NREL

National Renewable Energy Laboratory

Innovation for Our Energy Future

2006 Research Review

Clean Energy's Next Revolution

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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 Kevin Eber, Howard Brown, Ray David, Grace Griego, Linda Hill, Michelle Kubik, Paula Pitchford, and Gary Schmitz.

Cover photo: Researcher Michael Heben

Director's Perspective

PIX14353

Dr. Dan Arvizu

These are exciting times for those of us fortunate enough to work in the field of renewable energy and energy efficiency.

Never before have we witnessed such intense interest in—and rapid growth of—renewable energy and efficiency technologies. In particular, the industries for solar, wind, and biomass energy systems are expanding at rates exceeding 30% annually.

And yet, as the drive to commercialize existing technologies reaches new heights, there has never been a greater need for the innovative research that will be required to deliver subsequent generations of renewable energy and energy efficiency technologies, to make tomorrow's energy solutions more economically and environmentally beneficial and less costly than those available today.

President George W. Bush's visit to the National Renewable Energy Laboratory (NREL) in 2006 underscored the important role the laboratory is playing in moving our nation toward a more secure and more sustainable energy future. That the president chose the NREL campus as the locale for a "national dialogue" on energy issues made it clear that our work can indeed make a difference for the United States.

This past year also saw NREL being recognized for its leadership in reducing the environmental impacts of its facilities and operations. Our Sustainable NREL program has not only employed renewable energy to offset the total energy use of our buildings, but also the energy used by NREL vehicles, employee commuting, air travel, and other "life cycle" energy consumption as well. I am proud of our commitment to "walk the talk," by putting to productive use many of the same renewable energy and energy efficiency concepts and systems we have had a hand in developing over the years.

I'm pleased to say that our evolving plans for the "build out" of the NREL's research campus—ensuring that we have the new laboratories and other facilities our work will require over the next several decades—reflects that same commitment to minimizing our organization's energy and environmental footprint.

A key example of this commitment is NREL's new Science and Technology Facility. As this publication was about to go to press, the facility was certified as the first federal building to earn LEED Platinum from U.S. Green Building Council. LEED stands for Leadership in Energy and Environmental Design, and Platinum is the highest rating under the LEED Green Building Rating System.

As we look to the future, it is becoming clear that our nation must increasingly rely on the useful innovations that can only come from research if we are to continue to thrive. Fittingly, a report recently released by the Council on Competitiveness advises: "For the next quarter century, we must optimize our entire society for innovation."

Putting innovation front and center: that's the philosophy on which this laboratory was built, and it is the spirit that underlies what we strive to achieve here every day. Our mission at NREL has never been more relevant, and our work never more consequential, than it is today. ■

NREL In Focus

A Structure for Translational Science

In 2006, NREL created an organizational structure that facilitates work in translational science and reflects the laboratory's commitment to developing sustainable, accessible, affordable energy technologies to power the homes, businesses, and automobiles of the future.

Translational science at NREL focuses on renewable energy and energy efficiency innovations that will most benefit the nation in practical applications. The new organization reflects four main areas of expertise: renewable electricity science and technology, renewable fuels science and technology, basic energy sciences, and strategic analysis. Each area is represented in NREL's R&D and analytical centers.

The Renewable Electricity Science and Technology directorate is home to R&D centers for solar and wind power, distributed power generation, and energy-efficient buildings; it is headed by Associate Director Stanley Bull, who has had extensive management experience in more than 35 years of work in energy-related R&D.

Renewable Fuels Science and Technology is led by Associate Director Dale Gardner, who is experienced in hydrogen systems integration and was formerly a manager at Northrop Grumman Mission Systems. His directorate focuses on R&D in bioenergy, hydrogen, and transportation technologies.

Energy Sciences, headed by Associate Director Ray Stults, includes research centers in basic chemical, material, and biosciences as well as a scientific computing center. His background includes management positions in basic sciences R&D at three other U.S. Department of Energy (DOE) national laboratories: Idaho National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory (PNNL).

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NREL Associate Directors (left to right) Ray Stults, Bobi Garrett, Stan Bull, and Dale Gardner.

Strategic Development and Analysis focuses on important issues of technology transfer, energy economics, applications, and markets and is led by Associate Director Bobi Garrett, who held several management and program leadership positions at PNNL before joining NREL. ■

NREL Goes "Carbon Neutral"

It's official: NREL is carbon neutral. Because the laboratory purchases 30 million kilowatt-hours of renewable energy certificates annually through DOE's Western Area Power Administration, NREL's activities produce no net greenhouse gas emissions over the course of a year. Certificate purchases offset all the energy NREL uses annually in buildings, vehicles, and day-to-day activities, including the energy used by staff members in commuting and air travel.

This helped to earn NREL a Climate Protection Award from the U.S. Environmental Protection Agency (EPA) in 2006. The award included recognition for NREL's significant analytical contributions to EPA's Mobile Air Conditioning Climate Protection Partnership, which could help reduce automotive carbon dioxide emissions by more than 35 billion kilograms per year.

In addition, NREL produces solar- and wind-generated power on site, uses alternative fuels in fleet vehicles, and helps to design its own energy-efficient buildings. Several facilities feature passive solar heating, natural lighting, energy-efficient equipment, and solar-heated water and ventilation air. Features like these earned NREL's new Science and Technology Facility a federal showcase designation in 2006 from the DOE Federal Energy Management Program.

These are just some of the many staff members who drive hybrid and other fuel-efficient vehicles to and from work at NREL.

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Also in 2006, the Office of the Federal Environmental Executive recognized the Sustainable NREL initiative with a White House Closing the Circle Award Honorable Mention. Laboratory Director Dan Arvizu said the award is important in that it reflects NREL's goals for leadership in environmental management and sustainability. ■

NREL and Universities Form New Partnership

To help move clean, affordable energy technologies quickly to markets in its home state and beyond, NREL has joined with three Colorado institutions of higher learning in a new partnership, the Colorado Renewable Energy Collaboratory.

The Collaboratory is made up of renewable energy researchers from NREL, the Colorado School of Mines, Colorado State University, and the University of Colorado, Boulder. The State of Colorado is providing up to $2 million per year in matching funds for the Collaboratory to pursue federally and privately funded R&D projects over the next three years. Income from spin-off commercial technologies will be used to reimburse the state for the matching funds.

The Collaboratory has already submitted a proposal to DOE for an R&D center for producing solar hydrogen and electricity via photoelectrochemistry, photochemistry, and photobiology. NREL Research Fellow Art Nozik would be the Lead Principal Investigator of a team consisting of approximately 30 NREL scientists, 35 faculty members, 30 graduate students, and 35 postdoctoral researchers. The idea for the partnership emerged from the Renewable Energy Summit hosted in early 2006 by U.S. Senator Ken Salazar of Colorado. ■

President Bush Visits NREL

President George W. Bush visited NREL in 2006 to tour a key laboratory facility and to lead a panel that discussed approaches to achieving the goals of his Advanced Energy Initiative, which aims to develop the foundations for a reliable, affordable, and clean energy future.

The visit began with a tour of NREL's Biochemical Process Development Unit led by Michael Pacheco, director of the National Bioenergy Center. During the tour, the president was given a basic overview of the process of converting cellulosic biomass to ethanol.

Credit: Daniel Hansen, White House

President Bush tours the NREL's National Bioenergy Center and hosts a panel discussion with NREL Director Dan Arvizu.

Later the president led a panel discussion on the best and most promising alternatives to the use of oil. The panel included NREL Director Dan Arvizu; Larry Burns, vice president, Research and Development, General Motors (GM); Bill Frey, Global Business director, Biobased Materials, DuPont; Dale Gardner, NREL associate director, Renewable Fuels Science and Technology; Patty Stulp, president, Ethanol Management Company; Lori Vaclavik, executive director, Habitat for Humanity of Metro Denver; and Pat Vincent, president and CEO, Public Service Company of Colorado.

President Bush said that dependence on foreign oil is a threat to both economic stability and national security, and he recognized NREL's work as important in developing viable alternatives. He proposed doubling funding for basic sciences research and developing alternative fuels, plug-in hybrids, and hydrogen-powered vehicles as well as advanced electricity generation technologies.

"We're close to changing the way we live in an incredibly positive way," the president said.

During the discussion, Arvizu described some of the exciting progress being made in photovoltaic technologies, and Burns talked about new ways that GM is marketing its considerable fleet of flexible-fuel vehicles. Stulp pointed out how growing corn for ethanol boosts the supply of domestic fuels and creates new markets for America's farmers. Frey cited GM's long partnership with NREL on hybrids and talked about new work to develop biorefineries for producing valuable fuels, chemicals, and materials from biomass.

Vaclavik said Habitat for Humanity has worked with NREL to provide comfortable, affordable homes that use little or no net energy because of their energy efficiency and integrated solar systems. Gardner described the promise of hydrogen technology and current work on producing and storing it cost effectively. Finally, Vincent talked about Public Service's "Windsource" program, advanced wind turbine technologies, and plans for new solar power stations.

The president said that future generations would appreciate the work of these pioneers and entrepreneurs. His visit to NREL was the second by a U.S. president; the first was by former President Jimmy Carter in 1978. ■

Awards and Honors

The knowledge, innovation, and creativity of our researchers make NREL the nation's premier laboratory for research and development in renewable energy and energy efficiency. These awards and honors underscore their contributions and their dedication to science and technology and to NREL's mission.

National Bioenergy Center Wins Technology Transfer Awards

The Federal Laboratory Consortium (FLC) honored NREL's National Bioenergy Center with two Notable Technology Development awards for the center's work on an integrated biorefinery and on a related process for deriving chemicals from biomass. FLC recognizes federal laboratories and agencies for excellence in transferring government-sponsored technologies to the public and private sectors.

One award credits NREL for signing a $7.7 million Cooperative Research and Development Agreement with DuPont to jointly develop, build, and test a biorefinery pilot process that will convert the entire corn plant—kernels, leaves, and stalks—into ethanol, chemicals, and electric power. DuPont leads a team that includes NREL, Diversa Corporation, Michigan State University, and Deere & Co.

NREL was also honored for a highly efficient, single-phase process that converts cellulosic biomass—such as grain hulls and other agricultural residues—into pure streams of lignin, cellulose, and dissolved sugars. These are valuable and useful materials for the fuels, chemicals, food, packaging, and pulp and paper industries. NREL secured a worldwide exclusive technology license, shared between UTEK and Xethanol Corporation, and is working with Xethanol as the company develops and commercializes the new technology. ■


PIX15029

NREL retirees Tom Milne, Dick Crandall, and Dick Ahrenkiel (left to right) have received the honorary title of emeritus.

Three NREL Retirees Honored with Emeritus Designation

In 2006, Thomas R. Milne, Richard Crandall, and Richard Ahrenkiel became the first three NREL researchers to receive the honorary title of emeritus. NREL presents the honorary title to distinguished retirees in recognition of their extensive contributions. Though the three are retired, they continue to share their knowledge and expertise with the laboratory.

Before being appointed emeritus researcher, Tom Milne was a visiting scientist at NREL's National Bioenergy Center. Milne, who came to NREL in 1977 and retired in 1996, is known for his work on the thermochemical conversion of biomass using molecular beam mass spectrometry. He is credited with developing the fundamental knowledge underpinning advanced thermochemical technologies.

Emeritus Researcher Dick Crandall, who worked at NREL from 1987 to 2006, has been a leader in developing high-performance, thin-film photovoltaic (PV) devices. He led the PV community in developing the tools needed to understand the electronic activity of disordered material. A proactive mentor, he created NREL's working group on defects in PV materials and brought together scientists from throughout the laboratory.

Emeritus Researcher Dick Ahrenkiel came to NREL in 1981 and retired in 2005. He specializes in measuring and characterizing PV cells and materials, and he is one of the world's most well-known experts in measuring the lifetimes of charge carriers within solar cells. ■

Kazmerski Receives Solar and Materials Awards

Larry Kazmerski, director of NREL's National Center for Photovoltaics, received the World PV Award in May 2006 for his outstanding contributions to the worldwide advancements of PV science and technology. Sponsored by professional organizations from the European, Asian-Pacific Rim, and American PV communities, the award recognizes superior and sustained leadership in solar PV technologies.

