U.S. Department of Energy's

National Renewable Energy Laboratory
2002 Research Review

NREL

25 Years of Research Excellence 1977-2002

Transitions To A New Energy Future

Twenty-eight years ago, the first oil embargo was a rude awakening to our vulnerability to energy supply disruptions. But that oil embargo spurred Congress to create the Solar Energy Research Institute—designated a national laboratory and renamed the National Renewable Energy Laboratory in 1991—to help develop the technology to make it possible to achieve a transition to a new energy future.

What has happened since SERI/NREL first began operating 25 years ago? America uses nearly 50% more renewable energy than it did then. We are witnessing the emergence of markets based on new energy technologies. America is employing energy efficiency on a grander scale, decreasing its energy intensity (energy used per dollar of gross domestic product) by about 1% per year.

Yet, today America is more dependent on foreign oil than ever. We use more natural gas and 75% more coal than we did in 1977. Driven largely by economic growth, our energy consumption has jumped by about 23 quads (where one quad equals 10^{15} Btus), with less than 3 quads of that increase coming from renewable energy. This has resulted in large increases in greenhouse gas emissions and in air pollutants.

In light of these facts, is it still possible to achieve sustainable energy use? Yes—in the long run. We must remember that it took 50 years from the building of the first oil refinery until oil provided 10% of America's energy mix, and 60 years for natural gas to do likewise.

In the short term, with a portfolio of new energy technologies and an enlightened public policy, we will produce incremental changes. But these changes will, working with the existing energy infrastructure, begin to build exponentially to become significant in two, three, or four decades. And in the long term, what started as small changes will grow to become a paradigm shift in how America uses energy.

At the heart of this shift will be technology. And at the heart of the technology will be NREL. For the past 25 years, NREL has helped build a foundation of renewable energy and energy efficiency science and technology to put sustainable energy use within reach. For the next 25 years and more, NREL will remain at the technology forefront to spur various transitions toward sustainable energy. This silver anniversary first biennial *2002 Research Review* lays out a series of key transitions that will allow us to move toward a sustainable world and indicates ways in which NREL and its partners are making that possible.

Wind and solar electricity markets, for example, are growing at rates greater than 30% per year. With help from advances such as NREL's advanced airfoil designs, wind power is already nearly competitive with some fossil-fuel main-

The 2002 Research Review

This Silver Anniversary *2002 Research Review* is intended as the first in a series of biennial overview reports on research progress at NREL. These reports will become part of a series of semiannual journals, with the regular journal issues exploring particular NREL research efforts in depth.

grid electricity generation. With potential in the Great Plains alone to generate all of America's electrical needs, wind power could soon become a major energy contributor, especially as we develop the technology that enables wind turbines to produce competitive electricity in low-wind-speed regimes.

As the solid-state approach to converting solar energy to electricity, photovoltaic (PV) solar cells are the epitome of "futuristic" energy and are the best choice for high-tech applications such as communications satellites and space shuttles. They also are becoming a preferred choice for remote applications, for distributed generation, and for applications in which PV can be integrated directly into the façade or structure of buildings. NREL's research on innovative concepts that could help drop costs significantly also could make solar electricity a preferred choice for main-grid power in another couple of decades.

But the future could easily bring a move away from reliance on main-grid power or even electricity as the only energy carrier. New modular technologies (small gas turbines, fuel cells, solar cells, wind turbines, bioelectricity) and market needs—such as high-quality power for high-tech companies—have created opportunities for electrical generation at the user site. In the section on distributed energy resources, we explain how NREL works on improving the institutional as well as the technological ability to integrate these distributed energy resources with the electrical generation system.

Hydrogen, like electricity, is easy to transport and burns cleanly, so makes a great energy carrier. And because hydrogen can be produced and used as part of a clean, cyclic process when generated with a renewable source, it represents one of our most promising paths toward a sustainable energy future. In the section on the hydrogen economy, we describe several technologies that NREL researchers are exploring to cleanly and efficiently produce hydrogen with renewable energy.

When it comes to reducing vulnerability to dependence on foreign oil, it is vitally important to develop alternative transportation fuels. NREL leads efforts to develop technology to produce fuel ethanol from lignocellulosic biomass—the bulk of most plant materials. In the section on biorefineries, we describe how this technology and five other core biomass technologies can be used not only to produce fuel but also to make plastics, fibers, and other products now derived from chemicals produced at oil refineries from petroleum. These six biomass technologies are the platforms from which we can build the biomass economy and the biorefinery concept into a significant presence.

Hand-in-hand with research on fuels and products from biorefineries goes NREL's research on transportation technologies. This includes research to make transportation vehicles cleaner and more efficient, from "cool cars" that save on air-conditioning, to clean diesel engines and designer fuels, to vehicles that run on alternative fuels, to hybrid electric vehicles. All of which will help reduce demand for foreign oil.

And last but not least, as with money, the best way to make energy is to save energy. In the section on energy-efficient buildings, we describe a whole-building design approach, and a variety of technologies such as solar heating, natural daylighting, and building-integrated photovoltaics that NREL is developing to reduce energy use in homes and commercial buildings. Efficient design and modern technology will enable us to develop zero-energy buildings—where a building's energy use will be reduced to zero—an attainable goal for homes built during the next 25 years.

Each of these energy transitions will be important in its own right and will contribute to America's economy and to its path toward greater energy security. But taken together, they represent a formidable force that could pave the way to a new energy paradigm and a truly sustainable energy future.

25 Years of Research Excellence 1977-2002

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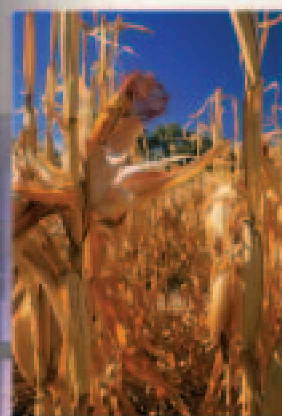
The Biomass Economy

The 20th century was the century of the petrochemical economy. Gasoline and diesel (made from petroleum) power almost all our vehicles. Myriad plastics made from petroleum or natural gas are used to make our clothes, carpets, food packaging, and increasingly, our car parts and building materials. Most of our chemicals and even toiletries and pharmaceuticals are petrochemically derived.



Current ethanol production is primarily from the starch in kernels of field corn. NREL researchers are developing technology to also produce ethanol from the fibrous material (cellulose and hemicellulose) in the corn husks and stalks or in other agricultural or forestry residues.

Unfortunately for the United States, most of the world's petroleum is located elsewhere, so we import more than half of what we use, creating heavy economic and security burdens. And unfortunately for the world, whenever gasoline, diesel, and other fossil fuels are burned, they release carbon dioxide that had been locked up underground for millions of years, increasing greenhouse gas levels.

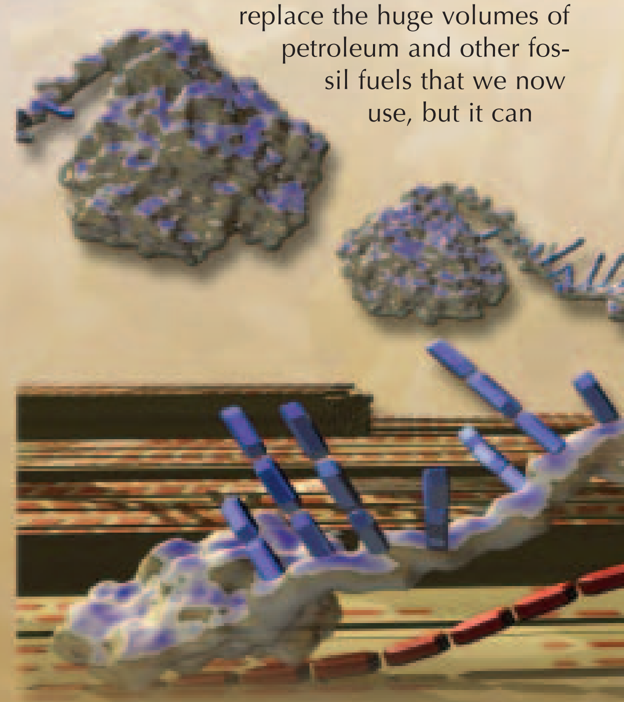
In the 21st century, use of biomass—plants and plant-based materials, produced by photosynthesis within biological rather than geologic time—will offset this petrochemical dependence. Biomass can't fully replace the huge volumes of petroleum and other fossil fuels that we now use, but it can

Biomass Conversion Facilities

NREL has world-class facilities for testing technologies that would be used for biorefineries. These facilities are available to NREL researchers as well as to NREL's research partners, under a variety of agreements.

On the biological side, NREL has a one-ton-per-day-feedstock bioethanol pilot plant that can take cellulosic biomass all the way from feedstock preparation through pretreatment, hydrolysis, and fermentation to distillation of fuel ethanol. The plant is certified to handle metabolically engineered fermentation organisms such as NREL's *Zymomonas mobilis*, can use any of several pretreatment options, and includes complete process monitoring.

On the thermochemical side, the Thermochemical Users Facility simulates thermochemical processes such as gasification, combustion, and pyrolysis. The facility includes cyclonic and fluidized bed reactors for pyrolysis or gasification and can easily accommodate research partners' reactors. A variety of secondary reactor and condensation equipment is available, and conversion products can be analyzed online with molecular beam mass spectrometry, fourier transform infrared spectrometry, infrared spectrometry, or gas chromatography.



Artistic rendition of a cellulase enzyme breaking cellulose down to component sugars. NREL's understanding and contin-

provide fuels and chemicals comparable to those derived from petroleum. American farmers and foresters can fuel as well as feed and house America—in a sustainable fashion.

During the past 25 years, NREL researchers have developed an impressive slate of core biological, physical, chemical, and engineering skills for biomass technologies. With primary responsibility for carrying out U.S. Department of Energy Biomass Programs, NREL's National Bioenergy Center is at the forefront of efforts to develop the biological and thermochemical technologies that will allow economically and environmentally responsible production of fuels, chemicals, and power from biomass to meet modern-day needs—the biomass economy.

Six Biomass Platforms

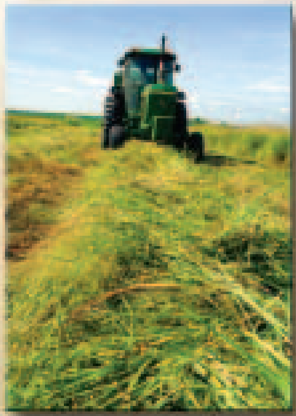
In 2000 and 2001, biomass, largely because of biomass power—combustion of materials such as timber industry scrap or municipal solid waste to generate electricity—surpassed hydroelectric power as the largest U.S. source of renewable energy. And in 2002, U.S. production of fuel ethanol, made from corn grain (starch), will surpass 2 billion gallons per year, displacing a modest but significant amount of imported oil. Also in 2002, a collaborative venture of two major companies began production of polylactic acid plastic made from biomass for clothing and packaging.

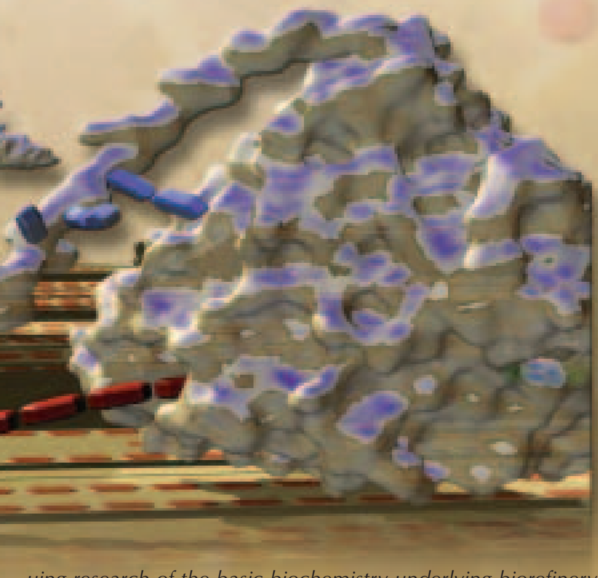
NREL researchers, who have made important contributions to each of these developments, are working to improve and greatly expand these technologies through six different core technologies or "platforms" for building the biomass economy. Just as oil refineries break down petroleum and natural gas into numerous materials that then serve as commodity or platform chemicals that the petrochemical industry can use to make a multitude of final products, these six biomass technology platforms will provide the base chemicals for making biobased fuels and products.

The Sugar-Lignin Platform. One out of eight gallons of gasoline sold in the United States already includes ethanol as an additive. Ethanol is made by fermenting sugar, most of which is derived from starch in corn kernels. In contrast, instead of starting with sugar, NREL's advanced bioethanol technology starts with cellulose and hemicellulose, two of the three main components of most plant material—vastly expanding potential feedstocks—breaking them down to sugars for fermentation. In addition to ethanol, the sugars, or intermediate breakdown products, can be fermented, polymerized, or otherwise processed into any number of products. Lignin, the third main component of biomass, can fuel the process or be used to produce a slate of different chemicals, expanding the number of products for the sugar-lignin platform biorefinery. (See sidebar "Lignocellulosic Bioethanol.")

The Syngas Platform. If biomass is heated with limited oxygen (about one-third that needed for ideal combustion), it gasifies to a "syngas" composed mostly of hydrogen and carbon monoxide. That syngas inherently burns cleaner and more efficiently than the

Switchgrass, which can be easily grown throughout much of the United States, represents a huge future resource of lignocellulosic biomass for use in biorefineries.





uing research of the basic biochemistry underlying biorefinery processes are key to major technology advances.

Biomass Characterization Technology

One reason NREL is so effective in biomass technology research and development is because of its capabilities to analyze biomass and intermediates from its processing. Biomass gasification and pyrolysis both require precise characterization of the breakdown products being generated, so that processes can be fine-tuned to produce optimal end products.

NREL uses sophisticated molecular beam mass spectrometry and has developed a portable system that could have great value for syngas and bio-oil platform industries.

NREL's R&D 100 Award-winning Rapid Biomass Analysis system quickly and inexpensively characterizes chemical and mechanical properties of raw or processed biomass. Using near-infrared spectrometry correlated by multivariate analysis, it characterizes in minutes what would otherwise require three or four days and cost far more. Opportunities for use in the lumber and paper industries, let alone biorefineries, are almost limitless. NREL researchers are currently using this approach to analyze variations in corn stover composition and their implications for ethanol production.

raw biomass. NREL scientists are using gasification technology to improve a large innovative biomass power plant in Vermont (see sidebar "Vermont Gasifier") and to provide electricity for the first time to isolated Philippine villages with small electric generators. The syngas also can be used to produce hydrogen (see "Hydrogen Economy" on pages 10-13) which, in turn, can be used as a fuel or to make plastics, fertilizers, and a wide variety of other products. Syngas can also be converted to sulfur-free liquid transportation fuels using a catalytic process (known as the Fischer-Tropsch Process), or provide base chemicals for producing biobased products.

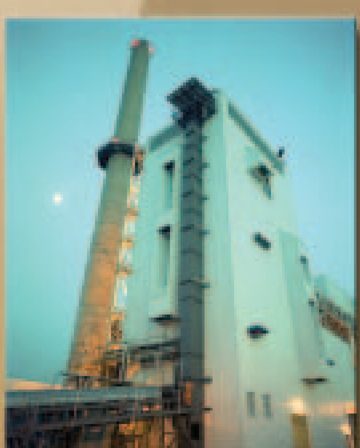
A researcher examines a beaker containing cellulase enzymes, a key element in producing ethanol from lignocellulosic biomass.

The Bio-Oil Platform. If biomass is heated to high temperatures in the total absence of oxygen, it pyrolyzes to a liquid that is oxygenated, but otherwise has similar characteristics to petroleum. This pyrolysis- or "bio-" oil can be burned to generate electricity or it can be used to provide base chemicals for biobased products. As an example, NREL researchers have extracted phenolics from bio-oil to make adhesives and plastic resins. NREL uses several thermochemical reactor systems—available for use by outside researchers—to efficiently pyrolyze and control the bio-oil components. NREL scientists have also used pyrolysis for "true recycling" of plastics such as nylon carpeting, selectively regenerating the base chemicals from which the plastics were made.

The Biogas Platform. Another way to convert "waste" biomass into useful fuels and products is to have natural consortiums of anaerobic microorganisms decompose the material in closed systems. Anaerobic microorganisms break down or "digest" organic material in the absence of oxygen and produce biogas as a waste product. Biogas produced in closed tanks, or anaerobic digesters, consists of 50% to 80% methane, 20% to 50% carbon dioxide, and trace levels of other gases such as hydrogen, carbon monoxide, oxygen, and nitrogen. NREL has developed an anaerobic digestion system that handles much higher solids loading than typical digesters. This system effectively converts cellulosic waste (such as municipal solid waste) and fatty waste (such as tuna cannery sludge) to a methane-rich biogas suitable for power generation (or as a starting material for biobased products) and usable compost material. Anaerobic digesters are currently getting considerable attention as a way to turn swine and cattle manure into useful fuel and chemicals.

