research on how to make biopolymeric nanofibers and on studies of their properties—for instance, some nanofibers are antimicrobial, some bind metals and others can form sturdy scaffolds. Electrospinning technology offers the prospect of recycling huge amounts of biopolymer wastes from the chemical, food and pharmaceutical industries and turning them into useful, biodegradable nanofibers. Weiss noted that these materials show particular promise in packaging, artificial tissues and filtration devices.

- Methodologies and tools for safe nanomanufacturing are starting to be developed, said **Julie Chen**, director of the Nanomanufacturing Center of Excellence at the University of Massachusetts, Lowell. Chen described studies investigating how to assess and improve the process of mixing nanocomposites—for instance, using aerosol monitoring to determine how much nanomaterial actually goes into a rubber product and how much is lost to the air. She also discussed a study that found emission of nanodust during manufacturing could be reduced through the use of electric fields.

"We synthesize our materials using inexpensive, non-toxic precursors, and we minimize solvents and unstable reagents. Our methods can be scaled up, and we can get control over size, shape and morphology of our nanostructures—all using environmentally friendly methods."

—Stanislaus Wong, chemist, State University of New York—Stonybrook and Brookhaven National Laboratory, Stonybrook, NY

FIGURE 5: Professor Julie Chen (right) working with students at the Nanomanufacturing Center of Excellence at the University of Massachusetts, Lowell.

(Photo from Adrianna Morris, Nanomanufacturing Center of Excellence)

III. Nano-Enhanced Green Technology

Green technologies have been around since the first public health projects were set up in cities to provide people with clean drinking water. Since then, we have seen the introduction of scrubbers for smokestacks, catalytic converters for cars, recycling plants, solar panels, energy-efficient appliances and many other "green" products.

Now, a new generation of green technologies is expected to arrive, as pressures on resources grow and investors see healthy profit in a wide range of innovative products. "Greentech could be the largest economic opportunity of the 21st century," said venture capitalist John Doerr, who set up a $100 million green technology investment fund, according to a *Washington Post* article on April 18, 2006, entitled, "Internet Visionaries Betting On Green Technology Boom." In 2005, Microsoft founder Bill Gates gave $84 million to a California company to build five ethanol biorefineries. Venture capitalists that year invested as much as $1.6 billion in green technologies, up 35 percent from 2004.

In the 21st century, the next wave of green technologies is likely to draw heavily from nanotechnology, scientists at the ACS Symposium said. As Scott Rickert, CEO of Nanofilm, put it, "Nanotechnology holds the potential to unlock advances that will enable us to replace current environmentally harmful practices with new greener ones." By making the most of nanomaterials and their unusual properties and by using advanced tools for manipulating matter at the nanoscale, researchers expect to gain greater performance and new capabilities in green technologies. Those advances should improve our ability to clean up air, water and soil, as well as to generate energy efficiently, reduce waste and recover resources.

A growing number of businesses are now pursuing nano-enhanced green technologies, according to **Sean Murdock**, executive director of the NanoBusiness Alliance. In one of the green nano seminars, he outlined promising efforts by companies, including some aiming to develop light bulbs that use energy more efficiently by generating more light and less heat; nanoporous sands that increase the selective recovery of metals in mining and reduce pollution; and new, rationally designed catalysts that are more effective at driving desirable chemical reactions.

Murdock, however, emphasized that we are still in the early days of discovering "how nanotechnology can green the world." At the ACS Symposium, researchers presented a broad range of investigations that could lead to more advanced green technologies for applications in energy, remediation and industry. These projects are just a start: researchers are envisioning many more green technologies for the future, as highlighted below.

Nano-Enhanced Energy Technologies

- Semiconducting nanocrystals show promise in new kinds of solar cells, said **Paul Alivisatos**, a chemist at the University of California at Berkeley. His group is aiming to make rolls of flexible, durable, inexpensive solar cells using solution chemistry. These could be used broadly throughout the landscape to generate electricity from sunlight. Alivisatos reported that he is currently working on finding an environmentally friendly system of nanocrystals.

- Another approach for making flexible solar cells was described by **Michael McGehee**, a materials scientist at Stanford University in Palo Alto, California. His group creates the active layer of their solar cells by making self-assembling nanoporous films of inorganic semiconductors and then filling the pores with organic semiconductors. McGehee's team is now testing the efficiency of these hybrid solar cells.

- Nanotechnology can help overcome obstacles in developing dye-sensitized solar cells, according to **Larry Lewis** of General Electric. His team's goal is to print flexible, highly efficient, organic solar cells that perform a kind of "artificial photosynthesis." Lewis described how his team invented a way to make pastes of titania nanoparticles and discovered how to process them greenly—at low temperatures using ultraviolet (UV) irradiation.