Kazmerski also received the Nelson W. Taylor Award in 2006. The Department of Materials Science and Engineering at Pennsylvania State University has been recognizing outstanding achievements and contributions in the field of materials science since 1970. Past awardees include Nobel Prize winners Alan G. MacDiarmid, Richard E. Smalley, and Linus Pauling.

The first scientist hired by NREL for PV research, Kazmerski has published more than 310 journal papers on solar cells, thin films, semiconductor materials and devices, surface and interface analysis, scanning probe microscopy, nanoscale technology, high-temperature superconductivity, and semiconductor defects. An author and editor of four books, he is editor-in-chief of the Elsevier journal *Renewable and Sustainable Energy Reviews*.

Kazmerski is a fellow of the Institute of Electrical and Electronics Engineers, the American Physical Society, and the American Vacuum Society. He has won three R&D 100 awards for novel measurement and characterization devices. Kazmerski was inducted into the National Academy of Engineering in 2005. ■

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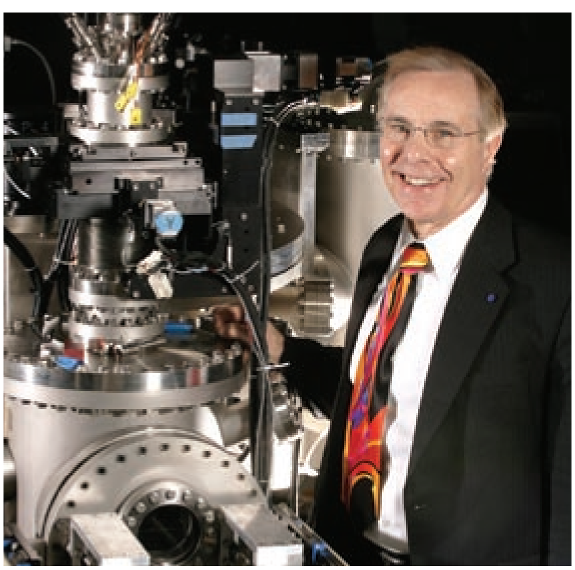

Larry Kazmerski proudly displays the new Silicon Cluster Tool at the Process Development and Integration Laboratory.

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Helena Chum

Chum Earns Green Engineering Honor

Helena Chum, group manager of Biorefinery Analysis and Exploratory Research, became the first person to receive the "Individual Trail Blazer" award from HENAAC and *Green Technology Magazine* in October 2006. The award cites her research and development work in bioenergy and renewable hydrogen production. Her work aims to solve the challenges involved in converting the world's vast biomass resources to energy and related products.

HENAAC, formerly the Hispanic Engineer National Achievement Awards Conference, is a nonprofit organization dedicated to promoting careers in science, technology, engineering, and math. Chum was honored as part of the first annual Green Engineering Honors at the October 2006 HENAAC conference.

"Ever since my early research years in my native Brazil, I envisioned bridging the gap between research in the laboratory and technology development—the creation of technology companies and commercialization of the technologies—which leads in turn to economic development," says Chum.

Working with NREL staff, industry, and academia, she has been building that bridge in the United States and in Brazil, thanks to bilateral programs. Since joining the laboratory in 1979, she has also monitored many young women and minorities and hosted a number of Hispanic professionals and Latin American students at NREL. ■

Kutscher Tapped for Solar Energy Award

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Chuck Kutscher

For his outstanding contributions in the research and development of active solar energy systems and solar thermal technologies, NREL's Chuck Kutscher was honored with the Charles Greeley Abbot Award at the 2006 annual conference of the American Solar Energy Society.

"During my 28 years at NREL, I've been fortunate to work on talented teams of solar researchers," says Kutscher. "My past and present colleagues very deservedly share in this award."

Kutscher is a group manager in NREL's Center for Buildings and Thermal Systems. His efforts have included designing a desiccant cooling test laboratory, producing NREL's solar industrial process heat design handbook, developing stretched-membrane parabolic dish solar concentrators, inventing a high-performance heat exchanger, and leading NREL's low-cost solar collector effort. ■

Clean Energy's Next Revolution

NREL's research accelerates the President's Advanced Energy Initiative

2006 was a banner year for renewable energy and energy efficiency. The wind power industry installed a record 2,700 megawatts of new capacity, while the PV industry now has the capacity to produce more than 1,000 megawatts of solar cells per year and is continuing its rapid expansion. Geothermal energy and concentrating solar power are also experiencing a renaissance.

Renewable fuels grew at a record pace, as well; the ethanol fuel industry produced about 5 billion gallons of ethanol, an increase of about 28% in just one year, while new projects are expected to double that capacity by mid-2008. Likewise, U.S. production of biodiesel tripled to 250 million gallons, and enough biodiesel production facilities were operating by year's end to more than double that production level.

Energy-efficient technologies also posted significant gains in 2006, and with President George W. Bush's declaration that "America is addicted to oil," the greatest emphasis was on hybrid electric vehicles. Thanks in part to state and federal tax credits, roughly 130,000 hybrid vehicles were sold in the United States. Automakers also started rolling out vehicles with efficient six-speed transmissions, lighter engine components, and other fuel-efficient innovations.

However, these impressive gains were accompanied by signs that some clean energy technologies are reaching limits in their rates of growth. Constraints in the supply of silicon held back growth in the PV industry, and despite the industry's rapid growth, some experts predict that the demand for solar cells will significantly exceed the supply through the end of this decade. Likewise, the expanded ethanol fuel industry is expected to consume 20% of next year's corn production, an outlook that contributed to a boost in corn prices near the end of 2006. Despite the growing number of hybrid vehicles on the road, U.S. petroleum consumption is expected to continue increasing for the foreseeable future.

Looking toward the future, President Bush unveiled his Advanced Energy Initiative (AEI) during the 2006 State of the Union Address. The AEI aims to change the ways in which we fuel our vehicles and power our homes and businesses by accelerating our use of five renewable energy and energy efficiency technologies: advanced batteries, cellulosic ethanol, hydrogen, solar power, and wind power.

Advanced lithium-ion batteries would help to commercialize plug-in hybrid vehicles, which can be charged from a home power outlet and can run on all-electric power for up to 40 miles. This would allow most people to use little or no gasoline during commutes to and from work and limit their gasoline use on longer trips, providing an opportunity to significantly reduce the nation's petroleum usage. Cellulosic ethanol draws on nonfood sources of biomass, such as trees, grasses, and agricultural wastes, and allows a large expansion in the production of ethanol fuel. And hydrogen vehicles present an opportunity to create a new hydrogen economy, which can be powered in part by renewable energy.

To advance solar energy technologies, the President launched the Solar America Initiative, which aims to make solar PV technologies cost-competitive with other forms of renewable electricity by 2015. And to boost the deployment of wind power throughout the country, the AEI emphasizes the development of new small-scale wind technologies to power homes and businesses in areas with low wind speeds.

This special section of the NREL Research Review examines how NREL is supporting the president's initiatives through innovative research. NREL's emphasis on translational science—scientific research conducted with industry goals in mind—is yielding significant advances in lithium-ion battery technologies, cellulosic ethanol, hydrogen production from sunlight, small wind turbines that capture low-speed winds, and new low-cost, high-efficiency solar cells. Through the research efforts highlighted here, plus many other related and ongoing efforts, NREL's research is truly enabling the next clean energy revolution. ■

Advanced Batteries

Nanotechnology Promises Capacity Boost for Lithium-Ion Batteries

NREL Scientist Anne Dillon examines the hot-wire chemical deposition system, which produces metal oxide nanoparticles for use in lithium-ion batteries.

PIX15026

An NREL-funded effort to create metal oxide nanomaterials could significantly boost the capacity of today's lithium-ion batteries, the leading contender in next-generation battery technology for plug-in hybrid vehicles.

"With these new nanostructured materials, we've come close to achieving an energy storage capacity that is double the capacity of graphite, which is the commercially employed anode material," says NREL Scientist Anne Dillon. "Furthermore, no degradation has been observed upon significant laboratory testing, indicating the films are very durable."

Nanostructured materials, or nanomaterials, consist of particles on the scale of a billionth of a meter (a nanometer)—hence the name. Dillon has been working with NREL Scientists Se-Hee Lee and Harv Mahan to make anodes for lithium-ion batteries using nanoparticles of molybdenum oxide. Over the past three years, the project has been funded through NREL discretionary funds, known as Laboratory Directed Research and Development funds.

The process starts with hot-wire chemical vapor deposition (CVD), a technique originally pioneered by NREL to deposit amorphous silicon films for solar cells, and subsequently adapted to deposit carbon nanotubes for a variety of applications. In this current adaptation of hot-wire CVD, a molybdenum filament is heated to a white-hot temperature, about 2000°C, inside a quartz tube filled mostly with argon, an inert gas.

Introducing a small amount of oxygen causes the surface of the filament to evaporate, resulting in nanoparticles of molybdenum oxide, which form in the gas phase and condense on the quartz surface as a powder. Once removed, this powder can then be suspended in a methanol solution, and when a voltage is applied to it, it will deposit in thin, porous films.

Because the oxide films are actually made of millions of tiny particles, they have a high surface area, which allows them to act extremely efficiently as an anode, or negative terminal, of a lithium-ion battery. The team plans to apply a similar approach to the battery's positive terminal, or cathode.

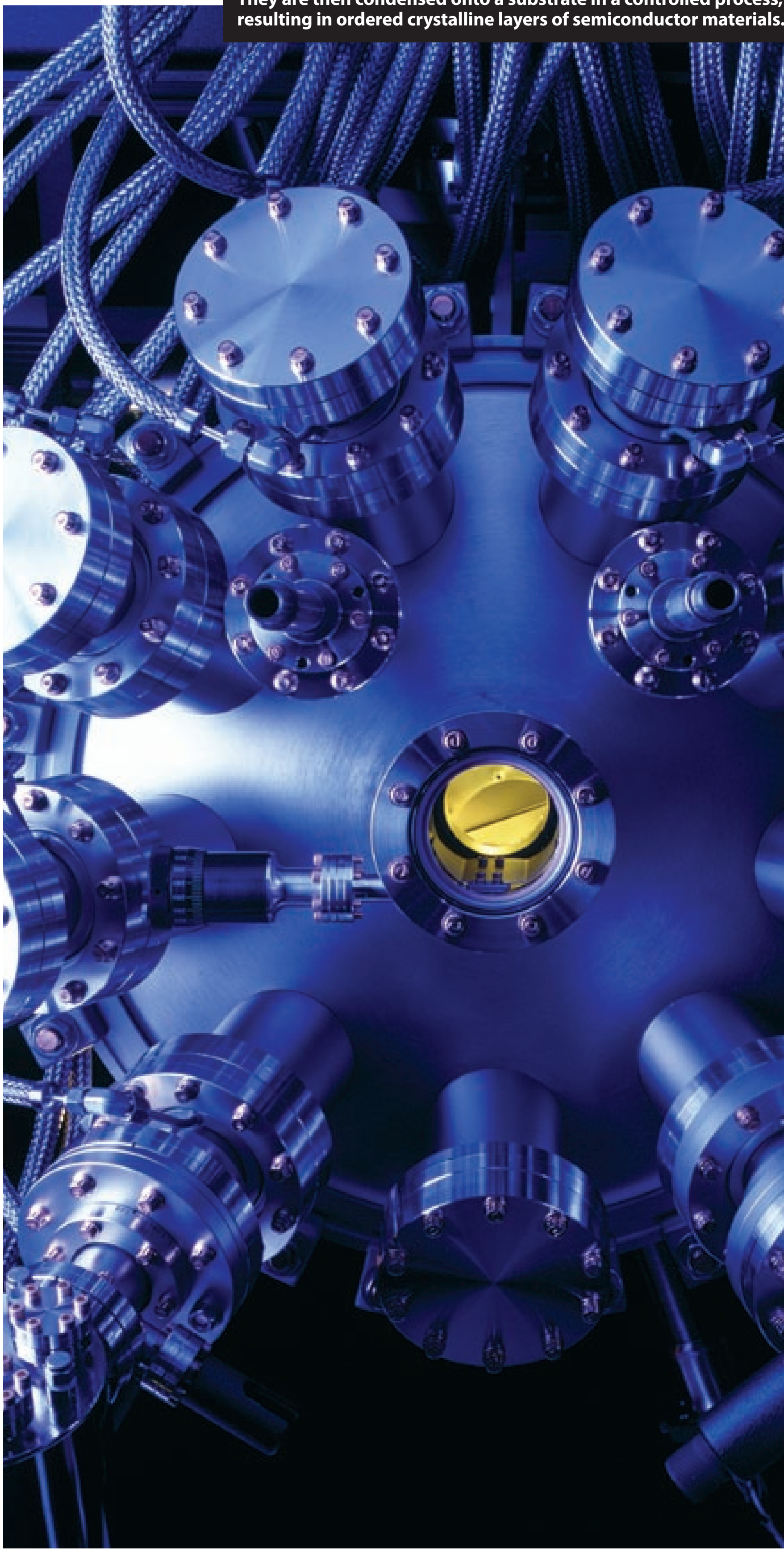
"We're going to develop other metal oxide materials for cathodes and hope to get a similar improvement in capacity," says Dillon.