The Carbon-Rich Chains Platform. Plant and animal fats and oils are long hydrocarbon chains, as are their fossil-fuel counterparts. Some are directly usable as fuels, but they can also be modified to better meet current needs. Fatty acid methyl ester—fat or oil "transesterified" by combination with methanol—substitutes directly for petroleum diesel. Known as biodiesel, it differs primarily in containing oxygen, so it burns cleaner,

Vermont Gasifier



The Vermont gasifier, one of the first large-scale demonstrations of biomass gasification, supplies clean, renewable fuel from biomass to the McNeil Biomass Power Generating Station in Burlington, Vermont.

At the McNeil Biomass Power Generating Station in Burlington, Vermont, NREL researchers helped design and install an R&D 100 Award-winning gasification system. The project is one of two major DOE projects to develop technology to dramatically improve the efficiency and air emissions quality of biomass power systems. The McNeil Station already is successfully burning up to 200 tons per day of gasified wood chips in its normal steam generator. Once the gas is hooked up to a planned gas turbine, efficiency should be double that of a combustion-boiler generation system.

either by itself or as an additive. Biodiesel use is small but growing rapidly. In the United States, it is made mostly from soybean oil and used cooking oil. Soybean meal, the coproduct of oil extraction is now used primarily as animal feed, but also could be a base for making biobased products. Glycerin, the coproduct of making biodiesel, is already used to make a variety of products, but has potential for many more. And the fatty acids are used for detergents and other products. So carbon-rich chains are already well on their way as a platform for the biorefinery.

The Plant Products Platform. Modern biotechnology not only can transform materials extracted from plants, but can transform the plants to produce more valuable materials. Selective breeding and genetic engineering can be used to improve production of chemical, as well as food, fiber, and structural products. Plants can be developed to produce high-value chemicals in greater quantity than they do naturally, or even to produce compounds they do not naturally produce. With its genetic engineering, material and economic analysis, and general biotechnology expertise, NREL could make major contributions in this exciting arena. For example, NREL researchers exploring variation in composition of stover for various strains of corn are analyzing the impact this makes on producing ethanol from stover.

Moving to Biorefineries

As exciting as these six platforms are, biorefineries will not happen overnight. The oil refineries, and the corn wet-mills and pulp and paper plants (the biorefineries of today) that they would parallel, are highly complex and very expensive. No new U.S. oil refineries have been built in the past 30 years. Corn wet-mills produce a variety of food products—as well as ethanol—from starch, but most new ethanol plants are smaller dry mills producing just ethanol and animal feed. To overcome the challenge and complexity of producing a slate of products starting with lignocellulosic material instead of oil or starch will require enhanced technology development. NREL is providing the foundation for this to occur.

Two important concepts are guiding NREL's efforts to create novel, successful biorefineries—taking maximum advantage of intermediate products and balancing high-value/low-volume products with high-volume/low-value fuels. High-value bioproducts may meet special needs and generate market excitement, but high-volume fuels are what America needs to reduce its dependence on foreign oil and to improve the environment.

Biorefineries will not eliminate the need for petrochemicals. But they will play a key role in reducing our level of dependence on imported petroleum and making the 21st century one of an increasingly sustainable, domestic, and environmentally responsible biomass economy.

Lignocellulosic Bioethanol

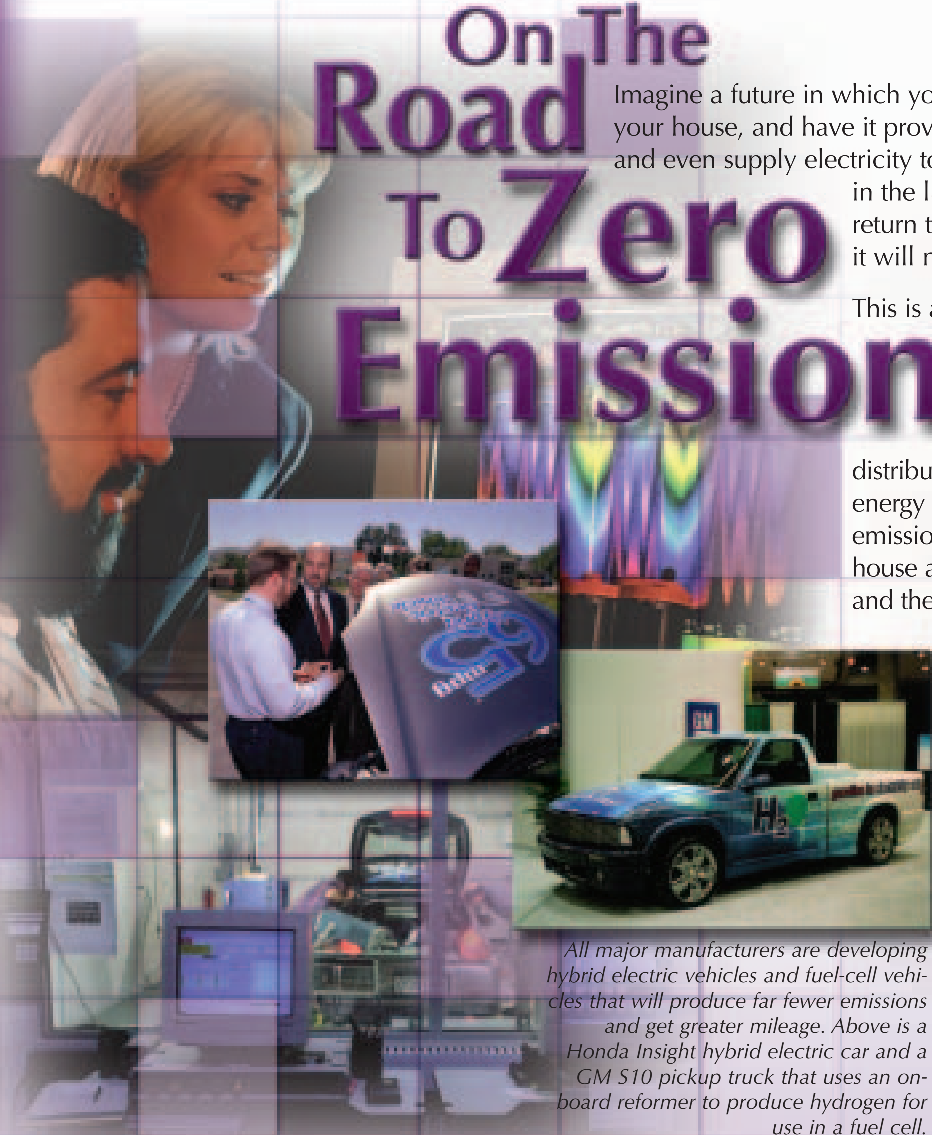
NREL and the corn-starch-to-fuel-ethanol industry have grown up together during the past 25 years. NREL has contributed significantly to the industry maturing to one utilizing energy-efficient technologies.

NREL researchers are focusing on the challenge of producing bioethanol from lignocellulosic biomass instead of corn starch. Toward this end, NREL researchers already have developed effective technology to thermochemically pretreat biomass; to hydrolyze hemicellulose to break it down into its component sugars and open up the cellulose to treatment; to enzymatically hydrolyze cellulose to break it down to sugars; and to ferment both five-carbon sugars from hemicellulose and six-carbon sugars from cellulose. This entire process has been integrated using an NREL-patented R&D 100 Award-winning metabolically engineered bacteria—*Zymomonas mobilis*. Using a one-ton-feedstock-per-day bioethanol pilot plant, NREL researchers are testing and improving these technologies under conditions that simulate industrial production.

Bioethanol and the biorefinery concept are closely linked. The cellulosic ethanol technology developed by NREL will open the door to making a wealth of other products. Just as cellulose and hemicellulose are polymers of sugars, new polymers can be made from those sugars. Biodegradable plastics and natural, nontoxic herbicides are just some of the possibilities NREL researchers are exploring.

NREL uses a one-ton-per-day pilot plant to test bioethanol technologies, including NREL's metabolically engineered bacteria, Zymomonas mobilis, *which enables the cofermentation of cellulose and hemicellulose.*

On The Road To Zero Emissions



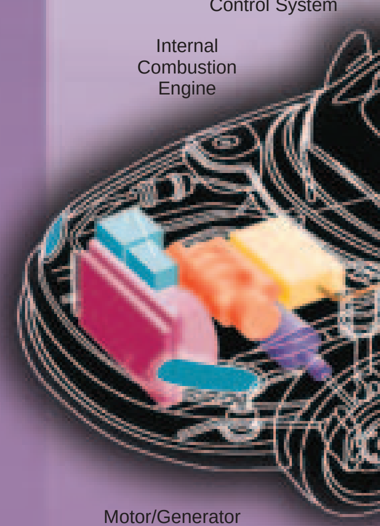
Imagine a future in which you drive home from work, plug your car into your house, and have it provide electricity for evening lights and meals and even supply electricity to the grid for the community's benefit. Then, in the lull of the night, your house or the grid will return the favor to produce for your car the energy it will need for the next day.

This is a technically possible future because your car could well be a fuel-cell car that uses hydrogen to produce electricity (see "Hydrogen Economy" on pages 10-13). Your car could become a distributed generator and your house a producer of energy and a refueling station. Concurrently, the emissions resulting from the use of energy for your house and car can approach zero, if the hydrogen and the electricity are produced using renewable energy resources and technologies.

For America's transportation sector, striving toward such a future is vitally important. Our transportation is almost entirely dependent on oil, nearly 60% of which arrives in tankers from foreign shores. And our use of petroleum in transportation translates directly into huge emissions of pollutants and greenhouse gases.

All major manufacturers are developing hybrid electric vehicles and fuel-cell vehicles that will produce far fewer emissions and get greater mileage. Above is a Honda Insight hybrid electric car and a GM S10 pickup truck that uses an on-board reformer to produce hydrogen for use in a fuel cell.

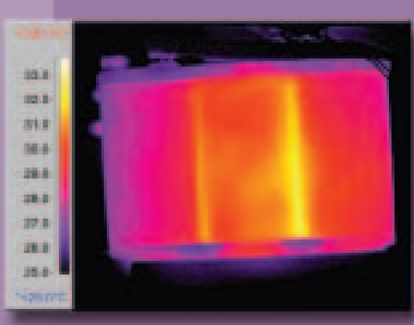
It is against this backdrop that Secretary of Energy Spencer Abraham announced the FreedomCAR program, for research into "advanced, fuel-cell technology, which uses hydrogen to power automobiles without creating pollution. The long-term results of this…effort will be cars and trucks that are more efficient, cheaper to operate, pollution free, and competitive."



Going Farther for Less

Areas of the country that have air-quality problems will soon require the introduction of ultra-low-emission vehicles into the transportation mix. One strategy to meet the emissions requirements is with hybrid electric vehicles. By 2010, there may be as many as 250,000 HEVs sold in America.

HEVs often use nickel metal-hydride (NiMH) batteries because they have greater energy density and last longer than the more familiar, less expensive lead-acid batteries.



Thermal infrared image of lead-acid battery during 5-amp overcharge shows temperature variation of 26°C to 33°C.

But things may be about to change, thanks to an R&D 100 Award-winning technology developed by NREL, Recombination Technologies, and Optima Batteries. Lead-acid batteries have traditionally been charged at a constant current and voltage. This constant-charge strategy does not sufficiently recharge the negative plate in the battery, and leads to a premature end of battery life.

NREL and its partners devised a clever, inexpensive technique—a current-interrupt charging algorithm—for charging the batteries properly. The technique involves overcharging the battery for 5 seconds then allowing it to rest for 5 seconds. The rest period permits the battery to cool and prevents it from going into a gassing cycle.

This algorithm, which increases battery life by three- to four-fold, enables lead-acid batteries to be competitive with NiMH batteries in terms of life cycle.

Multifaceted R&D Effort

Although the program and its emphasis are new, the long-term goals are familiar—greater energy independence, reducing emissions, and building a hydrogen-supply infrastructure. They are ones that NREL has been supporting for years under DOE guidance.

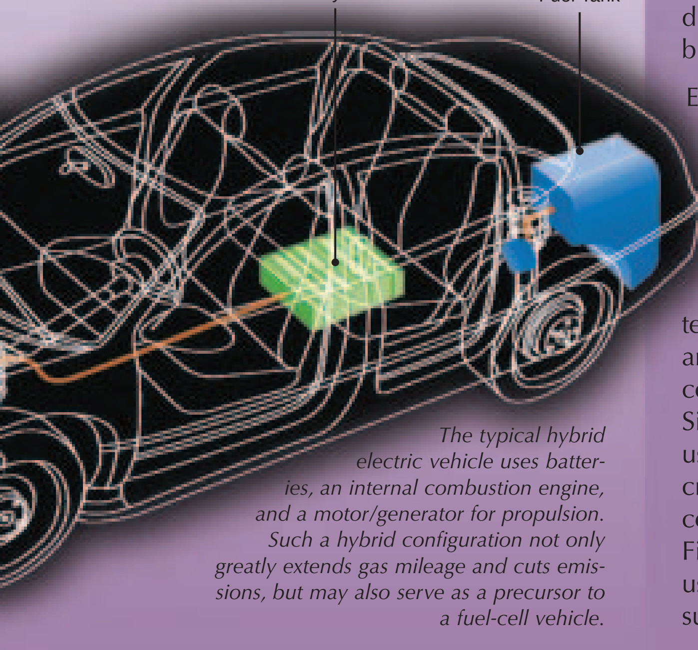
Achieving these goals requires a multitiered approach and will involve many players—auto and component manufacturers, the energy industry, government agencies, and national laboratories. For its part, NREL is helping the nation realize these goals through two general pathways: the development of advanced vehicles, systems, and components; and the testing and development of alternative fuels.

The Advanced Vehicle Pathway

A drawback of our current transportation system is that it relies heavily on internal combustion engines, which are quite inefficient—the typical gasoline internal combustion engine for cars converts less than 18% of the heat energy in gasoline into kinetic energy for the car. An alternative is the electric vehicle, whose efficiency can be greater than 60% and whose operation does not generate emissions. However, the most popular choice for powering electric vehicles—batteries—provides only a short driving range. But by combining internal combustion with electric propulsion, you get the best of both worlds: a hybrid electric vehicle (HEV) with a very good driving range, significantly increased efficiency over the internal combustion engine, and greatly reduced emissions.

You also get a pathway to the future fuel-cell vehicle—where fuels cells will eventually replace the engine in a hybrid electric vehicle. Toward this future, NREL emphasizes a systems approach, in which we analyze subsystems and components to determine how they may best be integrated to optimize vehicle performance. To do this, we develop interactive modeling tools and make them available to others so that they may more quickly optimize their designs of components and HEV systems (see sidebar "Accelerating Clean Vehicle Development").

One of the subsystems we analyze is the battery pack and its thermal management. Different batteries tend to operate best at particular temperature ranges, which can change with the cycling of the



The typical hybrid electric vehicle uses batteries, an internal combustion engine, and a motor/generator for propulsion. Such a hybrid configuration not only greatly extends gas mileage and cuts emissions, but may also serve as a precursor to a fuel-cell vehicle.

Accelerating Clean Vehicle Development

Car manufacturers are developing advanced vehicles that will use less fossil fuel and run cleaner. NREL created ADVISOR (ADvanced Vehicle SimulatOR) to help accelerate that development. ADVISOR is an analysis software package that provides fast and accurate simulations of vehicle configurations with an emphasis on advanced powertrains and on optimizing designs for fuel efficiency and reduced emissions. It allows engineers to simulate nearly endless design options, reducing the time and the expense for building and testing prototypes.

NREL's ADVISOR software analysis package uses interactive simulation to allow the user to interactively control the vehicle and to view vehicle and component response during the simulation.

Easy to use, flexible, and robust, ADVISOR uses three primary graphical interface screens to guide the user through the simulation process. With the Vehicle Input screen, the user chooses a predefined vehicle to test, or creates a new vehicle from an extensive data base of vehicle components and configurations. The Simulation Setup screen allows the user to test that vehicle under an incredible range of simulated test procedures, driving cycles, and loads. Finally, with the Results screen, the user can view second-to-second results from 127 output variables. This is an iterative process that enables the designer to vary the parameters and optimize vehicle characteristics.

ADVISOR is primarily used to quantify the fuel economy, performance, and emissions of vehicles that use advanced technologies such as fuel cells, batteries, and electric motors for hybrid electric vehicles, as well as conventional technologies such as internal combustion engines.

ADVISOR has attracted a rapidly growing worldwide community of users who incorporate it into their own software programs. Users include automotive manufacturers and suppliers, universities for research and training of engineers, research laboratories, and government organizations.

battery. Temperature variations from module to module can affect performance and life. Our analysis can point to ways in which to manage the temperature of the battery subsystems, for best performance (see sidebar "Going Farther for Less").

