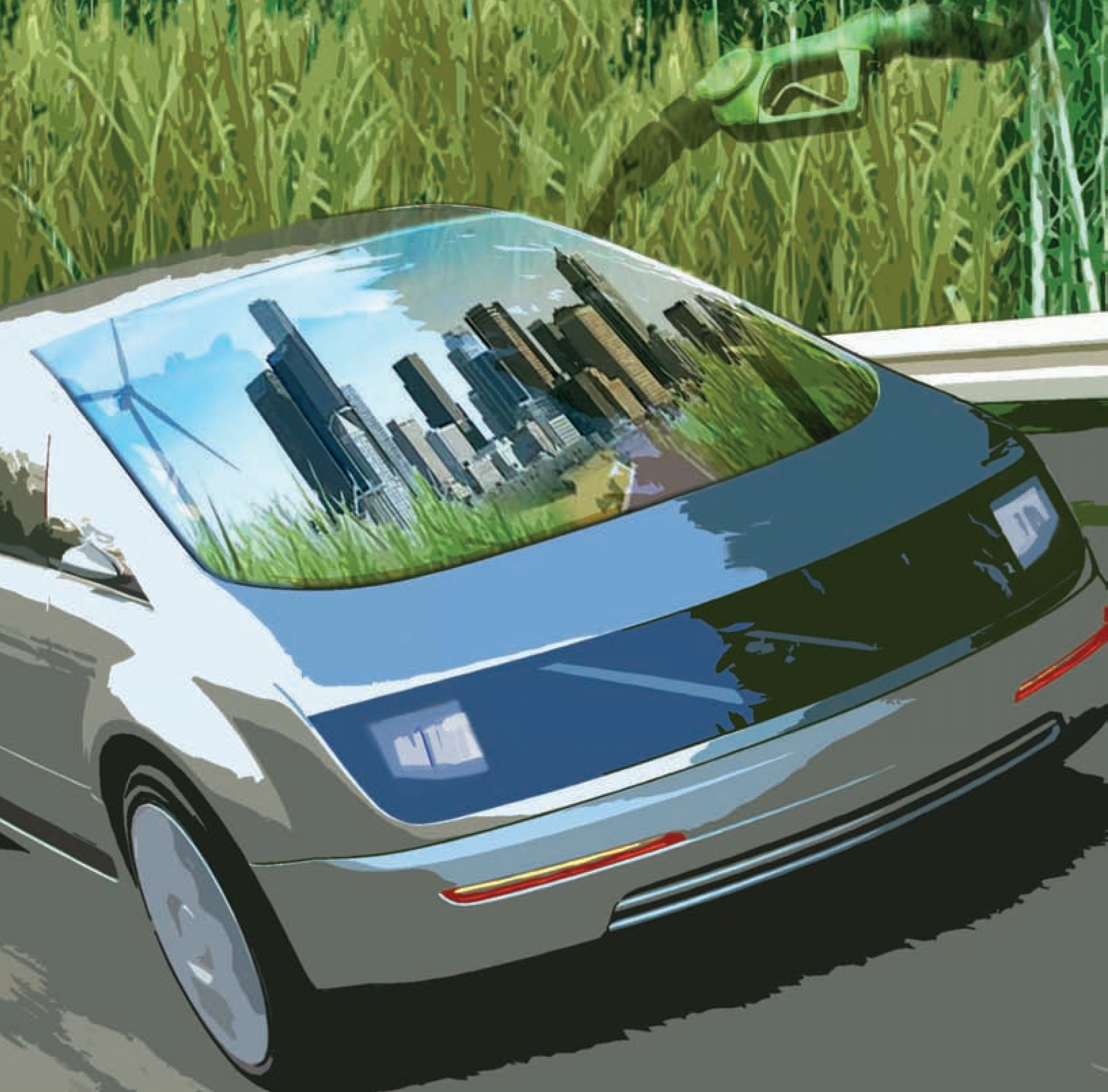
NREL National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

National Renewable Energy Laboratory
2005 Research Review



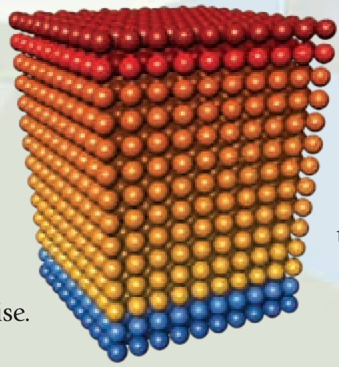
June 2006
ISSUE **4**
a publication about NREL R&D highlights

CONTENTS

feature

departments

articles



The National Renewable Energy Laboratory is operated by Midwest Research Institute and Battelle for the Department of Energy's Office of Energy Efficiency and Renewable Energy. 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 NREL *Research Review* staff includes Howard Brown, Don Gwinner, Molly Miller, and Paula Pitchford, writers, and Ray David and Al Hicks, graphic designers.

Perspective

PIX006943/Warren Gretz

Dr. Stanley R. Bull, Associate Director, Science & Technology

Securing Energy for the Future Through Science and Technology

Science and technology. They are at the heart of everything we do at the National Renewable Energy Laboratory, as we pursue innovative, robust, and sustainable ways to produce energy—and as we seek to understand and illuminate the physics, chemistry, biology, and engineering behind alternative energy technologies.

Although our nation is learning to use energy more wisely—for example, by producing and buying more energy-efficient vehicles and appliances—the demand is still great. Americans consumed 99.7 quadrillion Btu (quads) of energy in 2004; the Energy Information Administration projects that this will increase to 127 quads by 2025.

In his 2006 State of the Union address, President George W. Bush noted the seriousness of the situation and pointed the way to a remedy. The President said, "Keeping America competitive requires affordable energy. And here we have a serious problem: America is addicted to oil, which is often imported from unstable parts of the world. The best way to break this addiction is through technology."

With our emphasis on research and development in market-relevant, domestic energy technologies, NREL is working toward a long-term solution to this problem. In this issue of the NREL *Research Review*, we present three stories that highlight recent advances and future directions in areas the President particularly noted in his Address: biofuels and vehicles, energy-efficient buildings, and solar energy.

Biofuels and Vehicles—The alternative fuels industry is helping to reduce our dependence on imports by introducing more domestic ethanol and biodiesel options into the transportation fuels market. This issue describes NREL's contributions, which include expanding feedstock sources, developing methods for breaking down feedstock for further processing, and making conversion methods for fuels and other products more efficient and cost effective.

The President proposes to "fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years." Through the Advanced Energy Initiative, we will continue working toward this important goal in feedstock development and conversion methods.

Buildings—Our buildings consume nearly 40% of the energy Americans use each year. NREL's buildings research and development demonstrate that it is possible to design and construct attractive residential and commercial buildings that are much more energy efficient than the current standard practice. Our work also develops good ways to integrate renewable energy technologies into these buildings.

The President's Advanced Energy Initiative will invest in renewable energy technologies that "change how we power our homes and offices." In this way, we can continue to assist the U.S. building industry in constructing energy-smart, "high-performing" buildings, like the ones described in this issue.

Solar Energy—As part of NREL's research and development in photovoltaics, our scientists work closely with other expert groups to investigate and improve the way in which solar cells directly convert sunlight to electricity. The President's Solar America Initiative will support the development of solar cells that convert the sunlight much more efficiently than they do now.

Work in high-efficiency solar cells is one of many relevant areas of solar research conducted at NREL. In the article in this issue, we discuss the basic rationale of multijunction cells and some innovative twists on their design that can boost efficiencies to higher levels.

From NREL's inception in 1977 to the present, the science and technology of alternative energy has been the core of our mission. And this will continue in the decades to come. The advances we make in all areas of renewable energy and energy efficiency will play a vital role in assuring the security, strength, and competitiveness of the nation.

NREL In Focus

Bill Glover Is New NREL Deputy Director and COO

PIX14712/Mike Linenberger

Deputy Director and Chief Operating Officer Bill Glover

On February 1, 2006,NREL welcomed William (Bill) Glover as the Laboratory's new Deputy Director and Chief Operating Officer. "I'm glad to be here," he said. "I'm very excited about the Lab's mission and I am looking forward to working with everyone at NREL."

Bill has had more than 35 years of executive-level experience. His extensive experience with the Department of Energy (DOE) has included senior management responsibilities in standards identification and management, self-assessment and independent oversight, quality assurance, performance measurement and evaluation, and readiness reviews. He was on a headquarters level group overseeing the rollout of DOE's Standards Program, and he led a facilities maintenance program assessment team at Los Alamos National Laboratory.

Before joining NREL, Bill was an independent consultant, President/General Manager of TENERA Federal Services LLC, and Director of Performance Assurance with EG&G, Rocky Flats. He served with distinction for 26 years in the United States Navy, including managing a nuclear submarine squadron with more than 3,500 personnel.

Bill has a B.A. in chemistry from the University of Rochester and the equivalent of an M.S. in nuclear engineering (from the Navy Senior Officer Nuclear Power Training).

As Chief Operating Officer, Bill will oversee Laboratory operations. As Deputy Director, he will support the development and implementation of the Laboratory's operational strategic vision. He will also serve as a vice president for Midwest Research Institute, which has operated and managed NREL for DOE since NREL opened as the Solar Energy Research Institute in 1977.

New Colorado Research Partnership Formed to Develop Fuel Cells

Power generation in the 21st Century faces some tough challenges: it has to score very high in energy efficiency and, at the same time, very low in environmental impacts. Right now, the fuel cell is one of the few technologies that appears to do both these things at once.

PIX14679/Ray David

The new joint-venture Colorado Fuel Cell Center is housed at the Colorado School of Mines a few miles away from the NREL campus.

So, to help bring advanced fuel cell technologies to the marketplace, NREL has formed a partnership with the Gas Technology Institute, the Colorado School of Mines (CSM), and Versa Power Systems. Their joint venture, known as the Colorado Fuel Cell Center (CFCC), is focusing on fuel cell research, development, testing, and commercialization in a state that is home to several related high-tech industries.

The new center is housed in the General Research Laboratory at the Colorado School of Mines in Golden. The Colorado Governor's Office of Energy Management and Conservation has provided $2 million in start-up funding, and the partners are contributing $1 million. The CFCC aims to provide state leadership in the development and application of fuel cell technologies, increase the public's understanding of the technologies through education and outreach activities, and foster economic development through partnerships with local businesses.

The CFCC will also coordinate the development of fuel cell R&D programs, facilitate access to experts in NREL and CSM research labs, assist in forming strategic alliances among local developers and university research centers, and serve as an independent testing agency. In addition, the center will promote the development of fuel cell curriculums in colleges, universities, and trade schools in order to build a technically viable labor force for this young industry.

The tremendous growth expected in the fuel cell industry in the coming decade will mean new high-tech jobs in R&D and in manufacturing that will eventually extend well beyond Colorado and the industry itself.

At the end of two years, the CFCC should be self-sustaining through research and development contracts, consulting agreements, and other sources of funding. The center will then emphasize the development of the Colorado fuel cell industry as it responds to national solicitations. For more information, contact CFCC Executive Director Robert J. Remick, rremick@mines.edu.

NREL Computing Power Surpasses Teraflop

NREL's high-performance computing capability recently surpassed the peak-performance mark of 1 teraflop—or one trillion floating point operations per second. "We've gone from 96 gigaflops of power to 1.2 teraflops in less than four years," said Steve Hammond, director of NREL's Computational Sciences Center (CSC), highlighting this significant milestone in building high-performance computing expertise and capabilities at the Laboratory.

This increase in high-performance computing capability greatly aids scientific pursuits. For example, researchers in the Buildings & Thermal Systems Center have run computational fluid dynamics models of their novel patent-pending tab-fin heat exchanger without building expensive, time-consuming prototypes. Simulations help optimize the geometry by considering numerous different tab sizes and placements, leading to a design with the best performance.

Scientists in the National Bioenergy Center have likewise benefited. By using CSC's quantum mechanical modeling, they have investigated the loss of fermentable sugars during biomass pretreatment. The increased computing capability has been an essential tool for understanding the kinetics of these chemical reactions, which can lead to higher ethanol yields and lower process costs.

Computational science—the process of using computers to model and simulate real-world processes and phenomena—is an indispensable partner with theory and experiment to advance scientific knowledge and engineering practice. The NREL CSC helps researchers study complex systems and natural phenomena that would be too expensive, dangerous, or even impossible to study by direct experiment.

PIX14532/Jack Dempsey

NREL's Computational Sciences capabilities include cutting-edge tools and techniques for stereo 3D analysis and visualization of complex scientific data.

PIX14651/Mike Linenberger

Energy-Efficient Science and Technology Facility Set to Open

NREL is nearly ready to roll out its newest research facility on the South Table Mountain campus in Golden, Colorado. The Science and Technology Facility, or S&TF, is a 71,000-ft^2 (6,596-m^2), multilevel facility dedicated to research and development in solar cells, thin films, nanostructures, hydrogen energy, and fuel cells, which are several of the most important renewable energy technologies highlighted in the Solar America and Hydrogen Initiatives.

The building is designed to increase collaboration among researchers and shorten the time it takes new technologies to move from the laboratory bench to commercial manufacturing—and ultimately, to consumers.

Laboratories and office space are on the facility's ground level. The second level houses additional labs and a large, open Process Development and Integration Laboratory (PDIL). The third level contains mechanical equipment, such as exhaust fans. An elevated bridge connects the S&TF to the Solar Energy Research Facility next door.

The S&TF was especially designed to reduce technical and manufacturing barriers and accelerate the transfer of technology from R&D to industry. The centerpiece of the building will be the PDIL, an 11,400-ft^2 laboratory space specifically designed to accommodate a new class of tools for thin-film deposition, processing, and characterization. Six research bays will be available for industry partners as they scale up processes for early application in manufacturing devices such as PV modules.