One advantage of the nanoparticle terminals is their sponge-like texture, which allows them to easily expand and contract. That creates the potential to build a solid-state lithium-ion battery, replacing the battery's liquid electrolyte with a polymer.

As that polymer expands and contracts with temperature, the nanoparticle terminals could flex along with it; graphite, in contrast, is relatively brittle. The goal is to increase not only the energy capacity of the battery, but also the speed at which it can produce electricity, a factor known as its rate capability.

"If lithium-ion batteries are ever going to be used for plug-in hybrids, you need to improve the rate capability, and our nanostructured materials have shown a better rate," says Dillon. ■

NREL researchers often employ molecular beam epitaxy to build multi-junction solar cells. Within the vacuum chamber shown here, solar cell materials are heated until they begin to evaporate. They are then condensed onto a substrate in a controlled process, resulting in ordered crystalline layers of semiconductor materials.



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Solar Power

NREL Shoots for the Sun with New Photovoltaic Technologies

NREL is aiming for new solar power technologies that will significantly reduce the cost of solar electricity. What those technologies will be is anyone's guess, but the odds are good that NREL will have a hand in them.

"Some people think the thin-film approach is going to be 'the thing' of the future," says Researcher Supervisor Sarah Kurtz, "while others see great promise in organic solar cells and nanotechnologies. Meanwhile, researchers developing thinner silicon solar cells say 'don't bet against silicon,' because silicon is always the king. And other people are saying the concentrator approach has real potential."

The Concentrator Approach: A 40%-Efficient Solar Cell

Kurtz is likely part of that latter group, because she and Scientist Jerry Olson played a key role in developing multijunction solar cells, which have now achieved a 40% conversion efficiency. In other words, 40% of the sunlight hitting the solar cell is converted into electricity. The achievement by Spectrolab, a Boeing Company subsidiary, involved concentrating sunlight onto a triple-junction solar cell, which produced a world-record efficiency of 40.7%.

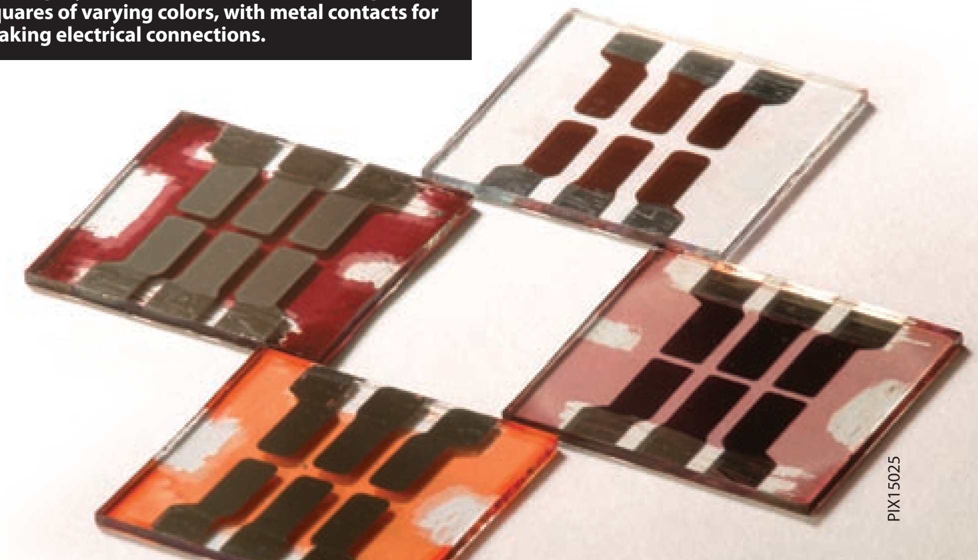
Such solar cells are much more expensive than today's silicon solar cells, but their high efficiency can help to offset the high cost. The cells use sunlight that is concentrated by mirrors or a plastic Fresnel lens, a design that requires a tracking device to keep the solar concentrators pointed toward the sun. For such concentrating solar cells, the level of concentration is generally referred to as the number of suns: "100 suns" is sunlight concentrated 100-fold. While the tracking device adds to the cost, a 100-sun concentrator only needs one square centimeter of solar cell material for every 100 square centimeters of collector area.

Through a combination of basic and applied research into the properties of semiconductor materials and devices, Kurtz and Olson advanced the concept of the two-junction solar cell—which places two layers of PV material atop one another—by developing a high-efficiency cell and bringing it to commercialization. With NREL's participation, Spectrolab and others extended that concept to a triple-junction cell, which consists of three layers of PV material. Each of the three materials captures a separate portion of the solar spectrum—this is known as the material's bandgap—and the aim is to capture as much of the solar spectrum in the three layers as possible. But that's not easy.

Traditionally, one difficulty in picking materials with the right bandgap is that the separate layers should also have similar crystal structures, in which the atoms are spaced the same distance apart. That equal lattice constant keeps the solar cell from suffering from fatal defects and poor bonds when the crystals don't line up well with each other in the interface between the layers. Unfortunately, limiting the solar cells to materials with the same lattice constant ultimately limits their efficiency.

A relatively new approach is the metamorphic or mismatched lattice solar cell, which combines materials with different lattice constants. To avoid problems with defects and poor bonding, these solar cells employ an inactive transitional layer that gradually shifts from one lattice constant to another. The transition is made by steadily changing the percentage of one material in the transitional layer as it is grown. Working under NREL's High-Performance Photovoltaic Program, Spectrolab used this approach to create its record-breaking cell.

NREL's polymer solar cells consist of small plastic squares of varying colors, with metal contacts for making electrical connections.



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"The real challenge," says Kurtz, "is to implement those bandgaps in a monolithic structure that's grown continuously, step-by-step, with materials of near perfect quality. You have to control thousands of little details all at once to hit that champion efficiency."

Metamorphic materials can be used in a wide variety of cell configurations, such as in the inverted solar cell approach that has been studied by both NREL and Spectrolab. In this approach, the cell is built upside down, laying down the top layer first on a substrate and adding the bottom layer last. The solar cell is then removed from the substrate it was grown on and can be applied to a material of choice. NREL Scientist Mark Wanlass was one of the first researchers to achieve high efficiencies in an inverted solar cell, as described in detail in the 2005 NREL Research Review. NREL's solar cell has already achieved an efficiency of 37.9% at 10 suns, but computer models suggest the cell, once perfected, could achieve an efficiency of 43% or higher at 500 suns.

"The inverted cell has a higher performance potential, and excellent cost and engineering advantages," says Wanlass. "For one thing, the original high-cost substrate is removed and can be reused, and the resulting ultra-thin tandem cell can be mounted on a desired supporting substrate. The supporting substrate can be engineered to address the needs of a particular application, such as flexible, ultra-lightweight cells for space, or robust, thermally conductive cells for terrestrial concentrators."

Meanwhile, NREL is working to develop a 50%-efficient cell, a goal that Kurtz sees as achievable.

"The ways to get closer to 50% are twofold," says Kurtz. "One way is to adjust the bandgap choices to come closer to optimal values, while still retaining very high perfection in the materials. The second approach is to add more junctions—again, with optimally chosen bandgaps—while maintaining perfection in the materials."

The Low-Cost Approach: Plastic, Nanotechnology, and Printed Solar Cells

While Kurtz, Olson, and Wanlass pursue the high-efficiency route, another group of NREL researchers are taking the opposite approach: produce a solar cell as cheaply as possible, because even if it has a low conversion efficiency, it will still

William Rance, a graduate student at the Colorado School of Mines, inserts a tray of polymer solar cells into a high-vacuum deposition chamber, where metal contacts are deposited onto the solar cells.

PIX15024

be a low-cost way to produce electricity.

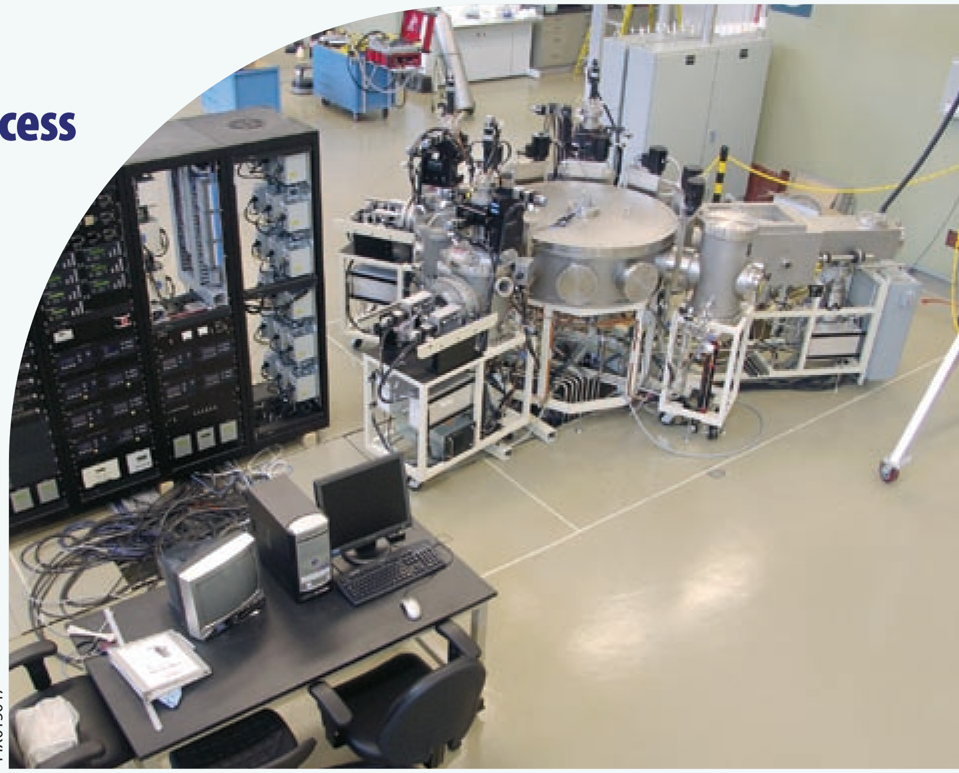
Scientist Sean Shaheen is leading an NREL effort to produce inexpensive solar cells made from plastics that can conduct electricity. These organic solar cells function differently than standard solar cells do, generating an exciton—a bound pair of an electron and a positively charged hole—that migrates to a nearby boundary and then separates, yielding free charges than can produce electrical current. Excitons won't migrate far, though, so these organic solar cells require the engineering of structures with features that are typically on the order of only tens of nanometers (billionths of a meter) thick.

NREL has been working with Konarka Technologies to create inexpensive plastic solar cells with conversion efficiencies exceeding 5%, which is high for plastic solar cells. The trick is to incorporate small nanometer-sized particles into the plastic. So-called buckyballs or fullerenes—nanoscale soccer balls made of carbon atoms—act as sites where excitons can separate into charge carriers.

NREL researchers are also investigating a number of analogous approaches to increasing the efficiency of plastic solar cells, such as embedding the polymer in a porous semiconductor film, impregnating the polymer with nanofibers of zinc oxide, or using polymers that branch out in a tree-like shape, called dendrimers.

Another way to cut solar cell costs is to fabricate them quickly and cheaply. Research Supervisor David Ginley has been working with HelioVolt Corporation to adapt ink-jet printing techniques to quickly deposit thin films of copper indium gallium selenide, a strong contender among thin-film solar cells. NREL has also employed ink jet printers to quickly apply metallic contacts to a range of solar cell materials. ■

NREL Launches Process Development and Integration Laboratory



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The silicon cluster tool, which allows for robotic manipulation of silicon solar cells in a vacuum environment, was the first addition to the new PDIL.

