National Renewable Energy Laboratory

# RESEARCH REVIEW 2007

## From Research Discoveries to Market

*Innovation*

*Technology Development*

*Product Development*

*Commercial Demonstration*

*Large-Scale Deployment*

National Renewable Energy Laboratory
*Innovation for Our Energy Future*

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Operated by Midwest Research Institute • Battelle

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The National Renewable Energy Laboratory is operated by Midwest Research Institute and Battelle for the Office of Energy Efficiency and Renewable Energy (EERE) at the U.S. Department of Energy (DOE). NREL is funded by EERE, the DOE Office of Basic Energy Sciences, and other funding sources. NREL is the nation's primary national laboratory for renewable energy and energy efficiency research and development.

The Research Review is published yearly and describes the laboratory's accomplishments in science and technology to a wide audience. The purpose is not simply to describe the progress being made, but also to show the promise and value of NREL's R&D to people, industry, the nation, and the world.

This year's Research Review staff includes Kim Adams, Karen Atkison, Howard Brown, Ray David, Kevin Eber, William Gillies, Don Gwinner, David Hicks, Anne Jones, Erik Ness, Trixie Phelps, Paula Pitchford, Julie Tuttle, and Theresa von Kugelgen.

Cover photo: NREL researchers Eric Knoshaug and Kim Christensen (PIX15693)

# Director's Perspective: Transforming Our Energy Enterprise

Aggressively pursuing innovation, commercialization at speed, and deployment at scale.


Dr. Dan Arvizu, Director of the National Renewable Energy Laboratory

By now, we are all familiar with the statistics: Global demand for energy is projected to increase 50% or more by the year 2030, and energy demand in developing countries is likely to double in that time.

The rapid growth of energy demand, the uncertainty of future supplies, the increasing reliance on oil from unstable regions, and the resulting dramatic rise in fossil fuel prices—all of these are creating formidable challenges to our economy and our energy security. At the same time, the growing concentration of carbon dioxide in the Earth's atmosphere is a looming threat to our environment.

Without fundamental changes in how we generate—and how we use—energy, these challenges threaten our livelihoods, our lifestyles, and our planet.

I strongly believe that these changes cannot be incremental. The world must transform its current energy system on a global scale, and in order to help achieve this transformation, our nation must focus on moving next-generation energy technologies into the marketplace far more quickly than we are doing now.

At NREL, we refer to this fast-moving approach as commercialization at speed. We have been preparing for it for decades, so that today, we have many technologies that are mature enough to make a compelling business case. The challenge is to move these technologies into the marketplace more quickly by breaking down the remaining barriers.

At the same time, we must create an infrastructure in which our current technologies have far-reaching and significant impacts. We call this deployment at scale, and it means that we must identify and remove the structural barriers that are preventing advanced energy technologies from being adopted quickly and easily.

We can achieve these two imperatives by aggressively pursuing innovation while accelerating our commercialization and deployment efforts. All three pursuits are needed to achieve the necessary transformation of the world's energy system.

At NREL, we are studying the energy marketplace and developing innovative technologies that are targeted to meet the needs of the marketplace. We are managing our intellectual property to help it reach its full commercial potential and are working closely with entrepreneurs who will help commercialize our technologies. We aim to provide consumers not just with clean energy options, but also the tools that will help them integrate advanced energy technologies into their everyday lives.

NREL's research provides a pathway for new solutions in the form of a steady flow of technological advances. New concepts and systems are emerging that will allow renewable energy industries to become more cost competitive, expand their markets, and keep moving forward.

Our work covers the spectrum—from promising, but as-yet unproven, technologies that could still require years of research, to the relatively near-term cost-cutting improvements needed to accelerate the market acceptance of well-demonstrated new technologies.

And as the most opportune concepts move to commercialization, we continue to find still more ways to improve advanced energy systems and to integrate them into our existing infrastructure. In this way, research continues to feed the technology pipeline, providing industry and society with the best options for solving our energy problems.

This work is enormously challenging, yet it's essential to our energy future. We continually ask ourselves, "How can we ensure that our initial steps toward a sustainable energy economy will take us where we need to go?" The answer, I feel, will be found through balanced efforts that simultaneously address aggressive innovation, commercialization at speed, and deployment at scale. As director of the national laboratory at our nation's epicenter of clean energy research and development, I am confident we can—and will—get there.

# From Research Discoveries to Market: Five Steps to Commercialization

Innovation | Technology Development | Product Development | Commercial Demonstration | Large-Scale Deployment

The meaning of the word "commercialization" is simple: it means moving a new technology, product, or process from its conceptual stage to the marketplace. At a research laboratory like NREL, that "conceptual stage" is usually a research discovery, but the ultimate goal is still a commercial product. And though we take stock of our progress in the number of technical reports published, patents awarded, and technologies licensed, we realize that these are just milestones on the path toward commercialization.

However, that *path* to commercialization can be quite complex. We know the general path to follow to bring our innovations to the marketplace, but we also acknowledge that the path for any one product is rarely linear. Most entrepreneurs have plenty of tales to tell us about challenges that were overcome, seemingly simple steps that involved significant efforts, and frustrating setbacks that were completely unforeseen. We've learned to handle setbacks along the way, because they often result in a better product. Finding new paths around roadblocks is part of the commercialization effort.

Accepting the possibility of hitting roadblocks, it is still possible to broadly trace the route to commercialization that most technologies will follow. Generally speaking, there are five major steps in this path: innovation, technology development, product development, commercial demonstration, and large-scale commercial deployment.

Let's take a closer look at those five steps, beginning with innovation. At NREL, innovations often spring from our research, which is our primary mission. An innovation could be a scientific finding that suggests the possibility of a commercial product, with no clear path to getting there, or it could be just a good new idea with commercial potential. So innovation can be the result of years of painstaking research or a single moment of brilliance.

Technology development is often the most challenging step, because it involves taking a discovery or idea and finding a way to make it work in the real world. But it's another area where NREL's scientists and engineers really shine. As the nation's applied research and development laboratory for renewable energy and energy efficiency, it is our forte and a central part of our mission for DOE. After all, for more than three decades, we have been starting with raw materials and knowledge and creating solar cells, wind turbine designs, biofuels, and a panoply of other energy technologies.

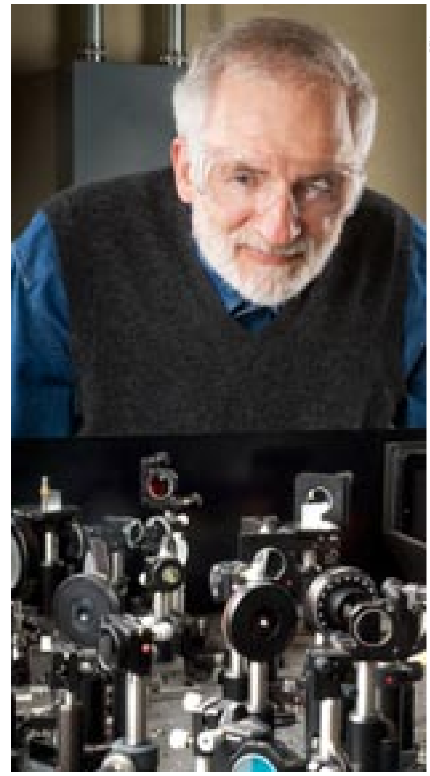
However, developing a commercial product out of a new technology is not our role, so that's when we bring in industry partners. These partners supply the business and manufacturing experience needed to create a successful product, and they also help take us to the next step, commercial demonstration. Along the way, we provide our technical expertise when needed, and we serve as objective experts who can analyze and test prototypes, validating their performance and suggesting areas for improvement, while also helping our partners to integrate their products into today's energy infrastructure.

When a demonstration is successful, the final step is the holy grail of commercialization, large-scale commercial deployment. That's what we're really after: not just making a niche product, but actually changing the way the world produces and uses energy. This is yet another area where NREL shines, as we have plenty of engineers with real-world experience who serve as advisors to project developers. Our work in high-performance buildings is a good example: we introduce designers and builders to new ideas, methods, and technologies that can lower the net energy use of buildings to near zero. If we're successful, those designers and builders carry those practices to every new building they work on.

And that's what NREL is all about—moving innovations from concepts to commercial products using our deep technical knowledge. The articles that follow present examples of this five-step path to commercialization.

# Are Silicon "Quantum Dots" a Key to High-Efficiency Solar Cells?

Research shows new promise for "nanoscale" particles of silicon.



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Art Nozik, who was recently named a fellow of the American Association for the Advancement of Science, is leading NREL's research of quantum-dot solar cells.

NREL's research shows new promise for "nanoscale" particles of silicon—particles on the scale of a billionth of a meter, or nanometer. These submicroscopic dots of material are called "quantum dots" because they are small enough to exhibit unexpected characteristics as a result of their quantum mechanical behavior. For instance, quantum dots made from the same photovoltaic solar cell material can capture different frequencies of light, depending on their size. This unique characteristic has led many researchers to try building quantum-dot solar cells.