Brent Nelson, who is leading the process integration project, says, "The PDIL will give us integrated tools, integrated data, and the added bonus of people with diverse skills working together."

The S&TF also includes laboratories for advanced materials, surface analysis, and novel deposition techniques. A flexible laboratory model guided the design, allowing smaller labs to be combined to form larger, more open ones, as needed. And the building's "interaction spaces" encourage the kind of informal discussions that often lead to R&D breakthroughs and other innovations. Each interaction area features a white board and computer access.

"Going into this project, our emphasis was on designing functional and flexible laboratory space that will meet our research needs both today and in the future," technical project manager Pete Sheldon says.

Like other NREL laboratory facilities, the S&TF is also a model of sustainable design and efficient energy use. It is expected to consume as much as 40% less energy than would a more conventional laboratory building. Daylighting, for example, which is the abundant use of natural light in a building, helps to reduce energy use by minimizing the use of artificial lights—and keeping the facility that much cooler—in the daytime. In the S&TF, natural light through numerous windows and clerestories illuminates the open office areas and even some of the labs. "Our goal was to have 100% daylighting in all office spaces," says Otto Van Geet, an NREL senior project leader.

In addition, energy recovery technologies use exhaust air to preheat or cool supply air. This allows smaller heating and cooling systems to be used. In line with Colorado's dry climate, evaporative cooling is also featured, as well as a raised-floor air distribution system. Overall, the facility has been designed to achieve a "Gold" rating as a U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) building.

Construction of the S&TF began in fall 2004 after designs were completed and contractors selected. Because of the excellent progress made, project managers expect occupancy to begin in July 2006.

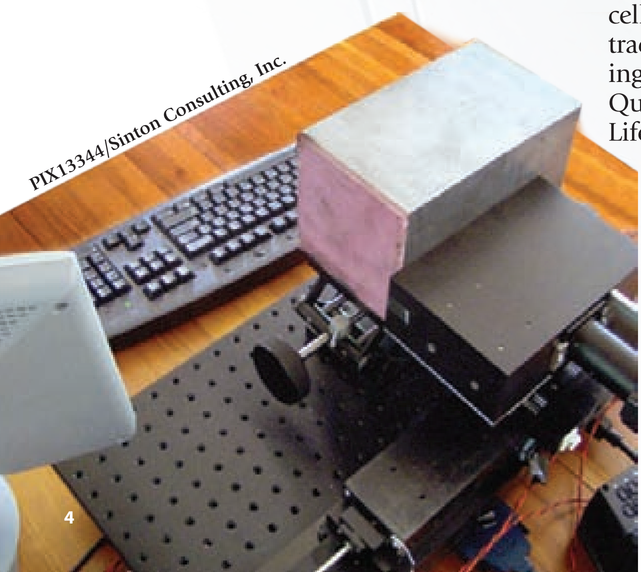
Awards & Honors

R&D 100 Awards

NREL won two R&D100 awards from *Research & Development (R&D)* Magazine in 2005. These awards recognize what the magazine editors consider to be the most significant products introduced into the marketplace over the past year. NREL won the awards for its work in advancing residential energy analysis software and improving the testing of silicon used in solar cell production.

Advances in Residential Energy Analysis The first R&D100 award recognizes the software application called TREAT—Targeted Residential Energy Analysis Tools—created by NREL and the New York State Energy Research and Development Authority (NYSERDA) and its partners. This software is a comprehensive energy analysis tool that models building energy consumption and identifies the most cost-effective energy-efficiency upgrades for both single and multifamily buildings. TREAT is based on SUNREL, a building energy simulation tool that NREL developed in the mid-1980s. Several innovations make TREAT particularly outstanding; for example, the software predicts occupant behavior, reports health and safety issues, and links users to outside data resources.

Advances in Silicon Testing The second R&D100 award highlights NREL's novel method of detecting impurities and defects in silicon boules, the material from which most commercial solar cells are made. Designed by subcontractor Ron Sinton of Sinton Consulting, the instrument is called the Sinton Quasi-Steady-State Minority-Carrier Lifetime Analyzer. It provides valuable information to manufacturers, identifying substandard silicon before it is fabricated into cells, and thereby increases the number of high-quality cells produced, while boosting manufacturing yields and reducing manufacturing costs. The evaluation system helps the photovoltaics industry be competitive by allowing manufacturers to produce consistently better silicon at the lowest possible price.



PIX13344/Sinton Consulting, Inc.

Technology Transfer Awards

The Federal Laboratory Consortium for Technology Transfer (FLC) recognized NREL with two "Notable Technology Development" awards in 2005 for technology transfer activities. The purpose of the FLC awards is to recognize achievements in moving technologies from the laboratory into the marketplace.

The first award recognized NREL's Thermal Comfort Project, which has resulted in several tools to analyze the efficiency of climate control in vehicles. The tools include the Advanced Automotive Manikin (ADAM), which mimics human physiological responses to hot and cold to predict how comfortable a vehicle occupant might feel. The project is managed by NREL's Center for Transportation Technologies and Systems.

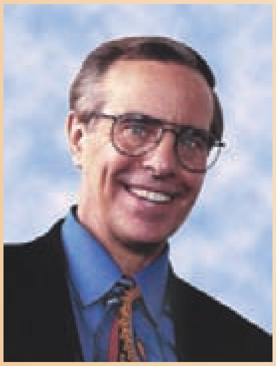
The FLC also recognized this center's Advanced Vehicles and Fuels Project. The project created a partnership with vehicle manufacturers, fuel providers, and others to incorporate innovative technologies into the industry to reduce fuel use and emissions.

The FLC also awarded Lawrence "Marty" Murphy, manager of NREL's Enterprise Development Programs, a Distinguished Service Award. The award recognizes his leadership during the last nine years in building and promoting the program. In addition, he has worked tirelessly on the Industry Growth Venture Forums, which encourage the creation and growth of companies that promote clean, efficient, and renewable energy. The FLC is a nationwide network of federal laboratories that strives to link developed technologies and expertise with the private sector.

PIX14684/Warren Gretz

Marty Murphy

Academy of Engineering Elects Kazmerski



Lawrence Kazmerski

Lawrence Kazmerski was elected a member of the National Academy of Engineering in 2005. Membership in the Academy is bestowed on engineers who have made outstanding contributions to engineering research, practice, or education, and to the pioneers of new and developing fields of technology. Kazmerski, who is the director of NREL's National Center for Photovoltaics, has worked at NREL since its inception. He has published more than 290 journal papers in the areas of solar cells, thin films, semiconductor materials and devices, surface and interface analysis, scanning probe microscopy, nanoscale technology, high-temperature superconductivity, and semiconductor defects. Kazmerski is also a Fellow of the Institute of Electrical and Electronics Engineers, the American Physical Society, and the American Vacuum Society. Under Secretary of Energy David Garman, invoking Kazmerski's oft-used nickname, said, "Kaz is known around the world for his leadership in solar energy research. NREL, DOE, and the nation are fortunate to have such a talented and tireless researcher who has devoted his life to this important work."

Ghirardi Among Nation's Brightest

The Hispanic Engineers National Achievement Awards Corporation (HENAAC) named NREL's Maria Ghirardi as one of the nation's best and brightest engineers and scientists. Ghirardi is a senior scientist at NREL and a Research Associate Professor at the Colorado School of Mines. Her research at NREL involves photobiological hydrogen production and includes developing a system for producing large quantities of active algal hydrogenase enzyme, a major breakthrough in research. She has authored 45 publications, and her research was the subject of a Discovery Channel program that aired in 2003. NREL Director Dan Arvizu adds, "Not only is her research on alternative fuels helping set the stage for our nation's energy future, she is a role model for students who want to pursue careers in engineering, science, technology, and math."

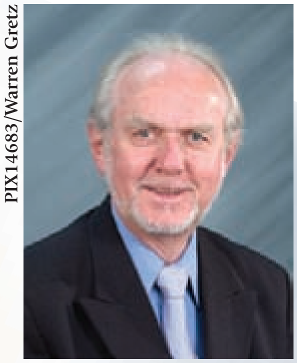
PIX13524/Warren Gretz

Maria Ghirardi

Coutts Wins IEEE Award

Timothy J. Coutts received the 2005 William R. Cherry award from the Institute of Electrical and Electronics Engineers (IEEE) for his long-term contributions to the science and technology of photovoltaic energy conversion, including the dissemination of substantial publications and presentations. Coutts leads NREL's device development work, within the National Center for Photovoltaics. This involves developing and optimizing both single- and polycrystalline solar cells. The annual award honors photovoltaics pioneer William R. Cherry and is bestowed each year at the IEEE Photovoltaics Specialists Conference.

PIX14683/Warren Gretz



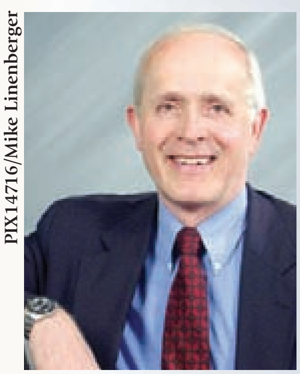
Timothy Coutts

Lawson Appointed to Air Quality Commission

Colorado Governor Bill Owens appointed Douglas Lawson to serve on the state's Air Quality Control Commission. Lawson, principal scientist in NREL's Center for Transportation Technologies and Systems, manages the Environmental Science and Health Impacts program for the Department of Energy. He has completed the first year of his three-year appointment to the commission, which consists of nine members representing different disciplines and interests.

Lawson was appointed because of his strong technical background. "I bring the air pollution science background to the commission," Lawson said. The commission is a rule-making body that reviews rules and regulations proposed by the state and the U.S. Environmental Protection Agency. Lawson has published more than 70 journal articles on various aspects of air pollution and served on two National Research Council committees on air quality.

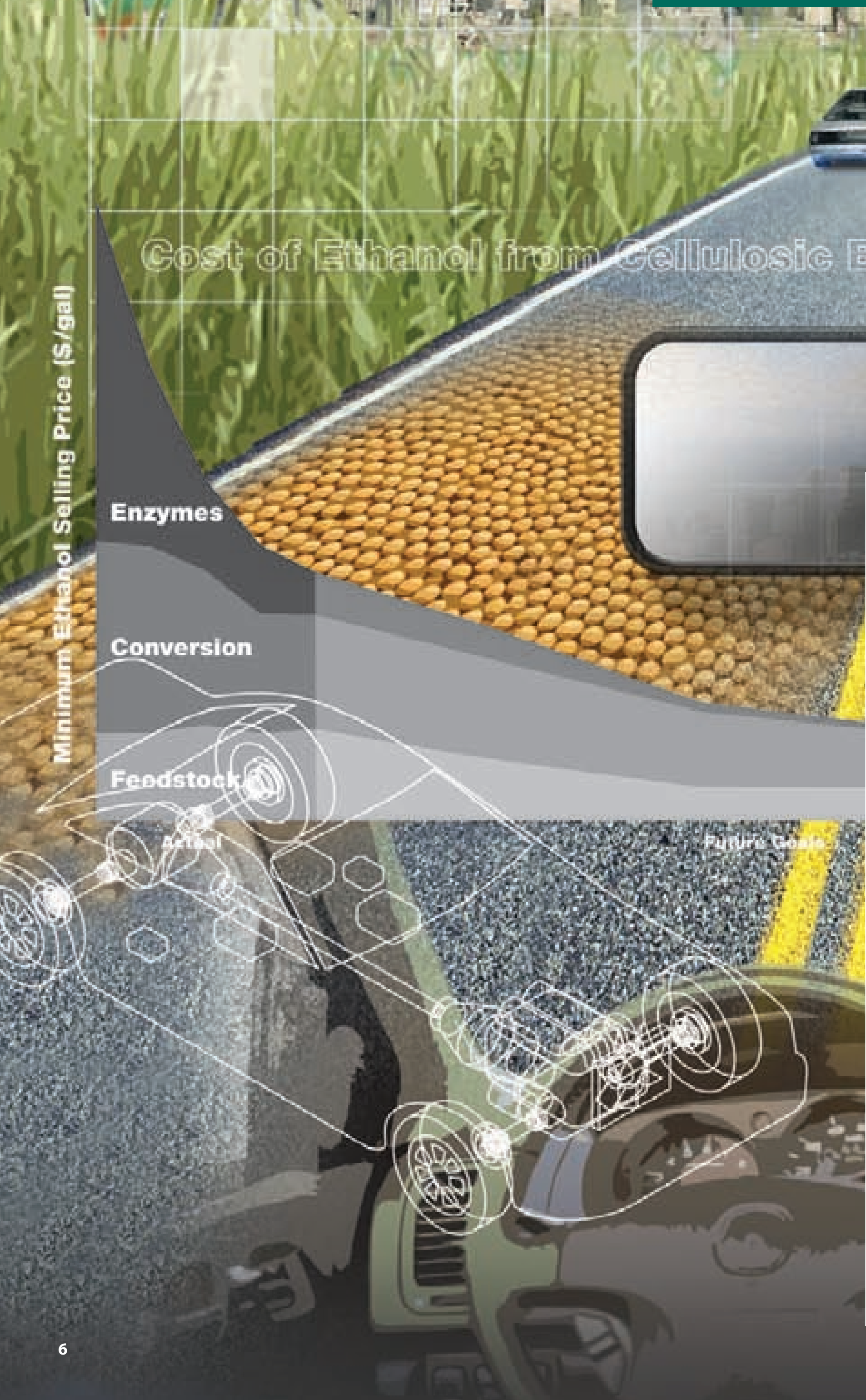
PIX14716/Mike Linenberger



Douglas Lawson

On the Road to Future Fuels and Vehicles

NREL's research helps move the nation toward energy independence



The total price that Americans pay for gasoline and diesel fuel isn't the one shown on the pump. Because we import about 60% of our crude oil, we are vulnerable to price fluctuations, disruptions in supplies, and political instabilities that affect our entire economy. We also pay a price in terms of our environment and health. For example, more than 30% of all U.S. air emissions come from burning traditional fossil fuels for transportation.

