Nanotechnology and ENERGY

POWERFUL Things from a TINY WORLD

Think big. **Really BIG.** Think about all the people on Earth—over 7 billion of them and counting. **Think about all the energy those people use every day**: to light, heat, and cool homes, schools, and office buildings—to refrigerate and cook food—to power computers and communications—to fuel cars, buses, trains, and airplanes—to make fertilizer for increasing the yield of crops—and to manufacture products.

Because of the promise of nanotechnology to improve lives and to contribute to economic growth and energy independence, the Federal Government is supporting research in nanotechnology through the guiding efforts of the U.S. National Nanotechnology Initiative (NNI). As a result of these efforts, the United States is a global leader in nanotechnology development.

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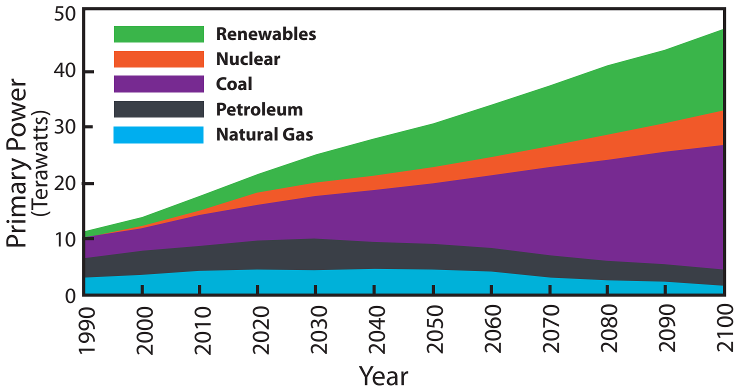
We use a **LOT** of energy, estimated to amount to over 1.3 quadrillion British Thermal Units (BTUs) or about 1.4 million terajoules per day from all sources. In the U.S. alone, energy costs run about $1 trillion per year, almost 10 percent of the Gross Domestic Product (GDP). Today, most energy comes from fossil fuels: crude oil, coal, and natural gas. Fossil fuels are refined into gasoline, diesel, or other fuels, or converted into other forms of energy such as electricity, which in turn power motors, lights, furnaces, air conditioners, vehicles, and manufacturing equipment.

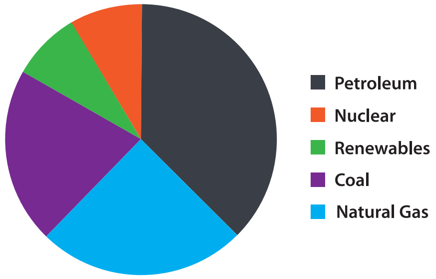
Projected Global Energy Demand



Projected global energy demand through the year 2100 is based on scenarios developed by the International Panel on Climate Change. Colors correspond to different primary energy sources. A rapidly increasing amount of renewable energy will be needed to meet global demand while lowering carbon emissions.

Marty Hoffert, Columbia University

U.S. Primary Energy Sources for 2009



According to the U.S. Energy Information Administration, 94.6 quadrillion BTUs of energy were consumed by the United States in 2009, with more than 83% coming from fossil resources. Globally, since about 2000, energy consumption has grown faster than population growth: world energy consumption in 2009 was over 19% more than it was in 2000, although the world's population grew only 11%. U.S. Energy Information Administration, *Annual Energy Review 2009* (published in 2010)

The U.S. Energy Mandate

The Federal Government's 2011 *Blueprint for a Secure Energy Future* calls for our nation to develop alternative sources of energy, with a goal of deriving 80 percent of our electricity from clean energy sources by 2035, including renewable energy sources like wind, solar, biomass, and hydropower.

Now, think small. Really, really small.

Smaller than anything you ever saw through a microscope at school. Think atoms and molecules. Now you're down at the **nanoscale**, where scientists are learning about unique properties of materials and are putting them to use in beneficial ways.

Many effects important for energy happen at the nanoscale. Inside a battery, chemical reactions release electrons, which then can move through an external circuit to do work. Similarly, within solar cells, photons —packets of light—can free electrons from a material, which can then flow through wires as an electric current. In both cases nanotechnology has the potential to significantly improve the efficiency of these processes.