It's tricky, though. When a normal photovoltaic material captures a photon of sunlight, it produces a negatively charged electron, which leaves behind a positively charged "hole" in the material. Under the solar cell's electrical field, the two charge carriers migrate to the terminals of the cell and produce a current. But quantum dots produce "excitons," consisting of electrons loosely bound to positive holes. Solar cells employing quantum dots must dissociate the excitons into electrons and holes that must then migrate to the cell terminals without recombining.

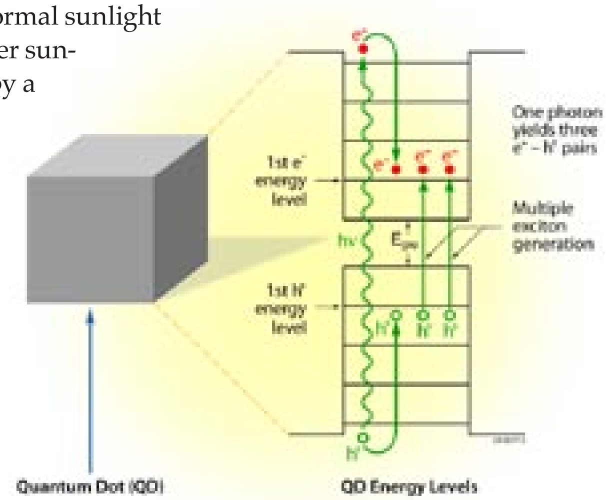
On the plus side, researchers have found that quantum dots of certain materials can produce more than one exciton per photon of light. That finding would hold promise for solar cells if it weren't for one problem: those quantum dots were made of materials not commonly used in solar cells.

That all changed in July 2007, when NREL researchers found the multiple-exciton effect in quantum dots made of silicon, the material used in most of today's solar cells. The finding, published in the August 8, 2007, edition of *Nano Letters*, suggests we are on a path toward solar cells that will produce more electrical current from the same amount of sunlight.

The NREL team discovered the effect using silicon quantum dots and exposing them to solar wavelengths from violet visible light into the ultraviolet. The research validated a prediction made by NREL Research Fellow Arthur Nozik in 1997. But despite the promise of the discovery, Nozik remains cautious about its practical applications.

"This is a significant scientific advance," says Nozik, "but for this discovery to be converted into a useful and technologically important solar cell, it is necessary to dissociate the excitons and collect the resulting free electrons and holes with high efficiency."

In other words, it's one thing to find a material that efficiently produces excitons from sunlight, but it's another thing altogether to build a device that can produce a current from those excitons. NREL and other laboratories are trying to tackle that challenge, knowing that the payoff could be great. Calculations by Nozik and NREL scientist Mark Hanna have shown that the maximum theoretical conversion efficiency of such quantum-dot solar cells would be about 44% under normal sunlight and about 68% under sunlight concentrated by a factor of 500. That's a big leg up over today's conventional solar cells, which have maximum theoretical efficiencies of 33% and 40%, respectively, under the same solar conditions.




One photon of solar energy excites one electron in conventional PV cells, but possibly more than one "exciton" in quantum dots. Also, by varying their size, quantum dots can be "tuned" to different wavelengths, dramatically increasing their efficiency in capturing solar energy.

# NREL's Research in Bioenergy Science Gets a Boost

NREL is part of a new DOE Bioenergy Science Center.


Researcher Shi-you Ding images cellulosome enzymes in NREL's Compositional Analysis Laboratory.

NREL's ability to pursue new discoveries in basic bioenergy science received a major boost in 2007, when DOE announced funding for a new Bioenergy Science Center. NREL will play a major role in the new center.

For more than 30 years, NREL researchers have been working to increase our knowledge of the science underlying renewable energy technologies. But according to Mike Himmel, manager of the NREL Biomolecular Science Group, new gains in bioenergy science will have to come from a renewed focus on a deeper understanding of the fundamental science underlying biotechnologies. The DOE Bioenergy Science Center will provide that ability.

In August 2006, the DOE Office of Science Genomics: GTL (formerly, Genomes to Life) Program issued a solicitation for genomics-related investigations that will accelerate basic research in the development of cellulosic ethanol and other biofuels. To respond to the solicitation, NREL teamed with DOE's Oak Ridge National Laboratory (ORNL) and several universities, bioenergy companies, and other institutions to propose a DOE Bioenergy Science Center. In June 2007, DOE announced that the proposal was one of three successful ones among more than 20 submitted. The center will be based at ORNL and is slated to receive $25 million per year for five years from the Genomics: GTL Program.

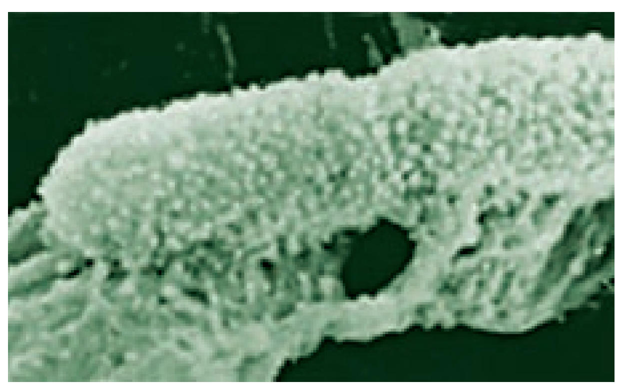
The new center's goal is to develop the science and technology that enables cost-effective conversion of cellulosic biomass to biofuels. To that end, the center will focus on two major research pathways, both involving recombinant genetics. For the first pathway, the center will develop plants that can be broken down more easily into their component sugars for fermentation, while the second pathway will focus on the microorganisms employed in biofuel production.

"The microorganisms we now use for biomass conversion tend to either be good at producing enzymes for breaking biomass down to sugar or good at fermenting those sugars, but not both," Himmel says.

The effort will develop new microorganisms that can do both well, so that today's multiple-step process can be carried out in a single step, called "consolidated bioprocessing." This achievement should increase process efficiency and reduce capital equipment costs.

NREL's three contributions to the work of the center will include advanced analysis and imaging, rapid analyses of large numbers of samples, and improvements in the biochemistry of cellulosomes. Cellulases are enzymes used to break cellulose down into its component sugars, and cellulosomes are complexes of cellulases that work together in the breakdown process.

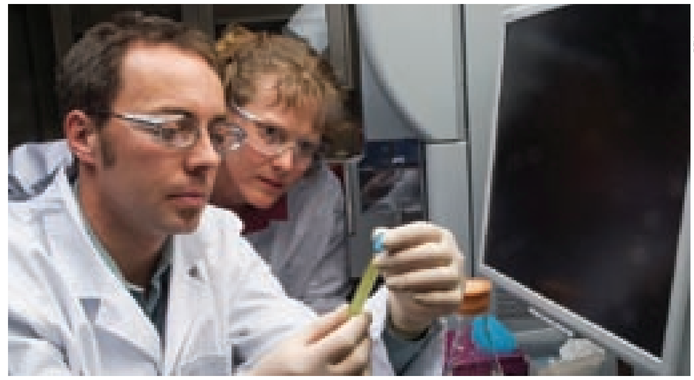
"This funding will allow us to work on the entire process in a way that we have not been able to do before," Himmel says.




Each spherical shape on the surface of this *Acetivibrio cellulolyticus* bacterium is a cellulosome containing several different enzymes active in breaking cellulose down to its component sugars. With new Bioenergy Science Center funding, NREL researchers can research the overall action of the cellulosome in a way that they have not been able to before.

# NREL–Chevron CRADA Cooks Up a Super Fuel

Collaboration will convert rapid-growing, oil-rich microscopic algae into renewable "green" diesel, jet fuel, or even gasoline.



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Researchers Eric Knoshaug and Kim Christensen are using fluorescence of lipids under laser light to analyze and sort algae samples for oil content.

Put some algae in a shallow pond of water unfit for agricultural uses, stir in some simple nutrients and an exhaust gas that's threatening the Earth's climate, and let it all cook in the sun for a few days.

That's NREL's recipe for a new sustainable fuel resource. If the recipe works, you can harvest a bumper crop of microscopic algae, or "microalgae," extract its oil, and ship the oil to a petroleum refinery, which can turn it into renewable-source "green" diesel, jet fuel, or even gasoline. The production of oil from microalgae could also be dramatically higher per acre than it is for soybeans and other oil seed crops—perhaps as much as 20 times higher.

Many species of microalgae naturally produce up to 20% of their body weight as lipids, fats, or oils that can be converted to fuel. When these microalgae are starved of the nutrients they need, their lipid content can increase as much as 60%.