- A new kind of proton-exchange membrane with nanoscale patterning holds promise for fuel cells, reported **Zhilian Zhou**, a chemist at the University of North Carolina at Chapel Hill. She and her colleagues found a solvent-free way to mold membranes out of a new fluoropolymer. By adding three-dimensional nanoscale patterning, they found that they could boost the material's surface area and proton conductivity. Tests in fuel cells—devices for converting chemical energy to electricity—showed that these new membranes outperformed traditional ones, Zhou said. The membranes could potentially be tailored to work in fuel cells that run directly on methanol, rather than hydrogen.

- Metal hydrides in combination with nanoporous scaffolds are good candidate materials for storing hydrogen, said **Adam F. Gross** of HRL Laboratories in Malibu, California. Such storage materials would be an essential part of the hydrogen economy, if built. Gross's group aims to develop materials that can readily take up and release hydrogen, as needed. Adding a nanoporous scaffold to the metal hydrides improved the reversibility of this process, he said. The team is testing different pore sizes and measuring the performance of these materials.

"We are looking at big challenges in removing pollutants like arsenic from water; it's an area where nanomaterials offer some solutions."

—Vicki Colvin, chemist and Director, Center for Biological and Environmental Nanotechnology, Rice University, Houston, TX

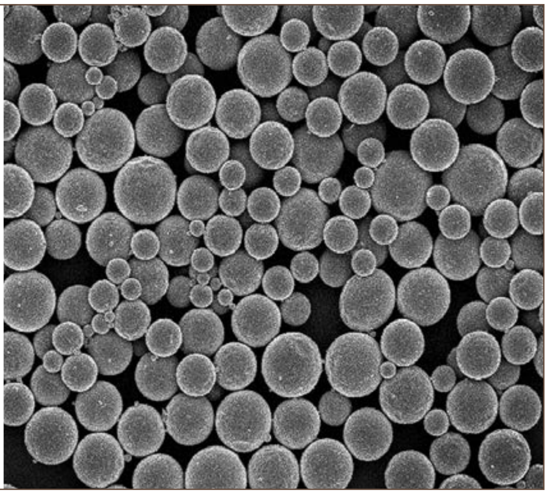

FIGURE 6: Nanostructured components offer promise for solar cells.

(Image from Nanosolar, Inc.)

Nano-Enhanced Clean-up Technologies

- Magnetic nanoparticles could become an important green tool for removing arsenic from drinking water, particularly for point-of-use treatment in developing countries, said **Vicki Colvin**, a chemist at Rice University in Houston, Texas. Nanoparticles of iron oxide bind strongly and specifically to arsenic and can be separated out of solution using magnets. Colvin described her group's studies to determine which size nanoparticles are optimal for efficient binding of arsenic and for easy separation. Particles of 12-nanometer size worked best, she reported, and they removed 99.2 percent of the arsenic in solution.

- Zero-valent nanoparticles of iron and magnesium more effectively degrade heavy metals and organic solvents in water and sediments when they are combined with emulsion liquid membranes, reported **Cherie Geiger**, a chemist at the University of Central Florida in Orlando. The membranes increased the contact between these catalytic nanoparticles and the targeted pollutants. Geiger and her colleagues tested this promising remediation tool under different conditions and described their results.

- Polymer nanospheres offer a new way to selectively detect hazardous materials in aquatic environments, according to **Barry K. Lavine**, a chemist at Oklahoma State University in Stillwater. He described how his group prepared polymer nanospheres that change their shape and optical properties whenever a certain chemical is present. The change can be measured by surface plasmon resonance, which enables the detection of pollutants at the level of parts per billion (ppb), he said. The nanospheres can be tailored to sense a specific chemical by molecular imprinting of the polymers. The method could prove particularly useful for detecting pharmaceuticals and other emerging pollutants in waterways that are currently difficult to detect, Lavine said.

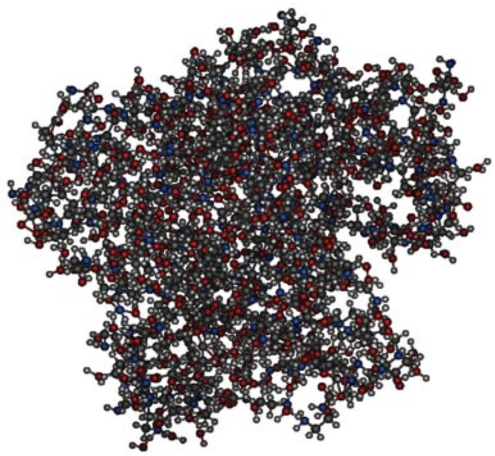

Figure 7: Image of a dendrimer. These nanoparticles can detect and remove metal ions and other contaminants from the environment.