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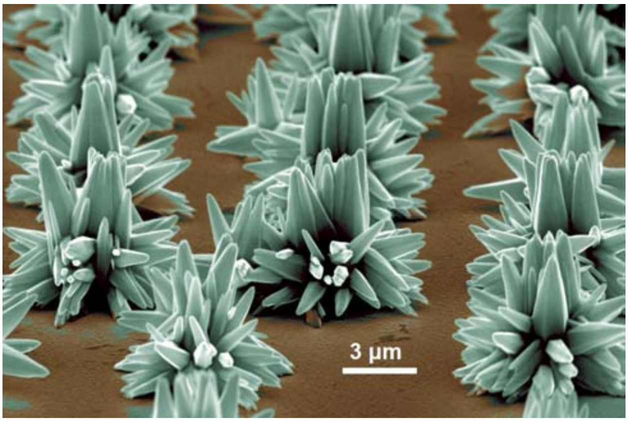
Nanotechnology research and development of commercial products can help create innovative ways for people to **generate, store, transmit**, and even **conserve** energy.



Zinc oxide nanorod clusters (false color). Zinc oxide is a transparent conductor that is promising for solar energy applications, including photocatalytic splitting of water molecules to release hydrogen fuel. These clusters were grown from ZnO nanorods that were 400 nanometers or less in diameter.

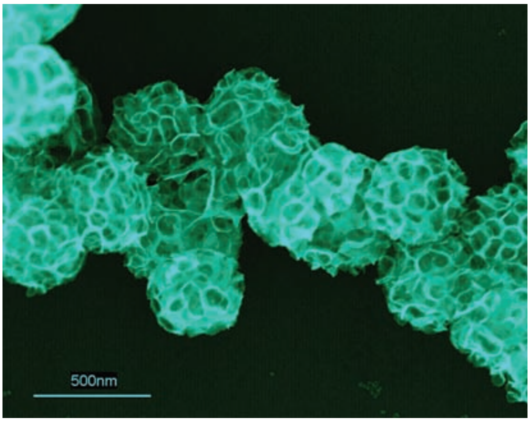
Julia Hsu, Neil Simmons, and Tom Sounart. Sandia National Laboratories

What's so *special* about the nanoscale?

Nanoscience is research to discover new behaviors and properties of materials with dimensions at the nanoscale. The nanoscale ranges roughly from 1 to 100 nanometers (nm), where **a nanometer is one billionth of a meter**. A sheet of paper is about 100,000 nanometers thick.

Materials can have **different properties** at the nanoscale than they do at larger sizes. Some materials become stronger or better at conducting electricity or heat or at reflecting light; others display different magnetic properties or become chemically active in specific ways.

Nanotechnology is the way nanoscience discoveries are put to use. For example, many nanoscale materials can spontaneously assemble themselves into ordered structures. It may also be possible to design materials atom by atom to achieve specific purposes. This makes nanotechnology extremely promising for energy applications.



Platinum lace nanoballs (false color) were grown by using proteins important in photosynthesis. When light shines on the proteins mixed with detergent foams, the proteins cause the platinum to grow into the form of foam-like nanoballs. The platinum nanoballs, when illuminated, can in turn release hydrogen from water—a reaction of potential interest for hydrogen fuel cells for vehicles.

DOE/Sandia National Laboratories

Triangles at right are sulfur atoms on a layer of copper, which in turn rests on a substrate (base) of ruthenium. Layered metals are often useful as catalysts, such as those that clean pollutants from automobile exhaust in catalytic converters, or that remove sulfur from petroleum.

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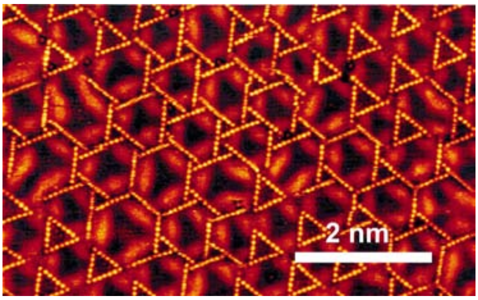


Giant Surface Area from Tiny Particles

Because of their intricate structures, nanomaterials can have far more surface area per volume than bulk materials. This means they can be far more chemically active and can even behave in new ways.

nanotechnology: Generating Energy

Nanotechnology may provide **big improvements** in many of the ways useful energy is generated. While energy cannot be created or destroyed, it can be converted from one form to another to perform useful tasks.

Success Story—Catalysts for Energy

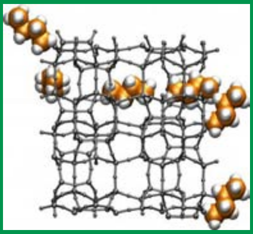
Catalysts are materials that speed up chemical reactions that occur in nature and also make possible reactions that do not readily occur in nature. Catalysts are often used to turn a raw material (such as crude oil) into a product (such as gasoline or plastic). **The best catalysts efficiently convert a raw material into a specific product with minimal waste heat or unwanted byproducts.**

Every oil refinery and petrochemical plant relies on catalysts. We depend on catalysts to make fuels for cars, trucks, and planes; synthetic fibers for clothing or home insulation; and fertilizer to raise enough crops for an adequate food supply. Catalysts also help convert harmful wastes into benign compounds before they enter the environment.