At least 240 million U.S. vehicles—one for 80% of all the men, women, and children in the country—were registered in 2004, according to Department of Transportation statistics. It takes a lot of fuel to keep all those wheels moving. The Department of Energy reports that the average American household uses more than 1,000 gallons of gasoline each year. Gasoline makes up nearly half of the 20 million barrels of petroleum products that we consume each day, to cover more than 7 billion daily miles.

Addressing these issues, in February 2006, President George W. Bush announced the Advanced Energy Initiative. This national initiative calls for greater reliance on domestic energy sources, including solar and wind energy, to power our homes and offices. And it increases funds for research and development (R&D) in advanced batteries for hybrid vehicles, electric cars, and hydrogen-powered vehicles, as well as alternative transportation fuels, particularly ethanol.

With the support of the Department of Energy's Office of Energy Efficiency and Renewable Energy, and in partnership with both public and private organizations, NREL's scientists and engineers are assisting in this effort by conducting R&D in innovative fuel and vehicle technologies. These technologies will help to reduce our nation's dependence on imports, enhance our energy security, and improve the quality of our air.

Here, we review where we are now, in terms of R&D and market readiness, as well as where we plan to be in 5 to 10 years and where we want to be in 20 years. This work has been, and will be, key to developing tomorrow's fuel and vehicle technologies. These technologies include advanced hybrid electric vehicles, plug-in hybrids, biodiesel and other biofuels, ethanol produced from cellulosic biomass, advanced batteries, hydrogen fuels, fuel cells, and more.

Where We Are Now

Today, ethanol, biodiesel, flexible-fuel vehicles, and hybrid-electric vehicles are all available in some form, but in limited quantities, in the United States. Since the Energy Policy Act of 2005 establishes a renewable-fuels standard requiring total U.S. transportation fuel sales in 2012 to include 7.5 billion gallons of renewable fuel, we should see steady increases in the use of biofuels and the vehicles that run on them.

Today, more than 30% of U.S. gasoline is E10—gasoline blended with 10% ethanol. About 90% of the U.S.-produced ethanol in this blend is made from the starch and simple sugars in corn. The availability of E10 depends on local prices and air-quality regulations, however.

Flexible-fuel vehicles. In some parts of the country, particularly the Midwest, consumers can purchase E85—an ethanol blend containing 15% gasoline. But E85 can be used only in "FFVs"—flexible-fuel vehicles that run on either gasoline or ethanol blends. At present, U.S. automakers manufacture flexible-fuel versions of several popular models, such as the Ford F150 truck and the Chevrolet Suburban sport utility vehicle. About 4½ million to 5 million FFVs are estimated to be on the road today.

However, many FFV owners are unaware that they have one. A recent survey of FFV owners by an ethanol producer found that 70% didn't know they owned a vehicle that can run on E85. Those who do know might wonder where they can purchase this fuel; less than 600 service stations offered E85 in January 2006. A tax credit in the Energy Policy Act of 2005 provides for developing an alternative fuel infrastructure, and this could help increase that number. And at least one automaker, GM, has stepped up public information efforts regarding FFVs and E85.

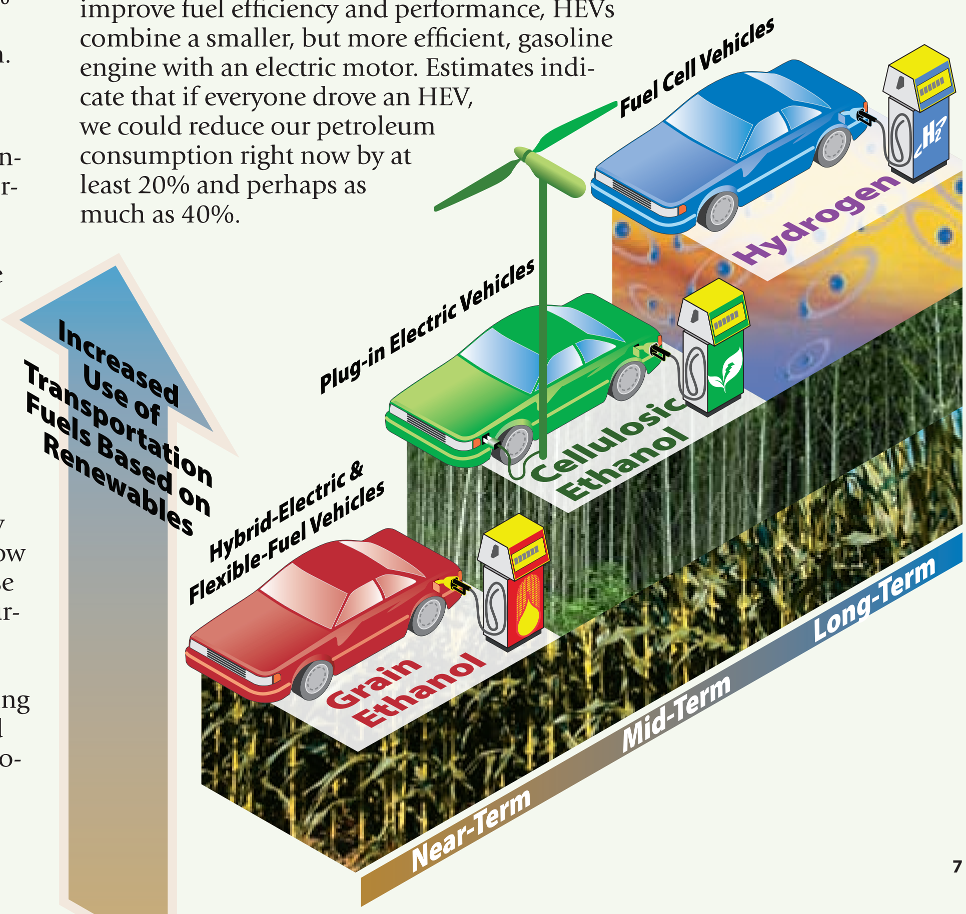
The Alternative Fuels Data Center. NREL is helping to expand the market for alternative fuels and vehicles through the Alternative Fuels Data Center, or AFDC. Supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy and housed at NREL for more than a decade, the AFDC is a searchable electronic library of technical data, publications, and information on advanced and alternative fuels and vehicles (see www.eere.energy.gov/afdc). It also contains information about financial incentives, regulations, fuel performance, emissions, funding and training resources, industry contacts, and updates on advanced vehicles.

In addition, the AFDC Vehicle Buyer's Guide helps both fleet managers and consumers evaluate various fuel and vehicle options. An Alternative Fuel Station Locator provides maps showing U.S. fueling stations. And additional databases provide useful technical data—for example, on vehicle emissions and performance.

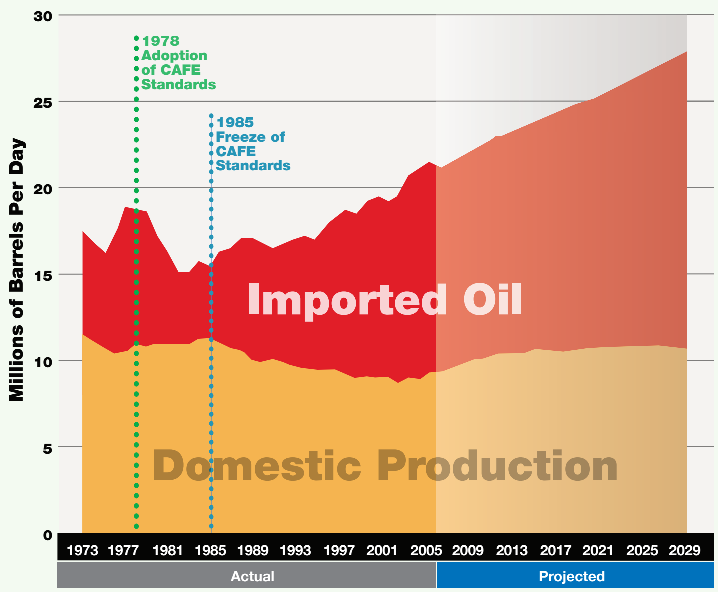
Hybrid-electric vehicles. Though they are still new kids on the road, hybrid-electric vehicles—HEVs—are becoming increasingly popular; about 1.3% of light vehicles sales in 2005 were HEVs. To improve fuel efficiency and performance, HEVs combine a smaller, but more efficient, gasoline engine with an electric motor. Estimates indicate that if everyone drove an HEV, we could reduce our petroleum consumption right now by at least 20% and perhaps as much as 40%.

PIX13531/Charles Bensinger, and Renewable Energy Partners of New Mexico

Options for reducing our use of imported oil are available to consumers now. Diesel vehicles can use 20% biodiesel. Flexible-fuel vehicles can use 85% ethanol. And 10% ethanol is widely used for fuel-efficient hybrid-electric or any regular vehicle. NREL is working to improve the competitiveness of these current alternatives and to develop new technologies for the future.



U.S. Dependence on Foreign Oil



Source: Historic data from Energy Information Administration (EIA), Monthly Energy Review 2006, Table 3.1A; projections from EIA Annual Energy Outlook 2006, Table 11.

Working with major U.S. automakers, NREL researchers have been contributing to the development of HEVs for more than a decade. Today, they are still investigating ways to improve the performance of HEV components and working with industry to put those improvements into practice.

One key to making HEVs more practical is to incorporate low-cost, integrated power electronics. NREL, other national laboratories, DOE, and industry are working on advanced components that condition the electrical signal between the power generation unit (a battery or fuel cell) and the electric motor.

Heavy-duty vehicles are prime subjects for R&D, because they consume much more fuel per vehicle than passenger cars do. Working with industry, NREL is developing advanced hybrid components and systems that could increase the fuel efficiency of heavy trucks as much as 100%.

Biodiesel. For diesel-powered vehicles, one renewable fuel option is B20—a blend consisting of 20% fatty acid methyl ester (known as biodiesel) and 80% petroleum diesel fuel. Biodiesel can be made from any animal or vegetable fat or oil and used in just about any diesel vehicle. It can reduce environmental emissions dramatically, depending on the blend. U.S. biodiesel is largely produced from soybean oil and recycled restaurant cooking oil.

Staff at NREL have been working to reduce the technical barriers that stand in the way of producing biodiesel and using it more widely. They also test biodiesel products in engines supplied by various industry partners. Their work will help to make biodiesel more cost-competitive, reliable, and plentiful.

Where We Should Be in 5 to 10 Years

Mid-term options such as cellulose-based ethanol and "plug-in" hybrid-electric vehicles are technologies in the latter stages of development, but they are still too expensive to compete in the marketplace. Therefore, NREL's researchers and engineers are working to improve these technologies so they can be competitive and widely available.

Cellulosic ethanol. The starchy material in corn kernels now used to produce most of our ethanol is only a small fraction of the biomass—the plant-based materials and waste products—that could be used. Two other components of plants, cellulose and hemicellulose, are also made of sugars, but those sugars are linked in long polymer chains that are not easy to convert to ethanol. Advanced biomass conversion technologies break down the polymer chains into their component sugars and then ferment them into alcohol to produce cellulosic ethanol.

This technology thus turns ordinary, low-value plant materials—such as corn stalks, sawdust, wood chips, wastepaper, and fast-growing trees and grasses—into ethanol and other valuable fuels and chemicals. Cellulosic ethanol could do much to reduce our dependence on imported oil and curb U.S. greenhouse gas emissions. The technology works—but it's still too expensive. So, national laboratories and private-sector groups alike are developing more cost-effective production methods.

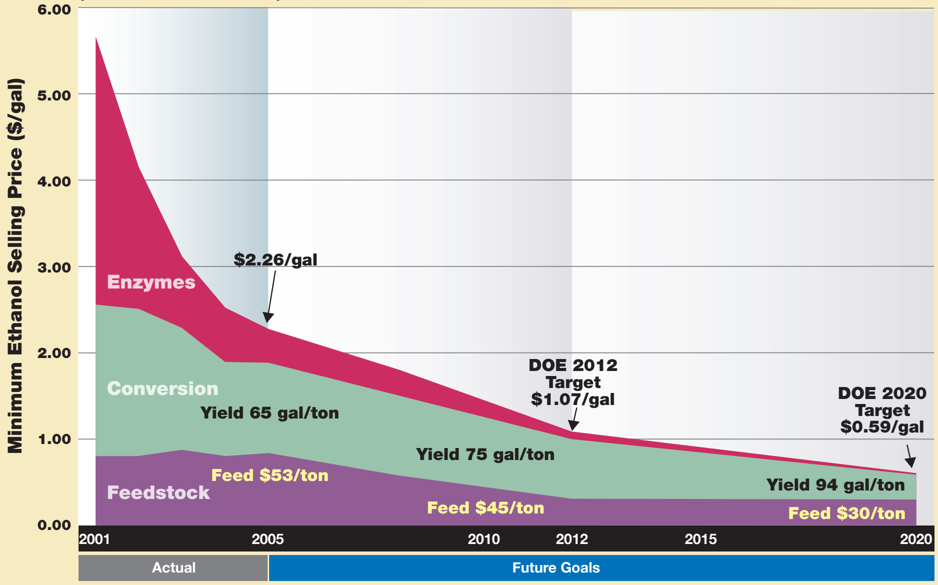
For many years, NREL has been developing technologies that produce ethanol and other valuable fuels and chemicals from cellulosic biomass. Our researchers have conducted much of the basic research underpinning a process in which a dilute acid is used to break down hemicellulose. In a step known as enzymatic hydrolysis, enzymes break cellulose down into its component sugars. While we focused on the process, our research partners made great strides in reducing the cost of the enzymes. Four years ago, these enzymes were too expensive to be used in a cellulosic ethanol process. Today, enzymatic hydrolysis is the lowest cost option for hydrolyzing cellulose to glucose.