(Image from Mamadou Diallo, Materials and Process Simulation Center, California Institute of Technology)

Nano-Enhanced Green Industry Technologies

- Environmentally-friendly catalysis is possible using cooperative catalytic systems incorporated in mesoporous silica nanoparticles (MSNs), according to **Victor S-Y. Lin**, a chemist at Iowa State University in Ames. He described how his team inserted catalysts inside the pores of MSNs and tailored them to perform a series of reactions—for instance, to synthesize biodiesel from free fatty acids in vegetable oils. These catalytic MSNs are environmentally benign and easy to recycle, he noted.

- It is possible to tailor the activity and stability of nanoparticle catalysts by modifying their support structure, reported **M. Samy El-Shall**, a chemist at Virginia Commonwealth University in Richmond. His group's goal is to make stable catalysts for use in removing poisonous carbon monoxide from the air in places such as mining shafts. El-Shall described a promising method for synthesizing nanogold and nanopalladium catalysts in an ordered mesoporous support structure with controllable pore sizes. The synthesis can be done at low temperatures using microwaves.

- A novel nanoporous sorbent effectively removes mercury and other toxic heavy metals from wastewater generated during offshore oil and gas platform drilling, according to **Shas Mattigod**, a researcher at the Pacific Northwest National Laboratory in Richland, Washington. The material, which is called thiol-SAMMS, removed 99 percent of mercury from gas condensate liquids containing 800 ppb mercury, he reported.

> "The economics of green nano depends on market pull. If clean technologies are valued by consumers, they will send positive market signals that help drive development and accelerate commercialization."
>
> —Sean Murdock, Executive Director, NanoBusiness Alliance, Skokie, IL

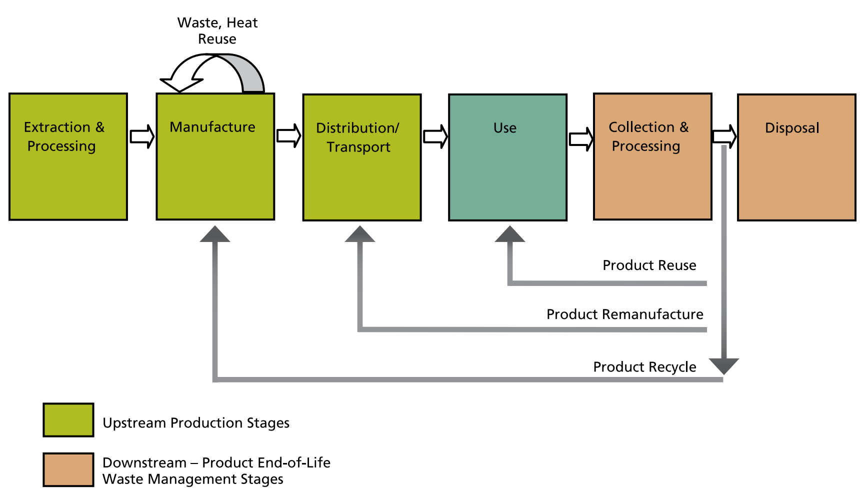

Figure 8: Industrial ecology life cycle diagram. Industrial ecology provides a framework for closing the material and energy loop within and between systems and across a product life cycle.

IV. Green Nano Policy

Nanotechnology naturally goes together with green chemistry and engineering, but whether green nano in the United States truly flourishes will likely depend upon policy decisions made by the federal government. Participants in the green nano seminar series, as well as scientists at the ACS Symposium, suggested that it is vitally important that the United States government encourage the development of clean and green nanotechnology and nano-enhanced green technologies. Policies that support green nano could potentially help the United States build a more sustainable economy and environment for the 21st century, they noted.

Indeed, the United States government is already investing heavily in nanotechnology—more than $5.5 billion has been authorized so far[8]—banking on the promise that it will drive the next industrial revolution. Several seminar participants argued, however, that this infant technology must become green if it is to survive to maturity; otherwise, it will be stunted by both real and perceived concerns about harmful impacts on the environment and human health. These participants suggested that a smart way to help nanotechnology "grow up" successfully is to raise it with green chemistry and engineering principles, so that nanoproducts and nanomanufacturing processes do not harm the environment. It makes sense for the United States government to support green nano as a way to protect its investment in nanotechnology, encourage the responsible development of nanotechnology and smooth its public acceptance, they said.

For a start, the federal government would be wise to invest in more basic research related to green nano, many participants emphasized. At the same time, there is an urgent need for data on nanomaterials in order to resolve environmental, health and safety questions. Under the 21st Century National Nanotechnology Research and Development Act of 2003, about four percent of the budget is used for research on societal impacts—a portion of which goes to research on health and the environment. A number of speakers suggested that this investment of less than $40 million[9] is far too small to ensure the safety of an industry now worth $3.5 billion in the United States.