Catalysts are so fundamental to energy production they have been called nano-reactors—"the engines that power the world at the nanometer length scale."

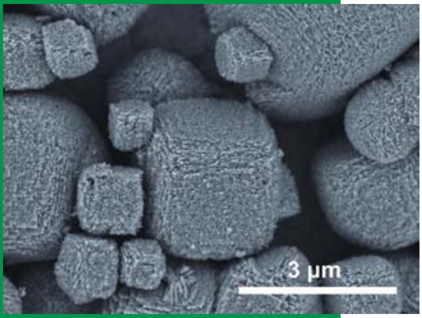
Designer Chemistry with Molecular Sieves

The petroleum industry has a vested interest in catalysts such as zeolites that refine crude oil into fuel. Zeolites are ceramic-like solids, permeated with millions of nanoscale-sized pores, that can have surface areas up to 1000 square meters, or roughly a quarter acre, per gram. Another name for zeolites is molecular sieves. Scientists have discovered that putting aluminum ions inside the pores of a zeolite can speed up the chemical reaction or tailor the end product. Other methods to improve a catalyst's efficiency include exposing specific crystal faces, or creating nanoscale junctions between materials where reactions occur.



Simulation of a butane molecule passing through a zeolite. This zeolite is used to catalyze oil refinement.

DOE/Lawrence Berkeley National Laboratory



Made from a nanoscale template, this unusual sodium zeolite has pores ranging from 2 to 50 nanometers across.

Ryong Ryoo, Korea Advanced Institute of Science and Technology

Today, the search is intense for new catalysts for refining fossil fuels for energy.

After more than a century of making gasoline, don't we already know how? Yes, but one goal is to create cleaner-burning **"green"** fuels.

The world's supplies of high-quality crude oil are diminishing. New catalysts are needed to refine the remaining supplies of crude oil, which are heavier and higher in contaminants such as sulfur. New catalysts are also needed for converting coal or biomass into diesel and other transportation fuels.

Lastly, many existing catalysts are **EXPEN$IVE** because they (including the one in your car's catalytic converter) are made of precious metals such as silver, gold, and platinum. So the search is on for cheaper substitutes, and for ways to use less precious metal in conventional catalysis.

"Green" fuels

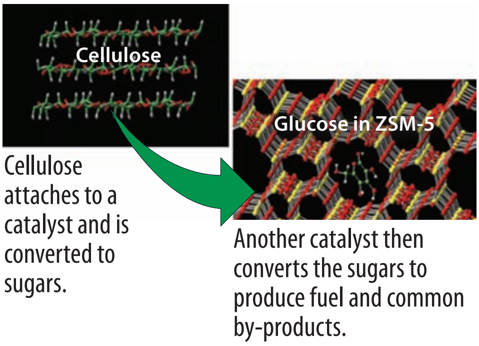
Will biofuels or other "green gasolines" one day fill your car's fuel tank? Many scientists think so: biofuels come from plants, which are renewable because plants can be grown every year. Promising new sources include corn stalks, sugar cane, and fast-growing switchgrass. But the water-based chemistry of biofuels is radically different from the oil-based chemistry of fossil fuels.

Fossil fuels such as crude oil, coal, and natural gas are hydrocarbons, composed almost entirely of carbon and hydrogen. The raw materials for biofuels are basically plant sugars dissolved in water. Plant sugars, being carbohydrates, are composed not only of carbon and hydrogen, but also of oxygen. The water-soluble chemistry of biofuels requires **totally different catalysts** from those used in refining fossil fuels. Nature uses enzymes to convert sugar to ethanol (think beer making). Nanoscience could provide catalysts that mimic nature to convert water-soluble molecules to ethanol or other fuels.

Also, different types of plant matter require different types of catalysts. For example, corn kernels have a lot of sugar, while corn stalks and other cellulose-based plant materials do not, so they require different catalytic chemistries. Whereas corn is already being used to generate some biofuels, using cellulose-based plant material is more challenging. So scientists are searching for new nanocatalysts that can break down cheaper and more abundant cellulosic plant materials.

Engineer holds cellulosic biomass.

DOE/National Renewable Energy Laboratory



"Green gasoline" might be made by catalytic fast pyrolysis of cellulosic biomass.