It's all about the vacuum. The 11,400-square-foot Process Development and Integration Laboratory (PDIL) in NREL's new Science and Technology Facility is a masterpiece in vacuum technology, featuring a variety of vacuum chambers and robotic sample handlers that keep thin-film solar cell samples isolated not only from dust but also from oxygen and other reactants in the air.

"Once the sample is initially introduced to the vacuum, it never sees air again until you're done with it," says NREL Scientist Brent Nelson, the process integration project leader.

Although the laboratory equipment is just starting to arrive in the massive laboratory space, one instrument completed in late 2006 and slated to arrive at NREL in early 2007 is indicative of the vision for the PDIL. Called the silicon cluster tool, it features a central vacuum robot that shuttles samples between eight surrounding vacuum chambers, where layers of silicon and transparent zinc oxides can be applied, as well as etching and passivation treatments. Scientist Qi Wang in NREL's Silicon Group will be the principal operator for the tool, which will be used to fabricate amorphous silicon solar cells and to passivate silicon wafers in support of thin crystalline-silicon solar cells.

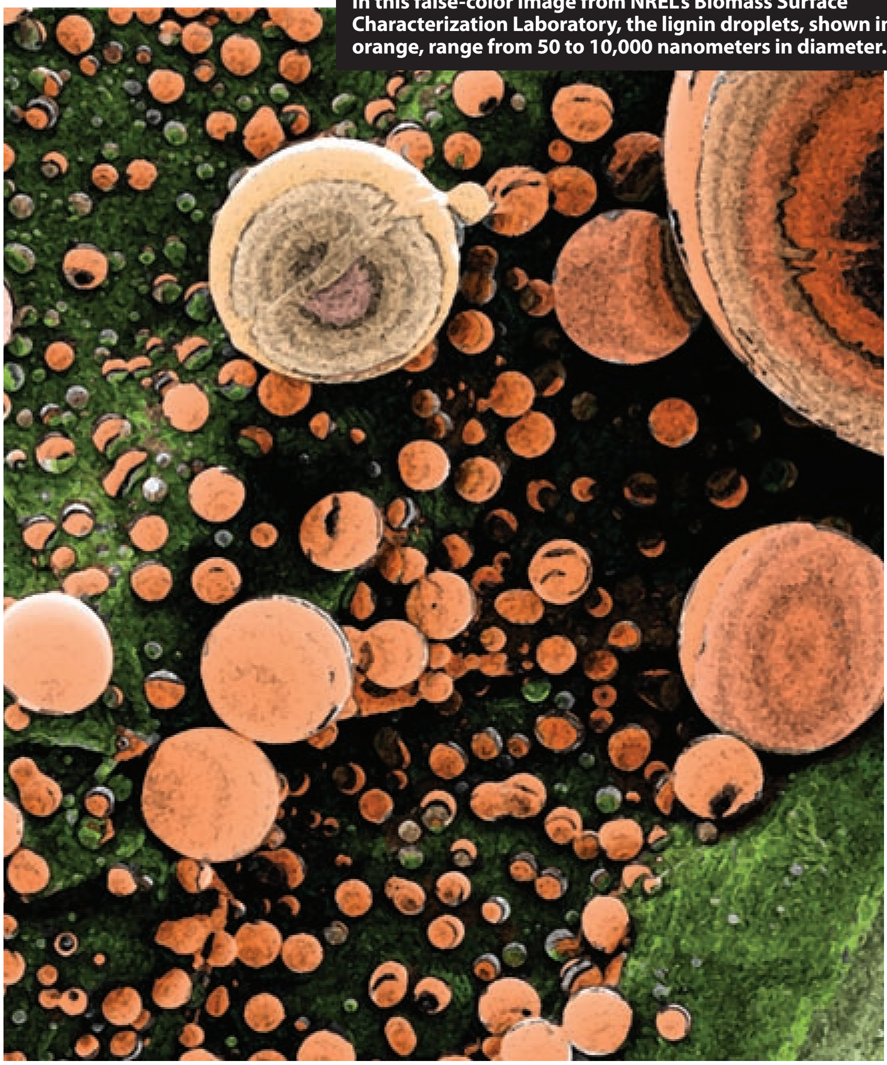
The cluster tool features several combinatorial chambers that will allow researchers to lay down 10 strips of material with different properties in both the horizontal and vertical directions, resulting in a 10-by-10 grid that provides 100 different combinations on one 6-inch-by-6-inch sample. Those chambers allow researchers to more quickly explore different parameters to find the optimal combinations, an approach often referred to as high-throughput research.

At any point in the process, a vacuum chamber containing a sample can be wheeled away to an analytical instrument or even to an entirely different cluster tool. Only a handful of places in the world employ such inter-tool transport while maintaining a vacuum in the chamber, and most of those are for small samples; NREL may be the only place in the world employing such tool integration with such large samples. The vacuum chambers made it unnecessary to build a clean room, which in turn would have made the PDIL a much more expensive facility. They also allow several different thin-film technologies to share one set of expensive analytical tools.

The idea is actually borrowed from the semiconductor industry, in which plastic boxes containing clean dry air are used to transfer semiconductor samples without exposing them to dust particles. The PDIL just takes the concept a step further by protecting samples from molecular level contamination; vastly reducing material reaction with molecules found in the air, such as water vapor and oxygen. The concept was first championed by NREL Group Manager Peter Sheldon in a technical paper published back in 2000.

The first cluster tool to be installed in the PDIL is for amorphous and crystalline silicon solar cells. However, the build-out plan for the laboratory includes characterization tools and similar cluster tools for solar cells made from cadmium telluride, copper indium diselenide, polymers, and nanomaterials. ■

Cellulosic Ethanol



PIX15105

The thermal pretreatment of lignocellulosic biomass disperses the glue-like lignin into droplets of varying sizes. In this false-color image from NREL's Biomass Surface Characterization Laboratory, the lignin droplets, shown in orange, range from 50 to 10,000 nanometers in diameter.

NREL Laboratory Aims to Break Down Nature's Defenses

Plants have evolved to be able to defend themselves against a wide variety of insect, fungal, and bacterial attackers. Although the attacking armies come equipped with a variety of enzymes that try to weaken a plant's defenses, the plants have quite a few tricks of their own up their sleeves.

Grasses and tree barks, for instance, have an outside rind consisting of a waxy barrier and densely packed cells. The plants' cell walls are made of highly crystalline cellulose, a material generally resistant to enzymes, and a coating of hemicellulose and lignin, which protects the cellulose from microbes. While cellulose and hemicellulose are both carbohydrates, lignin is a water-resistant polymer that also helps form the vascular channels within the plant.

All these components work together to form a strong defense for grasses, trees, and the inedible parts of agricultural crops, which scientists refer to as lignocellulosic biomass. But these same defenses make it difficult to free the sugars from within the biomass and allow them to be converted to fuels such as ethanol.

Scientists refer to the resistance of lignocellulosic biomass to being broken down as biomass recalcitrance. NREL and its industrial partners have discovered ways to get past plants' defenses, for instance, by using heat, pressure, and dilute acid to break down hemicellulose into its component sugars. A cocktail of three enzymes can then convert the cellulose into glucose molecules, in a process known as hydrolysis.

Despite these approaches, the general problem of recalcitrance of the plants has not been overcome. For instance, two batches of cornstalks and leaves might appear the same, but will react much differently to such acid pretreatments and hydrolysis steps. Clearly, a greater understanding of the structure of these plants is needed to understand what makes some plants more resistant to chemicals and enzymes than others.

To address these issues, NREL has launched the new Biomass Surface Characterization Laboratory (BSCL). The BSCL is well equipped with imaging tools to help NREL scientists understand the structure of plants. The instruments include a scanning electron microscope for high-power images; an atomic force microscope to study cell wall surfaces; a transmission electron microscope to reveal internal structures and their chemistry; a near-field scanning optical microscope, which can perform spectroscopic analysis of surfaces and focus on single molecules; and a confocal microscope, which can yield three-dimensional images of samples.

Launched in 2005, the BSCL has already yielded insights into biomass recalcitrance. By studying the pretreatment processes used to break down the hemicellulose and remove the lignin, the BSCL revealed that some of the hemicellulose is converted directly into sugars, while the hemicellulose that is linked to lignin is carried into the solution. That means that, for plants in which most of the hemicellulose is linked to lignin, a low percentage of that hemicellulose will be broken down into sugar, so less fuel will ultimately be generated from the biomass.

NREL is also attacking the problem from a different angle, trying to better understand the enzymes that break down cellulose. Called cellulases, the enzyme complexes actually consist of a collection of protein enzymes, and each one plays a role in breaking down cellulose to glucose molecules.

To understand how cellulases work, NREL is employing CHARMM (Chemistry at Harvard Molecular Mechanics), a software model for simulating the actions of large molecules. The NREL simulations include roughly one million atoms to model the enzyme, the cellulose, and the surrounding water simultaneously. If that's not enough, NREL needs to run the model for 25 million steps that will equal 50 billionths of a second, making it the largest biological computer model yet attempted.

To extend the CHARMM model to such a huge problem, NREL researchers and their partners at the Colorado School of Mines and Cornell University have teamed up with software developers at The Scripps Research Institute and with computational scientists at the San Diego Supercomputer Center at the University of California, San Diego. One solution is to run parts of the CHARMM model in parallel to speed the computations.

The computer model is expected to answer questions about how the cellulase enzyme complex interacts with cellulose; one such question is whether the enzyme acts on only one face of the cellulose crystal. Water is also an important part of the equation, because it forms a high-density layer on the surface of cellulose. Understanding how the cellulase complex disrupts that water layer may be key to understanding its function. ■

Hydrogen

Cellular "Factories" Aid Search for Key to Converting Sunlight to Hydrogen

NREL Scientist Maria Ghirardi has billions of factories churning out their products in support of her research. Her helpers are very small, though: they are tiny cellular factories of E. coli bacterium, busily manufacturing the hydrogenase enzyme that could be the key to producing hydrogen from sunlight. Such a process could one day provide a renewable energy source for fueling future hydrogen vehicles.

Scientists have long known that under some conditions, the green alga Chlamydomonas reinhardtii would produce hydrogen. The enzyme at the heart of this hydrogen-producing process is called hydrogenase, and it has a unique ability to combine protons and electrons to form a hydrogen molecule. Because photosynthesis—the process that plants use to convert sunlight to chemical energy—also generates a lot of electrons, scientists see a potential for combining photosynthesis with hydrogenases to generate hydrogen from sunlight.

But there's a big problem: photosynthesis also generates oxygen, and most hydrogenases can't tolerate oxygen. So the key to the process is to find a hydrogenase enzyme that tolerates oxygen and is still very active, churning out lots of hydrogen.

Back in 2000, Ghirardi and NREL Research Fellow Mike Seibert joined researchers from the University of California, Berkeley, to announce that they had found the key to forcing Chlamydomonas to produce the energy-rich gas: they deprived it of sulfur. This approach—based on an understanding of the alga's metabolism garnered through years of research—decreased the alga's internal production of oxygen and caused it to consume any oxygen produced by photosynthesis.

In the absence of net oxygen, the alga reverted to an alternate metabolic pathway, which generated hydrogen through the degradation of starch and through the photosynthetic oxidation of water. The process works, but the photosynthetic process yielded low amounts of hydrogen. In order to fully utilize the available sunlight for hydrogen production, the research team realized that they needed to find or engineer a hydrogenase that functions well in the presence of oxygen.

"There are a few hydrogenases in nature that are more tolerant to oxygen, but they're not found, so far, in photosynthetic organisms," says Ghirardi. "Why is that important? Because in photosynthetic organisms, you can get hydrogen directly from water, and in non-photosynthetic organisms, you have to feed them some carbon source, so it's not as economically desirable."

A major problem that NREL researchers faced was the lack of a simple way to study and engineer algal hydrogenases. The hydrogenase consists of a metallic catalytic cluster bound to a protein structure, and earlier attempts to insert the hydrogenase genes into E. coli, an organism commonly used for such purposes, yielded inactive enzymes that lacked the critical metallic cluster.

That all changed in 2005, when Ghirardi and Research Associate Matthew Posewitz were studying the green alga Chlamydomonas by creating random mutations in its genome. Using a process called insertional mutagenesis, the researchers inserted pieces of DNA at random on the alga's genome to disrupt genes.