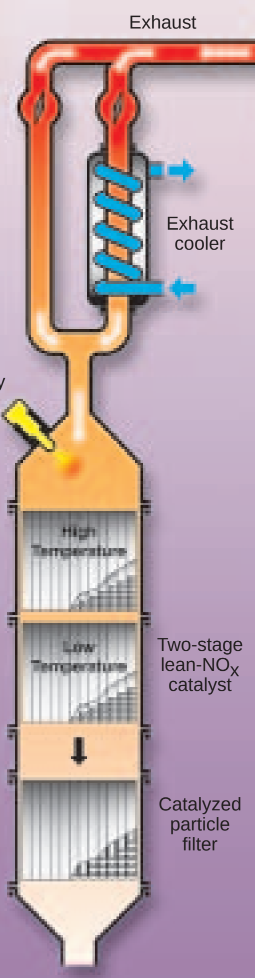
Other important subsystems are those that help determine the comfort of the passenger—heating, ventilation, cooling, and keeping the air clean. These auxiliary systems can consume a large amount of energy. NREL uses an optimization approach to analyze auxiliary loads, simultaneously modeling passenger comfort, heating and air-conditioning, and vehicle performance to determine how best to keep passengers comfortable while minimizing fuel use and emissions. This systems approach, which can minimize auxiliary loads while increasing vehicle performance and passenger comfort, could save the nation billions of gallons of gasoline per year—to painlessly reduce our dependence on foreign oil and enhance air quality.

The Fuel Pathway

A hydrogen infrastructure in which the hydrogen fuel-cell car plays a starring role may be the ideal to which to aspire, but there are many options available that would enable the nation to cut its use of petroleum and in the process reduce its emissions. Among these options are alternative fuels—including compressed natural gas, liquefied natural gas, ethanol, and methanol—that we can use in our cars, trucks, and buses.

The first step in understanding how best to cut emissions and curtail oil consumption with alternative fuels is to establish a base that enables us to make comparisons, to measure progress, and to understand the properties of fuels and the consequences of its use. NREL is establishing such a base with a testing program it manages for the Department of Energy—the Alternative Fuels Data Center. We test and analyze a wide variety of cars, trucks, vans, buses, and fleets that use alternative fuels. This program has enabled us to build an extensive database on alternative fuels, their properties, and their performance characteristics. The information from this database is available to anyone who wants the data, and it is used by fleet managers, municipalities, manufacturers of vehicles and components, the fuel industry, and researchers.

The next step is to develop alternative fuels, especially ones that are derived from renewable resources, such as biomass. NREL



Clearing the Air

One way of reaching our goals on energy, emissions, and infrastructure is, to coin a phase, to *just do it*—find ways in which to put more alternative-fuel vehicles (AFVs) on the road, and ways for those vehicles to use more alternative fuels. The DOE-sponsored Clean Cities program is finding ways. This program helps build coalitions among government agencies and private companies to promote the purchase of AFVs, the use of alternative fuels, and the expansion of refueling stations for those fuels. The coalition members can leverage their resources, collaborate on public policy issues, promote AFVs in their community, and help create AFV markets.

Opportunities are greatest in markets where fleets of vehicles can share their use of the infrastructure. This includes airports, campuses, military bases, government agencies, transit agencies, and freight and package delivery companies. By tapping these markets, the program and its cooperating members have built coalitions in more than 80 cities and 41 states. There are about 400,000 AFVs on the road today. And today, drivers are discovering a growing infrastructure of stations where they can fill up their tanks with compressed natural gas (CNG), E85 (a blend containing 85% ethanol and 15% gasoline), and other alternative fuels.

Two of the aims of this coalition-building effort are to get 1 million AFVs on the road by 2010 and to have these vehicles consume 1 billion equivalent gallons of alternative fuels. But the long-term goal is to build a sustainable alternative-fuel market, and thereby enhance energy security and air quality.

SuperShuttle, a van service that provides shared, door-to-door rides to seven major airports across the country, operates approximately 300 CNG vehicles. This one is filling up with CNG at the Denver International Airport.

develops these fuels through its biofuels and biomass programs (see “Biorefineries” on pages 2-5). These fuels are most often blended with gasoline—a strategy that not only gets more alternative fuels into the energy infrastructure, but also helps curtail emissions.

A third step is to produce hydrogen from renewable resources for use as both a fuel and an energy carrier. This will dovetail nicely with the parallel development of fuel-cell vehicles. NREL pursues this alternative through its research in basic energy sciences and through the DOE’s hydrogen program (see “Hydrogen Economy” on pages 10-13).

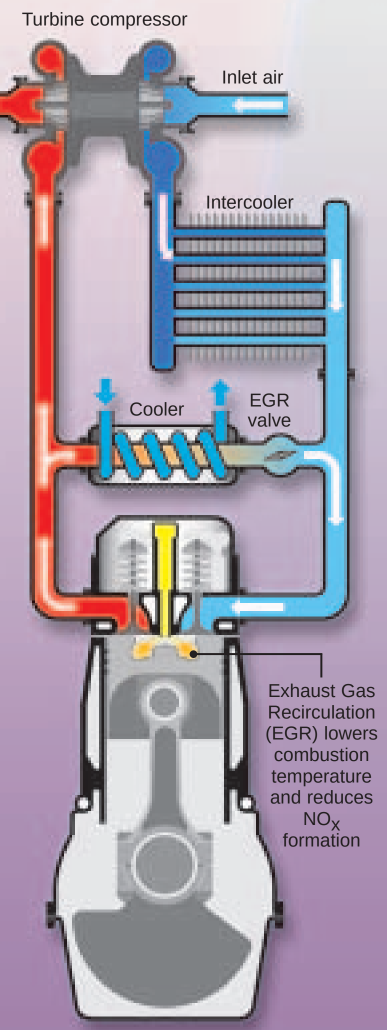
The Heavy-duty Option. Another option for reducing emissions is to develop clean diesel fuels for heavy-duty vehicles. Diesel fuel accounts for almost 20% of the fuel used on our highways, and its use in on-road heavy-duty vehicles generates thousands of tons of nitrogen oxides, particulate matter, and other pollutants each year. Working with industry, NREL has helped develop technologies and approaches in which diesel emissions can be drastically cut.

One approach by NREL and its partners is to develop clean “conventional” diesel fuels for use with catalyzed filters (see sidebar “Breathing Easier”). A second approach is to develop clean synthetic fuels from natural gas (or synthesis gas—primarily hydrogen and carbon monoxide) in conjunction with modifying a diesel engine to optimally burn the synthetic diesel. With this approach, carbon monoxide emissions can be nearly eliminated, while particulate matter and nitrogen oxides can be reduced by up to 97%.

Designer Fuels. A further strategy is to design diesel fuels on the molecular level. In this way, you can design for particular properties of a fuel—such as the cetane number (a measure of how readily the fuel will ignite), auto-ignition temperature, and the rate of combustion. Each of these properties is controlled by the molecular structure of the fuel. Eventually, through an iterative process, designer fuels can be optimized for high performance and low pollutants.

NREL researchers are just beginning this process. Their aim is to do it first for diesel with more conventional fossil-fuel stock, then to turn to renewable stock, and finally, to pass beyond diesel to other fuels.

Designing fuels at the molecular level is just one part of a multifaceted effort that NREL is engaged in to help the nation move away from foreign sources of oil, toward an infrastructure that includes a large percentage of renewable fuels and advanced vehicles and that may eventually culminate in zero emissions.



NREL and its partners explore many options for reducing emissions from diesel fuels. One option is this specially designed heavy-truck engine. The design reduces the temperature at which ignition occurs (to lower NO_X emissions); modifies the piston shape to increase the volume of gas in the combustion chamber (to lower ignition temperature); and re-circulates exhaust gases produced by each piston stroke (lowering the oxygen in the mixture, and hence lowering NO_X). When used with a Fischer-Tropsch Fuel, this approach reduces emissions of NO_X and particulate matter by more than 90% compared to conventional diesel engines.

One way to lower diesel emissions is to use the Fischer-Tropsch process to produce clean synthetic diesel, such as this fuel, which contains no sulfur and very few aromatics. Another way NREL is exploring is to design the fuel from the molecular level, to achieve not only low emissions but high performance.

Breathing Easier

NREL and its partners in industry and academia developed a new filter and fuel system that slashes particulate emissions from heavy-duty diesel trucks by 97%, cuts carbon monoxide emissions by more than 80%, and reduces total hydrocarbon emissions to below detection limits.

The system consists of a low-sulfur diesel fuel used in combination with either of two self-regenerating particulate filters. The fuel, which was developed by ARCO, contains less than 15 ppm of sulfur, is made using a conventional refinery process, does not require special handling, and is available on the California market.

The filters were developed by Engelhard and by Johnson Matthey. Each filter—installed in place of a muffler—is a catalyzed filter that oxidizes particulate matter, carbon monoxide, and unburned carbons from the diesel exhaust. Because they oxidize particulate matter at low exhaust temperatures, the filters regenerate themselves and do not need to be routinely serviced. Both filters have been certified by the California Air Resources Board as being able to meet the new, strict emissions standards to be phased in from 2007 to 2010.

Hydrogen Pure & Simple

Hydrogen is the simplest element in the universe. It is also the most abundant element, constituting more that 90% of the atoms of the universe and 75% of its mass. It is the third most abundant element in the Earth's surface and is found mostly in combination with oxygen as water (H_2O). As a gas (H_2), it is colorless, odorless, tasteless, and non-poisonous.

Hydrogen also may be one of the best bets to fuel the future economy of America and the world. Why? First, it is widely distributed in many resources. Hydrogen is not only present in water, but is in fossil fuels, like petroleum, coal, and natural gas, and it is in plants and organic waste. Hydrogen can be produced from these resources using electrolytic, thermochemical, or photolytic processes.

NASA's space shuttle (top) uses liquid hydrogen and oxygen for propulsion and hydrogen-powered fuel cells to provide onboard electricity and water. Car manufacturers (bottom) are beginning to produce vehicles powered by fuel cells. (Shuttle photo and Eagle Nebula photo in the background and on the front cover are courtesy of NASA.)

Second, as a fuel, hydrogen is clean. Solar energy can provide the electricity to split water into its constituent elements of hydrogen and oxygen (see sidebar "Solid-State Water Splitting"). The hydrogen then can be used in a

Harvesting Hydrogen from Microalgae

A scientist scrutinizes a flask containing microalgae for hydrogen production.

Scientists have known for decades that green algae can produce hydrogen. Researchers at NREL, ORNL, and the University of California at Berkeley have unlocked the secret to increasing the hydrogen yield of a certain type of green microalgae—*Chlamydomonas reinhardtii*—which shows promise of producing hydrogen cheaply, easily, and cleanly.

The process they've developed involves interrupting the algae's normal photosynthesis process. These algae, like all green plants, use photosynthesis—i.e., in the presence of light they "inhale" carbon dioxide and "exhale" oxygen. But hydrogenase—an enzyme that produces hydrogen—shuts down in the presence of oxygen, in the daylight, during prime photosynthesis time. This confines the algae's production of hydrogen to nighttime when photosynthesis does not occur, limiting the amount of hydrogen produced.

To overcome this limitation, the scientists developed a two-step method that allows the algae to make hydrogen while the sun shines. First they grow out ("fatten") the algae under normal photosynthetic conditions. Second, they withhold sulfur which, the scientists discovered, is essential for this green algae to maintain normal photosynthesis. Without sulfur, the algae stop emitting oxygen and stop storing energy. Instead, they switch to a new metabolic pathway—one that exploits stored energy reserves in the absence of net oxygen production. This kicks the hydrogenase into high gear to release large amounts of hydrogen.

This process induces the algae to produce 100,000 times more hydrogen than they do under normal conditions. Plus, the researchers have developed a process to fatten the algae again on a diet of sunshine and sulfur, and then to starve the algae of sulfur again to produce hydrogen. This cycle can be repeated several times. Still, much work remains to be done to make the process feasible on a larger scale.

fuel cell, where hydrogen and oxygen from air recombine to generate electricity, heat, and water (see sidebar "Fuel Cells"). Deriving and using hydrogen in this manner produces no particulates, carbon dioxide, or pollution.

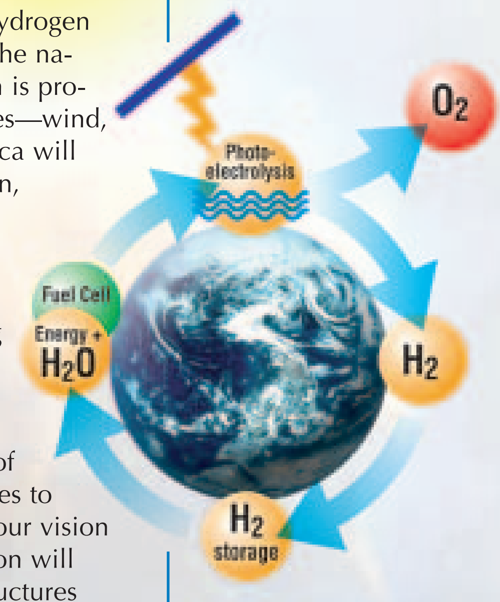
Third, hydrogen is versatile. We can produce hydrogen at one location or time to store energy and then distribute it to release the energy at another time or place. Hydrogen can be used to generate electricity, through the use of fuel cells, turbines, or microturbines. It can supply us with heat, warm our buildings, or power industrial processes. It can be used in internal combustion engines to power our cars, trucks, and buses, or in fuel cells for the same purpose. It can provide power for our jetliners and ocean fleets. Because fuel cells are modular, hydrogen can be used for both small- and large-scale applications—to provide heat and electricity for single homes or to supply the energy to run an entire large commercial building; to provide a small amount of electricity to a community grid, or a large amount of electricity to a large grid network.

The Road to the Hydrogen Economy

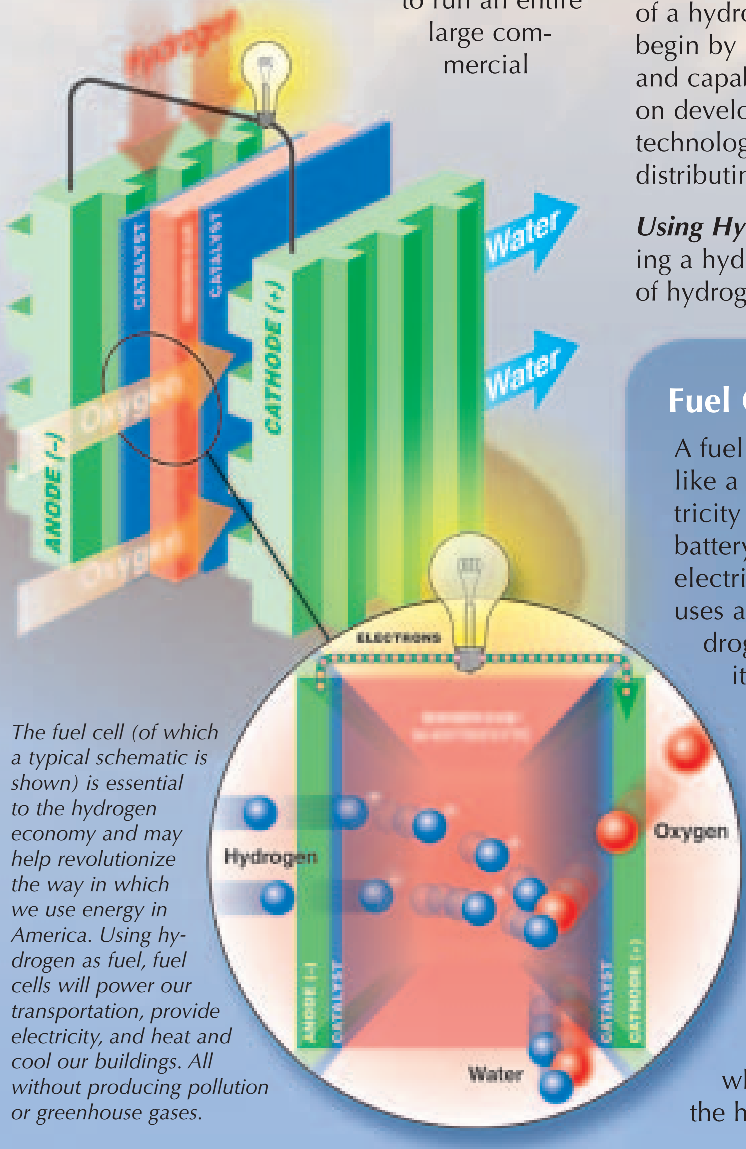
In the coming *hydrogen economy*, hydrogen will serve, along with electricity, as the nation's energy carrier. When hydrogen is produced from renewable energy sources—wind, solar energy, biomass, water—America will have an inexhaustible supply of clean, domestically produced energy.

Although making the transition to a renewable hydrogen economy will take decades, we are already starting down the road toward an energy economy based on hydrogen and electricity. NREL is working with industry, universities, the Department of Energy, and other national laboratories to outline the steps required to realize our vision of a hydrogen economy. The transition will begin by building on current infrastructures and capabilities; future progress will depend on developing and commercializing a range of technologies for using, producing, storing, and distributing hydrogen.

Using Hydrogen. An essential driver for reaching a hydrogen economy is to increase the use of hydrogen. Today, the United States uses



The hydrogen cycle: When generated from renewable sources, hydrogen production and use is part of a clean, cyclic process.



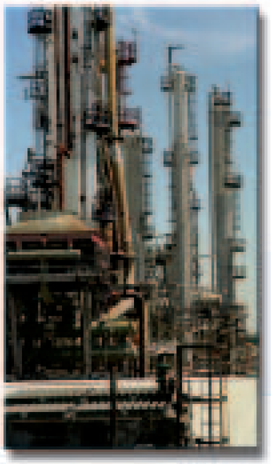
The fuel cell (of which a typical schematic is shown) is essential to the hydrogen economy and may help revolutionize the way in which we use energy in America. Using hydrogen as fuel, fuel cells will power our transportation, provide electricity, and heat and cool our buildings. All without producing pollution or greenhouse gases.