> "There's a tendency for people to say, 'I have a green nanoproduct,' and they point to one attribute. I fear there will suddenly be a backlash when some other problem is discovered. We have to analyze nanoproducts very broadly and up-front before we call them 'green.'"
>
> —Mark A. Greenwood, Partner, Ropes & Gray, LLP, Washington, DC

If the vision for green nano is to be realized, research on green nanomanufacturing will also need to be ramped up, some suggested. Innovative tools and methodologies using green chemistry and green engineering to design, mass-produce, test and monitor nanoproducts could pave the way for a new industrial infrastructure that uses materials, water and energy more efficiently. Most companies are interested in minimizing their use of resources and in reducing their toxic waste and emissions because these actions often save money, one industry representative said. The National Semiconductor Association was cited as one industry group that is continually searching for ways to minimize waste. Nanoparticle emissions are already seen as a major problem for the

8. With an additional $1.3 billion requested for 2007. See NNI. 2006. "Funding, NNI Budget Overview by Agency." National Nanotechnology Initiative. http://www.nano.gov/html/about/funding.html, accessed December 12, 2006.
9. And as low as $11 million annually, according to an analysis by the Project on Emerging Nanotechnologies. See Maynard, Andrew. *Nanotechnology: A Research Strategy for Addressing Risk.* Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, July 2006. Available at: http://www.nanotechproject.org/file_download/77, accessed December 11, 2006.

semiconductor industry, said one speaker. There is clearly a demand for green nanomanufacturing techniques that eliminate these emissions, but relatively few researchers are developing them.

Research policies should also focus on the human dimension, some suggested. Government research programs need to foster interdisciplinary cooperation in order to make nanotechnology experts more aware of green methodologies and to make environmental researchers more aware of the potential power of nanotechnology. Moreover, collaborations with industry should be encouraged as a way to increase the chances that green nano products and processes are successfully adopted and commercialized. Corporations have joined together to establish at least two groups that could consider ways to develop nanotechnology in a clean and green way. Sixteen members of the American Chemical Council—including Dow, DuPont, Procter & Gamble, Bayer and BASF—have formed a CHEMSTAR nanotechnology panel that has the potential to look at green nano. Members of the NanoBusiness Alliance are considering forming a similar group for smaller businesses.

One policy roadblock to developing nanotechnology, whether clean and green or not, is regulatory uncertainty, including the lack of international harmonization, said one industry representative. There is ongoing debate about whether existing laws can be used to safely regulate nanotechnology effectively, let alone encourage pollution prevention. Seminar participants raised a number of key challenges that the federal government is trying to tackle, including such mundane issues as how to properly name myriad new nanomaterials, as well as how to gain access to information and hold open discussions about materials and processes that are considered trade secrets by private companies. Perhaps the government's biggest challenge is to figure out how to build a regulatory framework that can function effectively while information on risks is still being gathered. Along those lines, one speaker commented that government agencies are finding it difficult to deal with increasing levels of complexity in the risk assessment process.

The federal government might consider an alternative strategy—developing green nano policies that actively promote pollution prevention. The best way to handle potential risks is to avoid them by using green chemistry and green engineering to minimize the spread of nanomaterials in the workplace, home and natural environment, seminar participants suggested. However, crafting effective policies to do this is a challenge. And so far, few resources are being devoted to this proactive approach. A policy analysis might be needed to help the federal government determine what kinds of incentives are needed and how to encourage various agencies to coordinate a pollution prevention initiative, one speaker suggested. Additionally, broader systems issues must be approached. The environmental impacts of nanomanufacturing are not just about nanoparticle toxicity; they also include energy, water, and chemical use, in manufacturing.

A couple of technical obstacles also currently stand in the way of preventing nanomaterial pollution, several speakers noted. Proper safety equipment and tools for use during research and manufacturing of nanomaterials—such as personal protective gear for workers, water filters and air-monitoring devices—are not yet widely available. In the case of nanoproducts, it will be difficult to determine how pollution could be prevented, since it is difficult to analyze product life cycles. Little is known about how consumers and industry will use nanoproducts, how long these products will last, whether nanomaterials will be shed from them, how they might be recycled and so on.

Another part of the vision for green nano—promoting nano-enhanced green technologies—poses its own policy challenges. Basic research funded by agencies such as the NSF, the Department of Energy and the Environmental Protection Agency, aims to exploit nanotechnology to develop new kinds of solar cells, water filtration membranes, remediation techniques and other green

"Green approaches—such as green chemistry and engineering—are great opportunities to mitigate both real and perceived risks from nanotechnology."