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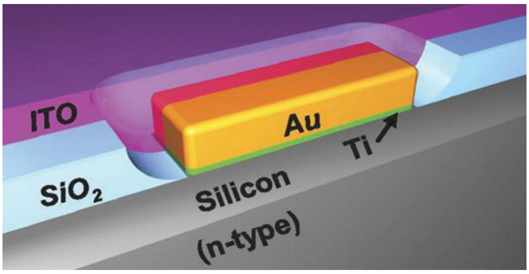
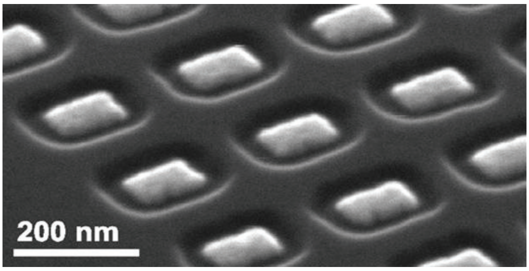
Generating Energy: **Harnessing** the Sun

More solar energy strikes the earth on a single day than the world's population uses in a year. That is why the sun is so appealing as an ultimate energy source. But converting solar energy into electricity or liquid fuels at a price competitive with fossil fuels remains a challenge. Nanotechnology holds promise for helping **raise solar energy conversion efficiency and lower costs**.

One approach is to make the solar cells themselves of **cheaper materials**. The current dominant technology, single-crystal silicon solar cells, are costly to grow. Cheaper solar cells can be built from nanocrystalline silicon and other inorganic or organic nanoscale materials, which can be deposited on cheap substrates (backings) like steel or plastic. Researchers are also using nanotechnology to make low-cost thin-film solar cells that are transparent (so they can cover windows) and flexible (so they can wrap around curved shapes), to be able to collect solar energy from an entire office building rather than just its roof.

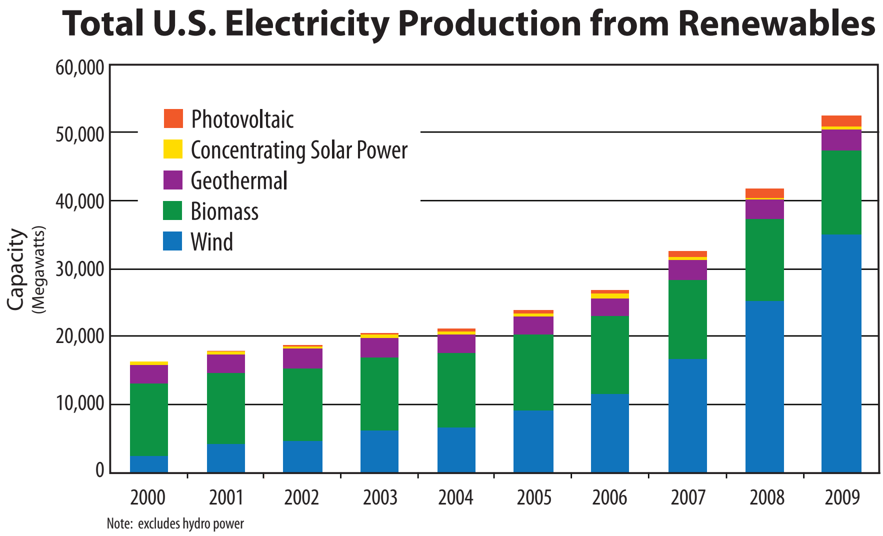




A single gold nanoantenna (cartoon above) is included in an array (right) that could be incorporated into silicon-based solar cells to capture infrared light.

Each year, the U.S. Department of Energy Solar Decathlon challenges 20 collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive, such as the one pictured at left.

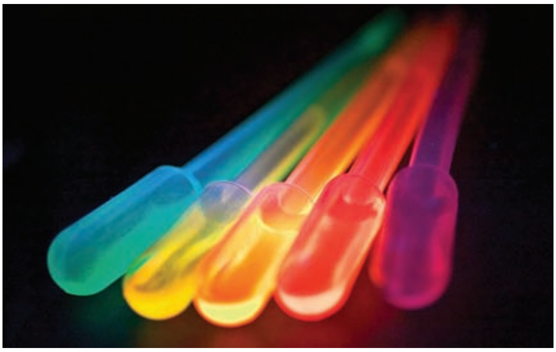
DOE/National Renewable Energy Laboratory



U.S. electrical energy derived from renewable sources is growing rapidly. While still proportionally small, solar electric energy derived from photovoltaics is growing by almost 30% per year, and advances due to nanotechnology could make it far more competitive.