Fuel Cells

A fuel cell is a device somewhat like a battery—it produces electricity electrochemically. Unlike a battery, it does not need to be electrically recharged because it uses an external fuel source, hydrogen gas, to generate electricity as long as hydrogen fuel is supplied.

A typical fuel cell employs a catalyzed membrane sandwiched between a negative electrode (anode) and a positive electrode (cathode). Oxygen flows into the fuel cell on the cathode side. Hydrogen flows into the cell on the anode side, where the catalyst separates the hydrogen atoms into protons (hydrogen ions) and electrons. The electrons are attracted to the cathode, but they are blocked by the membrane. Consequently, they flow to the cathode through an external circuit, creating a current of electricity. The protons are attracted by the oxygen at the cathode and flow through the membrane, where they combine with the electrons and the oxygen to produce heat and water.

Individual fuel cells can be combined into a fuel-cell stack. This modular design capability allows fuel-cell stacks to produce enough electric power or heat for almost any size application. In addition, by putting both the heat and electricity to effective use, a fuel cell could be 80% to 90% efficient.

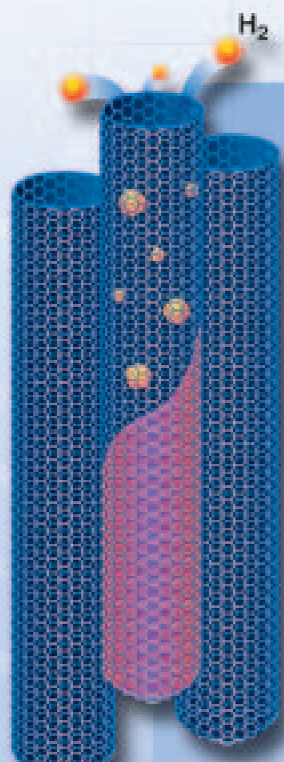


Today, most all hydrogen is produced via steam reformation of natural gas at oil refineries. The great majority of that hydrogen is used by oil refineries and petrochemical plants to refine fuel and to make industrial commodities.

more than 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen annually. The great majority of this is used for refining petroleum, making plastics, and producing fertilizers. Demonstrations are now under way to prove hydrogen's potential for transportation, for producing electricity, and for providing heat and electricity to buildings—all of which will help spur the growth of the hydrogen economy. Take transportation as an example. Initially we may witness the growth of hydrogen-fueled internal combustion engines—building on current transportation technologies and infrastructure. Ultimately, however, fuel cells will be integral to transportation (as well as to buildings, industry, and utilities). We will see fuel cells being incorporated into hybrid electric vehicles (which use both fuel-cell electricity and internal combustion), in which they will replace the engine. And eventually, fuel cells will provide the power for advanced fuel-cell vehicles (see also "Transportation Technologies" on pages 6-9).

Producing Hydrogen. Almost all of the hydrogen produced today is made by steam reformation of natural gas. For the near term, this method of production will continue to dominate. Hydrogen can also be produced by the gasification of coal or the partial oxidation of oil. Near-term improvements in these fossil-fuel-based processes will allow for the capture of the carbon dioxide byproduct, which can then be sequestered (stored or locked away). In the mid term, we'll see renewable energy technologies taking a larger role—via gasification or pyrolysis of biomass (see "Biorefineries" on pages 2-5) or via electrolysis of water with electricity produced by wind energy or other renewable electric technologies. Eventually, through long-term R&D, hydrogen will be produced directly using photobiological or photolytic processes (see sidebars "Harvesting Hydrogen from Microalgae" and "Solid-State Water Splitting"), in which hydrogen will be derived directly from sunlight and water.

Storing Hydrogen. Today, we store hydrogen as a compressed gas under high pressure or as a liquid at cryogenic temperatures. These will continue to be the primary means of storage for quite some time. There is also a possibility that we soon may be able to store hydrogen onboard vehicles or at the point of use as gasoline, methanol, or some other hydrogen-rich material, from which it could be extracted using a reformer (which breaks down hydrogen-carbon bonds to produce a gas from which hydrogen



Carbon nanotubes carry the promise of being able to store high volumes of hydrogen and to release the hydrogen on demand.

Storing Hydrogen in Nanotubes

The energy density (energy per mass) of hydrogen is more than three times that of gasoline. The problem is, because hydrogen is so light, it requires a large volume to store an appropriate amount of hydrogen energy onboard a vehicle. To overcome this, we can store the hydrogen at very low temperatures, under high pressure as a compressed gas, in chemical or metal hydrides (materials that reversibly absorb hydrogen), or even in liquid hydrocarbons that can be reformed to hydrogen on demand.

A team of NREL scientists is pursuing a novel and promising long-term solution: storage of hydrogen in carbon nanotubes—hollow tubes of carbon 1-2 nanometers in diameter. The walls of the tubes are made of a single layer of carbon atoms arranged in hexagonal patterns. These tubes can absorb and safely store high volumes of hydrogen in a small space at normal operating conditions. The stored hydrogen can be released on demand through small changes in temperature and pressure.

Researchers have been able to make some very pure carbon nanotubes that appear to be able to store up to 67 kilograms of hydrogen per cubic meter (kg/m^3). At such a capacity—which surpasses the goal of 62 kg/m^3 set by the Department of Energy—it would take only about 0.075 cubic meters to store 5 kilograms of hydrogen, which is about the size of gas tanks used in some cars and small trucks today. With this amount of stored hydrogen, an advanced fuel-cell car should be able to travel farther on a tank than today's typical car or small truck.

This photovoltaic system at SunLine Transit Agency in Thousand Palms, California, provides electricity for the Stuart Energy electrolysis unit (on the right).

is obtained). In the meantime, research will continue to explore ways in which to store hydrogen in chemical or metal hydrides or in carbon nanotubes. These long-term options could provide safe and high-density storage, reducing storage space and providing a range that could be greater than that provided by conventional vehicles (see sidebar "Storing Hydrogen in Nanotubes").

Distributing Hydrogen. America has an extensive distribution network for its energy. There are more than 3 million miles of pipelines for transporting natural gas and petroleum, 160,000 miles of high-voltage transmission lines, and thousands of tankers and trucks. And there are tens of thousands of gas stations for dispensing gasoline. This network is characterized by centralized production with distribution to regional and local markets. Hydrogen itself is transported primarily by truck, but also by tankers and pipeline. In the near term, hydrogen for energy will use the existing distribution systems. But as demand grows in the future, we could see natural gas piped to regional locations, where it will be reformed to hydrogen for regional distribution. Farther into the future, as production from renewable energy sources and technologies becomes less expensive, we may see hydrogen produced both regionally and locally, and distributed locally. Thus, the emerging hydrogen economy will not only provide secure and clean energy for the nation, but also will provide local communities with an important economic base from which to grow.

Hydrogen-powered vehicles, which are becoming more popular, include SUVs and fleets of buses. The SunLine Transit Agency, for example, uses two buses powered by a mixture of hydrogen and natural gas, and one bus powered by hydrogen fuel cells.

Solid-State Water Splitting

The cleanest way to produce hydrogen is by using sunlight to directly split water into hydrogen and oxygen. All you need is sunlight and water, and an appropriate system to split the water.

NREL scientists have devised such a system, in which a multijunction solar cell is immersed in an aqueous electrolytic solution. The top cell in the structure (made of gallium indium phosphide—$GaInP_2$) absorbs the high-energy photons in the solar spectrum to produce electron-hole pairs. The bottom cell (made of gallium arsenide—GaAs) does likewise with the lower-energy photons that pass through the top cell. The electrons flow toward the illuminated surface and the electrolytic-$GaInP_2$ interface, which serves as a cathode for the system. Holes travel to the GaAs bottom surface, which is coated with platinum to provide an ohmic contact. The tandem cell provides a sufficient voltage to drive an oxidation-reduction reaction that produces hydrogen at the cathode and oxygen at a platinum anode.

An NREL scientist holds a beaker containing a photolytic device submerged in an alkaline aqueous solution. This configuration produces hydrogen from water with greater than 12% efficiency.

This NREL system produces electricity from sunlight without the expense and complication of electrolyzers—and at 12.4% solar-to-hydrogen efficiency, does so more efficiently than other photolytic approaches. This approach represents one possible long-term solution for the sustainable production of hydrogen. In the meantime, there remains much to be explored, including non-aqueous electrolytes, alternate semiconductor systems, and lower-cost materials that may lead to the commercial production of hydrogen from sunlight and water.

Switching on the Sun

Something as seemingly simple as saran wrap. Thin—very thin —layers of stacked plastic sheets could represent the future of electricity. Those thin sheets are conductive polymers with embedded nanorods or quantum dots of semiconductor material that one day may produce electricity from the sun to power homes and businesses.

BP Solar's new semi-transparent amorphous silicon modules—developed through participation in the Amorphous Silicon National Research Team—are used to provide power to run pumps, lights, and other loads at BP gasoline stations.

Fanciful? Perhaps. But plastic solar cells serve as a benchmark for how far we've come since the middle of the 1970s, when solar electricity was only a reality for powering satellites and was still too expensive for uses on Earth. And they are a harbinger of what is to come. The first steps toward plastic solar cells have been taken by researchers at universities and research organizations under an NREL program. Scientists can convert from 2% to nearly 5% of sunlight to electricity (depending on the approach). And prospects look good for bumping conversion efficiencies well beyond 10%, toward viability and toward solar electricity that could someday cost less than 2¢/kWh.

This is part of the promise of the emerging solar electric revolution. Solar electricity is the ultimate distributed energy. Solar electric systems can provide electricity anywhere in any amount—from a few watts to billions of watts. Solar electricity is coming to America along two general technological pathways. One of these pathways is photovoltaics (PV or solar cells)—in which photons dislodge electrons in solid-state materials to directly convert sunlight to electricity. The other is concentrating solar power—in which the heat of concentrated sunlight is used to generate electricity.

Nanorods and Quantum Dots

NREL and its research partners have been investigating semiconductor-related nanotechnology since the early 1980s. In 1984, NREL researchers were among the first to report on quantization effects in nanosize semiconductor particles related to solar cells. Today, this pioneering research is showing promising results in the form of nanorod and quantum-dot solar cells.

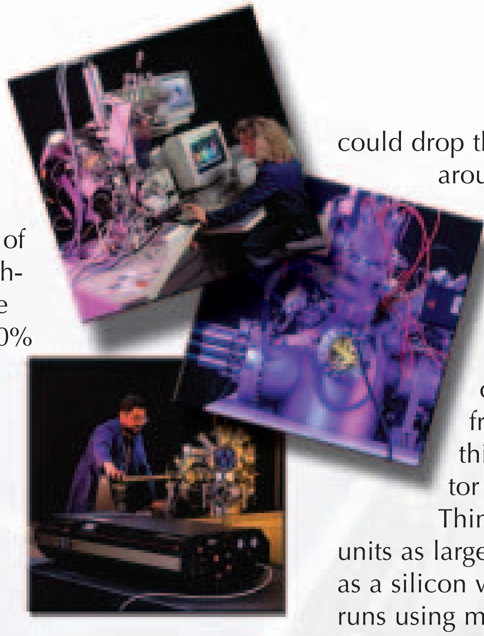
Nanorods are semiconductor "wires" that are a few nanometers wide and up to 100 nanometers long (a nanometer is one-billionth of a meter). Embedding nanorods in conductive plastic sheets results in thin, flexible solar cells. The nanorods absorb light of specific wavelengths to generate electrons and holes (vacancies in the material that move around similar to electrons). The rods conduct the electrons along their length. Holes are transferred to the plastic, which conducts them to an electrode.

Two innovative organic solar cells: The top cell employs nanorods of cadmium selenium embedded in conductive polymer. The bottom cell also uses a conductive polymer substrate, but with extremely thin embedded multilayers of organic molecules.

Quantum dots are dots of semiconductor material containing from just a few atoms to tens of thousands of atoms. Like nanorods, dots can be embedded in conductive polymer, or can be used with other materials, such as titanium dioxide. By varying their size, quantum dots can be tuned to absorb specific wavelengths of light and so represent an avenue toward multi-multijunction devices that could theoretically convert as much as 66% of sunlight to electricity.

Solar-Cell Generations

In 1977, when NREL first began its research on solar cells, the world produced less than 50,000 watts of solar cells; they were based on crystalline silicon wafer technology, and most were for use in space. Today, we are developing and exploring a wide range of material and device technologies, the worldwide market is growing by 30% to 40% per year and is fast approaching 500 million watts per year.



NREL has built what may be the world's finest center for measuring and characterizing photovoltaic and renewable energy materials and devices. Shown here are just a few of the dozens of sophisticated instruments used in the center: an XPS, for chemical-bonding information; a TOF SIMS, for surface and compositional analysis; and an STM, for nanoscale imaging and spectroscopic studies.

Several things are spurring this growth. First is the search for dependable alternative electricity systems that can be used in a distributive sense—to generate electricity at the point of demand—and that can provide security against supply disruptions, sabotage, or swings in energy prices. Second, PV has become a dependable and versatile technology. Third, the cost of electricity from solar cells has declined more than fourfold since 1980 and continues to decline.

In America today, tens of thousands of homes and businesses use PV electricity. By 2030, this number could increase to tens of millions, with PV providing 150 to 200 billion watts of power. "To get there," says Larry Kazmerski, director of NREL's National Center for Photovoltaics, "solar cells and modules must get much cheaper, get much more efficient, or both." NREL and its research partners in industry and universities are helping to push PV toward the cheaper and better along several generations.

1st Generation—Silicon Wafers. This path is one of continuous incremental improvements. Silicon-wafer technology uses "thick" (150- to 300-microns) wafers of crystalline silicon cells connected together to form modules and sandwiched between sheets of glass. In 2001, this mature technology constituted about 90% of the solar-cell market. Costs are dominated by the relatively high cost of semiconductor material. Module conversion efficiencies are expected to increase from today's 13% to beyond 16%. As a result of this and improvements in manufacturing technology, this path could drop the cost of solar electricity to around 7¢/kWh by 2010. This is good for the short run, but not as low as we can go in the long term.

2nd Generation, Part 1—Thin Films. This technology uses films of semiconductor material that are from 1 to 10 microns thick. Hence, thin films use far less semiconductor material than does wafer silicon. Thin-film devices can be made in units as large as a meter—100 times as large as a silicon wafer—and can be made in large runs using mass-production techniques. Thin films are versatile and are leading the charge for today's specialty, building-integrated applications. For example, thin-film modules can be made translucent, as shingles for roofs, and incorporated into architectural glass.

NREL has been researching thin-film materials since the late 1970s. Of these, three have emerged—amorphous silicon, copper indium diselenide, and cadmium telluride. Amorphous silicon has been building market share since the 1980s. The other two are relative newcomers to the market. Currently, the efficiency of commercial thin-film modules ranges from 5% to 11% (depending on the material and device structure), and costs are competitive with those of wafer silicon. But prospects are promising. For example, by layering thin-film materials on top of each other so that different layers capture and convert different portions of the solar spectrum—a concept known as "multijunction"—modules could eventually convert more than 15% of sunlight to electricity. This, along with improved production techniques, could drop electricity costs below 4¢/kWh—competitive with most conventional electricity, but with built-in advantages.

2nd Generation, Part 2—Multijunction. A third path is through high-efficiency multijunction. This is similar to the thin-film multijunction described above, except that it relies on semiconductor materials that could result in very high efficiencies. These are materials primarily from Groups III and V

The 4 Times Square building in Manhattan uses thin-film PV panels to supply 15 kW of power to supplement the building's electricity needs. Located on the top 14 floors on the south and east sides of the building, the PV panels are integrated into the spandrel—the opaque area of the façade below rows of windows—in 60-inch-wide strips. (Andrew Gordon Photography.)

of the Periodic Table of the Elements—such as gallium arsenide, indium phosphide, and gallium indium phosphide. Thus far, the best device is a three-layer (three-junction) cell that converts up to 34% of sunlight to electricity (see sidebar "From Space to the Earth"). Typically, this approach uses concentrated sunlight, where lenses focus large amounts of solar energy onto a small cell.

3rd Generation—Beyond the Horizon. To drastically lower the cost of solar electricity—below 2¢/kWh—you have to leapfrog the conventional to the innovative. This third generation is mostly at the basic research stage, but these are concepts that auger very low cost or very high efficiency (three or four times that of current state-of-the-art silicon-wafer cells). The plastic cells mentioned above are part of this future generation. Other concepts include:

- Hot-carrier solar cells (which capture and convert electrons in excited states before they return to stable energy levels).
- Cells that can convert a photon into two or more electron-hole pairs to carry the current, in contrast to conventional cells, in which a photon produces one electron-hole pair.
- Quantum-dot solar cells, in which nano-sized dots of semiconductor material are tuned to capture and convert specific wavelengths of the solar spectrum (see sidebar "Nanorods and Quantum Dots").

Concentrating Solar Power

Solar Troughs. When the federal research program began in the late 1970s, there were no concentrating solar power systems in existence. By 1991, thousands of acres of solar troughs in the Mojave Desert were generating 354 MW of power, thanks in large part to R&D by national laboratories (including NREL, along with Sandia National Laboratories) and industry that dropped costs three- to five-fold by 1990.