NREL researchers are also leading the development of better pretreatment methods, which use dilute acid at elevated temperatures and pressures to break down hemicellulose into component sugars. And they engineered one of only three organisms to date that can co-ferment cellulosic and hemicellulosic sugars.

In NREL's one-ton-per-day feedstock pilot plant, researchers continue to partner with companies in the vanguard of this emerging industry to validate new biomass-to-ethanol technologies. They still need to be simpler and less expensive; for example, the capital equipment and sophisticated processing steps required are costly. So NREL is

Cost of Ethanol from Cellulosic Biomass

(Costs in 2002 Dollars)



Source: U.S. Department of Energy, Biomass Program data

NREL continues to investigate technologies that allow us to produce ethanol economically from corn stover—the husks, leaves, and stalks that today are left behind in the field after the corn is harvested. This feedstock is both high in volume and low in cost. However, capital equipment and ethanol processing costs are still too high for the technology to compete with gasoline and with ethanol made from corn kernels. Though NREL has made great progress in reducing the cost of cellulosic ethanol technology, some key hurdles remain to be overcome. NREL's analysts calculate that a price of $2.26 per gallon is needed to allow industry to build a profitable plant today. And a price of $1.07 per gallon is needed for large-scale market penetration—a goal we hope to reach by 2012.

working to change this. When all process design targets are met and ethanol can be produced for a little more than $1.00 per gallon, cellulosic ethanol will be competitive with ethanol from starch and probably even with gasoline.

NREL researchers and their partners have received several technology awards for novel biomass conversion methods. And they are working to enable industry to produce fuels, chemicals, and other products in biorefineries that would manufacture a variety of products from biomass—much as today's oil refineries and petrochemical plants do from petroleum.

Other mid-term biofuels. NREL researchers have helped to develop processes for gasifying or liquefying biomass by heating it with little or no oxygen. Using the Fischer-Tropsch conversion process and others, they can catalytically convert the resulting synthesis gas to diesel substitutes and other fuels. NREL has also partnered with industry to explore whether a bio-oil produced through the pyrolysis of biomass could be a useful intermediate for producing clean biofuels. Several small biomass gasification and pyrolysis plants are already up and running.

In the biorefineries of the future, selected sugars and intermediates would be made into high-value products for various markets. The remaining sugars would be fermented to ethanol fuel. The lignin in plants might also be gasified or pyrolyzed and converted to fuels and chemicals.

NREL scientists and their industrial partners are also evaluating an option known as "green diesel." Biodiesel contains molecules

Ethanol from Corn Kernels: Is It an Effective Use of the Resource?

Critics of corn-based ethanol often say that it takes more energy to produce the ethanol than we get from the resulting fuel. But official studies demonstrate just the opposite. The efficiency of both corn farming and ethanol production has dramatically increased over the years. The latest U.S. Department of Agriculture (USDA) study calculates a net energy balance of 1.67 for ethanol production; that is, for every unit of energy that went into growing the corn and turning it into ethanol in 2001, we got back about two-thirds more energy in the form of automotive fuel and animal feed.

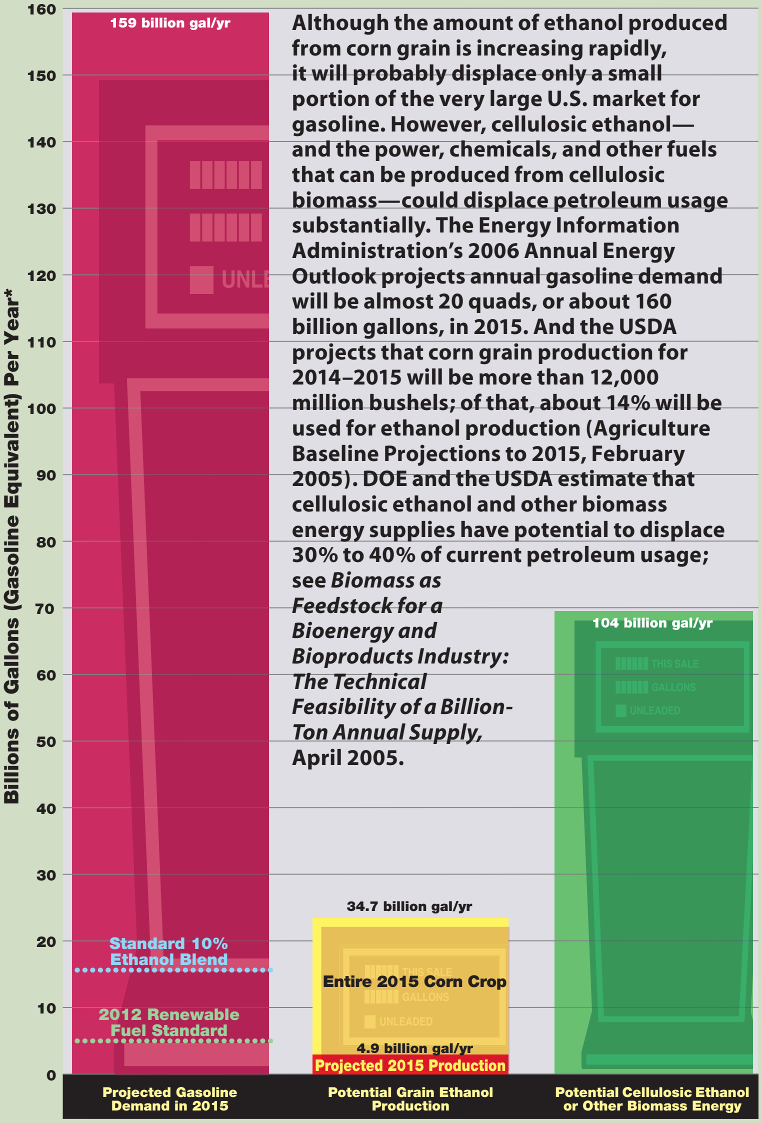
Even if that net energy balance were less than one, ethanol production and use still displaces oil imports with domestic nonpetroleum energy, which is a major plus in terms of reducing our dependence on imported fuel. On the basis of liquid fuels alone, the USDA calculated a net balance of 6.34. It is important to note that the energy in ethanol totally replaces gasoline energy, and relatively little petroleum product is used to produce it.

It is true that modern corn farming and ethanol production are both energy-intensive, and that the "net energy" gain of some early ethanol plants was relatively modest. But allegations about a negative net energy balance seem to be based either on using old data or failing to take into account the considerable value of the animal feed co-products of ethanol production.

Animal feed co-products are a critical part of any effectiveness analysis because they are a major part of the economics of ethanol production. Corn, the largest U.S. crop, is used primarily for high-starch animal feed. Ethanol production uses up most of the starch from the kernels, but leaves the protein and fiber, so ethanol co-products are very high in protein and therefore are high-value animal feeds.

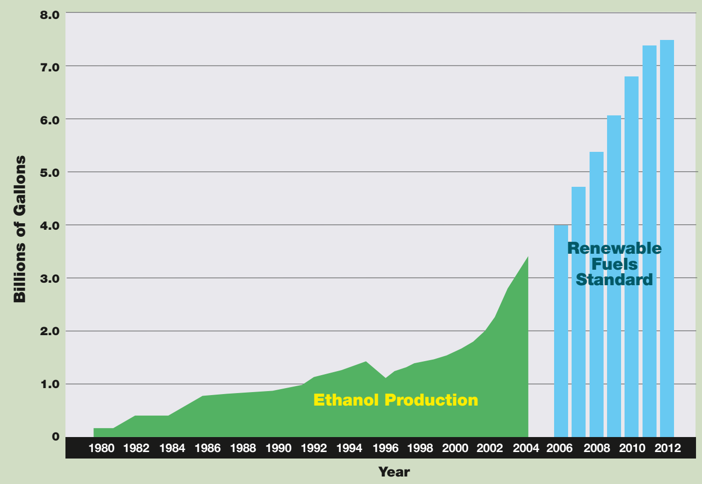
Can Biofuels Displace Gasoline?

Although the amount of ethanol produced from corn grain is increasing rapidly, it will probably displace only a small portion of the very large U.S. market for gasoline. However, cellulosic ethanol—and the power, chemicals, and other fuels that can be produced from cellulosic biomass—could displace petroleum usage substantially. The Energy Information Administration's 2006 Annual Energy Outlook projects annual gasoline demand will be almost 20 quads, or about 160 billion gallons, in 2015. And the USDA projects that corn grain production for 2014–2015 will be more than 12,000 million bushels; of that, about 14% will be used for ethanol production (Agriculture Baseline Projections to 2015, February 2005). DOE and the USDA estimate that cellulosic ethanol and other biomass energy supplies have potential to displace 30% to 40% of current petroleum usage; see *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply,* April 2005.

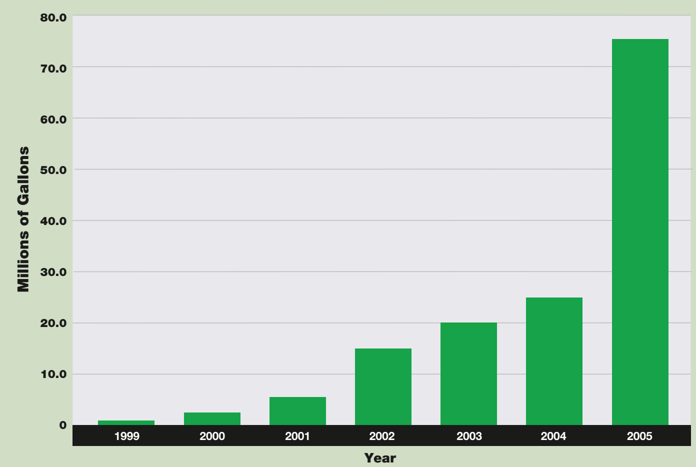


*The right- and left-hand scales are different because ethanol has only two-thirds as much energy per gallon as gasoline. For example, 90 billion gallons of ethanol is equivalent--in energy terms--to 60 billion gallons of gasoline.

Ethanol Production



Biodiesel Production



produced by trans-esterifying triglycerides with methanol. Green diesel consists of paraffin molecules produced by hydrogenating triglycerides by means of a conventional petroleum refining process. Green diesel has a very high cetane number, so it ignites fairly quickly after injection, and a low pour point—the lowest temperature at which a fuel will pour. Thus, it is a high-quality diesel fuel and is totally compatible with petroleum diesel.

Plug-in hybrids. In addition to producing transportation fuels from biomass, we can also put electricity to work to reduce our petroleum usage. Electric vehicles are clean and quiet, and there are already some vehicle recharging stations around the country. This vehicle technology could be fully renewable if the recharging stations provided electricity generated by wind, solar, and other renewable energy technologies.

Today's HEVs do not depend on an external means of recharging their batteries. NREL is working to move HEV technology a step further by developing hybrids that can be plugged in to store electricity for later use. Adding extra batteries to an HEV and a means to plug them in, we would drive most of a typical day on domestic electricity and still have fuel in the tank for longer trips.

Today's batteries are heavy and expensive, however. So, NREL is researching advanced drive trains and other vehicle components—such as batteries—that can be used in conventional, hybrid-electric, and plug-in hybrid vehicles. Advances in batteries and other energy-storage technologies are essential to the success of plug-in hybrids. NREL is also exploring ways to make plug-ins reversible, so that excess power stored in the vehicle would go back into the utility grid, to the owner's credit.

Where We Need to Be in 20 Years

Taking all this another step further, NREL foresees the emergence of "renewable communities" that would feature plug-in hybrids, zero-energy homes, and various renewable energy technologies. They might not be a reality now, but they are a part of our vision for the future.

We support the Department of Energy's "30 by 30" goal, which means that ethanol will make up at least 30% of our nation's transportation fuels by 2030. Research in other long-term technology options, such as renewable-based hydrogen fuel and fuel cells, is also important, especially in terms of the basic science underlying those technologies. Hydrogen fuel cells for transportation and hydrogen vehicles are so promising that California and some states on the Atlantic Coast are setting up prototype hydrogen fueling stations to test new technologies as they develop.

Hydrogen production. Producing hydrogen by steam-reforming natural gas, today's most economical method, would increase our reliance on an increasingly scarce fossil fuel. So, NREL is pursuing a renewable option: gasifying biomass and reforming the resulting syngas to hydrogen through a water-gas shift reaction.

NREL researchers are also exploring the use of cost-effective solar, wind, and other renewable technologies to electrolyze water to produce hydrogen. And they are pursuing both photoelectrochemical and photobiological technologies that could produce hydrogen directly.

The photoelectrochemical approach integrates elements of a photovoltaic cell with elements of an electrolyzer, so that the absorption of light energy triggers the splitting of a water molecule in an aqueous electrolyte. Because aqueous photovoltaic cells and electrolysis share anode, cathode, and electrolyte components, this approach is potentially much more efficient than the separate steps of electricity generation and electrolysis.

The photobiological approach takes advantage of the fact that certain microorganisms—such as green algae—naturally split water to produce hydrogen as a way to dissipate the energy they do not need in certain circumstances. Researchers have been creating new genetic forms of the microorganisms that can sustain hydrogen production in the presence of oxygen. One system uses a metabolic switch (sulfur deprivation) to cycle algal cells between a photosynthetic growth phase and a hydrogen production phase.