To make good use of this extraordinary oil-producing capability, NREL and Chevron Corporation signed a DOE Cooperative Research and Development Agreement (CRADA) in October 2007. Under the agreement, NREL will develop ways to increase the productivity of these microalgae. Chevron anticipates using the resulting oil as a feedstock for renewable transportation fuels.

Microalgal oil production has everything going for it in terms of being an environmentally ideal recipe for biomass energy. For example, microalgae can be grown on land that's not suitable for conventional crops and in salty water that's unfit for conventional agricultural or domestic uses.

Growing microalgae could also be one of the most effective ways of reducing carbon dioxide emissions. Algae, like terrestrial plants, take up carbon dioxide directly from the atmosphere as they convert light energy into chemical energy by means of photosynthesis. But algae can be stimulated to grow more vigorously by being "fed" with carbon-dioxide-rich air streams from power plant flue gases or other sources.

NREL is uniquely and highly qualified for advanced R&D in microalgal oil production. From 1978 to 1996, the laboratory was a pioneer in the field with the Aquatic Species Program. In it, researchers screened and characterized more than 3,000 potential strains, shed light on the growth conditions that stimulate lipid production, demonstrated open ponds for mass production of biomass, and made significant breakthroughs in genetic engineering. When the program ended, the technology was considered to be highly promising but not yet cost competitive with petroleum-based fuels.

Today, however, it's time to take the microalgal-fuel recipe off the back burner. While petroleum prices are up, new petroleum refinery processes are better able to handle algal-derived oils.

Algae farming techniques have also changed. NREL used to grow algae in large, shallow outdoor ponds. Today, microalgae are grown within inexpensive plastic tubes or similar enclosed bioreactors. In fact, more than 50 companies have sprung up over the last several years to research microalgal oil production, focusing primarily on developing novel bioreactors while using existing algal strains. The most exciting change for NREL's researchers, however, is that the science has improved.

"In the '80s and '90s, efforts to increase oil production in algae were largely based on the Edisonian approach: 'try something and observe what happens.' Now, new biotechnologies give us far greater capability to understand how an organism responds to various environmental factors that influence growth," says Al Darzins, who is directing the Chevron CRADA work.

"The new excitement about microalgal oil has lots of people looking at engineering better bioreactor systems, but not as many at the underlying biology of the organisms, and that is crucial," says Darzins. "We look forward to making substantial gains."

# Marrying Nanotechnology and Biology to Boost Hydrogen Production

"Biohybrids" could replace expensive precious-metal catalysts in electrolyzers and fuel cells.


Researcher Maria Ghirardi purifies biological catalysts for hydrogen production using fast protein liquid chromatography within an oxygen-free chamber.

NREL-developed "biohybrids" made of bacterial enzymes and carbon nanotubes—carbon tubes on the scale of a billionth of a meter—could one day allow hydrogen-producing bacteria to be put to work for either hydrogen production or for oxidizing fuels within fuel cells.

The goal of the hydrogen economy involves using hydrogen fuel cells to power vehicles, buildings, and portable devices. Unfortunately, it can be an expensive business, as both fuel cells and electrolyzers—devices that run a current through water to produce hydrogen—require expensive precious metal catalysts such as platinum.

"Hydrogen and fuel-cell technologies address the need to both mitigate greenhouse gas emissions and develop energy alternatives to fossil fuels," says NREL researcher Mike Heben. "Hydrogen gas is scarce, however, and cheap, efficient hydrogen production technologies will be required for its wide-scale deployment."

One inexpensive approach is found in nature. Microbes have had billions of years to figure out efficient ways to catalyze hydrogen reactions. Their solutions involve enzymes called hydrogenases, which use more abundant metals like iron and nickel to activate hydrogen. For years, scientists have searched for ways to employ hydrogenases in electrolyzers and fuel cells.

One challenge for scientists is their inability to electrically tap into the workings of the hydrogenase enzyme, but new research led by Heben and NREL researcher Paul King may point the way to a solution to that problem. The researchers found that under certain conditions, carbon nanotubes will spontaneously combine with hydrogenases to create an electrical connection.

In the experiment, the NREL team used photoluminescence and Raman spectroscopy to look at what happens when hydrogenase from the anaerobic bacterium *Clostridium acetobutylicum* interacts with single-walled carbon nanotubes. Carbon nanotubes normally absorb and re-emit light at wavelengths that can be measured using photoluminescence spectroscopy. After hydrogenase was added, the photoluminescence disappeared.

"This suggests that the enzyme is feeding electrons into the nanotubes as it catalyzes the oxidation of hydrogen," says King.

The resulting biohybrid has the catalytic properties of hydrogenase and the excellent electrical conductivity of carbon nanotubes. The team found that they could control the catalytic reaction by changing the pH balance and oxygen concentration of the solution. When they added oxygen, which inactivates hydrogenase, the nanotubes lit up again. In the absence of oxygen, the hydrogenase-nanotube connections continued to work for up to a week.

"Our research indicates that combining hydrogenase with carbon nanotubes may offer an inexpensive alternative to noble-metal catalysts," says King. "The results suggest the possible construction of functional biohybrids of hydrogenase and single-walled carbon nanotubes for applications in a variety of hydrogen-production and fuel cell technologies. Such biohybrids could replace expensive precious-metal catalysts in electrolyzers and fuel cells."

# Squeezing More Sugar from Cellulosic Biomass

DOE's goal is to move from a batch process to a continuous reactor and to reach 90% conversion by 2012.

PIX15646

The non-edible portions of corn, known as corn stover, can be converted into ethanol, but the process is much more difficult than today's processes to convert corn kernels into ethanol.

NREL researchers recently achieved an important goal in breaking down long molecular chains of xylan—a significant component of biomass plant material—into their component xylose sugar molecules. This is a very important step toward the goal of making ethanol from cellulosic biomass cost competitive with fossil fuels.

Bioenergy technology is focused on taking biomass plant matter apart and making useful products from it. But taking biomass apart can be quite difficult. Over millions of years, plants have evolved highly sophisticated structures to keep themselves intact.

Up to 50% of biomass is cellulose and up to 32% is hemicellulose, and these two carbohydrates are nature's main storehouses of sugars that researchers want to tap to make ethanol and other products. Although perhaps the easier of the two to break down, hemicellulose is by no means easy to take apart. It consists largely of xylan, long molecular chains of xylose sugar molecules, which are wrapped around cellulose to protect it.

To make cellulosic ethanol cost competitive by 2012, which is a goal of the President's Advanced Energy Initiative, NREL developed a set of specific annual goals for various aspects of biomass conversion technology. A key goal for 2007 was to be able to convert 75% of xylan to xylose. To do that, NREL used a dilute acid, high temperature, and pressure to "pretreat" biomass, breaking down the hemicellulose and making the cellulose more accessible for the next step in the process, called enzymatic hydrolysis.

Pretreatment expert Nick Nagle describes realizing the 75% xylan conversion goal—up from 63% the previous year—as "a big step in the right direction." And fellow researcher Andy Aden says it was a great challenge for a number of reasons.

"One, we are now working at 30% solids—kind of like oatmeal or paste—which is much more difficult than our earlier work with more free liquid, but it's also a key step toward making the overall process economically competitive," says Aden. "Two, our research has shown that the xylan release process occurs in two distinctly different segments, with the first step occurring swiftly and the second occurring much more slowly. This was the first really big gain with xylan release that draws on the slower, more difficult second step."

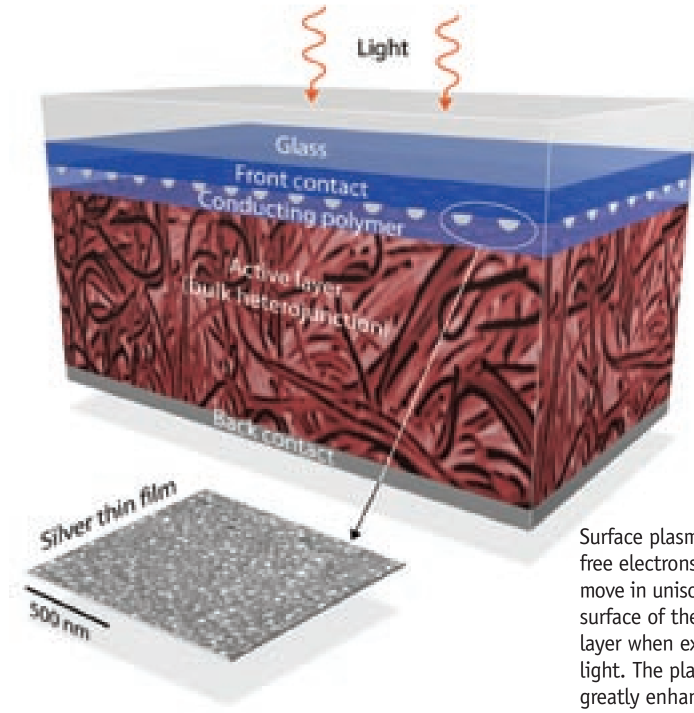
Key steps included thoroughly impregnating the biomass with acid before putting it into the pretreatment reactor and then reducing the actual reactor time to less than two minutes. The shorter time in the reactor limited the subsequent degradation of the xylose. The goal for 2008 is to move from a batch process to a continuous reactor, while the ultimate goal is to reach 90% conversion by 2012.