A solar trough uses parabolic-shaped mirrors to concentrate sunlight onto a receiver (a heat-collection element) running along the focus of the curved surface. For latitudes within the United States, the trough tracks the sun from east to west to maximize solar energy captured by the receiver. This concentrated solar energy heats oil flowing through the receiver, which is then used to generate electricity via a conventional steam generator.

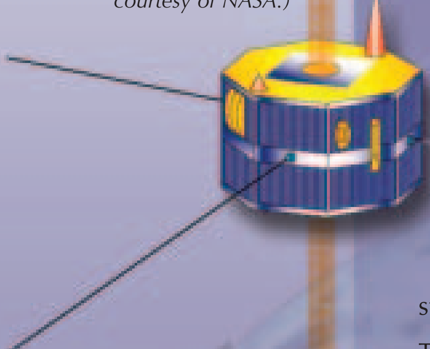
At 12¢ to 14¢/kWh, the troughs in the Mojave Desert produce electricity more cheaply than other solar electric alternatives. As such, they provide supplementary power to a highly competitive market—that of peaking and intermediate-load power for grid-scale applications. Moreover, with a federal R&D strategy that will help reduce the cost of electricity to about 6¢/kWh by the end of the decade, solar troughs will be able to compete directly with conventional power generation for peaking markets. This strategy may also reduce trough electricity to less than 5¢/kWh by 2020, making it com-

From Space to the Earth

For decades to come, satellites launched into Earth orbit will depend on power provided by innovative solar cells pioneered by NREL scientists and perfected in partnership with industry. These devices are lighter, more powerful, and more efficient than all previous solar-cell power systems shot into space. And more durable—they will easily withstand 15 years of particle storms sent by sun and solar wind.

The devices are double- and triple-junction cells based on gallium indium phosphide, gallium arsenide, and germanium. They convert about 30% of sunlight to electricity, far greater than other space solar cells. They're not just good for space, though. NREL and Spectrolab—an industrial partner—redesigned the cell for use on Earth under concentrated sunlight. This Earth-bound version, which is especially suited for use under direct sunlight, can convert up to 34% of sunlight to electricity, a world record for photovoltaics.

This research resulted in two prestigious R&D 100 Awards—one for the space cell and one for the redesign that brought it to Earth. But even more important, it has led to breakthroughs in understanding solid-state materials, their growth processes, and their optical and electronic properties. This understanding is leading the advance toward devices with four and more junctions and efficiencies beyond 40%.



The IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellite was one of the early satellites to use the new III-V multijunction cells to provide power for operations. IMAGE was launched in March of 2000 to study the Earth's magnetosphere and related phenomena, such as the aurora borealis. (Graphic courtesy of NASA.)

The Impact 2000 home in Massachusetts uses a 4.5-kW utility-interactive PV system. It also incorporates many other energy efficiency and renewable energy features—solar hot water, super insulation, passive solar heating and cooling, and an earth-coupled, geothermal heat pump.

petitive for central-station power. Toward these ends, R&D will focus on:

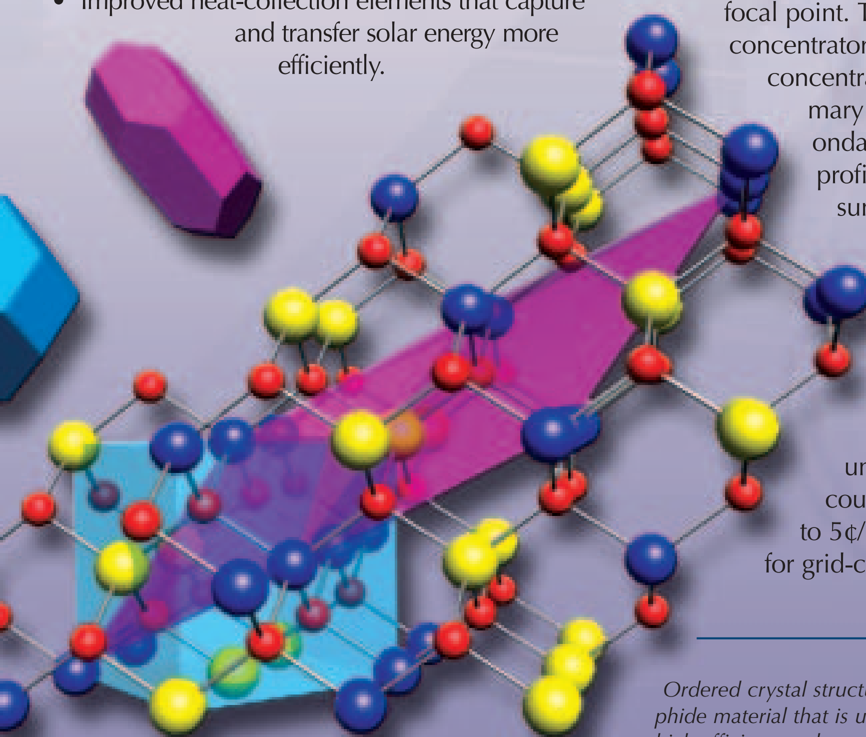
- A near-term capability to store solar energy for long periods—such as in a molten salt medium—which would allow energy to be captured while the sun shines and electricity to be generated and dispatched while the sun is not shining. The ability to dispatch energy when and where needed will extend the utility of concentrated solar power and reduce costs.
- Longer-term advanced fluids for thermal storage of solar energy—fluids whose properties would enable easy storage and retrieval of energy, at optimal working temperatures.
- Better, lighter, cheaper reflecting surfaces—such as very thin glass or flexible, high-density aluminum—laminated on a flexible substrate.
- Improved heat-collection elements that capture and transfer solar energy more efficiently.

The Perfect Dish. For greater modularity, one can turn to dish concentrator systems, which use mirrors or reflective membranes in a dish-shaped configuration to reflect and focus the sun onto a small area, and a receiver/engine located at the focal point to generate electricity. When used with a Stirling heat engine to convert solar heat energy to electricity, a dish concentrator can provide electricity in units that range in size from 3 kW to 25 kW.

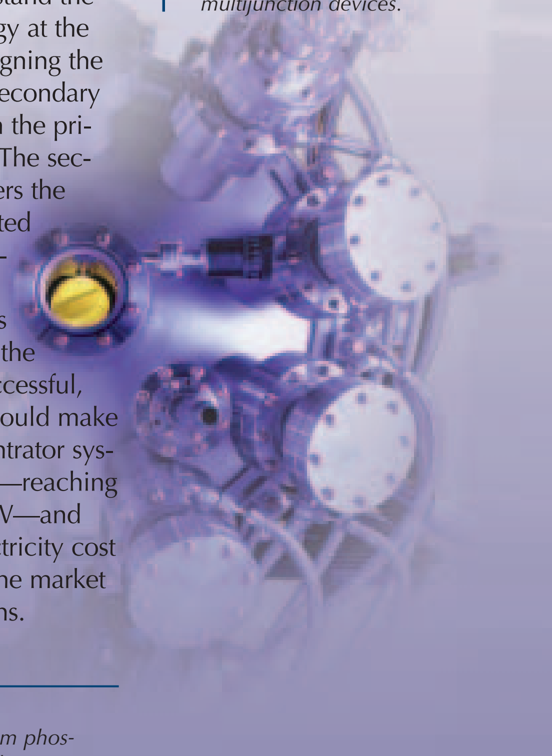
Although today's systems can convert nearly 30% of sunlight to electricity and although R&D by NREL, Sandia National Laboratories, and industry has dropped costs and improved reliability significantly since the early 1980s, the only systems in use today are those being built to test and demonstrate their viability. But large markets are just around the corner.

Once we prove the ability of systems to operate reliably, economies of scale could reduce the cost of current designs to 8¢-10¢/kWh and open the distributed generation market. R&D—especially that for developing a more reliable, efficient, and long-lasting engine system—will help drop costs even more.

Coming Full Circle. An innovative research direction combines the solar dish concentrator with that of a highly efficient silicon or multijunction PV module placed at the focal point of the concentrator. NREL researchers are engineering the PV module so that it can withstand the high concentration of solar energy at the focal point. They are also redesigning the concentrator concept, using a secondary concentrator in tandem with the primary dish concentrator. The secondary concentrator alters the profile of the concentrated sunlight so that the solar flux will be uniform across the surface of the module. If successful, this concept could make the dish concentrator system more modular—reaching units as small as 1 kW—and could help reduce electricity cost to 5¢/kWh, opening up the market for grid-connected substations.

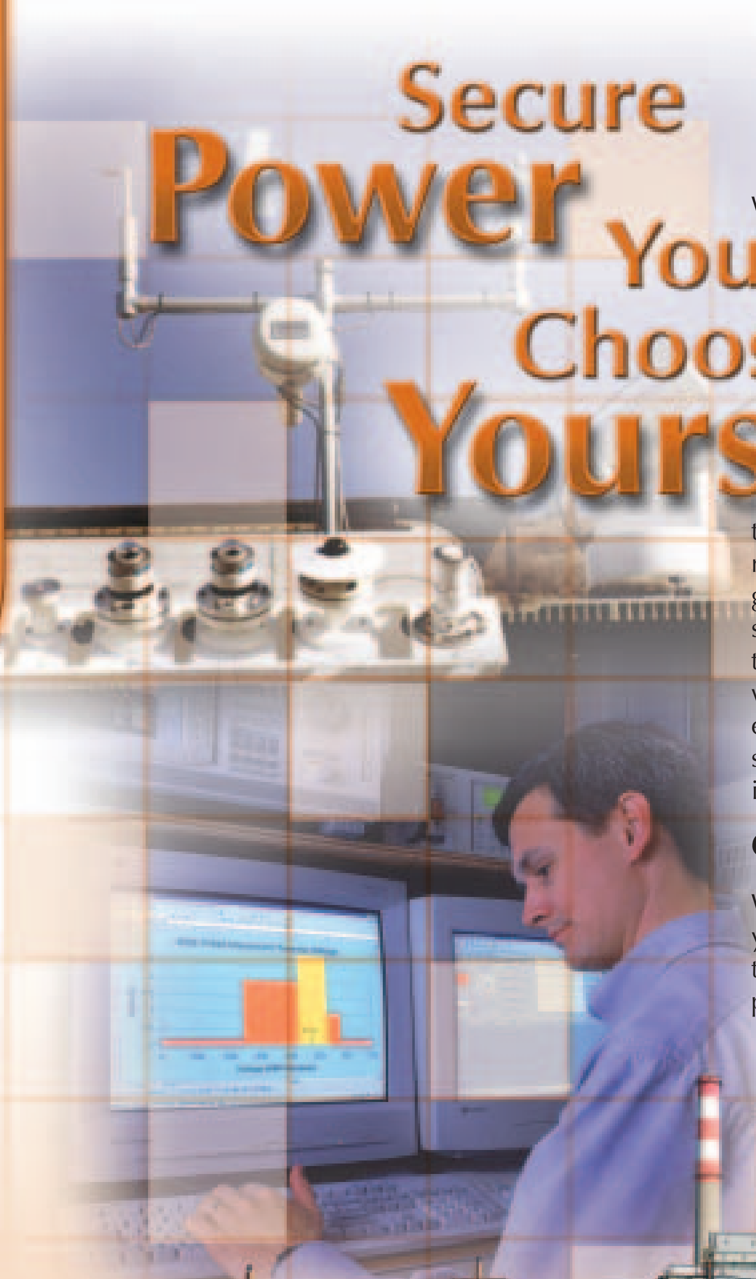


Ordered crystal structure of the gallium indium phosphide material that is used in double- and triple-junction high-efficiency solar cells.



Molecular beam epitaxy (MBE) is one of scores of systems NREL researchers use to grow, develop, design, and monitor PV cells and devices. The MBE, in fact, is integral to the growth and design of NREL's successful III-V family of high-efficiency multijunction devices.

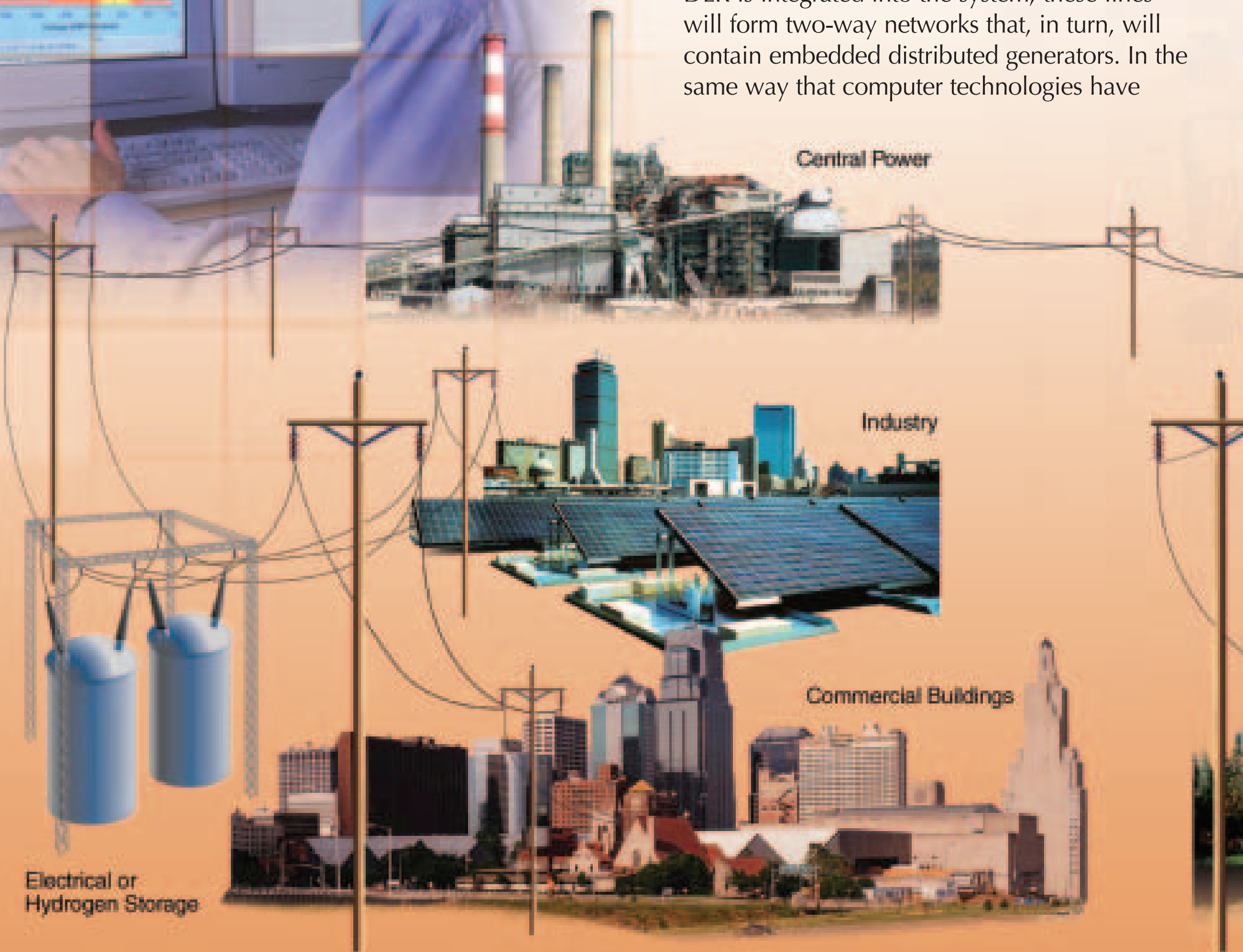
Secure Power You Choose Yourself



What IS *distributed energy resources*, or DER? The term refers to modular power generators that can be combined with energy management in storage to improve the electricity delivery system. In the future, DER will be the umbrella that connects exciting new technologies—fuel cells, building-integrated photovoltaics, and microturbines—together into power-generating packages that are located at your business or in your community. But, according to Dick DeBlasio, NREL's DER technology manager, "DER refers as much to the way that people will relate to energy—the way it will be distributed to your home, office, or school—as to the way the electricity is generated." DER is the way electricity will work in the future, but it is also the way we're going to make the transition to a more secure energy future, where businesses, hospitals, and schools can still operate even in emergencies and when the power grid is down.