"We looked for the mutants that could not produce hydrogen, and among the ones that we found was this particular

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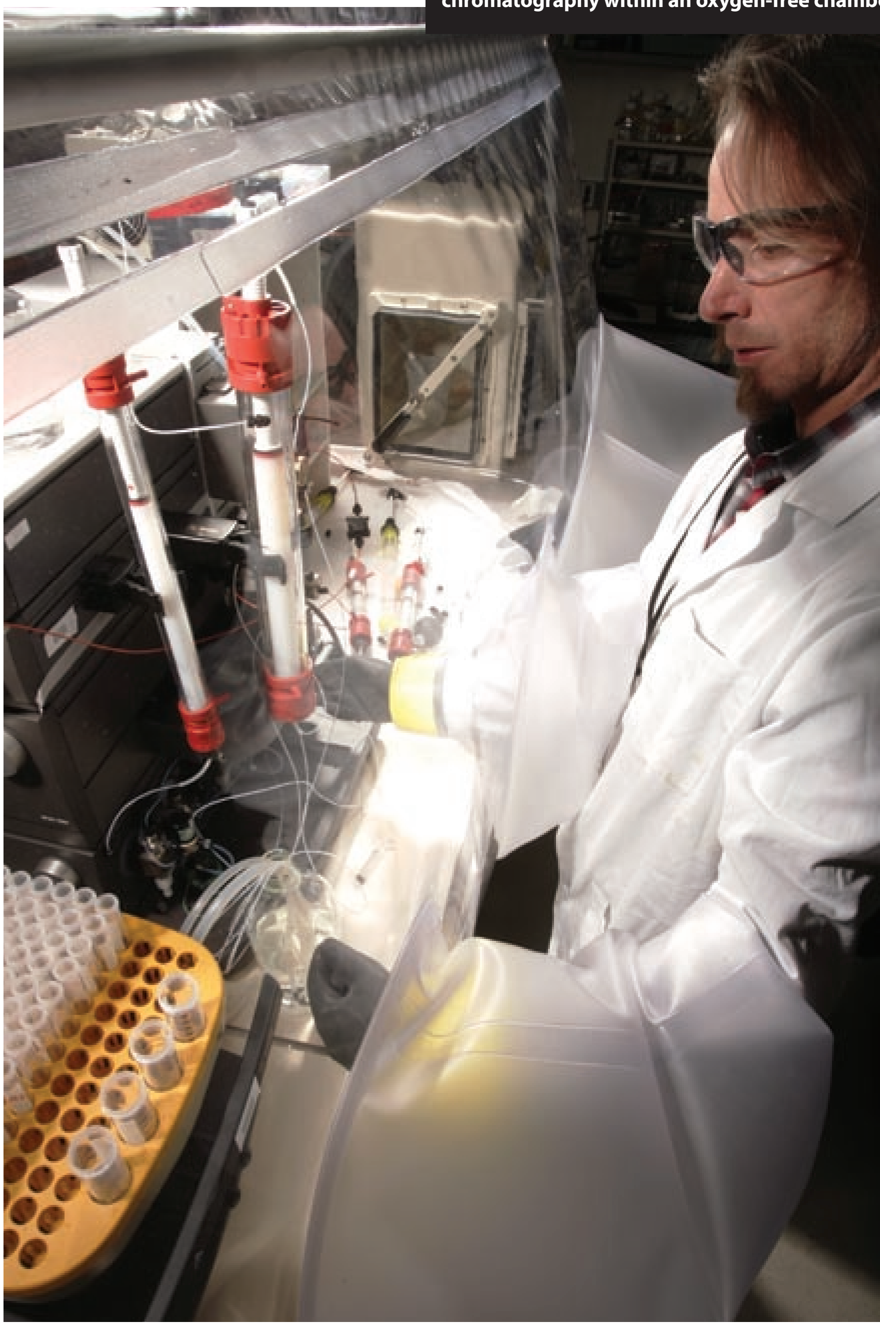
Paul King purifies biological catalysts for hydrogen production using fast protein liquid chromatography within an oxygen-free chamber.



mutant that was disrupted in a gene that nobody knew anything about," says Ghirardi. "It was called a HydEF gene. It turns out that this gene product is responsible for assembling the catalytic structure of the hydrogenase. We found not only this gene, but another adjacent gene to it in the genome, and together they function to put together the metallic catalytic cluster in the hydrogenase.

"Now we can not only transform the E. coli with the hydrogenase gene, but also with the assembly genes. So E. coli makes the structural protein, but it's also able to make the catalytic cluster and assemble it into the hydrogenase."

NREL Scientist Paul King was the first to demonstrate the gene insertions into E. coli, a breakthrough that allowed the research team to conscript the E. coli bacterium to produce large amounts of hydrogenase, making it much easier to study. The researchers can mutate the hydrogenase genes, insert them into the E. coli, and see how they behave in terms of oxygen tolerance and hydrogen production.

"This has had a major impact in the field of hydrogenases and hydrogen production," Ghirardi says.

So far, Ghirardi's team has used the E. coli to examine the oxygen tolerance of a hydrogenase found in the Clostridium bacterium. King suspected that an unusual appendage on the Clostridium hydrogenase was the key to its oxygen tolerance. Lopping off the appendage, he inserted the truncated enzyme into E. coli. He hoped the altered enzyme would lack the oxygen tolerance, but such was not the case.

"We learned something from it," says Ghirardi, "but I wish the result had been the other way around."

The team is in the process of developing new methods to study oxygen tolerance in hydrogenases, using both random mutations and intentional ones. The work is being aided by a fruitful collaboration with computational scientists at NREL and at the Beckman Institute. These scientists are employing computer simulations to map possible pathways by which oxygen can access the catalytic site of the hydrogenase enzyme and inactivate it. By mutating the hydrogenase into a form that blocks those pathways, Ghirardi's team hopes to find the key to an oxygen-tolerant hydrogenase.

"Such mutations could allow us to engineer an organism that efficiently produces hydrogen through photosynthesis," says Ghirardi. "And once we fully understand the process, perhaps we can move beyond the organism, and create an entirely synthetic photochemical pathway for producing hydrogen from sunlight in vitro." ■

Wind Power

PIX15030

The Skystream 3.7 is a small wind turbine engineered to quietly and efficiently produce power from low-speed winds. The turbine was designed by Southwest Windpower with help from NREL.

Award-Winning Wind Turbine Demonstrates a Successful NREL Collaboration

A cost-shared subcontract between NREL and Southwest Windpower has resulted in a small wind turbine that begins producing power at a lower wind speed than most wind turbines: only 7 miles per hour. The innovative Skystream 3.7 wind turbine earned a 2006 Best of What's New Award from Popular Science magazine and was recognized by Time Magazine as one of the "Best Inventions 2006." NREL started working with Southwest Windpower back in 2001, and the company took full advantage of the working relationship.

"They wanted to come out and pick our brains on a regular basis," says Project Leader Trudy Forsyth. "We were more closely involved with their design than we have been with anyone else. It was really rewarding for our technical staff, because they love to get into the technical details. And it was rewarding for Southwest Windpower, because they used NREL as their brain trust, which is a perfect role for us."

The 1.8-kilowatt wind turbine is quieter than most, drawing on acoustics research performed by NREL researcher Paul Migliore, who is now retired. That research called for a lower rotating speed and for blades with a blunt leading edge and a sharp, thin trailing edge. The turbine also employs NREL airfoils—developed by another NREL retiree, Jim Tangler—that are insensitive to roughness caused by dirt or bugs building up on the blades, and that yield a high energy capture for the turbine blades.

In addition, it draws on an idea conceived by Forsyth and NREL Engineer Ed Muljadi to use the turbine's generator to cause it to stall at high wind speeds. Combined with the turbine's downwind design, that approach simplifies the turbine, avoiding the need for a tail vane. NREL Project Leader Jim Green coordinated NREL's research support for the project.

David Calley, the president of Southwest Windpower, contributed another key innovation: the turbine uses a high-efficiency permanent magnet generator with a unique slotless stator. While most generators tend to stick or cog at a position where the rotating magnet aligns with one of the magnetic poles or slots in the stator, the slotless stator avoids cogging, allowing the generator to start turning at lower wind speeds.

Yet another innovation is the turbine's integrated electrical design. Southwest Windpower specifically designed the electrical characteristics of its generator to take advantage of the turbine's built-in power inverter, which delivers alternating current to the home. The electrical design avoids the energy losses that are common in such small wind turbines and delivers a higher system efficiency than most small wind turbines on the market.

The company is placing heavy emphasis on the "plug and play" characteristics of the Skystream turbine, which is designed for the suburban market. And to meet that market, the standard product offering is to mount the wind turbine on a 10-meter tower, which is a lower tower than many experts would consider ideal.

"For most of the United States, there are regulations that typically only allow you to put up about a 10-meter tower without getting zoning approval," says Forsyth. "Even though the wind resource is not ideal at that hub height, Southwest Windpower is banking on the fact that avoiding zoning approval will help them market and sell their turbine."

Forsyth also sees the company as having the ability to supply a large market with its turbine.

"They've been achieving high-volume wind turbine manufacturing for years—10 to 13 thousand per year—and they'll do that with the Skystream, as well," says Forsyth. ■

WinDS of Change

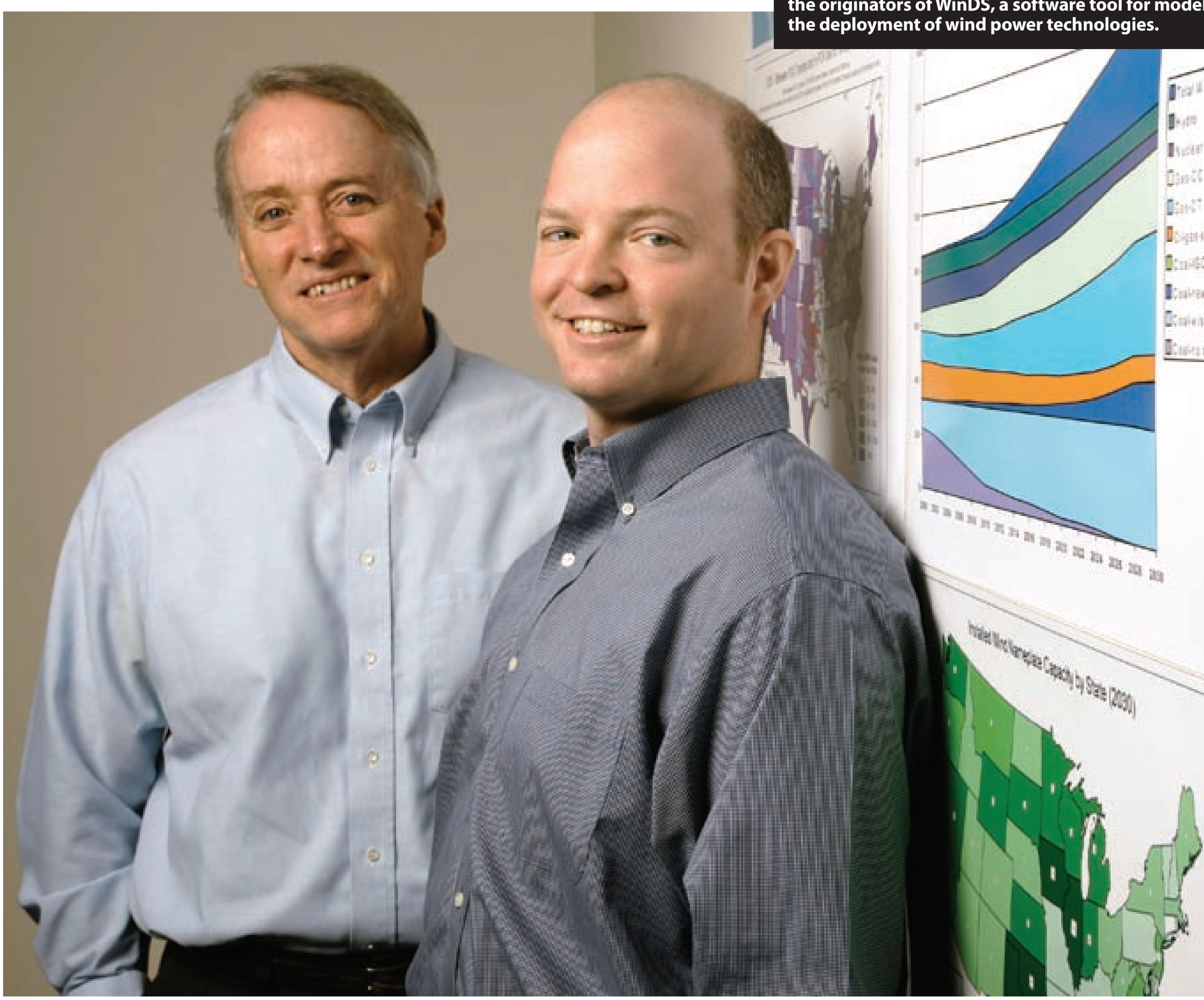
An NREL computer model shows us how and where to use the wind energy systems of the future, and more.