PIX15634 PIX15752

Researcher Noah Weiss feeds raw corn stover into a pretreatment reactor (left) and examines the product (right) after the reactor has extracted the hemicellulose as xylose.

# A Silver Bullet for Organic Solar Cells

Researchers boost conversion efficiency of plastic and fullerene molecules by adding silver.




Surface plasmons are free electrons that move in unison on the surface of the silver layer when excited by light. The plasmons greatly enhance the electromagnetic energy transmitted to the underlying active layer.

Centuries ago, stained-glass makers developed a technique for creating luminous colors by mixing minuscule droplets of metals into molten glass. Today, scientists at NREL are using a related concept to boost the efficiencies of organic solar cells.

Made largely from plastic, organic solar cells have the potential to be manufactured more easily and less expensively than solar cells made of silicon and other materials. They can be made of lower-cost materials in processes that are amenable to high-throughput manufacturing and that do not require high-temperature or high-vacuum conditions.

To explore this potential, Jao van de Lagemaat and his colleagues at NREL and the University of Colorado at Boulder are studying organic solar cells known as polymer-fullerene cells. The active layer of these cells consist of a mixture of plastic and fullerene molecules, which are molecules of 60 carbon atoms arranged in the shape of a soccer ball.

The two materials form interpenetrating phases within the active layer, and when blue light is absorbed by that layer, it forms "excitons," which are weakly bound pairs of a newly freed electron and the positive "hole" left behind in the material when the electron was freed. As the excitons diffuse to a boundary between the two materials, they split, and electrons move through the fullerenes to the back contact, while holes move through the plastic to the front contact. The result is a flow of electrical current.

There is one big roadblock to achieving high conversion efficiencies with these types of cells, however: The active layer does not absorb the low-energy red and infrared portions of the solar spectrum. But van de Lagemaat and his associates have overcome that obstacle. Their solution was to add a layer of silver with a thickness on the scale of a billionth of a meter (a nanometer).

"We are using a nanoscale layer of discontinuous silver particles, which boosts cell performance by exploiting a phenomenon called surface-plasmon resonance," van de Lagemaat says. "Surface plasmons are free electrons that move in unison on the surface of the silver layer when excited by light. These plasmons greatly enhance the electromagnetic energy transmitted to the underlying active layer. The result is a boost in current generation and hence, improved conversion efficiency of the cell," van de Lagemaat says.

The team has demonstrated that building a nanoscale silver layer within an organic solar cell can increase the output current of the device at long wavelengths. In experiments using a silver layer one nanometer thick, the solar energy conversion of the solar cell improved by a factor of 1.7. Fine-tuning will produce devices with even higher efficiencies.

Organic solar cells might not look quite as beautiful as a stained-glass window. But the performance improvement in these plastic cells—gained by using this silver "bullet"—will be very much appreciated by those wanting more affordable, clean electricity.

# NREL Effort Leads to New Solid-State Lithium Battery Company

NREL technology allows for a breakthrough in manufacturing highly compact batteries that last virtually forever.


PIX15747

Researchers from Planar Energy Devices, Inc., insert a sample into the vacuum chamber of the company's thin-film deposition system.

It can take decades to move from research and development to a commercial enterprise. But in one case, NREL's research has rather quickly led to a new start-up company that is developing solid-state batteries for use in sensors, medical devices, and other products that require safe power sources with high capacities and long lifetimes.

It all began when NREL researchers Ed Tracy, Se-Hee Lee, and Ping Liu decided to take their thin-film expertise from window technology research and apply it to a solid-state, thin-film lithium battery.

"Thin-film batteries have a problem with respect to being degraded very fast," says Tracy. "That's because the lithium metal anode is always on top, and if there were a way to get it on the bottom, it would be a much more durable device.

"We had a concept to construct this device by electrochemically plating the lithium anode on a lower layer of the battery, forming a 'buried' anode."

Although the team made progress, their work accelerated when Battelle Ventures visited NREL looking for new technologies. Battelle Ventures is a $220 million independent venture fund that aims to leverage the technologies and expertise of the national laboratories managed or co-managed by Battelle.

Coincidentally, the Battelle Ventures team had earlier visited DOE's Oak Ridge National Laboratory (ORNL), which was trying to commercialize a thin-film lithium battery. The Battelle Ventures team recognized the synergies between the two laboratories' work and provided funding for NREL to demonstrate working prototypes.

With Roland Pitts leading the task, the team found that their battery technology was very durable and had a high charge capacity, suggesting that it was commercially viable. Meanwhile, Battelle Ventures and entrepreneur Scott Faris jointly founded a company called Planar Energy Devices, Inc., which licensed both the NREL and the ORNL technology.

Since then, Roland Pitts has taken sabbatical leave to work at Planar and oversee the transfer of the technology from the labs to Planar.

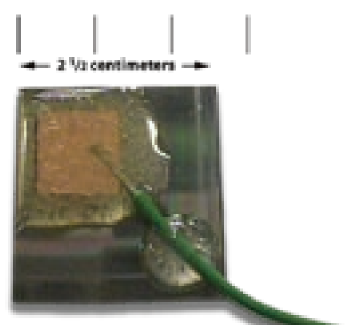
"We are currently in the stage of acquiring equipment and building out our prototype laboratory, and we're just starting to try to make some prototype batteries," says Pitts. "We recently acquired the facilities and equipment of another ORNL battery licensee, which will allow us to get to market much sooner than we had originally planned."

Planar's batteries will be highly compact and last virtually forever, changing the way electronic devices are used and designed. And because the solid-state lithium batteries are made from inorganic materials, they don't suffer from potential thermal runaway and fires, as do lithium-ion batteries. The NREL technology allows for a breakthrough in manufacturing as well.

"With the NREL technology, we can deposit all of the thin films at ambient temperatures, enabling the use of polymers and flexible substrates, as well as new types of high-capacity cathode materials," says Pitts. "Now we can make high-capacity, solid-state batteries on a true roll-to-roll manufacturing line, making it a very low cost approach."

The technology certainly has Battelle Ventures convinced. In June 2007, the fund committed $4 million in venture financing for the new start-up, providing the critically needed capital to keep the company going as it develops its promising technology.

Planar Energy Devices has advanced the solid-state lithium battery from NREL's crude prototype (below) to a miniaturized, integrated device (bottom).



PIX15761


PIX15748

# Setting the Foundation for Gigawatt-Scale Renewable Energy

A joint venture between NREL and Xcel Energy is studying how wind, solar, and hydrogen technologies can best be integrated with the electric grid.

PIX15758

Wind energy ...

PIX12812

or solar energy ...

Sitting on an exposed, wind-blown plateau along the front range of Colorado's Rocky Mountains, a 40-foot by 40-foot concrete pad may hold a key to our energy future. This is the home of the "wind to hydrogen" project, a unique facility that uses electricity from wind turbines and solar panels to produce hydrogen from water.

In chemical nomenclature, hydrogen is "$H_2$," and researchers at the "Wind2H2" facility are working to solve some of the biggest problems facing the world today: how to generate electricity and produce transportation fuels without accelerating climate change.

"The ultimate goal is to get more wind power onto the grid and provide cost-effective hydrogen for vehicles in an environmentally conscious manner, although economical and robust fuel-cell-powered cars are still years away," says project leader Kevin Harrison.

Producing electricity from renewable resources like the wind and the sun is an environmentally friendly way to meet our future needs for power. But there's a major drawback: these resources don't produce electricity when the wind isn't blowing and the sun isn't shining, and this variability has hampered their development and wide-scale adoption. So, the major goal of Wind2H2 is to improve the reliability, dispatchability, and economics of renewable energy by storing it as hydrogen, opening the door for gigawatt-scale renewable energy deployment. The hydrogen could then be converted to electricity when it's needed or used as a vehicle fuel.

Hydrogen is a flexible energy carrier that can be generated from coal, natural gas, biomass, water, and other hydrogen-rich materials. Using renewable energy to produce hydrogen from water allows inherently clean energy to be stored for later uses. Hydrogen can be stored and converted back to electricity or used to run vehicles while producing little or no greenhouse gases. That's why hydrogen is often regarded as the fuel of the future. There are, however, quite a few technical challenges to be overcome before that vision becomes a reality.

The Wind2H2 facility at NREL's National Wind Technology Center is a joint venture between NREL and Xcel Energy, the largest provider of wind energy in the country. Xcel provided most of the capital equipment, while NREL, designed, built, and now operates the facility, which had to comply with stringent safety codes and standards governing sites that produce and store hydrogen.