Changing the Way We Grid

When you flip on a light at home today, electricity comes to you from the power grid—a giant system of distribution and transmission lines that radiate out from large power generation plants to send electricity to where we need it. Increasingly, as DER is integrated into the system, these lines will form two-way networks that, in turn, will contain embedded distributed generators. In the same way that computer technologies have

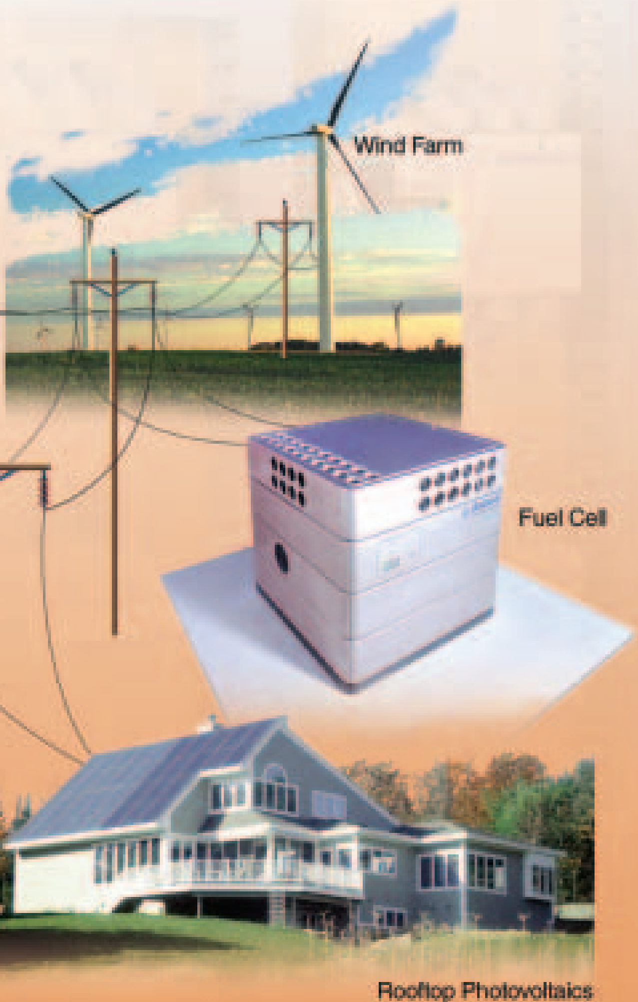


In the future, distributed energy resources will be the way energy works—connecting exciting new technologies into power-generating packages located at your business or in your community. In addition to central power plants, distributed energy means that a variety of electricity sources are distributed close to where they will be used, allowing for more efficient use of heat that is "wasted" at power plants today. It also provides greater security, spreading out sources of electricity so that operations can continue even if one source is not operational.

gone from mainframes to smaller computers networked together, the future power system will be decentralized. Smaller "mini-grids" containing their own generators will be distributed throughout the larger system, closer to where the electricity can be used.

These mini-grids can be as simple as one or two small generators feeding electricity to your business or back to the power grid if you're not using it. Or, they can be much more complicated—containing several types of generators, such as fuel cells that convert hydrogen into electricity, photovoltaics, or wind turbines, along with biomass or fossil-fuel generators for backup and energy storage systems—all networked together and controlled by computers that manage the power systems.

According to Tony Schaffhauser, NREL's DER center director, DER is really about flexibility and choice. "DER provides people with a greater choice of sources, including more control over what environmental effects the electricity they use will have," he says.



Making Power Reliable

DER is about flexibility and choice—and more. Moving toward an electricity model based on integrating distributed energy resources into the energy infrastructure has a variety of benefits. For one thing, having many power generators connected to a grid in a distributed fashion could greatly increase reliability—with a smart, well-designed distributed energy network, power would always be available (or at least 99.99999% of the time). Blackouts (which are caused primarily by failures in distribution lines) and rolling brownouts may even become a thing of the past.

Second, the quality of the power provided has a potential to become much better and more stable. As a result, there would be far fewer voltage surges, spikes, and sags. This could be important to the modern business community, much of which is run by digital technology and is very sensitive to variations in power

The Distributed Resource

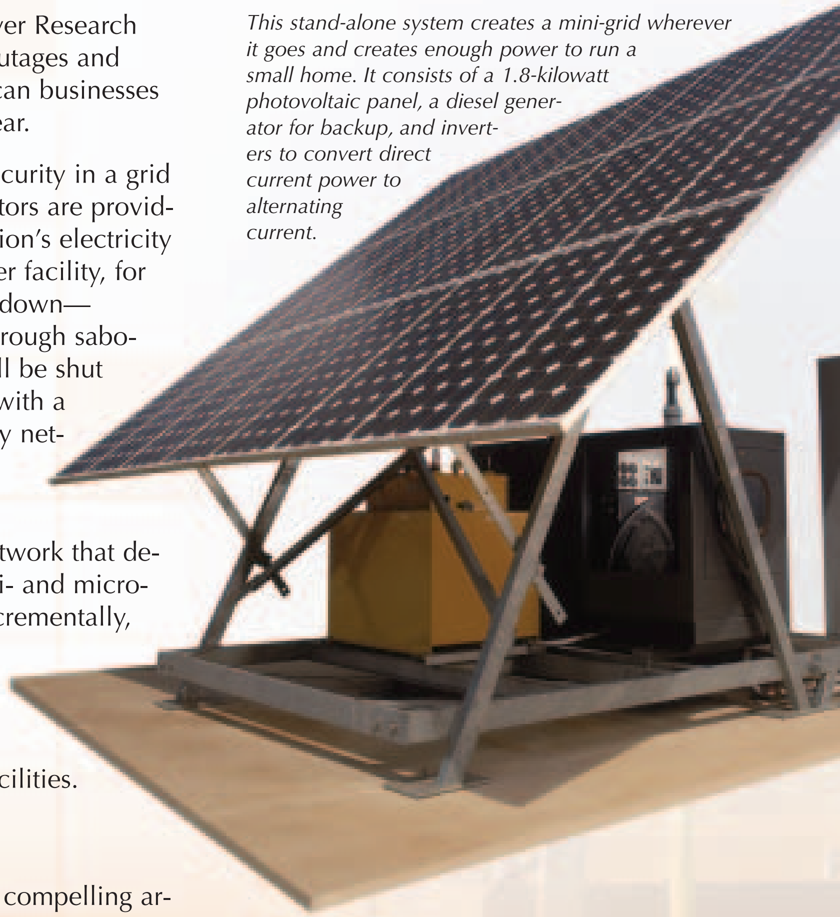
Distributed energy resources does not just refer to distributed generation of power. It also refers to the fact that much of the natural resources that can be used to provide the energy that generates the electricity also is distributed. This includes wind energy, geothermal energy, hydropower, biomass, and sunshine (or solar radiation). In making decisions on where or whether to locate a generator dependent on these resources, it is important to know their spatial distribution, intensity, availability, and other characteristics. NREL scientists have long been modeling, measuring, and characterizing these resources. In particular, throughout its existence, NREL has steadily built a world-renowned reputation for its research in solar radiation, especially in measuring and modeling this resource.

At the center of this reputation is NREL's Solar Radiation Research Laboratory. This unique research facility continually measures and monitors solar radiation and other meteorological data and disseminates the information to government, industry, academic, and international laboratories and agencies. The data that the laboratory measures includes global, diffuse, and direct-normal irradiance, ultraviolet radiation, infrared radiation from the Earth's surface, atmospheric aerosols, wind speed and direction, temperature, barometric pressure, relative humidity, and more. These data may not only be used for testing systems that convert solar energy to electricity, but also for climate-change studies, for research on weather and the atmosphere, and more.

A researcher adjusts an absolute cavity radiometer at NREL's Solar Radiation Research Laboratory. Absolute cavity radiometers are used to make very accurate measurements of solar irradiance and provide the reference from which other radiometers are calibrated.

quality. In fact, the Electric Power Research Institute estimates that power outages and poor power quality cost American businesses more than $100 billion each year.

Third, there is greater energy security in a grid network in which many generators are providing the electricity. If all of a region's electricity is supplied by one central power facility, for example, and that facility goes down—whether by natural means or through sabotage—then the entire region will be shut down. This would not happen with a well-designed distributed energy network, which provides inherent redundancy and safety.



This stand-alone system creates a mini-grid wherever it goes and creates enough power to run a small home. It consists of a 1.8-kilowatt photovoltaic panel, a diesel generator for backup, and inverters to convert direct current power to alternating current.

DER also benefits utilities. A network that depends on a wide variety of mini- and microgenerators can add capacity incrementally, when and where it is needed. Such a network can avoid the expensive financial and time commitment demanded by the construction of large, central facilities.

Using All the Heat

Microturbines are representative of just one of the many kinds of distributed power generators that are ideal for use in a distributed network. Microturbines, which can be powered by natural gas or biofuels, provide a reliable source of electricity and heat for commercial businesses and industries.

But efficiency may be the most compelling argument for distributed energy resources. Traditional power generation plants burn coal or gas. But only about one-third of the primary energy used is captured and converted to electricity. Then, as much as another 10% can be lost through transmission and distribution of the electricity. Since the point of DER, on the other hand, is to generate electricity close to where it is to be used, you can minimize losses due to transmission or distribution. Plus, heat that is traditionally "wasted" can be converted to power in other ways. Using waste heat efficiently, a micro-grid at your home will power your appliances; heat, cool, and adjust humidity levels in your home; and heat your water. In industrial settings, waste heat will power industrial processes.

Researchers are working on additional and more effective ways to use that waste heat and make power generation more effective. As we find ways to be more efficient, as much as 60% of the power used to generate electricity will be captured.

Making the Rules

As the brave new world of creating our own electricity evolves, we need to think strategically about the rules that will govern its use. Like codes and standards governing the way buildings are made or commerce is conducted, standards for the way that people can connect into the power grid, how they can send electricity back to the grid, and rules governing the way that utilities relate to these mini-grids are critical. Right now, businesses that install photovoltaic systems and try to tie in to the power grid face different procedures with different utilities, and states and local governments also have different rules.

Navigating the process can be frustrating and lengthy.

But for two years now, a national group of almost 300 members of the Institute of Electrical and Electronics Engineers (IEEE)—representatives from utilities, electricity producers, manufacturers, laboratories, and consulting groups—have been developing technical standards to make the process more consistent. NREL's Dick DeBlasio, chair of the IEEE working group, says that once the group has approved the standards, state and federal regulators will have the option of adopting them. "Right now there are hundreds, if not thousands, of utility rules for connecting to the grid," he says. "The standards we are developing will, as they are adopted by utilities and regulatory commissions, level the playing field for distributed resources and enable them to compete in the marketplace."

At the same time, from the regulatory perspective, state and local governments are also trying to address the challenges of bringing about a distributed energy generation future. Gary Nakarado, NREL's DER regulatory liaison, is working with regulators to make changes in the way that regulations are structured—moving to a different model that can accommodate more customer choice and more power providers. "The traditional regulatory model is turned on its head by distributed generation," Nakarado says. "We need to encourage policy makers to ask the important questions, like 'What's in the public interest?' because there are so many new tools and technologies available."

A researcher monitors the control panel for a simulated utility grid at NREL's Distributed Energy Resources Test Facility. Using the control panel, researchers can adjust voltage, frequencies, loads, and a variety of other parameters to determine how the network may work under different conditions.

Pulling It All Together

The full integration of renewable energy resources and distributed generation into the nation's energy infrastructure will be a long-term process that will involve research, technology, negotiations, and cooperation on many levels across the United States. But such an integration will liberate our dependence on traditional fuel sources. And it will provide a reliable, secure, and flexible system of powering America.

Electricity Soup

The Distributed Energy Resources Test Facility looks like a mass of electric switches, panels, and lines connecting large machines together. That's exactly what it is—the facility, which is the only one of its kind, tests how distributed generation sources connect and work together.

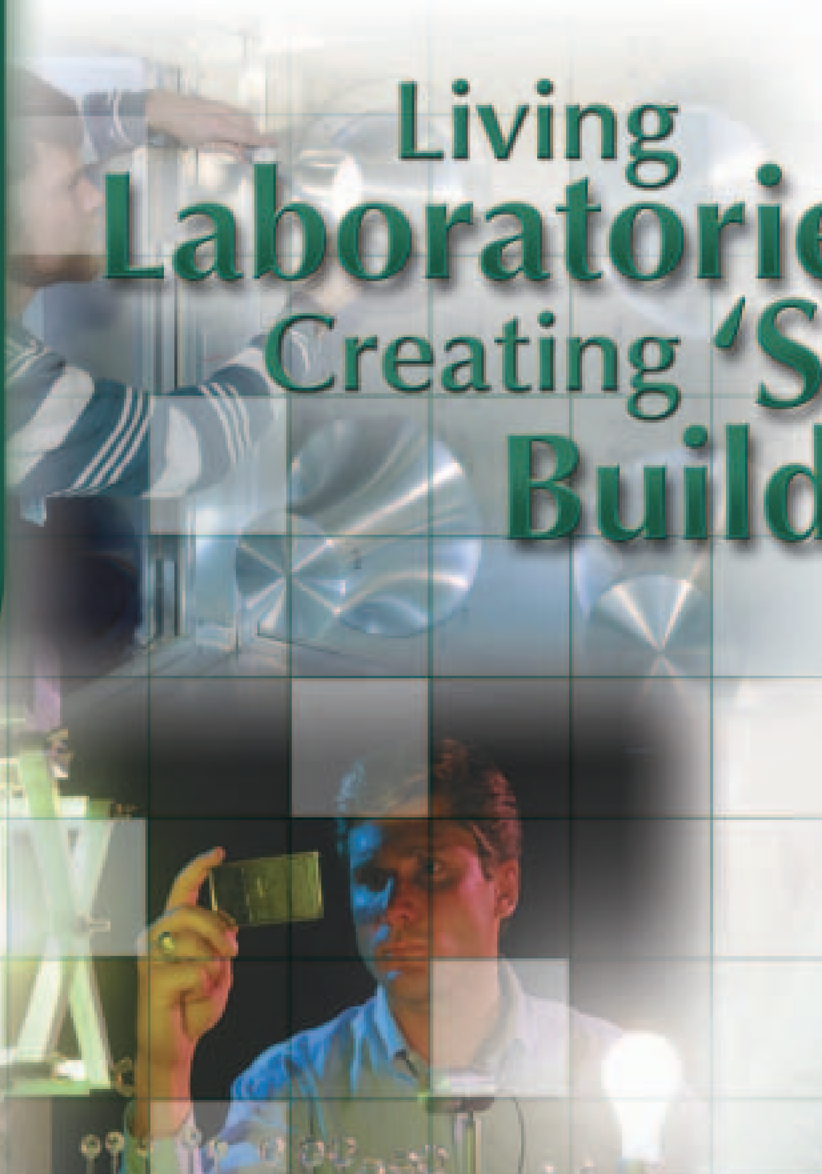
At the facility, generation sources such as a 30-kW microturbine, 60- or 100-kW wind turbines, various-sized diesel generators, and a 1.8-kW photovoltaics panel are connected to a 200-kW "grid"—simulating a utility. This allows researchers to test how each of the sources work together and how they interact.

A lightning-surge simulator tests what happens to the individual sources and the whole system during adverse weather conditions, and the grid can also be turned off to simulate emergency situations when the electric grid is down. Grid-simulator controls allow researchers to adjust the voltage and frequency of electricity moving in the grid to simulate sags and surges on the distribution system—similar to variations in the real power grid and distribution systems that result in blackouts or brownouts. Using an electric-load simulator, researchers can see how the systems work under different use patterns—up to 165 kW of load.

This kind of work requires a high-speed data acquisition system—and the facility has one that samples at 5 million samples per second. Collecting data that quickly allows researchers to monitor high-speed interconnections between the generation sources and to record electrical faults and disturbances.

The test facility will help determine how reliable distributed power systems are, provide research data to use when developing interconnection standards, and help understand how complex energy systems can be integrated together. Researchers can evaluate moment-by-moment dynamics of distributed power systems, gather data on long-term performance, and demonstrate new design concepts.

A new, larger, energy-efficient test facility is under design and is expected to open by 2005. The 10,000-square-foot facility will increase testing capacity to up to 1 MW of generation.



Living Laboratories Creating 'Smart Buildings'

What if your house were a mini-power plant, generating the power you need to live? Imagine—solar panels in the form of roof shingles, heat-collecting walls, and fuel cells powering your appliances, heating your home, and even charging your car. And buildings of the future will be "smarter," with windows that automatically darken to shade during the heat of summer and open or close to allow natural ventilation. Computer systems will automatically control lighting levels and turn on and off your appliances. All of these technologies and concepts will make the buildings of the future more productive and comfortable, extremely energy efficient, and secure—continuing to run even if the electric grid is down.

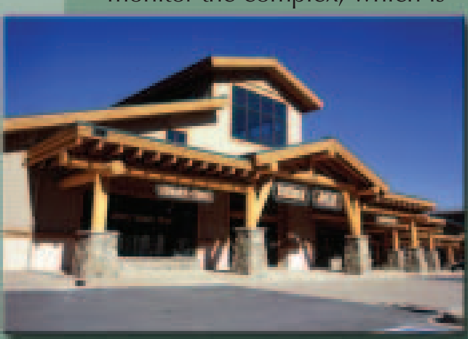
Living Laboratories

We might be further along the path to this future than you realize. Researchers are testing home and office designs today that are up to 80% more energy efficient than those built when NREL first began operating. These new building designs combine renewable and energy-efficient technologies in ways we could not have imagined in past decades.