At NREL, as in other research centers, every scientific discovery starts out as a theory. But before that theory can be tested, one R&D process is necessary to make sure the glimmer in the theorist's eye is even feasible: analysis.

NREL's strategic energy analysis capability is one of the laboratory's core competencies and a must-have element of every technology development process. But because analyses are often only as good as the tools the analysts have to work with, key models need to be designed to produce credible, reliable analyses that support NREL's research.

NREL analysts Walter Short (left) and Nate Blair are the originators of WinDS, a software tool for modeling the deployment of wind power technologies.

PIX15032



An analysis model starts with a software capability carefully programmed to make use of various inputs to produce a variety of outputs. Although many good energy models exist that different analysts and organizations use throughout the world, customized models are often required to meet individual researchers' needs. NREL discovered such a need while preparing to expand research in wind resources and to examine how to increase the amount of installed wind power capacity in the United States.

Starting with a Spreadsheet

What started out as a spreadsheet on one analyst's laptop has become one of the most credible models for projecting wind power capacities and energy deliveries for the future, and it has a name to match: the Wind Deployment System, or WinDS.

The WinDS concept became reality in 2001 when NREL's Wind Technologies Program requested an analysis of the feasibility of low-speed wind turbines in the United States by evaluating load and transmission requirements. NREL's Walter Short, a group manager in NREL's Strategic Energy Analysis Center, started with a simple spreadsheet model that drew on the geographic information systems expertise of NREL Scientist Donna Heimiller.

Short then took the spreadsheet and spent countless hours, along with an intern from the Colorado School of Mines, to develop the first version of WinDS. The model was able to find the optimal value for wind power capacity based on the wind resource, the available transmission lines, and the electrical load requirements. Short was soon joined in the effort by NREL Analyst Nate Blair, who provided his insights based on other analysis tools, while Heimiller helped to beef up the geographic aspects of the model.

The result was a new model unique in its ability to "regionalize." The model provides a solid, detailed analysis of wind that goes far beyond more simplistic models that consider only a few regions in the United States. The new regionalization capability makes it possible to evaluate numerous site-specific wind resources.

"The modeling capability provided by WinDS is unique in the field," says Bobi Garrett, NREL associate director for Strategic Development and Analysis. "The major national models cannot deal with the wide variation in regional energy resources, demand, policy, or physical infrastructure."

In developing WinDS, NREL sought significant input from a variety of wind industry professionals and other relevant researchers. Short took a direct approach, determining what characteristics would be important to capture—such as transmission access and wind resource variability. Taking all these things into consideration, he applied them to all 358 regions designated in the model.

After further testing and expansion, Short began demonstrating WinDS for other labs. As word got out, nonprofit groups and industry representatives alike became interested in applying the WinDS model to their analysis work.

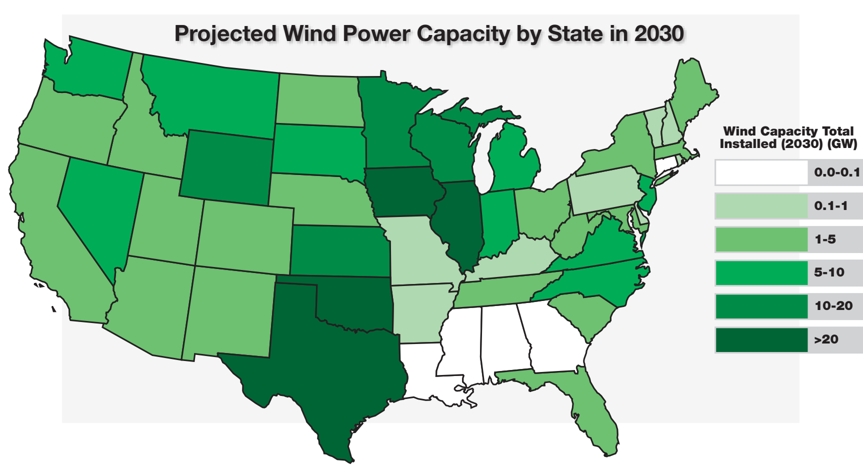
Enabling a National Action Plan

WinDS' regionalization capability is what distinguishes it from other models, such as the National Energy Modeling System. Most capacity expansion models do not have significant geographic capabilities and so cannot track the geographic dispersion of the installed wind energy or estimate transmission costs as penetration levels increase.

WinDS considers key market issues such as transmission system access and cost as well as the reliability of the wind resource. It can determine variability in wind output over time and consider inputs for ancillary service requirements and costs for the 358 individual regions. The model estimates the market potential of wind energy in the United States for the next 20 to 50 years under different technology development and policy scenarios, and it has already yielded important insights.

WinDS' innovative approach to modeling the potential deployment of wind energy addresses many of the shortcomings of large national energy models' representation of the competitive potential of wind energy.

"Many national models rely on assumptions and oversimplify wind energy," says NREL Project Leader Brian Parsons, who works in NREL's Wind Technologies



The WinDS model can examine where wind power will be developed under various scenarios. In this example, which shows one scenario for achieving 20% wind power by 2030, much of the wind power capacity is concentrated in the U.S. heartland.

Program. "This model's attention to detail has ensured accuracy in characterizing technologies and credibility for these numbers."

After President George W. Bush called for producing 20% of the nation's electricity from wind power by 2030, the American Wind Energy Association (AWEA) partnered with DOE and other stakeholders to develop a wind resource action plan. The plan required an analysis of the benefits of, and barriers to, wind production, as well as where transmission would be needed, an analysis that WinDS was able to provide in detail. Using WinDS, the team is analyzing the feasibility and economics of reaching the 20% goal.

"Wind industry and policymakers are very interested in knowing how much U.S. electricity can come from wind, and the WinDS model has proven to be an indispensable tool to evaluate this question," says Rob Gramlich, AWEA policy director. "We have learned a great deal from the model thus far and look forward to sharing these results with policymakers and the energy industry this spring."

NREL has demonstrated WinDS' ability to answer important deployment questions, highlighting transmission possibilities and where resources need to be built. For instance, WinDs uses the 358 regions in its system to show the locations of cumulative wind-power installations needed in 2050 under certain scenarios. As expected, the results show the installations located in areas with excellent wind resources. However, WinDS also shows how it makes sense to locate installations close to major load centers, such as in southern California.

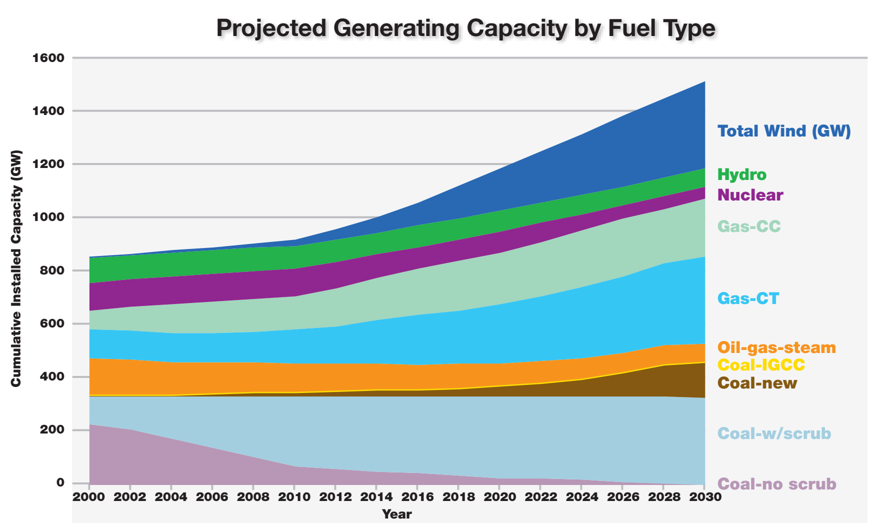
Addressing Specific Markets and Issues

Another practical application of WinDS was an analysis done in 2006 to evaluate the market impacts of specific state-level policies. The analysis looked at national and regional wind energy deployment and generation through 2050 and examined impacts on wind growth associated with state-level renewable portfolio standards (RPS). These standards require utilities to generate a certain percentage of their electricity from renewable energy resources, and wind power is currently the preferred choice. The analysis examined the effects of increased penalties for failing to meet the RPS requirements and also examined other mandates and tax credits.

"The analysis showed that these mandates increase industry size and lower costs, which results in wind capacity increases in states without the rules, and greater market growth even after the policies expire," says Blair. "Although the policies are enacted by individual states, the cumulative effect must be examined at a national level."

Another WinDS analysis examined several potential energy policy cases and how they could affect the U.S. market for wind power, including issues related to the penetration of wind energy technologies into the electricity sector. Principal market issues analyzed included access to and cost of transmission as well as variability. WinDS modeled the impact of various policy initiatives, including a wind production tax credit and an RPS.

The line for WinDS assistance doesn't stop there. The Bureau of Land Management (BLM) also used WinDS outputs within their programmatic environmental impact statement for wind power on the public land that the BLM manages in western states. WinDS was used to forecast the amount of land in the West that could be economically developed. NREL has provided additional results to the National Research Council, General Electric, and other groups interested in the regional-level analysis provided by WinDS.

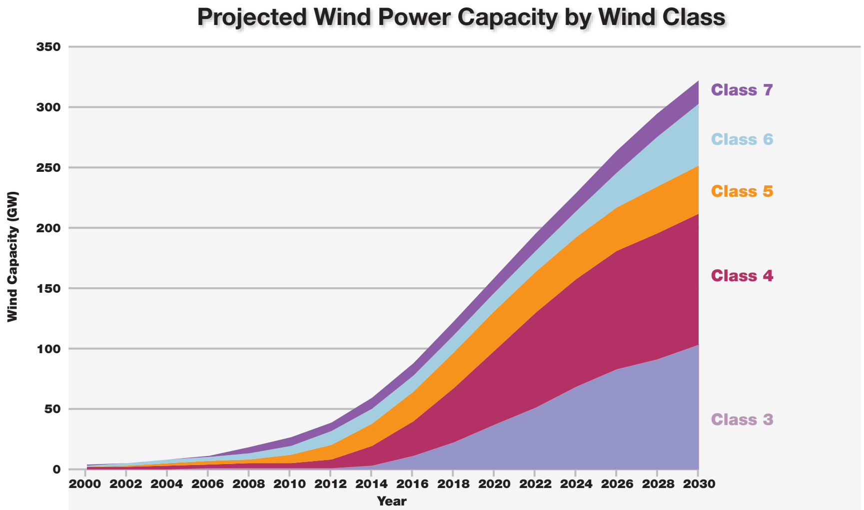


The WinDS model can examine how wind power will compete with other generating technologies under various policy scenarios. This example shows one path toward achieving 20% wind power by 2030, and shows wind competing with a strong growth in natural gas combustion turbine and combined-cycle technologies. The projection shows coal power growing slightly as the industry shifts to cleaner technologies, like integrated gasification and combined-cycle plants, while the generating capacity from oil, nuclear, and hydropower sources declines.

Modeling the Wind, and More

Success increases demand, and many people are hoping that WinDS will be able to do even more modeling in the near future. And NREL analysts have already applied WinDS' unique system to models for other technologies, such as concentrating solar power and hydrogen.

"The capabilities of WinDS have raised



Assuming that the nation will reach 20% wind generation by 2030, this output from the WinDS model shows an increasing need to make use of class 3 and class 4 wind resources—considered "fair" to "good" resources—in the future, following significant near-term exploitation of the "superb" class 7 wind resources.

some awareness within the modeling community of more sophisticated approaches to incorporating wind and other renewable energy technologies into their models," says Sam Baldwin, chief technology officer in DOE's Office of Energy Efficiency and Renewable Energy. "This innovative work also has been extended to hydrogen and solar and is already having a fundamental impact on understanding the potential of renewable energy in the broader market."