Fuel-cell research. Fuel cells could revolutionize the way we power our nation, providing clean, more efficient alternatives to burning fossil fuels. However, many challenges must be overcome before fuel cells will be competitive in the marketplace. Therefore, NREL's work focuses on

Where Will the Biomass Come From?

We are not likely to be able to replace all our petroleum-based fuels and chemicals with biomass-derived products. However, it is a good idea to set some goals for the contribution biomass can make to meet future petroleum demand.

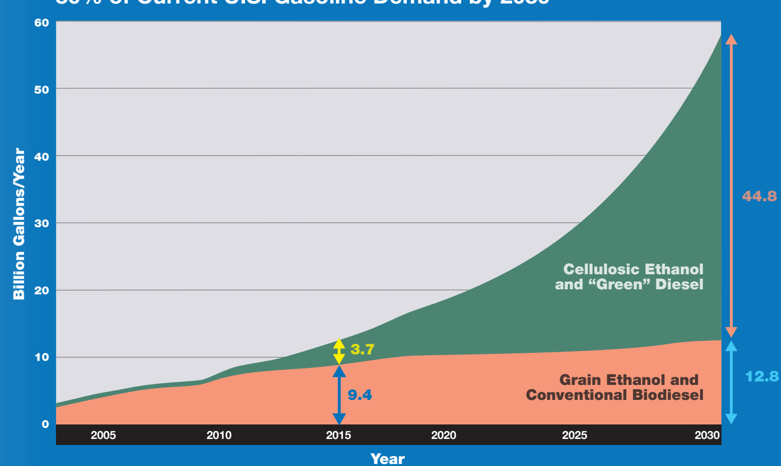
The Biomass R&D Technical Advisory Committee to the Secretaries of Energy and Agriculture has stated that biomass could supply 5% of current U.S. power needs, 20% of transportation fuel requirements, and 25% of chemical needs by 2030 (*Vision for Bioenergy and Biobased Products in the United States*, October 2002). This would displace 30% of our petroleum use and require about a billion tons of biomass per year to meet current U.S. consumption levels.

A subsequent joint DOE-USDA study headed by Oak Ridge National Laboratory that included contributions from NREL and others was conducted to determine whether that goal is feasible. The study found that forestlands and agricultural lands—the two largest sources of biomass—could produce the following annual tonnages by 2030:

Forestlands		
Fuelwood harvest from forests		52
Residues from wood processing & pulp & paper mills		145
Urban wood residues		47
Residues from logging and site-clearing operations		64
Forest thinnings to reduce fire hazards		60
Forestlands subtotal	**368**	
Agricultural Lands		
Annual crop residues		428
Perennial dedicated energy crops		377
Crop grains used for biofuels		87
Manures and miscellaneous		106
Agricultural lands subtotal	**998**	
Total production in 2030 (in million dry tons of biomass)	**1,366**	

The study concludes that enough biomass would be available in 2030 to meet about 40% of our current petroleum use. Business-as-usual projections for petroleum use predict a substantial increase. But much more efficient vehicles and the use of electricity rather than liquid fuels (for example, for plug-in electric hybrids) could reduce the need for petroleum dramatically. Key assumptions in the study included these: crop yields will increase by 50% by 2030; cropland will switch to no-till management; 55 million acres will be converted to dedicated energy crops; crop and residue harvesting technology will improve; and environmentally sensitive lands and forestlands not accessible by road would be excluded. (See *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, April 2005).

Required Growth of Advanced Renewable Fuels to Supply 30% of Current U.S. Gasoline Demand by 2030



PIX14682/Dean Armstrong

NREL's Bill Kramer shows a power inverter and a new cooling system that NREL developed and is testing in its new Electrical Systems Laboratory.

New NREL Facilities Provide Key Tools for Studying Surfaces and Heat Flow

Two new NREL laboratories provide researchers with important resources they can use to improve fuel and vehicle technologies. The state-of-the-art electron microscopes in the recently opened Biomass Surface Characterization Laboratory (BSCL) are powerful tools for understanding the core mechanisms underlying biomass conversion processes. The new Electrical Systems Laboratory (ESL) provides the essential capabilities needed to improve the efficiency and thermal management of power electronics for hybrid-electric, fuel-cell, and other advanced vehicles.

Surface analysis is key to understanding both biological and chemical reactions. These reactions are basically a function of the way a catalyst interacts with a substrate (for example, acid and water acting on hemicellulose or enzymatic proteins acting on cellulose). It takes sophisticated equipment to determine the actual shape of a chemical or protein and how it interacts with biomass. The new BSCL provides NREL biomass researchers with some of the best equipment available, including scanning-electron, atomic-force, transmission-electron, near-field-scanning-optical, and confocal microscopes.

For vehicle efficiency, it is important to understand heat flow and performance under anticipated uses. The ESL's capabilities start with a 125-kilowatt bidirectional power supply. This allows researchers to simulate the way electricity flows from a hybrid vehicle's battery to its motor and back, both to assess performance under various drive cycles and to represent actual heat-flow situations. A high-heat-flux test loop allows heat flow to be assessed within various power electronics components. Researchers are already using it to develop and test innovative cooling systems for the power inverters needed to convert the DC current of a battery to the AC required by the motor. Ultracapacitors are also being studied; they have less total power storage capability than batteries, but can deliver much more power for a short time and could boost the efficiency of certain types of vehicles.

improving the performance and cost effectiveness of fuel cell systems, subsystems, and components. Specific research areas include system analysis and component research.

Fuel cells are rather complex, so innovative analysis tools are needed to design them. NREL is using a variety of tools to identify critical design issues for fuel cell vehicles and systems. We work with industry to share and apply robust design tools and techniques to address such issues as durability, cost, and efficiency.

Simulation tools. Much of NREL's research in advanced vehicles makes use of computer simulations of vehicle technologies to model, evaluate, and optimize them. A basic problem underlying our dependence on imported oil is that today's cars and trucks are not very efficient. Even a hybrid-electric vehicle uses less than one-fifth of the energy—fossil or renewable—that goes into it. Because several different configurations for hybrid-electric and fuel-cell vehicles are possible, and numerous alternative technologies could be used in key vehicle components, computer modeling is critically important.

Using NREL-created models such as ADVISOR (Advanced Vehicle Simulator), which is now commercially available, we can simulate potential vehicle technologies and combinations of technologies in days or weeks, rather than the months or years it takes to build and test prototypes. Using these computer tools, we can advise automakers, equipment providers, other government programs, and our own researchers on the most promising avenues to pursue to reduce the environmental impacts of vehicles and improve their efficiency and performance.

NREL has also developed a unique thermal comfort manikin known as ADAM (the Advanced Automotive Manikin), which is designed to help the automotive industry design smaller, more efficient climate-control systems in vehicles.

The ultimate goal of all this research and development is to enable U.S. industry to produce advanced, low-emission, economically competitive fuels and vehicles that will meet our future transportation and environmental needs. Pursuing all options, we are on the way to greater energy independence.

For More Information

A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, J. Lukas. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*. June 2002. National Renewable Energy Laboratory. NREL/TP-510-32438 (www.nrel.gov/docs/fy02osti/32438.pdf).

Biomass Technical Advisory Committee. *Vision for Bioenergy and Biobased Products in the United States,* October 2002, and *Roadmap for Biomass Technologies in the United States,* December 2002 (www.biomass.govtools.us/pdfs/BioVision_03_Web.pdf; www.biomass.govtools.us/pdfs/FinalBiomassRoadmap.pdf).

R.D. Perlack, L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, D.C. Erbach. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. April 2005. Oak Ridge National Laboratory for the U.S. Department of Energy and U.S. Department of Agriculture (www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf).

T. Penney, J. Elling. "The Race to Connect Cars, Communities and Renewables." *Geotimes*. August 2005. American Geological Institute.

Renewable Fuels Association. *From Niche to Nation: Ethanol Industry Outlook 2006* (www.ethanolrfa.org/industry/outlook/).

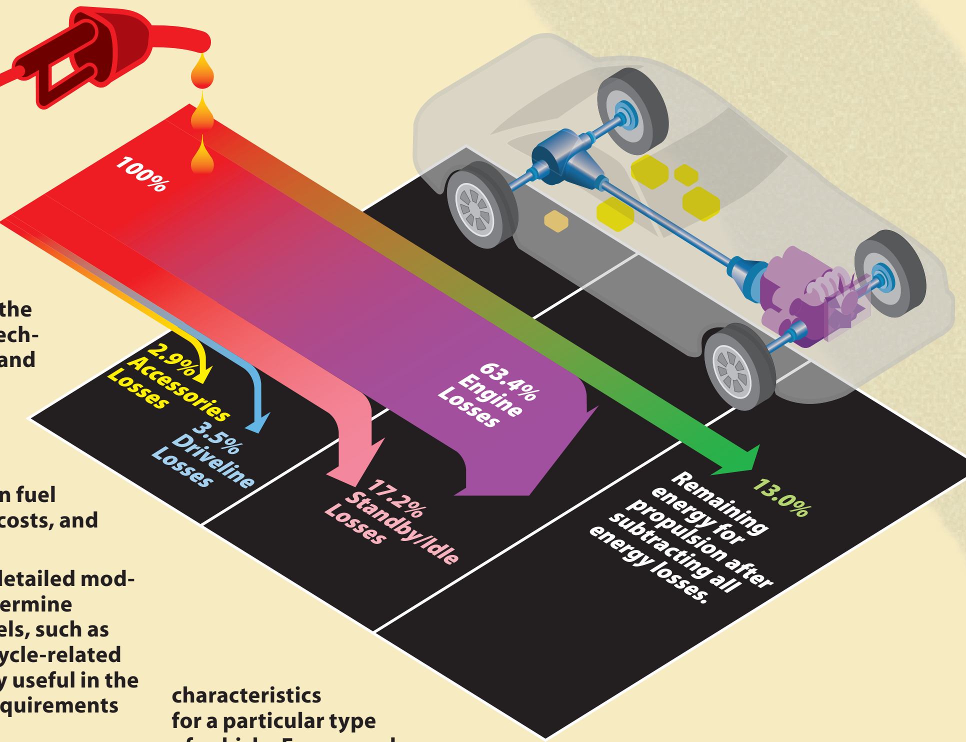
H. Shapouri, J. Duffield, A. McAloon, M. Wang. *The Energy Balance of Corn Ethanol: An Update*, 2002, Agricultural Economic Report No. 814, and *The 2001 Net Energy Balance of Corn-Ethanol,* presented at the Corn Utilization and Technology Conference, June 7-9, 2004, Indianapolis, IN. U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses (www.usda.gov/oce/reports/energy/aer-814.pdf; www.usda.gov/oce/reports/energy/net_energy_balance.pdf).

J. Sheehan, A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, R. Nelson. "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol." 2004. *Journal of Industrial Ecology*. Volume 7, Number 3-4 (http://devafdc.nrel.gov/pdfs/8427.pdf).

Web sites:

- **National Renewable Energy Laboratory Biomass Research, www.nrel.gov/biomass/**
- **National Renewable Energy Laboratory Advanced Vehicles and Fuels Research, www.nrel.gov/vehiclesandfuels/**
- **U.S. Department of Energy, Energy Efficiency and Renewable Energy Alternative Fuels Data Center, www.eere.energy.gov/afdc/**
- **U.S. Department of Energy, Energy Efficiency and Renewable Energy Biomass Program, www.eere.energy.gov/biomass/index.html, www.eere.energy.gov/biomass/publications.html**
- **U.S. Department of Energy, Energy Efficiency and Renewable Energy FreedomCAR and Vehicle Technologies Program, www.eere.energy.gov/vehiclesandfuels/**

Sophisticated Modeling Capabilities for Advanced Vehicles R&D



In developing a new vehicle, engineers can shave years off the process by using simulations that clearly show the designs and components that will (or won't) achieve their performance goals. At NREL, vehicle systems analyses help to guide the development of the most promising advanced vehicle and component technologies, such as plug-in hybrids, fuel cell vehicles, and advanced storage technologies.

NREL's expert analysts have considerable experience in evaluating advanced vehicle technologies. Using computer simulation and analysis tools, they evaluate new technologies and their impacts on fuel economy, vehicle performance, exhaust emissions, costs, and market potential.