—Martin Spitzer, Professional Staff, House Science Committee, Subcommittee on Environment Technology and Standards, United States Congress, Washington, DC technologies. Efforts to turn this research into commercially successful green technologies remain relatively slow and inconsistent.

> "Lack of information is a barrier to the greening of nanotechnology. We do not have the building blocks in place to make a regulatory framework or have a rational governance structure yet."
>
> —Martin Spitzer, Professional Staff, House Science Committee, Subcommittee on Environment Technology and Standards, United States Congress, Washington, DC

Some participants suggested that the federal government do more to promote the adoption of green technologies. However, this would require a concerted effort that is well thought-out, said one symposium speaker. Government agencies would need to coordinate in this effort, collaborate with stakeholders and find a fair way to select the most promising green technologies. In September 2006, the U.S. House of Representatives passed the Green Chemistry Research and Development Act of 2005, which calls for the President to "establish a Green Chemistry Research and Development Program to promote and coordinate Federal green chemistry research, development, demonstration, education, and technology transfer activities" and to establish an Interagency Working Group to carry out the program goals.[10] This bill was in review by the Senate Commerce, Science, and Transportation Committee at the end of the 109th Congress, and it is anticipated that it will be reintroduced in the 110th Congress.

Under this type of program or coordinated interagency effort, it would be necessary to set performance standards for products, define what it means to be "green," perform life cycle assessments and evaluate trade-offs. In the case of nano-enhanced green technologies, this process is tricky because there are little safety data on nanomaterials, it is difficult to monitor and track nanomaterial emissions from products and there will be ambiguous trade-offs. For example, what if a nanomaterial boosts energy efficiency in a product but is highly toxic? What if tires embedded with carbon nanotubes last longer and reduce landfill waste, but shed nanotubes during use? Could nanoscale filters for removing common chemical contaminants in drinking water release unsafe amounts of nanometals? Questions such as these are likely to be tough calls.

Green Nano Policy Recommendations

The following green nano recommendations were proposed either directly or indirectly during the meetings and discussions covered in this document:

- **Identify what is and what is not "green" in nanotechnology.** Using a life cycle approach can help us avoid surprises.
- **Ensure that nanoproducts are made using green methods.**
- **Build a database of current research in green nano** to determine present funding amounts and help project future resource needs.

10. GovTrack. 2006. "H.R. 1215: Green Chemistry Research and Development Act of 2005." http://www.govtrack.us/congress/bill.xpd?bill=h109-1215, accessed March 8, 2007.

- **Conduct an analysis of research gaps and develop a strategy to fill them.** This process should involve multiple stakeholders, including scientists, policymakers and industry leaders.

- **Boost funding for research related to green nano,** such as for pollution prevention in nanomaterials manufacturing and for nano-enhanced green technologies. We should be spending at least as much on avoiding risks as we do on studying them. A useful starting figure for targeted federal research on green nano is $50 million per year.

- **Create a "Green Nano Awards" program.** The EPA or another credible organization should spotlight firms that develop and adapt environmentally benign processes for making nanomaterials and products.

- **Identify useful surrogates and benchmarks** for evaluating whether and to what extent nanoproducts are green.

- **Use federal facilities as test beds** to evaluate new nano-enhanced green technologies.

- **Use federal procurement to increase demand** for effective green nanoproducts. Key agencies in such an effort would be the Department of Defense, the General Services Administration and the Postal Service.

- **Commission an analysis** of how the federal government's past efforts to promote green technology succeeded or failed, and apply the lessons learned to green nano.

- **Encourage efficient research methodologies** that will make limited funds go farther.

- **Encourage research-industry collaborations** that will explore ways to use green nanotechnology in building a new, more sustainable economy.

- **Coordinate future green chemistry legislation** with the 21st Century Nanotechnology Research and Development Act of 2003.

Moving forward with green nanotechnology policy will help accelerate the development of clean and renewable technologies, stimulate health and environmental stewardship during the manufacture of nanoproducts and use of nanomaterials, and encourage the replacement of existing products with nanoproducts that are more environmentally friendly throughout their life cycles.

"It's not easy bein' green, but we think the United States is on track to be a global leader in green nanotech, and that the country's research and development portfolio and policy incentives should be directed toward this goal. We believe green nanotechnology can be a source of American jobs and company profits in the future."

—David Rejeski, Director, Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, Washington, DC

"One of the big challenges of nanotechnology is monitoring—measuring nanoparticles at very low levels. If we want to develop performance-based standards for products, we have to figure out how to do this."

—Mark A. Greenwood, Partner, Ropes & Gray, LLP, Washington, DC

Appendix A: Green Nano Seminar Series

The following events were held between February and May 2006 as part of the Green Nano Program initiated by the Project on Emerging Nanotechnologies at the Woodrow Wilson Center. Webcasts and presentations from these events can be downloaded at: http://nanotechproject.org/41.