The hydrogen is produced by electrolysis, which is the process of splitting water into hydrogen and oxygen using electricity. The electricity needed for this process comes from utility-supplied power and three renewable sources:

- A 10-kilowatt wind turbine that produces alternating current (AC) that varies in magnitude and frequency as the wind speed changes
- A 100-kilowatt wind turbine, from which some direct current (DC) electricity is directed toward electrolysis before the remaining energy is inverted back to regulated AC for the grid
- An array of solar electric photovoltaic panels capable of producing 10 kilowatts of DC electricity.

The electricity from these sources is run through power converters—designed and built by NREL—that provide the electrolyzers with the DC power they need to operate efficiently. Two polymer electrolyte membrane (PEM) electrolyzers and one alkaline electrolyzer produce hydrogen and oxygen from an onsite water supply. The PEM electrolyzers

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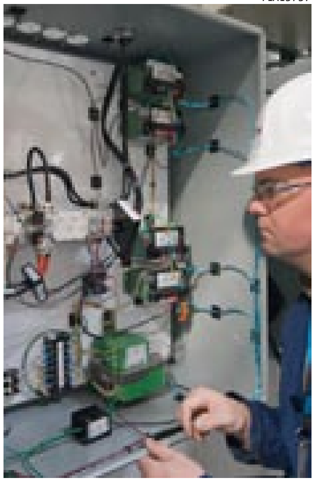

is converted to the appropriate current ...

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to electrolyze water to hydrogen ...

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which is compressed ...

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and stored ...

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for subsequent electrical generation.

each produce approximately 2.3 kilograms of hydrogen per day, and the alkaline electrolyzer produces 12 kilograms per day, for a total of 16.6 kilograms of hydrogen, equal in energy content to about 16.6 gallons of gasoline.

After the hydrogen is compressed, it's stored in tanks at 3,500 psi (pounds per square inch) for later use. When the demand for electricity is at its peak, the stored hydrogen is fed to an internal combustion engine connected to a generator, producing AC electricity that is fed into the utility grid. Future plans for the facility include adding the equipment necessary to compress and store hydrogen at the 5,000 psi or more needed for vehicle refueling. Another option would be a fuel cell, which could be used to convert the hydrogen back to electricity at nearly twice the efficiency of the internal combustion engine.

Today, the research focus is on developing the power electronics and control systems required to integrate all these different components into a single, smoothly functioning entity. The ability to do this is one of NREL's great strengths and the primary reason that Xcel chose the lab as a partner. NREL has a strong track record in integrating multiple generators and battery storage systems for village power grids in both the United States and the developing world.

Wind2H2 project partners hope to reduce the complexity of an integrated renewable hydrogen system and improve its overall efficiency. The first challenge is to convert the variable energy output from the wind turbines and photovoltaic array into a form that can be used by two different kinds of commercially available electrolyzers. Additional challenges involve creating a control system for integrating multiple electrolyzers of both PEM and alkaline technologies, which produce hydrogen at different pressures. If Wind2H2 facilities are to operate cost-effectively and propagate throughout the country, it is essential that they operate safely and smoothly without needing onsite monitoring.

"One of our major challenges is designing a fully autonomous system that does not require human input," says Harrison.

The design concept of the Wind2H2 facility is exquisitely simple, but the real-world challenges associated with operating it are legion. Despite those challenges, the pressing need for clean, autonomous energy systems has placed this project on a fast track. At the facility's inauguration in December 2006, NREL director Dan Arvizu emphasized a key advantage of joint ventures like this.

"Our growing strategic partnership with Xcel Energy helps us reduce the time and effort between research discoveries and sharing the benefits of what we learn with energy consumers," Arvizu said.

And according to Harrison, we won't have long to wait for the results of NREL's research on the optimal ways to integrate and control wind, solar, and hydrogen systems. "Expect answers by late 2008," he says. Now that's the power of partnership in action.

# Building New Markets for Energy Efficiency

NREL experts are teaming up with schools, the military, retailers, disaster recovery teams, and others to develop energy-efficient buildings.

PIX10674

NREL engineers contributed to a new publication that will help design teams plan and construct energy-efficient schools.

That clothing store you shop in, the office where you work, and even the garage where you take your car for service—all those buildings, and more, present great opportunities to save energy through improved energy efficiency and the use of clean, renewable energy.

Many of those energy- and money-saving opportunities are available to us today as a result of 30 years of building energy research and development at NREL. Today, engineers and researchers in NREL's Center for Buildings and Thermal Systems continue to share their expertise in advanced technologies with the commercial building industry.

"We have developed the analysis, model simulation and optimization, and field monitoring capabilities that enable us to best answer the industry's questions about the most cost-effective ways to save energy in buildings," says Center Director Ronald Judkoff.

Commercial buildings account for about 17% of all of the energy consumed in the United States and represent great potential for energy and cost savings. More and more businesses are beginning to realize that potential by applying energy-efficient technologies in both their new construction and in current facilities.

In recent years, many organizations have knocked on NREL's door to ask for help in moving advanced building energy technologies into the marketplace. As a result, NREL's technical specialists are now working with energy managers, builders, and marketing staff in some of the nation's largest commercial building organizations.

NREL is now a partner in some exciting projects that are helping DOE achieve its goal of transforming the commercial building industry. We have been assisting in the development of advanced energy guides for schools, hospitals, and retail buildings; helping the U.S. Army deploy energy-saving technologies in Army facilities; working alongside some of the largest retail companies in the country to cut energy costs; and helping distressed communities rebuild in the wake of a natural disaster.

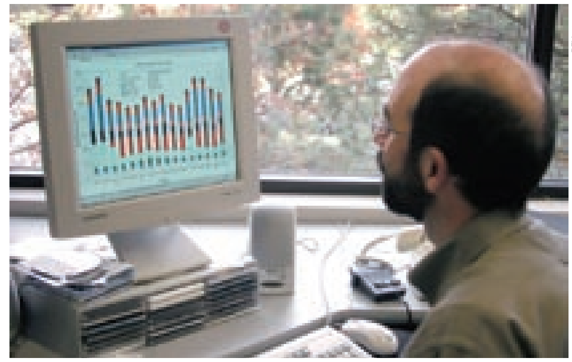
## Providing Energy Efficiency Guidance for K-12 Schools

What better place to save money by increasing energy efficiency than in our public schools? Today, fully 16% of the controllable cost of running a school district is spent on energy. Energy-efficient technologies and building practices can mean that a chunk of this money will be put to better use.

NREL engineer Paul Torcellini is helping to define the energy cost savings potential of our schools. He chaired a committee that developed a new publication written specifically for schools that serve students in kindergarten through twelfth grade (K-12). The guide will help design teams plan and construct energy-efficient schools using off-the-shelf technologies that can cut energy use by 30% or more, in comparison to the amount of energy used by buildings meeting minimum energy efficiency requirements.

"Many schools throughout the country have increased energy efficiency, cut costs, and reduced their environmental footprints through energy efficiency measures," says Torcellini. "Many others, however, still spend more money on energy than they do on educational supplies. Just think of all the things a school could do each year with the money it saves on energy: buy more books and computers, increase teachers' salaries, upgrade the media center and gymnasium . . . the list goes on and on."

The Advanced Energy Design Guide for K-12 School Buildings is published by the American Society of



PIX12311

NREL engineer Michael Deru is creating models and running simulations for different building types used by the Army. The results will help the Army build energy-efficient buildings around the world.

Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). It was written in partnership with the American Institute of Architects, the Illuminating Engineering Society of North America, the U.S. Green Building Council, and DOE. This same collaboration is developing an entire Advanced Design Guide series, which also includes design guides for small retail and office buildings. The series will soon feature a guide that addresses energy efficiency in warehouses.

The guide for schools builds on NREL's extensive experience in developing and advancing the concept of integrated building design. Integrated design consists of looking at a building as a system and then designing and using energy-efficient and renewable energy technologies on a system-wide basis.

"To build a highly energy-efficient building, you've got to focus on early design from a whole-building systems perspective," says NREL engineer Shanti Pless.

The school building guide features easy-to-follow recommendations for various climate zones and a series of case studies of actual school construction projects. It also includes suggestions for garnering green building energy credits, as well as supplemental strategies for achieving advanced energy savings beyond the target of 30% better than code.

To encourage schools to follow the new K-12 design guide, ASHRAE and its partners have sent free printed copies to 16,000 school boards throughout the United States. Following the guide's suggestions will result in more energy-efficient school buildings and help to create safe and comfortable environments that enhance learning.

## Teaming with the Army to Boost Energy Efficiency

The U.S. Army Corps of Engineers has joined the fight to broaden the use of energy-efficient and renewable energy technologies in the Army's facilities worldwide. According to the Energy Policy Act (EPAct) of 2005, new federal buildings must be 30% more energy-efficient than buildings complying with standard building codes. To meet that goal, the Corps of Engineers is getting help from engineers and analysts at NREL.