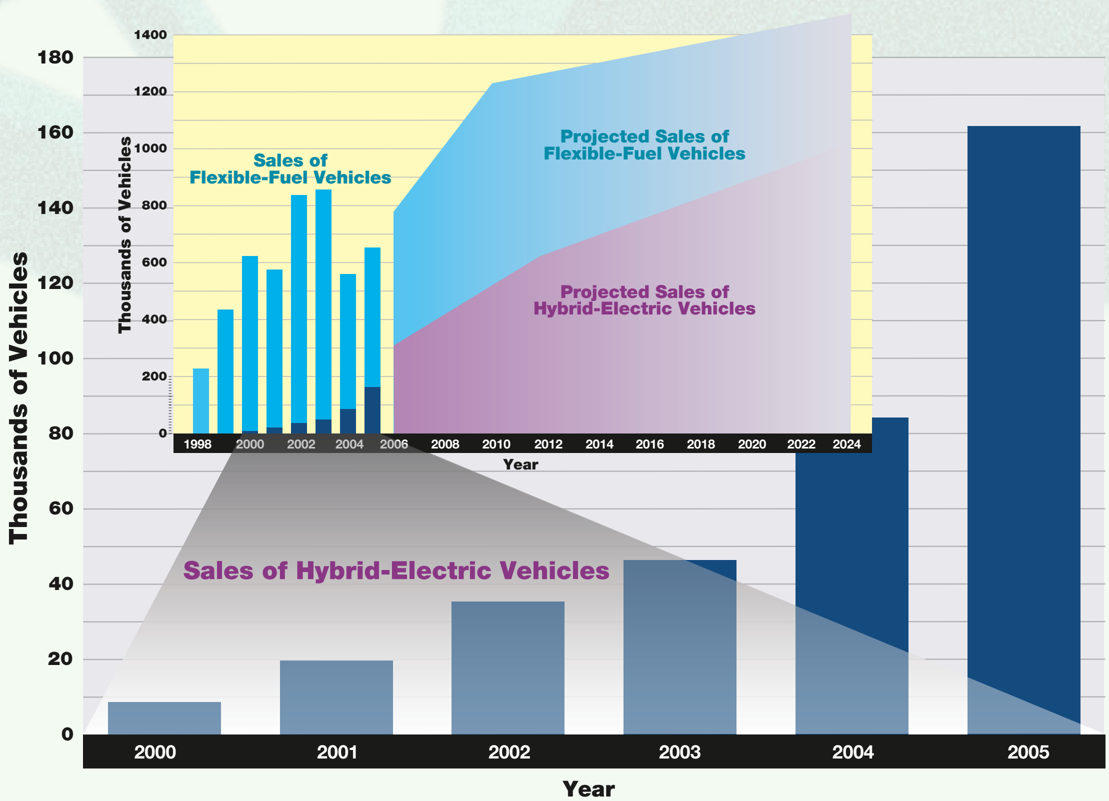
For example, they use high-level, exploratory, and detailed modeling tools, as well as robust design methods, to determine optimum designs and components. High-level models, such as VISION, are used in design studies and analyses of cycle-related requirements. These flexible models are particularly useful in the preliminary design stage, when assumptions and requirements can change quickly.

Exploratory models, such as ADVISOR, allow analysts to investigate energy management strategies, interactions among components of various types and sizes, and the performance and energy implications of different powertrain designs. These are important in developing future plug-in and heavy-duty hybrid vehicles.

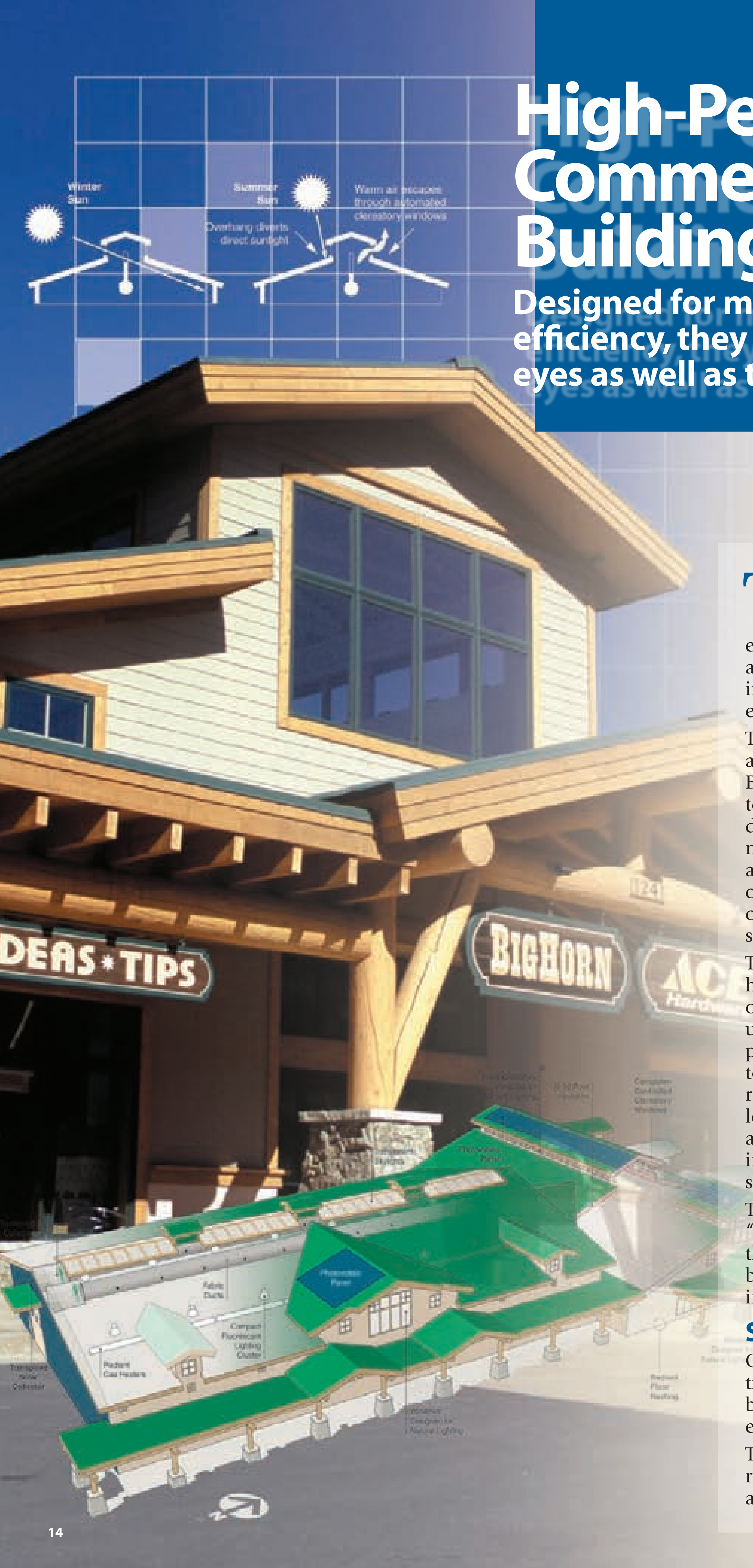
More detailed models, such as the Powertrain System Analysis Toolkit, provide in-depth analyses of components, events, and transients. And robust design integrates the latest computer-aided engineering and design tools with advanced design techniques to solve technical barriers and accelerate development.

The Laboratory's optimization tools and distributed computing capabilities complement this modeling work. Optimization tools help analysts find the best combinations of components and characteristics for a particular type of vehicle. For example, sometimes two or more design objectives—such as power and fuel economy—compete with each other; optimizing involves evaluating and comparing options to achieve the best overall effect. And analysts can tap into the considerable computational capability of NREL's distributed computing system, making the entire process more efficient.

NREL has also developed a tool to evaluate technical targets and R&D goals, estimate market penetration, and project the impacts of advanced vehicles on U.S. oil usage. For more information, and a list of vehicle simulation and analysis tools currently used at NREL, please see www.nrel.gov/vehiclesandfuels/vsa/simulation_tools.html.



Hybrid-electric vehicle (HEV) sales are still small, but high-efficiency vehicles are proving to be very popular. So, sales are expected to increase substantially. They also set the stage for "plug-in" HEVs, which could shift transportation energy use from largely imported oil to domestically generated electricity. There are already about 5 million flexible-fuel vehicles (FFVs) on the road that can use E85 fuel, a high-percentage blend of ethanol. The number of service stations selling E85 needs to grow proportionally to take advantage of the capabilities of this growing FFV fleet.



High-Performing Commercial Buildings

Designed for maximum energy efficiency, they are easy on the eyes as well as the budget

The buildings we live and work in consume about 39% of all the primary energy the nation uses annually—and 70% of the electricity. With energy costs on the rise, home and business owners need to know how to keep indoor areas comfortable without sending their energy bills through the roof.

To help meet that need, the engineers, architects, analysts, and programmers on the Commercial Building Integration (CBI) team in NREL's Center for Buildings and Thermal Systems study and design energy-efficient, high-performing commercial buildings. High-performing buildings are designed to provide superior levels of indoor comfort and lighting while consuming significantly less energy than those meeting minimum standards for energy efficiency.

The team monitors, analyzes, and documents how buildings actually perform. They make use of sophisticated building design software to simulate and analyze performance. And they support the U.S. Department of Energy (DOE) goal to have marketable zero-energy building designs ready by 2025. Zero-energy buildings produce at least as much energy as they consume. Thus, in addition to energy-efficient elements, these buildings incorporate energy-generating technologies such as photovoltaic (PV) solar electric systems.

The team's work reflects a system-integrated, "whole-building" approach to design. This means that they look carefully at how each element of a building will affect other elements, and the building as a whole, in terms of energy efficiency.

Six Good (Energy) Performers

CBI team leader Paul Torcellini says, "The best time to start thinking about a low- or zero-energy building is when you're designing the building envelope."

The envelope is the building's "skin"—walls, roofing, and other elements that together form a thermal barrier between the building and its environment. An energy-efficient envelope should provide most of the building's heating, ventilation, cooling (HVAC), and lighting needs.

Today, standard HVAC equipment (e.g., furnaces and air-conditioners) and electric lighting are usually required to supplement the work of an energy-efficient envelope. In the future, the envelope should supply most of the building's HVAC and lighting needs, with contributions from renewable energy. To move us closer to that future, the CBI team recently analyzed these six buildings:

- Adam Joseph Lewis Center for Environmental Studies, Oberlin College, Oberlin, Ohio
- BigHorn Home Improvement Center, Silverthorne, Colorado
- Cambria Office Building, Ebensburg, Pennsylvania
- Chesapeake Bay Foundation Philip Merrill Environmental Center, Annapolis, Maryland
- NREL Thermal Test Facility (TTF), Golden, Colorado
- Zion National Park Visitor Center Complex, Springdale, Utah.

Each one incorporates various energy efficiency and renewable energy design elements, such as daylighting (natural lighting), passive solar strategies, radiant heating, natural ventilation, evaporative cooling, ground-source heat pumps, and PV systems. NREL staff helped to design three of the six: the BigHorn Center, the TTF, and the Zion Visitor Center. They monitored all of them for a year or more when completed and analyzed data to compare actual energy performance with goals specified in original designs.

How the Buildings Measured Up

The thermal envelopes of all six buildings exceed those specified in ASHRAE Standard 90.1, published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. The buildings consume between 25% and 70% less energy than a comparable building would if designed to be ASHRAE code-compliant.

The monitoring revealed some gaps between design goals and actual performance, but later modifications helped to close those gaps. At the top of the list were problems with controls, insulation placement, and following the building plans. Here is a brief summary of the results of NREL's monitoring and analysis; see the table on page 17 for data from the six-building study.

Lewis Center. The Adam Joseph Lewis Center for Environmental Studies at Oberlin College in Ohio was designed to be an energy producer as well as an energy consumer and a teaching aid for students. The 13,600-ft^2 (1260-m^2) building, constructed in 2000, houses classrooms, offices, and an atrium. Features include passive solar design, daylighting, natural ventilation, an enhanced thermal envelope, and geothermal heat pumps for heating and cooling. A roof-integrated PV system provides electricity.

PIX10860/Robb Williamson

The Lewis Center for Environmental Studies at Oberlin College, Ohio

After construction, NREL staff monitored and evaluated the building's energy performance. The building uses 47% less energy than a comparable code-compliant one, and it demonstrates that a high-performance building works well even in a climate with high heating and cooling loads.

BigHorn Center. The BigHorn Development Project in Silverthorne, Colorado, is a retail complex in a mountain community. The building that NREL helped to design is a 36,980-ft^2 (3,436-m^2) structure housing a hardware store and a warehouse/lumberyard building. Calibrated simulations were used to estimate the performance of the building before construction. Monitoring and analysis since then show that the building has 53% lower energy costs than a typical code-compliant retail building of its size.

PIX09202/Jim Yost

The BigHorn Home Improvement Center, Silverthorne, Colorado

Daylighting and other design features reduced lighting energy requirements by 80%. Reducing electric lighting and controlling solar gains allowed the designers to use natural ventilation to meet the cooling load. An 8.9-kilowatt (kW) PV system initially provided 2.5% of the building's electricity needs. PV system and other improvements increased that to about 8%.

Cambria Building. The Cambria office building in Ebensburg, Pennsylvania, is one of the high-performing buildings constructed for the Pennsylvania Department of Environmental Protection. Completed in 2000, it features efficient wall and roof insulation, high-performance windows,

PIX10140/Jim Schafer

The Cambria Office Building in the Commonwealth of Pennsylvania Department of Environmental Protection, Ebensburg, Pennsylvania

PIX10884/Robb Williamson

The Chesapeake Bay Foundation Philip Merrill Environmental Center, Annapolis, Maryland

ground-source heat pumps, an under-floor air distribution system, energy recovery ventilators, and daylighting.

The design also specified an 18.2-kW PV system for on-site power production. These elements helped to achieve a LEED (Leadership in Energy and Environmental Design) 2.0 Gold Certification from the U.S. Green Building Council, and a 43% reduction in energy use in comparison to a standard building design. NREL staff collected performance data for comparison with a standard baseline computer model and then recommended further performance improvements.

Merrill Center. The Chesapeake Bay Foundation (CBF), dedicated to restoring and protecting the bay's resources, built the 31,000-ft^2 (2,880-m^2) Philip Merrill Environmental Center in Annapolis, Maryland, as its headquarters in 2000. The CBF incorporates many energy-saving features, including a ground-source heat pump to provide heat in winter and cooling in summer.

The building features large, south-facing windows for passive solar heating and daylighting. Sensors automatically dim lights when daylight levels are sufficient. Bay breezes provide natural ventilation. And an energy management system tracks outdoor temperatures and humidity to control the HVAC system. At CBF's request, NREL staff assessed the building's performance through a combination of monitoring and computer simulations; results showed a 12% annual energy cost savings compared with costs for a standard design.