Thursday, February 16, 2006

Green Nanotechnology I—What Is It?

Woodrow Wilson International Center for Scholars, Washington, DC

A discussion of how our current knowledge—on green chemistry, green engineering, environmentally benign manufacturing, eco-efficiency, industrial ecology, etc.—can be applied to a new technology. How would green nanotechnology change our approach to this new technology?

Speakers:

Jim Hutchison, University of Oregon

John Warner, University of Massachusetts—Lowell

Barbara Karn, Woodrow Wilson Center

March 26-30, 2006

4th Symposium in Nanotechnology and the Environment

American Chemical Society (ACS) Meeting, Atlanta, GA

Barbara Karn, visiting scientist at the Project on Emerging Nanotechnologies, along with three colleagues chaired the 4th Symposium in Nanotechnology and the Environment at the ACS National Meeting in Atlanta. The symposium began on Sunday, March 26 with Dr. Karn's presentation on the state of nanotechnology and the environment. Speakers focused on research topics in green nanotechnology for the remaining seven sessions, which were held over four days. The ACS Industrial and Engineering Chemistry, Inorganic Chemistry and Fuel Divisions sponsored the symposium. As shown in Appendix B of this report, the schedule included many of the most prominent researchers in green chemistry and in environmental and energy aspects of nanotechnology.

Wednesday, April 19, 2006

Green Nanotechnology II--Industrial Perspectives

Woodrow Wilson International Center for Scholars, Washington, DC

How does industry perceive its role in preventing environmental harm from new technologies? How can industry educate itself in preventive measures? What are the economics of being green? Is green a competitive advantage?

Speakers:

John Carberry, DuPont Corporation

Sean Murdock, The NanoBusiness Alliance

Wednesday, April 26, 2006

Green Nanotechnology III—Engineering Green Nanotechnology

Woodrow Wilson International Center for Scholars, Washington, DC

How can environmentally benign manufacturing, green engineering and design for the environment be integrated into nanoproduct manufacturing? What tools would engineers need to manufacture nanomaterials and products "greenly"?

Speakers:

Farhang Shadman, University of Arizona

Julie Chen, University of Massachusetts–Lowell

Wednesday, May 24, 2006

Green Nanotechnology IV—Policy Options for Greening New Technologies

Woodrow Wilson International Center for Scholars, Washington, DC

Are regulations necessary? Are there barriers to being green? What incentives might work? Who cares about green?

Speakers:

Martin A. Spitzer, Professional Staff, House Science Committee, Subcommittee on Environment Technology and Standards

Mark Greenwood, Partner, Ropes and Gray LLP

Appendix B: Agenda from ACS Green Nanotechnology and the Environment Symposium

The following titled presentations were given at the 4th Symposium in Nanotechnology and the Environment, held on March 26–29, 2006, at the American Chemical Society Meeting in Atlanta, GA. Abstracts for the following speaker presentations are available at: http://oasys2.confex.com/acs/231nm/techprogram/. More information about this symposium can be found at: http://acswebcontent.acs.org/nationalmeeting/atlanta2006/home.html.

Sunday, March 26, 2006

Nanotechnology and the Environment--Plenary Session

Presiding: **Nora F. Savage**

Barbara Karn Nanotechnology and the environment: Where we've come and where we're going

James E. Hutchison Green nanoscience

Satish V. Joshi, Lawrence T. Drzal, Amar K. Mohanty, Manjusri Misra Assessing life cycle environmental performance of bioplastic-montmorillonite clay nanocomposites

Paul T. Anastas Green chemistry and green nanotechnology

Green Chemistry: Synthesis of Nanomaterials Using Green Chemistry Principles, e.g., Solid State Manufacturing, Low Energy Manufacturing, Self-Assembly

Presiding: **Stanislaus S. Wong**

Elena V. Basiuk, Vladimir A. Basiuk Gas-phase functionalization of carbon nanotubes

Catherine J. Murphy Green synthesis of metallic nanorods and nanowires

Xiaogang Peng Synthesis of quantum dots: From greener methods to greener products

Raymond E. Schaak Low-temperature solution synthesis and benchtop processing of metallurgical nanomaterials

James E. Hutchison Toward greener nanomanufacturing: Greener approaches to functionalized gold nanoparticles and nanoscale patterns of metals

Mingbo Wu, Qingfang Zha, Jieshan Qiu, Yuzhen Zhang Preparation of porous carbon from petroleum coke and control of its pore size by chemical vapor deposition

Horst Weller Synthesis of luminescent and magnetic nanoparticles and their use in materials and life sciences