NREL engineer Michael Deru is creating models and running simulations for eight different building types used by the Army. The results will help the Army with new construction, and they can be applied to the same types of buildings in other organizations as well as in industry.

"What's exciting is that several of these building prototypes use NREL's optimization methods, which analyze thousands of building variations looking for the best energy solutions," Deru says.

The Corps of Engineers sent NREL specifications for two types of barracks, a dining facility, a vehicle maintenance building, headquarters office buildings for battalion and company personnel, a child development center, and an Army Reserve center. Using NREL-developed software, Deru and other NREL engineers are using the specifications to create models and run thousands of optimization simulations across 15 climate subzones. These simulations allow them to find innovative applications of a series of technologies that meet the EPAct requirements on a broad scale.

Like much of the U.S. commercial building industry, the Army recognizes NREL's analysis and simulation capabilities. These include the publicly available EnergyPlus software program, developed in part by NREL, which can model a wide range of parameters and provide comprehensive analytical results, as well as NREL's in-house software tool, Opti-E-Plus, which is a complex optimization program that will run tens of thousands of simulations to find the optimal energy-saving combination of products and technologies. NREL has also built a powerful distributed computing environment that effectively manages and performs the intricate calculations that create these models and simulations.

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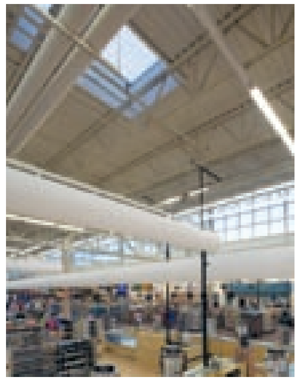

NREL has been monitoring and evaluating more than 50 different technologies that Wal-Mart installed in its experimental "Supercenter" store in Aurora, Colorado, including daylighting.

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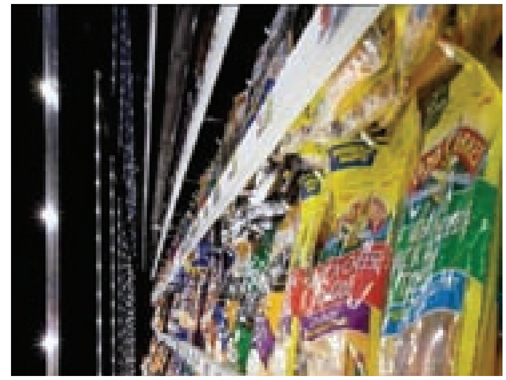


Wal-Mart recognized that using LED (light-emitting diode) lights in their refrigerated and frozen food cases achieved as much as a 70% energy savings compared to standard fluorescent lights.

## Showing Retailers the Value of Energy-Efficient Technologies

U.S. retail buildings account for approximately 20% of commercial energy consumption. They range from the small shops on the corner to huge retail stores of more than 200,000 square feet. Whatever the size, the retail industry is in general a highly competitive one characterized by slim profit margins, closely watched costs, and smart marketing.

A successful retail store understands and meets the needs of its customers. Whatever those needs might be, retailers are now seeing that good energy management is a vital part of providing cost-effective, customer-oriented goods and services. Many retailers have been looking at more energy-efficient and renewable energy technologies and coming to NREL for help in using them.

For example, for more than two years NREL has been working with one of the leaders in the construction and operation of large-scale retail outlets—Wal-Mart. Engineers are helping this retail giant find the most effective technologies for reducing its energy costs. They have been monitoring and evaluating more than 50 different technologies that Wal-Mart installed in its experimental "Supercenter" store in Aurora, Colorado. NREL's analyses determine which technologies are the most effective and which are ready to be applied to stores now being either built or retrofitted.

As one result of the monitoring, Wal-Mart recognized that using LED (light-emitting diode) lights in their refrigerated and frozen food cases achieved as much as a 70% energy savings in comparison to the energy consumed by fluorescent lights. LED lights do this by reducing the amount of installed wattage required.

Then, Wal-Mart staff found that adding motion sensors to LEDs allows them to program the lights so they go on only when a customer is standing in front of the door to the refrigerated case. Turning the lights off the rest of the time saves a significant amount of energy. NREL's work showed this technology to be so effective that Wal-Mart is rolling out the LED case lighting to 1,000 stores nationwide.

NREL's work with Wal-Mart and other retail stores has led to a separate, ground-breaking project, the Retailer Energy Alliance. As an outcome of retailers' ever-growing recognition of the value of energy management, NREL and DOE coordinated the formation of this Alliance to aid the retail industry in adopting energy-efficient and renewable energy strategies and technologies. The retailers who joined this Alliance recognize that not one of them is large enough by itself to bring about dramatic changes in the construction and operation of commercial buildings. Together, however, they can have an impact not only on the building industry, but also on the supply stream of materials used in construction.

Remarkably, the 12 companies that initiated the Alliance operate 1.25 billion square feet of retail store space and include some of the largest retail operators in the nation, such as Wal-Mart, Target, Food Lion, Whole Foods, Home Depot, Lowe's, and Best Buy. Large retailers tend to build multiple structures having the same design. Because of the similarities in the design and operation of stores among the companies, the Retailer Energy Alliance has great potential to implement successful technologies quickly and widely.

## Helping Stricken Communities Rebuild and Renew

The "renew" part of "renewable" takes on a different meaning when it comes to disaster recovery efforts. To the cities of New Orleans, Louisiana, and Greensburg, Kansas, it means resolving to start over and rebuild with energy efficiency and renewable energy

Credit: Associated Press

Greensburg, Kansas, was hit by an EF5 tornado on May 4, 2007, destroying 95% of the town and changing the lives of its 1,500 residents forever.

Credit: BNIM Architects

When BNIM Architects designed this new school for Greensburg, NREL provided technical advice about the use of solar electric systems, daylighting, and other energy efficiency and renewable energy features.

in mind. In both of these cities, NREL has been working with DOE and other federal, state, and local agencies to help people recover and rebuild.

The category 3 Hurricane Katrina and its aftermath began devastating 80% of New Orleans on August 29, 2005, but rebuilding efforts are still going on. For Greensburg, the fateful date was May 4, 2007. That night a level EF5 tornado, the highest level in the National Weather Service classification system, destroyed 95% of the town and changed the lives of its 1,500 residents forever.

Neither of those disasters has escaped the attention of staff at NREL. The laboratory has been providing recovery assistance to New Orleans since the fall of 2007, when Technology Manager Mary Colvin joined DOE officials in visiting the area and then began meeting with state and local officials. NREL has been managing $1 million in DOE funding directed at bringing energy-efficient and renewable energy technologies and expertise to the Gulf Coast rebuilding effort. As part of that effort, two NREL employees, Joe Ryan and Phil Voss, have been placed in New Orleans to provide direct assistance to the community.

In Greensburg, NREL has been involved with local and state officials, the Federal Emergency Management Agency, and other federal agencies to provide resources for energy-efficient rebuilding and greater use of renewable energy. The mayor of Greensburg, its city council, and the Kansas governor's office have all pledged to rebuild Greensburg as a green city. They do not just want to rebuild their community to have energy-efficient buildings, however. They also plan to construct a new renewable power generation facility, advance the use of renewable fuels and vehicles, encourage distributed solar and wind power, and establish green industries to bring investment and employment to the community.

In fact, NREL assisted the city in writing an ordinance that requires all buildings in excess of 4,000 square feet to be constructed to meet LEED Platinum certification. LEED is the U.S. Green Building Council's Leadership in Energy-Efficient Design program, and platinum is its highest rating. Many projects are now reaching for LEED levels on their own.

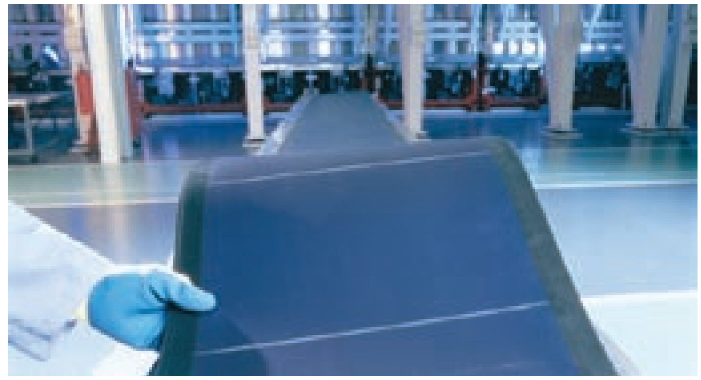
"A 32-unit townhome project for low-income seniors is going to be LEED Gold certified and very cost-effective," says Lynn Billman, NREL project lead. "Everything NREL is doing is based on cost-effectiveness. We help them understand real-world solid business models for efficiency and renewable energy."