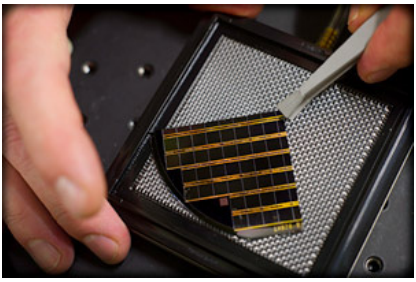
DOE/National Renewable Energy Laboratory

Another approach is to **boost efficiency** by collecting wavelengths of solar energy currently wasted. The theoretical maximum efficiency of traditional single-crystal silicon solar cells is 31% for converting photons of sunlight into electrons (electric current). Current technologies are already close to that. But traditional cells don't collect any of the sun's long-wavelength infrared (heat) radiation or most of the short-wavelength ultraviolet radiation. Researchers are working on new nanostructures to use the entire solar spectrum from ultraviolet to visible to infrared. One class of solar cells that uses nanostructures is based on "multi-junction" layers that allow a solar cell to capture a different part of the spectrum in each layer, and a broader spectrum overall. Another is "quantum dots," which can generate multiple electrons from a single photon, or even use energetic electrons from thermal gradients (local temperature differences). Experimental efficiencies of more than 40% have been reported with such nanostructures, and theoretical maximum efficiencies exceed 60%.



Quantum dots are semiconductor nanoparticles whose size and composition can be individually tuned to absorb specific frequencies of light, and sensitivity to several frequencies can then be built into a single solar cell to absorb a broader spectrum of sunlight.

DOE/Argonne National Laboratory



In multi-junction solar cell devices, several layers each capture part of the sunlight passing through the cell. These layers allow the combined cell to capture more of the solar spectrum, and convert it to electricity at a greater efficiency.

DOE/Argonne National Laboratory

nanotechnology: STORING energy

Batteries

With renewable energy sources, what do you do for energy when the sun is not shining or the wind is not blowing? One strategy is to use stored energy. One convenient way energy can be stored is in batteries, such as those that power flashlights, cameras, cell phones, and laptop computers.

Batteries *chemically* separate atoms into negatively charged electrons and positively charged ions. Batteries also store and release charge chemically, i.e., when the battery is charged, the positive (+) and negative (-) terminals have a different chemical composition than they do when the battery is discharged. Ions flow through a liquid electrolyte—one way to charge, the other way to discharge.

Experimental lithium ion battery for hybrid-electric cars capable of getting 100 mpg. DOE/Sandia National Laboratories

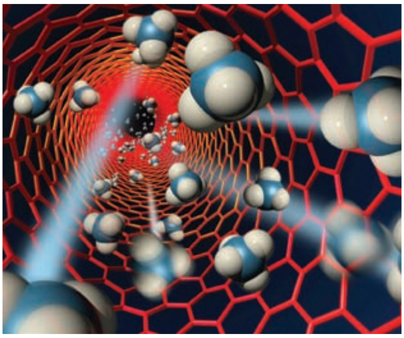
Nanotechnology is improving batteries in several ways.

In lithium-ion batteries, nanotechnology is improving the design of finely layered "intercalation compounds" for storing high densities of lithium ions, minimizing the distances the lithium ions must travel and allowing for faster charging and discharging.

Nanoengineering is being used to create an impermeable nanostructured membrane to prevent a battery's electrolyte from touching the electrodes until needed. This gives an unused portable battery an **almost unlimited shelf life**—desirable in applications such as remote sensors.

Practical, affordable electric vehicles may also be enabled by nanoengineered batteries, allowing longer range and faster charging.

Nanotechnology is also making possible the design of **large-scale** tractor-trailer-sized lithium-ion batteries for backup power supplies for electrical utilities, ships, or emergency operations.



Saving energy with nanotechnology

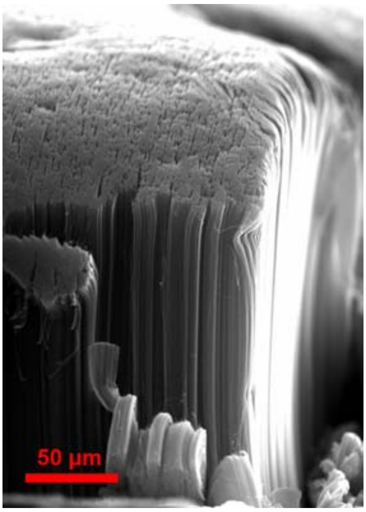
A permeable membrane of carbon nanotubes on a silicon chip can be designed with pores that could be used for desalination and demineralization of water, reducing energy costs by up to 75% compared to conventional membranes used for reverse osmosis. DOE/Lawrence Livermore National Laboratory

Pictured is a wind farm near Montfort, Wisconsin. Wind and solar power are intermittent, so energy must be stored to provide a steady supply to consumers. Todd Spink

Ultracapacitors

The next time you unplug your laptop from the wall socket, watch the little green light on the AC converter—there's a second or two delay before the light turns off. That's because the AC converter includes a capacitor that holds on to the charge.