Monday, March 27, 2006

Green Chemistry: Synthesis of Nanomaterials Using Green Chemistry Principles

Presiding: **Thomas E. Mallouk**

Vicki Colvin Non-toxic nanomaterials: The role of surface chemistry

Yubing Wang, Zafar Iqbal, Somenath Mitra Rapidly functionalized, highly water-soluble carbon nanotubes

Laura B. Hoch, Elizabeth J. Mack, Jessica M. Hershman, Bianca W. Hydutsky, Benjamin Beckerman, Thomas E. Mallouk Green synthesis of carbon-supported nanoscale iron particles for in situ environmental remediation

Yubing Wang, Mahesh Karwa, Chutarat Saridara, Zafar Iqbal, Somenath Mitra Approaches to carbon nanotubes self-assembly: Microwave induced reactions and chemical vapor deposition

Yuanbing Mao, Tae-Jin Park, Stanislaus S. Wong Environmentally-friendly methodologies of metal oxide nanostructure synthesis

Jasmine J. Erbs, Djuna M. Gulliver, R. Lee Penn Controlled growth of alpha-ferric oxy-hydroxide (FeOOH) nanorods by exploiting oriented aggregation

M. Samy El-Shall Nano catalysis: Design, synthesis, characterization and applications of nanoparticle catalysts with tailored activities

Use of Nanomembranes and Nanocatalysts to Improve Environmental Performance of Current Processes

Presiding: **Eric S. Peterson**

Vicki Colvin Using magnetic nanoparticles in water treatment

Boqiong Jiang, Zhongbiao Wu, Weirong Zhao, Bao-hong Guan Low-temperature SCR of nitric oxide (NO) with ammonia (NH_3) over manganese oxide–titanium dioxide (MnO_x-TiO_2) mixed oxides prepared by sol-gel method

Minghua Zhou, Jingpeng Zhang Preparation, characterization and photoelectrocatalytic activity of nanosized titanium dioxide (TiO_2) anode by metal-organic chemical vapor deposition

Victor S-Y. Lin Multifunctional mesoporous silica nanoparticles for environmentally friendly catalysis and delivery applications

Larken E. Euliss, Joseph M. DeSimone Environmentally-friendly fabrication of polymeric and organic nanomaterials for bionanotechnology and materials science using Particle Replication in Non-wetting Templates

Mostafa A. El-Sayed Shape-dependent nanocatalysis and the effect of catalysis on the nanoparticle shape and size in colloidal solution

Tuesday, March 28, 2006

Nano-enabled Green Energy: Synthesis of New Materials for Energy Applications

Presiding: **Larry N. Lewis, Kyle E. Litz**

Yi Li, Kyoung-sik Moon, C. P. Wong High performance environmental friendly nano-composite for lead-free interconnect

A. Paul Alivisatos Development of new nanocrystal based solar cells

Fan Xu, Warren Mino, Charles R. Sides, Charles R. Martin, Template synthesis of a 3-D, nanostructured, solid-state Lithium (Li)-ion battery

Michael D McGehee Improving organic-inorganic hybrid solar cells with interface modification and energy transfer

Larry N. Lewis, John Gui, Spivack James, Aharon Yakimov, Shellie Gasaway, Eric D. Williams, Venkatesan Manivannan, Oltea Siclovan Nano titania for dye-sensitized solar cells

Alexis T. Bell Nano-structured, copper (Cu)-based catalysts for the synthesis of methanol and the conversion of methanol to fuels and chemicals

Zhilian Zhou, Joseph M. DeSimone Applying nanotechnology to high surface area fuel cells

Jillian M. Buriak Green synthesis of metallic nanoscale patterned features on semiconductor interfaces

Nano-enabled Green Energy: Hydrogen Economy Related to Nanotechnology

Presiding: **J. Karl Johnson**

Bing Dai, J. Karl Johnson, David Sholl, Sudhakar Alapati First principles investigation of adsorption and dissociation of hydrogen on the magnesium silicide (Mg_2Si) surface

Kuen-Song Lin, Ruey-Bing Li, Li-Cheng Lou, Su-Wei Chiu, Chi-Nan Ku Spectroscopic characterization of surface-modified multi-wall carbon nanotube and its hydrogen storage capacity

Maciej S. Gutowski, Rafal A. Bachorz, Jun Li, Gregory K. Schenter, Shawn M. Kathmann Understanding of hydrogen storage in the NBH_x materials through computational studies

David M. Antonelli Low-valent microporous titanium oxides as novel hydrogen storage materials with enthalpy tuning functionality

Adam F. Gross, Sky L. Skeith, Channing Ahn, John J. Vajo, Gregory L. Olson Synthesis and characterization of nanoscale magnesium silicide (Mg_2Si) for hydrogen storage applications