For example, the Hydrogen Deployment System, or HyDS, model looks at U.S. market expansion of hydrogen production from wind and other sources over the next 50 years, evaluating future roles and contributions. With the current emphasis on production, it is important to look at the feasibility of producing hydrogen from three competing technologies: wind, steam methane reforming, and distributed electrolysis powered by electricity from the grid. The model has to consider the interconnection between wind and hydrogen as well as hydrogen storage and transportation issues. The resulting data are helping to shape DOE's R&D approach.

WinDS can also measure the interaction between electric and transportation technologies, such as analyzing the benefits of plug-in hybrid-electric vehicles (PHEVs). A PHEV can recharge its batteries with electricity from the electric utility grid. The vehicle can then drive with less gasoline or other alternative liquid fuels such as biofuels or hydrogen. PHEVs have recently emerged as a promising alternative for displacing a significant portion of fleet petroleum consumption.

Using WinDS, NREL analysts carried out a study of PHEVs that can be charged from or discharged to the grid. They found a synergism between PHEVs and wind energy, indicating that the electricity storage capacity of these vehicles can make a difference in the cost-effective wind capacity for the United States.

Finally, the WinDS model is being extended to other renewable electric technologies. The first of these is concentrating solar power, specifically, parabolic trough power plants equipped with six hours of thermal energy storage. Thanks to the lessons learned in constructing the wind features in WinDS, the extension of the model to concentrating solar power was relatively easy, and the new Concentrating Solar Deployment Systems model is already being put to good use.

WinDS of the Future

Although WinDS currently focuses exclusively on the electricity sector, future goals include examining electricity storage options, transmission power flows, carbon sequestration, energy storage, coal plant siting, and a full complement of renewable energy resources, including biomass, geothermal, and ocean energy. With such improvements, WinDS could be used to examine the synergies among renewable energy technologies and analyze such policies as climate change legislation or a national RPS.

One of the items at the top of many modelers' wish lists—especially Short's and Blair's—is for analysts all over the world to put their model's results to work in other analyses. To achieve that goal for WinDS, Short and Blair are currently refining a supply curve that can be used as an input into other models, providing a more sophisticated method of examining the transmission and variability issues associated with wind energy.

NREL is also working with modelers and analysts from a variety of organizations to examine the differences in various energy models. These experts, who have formed the Renewable Energy and Efficiency Modeling and Analysis Partnership, are conducting workshops to look at how outputs differ among the modelers in the group. By looking at these differences, they hope to create common scenarios for all models and improve their ability to evaluate policy decisions. And as these collaborative efforts grow, so does the laboratory's reputation.

"What started out as a single model for a single technology has grown into a suite of leading-edge models," Garrett says. "WinDS has taken NREL from a position of little recognition for its modeling ability to broad acknowledgment for a credible capability." ■

Next-Generation Fuels—What's Old Is New Again

In the search for new biofuels, NREL is reviving its research into biomass pyrolysis and gasification, as well as techniques for converting algae into biodiesel.

Al Darzins has been at NREL for less than 2 years, but finds himself spending a lot of time these days looking at research results from some of the laboratory's earliest research. As group manager for the National Bioenergy Center's Applied Sciences Group, he is overseeing several "new" research efforts that build on some very old ones. His efforts are aimed at converting biomass—plants and plant-derived materials—into fuels.

"Previous biofuels work performed at NREL under various programs has provided a strong foundation for our current efforts to kick-start that research again, ten years later," says Darzins.

When the laboratory first opened in 1977, the Arab Oil Embargo of 1974 was still fresh in people's minds. Early research included several different potential technologies for making liquid transportation fuel from biomass. Some of those, while promising, were subsequently set aside to focus on other research.

Today, with reducing dependence on imported oil a high presidential priority, three of these technologies—the production of pyrolysis oil, liquefied synthesis gas, and microalgal oil—are once again attracting a lot of attention. Darzins and his NREL colleagues are excited about moving forward with them, taking advantage of both our past research efforts and of applying new research capabilities to them.

Borrowing a "Clean Coal" Technology for Ethanol Production

Coal was once the transportation fuel of choice for the United States, powering our trains and even fueling an early automobile, the Stanley Steamer. But liquids and gases burn faster than solids, have high energy densities, and are more convenient to use in vehicles, all of which are reasons why gasoline and diesel fuel became the dominant transportation fuels.

Because of these advantages, it can be well worth expending energy to convert solid fuels—whether they be biomass or coal—to liquids. By heating biomass to very high temperature with limited or no oxygen, researchers can either liquefy or gasify it. When biomass is liquefied, the resulting pyrolysis oil can be used as a feedstock for conventional oil refining. When it is gasified, the synthesis gas can be catalytically converted to liquid fuels that substitute well for diesel or gasoline.

In fact, the pyrolysis and gasification technologies used for converting biomass to liquids were initially applied to coal to produce petroleum substitutes. With a strong utility interest in integrated gasification and combined-cycle technologies for coal power (so-called "clean coal" technologies), gasifier technology has advanced significantly.

While the core technology has advanced, biomass pyrolysis and gasification are gaining renewed interest in part because of the emphasis on producing ethanol from cellulosic biomass, such as wood chips and plant leaves and stalks. Cellulosic biomass is made up of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are plant-derived, sugar-based polymers, and biological biomass conversion technology can ferment the sugars to ethanol. But lignin, the third major component of biomass—making up 15% to 25% of biomass by weight—does not contain sugars.

PIX12684

Biomass pyrolysis involves heating the biomass to high temperature in the absence of oxygen. The process yields vapors that are condensed to form an oily liquid.

Until recently, NREL's process designs for ethanol production called for burning the lignin to provide heat and power for the ethanol plant. But with transportation fuels as a top priority, the new thought is to use multiple technologies to produce fuels. Because thermochemical processing can produce fuels from any biomass source, not just sugars, researchers can use it to convert the lignin and any other residue from biological processing to additional ethanol or other liquid fuels within the same biorefinery.

Also, biological processing is currently focused on agricultural residues such as cornstalks and husks. Other biomass—particularly softwoods, which may become extensively available from forest thinning operations—is more challenging for fermentation and may be more suitable for pyrolysis or gasification.

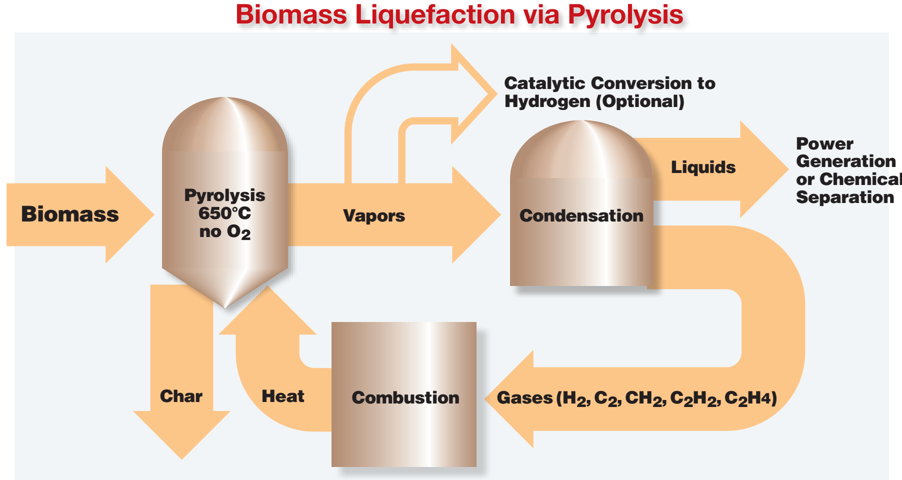
NREL Goes Full Circle on Pyrolysis Research

NREL's research on biomass pyrolysis has returned to its roots. Pyrolysis involves liquefying biomass by first heating it to about 550°C in the absence of oxygen and then condensing the vapors. The resulting pyrolysis oil is a complex mixture analogous to crude oil (except that it contains oxygen) and can be burned as fuel or used as a feedstock for conventional oil refineries.

NREL's original pyrolysis research had that direct product as its objective, but in the late 1980s, the laboratory turned its focus to making specific fuel additives or other petrochemicals from pyrolysis vapors before they condensed. NREL researchers worked on cracking the vapors to ethylene for gasoline production and then on catalytically converting them to aromatics and other liquid hydrocarbons.

In the 1990s, when Scientist Stefan Czernik joined NREL as a thermal and catalytic conversion specialist, the emphasis changed to producing chemical products other than fuels. One effort, for example, sought to develop wood adhesives from pyrolysis oil, a natural fit for reducing petrochemical use by an industry with ready access to biomass resources. Another effort sought to regenerate base chemicals for plastics production by pyrolyzing polymers, specifically from discarded carpeting. Now Czernik is heading up efforts to use

Biomass Liquefaction via Pyrolysis



Biomass pyrolysis involves heating the biomass to high temperature in the absence of oxygen. The process yields vapors that are condensed to form an oily liquid.

the whole pyrolysis oil along the lines of NREL's original pyrolysis work.

"The goal is to make pyrolysis oil a standard petroleum refinery feedstock," says Czernik.

One project is exploring the suitability of pyrolysis oil derived from lignin for such a feedstock. NREL produces the pyrolysis oil and research partners at DOE's PNNL and UOP LLC, a private petroleum research company, hydrotreat it, that is, they upgrade it by removing impurities. Among other things, the process removes oxygen, which is the primary difference between pyrolysis oil and crude petroleum.

NREL is conducting techno-economic and life-cycle analyses of the biorefinery pathway involving lignin pyrolysis and hydrotreating to determine how profitable it will be, what kinds of energy and environmental impacts it would have, and what changes could be made to most effectively improve that profitability and impact.

A second project seeks to upgrade pyrolysis oil during its production by reacting either the condensed oil or the oil vapors with ethanol. Researchers expect this process to reduce the acidity of the pyrolysis oil and make it more stable, both of which would improve its suitability as an oil refinery feedstock.

Because of the potential for either hydrotreating or ethanol upgrading, or a combination of both, the future for pyrolysis oil appears bright.

"We think pyrolysis is a powerful technology and are eager to use it to help meet transportation fuel needs," says Czernik.

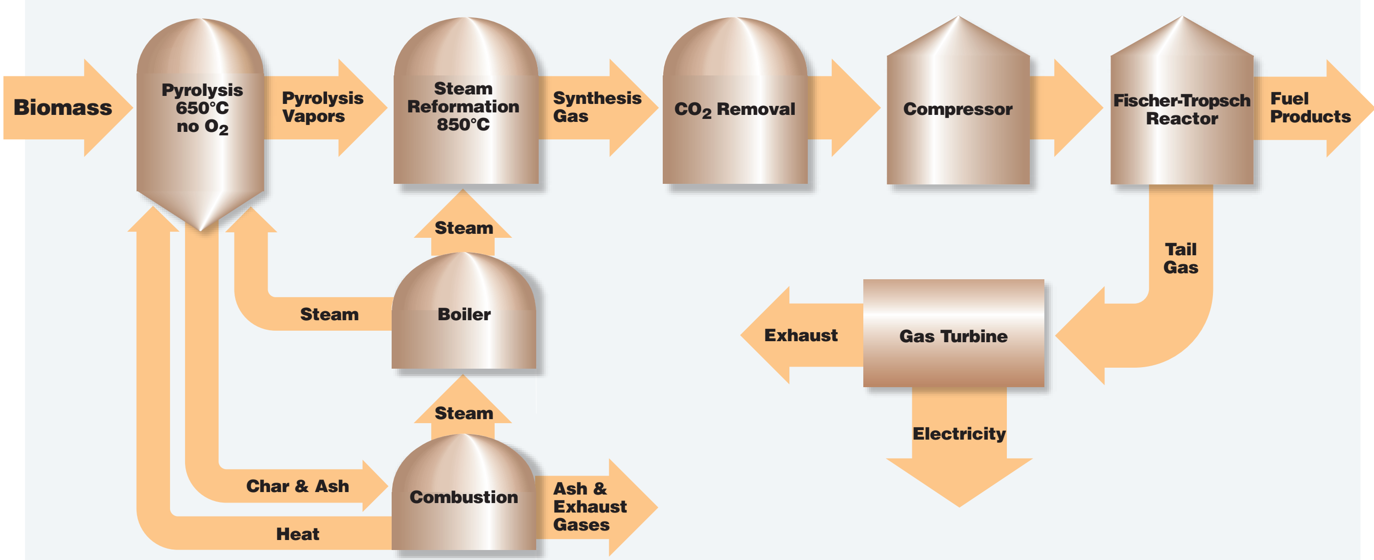
The Three-Phase Approach to Fuels: From Solid to Gas to Liquid

Another approach to converting solid biomass into a liquid fuel is to first convert it into a gas. NREL scientists gasify biomass to a mixture of carbon monoxide and hydrogen known as synthesis gas or syngas by taking the pyrolysis process a step further, heating to about 850°C with about one-third the oxygen needed for efficient combustion.