Most electronic devices have capacitors. Capacitors *physically* store and release charge as electrons rather than as ions. In a capacitor, electrons line up on the surfaces of the terminals. They are held there by **relatively weak electrical forces** rather than by the stronger chemical bonds that hold ions in a battery. Thus, a capacitor can charge and discharge very quickly. Capacitors are excellent for operating any device that requires high power, but in a short burst.



The ability to control the density of carbon nanotubes grown on aluminum substrates makes these nanotubes ideal for use in ultracapacitors. The carbon nanotubes pictured here are 50,000 times as long as they are wide. FastCAP Systems

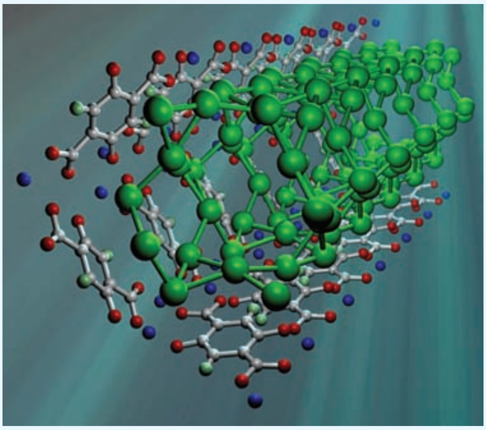
A new type of capacitor, called an "ultracapacitor" or "supercapacitor," can store unprecedented amounts of charge through a **double-layer nanostructure**. Ultracapacitors may be very useful for storing power generated by solar panels or wind farms because both sunlight and wind are intermittent.

A different type of ultracapacitor can even be used to **recover energy**. For example, ultracapacitors have been employed in elevators to recapture energy as the elevator car is lowered, thus reducing the amount of electricity needed to raise the elevator.

Scientists are researching different types of nanomaterials to enhance the storage of electrons in ultracapacitors, both to speed power delivery (like a capacitor) and to sustain power delivery (like a battery).

Hydrogen

A fuel cell converts chemical energy to electricity; hydrogen is a common fuel. Whether used to power a fuel cell in a vehicle or in a building, **storing hydrogen safely and efficiently** is a key technical challenge.



Metal-organic framework for storing hydrogen.

C. Brown, NIST

Hydrogen, unlike most gaseous elements, is most densely stored if it is bound to a solid structure. One promising structure is comprised of core-shell nanoparticles: spherical nanoparticles coated with a catalyst. When a hydrogen molecule (H_2) lands on the coating, the catalyst splits the molecule into two hydrogen atoms, which diffuse into the core. The process is reversed when the hydrogen is needed for power. For example, in a vehicle, the hydrogen might be stored in a tank already seemingly filled with "nano-sand"—which would also reduce any explosion risk.

Another challenge is devising economical catalysts to **make fuel cells more efficient**. Today's fuel cells use platinum as a catalyst, and there isn't enough platinum on this planet for fuel cells to power all the cars or buildings in the U.S., much less the world. The good news: researchers have found that coating nickel nanoparticles with an ultrathin coating of platinum not only drops the cost, but also enhances the catalyst's activity. The ultimate goal is to replace platinum with more earth-abundant materials.

Studying complex metal hydrides for storing hydrogen.

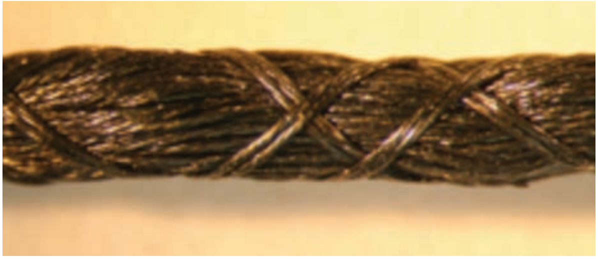
DOE/Sandia National Laboratories

Filling a hydrogen car.