Long Pan, Jeongyong Lee, Lauren Olonski, Ryan Heddy, Jing Li, Brian Zande, Richard T. Obermyer, Satoru Simizu, S. G. Sankar Microporous Metal Organic Framework (MMOF) materials for hydrogen storage

Harry W. Rollins, Lucia M. Petkovic, Daniel M. Ginosar, David N. Thompson Nanocatalysts for synthetic fuels to support biorefineries and the hydrogen economy

Wednesday, March 29, 2006

Bio-inspired Nanotechnology

Presiding: **John C. Warner**

Jochen Weiss, Kevin Kit, Svetlana Zivanovic, Michael Davidson Challenges and progress in the production of electrospun biopolymer nanofibers

Marinella G. Sandros, David E. Benson Maltose-responsive protein nanoparticles: Using ligand gated

Kei Saito, John C. Warner Synthesis of thymine-functionalized nano core-crosslinked micelles by poly(vinylbenzylthymine)-b-poly(styrene sulfonic acid sodium salt)

Magali B. Hickey, Matthew L. Peterson, Julius F. Remenar, Hector R. Guzman, Örn Almarsson Synthesis, characterization and properties of pharmaceutical co-crystals

Environmental Uses of Nanotechnology

Presiding: **Barbara Karn**

Barry K. Lavine, David J. Westover, Necati Kaval Compound specific imprinted polymer nanospheres for optical sensing

Steve Teague, Joshua D. Carter, Ting Guo, Kent Pinkerton Comparison of two apparatuses for aerosol generation from single-walled carbon nanotubes

Mason K. Harrup, Michael G. Jones, Linda A. Polson, Byron White Nanocomposite permeable reactive barriers: "Green" nanotech for environmental remediation

Ruihua Li, Donggang Yao, Pratapkumar Nagarajan Characterization and adhesion study of poly(ethylene terephthalate) single polymer composites prepared by rapid hot lamination

Cherie L. Geiger, Christian A. Clausen, Kristen M. Milum, Jacqueline Quinn Kow values and solvent/iron degradation kinetics: A predictive tool for solvent degradation efficiency with emulsified, nano-scale, zero-valent iron

Robert DeVor, Cherie L. Geiger, Christian A. Clausen, Jacqueline Quinn, Kristen M. Milum Emulsified nanoscale iron particles for environmental remediation of heavy metals

Neil Stewart, Cherie L. Geiger, Christian A. Clausen Reaction rates for the dehalogenation of trichloroethylene using various forms of nanoscale and microscale, zero-valent iron

John Carberry,
DuPont Corporation

John Warner,
University of
Massachusetts - Lowell

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Mark Greenwood,
Ropes and Gray LLP

Barbara Karn and
David Rejeski

Jim Hutchison,
University of Oregon

Selected Additional Products From The Project On Emerging Nanotechnologies*

Reports

PEN 1: Jane Macoubrie, *Informed Public Perceptions of Nanotechnology and Trust in Government*, September 2005.

PEN 2: J. Clarence Davies, *Managing the Effects of Nanotechnology*, January 2006.

PEN 3: Andrew D. Maynard, *Nanotechnology: A Research Strategy for Addressing Risk*, July 2006.

PEN 4: Jennifer Kuzma and Peter VerHage, *Nanotechnology in Agriculture and Food Production: Anticipated Applications*, September 2006.

PEN 5: Michael R. Taylor, *Regulating the Products of Nanotechnology: Does FDA Have the Tools It Needs?*, October 2006.

PEN 6: Karen F. Schmidt, *NanoFrontiers: Visions for the Future of Nanotechnology*, March 2007.

PEN 7: Mark Greenwood, *Thinking Big About Things Small: Creating an Effective Oversight System for Nanotechnology*, March 2007.

Congressional Testimonies

David Rejeski, "Environmental and Safety Impacts of Nanotechnology: What Research Is Needed," United States House of Representatives, Committee on Science, November 17, 2005.

J. Clarence Davies, "Developments in Nanotechnology," United States Senate, Committee on Commerce, Science and Transportation, February 15, 2006.

David Rejeski, "Promoting Economic Development Opportunities Through Nano Commercialization," United States Senate, Committee on Commerce, Science and Transportation, Subcommittee on Trade, Tourism and Economic Development, May 4, 2006.

Andrew D. Maynard, "Research on Environmental and Safety Impacts of Nanotechnology: What Are the Federal Agencies Doing?," United States House of Representatives, Committee on Science, September 21, 2006.

Inventories

Nanotechnology Environment, Health and Safety Risk Research, released November 2005.

Nanotechnology Consumer Products, released March 2006.

Agrifood Nanotechnology Research and Development, released March 2006.

Nanotechnology and Medicine, released October 2006.

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