The Zion National Park Visitor Center in Utah

PIX09243/Robb Williamson

Thermal Test Facility. NREL built the 10,000-ft^2 Thermal Test Facility (TTF) in 1996 to house buildings research and to refine and test a new integrated design process. The TTF's clerestory windows maximize the use of natural light and minimize summer cooling loads. A rigid exterior finish minimizes envelope heat transfer. A direct-indirect evaporative air-conditioning system meets cooling loads. And an energy management system monitors and controls internal temperatures, humidity, air pressure, duct pressure, light levels, and carbon dioxide levels.

PIX04116/Warren Gretz

NREL's Thermal Test Facility, Golden, Colorado

Using computer simulations, NREL tested several design concepts before construction. The goal was to reduce building energy requirements by 70%. After construction, simulated performance was compared with actual performance; results included energy cost savings of 51%.

Zion Visitor Center. To develop a new visitor center complex in Zion National Park in southwestern Utah, the National Park Service requested technical support from NREL. Their collaboration lasted throughout the design, construction, and evaluation phases.

The 8,800-ft^2 (817-m^2) main building that opened in May 2000 houses interpretative displays, offices, and retail space. Features include passive direct evaporative cooling, natural ventilation, external shading devices, and glazing that minimizes solar gain in summer and uses it in winter. Also featured are thermal mass sized for the direct-gain system, a Trombe wall, daylighting, PV power, and digital controls to integrate energy operations. The building has 67% lower energy costs than a similar one meeting applicable energy codes.

Summary of energy savings for the six buildings studied

Metric		Oberlin	Zion	Cambria	CBF	TTF[1]	BigHorn
Benchmark	ASHRAE Standard 90.1 Version	2001	1995[2]	2001	2001	1995[2]	2001
Savings[3]	Net Source Energy Savings[4]	79%	65%	42%	22%	45%	54%
	Net Site Energy Savings[5]	79%	65%	42%	25%	42%	36%
	Site Energy Savings[6]	47%	62%	40%	25%	42%	35%
	Energy Cost Savings	35%	67%	43%	12%	51%	53%
Project Goal Comparison	Design Goal or Predicted Performance	Net Site Energy Use: 0.0 kBtu/ft^2·yr	Energy Cost Saving: 80%[7]	Energy Cost Saving: 66%[7]	LEED 1.0 Platinum Rating	Energy Cost Saving: 70%[7]	Energy Cost Saving: 60%[7]
	Measured or Simulated Performance	Net Site Energy Use: 16.4 kBtu/ft^2·yr	Energy Cost Saving: 67%	Energy Cost Saving: 44%	LEED 1.0 Platinum Rating	Energy Cost Saving: 51%	Energy Cost Saving: 53%

1 TTF monitored for select periods; actual data used to calibrate simulations.
2 Code used was 1995 Federal Energy Code, 10 CFR 435 (DOE 1995); based on ASHRAE 90.1-1989 with more stringent lighting power densities.
3 Energy savings for Oberlin, Bighorn, TTF, and Cambria calculated with simulations of as-built and base-case buildings with typical weather data; Zion and CBF savings calculated with measured data and base-case simulations run with measured weather data.
4 Source energy is the energy required to supply energy in the form it is used at the site; the Cambria office building purchases 100% green power, so source energy could be calculated assuming 9% loss for transmission and distribution (EIA 2004).
5 Net site energy use allows credit for electricity generated on site by the PV system.
6 Total site energy use is the total electricity consumed.
7 Predicted energy costs, calculated before construction, may not indicate future performance because of volatile energy prices.

Selected Best Practices

The results of this study suggested several best practices for high-performing buildings:

- Use an integrated design process to system-engineer the building
- Use computer simulations to guide the design process; these help designers analyze trade-offs and examine the energy impacts of architecture and HVAC choices
- Simulate and measure the building's energy performance at design, construction, and occupancy stages
- Set specific, quantifiable energy performance goals
- Design the building envelope to meet or minimize as many HVAC and lighting loads as possible
- Size HVAC and lighting systems to meet loads not met by the envelope
- Use daylighting in all zones adjacent to exterior walls or roofs
- Install highly reflective surfaces in all daylit zones, especially ceilings
- Monitor and evaluate post-occupancy energy performance
- Implement standardized measurement procedures using standard metrics
- Carefully design and implement the use, control, and integration of economizers, natural ventilation, and energy recovery ventilators.

Practices like these can move us closer to new commercial buildings that save considerable energy and produce it, as well.

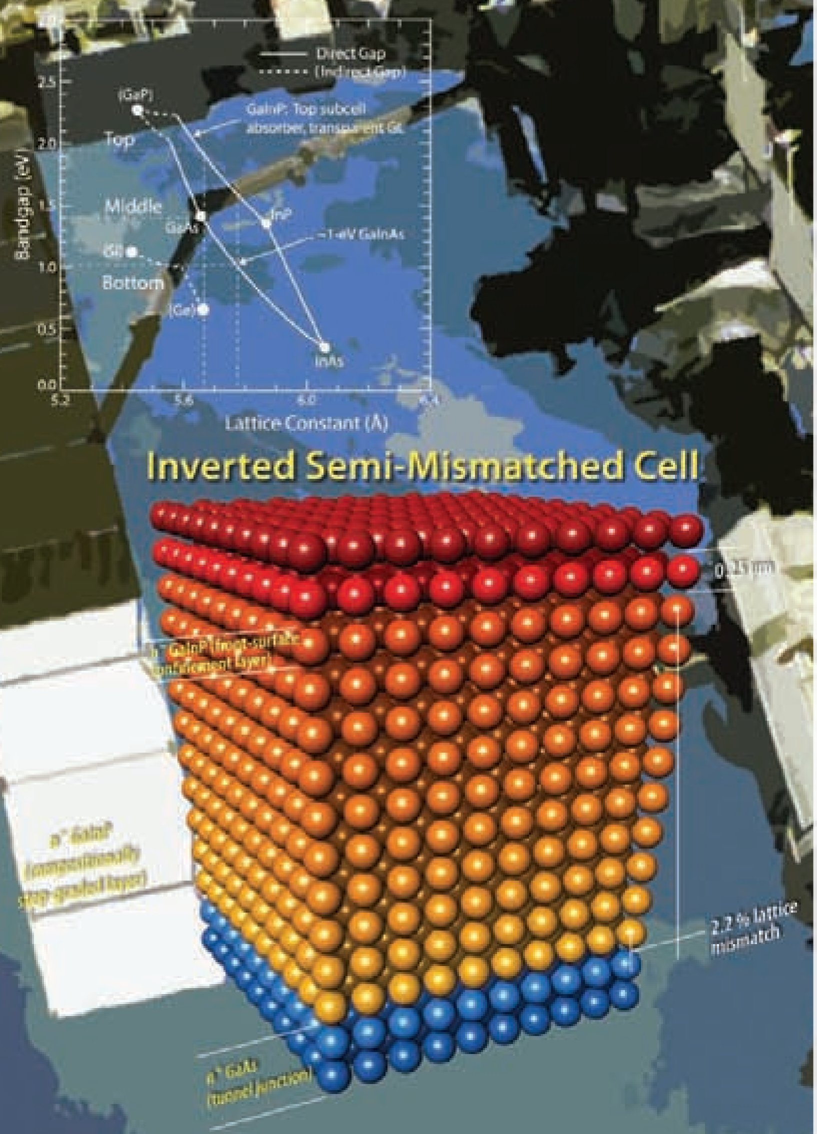
For more information, contact Paul Torcellini, Commercial Building Integration Team Leader, Paul_Torcellini@nrel.gov, and see www.nrel.gov/buildings/highperformance/.

Paul Torcellini examines an in-floor diffuser for the raised-floor air distribution system in the Cambria office building in Pennsylvania.

PIX11001/Robb Williamson

Closing the Gaps

Semi-mismatched semiconductor materials can boost solar device efficiency



In the world of solar cell design, conventional wisdom dictates that things work best when everything lines up properly—in other words, when the spacing of the atoms in one semiconductor layer of a solar device closely matches that of the adjacent layer. However, innovative research often calls for unconventional methods if we are to "build a better mousetrap"—or in this case, a more efficient solar device. The National Renewable Energy Laboratory's work on so-called "semi-mismatched" multijunction solar cells is one example of this.

A primary goal of NREL's solar energy research and development (R&D) is to create photovoltaic (PV) devices—cells and modules—that have excellent conversion efficiencies. A device's conversion efficiency is a measure of how well it uses the energy of sunlight to produce electrical energy. However, three critical "gaps" still get in the way of high efficiencies, as illustrated in Fig. 1.

Peering into the Gaps

These three gaps correlate with different aspects of solar cell R&D. The first gap is the difference between the *theoretical* efficiency of the semiconductor material used in a solar device and the efficiency of the fabricated device, as measured under the best *laboratory* conditions. For example, given certain assumptions, the theoretical best efficiency of a crystalline silicon cell is about 29%. But the top efficiency to date for a crystalline silicon cell measured in the lab is nearly 25%, which leaves us with a 4% gap.

The reasons for this gap include the efficiency losses inherent in the solar conversion process and the difficulty of fabricating a cell with the necessary properties. To overcome this gap, R&D is needed that will identify, explain, and minimize losses; enable the device to collect each photon or packet of light incident upon it; allow the photons to create the maximum number of electrical charge carriers; and make sure the charge

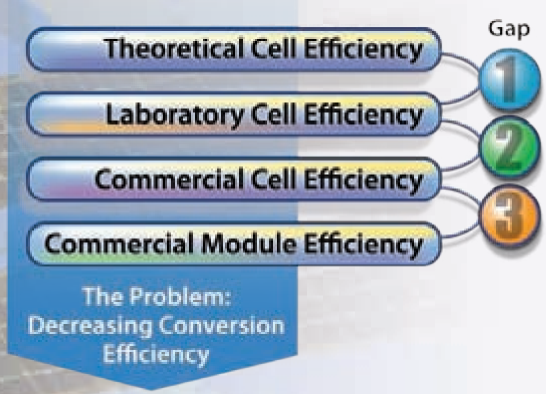


Figure 1. The three efficiency gaps for solar cells and modules

carriers last long enough to contribute to generating a current.

The second gap is the difference between the efficiencies of *laboratory* cells and the efficiencies of those produced in *commercial* production lines. This gap may be a result of scaling up the fabrication process to produce larger devices. Also, in the manufacturing environment, higher throughput is required and fabrication conditions are often less controlled.

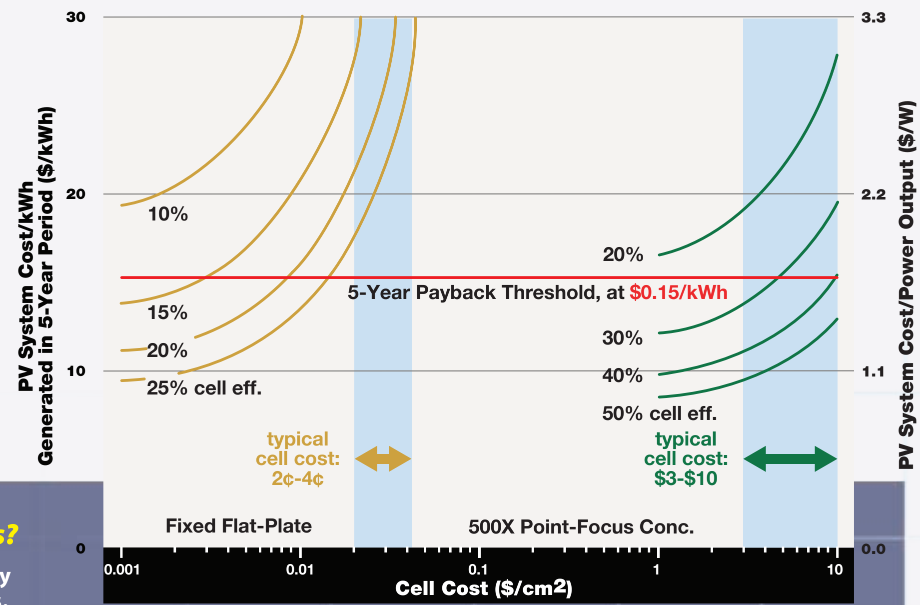
The third gap is the difference between *cell* efficiencies and *module* efficiencies. This gap will narrow when we can do at least three things: minimize the electrical losses that occur when cells are wired into circuits, bring the active area of the module closer to the cell area, and maximize the optical transmission of the protective encapsulant material.

Working in Tandem

Here we address several issues surrounding the first two gaps, focusing on an inverted semi-mismatched solar cell being developed at NREL. NREL's research is being carried out to develop laboratory cells with measured efficiencies closer to theoretical efficiencies, and to address design factors that will lead to more efficient manufactured cells and modules.

NREL's innovations could result in increasingly higher efficiencies as new devices are optimized. In turn, these devices will play an important role in the need for high-efficiency PV devices in space applications, as well as on land, for large-scale power production.

The multijunction or tandem cell has been the focus of R&D at NREL and other laboratories for a few decades. In single-junction cells, the energy of the illuminating light that is below the bandgap of the cell material is lost; thus, it cannot be used to generate electricity. (The bandgap—not



Why Worry About High Efficiencies?

High efficiencies are important because they are indicators of cost-effective solar devices. The cost-effectiveness of a PV system depends on the cell's cost per unit area. To determine a suitable cost range for a cell, researchers from Spectrolab, Inc., and NREL adapted[1] an analytical methodology by Swanson[2]. The PV system's cost per kilowatt-hour over a 5-year payback period was calculated as a function of the cell's cost per unit area, taking into account various assumptions relating to efficiencies, costs, packaging, and solar resources.

As shown, electricity costs for both flat-plate and concentrator systems can fall below 15 cents per kilowatt-hour (a near-term R&D target value) when high efficiencies are combined with low cell costs. Note two families of curves: those for flat-plate systems, requiring very low cell costs, and those for concentrator systems, which can tolerate relatively high cell costs.