DOE/National Renewable Energy Laboratory

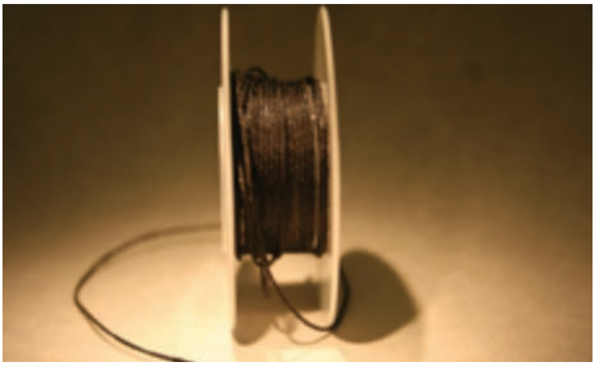
nanotechnology: transmitting energy

Most major energy sources must be transmitted from the point of generation to the point of use. For example, large national infrastructure networks exist to distribute fossil fuels and electric power. Electrical energy is still transmitted primarily through metal wires, which are heavy, bulky, and increasingly expensive. Even worse, a significant fraction of the energy transmitted is lost due to electrical resistance.



A close-up of a "nano cable," made from weaving many strands of carbon nanotubes.

Today, nanotechnology researchers are close to developing commercial nanotechnology products that can address many of these issues. For example, fibers of carbon nanotubes have been demonstrated as replacements for conventional electrical wiring. These nanowires are potentially much lighter, stronger, thinner, and corrosion-resistant than metal wiring. Most importantly, they could have much lower electrical resistance, translating into huge energy savings for electronics and electrical distribution networks.



A spool of nano cable.

Some companies are now able to make commercially useful lengths of wiring, sheeting, and cables from carbon nanotubes, which can be exceptionally light, strong, and thermally and electrically conductive.

Nanocomp Technologies

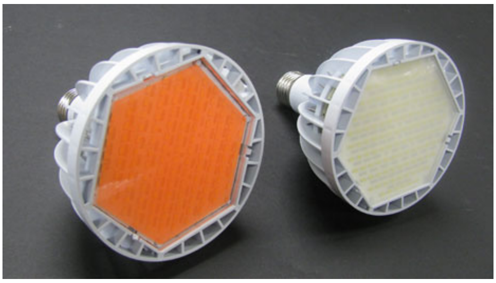
nanotechnology: *conserving* energy

One of the best ways we can meet our future energy needs is simply to reduce the amount of energy we use. Nanotechnology can help by providing new ways to increase the efficiency of existing technologies that use energy.

Solid-State Lighting

More than 22% of the electricity the U.S. generates goes to light the nation's homes, buildings, roads, and parking areas. Incandescent bulbs are only 5% efficient, and fluorescent bulbs are only 15% to 20% efficient. **Conserving just half the power** currently consumed in lighting would significantly reduce national energy consumption.

Nanoscale structures also are helping to address a related issue—efficiently getting white light out of light-emitting diodes (LEDs). LEDs theoretically are 10 times more efficient at converting electricity to light than incandescent bulbs, and more than twice as efficient as fluorescent bulbs. A relatively recent development, white LEDs are now commercially available in flashlights, automobile and bicycle headlights, and traffic signs. For home lighting, however, a big challenge has been getting **colors pleasing to consumers** while keeping efficiencies high and costs low. Through nanotechnology, engineers are designing semiconductor materials and phosphors that accurately mimic the spectrum of sunlight.



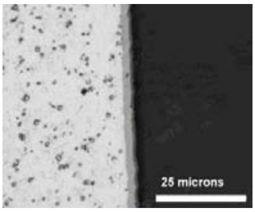
Quantum dot filter (left) fits over commercial LED lighting (right) to produce light that is more pleasing to the human eye than the LED alone. QD Vision Inc.

Organic nano-layer LED screen showing true radiated white light. GE

Organic solid-state lighting relies on nanoscale thin films. GE

Lubricants and Coatings

Friction within engines and industrial machinery wastes energy and causes wear and failure. Nanotechnology is already offering solutions across a range of applications.



Ultrahard boron-aluminum-magnesium-ceramic (BAM) coating on steel substrate is just one type of wear-resistant boride nanocoating.

DOE/Ames Laboratory

Some commercial high-performance lubricants and fuels for industrial, automotive, and medical use now contain nanostructured materials, such as inorganic fullerene-like tungsten disulfide. Basically, the fullerenes act like **nanoscale ball bearings**, providing enhanced lubrication. Other types of coatings, such as the boride nanocoating at left, produce ultrahard surfaces on parts, greatly reducing wear.

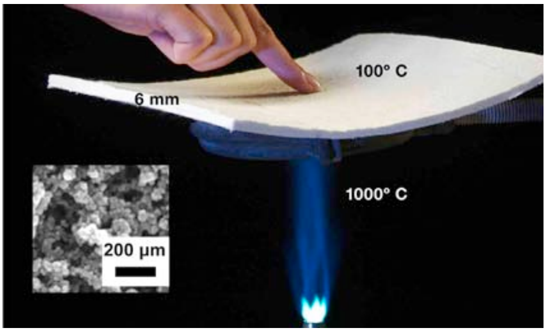
Lightweight Composites

The transportation sector accounts for over a quarter of U.S. energy use, and much of this energy is used in moving the vehicles and aircraft themselves. Reduce the mass (weight) of a vehicle or aircraft and its fuel efficiency increases.