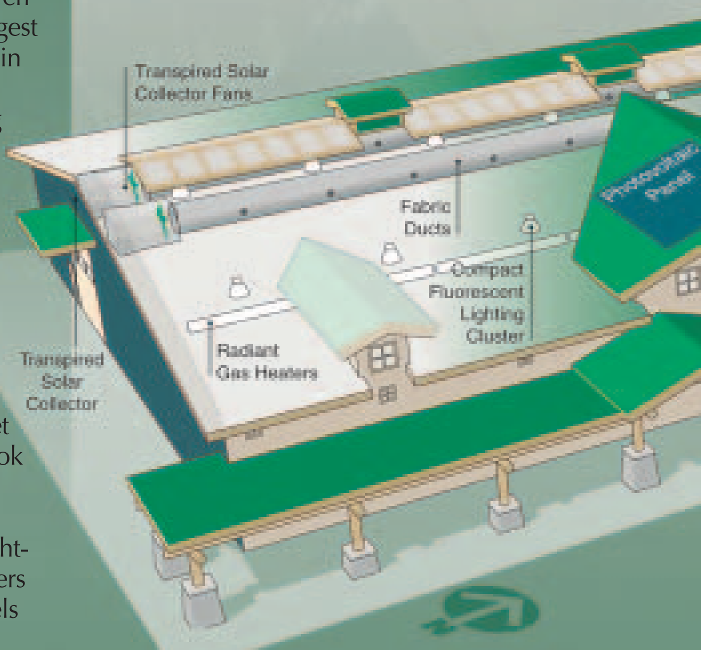
In fact, much of the focus in improving buildings today is taking knowledge gained in past research into the real world to test it there. These real-world test sites, or living laborato-

Shopping Mile High

Even high in the Colorado mountains, where winter temperatures cause heating challenges for any building, BigHorn's large, retail spaces and warehouse are consuming 62% less energy than a similar, conventional space. NREL's researchers helped to design and test, and continue to monitor the complex, which is breaking ground for the future of retail space with a lot of "firsts." The complex is one of the first retail buildings in the United States to use daylighting and natural ventilation cooling systems, the largest commercial photovoltaic array in Colorado (9-kW capacity), the state's first commercial building to have a standing-seam, roof-integrated PV system, and the first retail center in Colorado to have a net metering agreement (where electricity produced over the amount used is sold back to the utility). Inside the building, customers experience radiant floor heating, and large, operable windows that let in Colorado's bright sun and look out on the Rocky Mountains. A computer system automatically balances the ventilation and lighting levels to make sure customers have the optimum comfort levels for shopping.



The BigHorn high-performance building features PV, clerestory windows, daylighting, diffusing skylights, and solar wall. Anticipated energy cost savings from all the features, not including PV, is 62%.



ries, use technologies and research results from industry (as well as from laboratories) and look at them as a whole system—testing how all the separate pieces are functioning together. More important, living laboratories show how the various systems in the whole building can be more efficient and cost effective.

NREL's work in both the commercial building sector—schools, office buildings, and retail buildings—and the residential sector—single family homes, apartment buildings, and housing communities—helps move both markets forward by acting as a way for manufacturers, builders, and designers to find out how their products and technologies can be more effective.

Changing the Way We Work and Shop

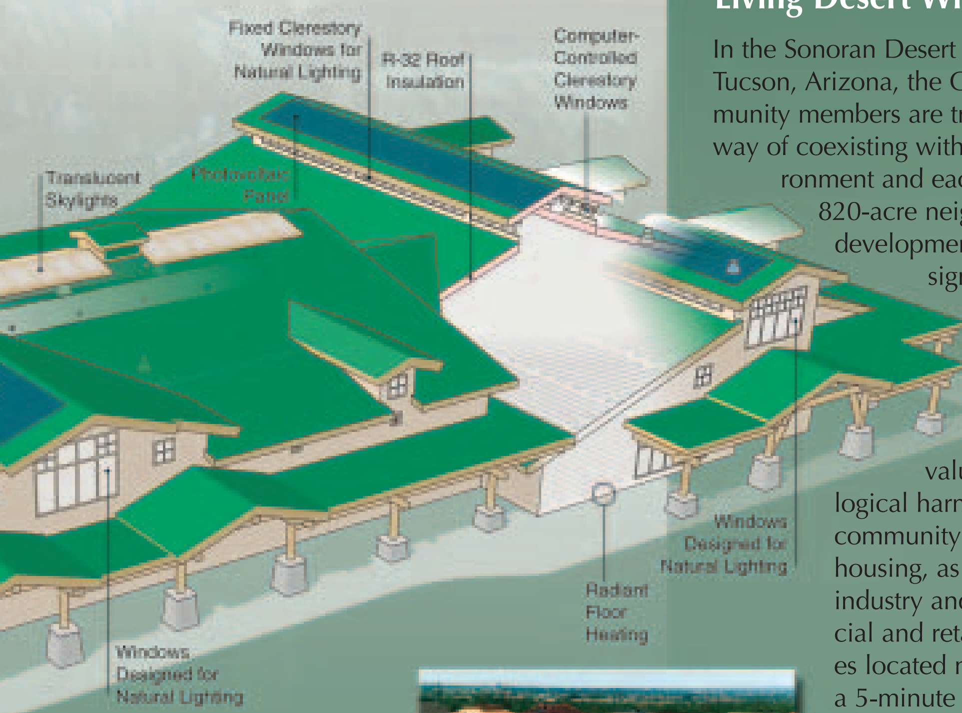
In the mountains of Colorado, the BigHorn Retail Complex in Silverthorne is one of the nation's first retail buildings to use natural daylight and ventilation cooling. The complex is designed to allow light into the building without creating too much heat, and because of careful design, no air-conditioning system is needed. A photovoltaic system integrated into the roof, along with energy-efficient features like a solar mass wall and compact fluorescent light fixtures, has reduced energy use by more than 60%.

BigHorn is one of many living laboratories testing the most advanced building technologies in the world. "Scientists have spent the last two decades measuring energy in buildings and finding out which technologies, by themselves, are most efficient," says High-Performance Buildings Task Leader Paul Torcellini. "Now," he says, "it's time to design a decision-making process to consider all the parts as a system."

"Designing efficient buildings is a process—based on hard science—that helps us build commercial buildings that are more environmentally sensitive and comfortable," Torcellini says. "In this stage of research, we're trying to weigh the benefits of different building features, instead of just testing windows or photovoltaic systems."

Changing the Way We Learn

In addition to being a living laboratory, where researchers hone energy efficiency and design technologies, Oberlin College's Center for Environmental Studies is a living classroom for students, where the building itself is the main topic of study. The building's wastewater is treated using a system of microbes, plants, snails, and insects. A solar electric system on the main south-



Living Desert Wise

Each home at the Civano development incorporates results of systems engineering developed by teams under the Building America program.

In the Sonoran Desert around Tucson, Arizona, the Civano community members are trying a new way of coexisting with the environment and each other. The 820-acre neighborhood development was designed to promote economic growth while focusing on social values and ecological harmony. The community supports housing, as well as light industry and commercial and retail businesses located no more than a 5-minute walk from the homes. Another goal of the community is to minimize the use of natural resources substantially below prevailing levels in comparable developments, in part by using renewable energy and creating building designs that are energy efficient—all the homes in Civano use less than 50% of the energy of a conventionally built home and all have solar water heaters. NREL's researchers have been monitoring the efficiency of Civano's homes, collecting data and creating virtual models of the buildings on computer to understand how energy is being used and how to improve performance.

The pool of the Civano development in Tucson, Arizona, uses a 6-kW photovoltaic installation to help meet the community's energy standard.

facing curved roof provides half of the electrical energy for the building. Overhanging eaves and trusses shade the summer sun while allowing winter heat gain. Natural light comes into the building through clerestories and south-facing windows, reducing the need for electrical lighting.

At the center, electronic sensors track light intensity, electricity produced by the solar electric panels, and energy consumed by the heating and ventilation systems. A monitoring system helps students and NREL researchers understand how a building interacts with its environment and how it behaves as a system.

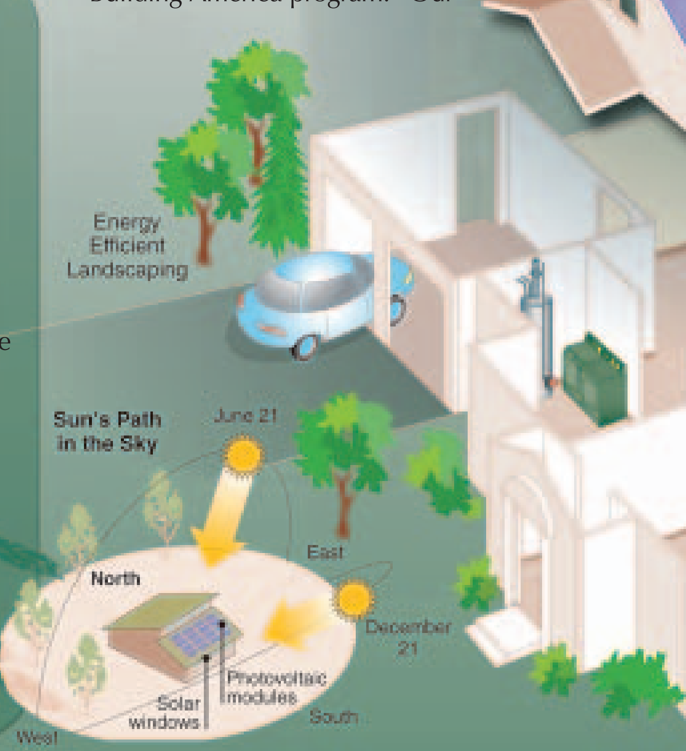
In many schools, students and researchers alike learn about energy efficiency and renewable technologies through partnerships—like the one with Oberlin—and programs like DOE's EnergySmart Schools. NREL's EnergySmart Schools Coordinator Patricia Plympton says that these programs are transitioning our schools to new ways of using and teaching about energy. "Sometimes students can teach us how to make classrooms more comfortable and productive using energy efficiency and renewable technologies," she says. "We're all learning from these living laboratories."

Changing the Way We Live

In the desert community of Civano, outside Tucson, Arizona, all homes use 50% less energy than a traditional home. The sun is used to heat water for swimming pools and homes, and photovoltaics help to offset electricity consumption. A network of bike and walking paths connect office buildings with homes to reduce the need for driving. Native landscaping and efficient building materials help the community live within the desert ecosystem, reducing water consumption and the need for air-conditioning.

Research on communities like Civano is helping scientists measure the effectiveness of technologies and improve designs. Energy performance is monitored and put into a computer system to model ways to make the homes even more efficient. This huge network of living laboratories is a catalyst for change in the home-building industry. Many large builders are starting to see the benefits of producing homes on a community scale that use 30% to 50% less energy, reduce construction time and waste by as much as 50%, and provide new product opportunities to manufacturers.

"We work with builders and designers, who are changing the way homes are built," said Paul Norton, NREL project manager for DOE's Building America program. "Our



Competing for the Future

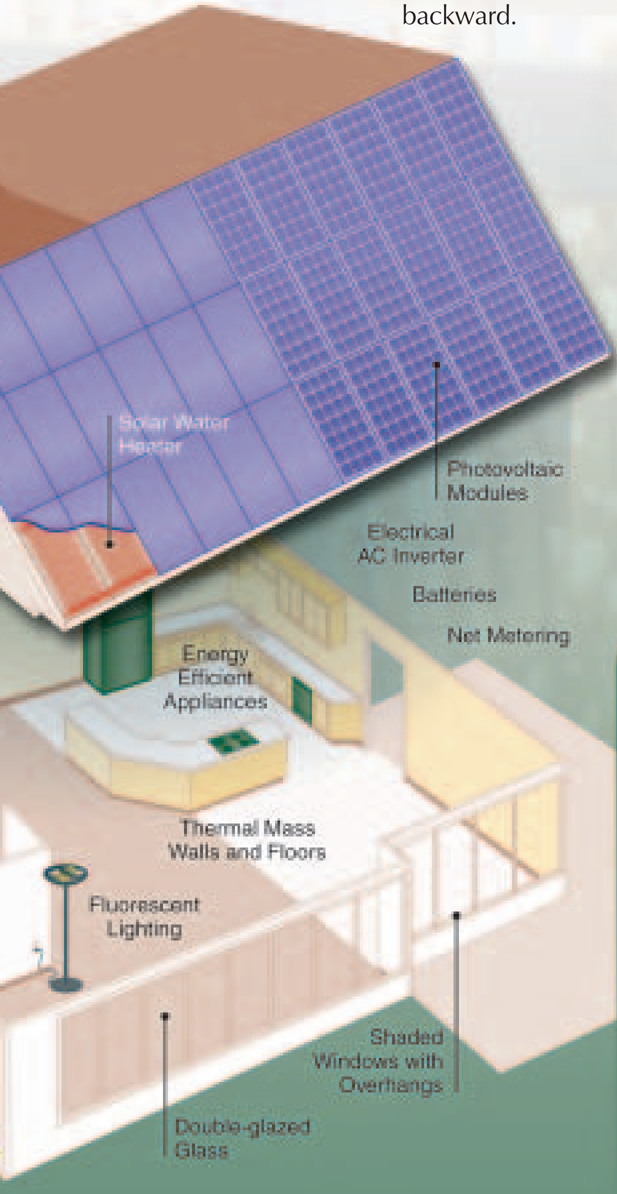
For eight days in 2002, 14 student teams will participate in a competition that will be a living laboratory for future designers, engineers, researchers, and communicators. The student teams will compete to capture, convert, store, and use enough solar energy to power a "home" they will build themselves on the Washington, DC, mall. Solar Decathletes will be required to provide all the energy for an entire household, including a home-based business and the transportation needs of the household and business. During the event, only the solar energy available within the perimeter of each house may be used to generate the power needed to compete in the ten Solar Decathlon contests. The Solar Decathlon, sponsored by DOE and administered by NREL, will educate consumers about solar energy and energy-efficient products and also guide the next generation of researchers, architects, engineers, and builders as they prepare to begin their careers.

The 2002 Solar Decathlon team from the University of Colorado at Boulder developed the design of their house in a collaborative effort between engineering and architecture students.

research develops and refines technologies to meet the builders' specific needs, and also to test performance to find solutions when things don't work the way we thought they would."

Getting to Zero—Buildings that Produce Energy

Compared to the off-grid, energy self-sufficient Earthships of the 1970s, the Solar Patriot house outside of Washington, D.C., is a space station. Many people have built homes that are self-sustaining, but the Solar Patriot house represents the first mass-market house that is connected to a power grid but not dependent on it. The house uses a photovoltaic system to generate electricity, aided by a solar hot-water system and passive solar design, which has been so successful that it has produced enough excess electricity to consistently spin its electric meter backward.



Installation of PV-integrated standing-seam metal roof panels.

Tim Merrigan, NREL project manager for the new DOE initiative for zero-energy homes, says that the Solar Patriot house is just one of the many zero-energy homes that will be tested during the next few years. NREL has awarded contracts to four teams of builders this past year to develop new kinds of designs for homes.

"Most people can't buy a zero-energy home today, but what does exist is a vast amount of knowledge that will make zero-energy homes available to everyone in the future—building technology research as well as long-term field testing of solar hot-water systems and photovoltaic systems," Merrigan said. "All that research exists and this program brings that research together. The Zero Energy Buildings program has very lofty goals, and we're on the brink of meeting those goals."

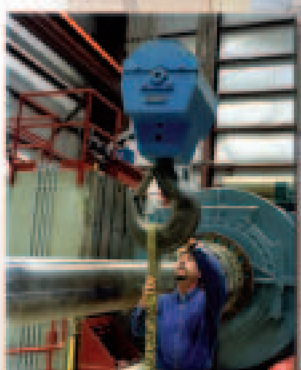
What if your house were a mini-power plant, your roof shingles were photovoltaic panels, and heat collecting walls heated your home? These technologies already exist today, and are already being used in living laboratories across the nation to hone them for efficient, large-scale use in the marketplace. It may sound futuristic, but buildings technologies like these are not far away.

A Future of Zero Energy

In a serene neighborhood just outside Washington, D.C., the Solar Patriot house is quietly heralding the next step in the transition to buildings of the future. The house is so efficient that its 6-kW photovoltaic system produced more electricity than the family used during 2-1/2 months in early fall 2001. Also during that time, the house remained fully powered, while the rest of the neighborhood went dark during eight power outages. In addition, the five-bedroom house is not only affordable for its rapidly growing area of the country, but its exterior needs no more maintenance than a conventional home. The standing-seam metal roof has a life expectancy of 40-50 years. Maintenance on the solar systems is minimal.

The "Solar Patriot," in Virginia has a 6-kW PV system, solar water heater, geothermal heat pump, compact fluorescent lighting, high-efficiency appliances,and low-e windows.

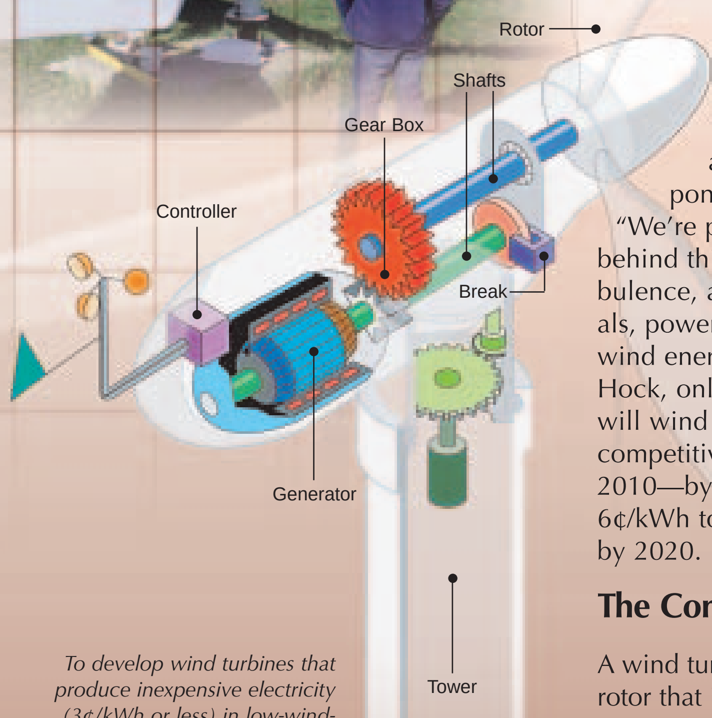
Research For A Low-Wind Future



With rotor diameters longer than football fields, wind turbines of the future will stand on towers 400 feet high, operate even in low-wind areas, and have adapting blades that change shape according to wind speed and direction. As researchers develop the technology to grow turbines to gargantuan size, they also are working to shrink efficient designs—small turbines effective for homes or small businesses.