Assistance to Greensburg also includes designing strategies for energy-efficient commercial buildings, a school, a hospital, and homes; evaluating options for renewable power generation and fuels; and developing sustainable community strategies. The NREL team of staff and contractors has provided expertise through a wide range of activities—from identifying big-picture efficiency and renewable opportunities to leading daily on-the-ground rebuilding efforts and offering energy efficiency training to residents, commercial building owners, and builders.

We might say that NREL and its partners are changing the nation's built environment one building at a time—but through its work on new design guides and collaborations with military agencies, retail alliances, and entire cities, NREL is finding efficient ways to be sure those changes happen to as many buildings as possible.

# NREL Sows the Seeds for a Thin-Film Solar Cell Bounty

A crop of new thin-film solar cell companies is now gaining prominence worldwide.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A recent crop of thin-film solar cell companies is growing in influence in the U.S. solar cell industry, thanks in part to years of care and nurturing by NREL.

Solar cells work by capturing photons of sunlight in a photovoltaic material, which is generally a semiconductor with at least one loosely-bound electron that can be freed from its atom by sunlight within a narrow range of wavelengths. Most of today's solar cells are made from wafers of crystalline silicon, which is also used in computer chips. But NREL has long been involved in the development of alternative solar cells made from thin films of semiconductors such as amorphous silicon, cadmium telluride, and alloys of copper, indium, gallium, and selenium known as "CIGS."

These thin-film solar cells have a number of advantages over traditional crystalline silicon solar cells: they use less semiconductor material, so they are generally less expensive, and they can be deposited rapidly onto a variety of substrates, such as glass, stainless steel, or even plastic. And while crystalline silicon is used to form individual solar cells, which are then assembled into large rectangular modules, thin-film manufacturers actually deposit the entire module at one time, avoiding some of the labor-intensive assembly that individual solar cells require. This provides potential cost savings while allowing for a wide range of possibilities for the form of the final product.

A perfect example of this wide range of possibilities can be found in the Uni-Solar brand of solar shingles, which consist of amorphous silicon deposited onto flexible stainless steel. The solar module is encapsulated in a clear plastic to yield a product that looks and functions like a shingle but also produces electricity.

United Solar Ovonic, a subsidiary of Energy Conversion Devices, Inc., first introduced the Uni-Solar shingles in the mid-1990s. The company then evolved the product into "peel and stick" laminates that can be directly bonded to the roofs of buildings. The solar laminates are one of the most popular examples of building-integrated photovoltaic devices, that is, solar cells that also serve a structural purpose for the building.

## Building an Industry

United Solar Ovonic is also an example of the thin-film solar revolution that is now taking place. NREL has long supported the research efforts of a number of companies that explored each of the thin-film technologies in what could be described as a friendly competition. At the same time, in-house teams of NREL scientists and engineers also tried to perfect the technologies. The story of United Solar Ovonic (often referred to by its Uni-Solar brand name) is one of those cases in which industry pulls ahead of a national laboratory while building on the laboratory's breakthroughs.

"In the thin-film area, we had national teams for each technology, so there was an amorphous silicon team, and Uni-Solar was the prime industrial member in that team," says Bolko von Roedern, the NREL technical monitor for the amorphous silicon work. "Historically, for amorphous silicon, the industry group always had the highest efficiencies, whereas for CIGS and cadmium telluride, our in-house groups were the world-record holders. In the U.S. amorphous silicon program, Uni-Solar was the champion cell maker."

A key to Uni-Solar's success was its ability to lay down three separate layers of amorphous silicon, each tuned to a different frequency of sunlight. This created a cell with three active semiconductor layers, called a "triple-junction" cell. The top active layer in a triple-junction cell captures a portion of the solar spectrum, and the remaining sunlight penetrates to the second layer, which captures another part of the

United Solar Ovonic is using a process similar to newspaper printing to deposit solar cells on long, flexible rolls of stainless steel.

PIX15778

This United Solar production line in Auburn Hills, Michigan, has the capacity to produce 28 megawatts of solar modules in one year.

solar spectrum, and likewise for the third and final layer. As a result, the cell converts more of the solar spectrum into electricity, achieving a higher conversion efficiency.

But despite its technical leadership, Uni-Solar still learned from NREL's research, particularly when it came to material characterization and the techniques for depositing the amorphous silicon onto a substrate. For instance, NREL pioneered hot-wire deposition, in which a material such as silicon is vaporized by a hot wire in a vacuum chamber, and the vapor then condenses onto the cooler surface of the substrate. Uni-Solar helped NREL to make high-efficiency solar cells using this technique.

"NREL developed the hot-wire deposition technology and other deposition technologies, but Uni-Solar often collaborated with NREL to achieve better results," says von Roedern.

In 1997, Uni-Solar started up its amorphous silicon pilot line, which had the capacity to produce enough solar modules in one year to generate 5 megawatts of power. In the solar cell industry, this is referred to as a 5-megawatt production line, big enough to provide 2-kilowatt solar power systems to 2,500 homes each year. This Uni-Solar pilot line was the first significant thin-film manufacturing facility in the United States.

The success of Uni-Solar's pilot line led the company to launch its first full-scale manufacturing plant in 2002. The facility, located in Auburn Hills, Michigan, produces the amorphous silicon solar modules using a roll-to-roll process similar to the printing presses used by newspapers. As a result, the Michigan production plant had a 25-megawatt production capacity, and back then that was big enough to boost U.S. solar cell production capacity by 20%. The process handles 9 miles of stainless steel at one time, advancing at a rate of about 2 feet per minute through the machine, to deposit triple-junction cells only 1 micron thick.

Uni-Solar eventually increased its production speed at the Auburn Hills plant, boosting its annual capacity to about 28 megawatts. In 2007, Uni-Solar added a second production line and doubled the plant's production capacity. Currently, more than 50% of the company's products are used in building-integrated applications such as their "peel and stick" roofing laminates.

Uni-Solar produced 48 megawatts of solar cells in 2007, and the company is now building four 30-megawatt production lines at a new facility in Greenfield, Michigan. When the first line begins production in 2008, the company will have an annual production capacity of 88 megawatts, and that will quickly grow to 178 megawatts. For comparison, U.S. manufacturing plants produced about 266 megawatts of solar cells in 2007, so amorphous silicon is having a significant impact on the domestic front.

"It has been a dream for a long time," says von Roedern, "and now a dream that has been realized."

## New Competition Arises

Uni-Solar and other manufacturers have achieved significant results for amorphous silicon solar cells. At the same time, NREL's work with the other thin-film technologies, CIGS and cadmium telluride, has triggered new industries that are growing even faster.

Their current growth is particularly impressive when you consider the humble beginnings of today's leading companies. For CIGS, for instance, Global Solar Energy is currently the largest manufacturer depositing CIGS thin films onto a flexible substrate. But when NREL started working with Global Solar back in 1996, the company had a much lower profile.

"Global Solar was a spin-off from ITN Energy Systems, of Littleton, Colorado, which was also

# NREL's Solar Research Garners Awards

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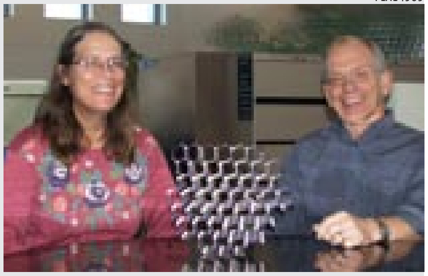

Sarah Kurtz and Jerry Olson

Decades of innovative research in solar cell technologies has led to prestigious, internationally recognized awards for NREL researchers in 2007. Researchers Sarah Kurtz and Jerry Olson received the Dan David Prize for their years of research, and in particular, their development of the multi-junction solar cell. The researchers shared the $1 million prize for their "Quest for Energy" with climate researcher James Hansen of the NASA Goddard Institute for Space Studies. Sarah Kurtz directed her share of the prize toward a trust that will support concentrating solar cell development at the University of California, Merced.

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Lawrence Kazmerski

In addition, Lawrence Kazmerski, the head of the National Center for Photovoltaics received the 2007 Karl W. Böer Solar Energy Medal of Merit. The Böer medal and a cash award of $40,000 is given every two years to an individual who has made significant pioneering contributions to the promotion of solar energy. Kazmerski plans to use the award to establish a trust that supports graduate student research using NREL's new Process Development and Integration Laboratory.

Last but not least, NREL earned an R&D 100 award in 2007 for its work with Spectrolab, Inc. to develop a triple-junction solar cell that exceeded 40% conversion efficiency. The cell uses an innovative approach to combine layers of semiconducting materials with different lattice spacing in their crystal structure, a technical challenge that previously resulted in cells with significant defects, which limited their efficiency and durability.

supported by NREL," says Harin Ullal, the lead project manager for NREL's work with the CIGS and cadmium telluride industries. "They basically had a building with four walls when we gave them the contract. We helped them get started developing the technology for CIGS."