The cell costs of flat-plate systems need to range from 0.1 to 1 *cent* per square centimeter, for cost-effective, 20%-efficient cells. In contrast, for concentrator systems with 30%-efficient cells, a cell cost of 1 to 5 *dollars* per square centimeter—which is 500 to 1000 times greater—is cost-effective. The challenge for flat-plate technologies is to reduce today's typical cell costs of 2 to 4 cents per square centimeter by an order of magnitude, while maintaining cell efficiencies of 20%. For concentrator systems, 30%-efficient cells are cost-effective now; the challenge is to reach efficiencies in the 40% to 50% range for even greater cost-effectiveness.

Sunlight is a "dilute" resource, and low-efficiency systems require very large areas of active PV material and all packaging and structural materials, such as metal, glass, and plastic. However, high-efficiency solar cells have at least two benefits: the module area needed for a given electricity output is greatly reduced, and module and balance-of-system costs are highly leveraged. At 500x concentration, relatively high cell costs per area are acceptable. Therefore, taking cell efficiencies into the 40% to 50% range may well be the best path to cost-effectiveness.

1. **R.R. King and others, *Intl. Conf. on Solar Concentrators for the Generation of Electricity or Hydrogen*, 1–5 May 2005, Scottsdale, AZ. NREL/CD-520-38172 (2005).**
2. **R. Swanson, *Prog. Photovolt. Res. Appl.* 8, 93–111 (2000).**

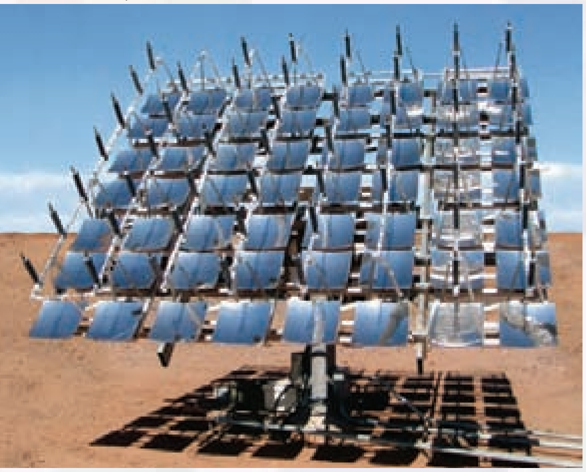
one of the "gaps" discussed here—is the energy needed to dislodge an outer electron from its bond.) The multijunction concept allows a PV device to capture and use this lost energy, resulting in a higher conversion efficiency and thus greater electrical output.

During the early to mid-1990s, NREL researchers developed and patented a two-junction device with high efficiency. The top cell was made of gallium indium phosphide (GaInP), which has a bandgap of ~1.9 electron-volts (eV). The bottom cell was made of gallium arsenide (GaAs), with a bandgap of ~1.4 eV. Earlier GaAs cells had efficiencies exceeding 25% under concentrated sunlight. Adding the GaInP layer to the GaAs layer further boosted the overall cell efficiency by capturing more of the energy in the spectrum.

This concept later evolved into three-junction devices, again with the goal of capturing more useful energy otherwise lost to the cell. One prominent system is made of GaInP / GaAs / germanium (Ge). The third or lowest layer, with a bandgap of ~0.7 eV, captures the long-wavelength, low-energy "red" light that passes unused through the two upper layers. This device is lattice matched, which means that the spacing of atoms in the Ge layer very closely mimics the spacing of the atoms in the GaAs layer above it.

When a crystal is grown through an epitaxial process—in which the overlying crystal has the same orientation as the underlying one—matching keeps the crystal lattice from being deformed at the transition point from one layer to another. Deformed layers—structural defects in the regularity of the crystal lattice, such as threading dislocations and stacking faults—negatively affect the movement of charge carriers through the material and thus reduce the performance of the device.

PIX13740/Arizona Public Service



Concentrating Technologies Microdish configured for Spectrolab multijunction cell

Researchers at NREL and elsewhere decided to develop a third layer having a more optimal bandgap; analyses indicated that material with a 1-eV bandgap could improve overall device efficiency as much as 10%–12%. The dilute nitride of a GaInAsN layer has such a favorable bandgap and is lattice matched to GaAs. However, efficiency measurements of GaInP / GaAs / GaInAsN devices have not been promising.

A logical next step was to investigate a four-junction device consisting of GaInP / GaAs / GaInAsN / Ge, which has a bandgap sequence of 1.9 / 1.4 / 1.0 / 0.7 eV. The efficiency of this device is about 31% at 500 suns; further optimization may boost that number.

Inverting and Mismatching to Increase Efficiency

Design options for some PV device structures based on lattice-matched epitaxy are constrained by the limited number of commercially available crystalline substrate materials (Ge and GaAs, for example). However, the "design space" increases substantially when we consider designs involving lattice-mismatched layers.

Traditionally, lattice-mismatched approaches have been dismissed because of problems such as high defect density, rough surfaces, and cracking or bowing of layers. At NREL, the goal is to produce semi-mismatched lattice heterostructures that look and perform like lattice-matched ones. In the process, we want to attain the highest charge-carrier lifetimes, the thinnest structures, and the flattest wafers possible.

Mark Wanlass and his colleagues in NREL's High-Efficiency Solar Cell team are pursuing a novel tandem cell approach. One key innovation involves growing the cell layers in inverted order; this approach could have several cost and manufacturing benefits and boost efficiency, as well. Another innovation is to incorporate a transparent, compositionally step-graded layer to accommodate lattice mismatching without penalizing cell efficiency.

Figure 2 illustrates the basic layer-cake structure of the inverted GaInP / GaAs / gallium indium arsenide (GaInAs) cell. The structure is considered to be inverted because it is grown upside down—that is, the top layer is grown on a substrate, then the next two main "active" subcell layers are deposited. In actual operation, the stack is flipped so that sunlight strikes the top subcell first.

The top two active subcell layers are lattice matched. A 1.9-eV top active layer of GaInP is deposited on a GaAs substrate before a 1.4-eV middle active layer is added. Each active subcell layer actually has a double-heterostructure configuration; this means the active material is sandwiched between thin layers of material with a somewhat higher bandgap. This configuration confines the charge carriers to the active subcell layer. Each active subcell layer also contains an n/p junction. The GaInP active subcell layer is sandwiched between negatively (n) and positively (p) doped aluminum indium phosphide (AlInP) to form the top subcell. Similarly, the GaAs active subcell layer is sandwiched between n- and p-doped GaInP to form the middle subcell.

The lowest (third) active subcell layer is made of GaInAs, with a bandgap of ~1.0 eV, and is sandwiched between GaInP layers to form a double-heterostructure bottom subcell. The GaInAs lattice is mismatched 2.2% in comparison to the lattices of GaInP and GaAs. To accommodate this mismatch, a compositionally step-graded

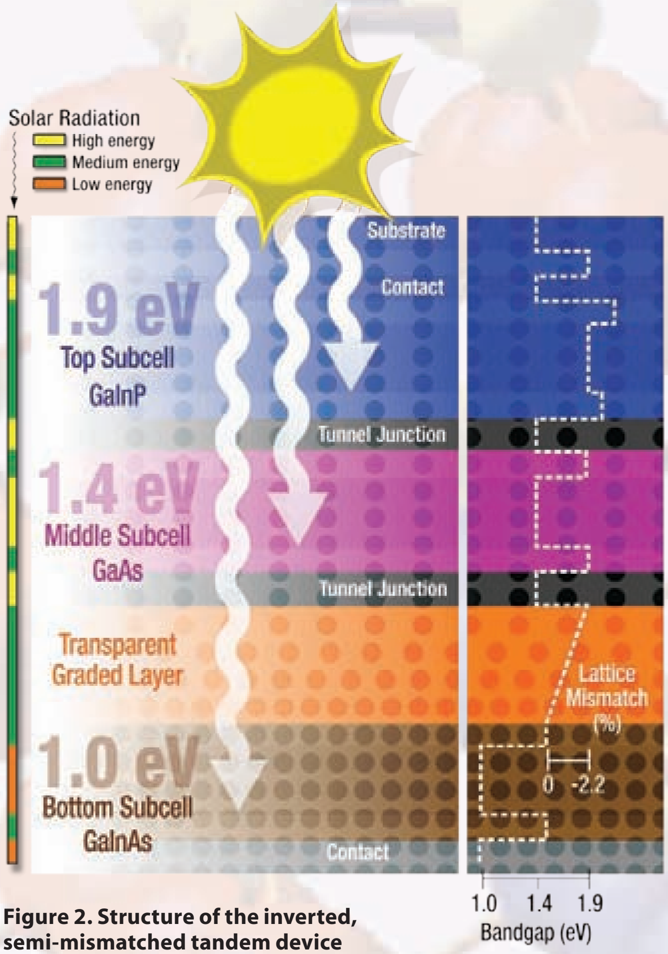


Figure 2. Structure of the inverted, semi-mismatched tandem device

layer of GaInP is included between the middle and bottom subcells. In detail, the transparent graded layer consists of nine 0.25-micrometer-thick steps that differ in composition from one another by 0.03 fractional percent Ga. Significantly, although cross-sectional transmission electron microscopy shows substantial defects in this graded layer, it identifies only a modest dislocation density in the active subcell layer.

The overall tandem cell is a two-terminal, monolithic device. In other words, individual subcells are not grown separately and then stacked mechanically. Rather, all subcells are grown in one continuous depositional process—in this case, by atmospheric-pressure metal-organic vapor-phase epitaxy in a system built by NREL. Layers of heavily p- and n-doped GaAs form "tunnel junctions" between the subcells, thus allowing charge carriers to move through the entire device, and front and back electrical contacts gather the cell's current.

The device's monolithic structure makes it relatively easy to manufacture in comparison to mechanically stacked devices. But to optimize the device, we must adjust the thicknesses of each subcell so that the photocurrents of each are the same. Otherwise, in a series-connected device, the subcell with the lowest photocurrent will be the limiting factor in regard to the current of the overall cell.

Seeing the Benefits

As PV researchers work diligently to overcome such performance gaps as the discrepancies in conversion efficiencies found in solar cells, this inverted GaInP / GaAs / GaInAs cell is a significant step forward. NREL has confirmed an efficiency of 37.9% at 10.1 suns (and a temperature of 25°C, a low aerosol optical depth air mass of 1.5 direct, and an area of 0.2428 cm^2); this is a very encouraging number for a device that has yet to be optimized.

The peak efficiency at such a low concentration ratio indicates that efficiencies exceeding 40%—perhaps as high as 45%—at several hundred suns should be achievable in the near future, once a true concentrator version is fabricated. Such high efficiencies should enhance the viability of terrestrial concentrator systems for cost-effective power generation.

Some key benefits of this design are that the device can be mounted on a surrogate substrate—or "handle"—of choice, and contact with a heat sink can also be achieved, which helps to manage the thermal issues of the concentrator cell. If it is composed of some strong, flexible material such as metal foil or kapton polymer, the handle can provide a robust device in comparison to one processed on relatively fragile Ge or GaAs substrates.

Handle-mounted, ultra-thin device fabrication is a natural consequence of the inverted-structure approach, which also has a number of advantages. These include potentially low cost, the ability to make use of back-surface reflectors, and possible reclamation or reuse of the parent crystalline substrate (e.g., to reclaim the relatively scarce, expensive Ga in a GaAs substrate).

Looking Ahead

Optimizing the inverted cell will shrink its performance gaps further. And other materials, designs, and methods will undoubtedly be explored in the pursuit of higher efficiencies. So, whether NREL's researchers are developing silicon-based, thin-film, or so-called "third-generation" PV technologies, one key objective prevails: to close the gaps and thus create even more efficient cells—cells that can be produced at lower cost while exhibiting greater reliability and stellar performance.

For more information

R.R. King, R.A. Sherif, G.S. Kinsey, S. Kurtz, C. M. Fetzer, K.M. Edmondson, D.C. Law, H.L. Cotal, D.D. Krut, J.H. Ermer, and N.H. Karam. "Bandgap Engineering in High-Efficiency Multijunction Concentrator Cells." 3rd International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, May 1-5, 2005, Scottsdale, AZ, NREL/CP-520-38172.

S. Kurtz, M. Wanlass, C. Kramer, M. Young, J. Geisz, S. Ward, A. Duda, T. Moriarty, J. Carapella, P. Ahrenkiel, K. Emery, K. Jones, M. Romero, A. Kibbler, J. Olson, D. Friedman, W. McMahon, and A. Ptak. "A New GaInP/GaAs/GaInAs, Triple-Bandgap, Tandem Solar Cell for High-Efficiency Terrestrial Concentrator Systems." 2005 Solar Program Review Meeting, Denver, CO, November 2005, NREL/CP-520-38997.

M.W. Wanlass, S.P. Ahrenkiel, R.K. Ahrenkiel, D.S. Albin, J.J. Carapella, A. Duda, J.F. Geisz, S. Kurtz, T. Moriarty, R.J. Wehrer, and B. Wernsman. "Lattice-Mismatched Approaches for High-Performance, III-V Photovoltaic Energy Converters." 31st IEEE PV Specialists Conference, Lake Buena Vista, FL, January 3-7, 2005, NREL/CP-520-37440.

M.W. Wanlass, S.P. Ahrenkiel, D.S. Albin, J.J. Carapella, A. Duda, J.F. Geisz, K. Jones, S. Kurtz, T. Moriarty, and M.J. Romero. "GaInP/GaAs/GaInAs Monolithic Tandem Cells for High-Performance Solar Concentrators." NREL/CP-520-38646, 2005.

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

NREL/BR-840-38668 • June 2006

Printed with renewable-source ink on paper containing at least
50% wastepaper, including 10% post consumer waste.