Already, wind power has made great leaps in technology and price competitiveness during the past two decades. Since the early 1980s, the cost of wind power has decreased from 80¢/kWh (in 2002 dollars) to about 4¢/kWh in high-wind-speed areas. And market use of wind power is growing at record speed—in the past two years alone, the amount of electric capacity produced by wind energy in the United States has almost doubled to 4,500 MW.

The challenge for wind power as we make the transition to our energy future is to hone the technology to be even more cost competitive and to operate under even lower wind speeds. By operating efficient turbines at low wind speeds—an average of 13.5 miles per hour annually versus the 15 miles per hour necessary now—20 times more land in the nation will be able to cost effectively access wind power.



To develop wind turbines that produce inexpensive electricity (3¢/kWh or less) in low-wind-speed areas, researchers are studying all the components of a wind turbine—rotors (which include blades and hub), towers, gearboxes, generators, shafts, and controllers—to make them more effective and less expensive.

With this goal in mind, the U.S. Department of Energy, NREL, and other wind research organizations are focusing on developing, testing, and lowering the costs of turbine components that operate in lower speeds. "We're putting our whole research program behind this—aerodynamics, understanding turbulence, advanced controls, advanced materials, power electronics," says NREL's Sue Hock, wind energy technology manager. According to Hock, only with continued low-wind research will wind power reach its goal of being cost competitive at low wind speeds with fuels by 2010—by bringing low-wind costs down from 6¢/kWh to 3¢/kWh, and even to below 2¢/kWh by 2020.

The Components of Wind Turbines

A wind turbine is composed of blades turning a rotor that is situated on top of a tower. Drivetrain components (which can include generators, gearboxes, shafts, and bearings) transfer the slow-rotating mechanical energy from the rotor and convert it to electrical energy. Researchers are studying all of these components to make them more effective and less expensive to manufacture and operate.

Modern wind turbines, such as these in Northern Colorado, generate competitive electricity in high-wind-speed areas. NREL's research is aimed at developing wind turbines that generate inexpensive electricity in low-wind-speed areas, opening up a vast wind resource for the nation.

One NREL program called WindPACT (Wind Partnerships for Advanced Component Technologies) combines laboratory research with applied, industry research to improve low-wind components. Promising research ideas and concepts generated in the laboratory are further developed and tested by a joint team of industry and laboratory researchers through WindPACT. Partnerships between new industry members and existing wind companies are encouraged, so the program attracts new organizations and ideas into the arena.

Making Towers Taller

One WindPACT study looks at how towers can be improved. Because wind speed increases with height above the ground, taller towers can find higher wind speeds even in lower-wind areas. But taller tower designs being tested now, between 200 and 300 feet, are still causing serious logistics problems during installation. The study found several alternative methods of constructing very tall towers, ranging from self-erecting concrete towers to telescoping tubes or jack-up devices. This work will form the foundation for further study by designers of low-wind technologies in the years ahead.

Sharpening Blades

Blade designs and manufacturing processes are also being honed for low-wind speeds. Transporting 300-foot blades across the country can be expensive and complicated—so researchers are looking at ways to set up mobile manufacturing "factories" at the site where the blades will be installed. WindPACT also found that new and lighter-weight materials will be necessary to grow blades to the larger sizes necessary. In addition to fiberglass (the material currently used) researchers are looking at carbon, which is stronger and lighter weight than fiberglass, or glass-carbon hybrids.

A blade for a 750-kW wind turbine is being fatigue tested at NREL's Industrial User Facility.

Testing the Wind

NREL's National Wind Technology Center (NWTC) south of Boulder, Colorado, houses the nation's most advanced, state-of-the-art facilities for testing wind energy systems. Eleven turbines—up to 600-kW capacity—tower over the plains, silhouetted by the foothills of the Rocky Mountains. Some of the wind turbines are prototypes of new designs, and others are baseline machines used for testing innovative components and control strategies.

Walt Musial, NREL's development testing team leader, says the wind site provides services to industry that they usually don't have access to: "This kind of testing and these kinds of facilities can be too expensive and too difficult to set up for one manufacturer." And, he says, the National Wind Technology Center's facilities are unique—the only blade-testing laboratory in North America that can test megawatt-scale blades and the only dynamometer facility that can do full-system wind turbine testing.

Through the installation and testing of these diverse kinds of turbines, researchers are learning how they operate and perform and how to enhance computer-aided analysis and design. During the next several years, NREL plans to install as many as 16 more experimental turbines at the center.

At NREL's Dynamometer Test Facility, a drivetrain for a 750-kW wind turbine undergoes tests to measure loading under realistic conditions and endurance tests to verify design life.

The site also hosts three specialized test facilities: The 10,000-square-foot Industrial User Facility tests the performance and structural reliability of individual wind turbine blades up to 85 feet long. This facility is the center for collaborative activities with the wind industry, and its unique building design enables several wind energy companies to simultaneously disassemble turbines, analyze the individual components, and modify the components while protecting proprietary information.

The Dynamometer Test Facility was constructed in response to industry requests. The facility gives engineers the ability to conduct lifetime endurance tests on a wide range of wind turbine drivetrains, gearboxes, brakes, control systems, and generators at various speeds, using low or high torque. A few months of testing on the dynamometer can simulate the equivalent of 30 years of use and a lifetime of braking cycles. Thus, engineers can determine which components are susceptible to wear and need redesigning to improve reliability and endurance of the components.

At the Hybrid Power Test Facility, researchers test existing systems and develop advanced controls for systems that use a variety of renewable and nonrenewable sources. The facility provides both real and simulated wind and photovoltaic energy sources, battery banks, and diesel generators, and allows testing under controlled combinations of solar and wind resources.

Secure Energy for our Nation's Security

September 11 changed America. It changed our belief that our shores were immune to attack. It changed the way in which many of us do business. It changed our idea of how our freedoms and our security are intertwined.

And it changed our concept of how important energy security—especially in the form of homegrown and diverse energy supplies—is to national security.

President Bush has stated that "one of the keys to energy security in America, and national security, is to have a diversified energy base," and that "Over-dependence on any one source of energy, especially a foreign source, leaves us vulnerable to price shocks, supply interruptions, and…blackmail."

(Top) Wind turbines generate electricity for a U.S. Naval base on San Clemente Island. (Center) Solar wall provides heat and ventilation for a helicopter maintenance hangar at Fort Carson in Colorado Springs. (Bottom) A solar electric panel supplies power for refrigerating vaccines at a remote health center. (Background) Biomass-derived fuel supplements fossil fuel used in a U.S. Army vehicle. Solar arrays provide 15 kW of supplemental power for the Pentagon.

Blackmail, indeed, and worse—sabotage of energy supplies in an effort to choke the vitality of our economy, eviscerate the vigor of our way of life, and curb our hard-won freedoms.

It is no wonder, then, that Secretary of Energy Spencer Abraham has stated that ". . . energy and science programs should be judged by whether they advance this nation's energy—and hence, national—security."

The R&D that NREL performs for the Department of Energy on renewable energy and energy efficiency is well placed in this regard.

When NREL began its mission 25 years ago, the popular refrain was, "No one can embargo the sun." Well, no one can embargo or disrupt energy that isn't spent, either—such as the energy saved through energy-efficient technologies. We can incorporate energy efficiency into every home, building, business, industry, and vehicle. And the simple fact is, the more efficient you become, the less vulnerable you are to disruptions of energy supply.

And renewable energy? The technologies and the energy resources for renewable energy are homegrown. We unravel the science, develop the technologies, and manufacture the systems here, in America. And the resources themselves—sunshine, wind, water, biomass, and the heat of the Earth—are vast, ubiquitous, safe, and uninterruptible here, in America.

And it is in America that we can use these resources and technologies to enhance national security. We can enhance it directly through our national defense by using energy efficiency technologies to improve fuel efficiencies for a wide range of weapons platforms and to make supply lines less vulnerable. We can employ biomass-derived fuels to supplement other fuels for strategic military purposes. And we can deploy photovoltaic systems for remote or mobile field service.

Photovoltaic systems, in fact, have long played an important military and strategic role. They are the preferred power supply for the Earth-orbiting satellites that the U.S. military and intelligence agencies rely on for gathering and communicating information from around the world.

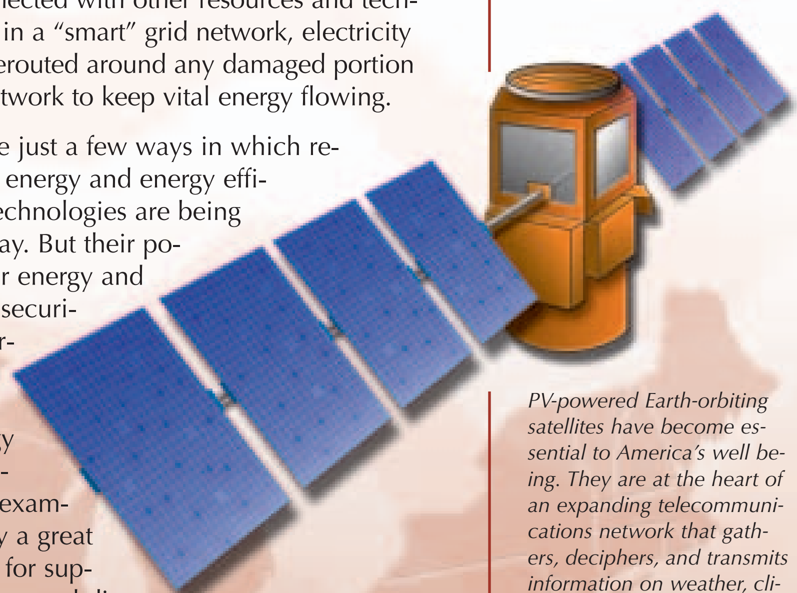
But renewable energy and energy efficiency technologies are equally important for other aspects of our national security. For example, certain liquid desiccants—often used for building dehumidification and cooling—are well known for their ability to absorb water. But they also can absorb a wide variety of suspended particles from the air, including potentially pathogenic bacterial and fungal spores. As a consequence, air-conditioning equipment based on liquid desiccants may prove to be a valuable technology for removing and destroying potential airborne pathogens—depending on how well the liquid desiccant-based air conditioner can remove these particles from the air and how effective the liquid-desiccant material is in deactivating the absorbed pathogens. Currently, researchers are investigating both of these issues.

Bacteria and viruses can also be easily filtered out of our water supply with an R&D 100 Award-winning technology developed by NREL and its partners. This technology is based on nanoscale ceramic fibers that have an extremely high surface area and a chemical affinity that makes them particularly adept for filtration of microbial pathogens and viruses whose sizes range from a few nanometers to a few micrometers. This material is also ideal for purifying blood plasma, sampling and detecting pathogens in lakes and streams, and removing heavy metals from water.

And consider again those PV-powered, Earth-orbiting satellites. They are at the heart of telecommunications, which has become fundamental to the way the nation communicates and does business. Telecommunications also has become extremely valuable in times of disaster—natural or man-induced—for keeping communications open and for locating people and areas of concern. And because photovoltaics and other renewable energy systems are portable and can be employed stand-alone, in times of disaster they can be used to refrigerate vital medical supplies and to provide power for critical services.

Renewable energy and energy efficiency technologies represent the ultimate distributed resource. For example, renewable electric technologies—photovoltaics, wind energy, concentrated solar power, bioelectric units—add redundancy, security, and reliability to any system, whether for a single home, a business, a repeater station, a community, or for an entire grid network. With renewable electric systems interconnected with other resources and technologies in a "smart" grid network, electricity can be rerouted around any damaged portion of the network to keep vital energy flowing.

These are just a few ways in which renewable energy and energy efficiency technologies are being used today. But their potential for energy and national security is enormous.



PV-powered Earth-orbiting satellites have become essential to America's well being. They are at the heart of an expanding telecommunications network that gathers, deciphers, and transmits information on weather, climate, aerosols, communications, oceans, volcanoes, trace gases, storms, disasters, troop movements, and much more.

Bioenergy technologies, for example, carry a great prospect for supplementing and displacing imported fossil fuels and for supplying feedstock for chemicals, fibers, and other materials. And one day we will be able to use renewable energy to generate hydrogen in almost any locality of the nation, and then to use that hydrogen to fuel our aircraft, heat our homes and offices, power our cars, and provide us with electricity.

In these and many other ways, renewable energy and energy efficiency technologies will help reshape America's energy infrastructure from one that relies heavily on foreign supplies and centrally delivered power to one that is decentralized and more dependent on domestic and local resources. And they will help move America toward a more secure energy future.

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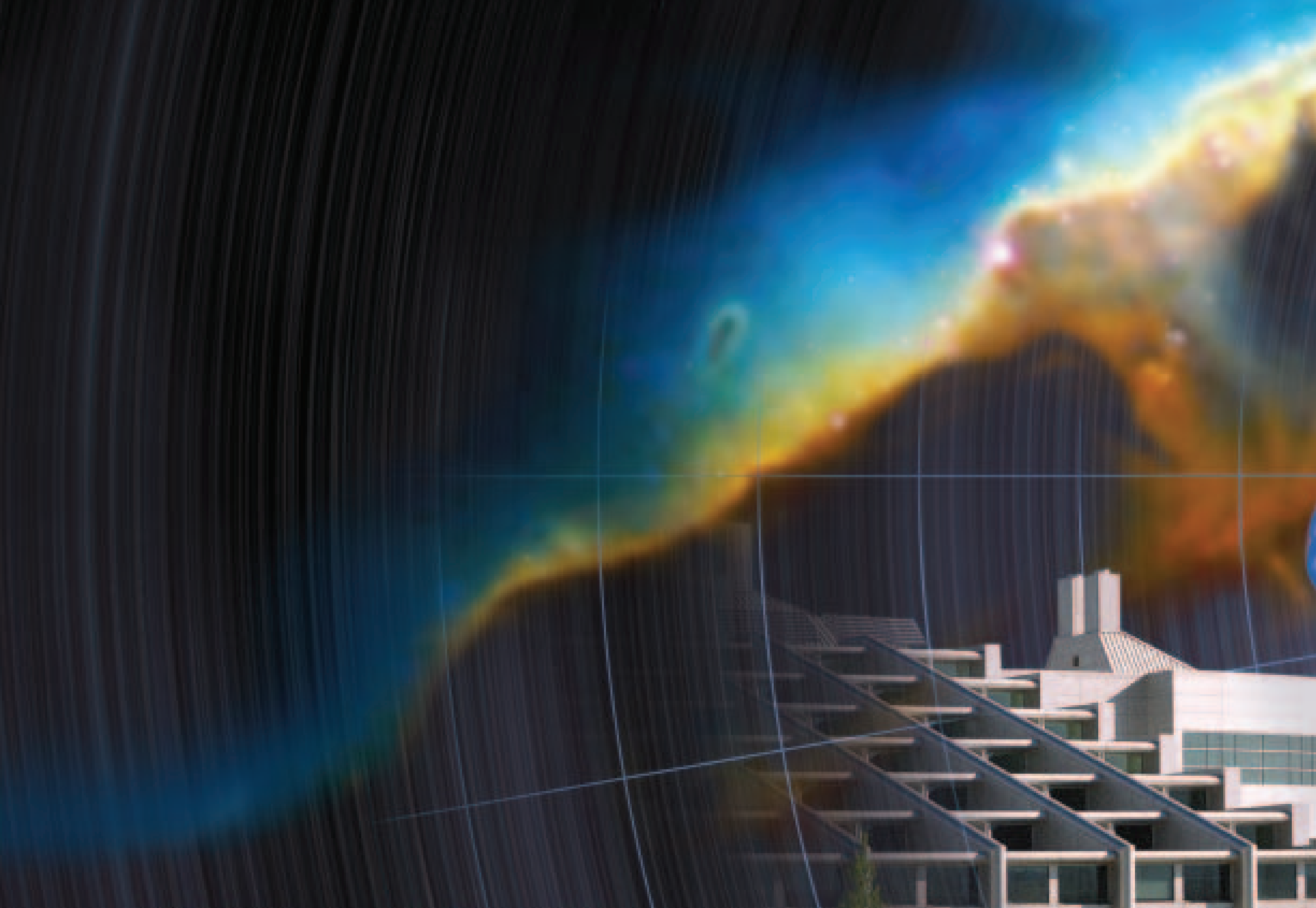

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