Nanotechnology research is focused on developing **strong, lightweight materials** not only for the bodies of cars and trucks, but also for the engine blocks and drive trains—all without compromising performance or safety. Commercial composite materials incorporating nanoclays form the cargo beds of some sport-utility vehicles for added durability and stability. Other nanomaterials being developed include carbon nanotubes for aircraft bodies and turbine blades, graphitic nanoplatelets to stiffen plastics, and lightweight carbon nanotubes as electrical conductors to replace heavy copper wiring in aircraft and satellites.

A NASA / MIT concept design for an advanced commercial aircraft that incorporates nanocomposites, and that could fly significantly quieter, cleaner, and with greater fuel efficiency. NASA/MIT/Aurora Flight Sciences

Insulation



A sheet of commercial aerogel insulation. Inset: Aerogel structure. Aerogels are filled with nanopores that minimize heat transfer.

Picture: Aspen Aerogel. Inset: Reprinted with permission from ACS *Appl. Mater. Interfaces,* 2011, 3 (3), pp 613–626. Copyright 2011 American Chemical Society.

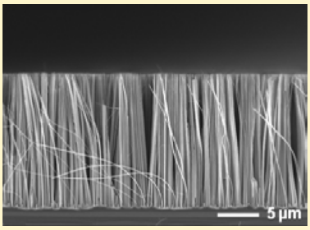
Heating and cooling systems are the single largest consumers of energy in buildings, accounting for 50 to 70 percent of the energy cost in an average single-family home. More effective insulation could reduce energy consumption in buildings by as much as 35 to 50 percent.

Commercial insulation materials can be wrapped around or sprayed on machinery, saving energy for manufacturing processes requiring high heat or refrigeration. These standard materials now can be replaced by nanostructured aerogels and nanofoams that are two to eight times more efficient than traditional forms of insulation because they can be up to 96% trapped air and only 4% solid material (commonly silicon, carbon, polymers, or ceramics). Nanostructured insulation, which can also be applied by spraying or wrapping, is being used in high-value applications, e.g., insulating oil pipelines, military ships, buildings, and even clothing and boots for astronauts and mountain climbers.

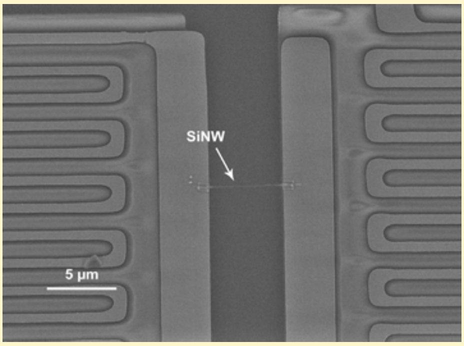
Reclaiming Waste Heat

One of the most promising ways to reduce overall energy use is to recover waste heat from applications such as industrial processes, car engines, and electronics, and to put this energy to use. Thermoelectric devices, which convert heat gradients directly into electricity, are ideal candidates, but so far their performance has been insufficient for large-scale use.

Breakthroughs in nanotechnology may yield a solution. For example, nanowires made of silicon have a conversion efficiency that is 60 times greater than bulk silicon. Making nanostructured thermoelectric devices out of silicon, which is abundant, cheap, and easily handled, could help create a new market for a wide range of devices that recover waste heat.



Cross-sectional scanning electron microscope image of an array of rough silicon nanowires. The nanoscale dimensions of the silicon enable more efficient conversion of heat to electricity than other materials. Peidong Yang, UC Berkeley



A device that uses silicon nanowires (SiNW) to turn a temperature difference into electricity. The one element is hotter than the other, generating an electric current in the nanowire. Peidong Yang, UC Berkeley

Nanotechnology and our *Energy Future*

There are many approaches to meeting the world's energy demands, by harnessing new energy sources and conserving the energy supplies we already have. Nanotechnology is not the whole answer, but it is a key part of the solution to help the nation and the world meet humanity's rapidly growing energy needs.

For more information:

Why nanotechnology is special – http://www.nano.gov/nanotech-101/special

Introduction to energy for students – http://www.eia.gov/kids/energy.cfm?page=1

Basic information about sources of energy – http://www.energyquest.ca.gov/story/index.html

Projections for global energy use through 2035 – http://www.eia.gov/oiaf/ieo/highlights.html

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