In the 1990s, syngas was envisioned primarily as a fuel for electrical power generation, with a focus first on large utility systems and then on smaller distributed generation systems. The shift from electricity production back to liquid fuels is in large measure a tribute to the great gains made by wind turbines, solar cells, and other renewable energy technologies for power generation. When it comes to liquid transportation fuels, however, biomass is the only renewable game in town.

Conversion of syngas to liquids also has a colorful and somewhat dark history. Franz Fischer and Hans Tropsch first studied conversion of syngas into larger, useful organic compounds in 1923. Using syngas made from coal and metal catalysts, they were able to produce liquid hydrocarbons. Fischer-Tropsch systems were used successfully in Germany during World War II and South Africa during apartheid embargoes when each faced limited oil supplies. Several commercial Fischer-Tropsch operations continue today, and the term Fischer-

Biomass Gasification via Staged Steam Reformation with a Fluidized Bed Gasifier



Biomass gasification is a multi-step process that starts with pyrolysis, followed by a high-temperature steam treatment that converts the pyrolysis products into a mixture of gases, called synthesis gas. After a treatment step, the gas is compressed and fed into a catalytic reactor to produce a liquid fuel. A byproduct from the process can be used to generate electricity.

Tropsch has come to be applied to any catalytic conversion of syngas to liquid fuel.

The NREL syngas-to-liquid system bubbles the gas through an oil slurry under high pressure, with the catalyst suspended in the liquid. While traditional Fischer-Tropsch processes seek to produce non-oxygenated hydrocarbons, NREL's objective is to produce ethanol or perhaps "higher alcohols"—a mixture of ethanol and larger-molecule alcohols.

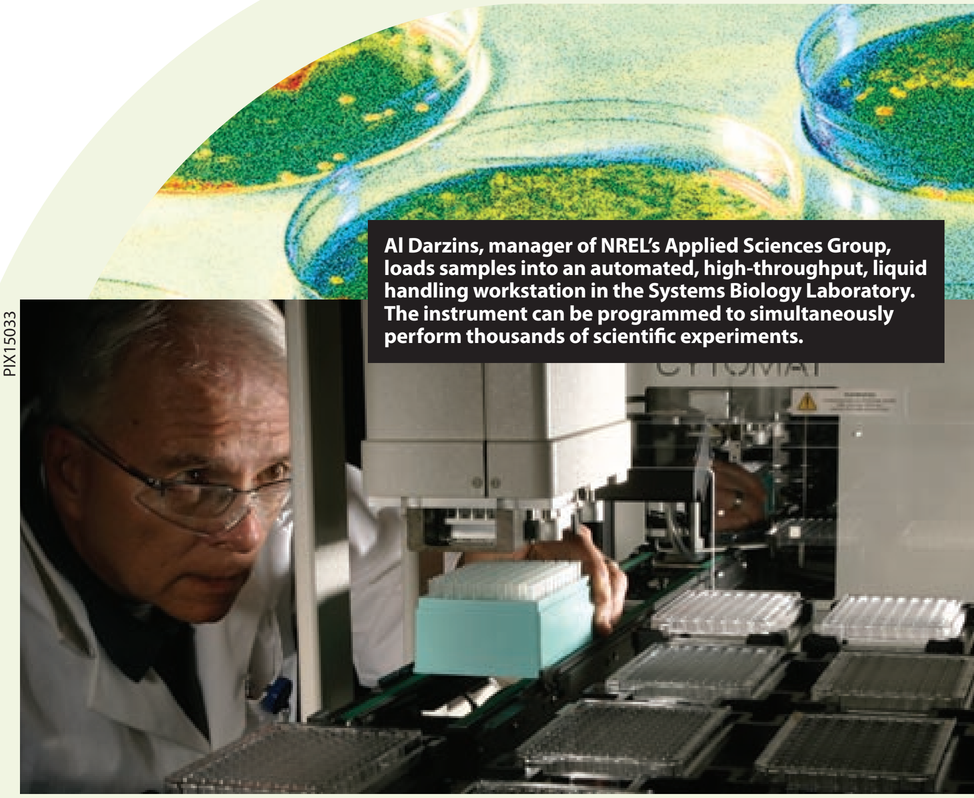
"The process is similar to Fischer-Tropsch or methanol reformation," says NREL Scientist Steve Deutch, "but we stop it at an earlier stage."

Producing ethanol from syngas would be an ideal companion technology for a biorefinery that ferments biomass into ethanol because the syngas process would produce ethanol from material that cannot be fermented, such as lignin. Because both processes would produce ethanol, the approach would avoid the need for additional infrastructure to deliver another product, such as a lignin-derived chemical.

NREL is currently working with DOE's PNNL on a joint effort to produce alcohols from syngas. PNNL is working to improve the catalyst, while NREL is focusing on improving the process conditions and testing the catalyst and process against a wide range of operating conditions, using actual syngas derived from biomass.

Microalgal Lipids—An Aquatic Approach to Future Fuels

Yet another early biofuel research area that is back in the spotlight is the conversion of algae to fuels. Although small in size compared to cellulosic ethanol efforts, the NREL research effort on fuels from algae involved extensive research through the 1980s and early 1990s. NREL's biomass researchers led the way in developing technology for growing



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Al Darzins, manager of NREL's Applied Sciences Group, loads samples into an automated, high-throughput, liquid handling workstation in the Systems Biology Laboratory. The instrument can be programmed to simultaneously perform thousands of scientific experiments.

New Lab Provides Powerful Tools for Biocatalyst Development

Be it microscopic algae for oil production, fungi for enzyme production or yeast or bacteria for sugar fermentation, the advanced biological technology for converting biomass to fuel is all about developing organisms that produce better biochemical agents or better perform desired functions themselves. NREL's bioconversion research capabilities have been greatly enhanced by opening of a major new facility. Applied Sciences Group Manager Al Darzins says the new Systems Biology Laboratory has three main components.

"New X-ray crystallography equipment allows us to determine the three-dimensional structure of enzymes, a key parameter required in understanding how they work," says Darzins. "This information also allows us to make them perform better. High-throughput robotics capabilities allow us to rapidly test large numbers of genetic variants or simultaneously conduct hundreds and even thousands of 'miniature experiments' in a single day.

"And 'omics' tools provide a three-part fundamental 'cataloguing' of the capabilities of a particular biocatalyst organism. Genomics allows one to identify all of the genes that are expressed within an organism. Proteomics identifies all of the enzymes or other proteins that an organism produces and metabolomics identifies all of the small molecule metabolites that an organism produces during growth. With these research tools, our researchers now have dramatically enhanced capabilities from just a few years ago for developing new strains to carry out desired biomass conversions."

NREL has been acquiring some of the new equipment over the last couple years and now has it all set up in a superb facility in two new laboratories in the Field Test Laboratory Building. The new Biology Systems Laboratory is a great complement to the recently opened Biomass Surface Characterization Laboratory.

"Together they arm NREL biomass conversion research efforts with the best tools available, and we look forward to using them to making key advances in the biofuels area," says Darzins. ■

NREL researchers were able to draw on the laboratory's extensive culture collection to develop strains of algae with high levels of lipids.

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microalgae that produce high levels of lipids (oils) for processing into biodiesel. NREL developed an extensive microalgae culture collection as well as a toolkit for the genetic engineering of these organisms. NREL Analyst John Sheehan, who managed the last few years of the microalgae program, cited economic factors for its being set aside.

"In addition to having to compete with 57-cent-per-gallon diesel at the time, one of the main reasons for dropping the microalgae program was realizing that even using simple outdoor ponds, the capital cost of facilities for growing the microalgae would always keep the technology relatively expensive," says Sheehan. "Today, however—in addition to dramatically higher petroleum diesel cost—low plastic container cost makes the possibility of growing the algae in closed systems such as transparent tubular reactors a very realistic possibility and is making the technology much more attractive again."

NREL Scientist Eric Jarvis, a genetic engineering specialist, is especially excited about the possibility of restarting microalgae research because of new capabilities developed since the mid-1990s.

"The metabolic engineering we did to try to make microalgae produce more lipids was cutting edge at the time," says Jarvis, "but the whole field of genetic engineering has advanced so dramatically since then that we will now have far greater ability to improve the organisms' performance." (see "New Lab" sidebar on page 23).

Another exciting reason for reestablishing microalgae research is the possibility of developing a new end product. Rather than converting the microalgal oil to biodiesel, it is possible to chemically convert it to jet fuel. The same hydrotreating process that could make pyrolysis oil a good oil refinery feedstock could also convert microalgal oil into kerosene, the basic component of jet fuel.

Jet fuel now accounts for about 8% of our petroleum use and no renewable alternative has been developed to this point. Ethanol is not dense enough, having only about half the energy per volume of jet fuel. Biodiesel has about 80% the energy density of kerosene, but can solidify at the low temperatures of high altitude flight.

Industry is very interested in this process because it could utilize existing hydrotreaters in the nation's oil refineries. A likely R&D participant is the U.S. Department of Defense, which is seeking a non-petroleum replacement for military jet fuel.

Darzins likes to characterize all of these research efforts as developing "next-generation fuels."

"They will probably never be as large as our ethanol or hydrogen research programs, but they could lay groundwork for key contributions to meeting our transportation energy needs," says Darzins. "Knowing that NREL has a running head start on them because of our past research says a lot about the value of our broad and continuing commitment to meeting transportation and other energy needs with renewable energy." ■

Capitalizing on the Nation's Investment

As the preceding pages illustrate, NREL's scientists and engineers are engaged in innovative research and development that is changing the way energy is created and used. However, research and development is only part of what we do. To effectively pursue our mission and take on the nation's energy challenges, it is critical that NREL's technological advances and solutions reach the marketplace in a timely manner. Through our numerous collaborations with industry, we ensure that our research and development is properly focused and market relevant. Our alliances with companies, universities, and other federal laboratories also increase the knowledge base and innovative capacity of NREL's technical staff, allowing us to better capitalize on the national investment in NREL's important work.

PIX14691

NREL worked with Northern Power Systems to develop a 1.5-megawatt direct-drive generator for wind turbines, shown here during testing at NREL's National Wind Technology Center.

Each year NREL's world-class staff works with industrial, academic, and government organizations on literally hundreds of projects. In addition to our collaborative projects, we test and validate technologies using our expertise, facilities, and equipment; prepare focused informational reports using our knowledge of state-of-the-art, clean, energy-related technologies; share NREL-developed software tools with the broader community; and license our patented technologies to entrepreneurial and established companies.

Any of these technology transfer mechanisms can lead to the creation of new enterprise opportunities for business growth and development, and accelerate the transition of NREL-developed technologies to the marketplace. "Accelerate" is a key word for us—our nation's energy challenges are immense and immediate, and we must rapidly move technologies out to our industrial partners in order to increase our nation's energy security, reduce the environmental impacts of energy use, and bolster U.S. competitiveness and productivity.

PIX11977

Every other year, NREL helps to sponsor and manage the Solar Decathlon on the National Mall. The event encourages university students to incorporate the latest technologies into small solar-powered, energy-efficient homes.

The examples presented in this issue of the *Research Review* are but a snapshot of our research and development projects that will lead to technology transfer activities. Technology is continually being transferred between NREL staff and the dozens of outside parties with which we interact. And it is not just a one-way flow, but a two-way exchange of ideas, problems, and solutions through individual and collective innovation. That is how we work: always with the goal of moving new concepts and technologies from the laboratory to applications that benefit society.

For more details on NREL's technology deployment and commercialization activities, visit our Technology Transfer Web site at **www.nrel.gov/technologytransfer/** and pick up a copy of our inaugural Technology Transfer Report, due out in late summer 2007. ■

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