NREL developed a laboratory procedure to produce CIGS solar cells with 19.9% conversion efficiencies using glass as a substrate. Global Solar licensed the technology from NREL and is using the same procedure, but is instead depositing the coating on flexible stainless steel in a roll-to-roll production process.

Global Solar started in Tucson, Arizona, with a 4-megawatt pilot line. In early 2008, the company opened its first full-scale manufacturing line, which has a capacity of 40 megawatts. The company is also building a 35-megawatt manufacturing plant in Berlin, Germany, and it plans to establish a new 100-megawatt manufacturing line in Tucson by 2010.

"NREL has been a steadfast partner to Global Solar throughout the changes that have occurred in our company and industry," says Jeff Britt, chief technology officer for Global Solar. "The technical support from NREL has led us in new directions and provided capabilities we could not find anywhere else in the world. In particular, their work on high-efficiency CIGS solar cells and the transfer of that know-how has directly benefited our production line."

## "Firsts" from First Solar

But NREL's biggest thin-film success to date is its work with First Solar, Inc. This manufacturer of cadmium telluride solar modules started out as a small company called Solar Cells, Inc.

"We started working with Solar Cells, Inc., way back in 1991 when they were about a six-person operation, almost a garage-type operation, on the campus of the University of Toledo in Ohio," says Ullal.


PIX15764

Global Solar Energy is currently the largest manufacturer depositing CIGS thin films onto a flexible substrate.

NREL was attracted to the company because it employed some experts from the glass industry as well as an expert in cadmium telluride technology. Solar Cells, Inc. was focused on depositing cadmium telluride on glass, forming rigid solar modules similar in appearance to solar modules made from crystalline silicon solar cells.

“We supported Solar Cells, Inc. in their early years through joint research projects, and after a couple of years or so, they produced their first prototype module, which was rated at an efficiency of 6% or so,” says Ullal.

Solar Cells, Inc. kept making steady progress and eventually started a pilot line with a capacity of about 2 to 3 megawatts. In 1999, private investors formed the First Solar company as a joint venture with Solar Cells, Inc., and later bought out Solar Cells’ stake in the company. In its early years, First Solar developed a range of novel technologies to make it easier to manufacture their thin-film-on-glass solar modules. Along the way, the company continued to collaborate with NREL.

“We’ve worked with them quite closely,” says Ullal. “For example, we’ve done a lot of measurements and characterizations of their materials, and we’ve helped them with NREL’s technical knowledge. We’ve also helped them through testing their modules and systems at our outdoor test facilities.”

First Solar launched a plant in Perrysburg, Ohio, that started with one production line and soon expanded to three production lines, each designed to produce 25 megawatts of solar modules per year. Today, each of those lines has been expanded to 45 megawatts, for a total of 135 megawatts of U.S. production capacity. The company has also improved the conversion efficiency of its solar modules to 10.6% while cutting its manufacturing costs from $2.96 per watt in 2003 to $1.14 per watt today.

“NREL expertise played a key role in helping First Solar get established in its early days,” says David Eaglesham, vice president of technology at First Solar. “NREL plays a very crucial role for the photovoltaic community in the United States and provides invaluable expertise and learning for companies getting started in this business.”

First Solar now operates a manufacturing plant in Germany with four lines, for a total of 180 megawatts, making it the largest U.S.-based manufacturer of solar cells and the world leader for thin-film solar modules. The company is now the world’s fifth-largest manufacturer of solar cells, producing 206 megawatts of solar cells in 2007.

First Solar is also constructing four new manufacturing plants in Malaysia, each one featuring four 45-megawatt production lines. Once those plants begin operating, the company’s total production capacity will exceed 1,000 megawatts per year. For comparison, about 3,700 megawatts of solar cells were produced globally in 2007.

“It’s an amazing story,” says Ullal. “NREL and DOE can really be proud of those accomplishments.”

The company’s manufacturing growth is indeed impressive, but it was its financial performance that drew the world’s attention in 2007. The company

In early 2008, Global Solar Energy opened its first full-scale manufacturing line, which has a capacity of 40 megawatts.

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First Solar, Inc. is NREL's biggest success to date with the manufacture of thin-film solar cells.

launched its initial public offering in late 2006 and garnered more than $400 million in investments. Then in 2007, its stock went up by a factor of 8, making it the top one-year performer on the Wall Street Journal's Shareholder Scoreboard.

While NREL can't take credit for the company's financial success, that success is built on the cadmium telluride technology that NREL helped develop. With a number of companies now successfully manufacturing solar modules using the three main thin-film technologies, NREL has undoubtedly helped to bring the nascent thin-film solar industry to life. But rather than resting on its laurels, NREL continues to work with new companies that are bringing fresh ideas to the thin-film solar cell industry.

The current CIGS manufacturing roster includes HelioVolt, which plans to build a 20-megawatt plant in Austin, Texas, in 2008; Ascent Solar, which plans to construct a 25-megawatt production line near Denver, Colorado, by 2009; and SoloPower, Inc., which is using electrodeposition to build CIGS solar modules on flexible thin-film substrates. SoloPower is in the process of building a 20-megawatt manufacturing plant in San Jose, California.

For cadmium telluride, the roster includes AVA Solar, which plans to begin pilot production in northern Colorado in 2008, and PrimeStar Solar, which has entered into a cooperative research agreement with NREL. It's worth noting that General Electric Company has also made a significant investment in PrimeStar Solar.

The future of thin-film solar cell manufacturing looks promising indeed, as former start-ups are becoming manufacturing giants, while a new crop of start-ups hope to inject added competition into the rapidly growing field.

Engineer Keith Emery checks the performance of an array of First Solar modules at NREL's Outdoor Test Facility. The facility has allowed First Solar and other solar manufacturers to test the long-term reliability of their solar modules when exposed to the elements.

# Investing in Energy for the Future

NREL innovations along the pathway to commercialization are gaining momentum—expanding R&D partnerships with industry, from start-up companies and entrepreneurs to Fortune 500 companies.


Colorado Governor Bill Ritter spoke to investors and energy experts in support of NREL's 20th Industry Growth Forum in November 2007.

As investments in clean energy continue to grow at record-breaking numbers, efforts to move NREL innovations along the pathway to commercialization are gaining momentum. These efforts are encouraging and expanding R&D partnerships with industry—from start-up companies and entrepreneurs to Fortune 500 companies—and will continue along that path in the future.

Through the DOE Technology Commercialization Deployment Fund (TCDF), NREL received $4 million in fiscal year 2008 to facilitate collaborative projects between researchers and industry to develop commercial products based on NREL innovations. Commercial partners share 50% or more of the project development costs, which will typically range from $150,000 to $1 million.

TCDF projects are selected based on their fit with the program, the value of NREL's intellectual property, and the potential for near-term commercial impacts. Project proposals can be submitted by either NREL researchers or our industrial partners, and once funded, the projects can move ahead quickly. NREL's first TCDF project moved from first contact with the start-up company to a funded project in only 17 days.

"The TCDF Program gives us some wonderful tools to address the commercialization 'valley of death' that exists between technologies at the laboratory and products in the private sector," says Tom Williams, NREL technology transfer director.

To further address the commercialization "valley of death," NREL has two other new programs that leverage the business creation skills of the private sector. The first is the DOE Entrepreneur-in-Residence Program, which involves placing an entrepreneur at the lab to identify opportunities for spin-off companies based on NREL-developed technologies. In February 2008, DOE selected the venture capitalist firm Kleiner Perkins Caufield & Byers, which will identify and sponsor an entrepreneur to work at NREL. The program is also being piloted at DOE's Oak Ridge and Sandia national laboratories.

The second program is the Commercialization Mentor Program, which offers seasoned business professionals an opportunity to provide a short-term contribution to NREL's commercialization efforts. These commercialization mentors, who are NREL employees during their time at the laboratory, are working alongside the lab's technology transfer staff as they evaluate new innovations for commercialization opportunities, allowing the mentors to share their commerical experience with NREL staff.

NREL also provides encouragement to clean energy entrepreneurs from outside the lab, who will receive feedback on their business plans from investors and energy experts at NREL's 21st Industry Growth Forum on October 28-30, 2008, in Denver, Colorado. NREL's Industry Growth Forum is considered the premier forum on clean energy investment. Companies participating in five of the most recent forums have collectively raised more than $1.2 billion to start up their businesses. Demonstrating industry's support of clean energy innovations, more than 430 participants attended the 20th Forum.

"When people look back at the 21st Century's greatest inventions, renewable energy technologies will be on that list," said John Denniston, a partner with Kleiner Perkins Caufield & Byers, at NREL's 20th Industry Growth Forum.

After an NREL-developed technology is licensed, the work doesn't necessarily stop there. NREL researchers often continue to work with industry partners on ways to improve the technologies, such as increasing their performance and lowering manufacturing costs. This starts the innovation process all over again, making it another beginning, not an end.

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